MIL-HDBK-23A
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MILITARY HANDBOOK

# STRUCTURAL SANDWICH COMPOSITES

DEPARTMENT OF DEFENSE
Washington, D.C. 20025

FSC 1500

MIL-HDBK-23A
NOTICE 3
19 June 1974

MILITARY STANDARDIZATION HANDBOOK

STRUCTURAL SANDWICH COMPOSITES

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1. On the second page of the Table of Contents under Chapter 4, delete the existing page numbers and substitute the following page numbers for the paragraphs indicated:

| Paragraph Number | New Page Number |
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| 4.1 | 4-1 |
| 4.2 | 4-1 |
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STRUCTURAL SANDWICH COMPOSITES

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STRUCTURAL SANDWICH COMPOSITES

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1. On the third page of the Table of Contents under Chapter 9 delete the existing page numbers and substitute the following page numbers for the paragraphs indicated:

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| 9.3 | 9-8 |
| 9.4 | 9-8 |
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| 9-1 thru 9-13 | 9 Mar 1972 | 9-1 thru 9-11 | 30 Dec 1968 |
| 9-14 thru 9-39 | 9 Mar 1972 | Figures 9-1 thru 9-11 (pages unnumbered) | 30 Dec 1968 |

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# STRUCTURAL SANDWICH COMPOSITES

## MIL-HDBK-23A

1. This standardization handbook has been developed and is being maintained as a joint effort by the Department of Defense and the Federal Aviation Agency.

2. The information contained in this publication has been obtained from numerous sources, including materials producers, the airframe and missile industry, reports on Government-sponsored research, the open literature, by contract with research laboratories, particularly the U.S. Forest Products Laboratory, and from members of the MIL-HDBK-23 Working Group.

3. Every effort has been made to reflect the latest information on design, fabrication methods, inspection procedures, durability, and repair techniques of sandwich composites for aerospace vehicles. It is the intent to review this handbook periodically to insure its completeness and accuracy. Users of this document are encouraged to report any errors discovered and recommendations for changes or inclusions to Air Force Flight Dynamics Laboratory, Structures Division (FDTS), Wright-Patterson Air Force Base, Ohio, 45433.

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## NOTATION

The following notation is used throughout the Handbook. Additionally, portions of the Handbook devoted to a particular component define the symbols used for the first time in that portion. An occasional symbol not in general use will appear in specific areas and not be included in this notation. Figure 1-2 shows notation for sandwich construction.

Units of dimensions, forces, stresses, constants, and other quantities are not specified unless they are employed in formulas wherein numerical coefficients are not non-dimensional. In applying formulas for which units are not specified, correct results will not be obtained unless units are consistent--for example: If thicknesses are given in inches and forces in pounds, then the length and width of a panel must be in inches (not feet) to give stresses in pounds per square inch.

1 - Subscript denoting facing 1 of a sandwich
2 - Subscript denoting facing 2 of a sandwich
a, b - Length of panel edge; subscripts denoting parallel to a or b edge
B - Subscript denoting bond or bending
c - Subscript denoting core or compression
cr - Subscript denoting critical
D - Bending stiffness or twisting stiffness depending on subscripts
d - Total sandwich depth or thickness
E - Young's modulus of elasticity; for orthotropic facing $E = \sqrt{E_a E_b}$
E' - Effective modulus of elasticity; for orthotropic facings $E' = \sqrt{E'_a E'_b}$
F - Allowable stress; subscript denoting facings when applied to buckling coefficients
$F_{12}$ - Geometric view factor between sandwich facings
f - Calculated stress
G - Modulus of rigidity; with subscripts $G_{ab}$ is the modulus of rigidity associated with shear distortion of the ab plane
G' - Effective modulus of rigidity
H - Extensional stiffness
h - Distance between facing centroids
K - A coefficient
L - Length, core axis (see chapter 2 for details)
M - Bending moment; subscript denoting behavior of sandwich with thin facings when applied to buckling coefficients.
m - Half width of corrugation or number of half waves
N - Load per unit length of edge
n - Number of half waves
O - Subscript denoting V = 0.

o - Subscript denoting honeycomb core ribbon or core corrugation sheet
P - Load
p - Intensity of distributed load
r - Radius; subscript denoting reduced
R - Ratio
S - Shear load normal to surface of panel
s - Core cell size; subscript denoting shear when applied to stress and secant when applied to moduli
T - Torque; core axis (see chapter 2 for details); facing dissimilarity index $T = \dfrac{1}{1 + \dfrac{E'_2 t_2}{E'_1 t_1}}$
$T_m$ - Mean temperature
t - Thickness; without subscript denotes facing thickness; subscript denoting tangent when applied to moduli
U - Transverse shear stiffness
u - Subscript to stress denoting ultimate
V - Parameter relating shear and bending stiffness
W - Weight; core axis (see chapter 2 for details) special parameter relating shear and bending stiffness for sandwich with corrugated core
w - Density; subscript denoting wrinkling
x - Axis; subscript denoting parallel to x-axis
y - Axis perpendicular to x-axis; subscript denoting parallel to y-axis; or denoting yield when applied to stress
z - Axis normal to surface of sandwich; subscript denoting parallel to z-axis
$\alpha$ - $\sqrt{E'_b/E'_a}$
$\beta$ - $\alpha\mu_{ab} + 2\gamma$
$\gamma$ - Shear strain; elastic property parameter $\gamma = \dfrac{\lambda G'_{ba}}{\sqrt{E'_a E'_b}}$
$\delta$ - Deflection
$\epsilon$ - Compression or extension strain; emissivity
$\eta$ - Plasticity coefficient; convective heat transfer coefficient
$\lambda$ - One minus the product of two Poisson's ratios $\lambda = 1 - \mu_{ab}\mu_{ba}$
$\mu$ - Poisson's ratio; with subscripts $\mu_{ab}$ is the ratio of contraction in the b direction to extension in the a direction due to a tensile stress in the a direction.
$\rho$ - Radius of gyration
$\sigma$ - Stefan-Boltzmann constant

## Conversion of U.S. Customary Units to SI Units[1]

| Quantity | U.S. Customary unit | Conversion factor[2] | SI Unit |
|---|---|---|---|
| Density | lbm/in.$^3$ | $27.68 \times 10^3$ | kilograms/meter$^3$ (kg/m$^3$) |
| | lbm/ft$^3$ | 16.02 | kilograms/meter$^3$ (kg/m$^3$) |
| Length | ft | 0.3048 | meters (m) |
| | in. | 0.0254 | meters (m) |
| Stress | psi | $6.895 \times 10^3$ | newtons/meter$^2$ (N/m$^2$) |
| Pressure | lb/in.$^2$ | $6.895 \times 10^3$ | newtons/meter$^2$ (N/m$^2$) |
| | lb/ft$^2$ | 47.88 | newtons/meter$^2$ (N/m$^2$) |
| Moduli { Elasticity, Rigidity } | psi | $6.895 \times 10^3$ | newtons/meter$^2$ (N/m$^2$) |
| Temperature | (°F + 460) | 5/9 | degrees Kelvin (°K) |
| Thermal conductivity | Btu in./hr ft$^2$ °F | 0.1240 | kg cal/hr m °C |

Prefixes to indicate multiples of units are as follows:

| Prefix | Multiple |
|---|---|
| giga (G) | $10^9$ |
| mega (M) | $10^6$ |
| kilo (k) | $10^3$ |
| milli (m) | $10^{-3}$ |
| micro (μ) | $10^{-6}$ |

[1] The International System of Units [Systeme International (SI)] was adopted by the Eleventh General Conference on Weights and Measures, Paris, Oct. 1960, in Resolution No. 12.

[2] Multiply value given in U.S. Customary Unit by conversion factor to obtain equivalent value in SI unit.

# STRUCTURAL SANDWICH COMPOSITES

## CHAPTER 1

## INTRODUCTION

### 1.1 SCOPE

Military Handbook 23 has been prepared for use in the design of structural sandwich composites, primarily for flight vehicles. Information presented includes design procedures, fabrication methods, inspection procedures, and repair techniques for both military and commercial vehicles. Methods and procedures other than those given herein are also acceptable, provided they give comparable results or are properly substantiated. This Handbook replaces the several parts previously published as the ANC-23 Bulletin, and more recently as Parts I and III of Military Handbook 23.

Structural design information is presented in a form for rapid calculation for sandwich construction. Formulas and charts for the solution of the formulas are given for the initial design of sandwich components. The charts are entered with parameters based on dimensions and material properties. Check of designs can be made with formulas and curves presented for various components. Limitations of formulas and charts are indicated and reference is made to more detailed analyses presented in other publications.

The design procedures are based principally on analyses and tests performed by the U.S. Forest Products Laboratory under the sponsorship of the MIL-HDBK-23 Working Group on Structural Sandwich Composites for Aerospace Vehicles (formerly ANC-23 Panel).

## 1.2 BASIC DESIGN PRINCIPLES

Structural sandwich is a layered composite formed by bonding two thin facings to a thick core. It is a type of stressed-skin construction in which the facings resist nearly all of the applied edgewise (in-plane) loads and flatwise bending moments. The thin spaced facings provide nearly all of the bending rigidity to the construction. The core spaces the facings and transmits shear between them so that they are effective about a common neutral axis. The core also provides most of the shear rigidity of the sandwich construction. By proper choice of materials for facings and core, constructions with high ratios of stiffness to weight can be achieved.

A basic design concept is to space strong, thin facings far enough apart to achieve a high ratio of stiffness to weight; the lightweight core that does this also provides the required resistance to shear and is strong enough to stabilize the facings to their desired configuration through a bonding medium such as an adhesive layer, braze, or weld. The sandwich is analogous to an I-beam in which the flanges carry direct compression and tension loads, as do the sandwich facings, and the web carries shear loads, as does the sandwich core.

In order that sandwich cores be lightweight, they are usually made of low-density material, some type of cellular construction (honeycomb-like core formed of thin sheet material), or of corrugated sheet material. As a consequence of employing a lightweight core, design methods account for core shear deformation because of the low effective shear modulus of the core. The main difference in design procedures for sandwich structural elements as compared to design procedures for homogeneous material is the inclusion of the effects of core shear properties on deflection, buckling, and stress for the sandwich.

Because thin facings can be used to carry loads in a sandwich, prevention of local failure under edgewise direct or flatwise bending loads is necessary just as prevention of local crippling of stringers is necessary in the design of sheet-stringer construction. Modes of failure that may occur in sandwich under edge load are shown in figure 1-1.

Shear crimping failure (fig. 1-1B) appears to be a local mode of failure, but is actually a form of general overall buckling (fig. 1-1A) in which the wavelength of the buckles is very small because of low core shear modulus. The crimping of the sandwich occurs suddenly and usually causes the core to fail in shear at the crimp; it may also cause shear failure in the bond between the facing and core.

Crimping may also occur in cases where the overall buckle begins to appear and then the crimp occurs suddenly because of severe local shear stresses at the ends of the overall buckle. As soon as the crimp appears, the overall buckle may disappear. Therefore, although examination of the failed sandwich indicates crimping or shear instability, failure may have begun by overall buckling that finally caused crimping.

If the core is of cellular (honeycomb) or corrugated material, it is possible for the facings to buckle or dimple into the spaces between core walls or corrugations as shown in figure 1-1C. Dimpling may be severe enough so that permanent dimples remain after removal of load and the amplitude of the dimples may be large enough to cause the dimples to grow across the core cell walls and result in a wrinkling of the facings.

Wrinkling, as shown in figure 1-1D, may occur if a sandwich facing subjected to edgewise compression buckles as a plate on an elastic foundation. The facing may buckle inward or outward, depending on the flatwise compressive strength of the core relative to the flatwise tensile strength of the bond between the facing and core. If the bond between facing and core is strong, facings can wrinkle and cause tension failure in the core. Thus, the wrinkling load depends upon the elasticity and strength of the foundation system; namely, the core and the bond between facing and core. Since the facing is never perfectly flat, the wrinkling load will also depend upon the initial eccentricity of the facing or original waviness.

The local modes of failure may occur in sandwich panels under edgewise loads or normal loads. In addition to overall buckling and local modes of failure, sandwich is designed so that facings do not fail in tension, compression, shear, or combined stresses due to edgewise loads or normal loads, and cores and bonds do not fail in shear, flatwise tension, or flatwise compression due to normal loads.

The basic design principles can be summarized into four conditions as follows:

1. Sandwich facings shall be at least thick enough to withstand chosen design stresses under design[1] loads.

2. The core shall be thick enough and have sufficient shear rigidity and strength so that overall sandwich buckling, excessive deflection, and shear failure will not occur under design[1] loads.

---

[1] Design load shall be "design ultimate load" when composite structures are to be designed for use in military aircraft where the requirements of Military Specification MIL-S-8698 and series MIL-A-8860 through MIL-A-8870 are applicable.

3. The core shall have high enough moduli of elasticity, and the sandwich shall have great enough flatwise tensile and compressive strength so that wrinkling of either facing will not occur under design[1] loads.

4. If the core is cellular (honeycomb) or of corrugated material and dimpling of the facings is not permissible, the cell size or corrugation spacing shall be small enough so that dimpling of either facing into the core spaces will not occur under design[1] loads.

The choice of materials, methods of sandwich assembly, and material properties used for design shall be compatible with the expected environment in which the sandwich is to be utilized. For example, facing to core bonding shall have sufficient flatwise tensile and shear strength to develop the required sandwich panel strength in the expected environment. Included as environment are effects of temperature, water or moisture, corrosive atmosphere and fluids, fatigue, creep, and any condition that may affect material properties.

Certain additional characteristics, such as thermal conductivity, resistance to surface abrasion, dimensional stability, permeability, and electrical properties of the sandwich materials should be considered in arriving at a thoroughly efficient design for the intended purpose.

Detailed procedures giving formulas and graphs for use in structural design are given in subsequent sections of this Handbook. The formulas and graphs can be used to determine dimensions of facings and core as well as necessary core properties for sandwich components under various types of loads. Graphs and formulas are presented in terms of general parameters, and are not for specific materials. Design procedures involving buckling are based on theoretical buckling coefficients. These coefficients are in fair agreement with average test results, but allowance can be made in the final design to account for the scatter characteristic of buckling test results, perhaps by choosing a slightly thicker core, so that buckling of the sandwich component does not occur at design load.

## 1.3 FUNDAMENTAL FORMULAS

In the development of formulas for deflection, stresses, and buckling of sandwich components, mathematical expressions for bending, extensional, and shear stiffness often appear as do parameters involving these stiffnesses. It is convenient to present the fundamental stiffness formulas at the outset. Here also are discussed the effects of facing and core stiffness on sandwich bending stiffness so that the degree of approximation implied by simplified formulas neglecting facing and core stiffness is known.

## 1.3.1 Sandwich Bending Stiffness

A structural sandwich under forces normal to its facings has a bending stiffness, per unit width, given by the formula

$$D = \frac{1}{\frac{E'_1t_1}{\lambda_1} + \frac{E'_ct_c}{\lambda_c} + \frac{E'_2t_2}{\lambda_2}} \left[ \frac{E'_1t_1}{\lambda_1} \cdot \frac{E'_2t_2}{\lambda_2} h^2 + \frac{E'_1t_1}{\lambda_1} \cdot \frac{E'_ct_c}{\lambda_c} \left( \frac{t_1 + t_c}{2} \right)^2 + \frac{E'_2t_2}{\lambda_2} \cdot \frac{E'_ct_c}{\lambda_c} \left( \frac{t_2 + t_c}{2} \right)^2 \right] + \frac{1}{12} \left[ \frac{E'_1t_1^3}{\lambda_1} + \frac{E'_ct_c^3}{\lambda_c} + \frac{E'_2t_2^3}{\lambda_2} \right] \qquad (1:1)$$

where E' is the effective modulus of elasticity of facing; $E'_c$ is effective core elastic modulus in the appropriate L or W direction*--not the T direction--(see chapter 2 for details); $\lambda$ is one minus the product of two Poisson's ratios ($\lambda = 1 - \mu_{ab}\mu_{ba}$); t is facing thickness; 1 and 2 are subscripts denoting facing 1 and 2; $t_c$ is core thickness; and h is distance between facing centroids. (See sketch of figure 1-2 for notation.) For many combinations of facing materials it will be found advantageous to choose thicknesses such that $E_1t_1 = E_2t_2$.

For sandwich with facings of the same material and thickness, formula (1:1) reduces to

$$D = \frac{E'th^2}{2\lambda} + \frac{1}{12} \left( \frac{2E't^3}{\lambda} + \frac{E'_ct_c^3}{\lambda_c} \right) \qquad (1:1a)$$

which can also be written as

$$D = K \frac{E'th^2}{2\lambda} \qquad (1:1b)$$

The second term of formula (1:1a) incorporating facing stiffness and core stiffness is neglected for most sandwich. The effect of this second term in increasing basic sandwich stiffness is obtained from values of K (formula 1:1b) shown graphically in figure 1-3.

*For honeycomb cores the elastic moduli (not shear moduli) parallel and perpendicular to the core ribbon (L or W direction) are essentially zero.

If the sandwich has thin facings on a core of negligible bending stiffness, as is usually the case, and after assuming $\lambda_1 = \lambda_2 = \lambda$, the bending stiffness is given by the formula:

$$D = \frac{E'_1 t_1 E'_2 t_2 h^2}{(E'_1 t_1 + E'_2 t_2)\lambda} \quad \text{(for unequal facings)} \qquad (1{:}2)$$

$$D = \frac{E' t h^2}{2\lambda} \quad \text{(for equal facings)} \qquad (1{:}2a)$$

## 1.3.2 Sandwich Extensional Stiffness

The extensional stiffness of a sandwich, stretched or compressed by force in its plane, is given by the formula.

$$H = E'_1 t_1 + E'_2 t_2 + E'_c t_c \qquad (1{:}3)$$

$$H = 2E' t + E'_c t_c \quad \text{(for equal facings)} \qquad (1{:}3a)$$

## 1.3.3 Sandwich Shear Stiffness

A sandwich that has fairly thin facings on a thick core has a transverse shear stiffness per unit width given approximately by the formula

$$U = \frac{h^2}{t_c} G_c \approx h G_c \qquad (1{:}4)$$

where $t_c$ is the core thickness and $G_c$ is the core shear modulus associated with the distortion of the TL or TW plane (see chapter 2 for details).

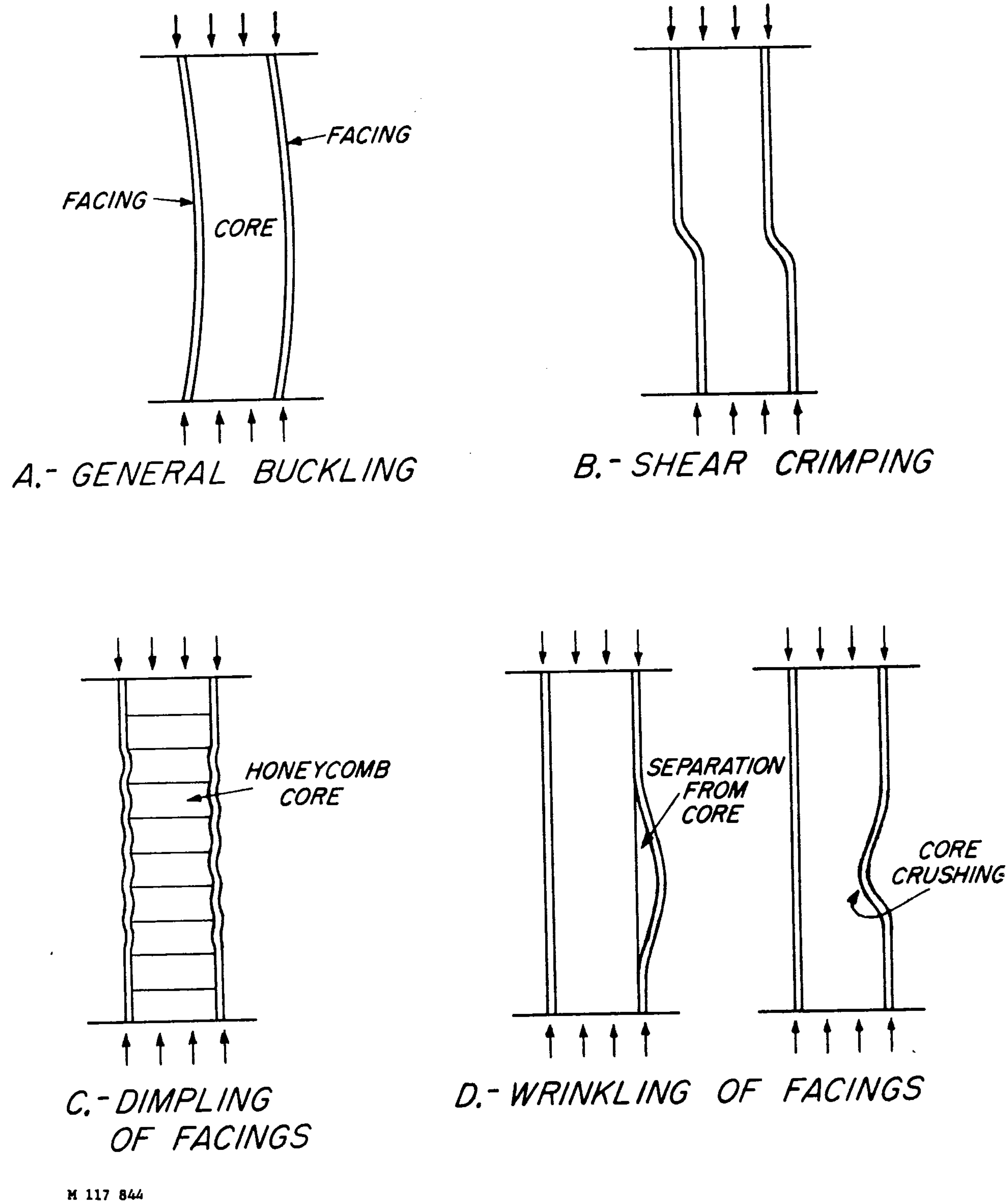


Figure 1-1.--Possible modes of failure of sandwich composite under edgewise loads: General buckling, shear crimping, dimpling of facings, and wrinkling of facings either away from or into the core.

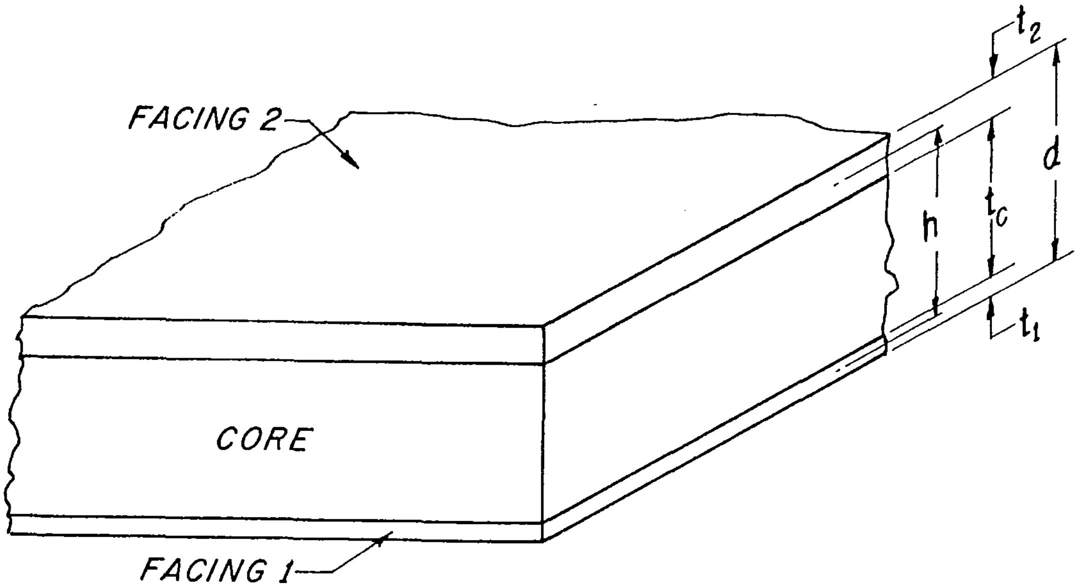


Figure 1-2.--Sketch showing notation for sandwich composite.

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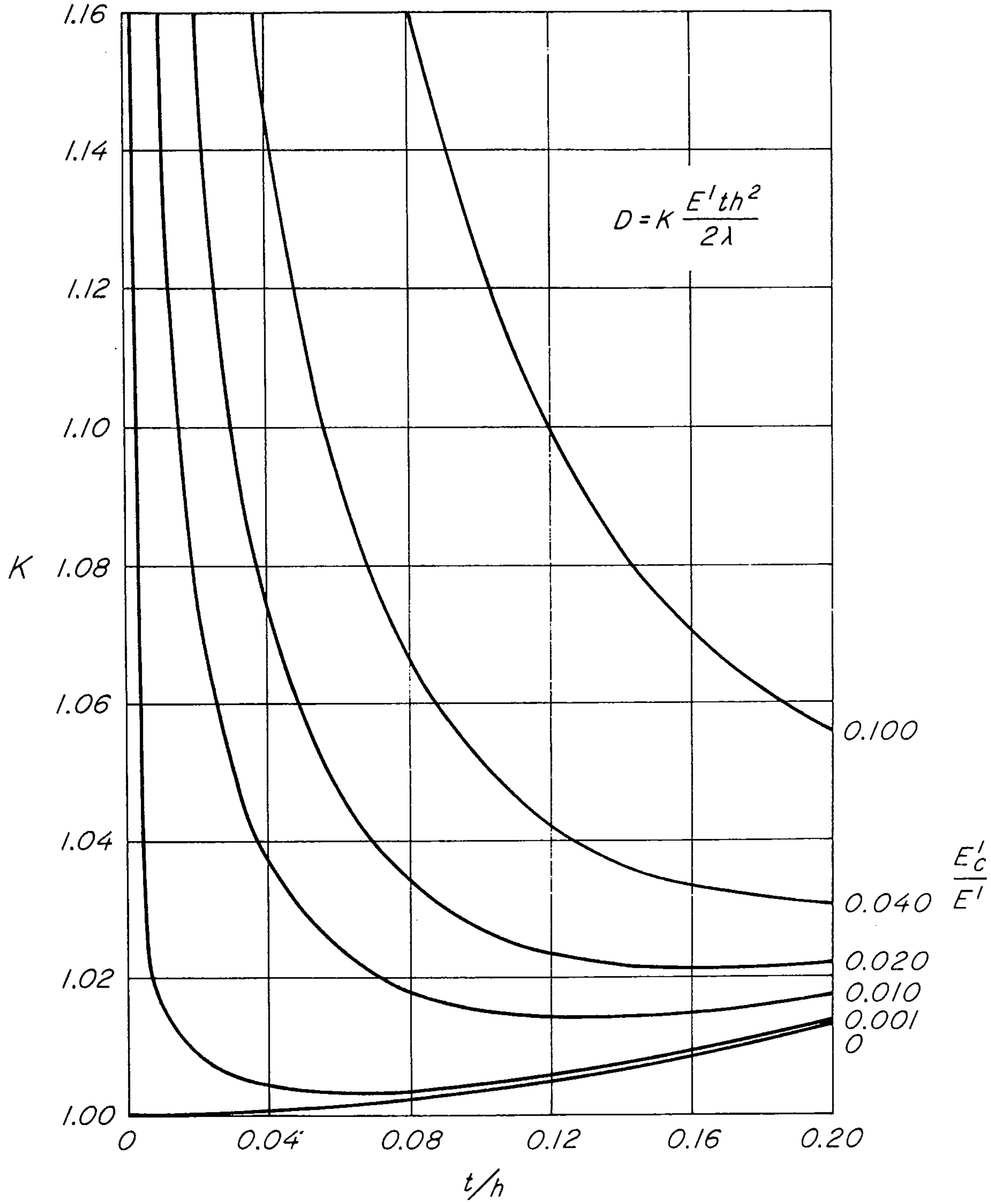


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Figure 1-3.--Effect of facing stiffness (Parameter t/h) and core stiffness (parameter $E'_c/E'$) on the bending stiffness of sandwich.

# CHAPTER 2

# MATERIALS

## 2.1 FACING MATERIALS

### 2.1.1 Functions, Descriptions, Usual Forms

The facings of a sandwich part serve many purposes, depending upon the application, but in all cases they carry the major applied loads. The stiffness, stability, configuration, and, to a large extent, the strength of the part are determined by the characteristics of the facings as stabilized by the core. To perform these functions the facings must be adequately bonded to a core of acceptable quality. Facings sometimes have additional functions, such as providing a profile of proper aerodynamic smoothness, a rough non-skid surface, or a tough wear-resistant floor covering. To better fulfill these special functions, one facing of a sandwich is sometimes made thicker or of slightly different construction than the other.

Any thin, sheet material can serve as a sandwich facing. A few of the materials usually used are discussed briefly in the following:

#### 2.1.1.1 Metals (ref. 2-35)

2.1.1.1.1 Aluminum Alloys.--The stronger alloys of aluminum, such as 7075-T6, 2024-T3, or 2014-T6, are commonly used as facings for structural as well as for nonstructural sandwich applications.

2.1.1.1.2 Steel Alloys.--Stainless steel sheets are finding increasing use as a facing material in airframe sandwich construction. The chief advantage of stainless steel sheet is its high strength at elevated temperatures. Alloys such as 18-8, 17-7PH, and PH15-7Mo are currently finding use because high stresses can be realized. The 18-8 alloys can be rolled to various degrees of hardness to produce high strength but it should be understood that a sheet rolled full hard has a longitudinal compressive yield stress about one-half of the compressive yield stress in the transverse direction. This discrepancy can be closed by subsequent stress relief. Alloys of the 17-7PH and PH15-7Mo are precipitation hardenable and can be strengthened by heat treatment--usually to condition TH1050.

2.1.1.1.3 Titanium Alloys.--Alloys of titanium are currently of interest as facing materials because of their high strength-weight ratios and because they can be utilized for moderately high temperature applications.

2.1.1.1.4 Magnesium Alloys.--Magnesium alloy sheets have been used only experimentally as facing materials, but may find increasing application because of their low density.

2.1.1.1.5 Nickel Base Alloys.--Nickel base alloys such as René 41 can be utilized for heat-resistant sandwich at temperatures of 1200°-1500° F. René 41 is a precipitation-hardening alloy that needs protection from the atmosphere during heat treating. The alloy can be welded.

2.1.1.1.6 Cobalt Base Alloys.--Alloys of cobalt with chromium, nickel, molybdenum, and tungsten are available for use in moderately stressed applications at temperatures of 1000°-1800° F. Alloys such as L605 can be brazed, or fusion or resistance welded.

2.1.1.1.7 Columbium Alloys.--Columbium alloys D-36, D-43, and Cb-752 are suitable for use at temperatures up to 2500° F if they are protected from oxidation by thin silicide coatings. These alloys can be brazed in an inert atmosphere or can be welded; however, degradation can be minimized by joining parts by diffusion bonding.

2.1.1.1.8 Molybdenum Alloys.--Alloy TZM of molybdenum can resist temperatures up to 2800° F. Need for protection and means of joining parts are the same as for the columbium alloys.

2.1.1.1.9 Beryllium.--The low weight and high elastic modulus of beryllium make it most attractive for use in sandwich composites. The metal is heat resistant in the range 1000°-1200° F. Parts can be joined by brazing or welding. Precautions must be taken to prevent individuals from inhaling toxic beryllium particles during fabrication of parts.

2.1.1.2 Reinforced Plastic Materials (ref. 2-34)

2.1.1.2.1 Glass-Fabric Reinforced.--Resin-impregnated glass-fabric facings possess acceptable properties for structural sandwiches when properly fabricated. Because of its excellent dielectric characteristics when fabricated with the proper resin, this type of facing is used almost universally for radomes of sandwich construction. A variety of weaves are available commercially, which makes it practicable, by orienting the fiber directions in the facing, to achieve a wide range of directional strength properties.

In many airframe applications, facings are exposed to moisture, either in the form of high humidity or free water. Even though the amounts of moisture absorbed by glass-reinforced plastic are quite small (on the order of 0.5 to 1.5 percent), the strength properties are decreased, with the amount of decrease depending upon the type of finish applied to the glass fabric. Current specification requirements permit only small losses of strength, after exposure to moisture, that are consistent with results of tests on fabrics made with more recent and effective finishes (such as Volan A, A-1100, Garan RS-49, T-31, NOL-24, and A-172). The most suitable finish for a given application is selected by the glass fabricator. For chemical resin types, such as phenolic, epoxy, and triallyl cyanurate-polyester resins, optimum properties are obtained by use of specific finishes with each resin formulation. The acceptable finishes for each approved resin are given in the qualified products lists that accompany the military specification for each chemical type of resin.

2.1.1.2.2 Glass Mats Reinforced.--Glass fibers are also commercially available in the form of mats, but owing to the relative nonuniformity in thickness and resin content and because of the low strength when compared to glass fabric, mats have found little use in aircraft sandwich construction.

## 2.2 SANDWICH CORES

### 2.2.1 Description of Cores

To permit an airframe sandwich construction to perform satisfactorily, the core of the sandwich must have certain mechanical properties, thermal characteristics, and dielectric properties under conditions of use and still conform to weight limitations. Cores of densities ranging from 1.6 to 23 pounds per cubic foot have found use in airframe sandwich, but the usual density range is 3 to 10 pounds per cubic foot. Specifications for cores intended for use in airframes are listed in 2.2.1.1.

Various core properties are given in U.S. Customary Units. Conversion to the International System of Units can be made by using factors given in Notation at the front of the Handbook.

2.2.1.1 Core Specifications

| Specification | Core type | Referenced document No. |
|---|---|---|
| MIL-C-7438 | Aluminum | 2-38 |
| MIL-C-8073 | Plastic Honeycomb, Laminated Glass Fabric Base | 2-39 |
| MIL-C-8087 | Foamed-In-Place, Urethane Type | 2-40 |
| MIL-C-21275 | Metallic, Heat-Resistant | 2-41 |
| MIL-S-7998 | Balsa Wood | 2-43 |
| MIL-S-25392 | Glass Fabric Base Laminated Facings and Urethane Foamed-In-Place Core | 2-44 |
| MIL-L-7970 | Mahogany | 2-42 |

2.2.1.2 Core Index

The cores for which strength data have been generated and included in this document are listed below.

Cellular (Honeycomb)

Hexagonal and square cells

Aluminum - 3003-H19
5052-H39
5056-H39
2024-T4
2024-T81

Glass fabric - Phenolic resin
Nylon-phenolic resin
Phenolic-polyester resin
Polyester resin
Silicone resin
Polyimide resin

Asbestos fabric - Phenolic resin
Silicone resin

Plastic film - Polyester
Polyimide
Polyamide

Paper - Phenolic resin
Epoxy resin

Steel - 17-7PH conditions A, T, and TH1050
PH15-7Mo condition A
AM350 condition A
321 conditions A and 1/2 hard
A286

Heat-resistant alloy - Inconel
Cobalt L-605
TZM Molybdenum
D36 Columbium

Titanium - Ti75A

Formable cells

Aluminum - 1145-H19
3003-H19
5052-H38

Paper-epoxy resin

Crossbanded - Aluminum 5052-H39

Corrugated

Glass fabric - Polyester resin

Steel - 301 (1/2 hard)
AM355

Foams

Foamed plastic - Cellular cellulose acetate
Polyester-Diisocyanate
Alkyd-Isocyanate
Silicone resin
Epoxy-phenolic resin

Foamed glass

Foamed aluminum

Natural

Balsa wood

2.2.1.2.1 Cellular (Honeycomb) Core. --A wide variety of core materials can be constructed of thin sheet materials or ribbons formed to honeycomb-like configurations. By varying the sheet material, sheet thickness, cell size, and cell shape, cores of a wide range in density and properties can be produced. Various core configurations are shown in figures 2-1 through 2-4. Most honeycomb cores presently available are of cells of types A, E, or F shown in figure 2-1. Most honeycomb cores can be formed to moderate amounts of single curvature, but cores shown in figure 2-2 of types A, B, C, D, and G cells can be easily formed to fairly severe single curvature and to moderate compound curvature (spherical shapes). Type A core (fig. 2-2) may have the straight ribbon of primary corrugated foil the full core thickness, in which case forming to single curvature is easy, or the straight ribbon may be only a portion of the core thickness, so that forming to compound curvature is easily done.

Cores of type F (fig. 2-2) cells form readily to cylindrical shape and to a radius approaching half the core thickness; cores of type E cells form readily to spherical shape and of a radius approaching twice the core thickness; and cores of types D and G cells to various single or compound curvature shapes.

Honeycomb core cell size is determined by the diameter of a circle which can be inscribed in a cell. Sketches of two types of honeycomb core showing the cell size "s" are shown in figure 2-5. Honeycomb core cell sizes used in aircraft vary from about 1/16 to 7/16 inch, usually in multiples of 1/16 inch. Not all sheet materials are formed to all of these cell sizes because some sheet materials are so thick and stiff that they cannot be formed to core of cells less than 3/16 inch in size. For special use, such as an insert, honeycomb cores can be densified locally by under-expanding or by crushing the cells together. Such densified core has properties increased approximately in proportion to density increase. Cores for airframe sandwich construction are presently being made of thin sheets of aluminum alloys, resin-treated glass fabric, resin-treated asbestos, resin-treated paper, stainless steel alloys, titanium alloys, and refractory metals.

Honeycomb cores fabricated from nonmetallic materials have better thermal insulating characteristics than metallic honeycomb cores, even though both allow transmission of heat by radiation in the open cells. In considering thermal effects on sandwich structure, it should be understood that the sandwich can act as a reflective thermal insulator.

The effective thermal conductivity of a honeycomb core depends upon conduction of the material of which the core is made, radiation between facings, and convection within the core cell (ref. 2-22, 2-30) and can be computed approximately with the formula

$$K_e = K_o A_c + \frac{4\sigma t_c(1 - A_c)T_m^3}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 2 + \frac{2}{1 + F_{12}}} + t_c(1-A_c)\eta$$

where $K_e$ -- effective conductivity

$K_o$ -- conductivity of core ribbon material

$A_c$ -- core solidity, $A_c = w_c/w_o$

$w_c$ -- core density

$w_o$ -- core ribbon material density

$\sigma$ -- Stefan-Boltzmann constant

$t_c$ -- core thickness

$T_m$ -- mean absolute temperature of the two sandwich facings

$\epsilon_1$ -- emissivity of inside of sandwich facing 1

$\epsilon_2$ -- emissivity of inside of sandwich facing 2

$F_{12}$ -- geometric view factor between facings (ref. 2-17)

$\eta$ -- convective heat transfer coefficient inside core cell

Sheets of corrugated metal foil are usually assembled with the corrugations parallel to form honeycomb cores. The foil may be perforated for use in core where solvents or gases must be vented. Perforated foil in sandwich panels that are not sealed or are poorly sealed will allow penetration of moisture etc., which may cause severe deterioration of the core. If the sheets are assembled with the corrugations in adjacent sheets perpendicular to each other, a well-vented crossbanded core is produced. Crossbanded cores may be cut so that the corrugation flutes are at an angle of 45° to the sandwich facings, giving the core a trussed appearance. A sandwich panel with this type of crossbanded core is shown in figure 2-3.

Crossbanded cores are not as strong in compression in the T direction or in shear in the TL or TW planes (see fig. 2-5) as honeycomb cores of the same density. Honeycomb cores, however, have negligible compressive strength in the W and L directions and shear strength in the WL plane, whereas crossbanded cores have considerable strength in these directions.

Because of the many cross connections between core flutes, crossbanded core is particularly adapted to construction of airframe sandwich panels with integral fuel tanks.

Crossbanded core is not readily formed to curved surfaces because of its relatively high stiffness in all directions. Curved parts and parts of unusual shape could, however, be machined from blocks of crossbanded core.

2.2.1.2.2 Corrugated Core.--Corrugated cores are produced by forming a sheet of metal foil or resin-treated glass cloth to a series of sine wave corrugations. Figure 2-4 shows sketches of sandwich having single and double rows of corrugations. The corrugation flutes run parallel to the facings, whereas honeycomb core cell axes are normal to the facings. Corrugated cores may be formed to single curvature. Approximate thermal conductivity expressions for corrugated core are given in reference 2-30.

2.2.1.2.3 Waffle-Type Core.--Cores of sheet material fabricated into a configuration resembling a waffle have been produced. Sheets of resin-treated glass-fiber mat have been formed to waffle-type core for use in radomes. Thin metal sheets embossed or dimpled into a waffle configuration of rows of square or triangular lands on either side have been manufactured. The waffle-type core does not lend itself well to sandwich constructions that require tapered core thickness.

2.2.1.2.4 Foam Cores.--To overcome the principal disadvantages of natural core materials, particularly undesirable variation in density and moisture absorption, attempts have been made to develop synthetic core materials having satisfactory properties. Plastic cores are foamed, expanded, or processed by other means to reduce the apparent density of the plastic to a practical range for core material. The expanding processes are subject to control; consequently, the properties of the resulting core material can be predicted. Metallic foamed cores can be produced by mixing molten aluminum-magnesium alloys with suitable foaming agents and cooling the mixture to form a porous solid. Glass foams can also be produced.

2.2.1.2.4.1 Foamed-in-place core materials.--In order to obtain necessary radiation-transmission characteristics, certain types of radomes require sandwich construction with homogeneous facings and core, together with tapering thickness of the sandwich and close control of thickness throughout (refs. 2-2, 2-23, 2-31). To obtain all these characteristics, foamed-in-place core materials have been developed that will adhere to accurately premolded glass-fabric-base plastic facings. This type of core material, while not as strong or stiff as glass-fabric honeycomb core of the same density, offers these advantages: Core joint elimination; thin and uniform bonding layer between facings and core; use of accurately premolded, void-free facings that can be readily inspected before assembly; good electrical properties; and flexibility in manufacture.

Satisfactory core material has been made from formulations based on combinations of alkyd resins and metatolylene diisocyanate. It has been possible to produce foams of uniform density of 3 to 30 pounds per cubic foot, but materials of a density of 10 to 16 pounds per cubic foot are most commonly used (ref. 2-16, 2-27). In addition to their use in radomes, alkyd-diisocyanate foams have also been used to a limited extent to stabilize the skins of hollow steel propeller blades and aluminum alloy control surfaces, particularly for complex configurations in which honeycomb core materials cannot readily be used. Other foamed-in-place core materials which have been produced experimentally are foamed polyester and silicone resins (ref. 2-28, 2-31).

The thermal insulation of foamed-in-place core is good as compared to honeycomb core. Figure 2-6 presents the results of limited tests on sandwich panels having alkyd-isocyanate and phenolic honeycomb cores (ref. 2-24).

2.2.1.2.4.2 Other foamed plastics.--Cellular cellulose acetate has been extruded to form strips of core similar to alkyd-isocyanate, but lacking the advantages of foaming in place (ref. 2-20). Several types of foamed plastics have been produced on a laboratory basis, such as foamed polystyrene, foamed synthetic resins, and cellular thermoplastics, but none have shown sufficient promise to be offered on a commercial scale for aircraft fabrication (ref. 2-3, 2-26, 2-31).

2.2.1.2.4.3 Epoxy-phenolic, aluminum-filled foam.--This is a relatively heavy foam core with a density of 18 to 30 pounds per cubic foot. It is used in local areas in metal honeycomb core where increased strength is needed (ref. 2-15).

2.2.1.2.4.4 Metallic foam.--Foamed aluminum-magnesium alloy cores have been produced experimentally in densities of about 15 to 35 pounds per cubic foot (ref. 2-1).

2.2.1.2.4.5 Glass foam.--Glass foam has been produced experimentally in a density of about 9 pounds per cubic foot.

2.2.1.2.5 Natural Cores.--The selection of natural core materials for airframe sandwich is confined principally to balsa wood, with mahogany, spruce, and poplar being used for inserts and edgings.

The thermal conductivity of wood across the grain can be computed by the formula (ref. 2-46).

$$k = (1.39 + 0.028M)S + 0.165$$

where k -- conductivity (Btu in./hr $ft^2$ F°)
M -- moisture content, (percent)
S -- specific gravity of wood

The thermal conductivity parallel to the grain is about 2-1/2 times that across the grain (ref. 2-46).

2.2.1.2.5.1 Balsa.--Balsa wood can be used with the grain direction oriented parallel or perpendicular to the sandwich facings. The present practice is to place the grain perpendicular to the facings--"end-grain" application (ref. 2-5, 2-10, 2-20, 2-26, 2-50).

2.2.1.2.5.2 Mahogany, spruce, and poplar.--Certain portions of sandwich panels, such as points of attachment and exposed edges, require a high-strength insert (ref. 2-4, 2-32, 2-33). End-grain mahogany is sometimes used at these points. The density of this mahogany, determined by weight and measurement of planed boards at a moisture content of 8 to 12 percent, is normally between 25 and 35 pounds per cubic foot.

As a substitute for mahogany, end-grain spruce has sometimes been used for inserts. Its relatively poor machinability across the grain and difficulty in bonding to the end-grain surface have limited its use to an occasional experimental or emergency application. End-grain poplar is reported to have found limited use for core inserts. Its selection for density and quality should be similar to that for mahogany. Edgings of sandwich panels sometimes include a band of plywood because of partially end-grain material and because the dimensional stability of such edge material is fairly good.

## 2.2.2 Mechanical Properties of Cores

### 2.2.2.1 Strength Properties at Normal Temperatures

The mechanical properties of core materials associated with their natural axes at normal temperatures (70° - 75° F ) as determined from tests of small specimens are given in tables 2-1 and 2-2. Axes notation for core properties in the different directions specified in the tables are illustrated in figures 2-5 and 2-7 and explained in detail in footnote 1 of the two tables. For each material, the average density and mechanical properties are given. The standard deviation and number of specimens evaluated are included to indicate the variability and reliability of the data as an aid in selection of design values. Average values and numbers of specimens of heat-resistant cores tested at normal temperatures are given, along with data at elevated temperatures, in tables 2-3, 2-4, 2-5.

Core materials are sometimes difficult to test because they may not have sufficient rigidity or hardness to support strain gages or because they may be available only in thin sheets. A number of methods of test have been devised. They are described in detail in Military Standard MIL-STD-401 (ref. 2-45).

In some of the tests the bond between the core material and the test apparatus, or between the core material and the facings when the material is tested as a sandwich, failed rather than the core material itself. This has been noted in the tables. Such failures will take place in sandwich construction incorporated in structures but not necessarily at the tabulated strength values because of the dependence of these values on the method of fabrication of the sandwich construction.

Mechanical properties of cores are usually evaluated on small specimens about 1/2 inch thick. While elastic moduli of cores are unaffected by core thickness, the compressive and shear strengths of honeycomb cores may vary with core thickness because core strength may depend upon the buckling strength of the cell walls, which is a function of the ratio of cell-wall width to core thickness. Figure 2-8 shows the effect of core thickness on compressive strength for aluminum and paper honeycomb cores (ref. 2-11, 2-12, 2-19). Figure 2-9 shows the effect of core thickness on the shear strength of aluminum and paper honeycomb cores (ref. 2-8, 2-11, 2-13).

Mechanical properties of resin-treated paper honeycomb cores depend not only on the core thickness, but also on core moisture content. The relationship between relative humidity and core moisture content for two kraft paper cores is shown in figure 2-10. The effect of core thickness and moisture content on shear or compressive strength is given in the "carpet plot" of figure 2-11. The relative shear or compressive strength is plotted to permit linear horizontal interpolation for both the independent variables of moisture content and core thickness. For example, the relative strength of a core 3/4 inch thick and at 16 percent moisture content is found to be 53 percent. The interpolation is shown by the dashed lines in figure 2-11. The effect of core moisture content on core elastic properties is shown in figure 2-12.

Minimum values of core compressive and shear strengths and proportional limit stresses at normal temperatures (70° - 75° F ) are presented in table 2-6. These minimum values are the lowest values obtained for the materials described in tables 2-1 to 2-5 for which at least 12 specimens were tested. The statistical assurance associated with these minimum values is that at least 78 percent of the population will exceed these values with a probability of 0.95, regardless of the shape of the frequency distribution curve of the population (ref. 2-51). In general, the probability is 0.95 that at least $100\,(0.05)^{1/n}$ percent of the population will exceed the lowest among the n strengths obtained. A graph of these percentage values as a function of sample size, n, is given in figure 2-13.

Minimum strength values given in table 2-6 are compared with values of average strength less two standard deviations in the graphs of figures 2-14, 2-15, and 2-16. These graphs show that the data for the various cores have least values of 12 tests that are seldom below average values less two standard deviations.

### 2.2.2.2 Strength Properties at Elevated Temperatures

The mechanical properties of cores at elevated temperatures are presented in tables 2-3, 2-4, and 2-5. Most of the heat-resistant cores in table 2-3 have their normal temperature properties presented in detail in tables 2-1 and 2-2. Tables 2-4 and 2-5 present mechanical properties of heat-resistant and refractory metal cores. Average core properties and the number of specimens evaluated at each test temperature are presented in tables 2-3, 2-4, and 2-5 for each core material. Table 2-5 presents values of the shear modulus at 75° F. Figure 2-17 shows the effect of elevated temperatures on the shear modulus of heat-resistant cores.

### 2.2.2.3 Fatigue Properties of Core Materials

The major stress resisted by a core material in a sandwich construction is shear. Sandwich airframe components subjected to many cycles of flexural loading must have cores possessing adequate shear fatigue strength. Figure 2-18 presents shear fatigue curves for four types of low-density core material (ref. 2-49). Figure 2-19 presents shear fatigue curves for two types of metal honeycomb core (ref. 2-14). Fatigue failures of alkyd-isocyanate foamed-in-place cores may occur either near the core-facing interface or through the center of the core parallel to the facings. End-grain balsa fails by shear parallel to the grain. Glass-fabric honeycomb core may fail in fatigue by spalling of resin from the fabric along lines parallel or perpendicular to the core flutes, leaving the fabric unsupported. Metal honeycomb cores fail in shear fatigue by shear buckling and diagonal tension cracking of the cell walls. Brittle foils tend to fail by cracking and do not perform as well in fatigue as more ductile foils which fail by shear buckling. Perforations tend to promote fatigue cracks and premature failure.

### 2.2.2.4 Creep Properties of Core Materials

When a constant shear stress is applied to core materials, a certain amount of creep may take place. If the stress is applied for long periods, the core may fail at a stress well below the short-time shear strength or undesirable deformations may occur. Some creep measurements have been made on sandwich cores (ref. 2-48), but creep data for the core materials currently being used in airframe sandwich are not available.

## 2.2.2.5 Estimation of Core Properties

If core properties have not been established by test, it is possible to obtain reasonable estimates by consideration of core material, density, and configuration. Conversely, if a design requires a core with certain properties, it is possible to estimate the density, material, and configuration of core needed to obtain a satisfactory sandwich construction.

The elastic moduli and strength of cores of a particular material increase as core density increases. Thus if properties at a certain density are known, a linear extrapolation can be used to obtain estimates of properties at a different density. If properties of cores of several densities are known, a curvilinear relationship may be exhibited between property and density, and this should be used rather than a linear extrapolation.

For cellular (honeycomb) cores, the density and elastic moduli can be estimated from properties of the foil or ribbon material, thickness of the ribbons, and core cell size and shape.

Estimates of honeycomb core density can be made by determining the amount of foil or ribbon material per unit volume of core. Results for two commonly used types of core (Fig. 2-1, A and F) are given by the formulas:

$$w_c = \frac{8t_o}{3s} w_o \quad \text{for core with hexagon cells}$$

$$w_c = \frac{2t_o}{s} w_o \quad \text{for core with square cells}$$

where $w_c$ is core density; $w_o$ is density of foil or ribbon material; $t_o$ is thickness of foil or ribbon material; and s is cell size (diameter of inscribed circle).

The core modulus of elasticity, $E_T$, can be estimated by multiplying the modulus of elasticity of the foil or ribbon material, $E_o$, by the ratio of core density to foil or ribbon density:

$$E_T = \frac{w_c}{w_o} E_o$$

The core shear moduli can be estimated by considering only portions of foil ribbons in planes being distorted by shearing force as being effective and then modifying by experimental constants to determine effective shear moduli in other planes. Results for two commonly used types of core are given by the formulas:

$$G_{TL} = \frac{4t_o}{3s} G_o \qquad G_{TW} = \frac{16t_o}{30s} G_o \qquad \text{for core with hexagon cells}$$

$$G_{TL} = G_{TW} = \frac{t_o}{s} G_o \quad \text{for core with square cells}$$

where $G_o$ is foil or ribbon shear modulus.

The flatwise tensile strength of sandwich with honeycomb core is determined by strength of the bond between facing and core, provided that the core foil or ribbon material is not failed in tension. The core strength at foil failure ($F_{ct}$) can be estimated by multiplying the foil or ribbon strength by the ratio of core density to foil or ribbon density:

$$F_{ct} = \frac{w_c}{w_o} F_o$$

If the bond strength per unit length of bond fillet, $F_{oB}$, is known (determined by tests of cores), the sandwich tensile strength (bond failure) can be estimated by multiplying the bond strength per unit length of fillet by the length of fillet per unit core area. This length of bond fillet per unit core area has been found to be 4/s for honeycomb cores of hexagon or square cells. Thus the sandwich tensile strength (bond failure), $F_{cB}$, can be estimated by:

$$F_{cB} = \frac{4}{s} F_{oB} \quad \text{for core with hexagon or square cells}$$

The final sandwich flatwise tensile strength will be given by the smaller of the values of $F_{ct}$ or $F_{cB}$.

2.2.2.5.1 Corrugated Core--Single Row of Corrugations (ref. 2-21).--Estimates of density of corrugated core having a single row of corrugations can be made using the formula

$$w_c = w_o \frac{1 + \frac{h_c}{p} B}{1 + \frac{h_c}{t_o}}$$

where $w_c$ and $w_o$ are as defined previously and $h_c$, p, and $t_o$ are defined and B is given in figure 2-20 for cores with various corrugation slopes, θ, and corrugation radii of $R_o = 0$ and $R_o = 0.18\ h_c$.

The core area $A_c$ per unit width in a plane perpendicular to the direction of the corrugation flutes is given by

$$A_c = t_o \left(1 + \frac{h_c}{p} B\right)$$

where B is given in figure 2-20. The core modulus of elasticity $E_c$ in a direction parallel to the core flutes is given by

$$E_c = E_o \frac{1 + \frac{h_c}{p} B}{1 + \frac{h_c}{t_o}}$$

where $E_o$ is the modulus of elasticity of the core foil material. The core moment of inertia $I_c$ per unit width is given by

$$I_c = \frac{h_c^3}{4} \frac{t_o}{p} \left(\frac{p}{h_c} + 4C\right)$$

where $h_c$, $t_o$, and p are defined and C is given in figure 2-20 for cores with various corrugation slopes, θ, and corrugation radii of $R_o = 0$ and $R_o = 0.18\ h_c$.

The core shear modulus associated with a shear force perpendicular to the direction of the corrugation flutes may be estimated by the formula

$$G_{zy} = S \frac{E_o}{\lambda_o} \left(\frac{t_o}{h_c}\right)^3$$

where $\lambda_o = 1 - \mu_o^2$, $\mu_o$ is the Poisson's ratio of the core foil material, and S is given in the graphs of figure 2-21 for $R_o = 0.18\ h_c$ and in figure 2-22 for $R_o = 0$. As $R_o/h_c$ increases, the value of S increases slightly. The parameter S is relatively insensitive to variations in the ratio $h_c/t_o$ when $h_c/t_o$ is 30 or larger. The graphs were drawn for $h_c/t_o = 40$. The charts for S are for sandwich with similar facings ($E_1 = E_2$ and $t_1 = t_2$). If the facings are dissimilar a good approximation (within 3 percent) may be obtained from the formula

$$S = \frac{1.26\ S_1 S_2}{(S_1^3 + S_2^3)^{1/3}}$$

where $S_1$ and $S_2$ are the values of S determined from the graphs of figures 2-21 or 2-22, assuming that both facings are similar to facings 1 and 2, respectively.

<u>2.2.2.5.2 Corrugated Core--Double Row of Corrugations (ref. 2-21, 2-25.</u>--For estimating the properties of a core having two rows of corrugations (fig. 2-4), the dimensions p and $h_c$ apply to one of the rows of corrugations and are again defined in figure 2-20. The core density is again given by

$$w_c = w_o \frac{1 + \frac{h_c}{p} B}{1 + \frac{h_c}{t_o}}$$

The core area $A_{c2}$ per unit width, in a plane perpendicular to the direction of the corrugation flutes is given by

$$A_{c2} = 2t_o \left(1 + \frac{h_c}{p} B\right)$$

The core modulus of elasticity $E_c$ is again given by

$$E_c = E_o \frac{1 + \frac{h_c}{p} B}{1 + \frac{h_c}{t_o}}$$

The core moment of inertia $I_{c2}$ per unit width is given by

$$I_{c2} = 2I_c + \frac{A_c}{2}(h_c + t_o)^2$$

where $I_c$ and $A_c$ are the properties for a single row of corrugations defined previously.

The core shear modulus perpendicular to the direction of the corrugation flutes may again be estimated by the formula

$$G_{zy} = S \frac{E_o}{\lambda_o} \left(\frac{t_o}{h_c}\right)^3$$

where the dimensions are shown in the sketches of figures 2-21 and 2-22 the parameter S may be read from the charts of figures 2-21 and 2-22, and other quantities are as previously defined.

If the sandwich facings are dissimilar, a good estimate of the value of S may be obtained by the methods discussed for sandwich having a single row of corrugations.

## 2.3 ADHESIVES

In the fabrication of sandwich constructions, adhesives are used for bonding facings to core and bonding between facings and fittings, reinforcing plates, edge strips and other inserts. The adhesives used are resin formulations especially developed to give high-strength bonds over a wide range of exposure and stressing conditions. Adhesives can be used to bond many types of metal in highly stressed applications. They can also be formulated to have resistance to moderately elevated temperatures. The ever-expanding advances in chemical discovery and application in the field of adhesives prevents a complete current presentation, and various adhesive manufacturers should be consulted for their recommendations and properties of adhesives and processes for any given application.

Adhesives of this type presently are intended to qualify for use in airframes under Federal Specification MMM-A-132, Adhesives, Heat Resistant, Airframe Structural, Metal to Metal (ref. 2-47). The evaluation tests of that specification utilizes sheet metal lap-joint specimens. Military Specification MIL-A-25463, Adhesive, Metallic, Structural Sandwich Construction (ref. 2-37) is used to qualify an adhesive for core-to-facing bonds, and the requirements of Specification MMM-A-132 are added for bonding complete sandwich construction, including such parts as edge members, inserts, attachments, and doublers.

## 2.3.1 Types

The metal-bonding adhesives can be classified into types by several methods. The above specifications classify the adhesives by form such as liquid, film, powder, or solid, and by the relative resistance of the resultant bonds to elevated temperature exposure. Frequently, these adhesives are also classified by general chemical types and by the general range of curing conditions recommended for use with the adhesive. Manufacturers now classify their adhesives into general chemical types with a wide variation in the properties obtainable within each type, depending on the material and formulation procedures of the manufacturers. The metal-bonding adhesives are classified in this Handbook by chemical type, with physical form, curing conditions, and service temperature as subtypes.

### 2.3.1.1 Phenolic Resin Adhesives

One of the principal types of adhesives developed specifically for bonding metals is based on phenolic resins modified with the elastomers neoprene or butadiene-acrylonitrile synthetic rubbers, or the polyvinyls.

2.3.1.1.1 Neoprene Elastomer-Phenolic. --One of the first structural metal-bonding adhesives used in this country in 1942 was a liquid formulation of phenol resin and neoprene rubber dispersed in a suitable solvent. The adhesive was formulated to have a minimum of creep. However, it also had little flow during the bonding process and therefore the adhesive had to be applied as a smooth film, utilizing uniformly high pressures to obtain contact over the entire bonding area. This adhesive was formulated to be cured in the range of 300° to 335° F , and adhesives cured within this range are commonly referred to as being elevated-temperature-setting.

A two-step adhesive process has been developed for use with this adhesive in bonding metal to wood or to low-density cores that can be bonded with the synthetic-resin woodworking adhesives. This process permits the final bonding operation to be done at lower temperatures than is possible by direct bonding with elevated-temperature-setting adhesives. First, the metal-bonding adhesive is applied to the metal, and the film cured in an oven without pressure at the normal cure temperature. This adhesive coat on the metal is then bonded to the wood or to the low-density core using phenol or resorcinol-resin woodworking adhesives at room or slightly elevated temperatures. This metal-primer principle has also been used with other metal-bonding adhesives.

A more recent formulation of this general type of adhesive has been the development of a combination of neoprene, phenol, and nylon resins deposited on a nylon or glass-fabric cloth carrier. This combination may be supplied as a single tape, as one liquid component to be used with the tape, or as two liquid components to be added on the carrier. This adhesive has much better flow during bonding than the older formulation, and can be used under bonding pressures as low as 25 pounds per square inch, as compared to 150 to 200 pounds per square inch for the original formulation.

These neoprene phenol adhesives are generally classified as having moderate shear strength (2,500 to 3,500 pounds per square inch) in the standard 1/2-inch aluminum lap-joint specimens at room temperatures. The strength of bonds made to aluminum with these adhesives have been found to deteriorate, in some instances, when exposed to salt-water spray or high humidity conditions. Adhesives of this type are generally being replaced by acrylonitrile-modified phenolic adhesives or others having improved properties.

2.3.1.1.2 Nitrile Elastomer-Phenolic.--In the search for adhesives having better resistance to elevated temperature, numerous formulations based on the combination of phenol resin with butadiene-acrylonitrile synthetic rubber have been developed. These adhesives are available as solvent solutions, as unsupported films, and as films on nylon or glass-fabric carrier. Some of these formulations have good strength and aging properties at temperatures to 350° F and short intermittent exposure at temperatures as high as 500° F may be possible. However, for many of the butadiene-acrylonitrile phenolic adhesives, the maximum design temperature is 250° to 260° F. These adhesives usually have a shear strength from 2,800 to 4,600 pounds per square inch at room temperatures in the standard 1/2-inch aluminum lap-joint specimens.

2.3.1.1.3 Polyvinyl-Phenolic.--Shortly after the introduction in this country of the phenol-neoprene adhesives for high-strength bonding of metals, adhesives for bonding metals were formulated from combinations of phenol resins with polyvinyl butyral, polyvinyl formal, or other polyvinyl acetal resins. Originally, these polyvinyl phenolic adhesives were found to have poorer strength properties and more creep in the temperature range of 160° to 200° F than the phenolic-neoprene adhesives. However, with improved formulations and curing procedures, some of the polyvinyl phenolic adhesives can be used for designs exposed to temperatures as high as 250° F.

These adhesives are furnished in several forms, such as solvent solutions, as solvent solutions with separate polyvinyl powder component, as unsupported films, and as films on nylon or glass-fabric carrier.

Adhesives of this type are generally classified as having high shear strength (4,100 to 5,100 pounds per square inch) in the standard 1/2-inch aluminum lap joints at room temperature. Bonds made to aluminum with these adhesives have generally been found to be very durable when exposed to salt-water spray or high humidity conditions.

2.3.1.2 Epoxy Resin Adhesives

Extensive development of resin adhesives based on synthetic resins from the condensation of epichlorohydrin and bisphenol, known as epoxy resins, was started about 1947 in this country. These resins have good adhesion to metals, glass, plastics, rubber, and other materials, even when used at low bonding pressures. Typically, these epoxy (or as sometimes referred to as epoxide) adhesive formulations are made to be used at curing temperatures of 70° to 200° F, which are much lower than for other types of metal-bonding adhesives. These adhesive formulations can be used without adding solvents and have the advantage of curing without the evolution of volatile byproducts; therefore the volume shrinkage is low.

Most of the epoxy-resin adhesives formulated for curing at the lower temperatures are furnished in viscous liquid form with a separate liquid curing agent. However, many different epoxy adhesive formulations are available, including types for high-temperature curing (260° to 450° F) and those that utilize separate special curing agents. These adhesives may be supplied as one part paste, powder, films, or as solid adhesives. Most of the epoxy adhesives that cure at room temperatures have the disadvantage of a short pot life of less than 2 hours after the catalyst has been added to the base resin.

These adhesives form good fillets and bonds between facings and honeycomb core for sandwich construction. In addition to use for fabrication of sandwich and metal-to-metal parts, the epoxy-resin adhesives have proved to be of special value in the repair of sandwich constructions where it may not be convenient to use elevated-temperature and high-pressure curing conditions. Modified formulations of the epoxy-resin adhesives are also used for reinforcing and edging the cores of sandwich panels.

Adhesives of this type generally have moderate room-temperature shear strength (3, 100 to 3, 500 pounds per square inch) in the standard 1/2-inch aluminum lap-joint specimens. There have been some indications that these adhesives are not as durable in bonds to aluminum when exposed to salt-water spray, high humidity, or weathering conditions as are some other types of metal-bonding adhesives (ref. 2-6, 2-7). The durability can be improved if the assemblies are protected with one coat of zinc chromate primer and two coats of aluminized lacquer. These adhesives, as usually formulated, do not have good peel resistance, and the types formulated for curing at the lower temperatures also show poor creep resistance at temperatures of 180° to 200° F. The performance of these adhesives in moisture and peel resistance can be improved by using cured prime coats of other metal-bonding adhesives on the metal prior to bonding. Certain synthetic rubber materials, such as polysulfide elastomers, can also be added to the epoxy-resin adhesives to improve the peel resistance. However, the addition of these plasticizing materials also increases the creep tendencies of the adhesive and lowers heat resistance. Epoxy-resin adhesives formulated for elevated-temperature curing (325° F ) have been reported by their manufacturers to have good strength properties at temperatures as high as 350° F and also show better weathering and salt-water spray resistance. The use of these higher curing temperatures must, however, be used with caution so as not to reduce the strength of facing materials.

2. 3. 1. 2. 1 Epoxy-Phenolic--Formulations including both epoxy resins and phenol resins have good strength at elevated temperatures. Adhesives of this type may be in liquid form but are usually supplied as films supported on a wide-mesh glass fabric. Film thicknesses of 0. 008 to 0. 012 inch are available for metal-to-metal bonding and 0. 012 to 0. 030 inch for honeycomb sandwich fabrication. When used for bonding standard 1/2-inch aluminum lap-joint specimens, these adhesives normally have a room-temperature shear strength of from 3, 100 to 3, 800 pounds per square inch. However, compared to other available types, their strength at 450° to 500° F is very good, being in the range of 1, 400 to 1, 800 pounds per square inch. A strength of approximately 1, 000 pounds per square inch is obtained after aging of aluminum specimens for 192 to 200 hours at 500° F. When used for bonding stainless steel, the aging properties at 500° F of this and all other conventional types of heat-resistant adhesives have generally been poor, but they do have good strengths at temperatures up to 400° F.

The storage life of this type of phenol-epoxy resin tape adhesive is rather limited, normally being 24 to 36 hours at room temperatures, 1 month at 40° F, and 3 to 6 months at 0° F.

2.3.1.2.2 Epoxy-Polyamide.--Brought to commercial availability about 1960, this chemical classification of unsupported film has received widespread application in aircraft assemblies of both the metal-to-metal and sandwich construction types. It features exceptionally high shear (lap-joint strength of 5,600 to 6,700 pounds per square inch) and peel strengths and general toughness, as well as a forgiving nature with respect to surface preparation. Reputedly strengths are significantly reduced as a result of extended high humidity or water immersion exposure. Rated service temperature range is -423° to +180° F. Processing is simple largely because of the material's unique surface tension characteristics; cure pressures of 5 to 50 pounds per square inch and cure temperatures of 310° to 360 ° F are used. Storage life is good. The material is available in several weights or thicknesses and also can be procured in a supported form.

Allied but different formulations of epoxy and polyamide resins are available as two-part liquids or pastes but are not generally used for sandwich construction despite their ability to cure at temperatures between 75° and 180° F.

2.3.1.2.3 Modified Epoxy Resin, Low Temperature Curing.--Motivated by airframe manufacturers' desire to avoid reduction in design allowables of some aluminum alloy facing material as a result of 350° F adhesive cure temperature, most major adhesive manufacturers have been supplying, since 1965, a supported film material which cures at a nominal 250° F for 1 hour. This chemical classification can in most instances be cured as low as 180° F or as high as 350° F (for production speed) under 10 to 50 pounds per square inch, and exhibits high shear strength (lap-joint strength of 4,000 to 5,900 pounds per square inch) and good peel strength over the service temperature range of -65° to +180° F. The material is available in several weights or thicknesses, most often with a synthetic random mat carrier. Refrigerated storage is mandatory with open time at ambient temperatures limited to a few days.

2.3.1.3 Polyaromatic Resin Adhesives

Three basic types of heterocyclic polymers have recently been brought to commercial availability in the form of supported adhesive film and preimpregnated glass fabric for laminated sandwich facings. As a result, a new class of structural material capable of resisting temperatures up to 1000° F is in a well advanced development status with several other chemical types under active laboratory scale development. The three types are:

(1) Polybenzimidazole (PBI)--reaction product of a tetraimine and a bisphenylester. It provides bond strengths comparable to the epoxy-phenolic resin adhesives in the range of -423° to 1000° F (for short term) but much improved thermal stability after moderately extended exposures to elevated temperatures. Significant degradation of strengths occurs after 500 hours at 500° F and 50 hours at 600° F. Cure temperature is about 600° F and extended postcure in an inert atmosphere through the design temperature is usually necessary.

(2) Polyimide (PI)--reaction product of a diamine and a dianhydride. This class of adhesive has the outstanding thermal stability of the PBI type and almost comparable bond strengths but superior resistance to oxidation. They are generally rated for medium to long-term service in the range of 400° to 600° F as well as down to -320° F. Cure temperature may be as low as 350° F but generally is 500° F or the design temperature. Postcure is usually not necessary. Cure pressures may be as low as 40 pounds per square inch.

Where extremely long-term thermal stability is a requirement, polyimide-based adhesives have been developed that are suitable for structural applications. They exhibit room temperature lap-shear strengths of approximately 3,400 pounds per square inch on titanium and retain strengths of approximately 2,000 pounds per square inch when tested at 500° F , even after several thousand hours at 500° F. These adhesives generally contain an arsenic-based anti-oxidant that degrades rapidly at 600° F. The uncured adhesive is extremely sensitive to humidity and should not be exposed to relative humidity in excess of 30 percent during processing.

(3) Polyimide-Polyamide Copolymer--This class of adhesive is essentially comparable in performance to the PI type but is, as of early 1967, in a less developed status.

All three types of adhesives evolve 9 to 16 percent condensation products (chiefly water and residual pyridene solvent) during cure. Thus, it is often necessary to employ augmented vacuum bag or press pressures of about 200 pounds per square inch to achieve reliable high-strength bonds with metal-to-metal (stainless steel and titanium alloys) joints. This is not as feasible with core which may crush at such cure pressures. Porosity of bonds resulting from the evolved volatiles and/or low cure pressures increase the probability of atmospheric moisture penetration along the glass fibers of the carrier fabric, a condition making for strength degradation during service. Accordingly careful attention must be given to the processing techniques.

2.3.1.4 Inorganic Adhesives

Heat-resistant ceramic materials have been investigated for use as adhesives in metal-to-metal bonding, because of the need for adhesives capable of maintaining their strength at elevated temperatures up to and above 1000° F. Ceramic-type adhesives, when prepared and applied to metal in a manner similar to application of porcelain enamel or ceramic coatings, can develop lap-shear strengths of 1,500 pounds per square inch and higher on precipitation-hardened 17-7PH stainless steel at 1000°F. The thermal expansion of the ceramic adhesive should approach that of the metal, but not exceed it, in order to obtain maximum shear strengths. In other words, the ceramic should always be held slightly in compression. If the coefficient of expansion of the ceramic is greater than that of the metal, crazing will develop and the bond could destroy itself. The addition of fine metal powders, resulting in a cement, have been found to improve impact and thermal shock resistance and reduce brittleness. The incorporation of very fine metal screen or thin metal fiber mats into the bond as carriers also improves the bond. The ceramic adhesives have a use temperature about two-thirds of the application temperature. Curing furnaces do not require inert atmospheres, as in the case for brazes. In fact, the oxygen content of the air seems to improve the bond.

2.3.2 Available Sources

The trade names and manufacturers of structural adhesives suitable for sandwich and metal bonding can be obtained from qualified products lists for U.S. Military Specification MIL-A-25463 or Federal Specification MMM-A-132 (ref. 2-37, 2-47).

2.3.3 Forms

The adhesives are supplied in a variety of forms. Some of the adhesives are furnished as solvent solutions of the resin, ranging from 8 to 30 percent by weight of resin solids. The epoxy resin adhesives are frequently supplied as thick viscous liquids of which the resin is almost 100 percent chemically reactive, but contains various proportions of fillers. Some of the epoxy resins are also supplied as solid powders or sticks.

Adhesives are also furnished in the form of unsupported films for metal bonding, or as tapes with the adhesive supported on wide-mesh nylon or glass-fabric scrim cloth for bonding sandwich constructions. Films or tape adhesives have generally been used to simplify the operation of applying the adhesive and reduce problems in spreading and removing solvents. Also, the films with scrim cloth carriers usually have greater peel resistance because of the addition of the cloth, which aids in the formation of satisfactory fillets. Composite films have also been devised wherein one side of a scrim cloth has a fillet-forming adhesive for bonding to honeycomb cores and the other side of the scrim has a standard metal-bonding adhesive.

Many adhesives are supplied as a one-part system. However, with some adhesives it is necessary to add a separate catalyst to the resin prior to use. With one of the polyvinyl-phenolic resin adhesives, the system is supplied in two parts with a liquid phenol resin and vinyl powder that is sprinkled into the liquid resin after spreading. Separate liquid adhesive primers are also required for use on the metal facings or core with some of the film and tape adhesives.

## 2.3.4 Storage and Mixing of Adhesives

While some of the adhesives for sandwich and metal bonding can be stored for long periods at room temperature, manufacturers usually recommend storage at lower temperatures of 0° to 50° F or lower to prolong adhesive life. At these temperatures the storage life of many adhesives will vary from 6 months to several years, depending upon the type. Some of the adhesives formulated for elevated temperature resistance have even shorter life, and these adhesives are usually shipped in dry ice and should be stored at 0° to 32° F. The relative stability of adhesives during storage can be determined by making periodic tests such as described in Military Specification MIL-A-9067 (ref. 2-36). This specification requires that no adhesive sample shall be used for production bonding that has not been tested for quality within 96 hours of use.

Many of the adhesives are sensitive to the presence of moisture. Liquid adhesives should be stored in cans with tightly fitting covers and films should be tightly wrapped in a suitable protective film. Care should be taken to prevent contamination of the adhesive with condensed moisture when the adhesive is removed from cold storage. Cans or films taken from cold storage should be permitted, if possible, to warm to room temperatures before being opened. Each container should be of such size that it holds no more than can be used during the normal storage life of the adhesive at room temperature. Adhesives that are sensitive to moisture should not be returned to cold storage in partially filled containers.

Some adhesives are supplied as one-part adhesives and require only thorough stirring before being ready to use. Frequently, the viscosity of the adhesive as received will be too great for proper application. The manufacturer's recommendation as to the proper method of thinning should be closely followed. The solvents for use with these adhesives are usually carefully formulated by the manufacturer to insure long-term compatibility of the solids, proper flow, assembly, and curing requirements.

## 2.3.5 Strength of Adhesive Bonds

The intrinsic elastic properties and strength of adhesives have not been evaluated to any great extent, probably because design information for adhesive-bonded joints, wherein these properties could be used, have not been derived. However, several types of adhesives have been evaluated in bond lines between ends of aluminum tubes by torsion and tension tests (ref. 2-18). Properties determined are given in table 2-7 for purposes of comparison of the elastic properties and strength of the adhesive types and possible inclusion in future designs for specific joints.

### 2.3.5.1 Lap-Joint Strength Data

A large amount of data has been obtained on the strength of adhesive-bonded lap joints between metal adherends. These data are useful for determining effects of environmental conditions on such joints and can furnish guidelines for the design of metal-to-metal joints in sandwich such as occur at edgings and inserts. The results of the lap-joint tests are usually expressed as shear strength values based on the load divided by the area of the lap. Studies of lap-joint stresses (ref. 2-9 and 2-18) have shown that shear stress distribution is dependent upon adhesive properties and thickness as well as lap-joint dimensions. Normal stresses are also developed in lap joints and, while these stresses could initiate tensile failure, they are usually not considered because of complications of analysis. Despite these anomalisms the standard of comparison for metal-to-metal bonds has been the lap-joint specimen with adherends of 0.063-inch aluminum alloy sheets bonded in 1/2-inch overlap (ref. 2-47). The adhesive shear strengths produced by tests of this type of specimen cannot be used as a value for design, even if the designs utilize the same materials, because of an "L/t effect". If L is the length of overlap in a bonded joint and t is adherend thickness, then the apparent shear strengths of adhesives are nonlinear functions of L/t and decrease as the L/t ratio increases. The L/t ratio of the standard lap-joint specimen is approximately 8.0 and, if a potential design utilized the apparent shear strength produced by tests of the standard specimen for an L/t greater than 8.0, the resulting bonded joint may not be conservative. The dependence of average lap-joint shear stress on ratio of lap length to adherend thickness is shown in figure 2-23. The curves are based on theoretical analyses and properties of two types of adhesives in lap joints of aluminum (ref. 2-9, 2-18).

A summary of standard lap-joint strength data for several types of adhesives is given in table 2-8. Included are data on effects of environmental conditions such as temperature, chemical, and wet exposure. The results of the lap-joint tests vary greatly according to the material selection, configuration of specimen, bonding conditions, and evaluation environment. Therefore, test results must be judiciously considered when selecting an adhesive for a bonding process. For example, in room-temperature tests of adhesives using the standard lap-joint specimen, one adhesive might have an average lap-joint strength of 3,200 pounds per square inch, and another a lap-joint strength of 3,700 pounds per square inch as compared to the specification requirements of 2,500 pounds per square inch. There would be little difference in the choice of these adhesives, from the standpoint of design, and therefore, final selection would probably depend on the results of other property tests in which important differences could be obtained between adhesives.

### 2.3.5.2 Strength of Adhesives in Sandwich with Honeycomb Cores

Lap-joint strength data are not considered of prime use for determining adequacy of adhesives for bonding sandwich facings to honeycomb cores. The need of an adhesive to form strong fillets at the ends of the core cells to produce satisfactory sandwich has prompted the evaluation of peel strength and sandwich flatwise tensile strength (ref. 2-37). Peel strength is determined as the torque necessary to peel a facing from a sandwich core. Data for several typical adhesives are given in table 2-9. The sandwich flatwise tensile strength data have been converted to fillet strength in pounds per inch of fillet length so that flatwise tensile strength of sandwich with cores of any cell size can be estimated. The fillet length for cores of hexagonal or square cells is determined by dividing 4 by the cell size (4/s) (ref. 2-29). Thus the sandwich tensile strength at facing-to-core bond failure is given by the formula

$$\text{Sandwich flatwise tensile strength} = \frac{4}{s} \times (\text{fillet strength})$$

where s is core cell size.

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Table 2-1.--Compression properties of core materials for structural sandwich constructions

| Core material | Core density: Average | Core density: Standard deviation | Conditioning prior to test: Temperature | Conditioning prior to test: Relative humidity | Compression[1] Strength T: Average | Strength T: Standard deviation | Proportional limit stress T: Average | Proportional limit stress T: Standard deviation | Modulus of elasticity T: Average | Modulus of elasticity T: Standard deviation | Number of specimens |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pcf | Pcf | °F | Percent | Psi | Psi | Psi | Psi | 1,000 psi | 1,000 psi | |
| Balsa Wood[2,3,4] | 5.0 | --- | 70 | 64 | 670 | 90 | 290 | 130 | 222 | 33 | -- |
| Do[2,3,4] | 6.0 | --- | 70 | 64 | 910 | 110 | 520 | 160 | 313 | 40 | -- |
| Do[2,3,4] | 7.0 | --- | 70 | 64 | 1160 | 120 | 750 | 180 | 404 | 47 | -- |
| Do[2,3,4] | 8.0 | --- | 70 | 64 | 1410 | 140 | 980 | 210 | 495 | 54 | -- |
| Do[2,3,4] | 9.0 | --- | 70 | 64 | 1650 | 160 | 1210 | 240 | 586 | 60 | -- |
| Do[2,3,4] | 10.0 | --- | 70 | 64 | 1900 | 180 | 1440 | 260 | 678 | 67 | -- |
| Do[2,3,4] | 11.0 | --- | 70 | 64 | 2150 | 190 | 1670 | 290 | 769 | 74 | -- |
| Aluminum-foil honeycomb (fig. 2-1 A): | | | | | | | | | | | |
| Preformed, perforated 0.002-inch 3003-H19 foil, 3/8-inch cells[5] | 3.0 | 0.3 | 75 | 50 | 230 | 40 | 130 | 30 | 122 | 26 | 12 |
| Preformed, perforated 0.003-inch 3003-H19 foil, 3/8-inch cells[5] | 4.0 | 0.2 | 75 | 50 | 360 | 40 | 220 | 40 | 190 | 27 | 12 |
| Expanded, perforated 0.002-inch 3003-H19 foil, 1/4-inch cells[5] | 4.4 | 0.1 | 75 | 50 | 440 | 40 | --- | --- | --- | -- | 10 |
| Preformed, perforated 0.002-inch 3003-H19 foil, 1/4-inch cells[5] | 4.5 | 0.5 | 75 | 50 | 390 | 40 | 250 | 40 | 191 | 12 | 12 |
| Expanded, perforated 0.001-inch 3003-H19 foil, 1/8-inch cells[5] | 4.8 | 0.2 | 75 | 50 | 590 | 40 | --- | --- | --- | -- | 12 |
| Preformed, perforated 0.004-inch 3003-H19 foil, 3/8-inch cells[5] | 5.2 | 0.4 | 75 | 50 | 570 | 60 | 380 | 80 | 252 | 16 | 12 |
| Expanded, perforated 0.004-inch 3003-H19 foil, 3/8-inch cells[5] | 5.3 | 0.1 | 75 | 50 | 630 | 20 | --- | --- | --- | -- | 4 |
| Expanded, perforated 0.002-inch 3003-H19 foil, 3/16-inch cells[5] | 5.8 | 0.3 | 75 | 50 | 720 | 130 | --- | --- | --- | -- | 12 |
| Preformed, perforated 0.003-inch 3003-H19 foil, 1/4-inch cells[5] | 6.0 | 0.1 | 75 | 50 | 690 | 40 | 410 | 30 | 315 | 20 | 12 |
| Expanded, perforated 0.003-inch 3003-H19 foil, 1/4-inch cells[5] | 6.2 | 0.5 | 75 | 50 | 770 | 60 | --- | --- | --- | -- | 4 |
| Preformed, perforated 0.005-inch 3003-H19 foil, 3/8-inch cells[5] | 6.3 | 0.3 | 75 | 50 | 770 | 60 | 440 | 30 | 306 | 21 | 12 |
| Preformed, perforated 0.004-inch 3003-H19 foil, 1/4-inch cells[5] | 7.7 | 0.3 | 75 | 50 | 870 | 180 | 510 | 80 | 330 | 36 | 12 |
| Preformed, perforated 0.005-inch 3003-H19 foil, 1/4-inch cells[5] | 9.0 | 0.3 | 75 | 50 | 1160 | 110 | 690 | 90 | 492 | 15 | 12 |
| Aluminum-foil honeycomb (fig. 2-1 A): | | | | | | | | | | | |
| Expanded, perforated 0.0007-inch 5052-H39 foil, 1/4-inch cells[6] | 2.0 | 0.02 | 75 | 50 | 140 | 10 | --- | --- | --- | -- | 12 |
| Expanded, perforated 0.002-inch 5052-H39 foil, 1/4-inch cells[6] | 3.9 | 0.04 | 75 | 50 | 480 | 40 | 350 | 50 | 259 | 60 | 12 |
| Preformed, unperforated 0.002-inch 5052-H39 foil, 1/4-inch cells[7] | 4.2 | 0.02 | 75 | 50 | 550(11)[8] | 40 | 300 | 30 | 231 | 15 | 6 |
| Expanded, perforated 0.001-inch 5052-H39 foil, 1/8-inch cells[6] | 4.5 | 0.02 | 75 | 50 | 580 | 50 | --- | --- | --- | -- | 10 |
| Preformed, perforated 0.002-inch 5052-H39 foil, 1/4-inch cells[6] | 5.5 | 0.04 | 75 | 50 | 400 | 20 | --- | --- | --- | -- | 3 |
| Expanded, perforated 0.003-inch 5052-H39 foil, 1/4-inch cells[6] | 5.9 | 0.2 | 75 | 50 | 900 | 60 | 710(8)[8] | 100 | 437(8)[8] | 89 | 12 |
| Expanded, perforated 0.004-inch 5052-H39 foil, 1/4-inch cells[6] | 7.7 | 0.1 | 75 | 50 | 1390 | 80 | 1010 | 200 | 535 | 69 | 12 |
| Aluminum-foil honeycomb: | | | | | | | | | | | |
| Preformed, unperforated 0.003-inch 2024-T4 foil, 3/8-inch-cells[6] (fig. 2-2 B) | 3.6 | 0.2 | 75 | 50 | 230 | 20 | --- | --- | --- | -- | 3 |
| Preformed, perforated 0.003-inch 2024-T4 foil, 1/4-inch cells[6] (fig. 2-1 A) | 6.0 | 0.02 | 75 | 50 | 670 | 50 | --- | --- | --- | -- | 6 |
| Aluminum-foil crossbanded core (fig. 2-3): | | | | | | | | | | | |
| Preformed, unperforated 0.002-inch 5052-H39 foil, 1/8-inch corrugations[7] | 4.4 | 0.03 | 75 | 50 | 220 | 10 | 150(6)[8] | 30 | 81(6)[8] | 7 | 11 |
| Aluminum-foil honeycomb (fig. 2-2 A): | | | | | | | | | | | |
| Type I, perforated 0.002-inch 1145-H19 foil, 1/4-inch cells[9] | 4.0 | 0.05 | 75 | 50 | 210 | 20 | 150 | 10 | 208[10] | -- | 12 |

Sheet 1 of 5

Table 2-1.--Compression properties of core materials for structural sandwich constructions--con.

| Core material | Core density: Average | Core density: Standard deviation | Conditioning prior to test: Temperature | Conditioning prior to test: Relative humidity | Compression[1] Strength T: Average | Strength T: Standard deviation | Proportional limit stress T: Average | Proportional limit stress T: Standard deviation | Modulus of elasticity T: Average | Modulus of elasticity T: Standard deviation | Number of specimens |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pcf | Pcf | °F | Percent | Psi | Psi | Psi | Psi | 1,000 psi | 1,000 psi | |
| Aluminum-foil honeycomb (fig. 2-2 A) cont.: | | | | | | | | | | | |
| Type I, perforated 0.002-inch 3003-H19 foil, 1/4-inch cells[9] | 4.6 | 0.02 | 75 | 50 | 440 | 30 | 380 | 30 | 208[10] | -- | 12 |
| Type I, perforated 0.002-inch 5052-H38 foil, 1/4-inch cells[9] | 4.6 | 0.04 | 75 | 50 | 460 | 40 | 400 | 30 | 208[10] | -- | 12 |
| Glass fabric honeycomb (fig. 2-1 A): | | | | | | | | | | | |
| Preformed, fabric 112, finish 114 | 3.5 | 0.3 | 73 | 50 | 290 | 50 | 160 | 40 | 64 | 11 | 12 |
| Phenolic resin, 1/4-inch cells[11] | --- | ---- | | Wet[12] | 290 | 60 | 150 | 20 | 65 | 8 | 12 |
| Expanded, fabric 12, nylon-phenolic resin, 1/4-inch cells[13] | 3.8 | 0.1 | 73 | 50 | 740 | 50 | --- | --- | --- | -- | 10 |
| Expanded, fabric 21, finish 114 | 4.4 | 0.2 | 73 | 50 | 440 | 40 | 210 | 40 | 113 | 8 | 12 |
| Nylon-phenolic resin, 1/4-inch cells[11] | --- | ---- | | Wet[12] | 300 | 30 | 160 | 30 | 97 | 9 | 12 |
| Preformed fabric 112, finish 114 | 5.6 | 0.4 | 73 | 50 | 460 | 80 | 270 | 60 | 75 | 6 | 12 |
| Phenolic-polyester resin, 1/4-inch cells[11] | --- | ---- | | Wet[12] | 460 | 90 | 240 | 50 | 80 | 10 | 12 |
| Expanded, Fabric 112, finish 114 | 6.3 | 0.3 | 73 | 50 | 790 | 80 | 490 | 80 | 118 | 9 | 12 |
| Nylon-phenolic resin, 3/16-inch cells[11] | --- | ---- | | Wet[12] | 430 | 50 | 260 | 70 | 102 | 9 | 12 |
| Expanded, fabric 21, finish 114 | 6.3 | 0.1 | 73 | 50 | 830 | 80 | 590 | 120 | 125 | 4 | 12 |
| Nylon-phenolic resin, 1/4-inch cells[11] | --- | ---- | | Wet[12] | 350 | 60 | 190 | 40 | 92 | 9 | 12 |
| Preformed, fabric 112, finish 114 | 6.4 | 0.3 | 73 | 50 | 650 | 60 | 460 | 100 | 98 | 5 | 12 |
| Phenolic-polyester resin, 3/16-inch cells[11] | --- | ---- | | Wet[12] | 700 | 60 | 440 | 70 | 111 | 8 | 12 |
| Preformed, fabric 112, finish 136 | 8.2 | 0.5 | 73 | 50 | 880 | 100 | 620 | 90 | 116 | 4 | 12 |
| Polyester resin, 3/16-inch cells[11] | --- | ---- | | Wet[12] | 480 | 70 | 400 | 50 | 94 | 8 | 12 |
| Expanded, fabric 21, finish 114 | 8.2 | 0.1 | 73 | 50 | 1490 | 180 | 1060 | 160 | 152 | 6 | 12 |
| CTL-91LD phenolic resin, 1/4-inch cells[11] | --- | ---- | | Wet[12] | 1400 | 210 | 1040 | 230 | 156 | 5 | 12 |
| Preformed, fabric 112, finish 136 | 8.3 | 0.4 | 73 | 50 | 890 | 70 | 640 | 160 | 100 | 6 | 12 |
| Polyester resin, 1/4-inch cells[11] | --- | ---- | | Wet[12] | 570 | 60 | 320 | 50 | 73 | 5 | 12 |
| Expanded, fabric 112, volan A finish, heat-resistant polyester resin, 3/16-inch cells[14] | 8.4 | ---- | 73 | 50 | 1300 | --- | 810 | --- | 130 | -- | 2 |
| Expanded, fabric 13, heat-resistant silicone resin, 3/16-inch cells[6] | 8.5 | 0.4 | 73 | 50 | 540 | 40 | 210 | 80 | 146 | 82 | 3 |
| Do[6] | --- | ---- | | Wet[12] | 460 | 60 | 260 | 40 | 76 | 22 | 3 |
| Preformed, fabric 112, finish 112, heat-resistant silicone resin, 3/16-inch cells[14] | 8.6 | 0.3 | 73 | 50 | 250 | 50 | 170 | 40 | 70 | 10 | 4 |
| Preformed, fabric 112, volan A finish, heat-resistant polyester resin, 3/16-inch cells[14] | 8.6 | 0.4 | 73 | 50 | 840 | 80 | 470 | 60 | 126 | 9 | 4 |
| Expanded, fabric 112, finish 114, heat-resistant phenolic resin, 3/16-inch cells[14] | 8.7 | ---- | 73 | 50 | 1540 | --- | 940 | --- | 150 | -- | 2 |
| Expanded, fabric 13, heat-resistant phenolic resin, 3/16-inch cells[6] | 8.8 | ---- | 73 | 50 | 1670 | 20 | 990(2)[8] | --- | 179(2)[8] | -- | 3 |
| Do[6] | --- | ---- | | Wet[12] | 1260 | 40 | 800(2)[8] | 100 | 94(2)[8] | 5 | 3 |
| Preformed, fabric 112, finish 114, heat-resistant phenolic resin, 3/16-inch cells[14] | 8.8 | 0.2 | 73 | 50 | 1580 | 320 | 1020 | 260 | 150 | 10 | 4 |
| Expanded, fabric 112, finish 114, CTL-91LD phenolic resin, 3/16-inch cells[14] | 8.8 | ---- | 73 | 50 | 1640 | --- | 1070 | --- | 156 | -- | 2 |

Table 2-1.--Compression properties of core materials for structural sandwich constructions--con.

| Core material | Core density | | Conditioning prior to test | | Compression[1] | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Temperature | Relative humidity | Strength T | | Proportional limit stress T | | Modulus of elasticity T | | Number of specimens |
| | Average | Standard deviation | | | Average | Standard deviation | Average | Standard deviation | Average | Standard deviation | |
| | Pcf | Pcf | °F | Percent | Psi | Psi | Psi | Psi | 1,000 psi | 1,000 psi | |
| Glass fabric honeycomb continued: | | | | | | | | | | | |
| Preformed, fabric 112, finish 114, CTL-91LD phenolic resin, 3/16-inch cells[14] | 8.9 | 0.4 | 73 | 50 | 1750 | 120 | 1260 | 30 | 159 | 2 | 4 |
| Expanded, fabric 112, finish 114 | 9.2 | 0.2 | 73 | 50 | 1510 | 120 | 920 | 100 | 151 | 11 | 12 |
| Nylon-phenolic resin, 3/16-inch cells[11] | --- | ---- | | Wet[12] | 590 | 80 | 400 | 100 | 108 | 10 | 12 |
| Asbestos fabric honeycomb (fig. 2-1 A): | | | | | | | | | | | |
| Expanded, asbestos fiber mat, heat-resistant silicone resin, 3/16-inch cells[6] | 8.7 | 0.11 | 73 | 50 | 700 | 90 | 270 | 100 | 146 | 35 | 3 |
| Do[6] | --- | ---- | | Wet[12] | 610 | 10 | 250 | 30 | 78 | 22 | 3 |
| Expanded, asbestos fiber mat, heat-resistant phenolic resin, 3/16-inch cells[6] | 9.3 | ---- | 73 | 50 | 1560 | 300 | 970(2)[8] | --- | 198(2)[8] | -- | 3 |
| Do[6] | --- | ---- | | Wet[12] | 1170 | 210 | 800 | 240 | 134 | 36 | 3 |
| Glass fabric corrugated core with integrally woven liners (fig. 2-4): | | | | | | | | | | | |
| Fabric 301, polyester resin, sine wave corrugations, 3/16-inch crest to trough[13,15] | 20.4[15] | ---- | 73 | 50 | 370 | 60 | --- | --- | --- | -- | 12 |
| Plastic film honeycomb (fig. 2-1 A): | | | | | | | | | | | |
| Expanded, 0.003-inch polyester film, 3/8-inch cells[16] | 2.1 | 0.03 | 73 | 50 | 85 | 3 | 55 | 5 | 12.2 | 1.4 | 12 |
| Expanded, 0.003-inch polyimide film, 3/8-inch cells[16] | 2.4 | 0.1 | 73 | 50 | 80 | 8 | 45 | 7 | 6.8 | 1.6 | 12 |
| Expanded, 0.002-inch polyamide film, phenolic resin, 1/4-inch cells[17] | 1.6 | ---- | 73 | 50 | 95 | 2 | 55 | 2 | 9.4 | 0.4 | 6 |
| Expanded, 0.002-inch polyamide film, phenolic resin, 1/8-inch cells[17] | 3.0 | ---- | 73 | 50 | 320 | 10 | 175 | 10 | 21.5 | 0.6 | 6 |
| Foamed cores: | | | | | | | | | | | |
| Foamed-in-place polyester-diisocyanate[18] | 12.0 | ---- | 75 | 50 | 330 | --- | 280 | --- | --- | -- | 2 |
| Foamed-in-place alkyd-isocyanate[19] | 10.3 | ---- | 75 | 50 | 240 | 5 | 50 | 20 | 16 | 6 | 6 |
| Do[19] | 19.7 | ---- | 75 | 50 | 900 | 60 | 250(3)[8] | 10 | 58(3)[8] | 9 | 15 |
| Foamed-in-place silicone resin[18] | 12.6 | ---- | 75 | 50 | 90 | 20 | 70 | 20 | --- | -- | 3 |
| Do[18] | 15.4 | ---- | 75 | 50 | 140 | 20 | 110 | 20 | --- | -- | 9 |
| Do[18] | 17.5 | ---- | 75 | 50 | 190 | 10 | 130 | 20 | --- | -- | 3 |
| Foamed-in-place epoxy-phenolic resin[20] | 18.0 | 0.7 | 75 | 50 | 340 | 50 | --- | --- | 53 | 5 | 3 |
| Foamed glass[21] | 31.8 | 2.0 | 75 | 50 | 720 | 90 | 620 | 80 | 337 | 20 | 5 |
| Foamed aluminum[22] | 33.4 | 2.6 | 75 | 50 | 1120 | 100 | 320 | 80 | 358 | 40 | 4 |
| Paper honeycomb: | | | | | | | | | | | |
| Expanded, 60 lb. kraft paper, 20 percent alcohol-soluble phenolic resin, 7/16-inch cells[23] (fig. 2-1 A) | 1.7 | 0.06 | 80 | 30 | 120 | 10 | 80 | 5 | 18.6 | 2.4 | 12 |
| Do[23] | 1.7 | 0.06 | 73 | 50 | 100 | 10 | 70 | 5 | 20.7 | 1.8 | 12 |
| Do[23] | 1.8 | 0.07 | 80 | 90 | 60 | 5 | 40 | 5 | 13.6 | 1.5 | 12 |
| Do[23] | 2.9 | 0.11 | | Wet[24] | 25 | 5 | 20 | 1 | 4.8 | 0.5 | 12 |

Table 2-1.--Compression properties of core materials for structural sandwich constructions--con.

| Core material | Core density: Average | Core density: Standard deviation | Conditioning prior to test: Temperature | Conditioning prior to test: Relative humidity | Compression[1] Strength T: Average | Strength T: Standard deviation | Proportional limit stress T: Average | Proportional limit stress T: Standard deviation | Modulus of elasticity T: Average | Modulus of elasticity T: Standard deviation | Number of specimens |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pcf | Pcf | °F | Percent | Psi | Psi | Psi | Psi | 1,000 psi | 1,000 psi | |
| Paper honeycomb continued: | | | | | | | | | | | |
| Expanded, 0.005-inch, 60 lb. kraft paper, 50 percent epoxy resin, 3/8-inch cells[25] (fig. 2-1 A) | 2.9 | 0.2 | 73 | 50 | 170 | 5 | --- | --- | 56(4)[8] | 7 | 6 |
| Expanded, 0.005-inch, 60 lb. kraft paper, 50 percent epoxy resin, [25](fig. 2-2 F) | 3.0 | 0.2 | 73 | 50 | 170 | 10 | --- | --- | 66(2)[8] | -- | 6 |
| Expanded, 0.005-inch, 60 lb. kraft paper, 50 percent epoxy resin, [25](fig. 2-2 E) | 3.0 | 0.3 | 73 | 50 | 150 | 10 | --- | --- | 57(2)[8] | -- | 6 |
| Expanded, 0.005-inch, 60 lb. kraft paper, 50 percent epoxy resin, [25](fig. 2-2 G) | 3.1 | 0.3 | 73 | 50 | 180 | 10 | --- | --- | --- | -- | 6 |
| Expanded, 0.009-inch, 90 lb. kraft paper, 30 percent alcohol-soluble phenolic resin, 7/16 inch cells[26] (fig. 2-1 A) | 3.0 | 0.05 | 73 | 50 | 270 | 5 | --- | --- | 77 | 9 | 6 |
| Expanded, 125 lb. kraft paper, 35 percent alcohol-soluble phenolic resin, 7/16-inch cells[23] (fig. 2-1 A) | 3.6 | 0.08 | 80 | 30 | 420 | 30 | 270 | 30 | 49.3 | 3.7 | 12 |
| Do[23] | 3.7 | 0.08 | 73 | 50 | 350 | 30 | 200 | 20 | 53.1 | 3.9 | 12 |
| Do[23] | 3.9 | 0.08 | 80 | 90 | 260 | 30 | 160 | 5 | 33.2 | 1.9 | 12 |
| Do[23] | 5.5 | 0.12 | Wet[24] | | 110 | 30 | 70 | 5 | 14.6 | 1.7 | 12 |
| Expanded, 0.006-inch, 90 lb. filter paper, 50 percent epoxy resin, 7/16-inch cells[27] (fig. 2-1 A) | 4.9 | 0.06 | 73 | 50 | 490 | 10 | 190 | 10 | 55 | 1 | 6 |
| Expanded, 0.006-inch, 100 lb. filter paper, 35 percent epoxy resin, 1/4-inch cells, 50 percent expansion[28] (fig. 2-1 A) | 9.8 | 0.4 | 73 | 50 | 1280 | 60 | 500 | 20 | 116 | 8 | 6 |
| Expanded, 0.009-inch, 100 lb. kraft paper, 50 percent alcohol-soluble phenolic resin, 3/8-inch cells, 50 percent expansion[28] (fig. 2-1 A) | 11.4 | --- | 73 | 50 | 1480 | --- | 800 | -- | 141 | -- | 2 |
| Expanded, 0.006-inch, 100 lb. filter paper, 45 percent alcohol-soluble phenolic resin, 3/8-inch cells, 40 percent expansion[28] (fig. 2-1 A) | 12.3 | 0.3 | 73 | 50 | 1760 | 120 | 910 | 60 | 175 | 8 | 4 |
| Expanded, 0.010-inch, 160 lb. filter paper, 40 percent epoxy resin, 1/4-inch cells, 70 percent expansion[28] (fig. 2-1 A) | 13.3 | 0.6 | 73 | 50 | 1840 | 90 | 620 | 40 | 150 | 6 | 6 |
| Expanded, 0.010-inch, 160 lb. filter paper, 45 percent epoxy resin, 3/16-inch cells, 40 percent expansion[28] (fig. 2-1 A) | 27.9 | 1.7 | 73 | 50 | 4200 | 300 | 1460 | 90 | 329 | 30 | 3 |

<u>Footnotes for Table 2-1</u>

1 Balsa properties were determined by standard ASTM test methods for wood. Other core materials were evaluated in accordance with MIL-STD-401 for sandwich. T direction refers to thickness of core and is parallel to grain of balsa and quipo woods and parallel to flutes of honeycomb cores.

2 Wiepking, C. A., and Doyle, D. V. Strength and related properties of balsa and quipo woods. U.S. Forest Prod. Lab. Rep. 1511. 1944.

3 Doyle, D. V., Drow, J. T., and McBurney, R. S. Elastic properties of wood--The Young's moduli, moduli of rigidity, and Poisson's ratios of balsa and quipo. U.S. Forest Prod. Lab. Rep. 1528. 1945.

4 Density of balsa specimens varied from about 4.5 to 14 pounds per cubic foot. Average mechanical properties were obtained by least squares. The standard deviations increase linearly with increasing density. Compression data are based on 85 specimens.

5 Kuenzi, E. W. Mechanical properties of aluminum honeycomb cores. U.S. Forest Prod. Lab. Rep. 1849. 1955.

6 Stevens, G. H., and Kuenzi, E. W. Mechanical properties of several honeycomb cores. U.S. Forest Prod. Lab. Rep. 1887. 1962.

7 Stevens, G. H. Compressive and shear properties of two configurations of sandwich cores of corrugated foil. U.S. Forest Prod. Lab. Rep. 1889. 1962.

8 Value is based on number of specimens indicated in parentheses.

9 Kuenzi, E. W., and Setterholm, V. C. Mechanical properties of aluminum multiwave cores. U.S. Forest Prod. Lab. Rep. 1855. 1956.

10 Computed from the formula: $E = 26 \times 10^6\ t/s$; where E is the modulus of elasticity, t is the foil thickness, and s is the cell size. (See reference of footnote 9.)

11 Kuenzi, E. W. Mechanical properties of glass-fabric honeycomb cores. U.S. Forest Prod. Lab. Rep. 1861. 1957.

12 Wet values are for cores at 73° F after 60 days' exposure at 100° F and 100 percent relative humidity.

13 Stevens, G. H. Shear properties and performance in a sandwich panel of a corrugated glass-fiber-reinforced plastic core with integrally woven liners. U.S. Forest Prod. Lab. Rep. WER-241. 1962.

14 Setterholm, V. C., and Kuenzi, E. W. Performance of glass-fabric sandwich and honeycomb cores at elevated temperatures. WADC TR 56-119 (ASTIA Doc. No. AD 97290). 1956.

15 The core, including liners, was 0.190 inch thick and weighed 0.32 pound per square foot. The corrugations accounted for about one-half the panel weight. Thus, the core was comparable to one of 10 pounds per cubic foot density, with the liners acting as part of the sandwich facings.

16 Jenkinson, P. M. Compressive and shear properties of polyester and polyimide film honeycomb core. U.S. Forest Serv. Res. Pap. FPL 75, Forest Prod. Lab., Madison, Wis. 1967.

17 Jenkinson, P. M. Compressive and shear properties of polyamide honeycomb core. U.S. Forest Serv. Res. Note FPL-0202, Forest Prod. Lab., Madison, Wis. 1969.

18 Setterholm, V. C., and Kuenzi, E. W. Performance of sandwich with cores of foamed silicone and modified polyester resins at elevated temperatures and at high humidity. WADC TR 56-230 (ASTIA Doc. No. AD 110421). 1956.

19 Jenkinson, P. M., and Kuenzi, E. W. Properties of alkyd-isocyanate foamed-in-place core. WADC TR 57-182 (ASTIA Doc. No. 155884). 1958.

20 Jenkinson, P. M., and Kuenzi, E. W. Mechanical properties of 422-J Bacfoam core for sandwich construction. WADC TR 57-132 (ASTIA Doc. No. AD 118249). 1957.

21 U.S. Forest Prod. Lab. letter report to the U.S. Dep. Navy, Bur. Aeron., April 1958.

22 Composition: 92 percent aluminum, 6 percent magnesium. U.S. Forest Prod. Lab. letter rep. to USAF, WADC. July 1954.

23 Jenkinson, P. M. Effect of core thickness and moisture content on mechanical properties of two resin-treated paper honeycomb cores. U.S. Forest Serv. Res. Pap. FPL 35, Forest Prod. Lab., Madison, Wis. 1965.

24 Wet values are for cores at 75° F after soaking in distilled water for 48 hours at 75° F.

25 Jenkinson, P. M., Fahey, D. J., and Selbo, M. L. Strength of resin-treated paper cores of four cell configurations. U.S. Forest Prod. Lab. Rep. PE-198. 1960.

26 Norris, C. B., Fahey, D. J., Black, J. M., and Setterholm, V. C. Compression properties of resin-treated paper as obtained by evaluating tubes and honeycomb cores. U.S. Forest Prod. Lab. Rep. PE-197. 1960.

27 Jenkinson, P. M., Fahey, D. J., Kuenzi, E. W., and Kutscha, D. F. Effect of paper thickness on compression properties of resin-treated paper honeycomb core. U.S. Forest Prod. Lab. Rep. SANDIA-3. 1961.

28 Fahey, D. J., Hann, R. A., Jenkinson, P. M., and Kuenzi, E. W. Compressive properties of high-density resin-treated paper honeycomb cores. U.S. Forest Prod. Lab. Rep. SANDIA-7. 1962.

Table 2-2.--Shear properties of core materials for structural sandwich constructions

| Core material | Core density: Average | Core density: Standard deviation | Conditioning prior to test: Temperature | Conditioning prior to test: Relative humidity | Shear[1,2] Strength TL: Average | Strength TL: Standard deviation | Strength TW: Average | Strength TW: Standard deviation | Proportional limit stress TL: Average | Proportional limit stress TL: Standard deviation | Proportional limit stress TW: Average | Proportional limit stress TW: Standard deviation | Modulus of rigidity TL: Average | Modulus of rigidity TL: Standard deviation | Modulus of rigidity TW: Average | Modulus of rigidity TW: Standard deviation | Number of specimens: TL | Number of specimens: TW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pcf | Pcf | °F | Percent | Psi | Psi | Psi | Psi | Psi | Psi | Psi | Psi | 1,000 psi | 1,000 psi | 1,000 psi | 1,000 psi | | |
| Balsa wood[3,4,5] | 5.0 | ---- | 70 | 64 | 160 | 30 | 150 | 40 | --- | -- | --- | -- | 9.8 | 2.4 | 12.2 | 2.4 | -- | -- |
| Do[3,4,5] | 6.0 | ---- | 70 | 64 | 190 | 40 | 180 | 40 | --- | -- | --- | -- | 12.3 | 2.9 | 16.6 | 2.9 | -- | -- |
| Do[3,4,5] | 7.0 | ---- | 70 | 64 | 230 | 50 | 200 | 50 | --- | -- | --- | -- | 14.9 | 3.4 | 21.0 | 3.4 | -- | -- |
| Do[3,4,5] | 8.0 | ---- | 70 | 64 | 270 | 50 | 230 | 60 | --- | -- | --- | -- | 17.5 | 3.9 | 25.3 | 3.9 | -- | -- |
| Do[3,4,5] | 9.0 | ---- | 70 | 64 | 300 | 60 | 260 | 70 | --- | -- | --- | -- | 20.1 | 4.4 | 29.7 | 4.4 | -- | -- |
| Do[3,4,5] | 10.0 | ---- | 70 | 64 | 340 | 70 | 290 | 70 | --- | -- | --- | -- | 22.6 | 4.8 | 34.0 | 4.9 | -- | -- |
| Do[3,4,5] | 11.0 | ---- | 70 | 64 | 380 | 70 | 320 | 80 | --- | -- | --- | -- | 25.2 | 5.3 | 38.4 | 5.3 | -- | -- |
| Aluminum-foil honeycomb (fig. 2-1 A): | | | | | | | | | | | | | | | | | | |
| Expanded, perforated 0.002-inch 3003-H19 foil, 3/8-inch cells[6] | 2.9 | 0.03 | 75 | 50 | 190 | 5 | 100 | 5 | 100 | 10 | 50 | 10 | 37.7 | 2.7 | 18.0 | 1.2 | 8 | 9 |
| Preformed, perforated 0.002-inch 3003-H19 foil, 3/8-inch cells[7] | 3.0 | 0.3 | 75 | 50 | 150 | 20 | 80 | 10 | 80 | 10 | 40 | 5 | 29.1 | 4.8 | 12.8 | 2.0 | 12 | 12 |
| Preformed, perforated 0.003-inch 3003-H19 foil, 3/8-inch cells[7] | 4.0 | 0.2 | 75 | 50 | 240 | 20 | 120 | 20 | 130 | 30 | 70 | 10 | 42.3 | 5.8 | 18.6 | 2.4 | 12 | 12 |
| Expanded, perforated 0.002-inch 3003-H19 foil, 1/4-inch cells[7] | 4.4 | 0.1 | 75 | 50 | 240 | 20 | 170 | 10 | 140 | 20 | 110 | 20 | 41.9 | 3.6 | 25.4 | 2.5 | 10 | 10 |
| Preformed, perforated 0.002-inch 3003-H19 foil, 1/4-inch cells[7] | 4.5 | 0.5 | 75 | 50 | 260 | 30 | 140 | 20 | 130 | 20 | 70 | 5 | 47.9 | 10.0 | 19.0 | 1.7 | 12 | 12 |
| Expanded, perforated 0.001-inch 3003-H19 foil, 1/8-inch cells[7] | 4.8 | 0.2 | 75 | 50 | 320 | 40 | 210 | 10 | 160 | 30 | 110 | 20 | 59.4 | 11.0 | 37.6 | 5.7 | 12 | 12 |
| Preformed, perforated 0.004-inch 3003-H19 foil, 3/8-inch cells[7] | 5.2 | 0.4 | 75 | 50 | 330 | 30 | 170 | 20 | 160 | 20 | 80 | 10 | 57.0 | 11.6 | 25.6 | 3.6 | 12 | 12 |
| Expanded, perforated 0.004-inch 3003-H19 foil, 3/8-inch cells[7] | 5.3 | 0.1 | 75 | 50 | 350 | 10 | 210 | 20 | 180 | 20 | 120 | 10 | 61.8 | 16.0 | 39.7 | 3.9 | 4 | 4 |
| Expanded, perforated 0.002-inch 3003-H19 foil, 3/16-inch cells[7] | 5.8 | 0.3 | 75 | 50 | 400 | 40 | 250 | 30 | 240 | 50 | 130 | 20 | 87.0 | 22.8 | 39.8 | 7.6 | 12 | 12 |
| Preformed, perforated 0.003-inch 3003-H19 foil, 1/4-inch cells[7] | 6.0 | 0.1 | 75 | 50 | 400 | 10 | 210 | 5 | 210 | 30 | 100 | 10 | 87.8 | 13.2 | 29.6 | 2.8 | 12 | 12 |
| Expanded, perforated 0.003-inch 3003-H19 foil, 1/4-inch cells[7] | 6.2 | 0.5 | 75 | 50 | 410 | 40 | 270 | 20 | 230 | 40 | 120 | 20 | 87.6 | 20.4 | 57.2 | 7.2 | 4 | 4 |
| Preformed, perforated 0.005-inch 3003-H19 foil, 3/8-inch cells[7] | 6.3 | 0.3 | 75 | 50 | 390 | 20 | 230 | 20 | 180 | 30 | 120 | 20 | 75.2 | 23.6 | 32.9 | 3.6 | 12 | 12 |
| Preformed, perforated 0.004-inch 3003-H19 foil, 1/4-inch cells[7] | 7.7 | 0.3 | 75 | 50 | 540 | 40 | 290 | 20 | 280 | 30 | 120 | 10 | 98.4 | 13.0 | 33.8 | 4.2 | 12 | 12 |
| Preformed, perforated 0.005-inch 3003-H19 foil, 1/4-inch cells[7] | 9.0 | 0.3 | 75 | 50 | 590 | 50 | 320 | 20 | 340 | 40 | 160 | 20 | 144.6 | 34.4 | 42.1 | 3.0 | 12 | 12 |
| Aluminum-foil honeycomb (fig. 2-1 A): | | | | | | | | | | | | | | | | | | |
| Expanded, perforated 0.0007-inch 5052-H39 foil, 1/4-inch cells[8] | 2.0 | 0.02 | 75 | 50 | 140 | 5 | 80 | 5 | 90 | 10 | 40 | 5 | 20.4 | 2.3 | 10.2 | 1.0 | 12 | 12 |
| Expanded, perforated 0.002-inch 5052-H39 foil, 1/4-inch cells[8] | 3.9 | 0.04 | 75 | 50 | 340 | 20 | 170 | 5 | 190 | 10 | 120 | 5 | 47.7 | 3.9 | 18.8 | 2.5 | 12 | 12 |
| Preformed, unperforated 0.002-inch 5052-H39 foil, 1/4-inch cells[9] | 4.2 | 0.02 | 75 | 50 | 340 | 10 | 200 | 10 | 220(9)[10] | 15 | 140 | 10 | 60.6(9)[10] | 5.0 | 29.6 | 2.3 | 12 | 12 |
| Expanded, perforated 0.001-inch 5052-H39 foil, 1/8-inch cells[8] | 4.5 | 0.02 | 75 | 50 | 390 | 10 | 230 | 5 | 270 | 30 | 180 | 5 | 57.7 | 4.0 | 29.4 | 1.2 | 6 | 6 |
| Preformed, perforated 0.002-inch 5052-H39 foil, 1/4-inch cells[8] | 5.5 | 0.04 | 75 | 50 | 320 | 5 | 200 | 20 | 190 | 20 | 130 | 10 | 75.0 | 11.6 | 43.2 | 12.0 | 4 | 4 |
| Expanded, perforated 0.003-inch 5052-H39 foil, 1/4-inch cells[8] | 5.9 | 0.2 | 75 | 50 | 560 | 40 | 280 | 10 | 350 | 30 | 170 | 10 | 75.4 | 6.5 | 25.7 | 1.9 | 12 | 12 |
| Expanded, perforated 0.004-inch 5052-H39 foil, 1/4-inch cells[8] | 7.7 | 0.1 | 75 | 50 | 770(4)[10] | 10 | 380 | 10 | 480 | 30 | 220 | 20 | 108.7 | 6.8 | 32.2 | 3.2 | 12 | 12 |

Table 2-2.--Shear properties of core materials for structural sandwich constructions--con.

| Core material | Core density: Average | Core density: Standard deviation | Conditioning prior to test: Temperature | Conditioning prior to test: Relative humidity | Shear[1,2] Strength TL: Average | Strength TL: Standard deviation | Strength TW: Average | Strength TW: Standard deviation | Proportional limit stress TL: Average | Proportional limit stress TL: Standard deviation | Proportional limit stress TW: Average | Proportional limit stress TW: Standard deviation | Modulus of rigidity TL: Average | Modulus of rigidity TL: Standard deviation | Modulus of rigidity TW: Average | Modulus of rigidity TW: Standard deviation | Number of specimens: TL | Number of specimens: TW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pcf | Pcf | °F | Percent | Psi | Psi | Psi | Psi | Psi | Psi | Psi | Psi | 1,000 psi | 1,000 psi | 1,000 psi | 1,000 psi | | |
| Aluminum-foil honeycomb: | | | | | | | | | | | | | | | | | | |
| Preformed, unperforated 0.003-inch 2024-T4 foil, 3/8-inch cells[8] (fig. 2-2 B) | 3.6 | 0.2 | 75 | 50 | 170 | 10 | 60 | 5 | 110 | 10 | 40 | 1 | 56.6 | 0.6 | 13.0 | 0.6 | 3 | 3 |
| Preformed, perforated 0.003-inch 2024-T4 foil, 1/4-inch cells[8] | 6.0 | 0.02 | 75 | 50 | 470 | 20 | 280 | 20 | 240 | 10 | 150 | 5 | 79.7 | 3.8 | 51.6 | 9.5 | 3 | 3 |
| (fig. 2-1 A) | 6.0 | 0.02 | 75 | 50 | 470 | 20 | 280 | 20 | 240 | 10 | 150 | 5 | 79.7 | 3.8 | 51.6 | 9.5 | 3 | 3 |
| Aluminum-foil crossbanded core (fig. 2-3): | | | | | | | | | | | | | | | | | | |
| Preformed, unperforated 0.002-inch 5052-H39 foil, 1/8-inch corrugations[9] | 4.4 | 0.03 | 75 | 50 | 270 | 10 | 100 | 5 | 170 | 20 | 50 | 5 | 79.6 | 8.7 | 9.8 | 1.9 | 12 | 12 |
| Aluminum-foil honeycomb (fig. 2-2 A): | | | | | | | | | | | | | | | | | | |
| Type I, perforated 0.002-inch 1145-H19 foil, 1/4-inch cells[11] | 4.0 | 0.05 | 75 | 50 | 140 | 10 | 80 | 5 | 50 | 10 | 30 | 5 | 47.2 | 4.6 | 20.2 | 2.2 | 12 | 12 |
| Type I, perforated 0.002-inch 3003-H19 foil, 1/4-inch cells[11] | 4.6 | 0.02 | 75 | 50 | 270 | 10 | 150 | 5 | 110 | 20 | 70 | 10 | 45.9 | 4.1 | 23.6 | 1.5 | 12 | 12 |
| Type I, perforated 0.002-inch 5052-H38 foil, 1/4-inch cells[11] | 4.6 | 0.04 | 75 | 50 | 310 | 10 | 160 | 10 | 170 | 20 | 90 | 10 | 51.3 | 2.9 | 24.3 | 2.6 | 12 | 12 |
| Glass fabric honeycomb (fig. 2-1 A): | | | | | | | | | | | | | | | | | | |
| Preformed, fabric 112, finish 114 | 3.5 | 0.3 | 73 | 50 | 160 | 30 | 80 | 10 | 70 | 10 | 30 | 10 | 11.9 | 1.9 | 6.6 | 1.7 | 12 | 12 |
| Phenolic-resin, 1/4-inch cells[12] | --- | --- | Wet[13] | | 150 | 40 | 60 | 20 | 50 | 10 | 20 | 10 | 12.6 | 3.1 | 6.1 | 1.7 | 12 | 12 |
| Expanded, fabric 12, nylon-phenolic resin, 1/4-inch cells[14] | 3.8 | 0.1 | 73 | 50 | 350 | 20 | 190 | 10 | 140 | 20 | 90 | 10 | 15.0 | 2.3 | 7.0 | 0.3 | 12 | 11 |
| Expanded, fabric 21, finish 114 | 4.4 | 0.2 | 73 | 50 | 280 | 30 | 140 | 10 | 120 | 20 | 50 | 10 | 17.9 | 1.7 | 8.4 | 1.0 | 12 | 12 |
| Nylon-phenolic resin, 1/4-inch cells[12] | --- | --- | Wet[13] | | 220 | 30 | 110 | 10 | 100 | 10 | 50 | 10 | 16.4 | 3.3 | 8.1 | 2.7 | 12 | 12 |
| Preformed fabric 112, finish 114 | 5.6 | 0.4 | 73 | 50 | 250 | 40 | 130 | 20 | 100 | 20 | 50 | 10 | 14.6 | 2.6 | 8.8 | 1.2 | 12 | 12 |
| Phenolic-polyester resin, 1/4-inch cells[12] | --- | --- | Wet[13] | | 220 | 30 | 100 | 20 | 70 | 20 | 30 | 10 | 13.6 | 1.0 | 8.2 | 1.8 | 12 | 12 |
| Expanded, fabric 112, finish 114 | 6.3 | 0.3 | 73 | 50 | 460 | 30 | 240 | 20 | 180 | 40 | 110 | 20 | 23.0 | 3.2 | 10.6 | 1.3 | 12 | 12 |
| Nylon-phenolic resin, 3/16-inch cells[12] | --- | --- | Wet[13] | | 300 | 60 | 150 | 20 | 130 | 40 | 70 | 10 | 19.8 | 4.8 | 9.7 | 2.5 | 12 | 12 |
| Expanded, fabric 21, finish 114 | 6.3 | 0.1 | 73 | 50 | 420 | 30 | 240 | 20 | 150 | 30 | 80 | 20 | 20.8 | 2.6 | 11.4 | 1.3 | 12 | 12 |
| Nylon-phenolic resin, 1/4-inch cells[12] | --- | --- | Wet[13] | | 280 | 70 | 130 | 20 | 120 | 30 | 50 | 20 | 18.4 | 6.9 | 8.5 | 1.7 | 12 | 12 |
| Preformed, fabric 112, finish 114 | 6.4 | 0.3 | 73 | 50 | 340 | 40 | 180 | 20 | 140 | 30 | 70 | 10 | 21.6 | 3.0 | 11.2 | 2.0 | 12 | 12 |
| Phenolic-polyester resin, 3/16-inch cells[12] | --- | --- | Wet[13] | | 280 | 50 | 110 | 20 | 80 | 20 | 30 | 5 | 20.8 | 3.0 | 8.2 | 1.7 | 12 | 12 |
| Preformed, fabric 112, finish 136 | 8.2 | 0.5 | 73 | 50 | 480 | 30 | 220 | 10 | 230 | 40 | 110 | 20 | 28.8 | 2.4 | 10.5 | 5.3 | 12 | 11 |
| Polyester resin, 3/16-inch cells[12] | --- | --- | Wet[13] | | 320 | 30 | 110 | 10 | 120 | 20 | 40 | 10 | 17.7 | 2.9 | 0.9 | 1.2 | 11 | 12 |
| Expanded, fabric 21, finish 114 | 8.2 | 0.1 | 73 | 50 | 570 | 30 | 420 | 30 | 250 | 30 | 160 | 30 | 29.8 | 5.2 | 18.0 | 2.2 | 12 | 12 |
| CTL-91LD phenolic resin, 1/4-inch cells[12] | --- | --- | Wet[13] | | 380[15] | 100 | 350[15] | 60 | 190 | 40 | 180 | 20 | 29.3 | 4.0 | 19.4 | 2.9 | 12 | 12 |
| Preformed, fabric 112, finish 136 | 8.3 | 0.4 | 73 | 50 | 320 | 30 | 200 | 10 | 140 | 10 | 70 | 10 | 18.2 | 2.1 | 10.5 | 0.7 | 12 | 12 |
| Polyester resin, 1/4-inch cells[12] | --- | --- | Wet[13] | | 230 | 20 | 110 | 10 | 100 | 30 | 40 | 5 | 12.5 | 3.1 | 6.2 | 0.9 | 12 | 12 |
| Expanded, fabric 112, Volan A finish, heat-resistant polyester resin, 3/16-inch cells[16,17] | 8.4 | --- | 73 | 50 | 640 | --- | --- | -- | 210 | -- | --- | -- | ---- | ---- | ---- | --- | 2 | -- |

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Table 2-2.--Shear properties of core materials for structural sandwich constructions--con.

| Core material | Core density: Average | Core density: Standard deviation | Conditioning prior to test: Temperature | Conditioning prior to test: Relative humidity | Shear[1,2] Strength TL: Average | Strength TL: Standard deviation | Strength TW: Average | Strength TW: Standard deviation | Proportional limit stress TL: Average | Proportional limit stress TL: Standard deviation | Proportional limit stress TW: Average | Proportional limit stress TW: Standard deviation | Modulus of rigidity TL: Average | Modulus of rigidity TL: Standard deviation | Modulus of rigidity TW: Average | Modulus of rigidity TW: Standard deviation | Number of specimens: TL | Number of specimens: TW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pcf | Pcf | °F | Percent | Psi | Psi | Psi | Psi | Psi | Psi | Psi | Psi | 1,000 psi | 1,000 psi | 1,000 psi | 1,000 psi | | |
| Glass fabric honeycomb continued: | | | | | | | | | | | | | | | | | | |
| Expanded, fabric 13, heat-resistant silicone resin, 3/16-inch cells[8] | 8.5 | 0.4 | 73 | 50 | 250 | --- | 150 | 10 | 100 | -- | 60 | 1 | 8.6 | ---- | 8.3 | 5.8 | 2 | 3 |
| Do[8] | --- | --- | Wet[13] | | 260 | 10 | 130 | 10 | 60 | 20 | 40 | 10 | 21.5 | 11.2 | 5.9 | 0.7 | 6 | 6 |
| Preformed, fabric 112, finish 112, heat-resistant polyester resin, 3/16-inch cells[16,17] | 8.6 | 0.3 | 73 | 50 | 190 | 30 | --- | -- | 40 | 20 | --- | -- | ---- | ---- | ---- | --- | 4 | -- |
| Preformed, fabric 112, Volan A finish, heat-resistant polyester resin, 3/16-inch cells[16,17] | 8.6 | 0.4 | 73 | 50 | 360 | 20 | --- | -- | 140 | 50 | --- | -- | ---- | ---- | ---- | --- | 4 | -- |
| Expanded, fabric 112, finish 114, heat-resistant phenolic resin, 3/16-inch cells[16,17] | 8.7 | --- | 73 | 50 | 640[18] | --- | --- | -- | 490 | -- | --- | -- | ---- | ---- | ---- | --- | 1 | -- |
| Expanded, fabric 13, heat-resistant phenolic resin, 3/16-inch cells[8] | 8.8 | --- | 73 | 50 | 620[15] | 80 | 460 | 10 | 270 | 20 | 160 | 20 | 63.6 | 5.8 | 33.8 | 17.4 | 4 | 3 |
| Do[8] | ---- | --- | Wet[13] | | 660(2)[10] | --- | 350 | 10 | 230 | 20 | 120(3)[10] | 10 | 61.6 | 15.0 | 21.9(3)[10] | 1.2 | 4 | 5 |
| Preformed, fabric 112, finish 114, heat-resistant phenolic resin, 3/16-inch cells[16,17] | 8.8 | 0.2 | 73 | 50 | 580 | --- | --- | -- | 280 | -- | --- | -- | ---- | ---- | ---- | ---- | 2 | -- |
| Expanded, fabric 112, finish 114, CTL-91LD phenolic resin, 3/16-inch cells[16,17] | 8.8 | --- | 73 | 50 | 770 | --- | --- | -- | 520 | -- | --- | -- | ---- | ---- | ---- | ---- | 2 | -- |
| Preformed, fabric 112, finish 114, CTL-91LD phenolic resin, 3/16-inch cells[16,17] | 8.9 | 0.4 | 73 | 50 | 580[18] | --- | --- | -- | 210 | -- | --- | -- | ---- | ---- | ---- | ---- | 1 | -- |
| Expanded, fabric 112, finish 114 | 9.2 | 0.2 | 73 | 50 | 610 | 20 | 370 | 20 | 280 | 50 | 110 | 10 | 31.9 | 2.6 | 15.6 | 1.6 | 12 | 12 |
| Nylon-phenolic resin, 3/16-inch cells[12] | ----- | ---- | Wet[13] | | 340 | 70 | 180 | 50 | 130 | 30 | 80 | 30 | 19.6 | 5.2 | 9.9 | 2.0 | 12 | 12 |
| Asbestos fabric honeycomb (fig. 2-1A): | | | | | | | | | | | | | | | | | | |
| Expanded, asbestos fiber mat, heat-resistant, silicone resin, 3/16-inch cells[8] | 8.7 | 0.1 | 73 | 50 | 460 | 30 | 260 | 10 | 160 | 40 | 100 | 30 | 52.6 | 8.3 | 21.1 | 3.1 | 6 | 3 |
| Do[8] | ---- | --- | Wet[13] | | 440 | 30 | 220 | 10 | 190 | 30 | 90 | 10 | 56.0 | 2.4 | 18.0 | 1.0 | 3 | 3 |
| Expanded, asbestos fiber mat, heat-resistant phenolic resin, 3/16-inch cells[8] | 9.3 | --- | 73 | 50 | 580(2)[10] | --- | 450 | 10 | 320 | 70 | 180 | 20 | 61.9 | 4.8 | 31.5 | 2.3 | 6 | 3 |
| Do[8] | ---- | --- | Wet[13] | | 570(4)[10] | 20 | 410 | 60 | 280 | 30 | 190 | 40 | 45.3 | 6.2 | 32.3 | 6.0 | 6 | 5 |
| Glass fabric corrugated core with integrally woven liners (fig. 2-4): | | | | | | | | | | | | | | | | | | |
| Fabric 301, polyester resin, sine wave corrugations, 3/16-inch crest to trough[14,19] | 20.4[19] | --- | 73 | 50 | 480 | 110 | 170 | 30 | 200 | 50 | 70 | 10 | 56.8 | 13.7 | 13.4 | 2.7 | 12 | 12 |
| Plastic film honeycomb (fig. 2-1 A): | | | | | | | | | | | | | | | | | | |
| Expanded, 0.003-inch polyester film, 3/8-inch cells[20] | 2.1 | 0.03 | 73 | 50 | 65 | 4 | 30 | 4 | 35 | 6 | 15 | 3 | 5.0 | 0.3 | 1.9 | 0.1 | 12 | 12 |
| Expanded, 0.003-inch polyimide film, 3/8-inch cells[20] | 2.0 | 0.1 | 73 | 50 | 55 | 9 | 25 | 4 | 15 | 2 | 5 | 1 | 3.7 | 0.4 | 0.7 | 0.1 | 12 | 12 |
| Expanded, 0.002-inch polyamide film, phenolic resin, 1/4-inch cells[21] | 1.5 | 0.1 | 73 | 50 | 60 | 7 | 40 | 3 | 20 | 2 | 10 | 2 | 2.8 | 0.3 | 1.6 | 0.1 | 6 | 6 |
| Expanded, 0.002-inch polyamide film, phenolic resin, 1/8-inch cells[21] | 2.9 | 0.1 | 73 | 50 | 170 | 13 | 95 | 8 | 85 | 10 | 40 | 5 | 6.1 | 0.7 | 3.0 | 0.3 | 10 | 10 |

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Table 2-2.--Shear properties of core materials for structural sandwich constructions--con.

| Core material | Core density: Average | Core density: Standard deviation | Conditioning prior to test: Temperature | Conditioning prior to test: Relative humidity | Shear[1,2] Strength TL: Average | Strength TL: Standard deviation | Strength TW: Average | Strength TW: Standard deviation | Proportional limit stress TL: Average | Proportional limit stress TL: Standard deviation | Proportional limit stress TW: Average | Proportional limit stress TW: Standard deviation | Modulus of rigidity TL: Average | Modulus of rigidity TL: Standard deviation | Modulus of rigidity TW: Average | Modulus of rigidity TW: Standard deviation | Number of specimens: TL | Number of specimens: TW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pcf | Pcf | °F | Percent | Psi | Psi | Psi | Psi | Psi | Psi | Psi | Psi | 1,000 psi | 1,000 psi | 1,000 psi | 1,000 psi | | |
| Foamed cores: | | | | | | | | | | | | | | | | | | |
| Cellular cellulose acetate[22] | 6.7 | --- | 75 | 50 | 120 | 20 | 210 | 30 | --- | -- | --- | -- | 5.9 | 0.8 | 11.8 | 0.6 | 5 | 5 |
| Foamed-in-place polyester-diisocyanate[17,23] | 12.0 | --- | 75 | 50 | 110 | --- | --- | -- | 100 | -- | --- | -- | 10.2 | ---- | ---- | ---- | 2 | -- |
| Foamed-in-place alkyd-isocyanate[24] | 10.3 | --- | 75 | 50 | 180 | 5 | 180(4)[10] | 5 | 80 | 20 | 50 | 5 | 3.9 | 0.2 | 3.8 | 0.3 | 6 | 6 |
| Do[24] | 19.7 | --- | 75 | 50 | 360(9)[10] | 80 | 330 | 90 | 110 | 40 | 110 | 40 | 12.4 | 0.7 | 12.3 | 1.5 | 13 | 12 |
| Foamed-in-place silicone resin[17,23] | 12.6 | --- | 75 | 50 | 16 | --- | --- | -- | 10 | -- | --- | -- | 3.4 | ---- | ---- | ---- | 2 | -- |
| Do[17,23] | 15.4 | --- | 75 | 50 | 16 | 3 | --- | -- | 10 | 4 | --- | -- | 3.8(8)[10] | ---- | ---- | ---- | 4 | -- |
| Do[17,23] | 17.5 | --- | 75 | 50 | 12 | 1 | --- | -- | 10 | 1 | --- | -- | ---- | ---- | ---- | ---- | 3 | -- |
| Foamed-in-place epoxy-phenolic resin[17,25] | 18.0 | 0.7 | 75 | 50 | 300 | --- | --- | -- | --- | -- | --- | -- | 28.6 | ---- | ---- | ---- | 1 | -- |
| Paper honeycomb: | | | | | | | | | | | | | | | | | | |
| Expanded, 60-pound kraft paper, 20 percent alcohol soluble phenolic resin, 7/16-inch cells[26] (fig. 2-1A) | 1.7 | 0.06 | 80 | 30 | 110 | 10 | 60 | 5 | 55 | 5 | 20 | 5 | 12.4 | 1.6 | 5.0 | 0.6 | 12 | 12 |
| Do[26] | 1.7 | 0.06 | 73 | 50 | 80 | 10 | 50 | 5 | 35 | 10 | 25 | 3 | 11.1 | 0.9 | 4.0 | 0.5 | 12 | 12 |
| Do[26] | 1.8 | 0.07 | 80 | 90 | 50 | 8 | 30 | 4 | 20 | 2 | 10 | 1 | 7.0 | 1.1 | 2.3 | 0.4 | 12 | 12 |
| Do[26] | 2.9 | 0.11 | Wet[27] | | 20 | 3 | 10 | 2 | 4 | 2 | 2 | 0.5 | 2.9 | 0.5 | 0.9 | 0.2 | 12 | 12 |
| Expanded, 0.005-inch, 60-pound kraft paper, 50 percent epoxy resin, 3/8-inch cells[26] (fig. 2-1 A) | 2.9 | 0.2 | 73 | 50 | 120 | 6 | --- | -- | 60 | 10 | --- | -- | 14.4 | 0.4 | ---- | ---- | 3 | -- |
| Expanded, 0.005-inch, 60-pound kraft paper, 50 percent epoxy resin,[28] (fig. 2-2 F) | 3.0 | 0.2 | 73 | 50 | 120 | 5 | --- | -- | 50 | 20 | --- | -- | 9.9 | 0.4 | ---- | ---- | 3 | -- |
| Expanded, 0.005-inch, 60-pound kraft paper, 50 percent epoxy resin,[28] (fig. 2-2 E) | 3.0 | 0.3 | 73 | 50 | 110 | 20 | --- | -- | 50 | 5 | --- | -- | 9.7 | 1.0 | ---- | ---- | 3 | -- |
| Expanded, 0.005-inch, 60-pound kraft paper, 50 percent epoxy resin,[28] (fig. 2-2 G) | 3.1 | 0.3 | 73 | 50 | 110 | 20 | --- | -- | 40 | 10 | --- | -- | 11.5 | 1.0 | ---- | ---- | 3 | -- |
| Expanded, 125-pound kraft paper, 35 percent alcohol-soluble phenolic resin, 7/16-inch cells[26] (fig. 2-1 A) | 3.6 | 0.08 | 80 | 30 | 320 | 20 | 170 | 10 | 100 | 20 | 70 | 10 | 24.3 | 1.4 | 8.6 | 0.4 | 12 | 12 |
| Do[26] | 3.7 | 0.08 | 73 | 50 | 220 | 30 | 140 | 10 | 80 | 10 | 45 | 10 | 16.4 | 1.7 | 7.7 | 0.6 | 12 | 12 |
| Do[26] | 3.9 | 0.08 | 80 | 90 | 210 | 30 | 100 | 10 | 40 | 10 | 20 | 3 | 18.2 | 2.3 | 6.0 | 0.5 | 12 | 12 |
| Do[26] | 5.5 | 0.12 | Wet[25] | | 80 | 20 | 60 | 15 | 15 | 5 | 15 | 5 | 8.0 | 1.7 | 3.2 | 0.6 | 12 | 12 |

## Footnotes for Table 2-2

1 T direction refers to thickness of core and is parallel to grain of balsa wood and parallel to flutes of honeycomb cores. L direction refers to direction tangential to annual growth rings of balsa wood, parallel to ribbons of honeycomb cores, and parallel to direction of extrusion of cellular cellulose acetate and the direction of foam rise of alkyd-isocyanate. Shear properties of other cellular cores were not dependent on the direction of foam rise and are listed under TL for convenience. W direction refers to direction radial to annual growth rings of balsa wood, perpendicular to ribbons of honeycomb cores, and perpendicular to direction of extrusion or foam rise of cellular cores.

2 Balsa properties were determined by standard ASTM test methods for wood. Other core materials were evaluated in accordance with MIL-STD-401 for sandwich. Shear properties were obtained from the core shear test except for cores where sandwich flexure is specifically indicated.

3 Wiepking, C. A., and Doyle, D. V. Strength and related properties of balsa and quipo woods. U.S. Forest Prod. Lab. Rep. 1511. 1944.

4 Doyle, D. V., Drow, J. T., and McBurney, R. S. Elastic properties of wood--The Young's moduli, moduli of rigidity and Poisson's ratios of balsa and quipo. U.S. Forest Prod. Lab. Rep. 1528. 1945.

5 Density of balsa specimens varied from about 4.5 to 14 pounds per cubic foot. Average mechanical properties were obtained by least squares. The standard deviations increase linearly with increasing density. Shear strength is based on 60 specimens and shear modulus on 25 specimens.

6 Jenkinson, P. M., and Kuenzi, E. W. Effect of core thickness on shear properties of aluminum honeycomb cores. U.S. Forest Prod. Lab. Rep. 1886. 1962.

7 Kuenzi, E. W. Mechanical properties of aluminum honeycomb cores. U.S. Forest Prod. Lab. Rep. 1849. 1955.

8 Stevens, G. H., and Kuenzi, E. W. Mechanical properties of several honeycomb cores. U.S. Forest Prod. Lab. Rep. 1887. 1962.

9 Stevens, G. H. Compressive and shear properties of two configurations of sandwich cores of corrugated foil. U.S. Forest Prod. Lab. Rep. 1889. 1962.

10 Value based on number of specimens indicated in parentheses.

11 Kuenzi, E. W., and Setterholm, V. C. Mechanical properties of aluminum multiwave cores. U.S. Forest Prod. Lab. Rep. 1855. 1956.

12 Kuenzi, E. W. Mechanical properties of glass-fabric honeycomb cores. U.S. Forest Prod. Lab. Rep. 1861. 1957.

13 Wet values are for core at 73° F after 60 days' exposure at 100° F. and 100 percent relative humidity.

14 Stevens, G. H. Shear properties and performance in a sandwich panel of a corrugated glass-fiber-reinforced plastic core with integrally woven liners. U.S. Forest Prod. Lab. Rep. WER-241. 1962.

15 Denotes bond failure between core and loading plate.

16 Setterholm, V. C., and Kuenzi, E. W. Performance of glass-fabric sandwich and honeycomb cores at elevated temperatures. WADC TR 56-119 (ASTIA Doc. No. AD 97290). 1956.

17 Shear properties determined by sandwich flexure test.

18 Denotes bond failure between facing and core.

19 The core, including liners, was 0.190 inch thick and weighed 0.32 pound per square foot. The corrugations accounted for about one-half the panel weight. Thus, the core was comparable to one of 10 pounds per cubic foot density, with the liners acting as part of the sandwich facings.

20 Jenkinson, P. M. Compressive and shear properties of polyester and polyimide film honeycomb core. U.S. Forest Serv. Res. Pap. FPL 75, Forest Prod. Lab., Madison, Wis. 1967.

21 Jenkinson, P. M. Compressive and shear properties of polyamide honeycomb core. U.S. Forest Serv. Res. Note FPL-0202, Forest Prod. Lab., Madison, Wis. 1969.

22 Kuenzi, E. W. Effect of elevated temperatures on the strengths of small specimens of sandwich construction of the aircraft type. U.S. Forest Prod. Lab. Rep. 1804. 1949.

23 Setterholm, V. C., and Kuenzi, E. W. Performance of sandwich with cores of foamed silicone and modified polyester resins at elevated temperatures and at high humidity. WADC TR 56-230 (ASTIA Doc. No. AD 110421). 1956.

24 Jenkinson, P. M., and Kuenzi, E. W. Properties of alkyd-isocyanate foamed-in-place core. WADC TR 57-182 (ASTIA Doc. No. 155884). 1958.

25 Jenkinson, P. M., and Kuenzi, E. W. Mechanical properties of 422-J Bacfoam core for sandwich construction. WADC TR 57-132 (ASTIA Doc. No. AD 118249). 1957.

26 Jenkinson, P. M. Effect of core thickness and moisture content on mechanical properties of two resin-treated paper honeycomb cores. U.S. Forest Serv. Res. Pap. FPL 35, Forest Prod. Lab., Madison, Wis. 1965.

27 Wet values are for cores at 75° F. after soaking in distilled water for 48 hours at 75° F.

28 Jenkinson, P. M., Fahey, D. J., and Selbo, M. L. Strength of resin-treated paper cores of four cell configurations. U.S. Forest Prod. Lab. Rep. PE-198. 1960.

Table 2-3.--Typical values of mechanical properties for some heat-resistant sandwich core materials

| Core material | Average core density | Test temperature[1] | Compression[2] Strength | Compression[2] Proportional limit stress | Compression[2] Modulus of elasticity | Compression[2] Number of specimens | Shear[2] Strength | | Shear[2] Proportional limit stress | | Shear[2] Modulus of rigidity | | Shear[2] Number of specimens | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | T | T | T | | TL | TW | TL | TW | TL | TW | TL | TW |
| | Pcf | °F | Psi | Psi | 1,000 psi | | Psi | Psi | Psi | Psi | 1,000 psi | 1,000 psi | | |
| Aluminum-foil honeycomb (fig. 2-1 A): | | | | | | | | | | | | | | |
| Expanded, perforated, 0.001-inch 3003-H19 foil, 1/8-inch cells[3,4] | 4.6 | 75 | 560 | -- | -- | 2 | 310 | 180 | -- | -- | -- | -- | 2 | 2 |
| | 4.6 | 250 | 440 | -- | -- | 4 | 250 | 150 | -- | -- | -- | -- | 3 | 3 |
| | 4.6 | 350 | 400 | -- | -- | 4 | 200 | 120 | -- | -- | -- | -- | 3 | 3 |
| | 4.6 | 500 | 150 | -- | -- | 4 | 60 | 40 | -- | -- | -- | -- | 3 | 3 |
| Expanded, nonperforated, 0.0007-inch 5052-H39 foil, 1/8-inch cells[4,5] | 3.1 | 75 | -- | -- | -- | -- | 220 | 130 | -- | -- | 54 | 27 | 8 | 8 |
| | 3.1 | 270 | -- | -- | -- | -- | 180 | 100 | -- | -- | 46 | 18 | 7 | 8 |
| | 3.1 | 350 | -- | -- | -- | -- | 170 | 90 | -- | -- | 37 | 15 | 8 | 8 |
| | 3.1 | 400 | -- | -- | -- | -- | 120 | 60 | -- | -- | 28 | 13 | 8 | 8 |
| Expanded, nonperforated, 0.0010-inch 5052-H39 foil, 1/8-inch cells[4,5] | 4.5 | 75 | -- | -- | -- | -- | 400 | 220 | -- | -- | 90 | 40 | 8 | 8 |
| | 4.5 | 270 | -- | -- | -- | -- | 360 | 200 | -- | -- | 104 | 25 | 8 | 8 |
| | 4.5 | 350 | -- | -- | -- | -- | 300 | 160 | -- | -- | 75 | 24 | 7 | 7 |
| | 4.5 | 400 | -- | -- | -- | -- | 250 | 120 | -- | -- | 60 | 18 | 8 | 8 |
| Expanded, perforated, 0.001-inch 5052-H39 foil, 1/8-inch cells[3,5] | 4.6 | 75 | 560 | -- | -- | 2 | 390 | 210 | -- | -- | -- | -- | 1 | 1 |
| | 4.6 | 250 | 500 | -- | -- | 3 | 340 | 190 | -- | -- | -- | -- | 3 | 3 |
| | 4.6 | 350 | 500 | -- | -- | 4 | 310 | 170 | -- | -- | -- | -- | 3 | 3 |
| | 4.6 | 500 | 370 | -- | -- | 3 | 110 | 50 | -- | -- | -- | -- | 3 | 3 |
| Preformed, perforated, 0.002-inch 5052-H39 foil, 1/4-inch cells[6] | 4.6 | 75 | 490 | -- | -- | 2 | 360 | 220 | 250 | 160 | 70.6 | 38.1 | 3 | 1 |
| | 4.6 | 250 | 480 | -- | -- | 3 | 320 | 190 | 200 | 120 | 45.9 | 19.0 | 3 | 3 |
| | 4.6 | 350 | 340 | -- | -- | 3 | 180 | 80 | 70 | 30 | 16.0 | 5.5 | 3 | 3 |
| Expanded, nonperforated, 0.0020-inch 5052-H39 foil, 3/16-inch cells[4,5] | 5.8 | 75 | -- | -- | -- | -- | 600 | 300 | -- | -- | 100 | 46 | 8 | 8 |
| | 5.8 | 270 | -- | -- | -- | -- | 560 | 290 | -- | -- | 128 | 32 | 8 | 8 |
| | 5.8 | 350 | -- | -- | -- | -- | 420 | 210 | -- | -- | 86 | 23 | 8 | 8 |
| | 5.8 | 400 | -- | -- | -- | -- | 360 | 170 | -- | -- | 64 | 20 | 7 | 8 |
| Expanded, nonperforated, 0.0015-inch 5052-H39 foil, 1/8-inch cells[4,5] | 6.2 | 75 | -- | -- | -- | -- | 560 | 320 | -- | -- | 106 | 44 | 8 | 8 |
| | 6.2 | 270 | -- | -- | -- | -- | 560 | 310 | -- | -- | 114 | 30 | 8 | 8 |
| | 6.2 | 350 | -- | -- | -- | -- | 550 | 280 | -- | -- | 105 | 24 | 7 | 8 |
| | 6.2 | 400 | -- | -- | -- | -- | 410 | 180 | -- | -- | 73 | 17 | 7 | 8 |
| | 6.2 | 500 | -- | -- | -- | -- | 220 | 80 | -- | -- | 47 | 13 | 4 | 4 |

Table 2-3.--Typical values of mechanical properties for some heat-resistant sandwich core materials--con.

| Core material | Average core density | Test temperature[1] | Compression[2] Strength | Compression[2] Proportional limit stress | Compression[2] Modulus of elasticity | Compression[2] Number of specimens | Shear[2] Strength | | Shear[2] Proportional limit stress | | Shear[2] Modulus of rigidity | | Shear[2] Number of specimens | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | T | T | T | | TL | TW | TL | TW | TL | TW | TL | TW |
| | Pcf | °F | Psi | Psi | 1,000 psi | | Psi | Psi | Psi | Psi | 1,000 psi | 1,000 psi | | |
| Aluminum-foil honeycomb continued: | | | | | | | | | | | | | | |
| Expanded, nonperforated, 0.0020-inch 5052-H39 foil, 1/8-inch cells[4,5] | 8.1 | 75 | -- | -- | -- | -- | 950 | 470 | -- | -- | 158 | 61 | 6 | 8 |
| | 8.1 | 270 | -- | -- | -- | -- | 910 | 470 | -- | -- | 154 | 48 | 8 | 7 |
| | 8.1 | 350 | -- | -- | -- | -- | 860 | 350 | -- | -- | 114 | 30 | 7 | 8 |
| | 8.1 | 400 | -- | -- | -- | -- | 620 | 240 | -- | -- | 91 | 23 | 8 | 8 |
| | 8.1 | 500 | -- | -- | -- | -- | 300 | 80 | -- | -- | 58 | 23 | 4 | 4 |
| Expanded, nonperforated, 0.0007-inch 5056-H39 foil, 1/8-inch cells[4,5] | 3.1 | 75 | -- | -- | -- | -- | 290 | 160 | -- | -- | 58 | 20 | 4 | 4 |
| | 3.1 | 270 | -- | -- | -- | -- | 240 | 110 | -- | -- | 50 | 17 | 4 | 4 |
| | 3.1 | 350 | -- | -- | -- | -- | 160 | 90 | -- | -- | 45 | 15 | 4 | 4 |
| Expanded, nonperforated, 0.0010-inch 5056-H39 foil, 1/8-inch cells[4,5] | 4.8 | 75 | -- | -- | -- | -- | 500 | 280 | -- | -- | 98 | 31 | 4 | 4 |
| | 4.8 | 270 | -- | -- | -- | -- | 490 | 240 | -- | -- | 80 | 28 | 4 | 4 |
| | 4.8 | 350 | -- | -- | -- | -- | 380 | 160 | -- | -- | 70 | 21 | 4 | 4 |
| Expanded, nonperforated, 0.0015-inch 5056-H39 foil, 1/8-inch cells[4,5] | 6.5 | 75 | -- | -- | -- | -- | 830 | 400 | -- | -- | 135 | 41 | 8 | 8 |
| | 6.5 | 270 | -- | -- | -- | -- | 820 | 390 | -- | -- | 106 | 34 | 8 | 8 |
| | 6.5 | 350 | -- | -- | -- | -- | 640 | 220 | -- | -- | 88 | 26 | 8 | 8 |
| Expanded, nonperforated, 0.0020-inch 5056-H39 foil, 1/8-inch cells[4,5] | 7.8 | 75 | -- | -- | -- | -- | 1120 | 530 | -- | -- | 156 | 47 | 4 | 4 |
| | 7.8 | 270 | -- | -- | -- | -- | 1000 | 480 | -- | -- | 122 | 37 | 4 | 4 |
| | 7.8 | 350 | -- | -- | -- | -- | 830 | 280 | -- | -- | 98 | 29 | 4 | 4 |
| Expanded, nonperforated, 0.0020-inch 5056-H39 foil, 1/8-inch cells[4,5] | 8.5 | 75 | -- | -- | -- | -- | 1140 | 600 | -- | -- | 165 | 49 | 4 | 4 |
| | 8.5 | 270 | -- | -- | -- | -- | 1050 | 510 | -- | -- | 128 | 38 | 4 | 4 |
| | 8.5 | 350 | -- | -- | -- | -- | 870 | 300 | -- | -- | 98 | 30 | 4 | 4 |
| Preformed, nonperforated, 0.003-inch 2024-T4 foil, 3/8-inch cells[6] (fig. 2-2 B) | 3.6 | 75 | 230 | -- | -- | 3 | 180 | 60 | 110 | 40 | 56.6 | 13.0 | 3 | 3 |
| | 3.6 | 250 | 140 | -- | -- | 3 | 100 | 40 | 40 | 30 | 24.7 | 5.1 | 3 | 3 |
| | 3.6 | 350 | 100 | -- | -- | 3 | 50 | 30 | 10 | 10 | 9.0 | 2.3 | 3 | 3 |

Table 2-3.--Typical values of mechanical properties for some heat-resistant sandwich core materials--con.

| Core material | Average core density | Test temperature[1] | Compression[2] Strength | Compression[2] Proportional limit stress | Compression[2] Modulus of elasticity | Compression[2] Number of specimens | Shear[2] Strength | | Shear[2] Proportional limit stress | | Shear[2] Modulus of rigidity | | Shear[2] Number of specimens | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | T | T | T | | TL | TW | TL | TW | TL | TW | TL | TW |
| | Pcf | °F | Psi | Psi | 1,000 psi | | Psi | Psi | Psi | Psi | 1,000 psi | 1,000 psi | | |
| Aluminum-foil honeycomb continued: | | | | | | | | | | | | | | |
| Preformed, perforated, 0.003-inch 2024-T4 foil, 1/4-inch cells[6] | 6.0 | 75 | 670 | -- | -- | 6 | 470 | 280 | 240 | 150 | 79.8 | 51.6 | 3 | 3 |
| | 6.0 | 250 | 640 | -- | -- | 6 | -- | 270 | -- | 140 | -- | 37.3 | -- | 2 |
| | 6.0 | 350 | 560 | -- | -- | 3 | 150 | 150 | 60 | 50 | 16.0 | 13.5 | 3 | 3 |
| Expanded, nonperforated, 0.0015-inch 2024-T81 foil, 1/4-inch cells[4,7,8] | 2.8 | 75 | 290 | -- | -- | 16 | 190 | 120 | -- | -- | -- | -- | 19 | 19 |
| | 2.8 | 270 | 220 | -- | -- | 8 | 170 | 100 | -- | -- | -- | -- | 8 | 8 |
| | 2.8 | 350 | 200 | -- | -- | 8 | 150 | 90 | -- | -- | -- | -- | 11 | 11 |
| | 2.8 | 430 | 200 | -- | -- | 8 | 130 | 80 | -- | -- | -- | -- | 11 | 11 |
| Expanded, nonperforated, 0.0015-inch 2024-T81 foil, 3/16-inch cells[4,7,8] | 3.6 | 75 | 450 | -- | -- | 16 | 270 | 170 | -- | -- | -- | -- | 19 | 19 |
| | 3.6 | 270 | 360 | -- | -- | 8 | 230 | 150 | -- | -- | -- | -- | 8 | 8 |
| | 3.6 | 350 | 340 | -- | -- | 8 | 210 | 140 | -- | -- | -- | -- | 11 | 11 |
| | 3.6 | 430 | 290 | -- | -- | 8 | 190 | 140 | -- | -- | -- | -- | 11 | 11 |
| Expanded, nonperforated, 0.0015-inch 2024-T81 foil, 1/8-inch cells[4,7,8] | 5.1 | 75 | 760 | -- | -- | 16 | 540 | 300 | -- | -- | -- | -- | 20 | 20 |
| | 5.1 | 270 | 720 | -- | -- | 8 | 470 | 260 | -- | -- | -- | -- | 12 | 12 |
| | 5.1 | 350 | 620 | -- | -- | 12 | 440 | 240 | -- | -- | -- | -- | 18 | 18 |
| | 5.1 | 430 | 550 | -- | -- | 8 | 360 | 220 | -- | -- | -- | -- | 15 | 15 |
| Expanded, nonperforated, 0.0020-inch 2024-T81 foil, 1/8-inch cells[4,7,8] | 6.8 | 75 | 1240 | -- | -- | 12 | 840 | 480 | -- | -- | -- | -- | 21 | 23 |
| | 6.8 | 270 | 1170 | -- | -- | 8 | 750 | 450 | -- | -- | -- | -- | 11 | 11 |
| | 6.8 | 350 | 1050 | -- | -- | 8 | 670 | 380 | -- | -- | -- | -- | 14 | 14 |
| | 6.8 | 430 | 840 | -- | -- | 8 | 590 | 330 | -- | -- | -- | -- | 14 | 14 |
| Expanded, nonperforated, 0.0025-inch 2024-T81 foil, 1/8-inch cells[4,7,8] | 8.5 | 75 | 2030 | -- | -- | 8 | 1180 | 770 | -- | -- | -- | -- | 8 | 8 |
| | 8.5 | 270 | 1640 | -- | -- | 4 | 1020 | 650 | -- | -- | -- | -- | 4 | 4 |
| | 8.5 | 350 | 1570 | -- | -- | 4 | 870 | 600 | -- | -- | -- | -- | 4 | 4 |
| | 8.5 | 430 | 1570 | -- | -- | 4 | 740 | 500 | -- | -- | -- | -- | 4 | 4 |
| Expanded, nonperforated, 0.0030-inch 2024-T81 foil, 1/8-inch cells[4,7,8] | 9.5 | 75 | 2350 | -- | -- | 4 | 1350 | 930 | -- | -- | -- | -- | 12 | 8 |
| | 9.5 | 270 | 1990 | -- | -- | 4 | 1190 | 650 | -- | -- | -- | -- | 8 | 4 |
| | 9.5 | 350 | 1890 | -- | -- | 4 | 1090 | 570 | -- | -- | -- | -- | 8 | 4 |
| | 9.5 | 430 | 1760 | -- | -- | 4 | 980 | 490 | -- | -- | -- | -- | 4 | 4 |

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Table 2-3.--Typical values of mechanical properties for some heat-resistant sandwich core materials--con.

| Core material | Average core density | Test temperature[1] | Compression[2] Strength T | Compression[2] Proportional limit stress T | Compression[2] Modulus of elasticity T | Compression[2] Number of specimens | Shear[2] Strength TL | Shear[2] Strength TW | Shear[2] Proportional limit stress TL | Shear[2] Proportional limit stress TW | Shear[2] Modulus of rigidity TL | Shear[2] Modulus of rigidity TW | Shear[2] Number of specimens TL | Shear[2] Number of specimens TW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pcf | °F | Psi | Psi | 1,000 psi | | Psi | Psi | Psi | Psi | 1,000 psi | 1,000 psi | | |
| Glass fabric honeycomb (fig. 2-1 A): | | | | | | | | | | | | | | |
| Expanded, fabric 11, heat-resistant phenolic resin, 3/16-inch cells[9] | 4.0 | -65 | 700 | | | 2 | 330 | 140 | -- | -- | -- | -- | 5 | 5 |
| | 4.0 | 75 | 650 | -- | -- | 5 | 310 | 140 | -- | -- | -- | -- | 13 | 13 |
| | 4.0 | 160 | 620 | -- | -- | 5 | 300 | 140 | -- | -- | -- | -- | 5 | 5 |
| | 4.0 | 200 | 630 | -- | -- | 5 | 300 | 130 | -- | -- | -- | -- | 5 | 5 |
| | 4.0 | 400 | --- | -- | -- | -- | 220 | 110 | -- | -- | -- | -- | 34 | 28 |
| | 4.0 | 500 | --- | -- | -- | -- | 260 | 120 | -- | -- | -- | -- | 5 | 5 |
| | 4.0 | 550 | --- | -- | -- | -- | 220 | 100 | -- | -- | -- | -- | 5 | 5 |
| Expanded, tight bias weave fabric 108, A1100 finish, polyimide resin, 3/16-inch cells[9] | 5.0 | 75 | --- | -- | -- | -- | 330 | -- | -- | -- | 25.4 | -- | 4 | -- |
| | 5.0 | 450 | 490 | -- | 29 | 4 | 270 | -- | -- | -- | 21.4 | -- | 4 | -- |
| Expanded, tight weave fabric 108, A1100 finish, polyimide resin, 3/16-inch cells[9] | 5.4 | 75 | 530 | -- | 38 | 4 | 280 | -- | -- | -- | 14.4 | -- | 5 | -- |
| | 5.4 | 400 | [10]490 | -- | [10]40 | 3 | 260 | -- | -- | -- | 13.2 | -- | 3 | -- |
| | 5.4 | 450 | 500 | -- | 40 | 5 | 240 | -- | -- | -- | 8.8 | -- | 4 | -- |
| | 5.4 | 500 | 490 | -- | 32 | 3 | 230 | -- | -- | -- | 11.7 | -- | 3 | -- |
| | 5.4 | 550 | [11]480 | -- | [11]45 | 4 | 210 | -- | -- | -- | 9.7 | -- | 3 | -- |
| Expanded, fabric 12, heat-resistant phenolic resin, 3/16-inch cells[9] | 5.5 | -65 | 1180 | -- | -- | 5 | 490 | 240 | -- | -- | -- | -- | 5 | 5 |
| | 5.5 | 75 | 1030 | -- | -- | 5 | 460 | 230 | -- | -- | -- | -- | 5 | 72 |
| | 5.5 | 160 | 1030 | -- | -- | 5 | 445 | 220 | -- | -- | -- | -- | 5 | 5 |
| | 5.5 | 200 | 980 | -- | -- | 5 | 430 | 220 | -- | -- | -- | -- | 5 | 5 |
| Expanded, fabric 13, heat-resistant phenolic resin, 3/16-inch cells[9] | 8.0 | -65 | 2200 | -- | -- | 5 | 890 | 470 | -- | -- | -- | -- | 5 | 5 |
| | 8.0 | 75 | 1940 | -- | -- | 5 | 780 | 430 | -- | -- | -- | -- | 5 | 5 |
| | 8.0 | 160 | 1680 | -- | -- | 5 | 790 | 430 | -- | -- | -- | -- | 5 | 5 |
| | 8.0 | 200 | 1800 | -- | -- | 5 | 770 | 400 | -- | -- | -- | -- | 5 | 5 |
| Expanded, fabric 112, volan A finish, heat-resistant polyester resin, 3/16-inch cells[4,12] | 8.4 | 75 | 1300 | 810 | 130 | 2 | 640 | -- | 210 | -- | -- | -- | 2 | -- |
| | 8.4 | 300 | 700 | 260 | -94 | 2 | 370 | -- | 180 | -- | -- | -- | 2 | -- |
| | 8.4 | 500 | 310 | 170 | 62 | 2 | 220 | -- | 80 | -- | -- | -- | 2 | -- |
| | 8.4 | 700 | 100 | -- | -- | 1 | 70 | -- | 20 | -- | -- | -- | 2 | -- |

Table 2-3.--Typical values of mechanical properties for some heat-resistant sandwich core materials--con.

| Core material | Average core density | Test temperature[1] | Compression[2] Strength T | Compression[2] Proportional limit stress T | Compression[2] Modulus of elasticity T | Compression[2] Number of specimens | Shear[2] Strength TL | Shear[2] Strength TW | Shear[2] Proportional limit stress TL | Shear[2] Proportional limit stress TW | Shear[2] Modulus of rigidity TL | Shear[2] Modulus of rigidity TW | Shear[2] Number of specimens TL | Shear[2] Number of specimens TW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pcf | °F | Psi | Psi | 1,000 psi | | Psi | Psi | Psi | Psi | 1,000 psi | 1,000 psi | | |
| Glass fabric honeycomb continued: | | | | | | | | | | | | | | |
| Expanded, fabric 13, heat-resistant silicone resin, 3/16-inch cells[6] | 8.5 | 75 | 540 | 210 | 146 | 3 | 250 | 150 | 100 | 60 | 8.6 | 8.3 | 2 | 3 |
| | 8.5 | 250 | 220 | 130 | 21 | 3 | -- | 70 | 30 | 20 | 2.1 | 1.2 | 3 | 3 |
| | 8.5 | 350 | 190 | 110 | 46 | 3 | 80 | 40 | 30 | 20 | 2.5 | .9 | 2 | 3 |
| Preformed, fabric 112, finish 112, heat-resistant silicone resin, 3/16-inch cells[4,12] | 8.6 | 75 | 250 | 170 | 70 | 4 | 190 | -- | 40 | -- | -- | -- | 4 | -- |
| | 8.6 | 300 | 110 | 70 | 56 | 4 | 90 | -- | 50 | -- | -- | -- | 4 | -- |
| | 8.6 | 500 | 90 | 70 | 51 | 4 | 70 | -- | 50 | -- | -- | -- | 4 | -- |
| | 8.6 | 700 | 50 | 40 | 43 | 4 | 40 | -- | 30 | -- | -- | -- | 4 | -- |
| Preformed, fabric 112, volan a finish, heat-resistant polyester resin, 3/16-inch cells[4,12] | 8.6 | 75 | 840 | 470 | 126 | 4 | 360 | -- | 140 | -- | -- | -- | 4 | -- |
| | 8.6 | 300 | 630 | 400 | 99 | 4 | 340 | -- | 200 | -- | -- | -- | 4 | -- |
| | 8.6 | 500 | 480 | 270 | 76 | 4 | 250 | -- | 150 | -- | -- | -- | 4 | -- |
| | 8.6 | 700 | 70 | 30 | 38 | 4 | 50 | -- | 20 | -- | -- | -- | 4 | -- |
| Expanded, fabric 112, finish 114, heat-resistant phenolic resin, 3/16-inch cells[4,12] | 8.7 | 75 | 1540 | 940 | 150 | 2 | [13]640 | -- | 490 | -- | -- | -- | 1 | -- |
| | 8.7 | 300 | 1280 | 640 | 120 | 2 | [13]600 | -- | 350 | -- | -- | -- | 2 | -- |
| | 8.7 | 500 | 680 | 260 | 94 | 2 | 340 | -- | 130 | -- | -- | -- | 2 | -- |
| | 8.7 | 700 | 330 | 120 | 73 | 2 | [13]110 | -- | 30 | -- | -- | -- | 1 | -- |
| Expanded, fabric 13, heat-resistant phenolic resin, 3/16-inch cells[6] | 8.8 | 75 | 1670 | 990 | 179 | 3 | [14]620 | 460 | 270 | 160 | 63.6 | 33.8 | 4 | 3 |
| | 8.8 | 250 | 1640 | 1090 | 126 | 3 | [14]-- | [14]-- | -- | -- | -- | -- | -- | -- |
| | 8.8 | 350 | 1500 | 840 | 114 | 3 | [14]330 | [14]230 | 110 | 70 | 26.3 | 12.2 | 3 | 3 |
| Preformed, fabric 112, finish 114, heat-resistant phenolic resin, 3/16-inch cells[4,12] | 8.8 | 75 | 1580 | 1020 | 150 | 4 | [13]580 | -- | 280 | -- | -- | -- | 2 | -- |
| | 8.8 | 300 | 1210 | 700 | 114 | 4 | [13]460 | -- | 250 | -- | -- | -- | 2 | -- |
| | 8.8 | 500 | 400 | 190 | 50 | 4 | [13]240 | -- | 110 | -- | -- | -- | 2 | -- |
| | 8.8 | 700 | 410 | 250 | 58 | 4 | [13]100 | -- | 70 | -- | -- | -- | 2 | -- |
| Expanded, fabric 112, finish 114, CTL-91LD heat-resistant phenolic resin, 3/16-inch cells[4,12] | 8.8 | 75 | 1640 | 1070 | 156 | 2 | 770 | -- | 520 | -- | -- | -- | 2 | -- |
| | 8.8 | 300 | 1310 | 940 | 121 | 2 | -- | -- | 260 | -- | -- | -- | 2 | -- |
| | 8.8 | 500 | 800 | 320 | 99 | 2 | [13]340 | -- | 190 | -- | -- | -- | 2 | -- |
| | 8.8 | 700 | 380 | 140 | 79 | 2 | [13]70 | -- | 70 | -- | -- | -- | 2 | -- |

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Table 2-3.--Typical values of mechanical properties for some heat-resistant sandwich core materials--con.

| Core material | Average core density | Test temperature[1] | Compression[2] Strength | Compression Proportional limit stress | Compression Modulus of elasticity | Compression Number of specimens | Shear[2] Strength | | Shear Proportional limit stress | | Shear Modulus of rigidity | | Shear Number of specimens | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | T | T | T | | TL | TW | TL | TW | TL | TW | TL | TW |
| | Pcf | °F | Psi | Psi | 1,000 psi | | Psi | Psi | Psi | Psi | 1,000 psi | 1,000 psi | | |
| Glass fabric honeycomb continued: | | | | | | | | | | | | | | |
| Preformed, fabric 112, finish 114, CTL-91LD heat-resistant phenolic resin, 3/16-inch cells[4,12] | 8.9 | 75 | 1750 | 1260 | 159 | 4 | [13]580 | -- | 210 | -- | -- | -- | 1 | -- |
| | 8.9 | 300 | 990 | 320 | 110 | 4 | [13]310 | -- | 140 | -- | -- | -- | 1 | -- |
| | 8.9 | 500 | 470 | 270 | 70 | 4 | 200 | -- | 80 | -- | -- | -- | 2 | -- |
| | 8.9 | 700 | 390 | 220 | 68 | 4 | [13]140 | -- | 70 | -- | -- | -- | 1 | -- |
| Expanded, fabric 13, heat-resistant phenolic resin, 3/16-inch cells[9] | 9.0 | -65 | 2330 | -- | -- | 5 | 940 | 490 | -- | -- | -- | -- | 5 | 5 |
| | 9.0 | 75 | 2200 | -- | -- | 5 | 860 | 480 | -- | -- | -- | -- | -- | 4 |
| | 9.0 | 160 | 2140 | -- | -- | 5 | 780 | 470 | -- | -- | -- | -- | 5 | 5 |
| | 9.0 | 200 | 1970 | -- | -- | 5 | 720 | 430 | -- | -- | -- | -- | 5 | 5 |
| Expanded, fabric 14, heat-resistant phenolic resin, 3/16-inch cells[9] | 12.0 | -65 | 2840 | -- | -- | 5 | 1100 | 640 | -- | -- | -- | -- | 3 | -- |
| | 12.0 | 75 | 2750 | -- | -- | 5 | 1080 | 630 | -- | -- | -- | -- | 5 | 5 |
| | 12.0 | 160 | 2590 | -- | -- | 5 | 900 | 600 | -- | -- | -- | -- | 5 | 5 |
| | 12.0 | 200 | 2520 | -- | -- | 5 | 880 | 600 | -- | -- | -- | -- | 5 | 5 |
| Asbestos fabric honeycomb (fig. 2-1A): | | | | | | | | | | | | | | |
| Expanded, asbestos fiber mat, heat-resistant silicone resin, 3/16-inch cells[6] | 8.7 | 75 | 700 | 270 | 146 | 3 | 460 | 260 | 160 | 100 | 52.6 | 21.1 | 6 | 3 |
| | 8.7 | 250 | 450 | 250 | 55 | 3 | 240 | 40 | 60 | 20 | 14.8 | 3.1 | 3 | 3 |
| | 8.7 | 350 | 400 | 190 | 43 | 3 | 50 | 40 | 20 | 10 | 8.7 | 3.2 | 3 | 3 |
| Expanded, asbestos fiber mat, heat-resistant phenolic resin, 3/16-inch cells[6] | 9.3 | 75 | 1560 | 970 | 198 | 3 | 580 | 450 | 320 | 130 | 61.9 | 31.5 | 6 | 3 |
| | 9.3 | 250 | 1400 | 770 | 97 | 3 | [14]610 | -- | 220 | -- | 50.8 | 9.7 | 2 | 3 |
| | 9.3 | 350 | 1320 | 810 | 83 | 3 | -- | -- | -- | -- | -- | -- | -- | -- |
| Plastic film honeycomb (fig. 2-1A): | | | | | | | | | | | | | | |
| Expanded, 0.002-inch polyamide film, phenolic resin, 1/4-inch cells[15] | 1.6 | 75 | 95 | 55 | 9 | 6 | 60 | 40 | 20 | 10 | 2.8 | 1.6 | 6 | 6 |
| | 1.6 | 300 | 80 | 45 | 6 | 6 | | | | | | | | |
| | 1.6 | 500 | 55 | 20 | 5 | 6 | | | | | | | | |
| Expanded, 0.002-inch polyamide film, phenolic resin, 1/8-inch cells[15] | 3.0 | 75 | 320 | 180 | 22 | 6 | 170 | 95 | 85 | 40 | 6.1 | 3.0 | 10 | 10 |
| | 3.0 | 300 | 250 | 110 | 13 | 6 | | | | | | | | |
| | 3.0 | 500 | 130 | 30 | 8 | 6 | | | | | | | | |
| Foamed cores: | | | | | | | | | | | | | | |
| Cellular cellulose acetate[16] | 6.7 | 75 | -- | -- | -- | -- | 110 | 210 | -- | -- | 5.1 | 11.8 | 10 | 5 |
| | 6.7 | 250 | -- | -- | -- | -- | 100 | 100 | -- | -- | 3.4 | 5.2 | 10 | 5 |
| | 6.7 | 350 | -- | -- | -- | -- | 60 | 80 | -- | -- | 2.1 | 3.9 | 10 | 3 |
| Foamed in place polyester-diisocyanate[4,17] | 12.0 | 75 | 330 | 280 | -- | 2 | 110 | -- | 100 | -- | 10.2 | -- | 2 | -- |
| | 12.0 | 300 | 230 | 120 | -- | 2 | 100 | -- | 50 | -- | 10.8 | -- | 2 | -- |
| | 12.0 | 400 | 40 | 20 | -- | 2 | 20 | -- | 10 | -- | 0.4 | -- | 2 | -- |
| | 12.0 | 500 | 10 | 5 | -- | 2 | -- | -- | -- | -- | -- | -- | -- | -- |
| Foamed in place silicone resin[4,17] | 12.6 | 75 | 95 | 70 | -- | 3 | 16 | -- | 10 | -- | 3.4 | -- | 2 | -- |
| | 12.6 | 300 | 55 | 45 | -- | 3 | 13 | -- | 9 | -- | 2.2 | -- | 3 | -- |
| | 12.6 | 500 | 25 | 15 | -- | 3 | 8 | -- | 6 | -- | 1.3 | -- | 3 | -- |
| | 12.6 | 700 | 15 | 10 | -- | 3 | 4 | -- | 3 | -- | 1.2 | -- | 3 | -- |

Table 2-3.--Typical values of mechanical properties for some heat-resistant sandwich core materials--con.

| Core material | Average core density | Test temperature[1] | Compression[2] Strength: T | Compression[2] Proportional limit stress: T | Compression[2] Modulus of elasticity: T | Compression[2] Number of specimens | Shear[2] Strength: TL | Shear[2] Strength: TW | Shear[2] Proportional limit stress: TL | Shear[2] Proportional limit stress: TW | Shear[2] Modulus of rigidity: TL | Shear[2] Modulus of rigidity: TW | Shear[2] Number of specimens: TL | Shear[2] Number of specimens: TW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pcf | °F | Psi | Psi | 1,000 psi | | Psi | Psi | Psi | Psi | 1,000 psi | 1,000 psi | | |
| Foamed cores continued: | | | | | | | | | | | | | | |
| Foamed in place silicone resin[4,17] | 15.4 | 75 | 135 | 105 | -- | 9 | 16 | -- | 10 | -- | 3.8 | -- | 4 | -- |
| | 15.4 | 300 | 70 | 50 | -- | 9 | 11 | -- | 9 | -- | 0.9 | -- | 5 | -- |
| | 15.4 | 500 | 45 | 30 | -- | 9 | 9 | -- | 8 | -- | 1.1 | -- | 5 | -- |
| | 15.4 | 700 | 30 | 25 | -- | 3 | 6 | -- | 5 | -- | 0.3 | -- | 3 | -- |
| Foamed in place silicone resin[4,17] | 17.5 | 75 | 185 | 130 | -- | 3 | 12 | -- | 10 | -- | -- | -- | 3 | -- |
| | 17.5 | 300 | 105 | 80 | -- | 3 | 11 | -- | 9 | -- | 6.5 | -- | 3 | -- |
| | 17.5 | 500 | 50 | 40 | -- | 3 | 7 | -- | 6 | -- | 0.8 | -- | 3 | -- |
| | 17.5 | 700 | 25 | 20 | -- | 3 | 5 | -- | 4 | -- | -- | -- | 3 | -- |
| Foamed in place epoxy-phenolic resin[4,13] | 18.0 | 75 | 340 | -- | 53 | 3 | 300 | -- | -- | -- | 28.6 | -- | 1 | -- |
| | 18.0 | 300 | 245 | -- | -- | 3 | 170 | -- | -- | -- | 13.0 | -- | 2 | -- |
| | 18.0 | 500 | 145 | -- | -- | 3 | 110 | -- | -- | -- | 7.6 | -- | 2 | -- |
| Foamed glass[19] | 31.8 | 75 | 720 | 620 | 337 | 5 | -- | -- | -- | -- | -- | -- | -- | -- |
| | 31.8 | 600 | 740 | -- | -- | 6 | -- | -- | -- | -- | -- | -- | -- | -- |
| | 31.8 | 1000 | 440 | -- | -- | 6 | -- | -- | -- | -- | -- | -- | -- | -- |

1 Specimens evaluated at 75° F were conditioned in a room maintained at 73° F and 50 percent relative humidity prior to test. Specimens evaluated at elevated temperatures were heated in an oven maintained at test temperature for 15 to 30 minutes prior to application of load.

2 T direction refers to thickness of core and is parallel to flutes of honeycomb cores. L direction refers to direction parallel to ribbons of honeycomb cores and parallel to direction of extrusion of cellular cellulose acetate core. Shear properties of other cellular cores were not dependent on the direction of foam rise and are listed under TL for convenience. W direction refers to direction perpendicular to ribbons of honeycomb core and perpendicular to direction of extrusion of cellular cellulose acetate.

3 Hexcel Products Company, Berkeley, Calif. Hexcel Prod. Res. Develop. Rep. 191-1. 1956.

4 Shear properties determined from sandwich flexure test.

5 Data furnished by General Dynamics Corporation, Fort Worth, Texas.

6 Stevens, G. H., and Kuenzi, E. W. Mechanical properties of several honeycomb cores. U.S. Forest Prod. Lab. Rep. 1887. 1962.

7 Data furnished by Grumman Aircraft Engineering Corporation, Bethpage, L. I., N.Y.

8 Core aged for 7 hours at 430° F before testing at temperature indicated.

9 Data furnished by the Boeing Company Aerospace Group, Seattle, Washington, Dec. 1966.

10 Core aged at 400° F for 100 hours before testing.

11 Core aged at 550° F for 1000 hours before testing.

12 Setterholm, V. C., and Kuenzi, E. W. Performance of glass-fabric sandwich and honeycomb cores at elevated temperatures. WADC TR 56-119 (ASTIA Doc. No. AD 97290). 1956.

13 Specimens failed in core-to-facing bond.

14 Failure occurred in bond between core and loading plates.

15 Jenkinson, P. M. Compressive and shear properties of polyamide honeycomb core. U.S. Forest Serv. Res. Note FPL-0202, Forest Prod. Lab., Madison, Wis. 1969.

16 Kuenzi, E. W. Effect of elevated temperatures on the strengths of small specimens of sandwich construction of the aircraft type. U.S. Forest Prod. Lab. Rep. 1804. 1949.

17 Setterholm, V. C., and Kuenzi, E. W. Performance of sandwich with cores of foamed silicone and modified polyester resins at elevated temperatures and at high humidity. WADC TR 56-230 (ASTIA Doc. No. AD 110421). 1956.

18 Jenkinson, P. M., and Kuenzi, E. W. Mechanical properties of 422-J Bacfoam core for sandwich construction. WADC TR 57-132 (ASTIA Doc. No. AD 118249). 1957.

19 U.S. Forest Prod. Lab. letter to the U.S. Dep. Navy, Bur. Aeron., April 1958.

Table 2-4.--Typical values of compressive properties for some heat-resistant metal sandwich core materials.

| Core material: Foil | Nominal foil thickness | Cell size | Cell shape | Joining method | Average core density | Compressive strength[1]: 75° F | 400° F | 600° F | 800° F | 1000° F | 1200° F | 1600° F | 2000° F | 2400° F | Number of specimens at each temperature |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Inch | Inch | | | Pcf | Psi | Psi | Psi | Psi | Psi | Psi | Psi | Psi | Psi | |
| Cellular (honeycomb) core: | | | | | | | | | | | | | | | |
| Stainless steel, 17-7PHA[2] | 0.0015 | 1/4 | Hexagon | Bonded | 7.4 | 500 | --- | --- | 250 | 220 | 180 | --- | --- | --- | 4 |
| Stainless steel, 17-7PHA[2] | .002 | 3/8 | Hexagon | Bonded | 7.7 | 390 | 200 | 190 | 190 | 120 | --- | --- | --- | --- | 6 |
| Stainless steel, 17-7PHA[2] | .002 | 1/4 | Hexagon | Bonded | 9.3 | 660 | 390 | 380 | 340 | 360 | 280 | --- | --- | --- | 6 |
| Stainless steel, 17-7PHA[2] | .002 | 1/4 | Square | Welded | 8.9 | 540 | 440 | 420 | 390 | 320 | 320 | --- | --- | --- | 6 |
| Stainless steel, 17-7PHA, corrugated foil[2] | .002 | 1/4 | Square | Welded | 9.5 | 1160 | 960 | 820 | 820 | 890 | 640 | --- | --- | --- | 6 |
| Stainless steel, 17-7PHA[2] | .0015 | 3/16 | Square | Welded | 8.0 | 500 | 420 | 400 | 340 | 350 | 300 | --- | --- | --- | 6 |
| Stainless steel, 17-7PHA[2] | .0015 | 3/16 | Square | Welded | 9.2 | 500 | 470 | 460 | 420 | 400 | 350 | --- | --- | --- | 3 |
| Stainless steel, 17-7PHA[2] | .002 | 3/16 | Square | Welded | 11.6 | 760 | 660 | 620 | 580 | 560 | 450 | --- | --- | --- | 3 |
| Stainless steel, 17-7PHT[2] | .002 | 1/4 | Square | Welded | 7.8 | 700 | 540 | 500 | 570 | 490 | 200 | --- | --- | --- | 6 |
| Stainless steel, 17-7PHT[2] | .002 | 1/4 | Square | Welded | 8.7 | 970 | 840 | 740 | 720 | 620 | 280 | --- | --- | --- | 6 |
| Stainless steel, 17-7PH TH1050[2] | .002 | 1/4 | Square | Welded | 7.8 | 960 | 820 | 720 | 700 | 580 | 270 | --- | --- | --- | 6 |
| Stainless steel, 17-7PH TH1050[2] | .002 | 1/4 | Square | Welded | 8.9 | 1020 | --- | 770 | 840 | 740 | 300 | --- | --- | --- | 6 |
| Stainless steel, PH15-7 MoA[2] | .002 | 1/4 | Square | Welded | 8.2 | 460 | --- | 400 | 360 | 320 | 300 | --- | --- | --- | 6 |
| Stainless steel, AM 350A[2] | .002 | 1/4 | Square | Welded | 8.2 | 440 | --- | 310 | 330 | 300 | 300 | --- | --- | --- | 6 |
| Stainless steel, 321A[2] | .0015 | 1/4 | Hexagon | Bonded | 9.2 | 630 | --- | --- | 340 | 300 | 280 | --- | --- | --- | 4 |
| Stainless steel, 321A[2] | .003 | 3/8 | Square | Welded | 9.0 | 600 | 500 | --- | 500 | 540 | 370 | --- | --- | --- | 3 |
| Titanium alloy, Ti 75A[2] | .003 | 1/4 | Square | Welded | 6.7 | 900 | 540 | 420 | 320 | 280 | 140 | --- | --- | --- | 6 |
| Titanium alloy, Ti 75A[2] | .002 | 3/16 | Square | Welded | 7.3 | 1080 | 620 | 460 | 380 | 320 | 160 | --- | --- | --- | 6 |
| Nickel base alloy, Inconel[2] | .002 | 1/4 | Square | Welded | 7.8 | 360 | 260 | 260 | 250 | 280 | 240 | --- | --- | --- | 6 |
| Molybdenum alloy, TZM molybdenum[3] | .002 | 3/16 | Square | Welded | 14.1 | --- | 2540 | --- | --- | --- | --- | 2570 | 2160 | 1400 | 4 |
| Columbium alloy, D36 columbium[3] | .002 | 3/16 | Square | Welded | 10.4 | 2080 | --- | --- | 1480 | --- | --- | 840 | 560 | 360 | 4 |
| Corrugated core: | | | | | | | | | | | | | | | |
| Stainless steel, 301 1/2-hard[4] | .002 | 5/32 | Sine wave corrugations | Welded | 18.7 | 430 | --- | --- | --- | --- | --- | --- | --- | --- | 18 |

1 Flatwise compression parallel to flutes of honeycomb core. Specimens exposed to elevated temperature for about 30 minutes prior to test.
2 Kuenzi, E. W., and Jahnke, W. E. Mechanical properties of some heat-resistant metal honeycomb cores. U.S. Forest Prod. Lab. Rep. 1872. 1959.
3 McCown, J. W. Final report on manufacturing methods and design procedures of brazed refractory metal honeycomb sandwich panels. ASD-TDR Rep. No. 63-767. 1963.
4 Baker, E. H., and Harris, L. A. Spacemetal sandwich analysis procedures. North American Aviation Missile Division Rep. No. STR-69. 1959.

Table 2-5.--Typical values of shear properties for some heat-resistant metal sandwich core materials.

| Core material: Foil | Nominal foil thickness | Cell size | Cell shape | Joining method | Average core density | Shear[1] Modulus of rigidity at 75° F: TL | Modulus of rigidity at 75° F: TW | Strength 75° F: TL | 75° F: TW | 600° F: TL | 600° F: TW | 800° F: TL | 800° F: TW | 1,000° F: TL | 1,000° F: TW | 1,200° F: TL | 1,200° F: TW | 1,600° F: TL | 1,600° F: TW | 2,000° F: TL | 2,400° F: TL | No. of specimens at each temperature |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Inch | Inch | | | Pcf | 1,000 psi | 1,000 psi | Psi | Psi | Psi | Psi | Psi | Psi | Psi | Psi | Psi | Psi | Psi | Psi | Psi | Psi | |
| Cellular (honeycomb) core: | | | | | | | | | | | | | | | | | | | | | | |
| Stainless steel, 17-7PHA[2] | 0.002 | 3/8 | Hexagon | Bonded | 7.7 | 75 | 30 | 320 | 140 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | --- | --- | 6 |
| Stainless steel, 17-7PHA[2] | .002 | 1/4 | Hexagon | Bonded | 9.3 | 151 | 88 | 370 | 240 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | --- | --- | 6 |
| Stainless steel, 17-7PHA[3] | .002 | 3/8 | Square | Welded | 5.8 | 46 | 22 | 150 | 100 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | --- | --- | 5 |
| Stainless steel, 17-7PHA[3,4] | .0015 | 1/4 | Square | Welded | 5.9 | --- | --- | 390(3)[5] | 320(3)[5] | 340 | 270 | 300 | 210 | 140 | 90 | 50 | -- | -- | -- | --- | --- | 1 |
| Stainless steel, 17-7PHA[3] | .002 | 1/4 | Square | Welded | 7.5 | 84 | 31 | 230 | 160 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | --- | --- | 2 |
| Stainless steel, 17-7PHA[6] | .002 | 1/4 | Square | Welded | 8.5 | --- | --- | 280 | --- | 230[7] | -- | -- | -- | -- | -- | -- | -- | -- | -- | --- | --- | 3 |
| Stainless steel, 17-7PHA[2] | .002 | 1/4 | Square | Welded | 8.9 | 99 | 57 | 300 | 260 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | --- | --- | 6 |
| Stainless steel, 17-7PHA, corrugated foil[2] | .002 | 1/4 | Square | Welded | 9.5 | 78 | 50 | 420 | 360 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | --- | --- | 5 |
| Stainless steel, 17-7PHA[2] | .0015 | 3/16 | Square | Welded | 8.0 | 95 | 79 | 220 | 220 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | --- | --- | 3 |
| Stainless steel, 17-7PHA[2] | .0015 | 3/16 | Square | Welded | 9.2 | 109 | --- | 280 | --- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | --- | --- | 6 |
| Stainless steel, 17-7PHA[2] | .002 | 3/16 | Square | Welded | 11.6 | --- | 64 | --- | 260 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | --- | --- | 6 |
| Stainless steel, 17-7PHT[3] | .0015 | 1/4 | Square | Welded | 5.9 | 80 | 71 | 430 | 300 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | --- | --- | 2 |
| Stainless steel, 17-7PHT[2] | .002 | 1/4 | Square | Welded | 7.8 | 94 | 76 | 350 | 340 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | --- | --- | 6 |
| Stainless steel, 17-7PHT[2] | .002 | 1/4 | Square | Welded | 8.7 | 150 | 76 | 500 | 340 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | --- | --- | 6 |
| Stainless steel, 17-7PH TH1050[3,4] | .002 | 3/8 | Hexagon | Bonded | 6.7 | --- | --- | 320 | 120 | -- | -- | 310 | 150 | 280 | 120 | 160 | 100 | -- | -- | --- | --- | 3 |
| Stainless steel, 17-7PH TH1050[4,8] | .0015 | 3/8 | Square | Welded | 4.5 | 23 | 21 | 140 | 130 | 120 | 110 | 110 | 110 | 70 | 70 | -- | -- | -- | -- | --- | --- | 3 |
| Stainless steel, 17-7PH TH1050[4,8] | .002 | 3/8 | Square | Welded | 5.8 | --- | --- | 860 | 340 | -- | -- | 470 | 490 | 650 | -- | 360 | 280 | -- | -- | --- | --- | 1 |
| Stainless steel, 17-7PH TH1050[4,8] | .0015 | 1/4 | Square | Welded | 6.0 | 45 | 37 | 670 | 600 | 610 | 520 | 530 | 480 | 290 | 270 | -- | -- | -- | -- | --- | --- | 3 |
| Stainless steel, 17-7PH TH1050[4,8] | .002 | 1/4 | Square | Welded | 7.5 | -- | --- | 740 | 340 | -- | -- | 610 | 310 | 420 | 250 | 260 | -- | -- | -- | --- | --- | 2 |
| Stainless steel, 17-7PH TH1050[4,8] | .002 | 1/4 | Square | Welded | 8.0 | 59 | 54 | 860 | 840 | 730 | 730 | 620 | 620 | 370 | 350 | -- | -- | -- | -- | --- | --- | 3 |
| Stainless steel, 17-7PH TH1050[2] | .002 | 1/4 | Square | Welded | 8.9 | 103 | 103 | --- | --- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | --- | --- | 4 |
| Stainless steel, 17-7PH TH1050[4,8] | .0015 | 3/16 | Square | Welded | 8.0 | 44 | 39 | 490 | 280 | 430 | 210 | 410 | 220 | 250 | 190 | -- | -- | -- | -- | --- | --- | 3 |
| Stainless steel, 17-7PH TH1050[4,8] | .0015 | 3/16 | Square | Welded | 8.0 | 69 | 54 | 880 | 710 | 740 | 610 | 610 | 500 | 380 | 320 | -- | -- | -- | -- | --- | --- | 3 |
| Stainless steel, 17-7PH TH1050[4,8] | .002 | 3/16 | Square | Welded | 10.7 | 100 | 72 | 1280 | 1060 | 1030 | 900 | 680 | 710 | 470 | 400 | -- | -- | -- | -- | --- | --- | 3 |
| Stainless steel, PH15-7MoA[2] | .002 | 1/4 | Square | Welded | 8.2 | 127 | 84 | 300 | 260 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | --- | --- | 6 |
| Stainless steel, AM350A[2] | .002 | 1/4 | Square | Welded | 8.2 | 115 | 84 | 320 | 270 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | --- | --- | 6 |
| Stainless steel, 321A[3,4] | .002 | 3/8 | Hexagon | Bonded | 6.7 | 80(4)[5] | 39 | 230(4)[5] | 130 | -- | -- | 180 | 110 | 150 | 130 | -- | -- | -- | -- | --- | --- | 2 |
| Stainless steel, 321A[3,4] | .002 | 3/8 | Hexagon | Bonded | 6.7 | --- | --- | 120 | 100 | -- | -- | 80 | 70 | 70 | 60 | 70 | 60 | -- | -- | --- | --- | 1 |
| Stainless steel, 321A[4,8] | .0015 | 3/8 | Square | Welded | 4.5 | 17 | 14 | 80 | 70 | 70 | 60 | 70 | 60 | 60 | 60 | -- | -- | -- | -- | --- | --- | 3 |
| Stainless steel, 321A[3,4] | .002 | 3/8 | Square | Welded | 5.8 | 46(5)[5] | 33(4)[5] | 280 | 220 | -- | -- | 210 | 150 | 230 | 180 | 150 | 130 | -- | -- | --- | --- | 3 |
| Stainless steel, 321A[2] | .003 | 3/8 | Square | Welded | 9.0 | 63 | 73 | 400 | 420 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | --- | --- | 3 |
| Stainless steel, 321 1/2-hard[4,8] | .0015 | 3/16 | Square | Welded | 8.0 | 38 | 33 | 240 | 240 | 190 | 200 | 170 | 190 | 170 | 180 | -- | -- | -- | -- | --- | --- | 3 |

Table 2-5.--Typical values of shear properties for some heat-resistant metal sandwich core materials--con.

| Core material: Foil | Core material: Nominal foil thickness | Core material: Cell size | Core material: Cell shape | Core material: Joining method | Core material: Average core density | Shear[1]: Modulus of rigidity at 75° F: TL | Modulus of rigidity at 75° F: TW | Strength: 75° F: TL | 75° F: TW | 600° F: TL | 600° F: TW | 800° F: TL | 800° F: TW | 1,000° F: TL | 1,000° F: TW | 1,200° F: TL | 1,200° F: TW | 1,600° F: TL | 1,600° F: TW | 2,000° F: TL | 2,400° F: TL | No. of specimens at each temperature |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Inch | Inch | | | Pcf | 1,000 psi | 1,000 psi | Psi | Psi | Psi | Psi | Psi | Psi | Psi | Psi | Psi | Psi | Psi | Psi | Psi | Psi | |
| Cellular (honeycomb) core continued: | | | | | | | | | | | | | | | | | | | | | | |
| Nickel-chromium steel, A286[4,8] | .002 | 1/4 | Square | Welded | 8.7 | 52 | 28 | 290 | 170 | 280 | 140 | 360 | 180 | 310 | 130 | 190 | 110 | -- | -- | --- | --- | 2 |
| Titanium alloy, T175A[2] | .003 | 1/4 | Square | Welded | 6.7 | 79 | 61 | 420 | 350 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | --- | --- | 6 |
| Titanium alloy, T175A[2] | .002 | 3/16 | Square | Welded | 7.3 | 115 | 48 | 420[7] | 380 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | --- | --- | 4 |
| Nickel base alloy, Inconel[2] | .002 | 1/4 | Square | Welded | 7.8 | 96 | 66 | 180 | 140 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | --- | --- | 6 |
| Cobalt base alloy, L-605[8] | .002 | 1/4 | Square | Welded | 8.0 | 118 | 82 | 920 | 880 | -- | -- | 440 | 370 | -- | -- | 740 | 720 | 220 | 200 | --- | --- | 2 |
| Molybdenum alloy, TZM molybdenum[9] | .002 | 3/16 | Square | Welded | 14.1 | --- | --- | --- | --- | 570 | -- | 580 | -- | -- | -- | -- | -- | 450 | -- | 260 | 220 | 4 |
| Columbium alloy, D36 columbium[9] | .002 | 3/16 | Square | Welded | 10.4 | --- | --- | 840 | --- | 510 | -- | 380 | -- | -- | -- | -- | -- | 300 | -- | 200 | 100 | 3 |
| Corrugated core: | | | | | | | | | | | | | | | | | | | | | | |
| Stainless steel, 301 1/2-hard[10] | .002 | 5/32 | Sine wave corrugations | Welded | 18.7 | 38 | 5 | 990 | 110 | -- | 130 | -- | 120 | -- | 100 | -- | -- | -- | -- | --- | --- | 5 |
| Stainless steel, AM355[4,8] | .012 | 1/4 | Two rows of sine wave corrugations | Welded | 38.2 | 165 | 42 | 2350 | 1280 | 2430 | 1150 | 2070 | 1170 | 1640 | 740 | -- | -- | -- | -- | --- | --- | 3 |

1 Shear at temperature indicated after about 30 minutes' exposure to test temperature. T refers to direction parallel to core flutes of honeycomb core and normal to facings of corrugated core sandwich. L is parallel to core ribbons of honeycomb core and parallel to flutes of corrugated core sandwich. W is perpendicular to core ribbons of honeycomb core and perpendicular to the flute direction of corrugated core sandwich. Shear properties were obtained from core shear test unless sandwich flexure is specifically indicated.

2 Kuenzi, E. W., and Jahnke, W. E. Mechanical properties of some heat-resistant metal honeycomb cores. U.S. Forest Prod. Lab. Rep. 1872. 1959.

3 Setterholm, V. C., and Kuenzi, E. W. Performance of stainless steel sandwich construction at high temperatures. WADC TR 55-417, Part I (ASTIA Doc. No. AD 97288). 1956.

4 Shear properties determined from sandwich flexure test.

5 Denotes number of specimens when different from number indicated for entire group of specimens.

6 Kuenzi, E. W., and Jahnke, W. E. Performance of stainless steel sandwich constructions at high temperatures. WADC TR 55-417, Part II (ASTIA Doc. No. AD 142052). 1957.

7 Denotes bond failure between facings and core.

8 Stevens, G. H., and Kuenzi, E. W. Mechanical properties of sandwich constructions of heat-resistant metal. ASD-TDR Rep. No. 62-909. 1962.

9 McCown, J. W. Final report on manufacturing methods and design procedures of brazed refractory metal honeycomb sandwich panels. ASD-TDR Rep. No. 63-767. 1963.

10 Baker, E. H., and Harris, L. A. Spacemetal sandwich analysis procedures. North American Aviation Missile Division Rep, No. STR-69. 1959.

Table 2-6.--Minimum strength values of core materials for structural sandwich[1]

| Core material | Core density: Average | Conditioning prior to test: Temperature | Conditioning prior to test: Relative humidity | Compression: Strength: T | Compression: Proportional limit stress: T | Shear: Strength: TL | Shear: Strength: TW | Shear: Proportional limit stress: TL | Shear: Proportional limit stress: TW |
|---|---|---|---|---|---|---|---|---|---|
| | Pcf | °F | Percent | Psi | Psi | Psi | Psi | Psi | Psi |
| Balsa wood | 5.0 | 70 | 64 | 490 | 30 | 100 | 70 | --- | --- |
| Do | 6.0 | 70 | 64 | 690 | 200 | 110 | 100 | --- | --- |
| Do | 7.0 | 70 | 64 | 920 | 390 | 130 | 100 | --- | --- |
| Do | 8.0 | 70 | 64 | 1130 | 560 | 170 | 110 | --- | --- |
| Do | 9.0 | 70 | 64 | 1330 | 730 | 180 | 120 | --- | --- |
| Do | 10.0 | 70 | 64 | 1540 | 920 | 200 | 150 | --- | --- |
| Do | 11.0 | 70 | 64 | 1770 | 1090 | 240 | 160 | --- | --- |
| Aluminum-foil honeycomb (fig. 2-1 A): | | | | | | | | | |
| Preformed, perforated 0.002-inch 3003-H19 foil, 3/8-inch cells | 3.0 | 75 | 50 | 190 | 80 | 120 | 60 | 60 | 30 |
| Preformed, perforated 0.003-inch 3003-H19 foil, 3/8-inch cells | 4.0 | 75 | 50 | 290 | 150 | 210 | 90 | 100 | 60 |
| Preformed, perforated 0.002-inch 3003-H19 foil, 1/4-inch cells | 4.5 | 75 | 50 | 300 | 170 | 220 | 110 | 110 | 60 |
| Expanded, perforated 0.001-inch 3003-H19 foil, 1/8-inch cells | 4.8 | 75 | 50 | 530 | --- | 250 | 190 | 100 | 60 |
| Preformed, perforated 0.004-inch 3003-H19 foil, 3/8-inch cells | 5.2 | 75 | 50 | 460 | 250 | 300 | 140 | 140 | 60 |
| Expanded, perforated 0.002-inch 3003-H19 foil, 3/16-inch cells | 5.8 | 75 | 50 | 460 | --- | 340 | 200 | 120 | 110 |
| Preformed, perforated 0.003-inch 3003-H19 foil, 1/4-inch cells | 6.0 | 75 | 50 | 600 | 350 | 380 | 200 | 160 | 60 |
| Preformed, perforated 0.005-inch 3003-H19 foil, 3/8-inch cells | 6.3 | 75 | 50 | 690 | 400 | 350 | 190 | 140 | 80 |
| Preformed, perforated 0.004-inch 3003-H19 foil, 1/4-inch cells | 7.7 | 75 | 50 | 620 | 440 | 460 | 250 | 230 | 110 |
| Preformed, perforated 0.005-inch 3003-H19 foil, 1/4-inch cells | 9.0 | 75 | 50 | 1080 | 600 | 530 | 300 | 280 | 120 |
| Aluminum-foil honeycomb (fig. 2-1 A): | | | | | | | | | |
| Expanded, perforated 0.0007-inch 5052-H39 foil, 1/4-inch cells | 2.0 | 75 | 50 | 130 | --- | 120 | 70 | 80 | 30 |
| Expanded, perforated 0.002-inch 5052-H39 foil, 1/4-inch cells | 3.9 | 75 | 50 | 420 | 280 | 320 | 160 | 180 | 110 |
| Preformed, unperforated 0.002-inch 5052-H39 foil, 1/4-inch cells | 4.2 | 75 | 50 | --- | --- | 330 | 180 | --- | --- |
| Expanded, perforated 0.003-inch 5052-H39 foil, 1/4-inch cells | 5.9 | 75 | 50 | 840 | --- | 480 | 260 | 290 | 150 |
| Expanded, perforated 0.004-inch 5052-H39 foil, 1/4-inch cells | 7.7 | 75 | 50 | 1250 | --- | --- | 370 | --- | 170 |
| Aluminum-foil honeycomb (fig. 2-1 A): | | | | | | | | | |
| Expanded, unperforated 0.0015-inch 2024-T81 foil, 1/4-inch cells | 2.8 | 75 | 50 | 240 | --- | 170 | 100 | --- | --- |
| Expanded, unperforated 0.0015-inch 2024-T81 foil, 3/16-inch cells | 3.6 | 75 | 50 | 380 | --- | 250 | 150 | --- | --- |
| Expanded, unperforated 0.0015-inch 2024-T81 foil, 1/8-inch cells | 5.1 | 75 | 50 | 620 | --- | 470 | 260 | --- | --- |
| Expanded, unperforated 0.0020-inch 2024-T81 foil, 1/8-inch cells | 6.8 | 75 | 50 | 890 | --- | 780 | 430 | --- | --- |
| Aluminum-foil crossbanded core (fig. 2-3): | | | | | | | | | |
| Preformed, unperforated 0.002-inch 5052-H39 foil, 1/8-inch corrugations | 4.4 | 75 | 50 | --- | --- | 260 | 90 | --- | 40 |
| Aluminum-foil honeycomb (fig. 2-2 A): | | | | | | | | | |
| Type I, perforated 0.002-inch 1145-H19 foil, 1/4-inch cells | 4.0 | 75 | 50 | 190 | 130 | 120 | 70 | 50 | 25 |
| Type I, perforated 0.002-inch 3003-H19 foil, 1/4-inch cells | 4.6 | 75 | 50 | 360 | 290 | 270 | 150 | 80 | 60 |
| Type I, perforated 0.002-inch 5052-H38 foil, 1/4-inch cells | 4.6 | 75 | 50 | 400 | 320 | 290 | 140 | 130 | 80 |
| Stainless steel corrugated core (fig. 2-4): | | | | | | | | | |
| Preformed, welded, 0.002-inch 301 1/2-hard foil, 5/32-inch-deep sine wave corrugations | 18.7 | 75 | 50 | 290 | --- | --- | --- | --- | --- |

Sheet 1 of 2

Table 2-6.--Minimum strength values of core materials for structural sandwich[1]--con.

| Core material | Core density: Average | Conditioning prior to test: Temperature | Conditioning prior to test: Relative humidity | Compression: Strength: T | Compression: Proportional limit stress: T | Shear: Strength: TL | Shear: Strength: TW | Shear: Proportional limit stress: TL | Shear: Proportional limit stress: TW |
|---|---|---|---|---|---|---|---|---|---|
| | Pcf | °F | Percent | Psi | Psi | Psi | Psi | Psi | Psi |
| Glass fabric honeycomb (fig. 2-1 A): | | | | | | | | | |
| Preformed, fabric 112, finish 114 | 3.? | 73 | 50 | 190 | 110 | 120 | 60 | 50 | 25 |
| Phenolic resin, 1/4-inch cells | --- | | wet | 180 | 130 | 80 | 30 | 30 | 10 |
| Expanded, fabric 21, finish 114 | 4.4 | 73 | 50 | 380 | 140 | 250 | 120 | 90 | 40 |
| Nylon-phenolic resin, 1/4-inch cells | --- | | wet | 240 | 100 | 190 | 90 | 80 | 30 |
| Preformed, fabric 112, finish 114 | 5.6 | 73 | 50 | 370 | 200 | 200 | 100 | 70 | 40 |
| Phenolic-polyester resin, 1/4-inch cells | --- | | wet | 330 | 170 | 180 | 80 | 40 | 20 |
| Expanded, fabric 112, finish 114 | 6.3 | 73 | 50 | 690 | 350 | 400 | 190 | 120 | 80 |
| Nylon-phenolic resin, 3/16-inch cells | --- | | wet | 380 | 150 | 230 | 120 | 90 | 50 |
| Expanded, fabric 21, finish 114 | 6.3 | 73 | 50 | 670 | 370 | 360 | 210 | 100 | 70 |
| Nylon-phenolic resin, 1/4-inch cells | --- | | wet | 240 | 130 | 190 | 100 | 70 | 30 |
| Preformed, fabric 112, finish 114 | 6.4 | 73 | 50 | 580 | 300 | 280 | 150 | 110 | 40 |
| Phenolic-polyester resin, 3/16-inch cells | --- | | wet | 620 | 340 | 200 | 80 | 60 | 20 |
| Preformed, fabric 112, finish 136 | 8.2 | 73 | 50 | 740 | 490 | 440 | --- | 160 | --- |
| Polyester resin, 3/16-inch cells | --- | | wet | 370 | 320 | --- | 80 | --- | 30 |
| Expanded, fabric 21, finish 114 | 8.2 | 73 | 50 | 1180 | 860 | 520 | 380 | 200 | 120 |
| CTL-91LD phenolic resin, 1/4-inch cells | --- | | wet | 1140 | 750 | --- | --- | --- | --- |
| Preformed, fabric 112, finish 136 | 8.3 | 73 | 50 | 740 | 370 | 290 | 180 | 110 | 60 |
| Polyester resin, 1/4-inch cells | --- | | wet | 470 | 230 | 210 | 90 | 70 | 40 |
| Expanded, fabric 112, finish 114 | 9.2 | 73 | 50 | 1250 | 760 | 570 | 340 | 180 | 100 |
| Nylon-phenolic resin, 3/16-inch cells | --- | | wet | 490 | 250 | 170 | 90 | 90 | 50 |
| Glass fabric corrugated core with integrally woven liners (fig. 2-4): | | | | | | | | | |
| Fabric 301, polyester resin, sine wave corrugations, 3/16-inch crest to trough | 20.4 | 73 | 50 | 260 | --- | 340 | 120 | 100 | 40 |
| Plastic film honeycomb (fig. 2-1 A): | | | | | | | | | |
| Expanded, 0.003-inch polyester film, 3/8-inch cells | 2.1 | 73 | 50 | 70 | 40 | 50 | 30 | 20 | 10 |
| Expanded, 0.003-inch polyimide film, 3/8-inch cells | 2.4 | 73 | 50 | 60 | 20 | 40 | 20 | 10 | 5 |
| Foamed cores: | | | | | | | | | |
| Foamed-in-place alkyd-isocyanate | 19.7 | 75 | 50 | 800 | --- | --- | 240 | --- | 80 |
| Paper honeycomb (fig. 2-1 A): | | | | | | | | | |
| Expanded, 60 lb. kraft paper, 20 percent alcohol-soluble | 1.7 | 80 | 30 | 100 | 70 | 90 | 55 | 50 | 10 |
| Phenolic resin, 7/16-inch cells | 1.7 | 73 | 50 | 90 | 60 | 70 | 45 | 15 | 20 |
| Do | 1.8 | 80 | 90 | 60 | 35 | 40 | 25 | 15 | 5 |
| Do | 2.9 | | wet | 20 | 15 | 15 | 10 | 2 | 2 |
| Expanded, 125 lb. kraft paper, 35 percent alcohol-soluble | 3.6 | 80 | 30 | 390 | 220 | 290 | 150 | 80 | 60 |
| Phenolic resin, 7/16-inch cells | 3.7 | 73 | 50 | 300 | 170 | 180 | 120 | 70 | 35 |
| Do | 3.9 | 80 | 90 | 210 | 140 | 160 | 80 | 30 | 10 |
| Do | 5.5 | | wet | 80 | 60 | 60 | 35 | 10 | 5 |

[1] These minimum values are the lowest values obtained for the materials described in tables 2-1 through 2-5 for which at least 12 specimens were tested. The statistical assurance associated with these minimum values is that at least 78 percent of the population will exceed these values with a probability of 0.95, regardless of the shape of the frequency distribution curve of the population (ref. 2-51). In general, the probability is 0.95 that at least $100(0.05)^{1/n}$ percent of the population will exceed the lowest among the n strenghs obtained. A graph of these percentage values as a function of sample size, n, is given in figure 2-13.

Table 2-7.--Typical Mechanical Properties of Adhesives[1]

| Adhesive type | Form | Modulus of elasticity | Modulus of rigidity | Poisson's ratio | Shear strength | Tensile strength |
|---|---|---|---|---|---|---|
| | | Psi | Psi | | Psi | Psi |
| Neoprene elastomer-phenolic | On nylon fabric tape | 4,800 | 1,600 | 0.50 | 2,500 | 1,200 |
| Nitrile elastomer-phenolic | Unsupported tape | 6,300 to 18,000 | 2,100 to 6,000 | 0.50 | 4,200 | 2,500 |
| Polyvinyl-phenolic | Liquid and powder | 500,000 | 184,000 | 0.36 | 8,200 | 8,300 |
| Polyvinyl-phenolic | On woven glass fabric | 325,000 | 118,000 | 0.38 | 3,700 | 4,400 |
| Epoxy | Liquid | 508,000 | 180,000 | 0.41 | 6,000 | --- |
| Epoxy-phenolic | On woven glass fabric | 400,000 | 160,000 | 0.25 | 5,500 | 2,600 |
| Epoxy-polyamide | Unsupported film | 180,000 | 64,000 | 0.41 | 7,900 | 7,000 |
| Modified epoxy (350°F cure) | Unsupported film | 140,000 | 50,000 | 0.41 | 5,600 | 8,000 |

[1]Properties determined from torsion and tension tests of adhesives in end-bonded aluminum tubes (ref. 2-18).

Table 2-8.--Strength of Lap Joints of Various Types of Adhesives[1]

| | Nitrile elastomer-phenolic[2] | Nitrile elastomer-phenolic[3] | Polyvinyl-phenolic[2] | Epoxy[2] | Epoxy-polyamide[2] | Epoxy-phenolic[4] | Epoxy-phenolic[3] | Modified epoxy[2] 350°F cure | Modified epoxy[2] 250°F. cure |
|---|---|---|---|---|---|---|---|---|---|
| | Psi | Psi | Psi | Psi | Psi | Psi | Psi | Psi | Psi |
| At 74° F | 2800-4600 | 5500-6300 | 4100-5100 | 3100-3500 | 5600-6700 | 3100-3800 | 2600-3800 | 2900-3700 | 4000-5900 |
| At -67° F | 3000-3800 | 4500-6900 | 2500-4100 | 2700-3600 | 5000-6900 | 3200-3700 | 2700-3200 | 3000-3600 | 3100-6400 |
| At 180° F | 1500-3000 | | 1700-4800 | | 2800-4800 | | | 3200-3600 | 1900-3500 |
| At 300° F | 2300-2400 | 2000-3100 | | 2100-3500 | | 2400-2700 | 2000-2500 | 2600-3000 | |
| At 300° F after 192 hours | 2500-2600 | 2300-3300 | | 2600-3100 | | | 2000-2100 | 2800-3400 | |
| At 500° F | | 1800-2200 | | | | 2000-2300 | 1900-2100 | | |
| At 500° F after 192 hours | | 1500-2100 | | | | | | | |
| After 30 days' salt water spray | 2900-4200 | 5100-5800 | 4200-5100 | 3100-3700 | 4500-6500 | 2600-2900 | 2700-3400 | 3000-3200 | 3400-5600 |
| After 30 days in tap water | 3100-4600 | 5100-6400 | 4400-5500 | 2800-3800 | 4700-6100 | 2700-3300 | 2500-3400 | 3100-3700 | 3500-5800 |
| After 7 days in JP-4 fuel | 3600-4900 | 5300-6000 | 3900-5000 | 2800-3700 | 5800-6900 | 3400-3700 | 2700-4000 | 2900-3700 | 4100-6000 |
| After 7 days in anti-icing fluid | 3100-4800 | 5400-6300 | 3400-4900 | 2800-3500 | 5600-7000 | 3000-3500 | 2400-3500 | 2800-3700 | 3800-6100 |
| After 7 days in hydraulic oil | 3500-4800 | 5400-6200 | 3700-5100 | 2700-3700 | 5400-7100 | 3200-3700 | 2500-3800 | 2700-3700 | 4200-6100 |
| After 7 days in hydrocarbon fluid | 3200-4700 | 5000-6900 | 3800-5300 | 2700-3600 | 5800-6900 | 3100-3500 | 2700-3900 | 2900-3800 | 3600-6100 |

[1]Average shear strength values for 1/2-in. overlap specimens tested as specified in ref. 2-47.

[2]Adherends of 0.063-in. clad 2024-T3 aluminum.

[3]Adherends of 0.050-in. type 17-7PH (TH1050) corrosion-resisting steel.

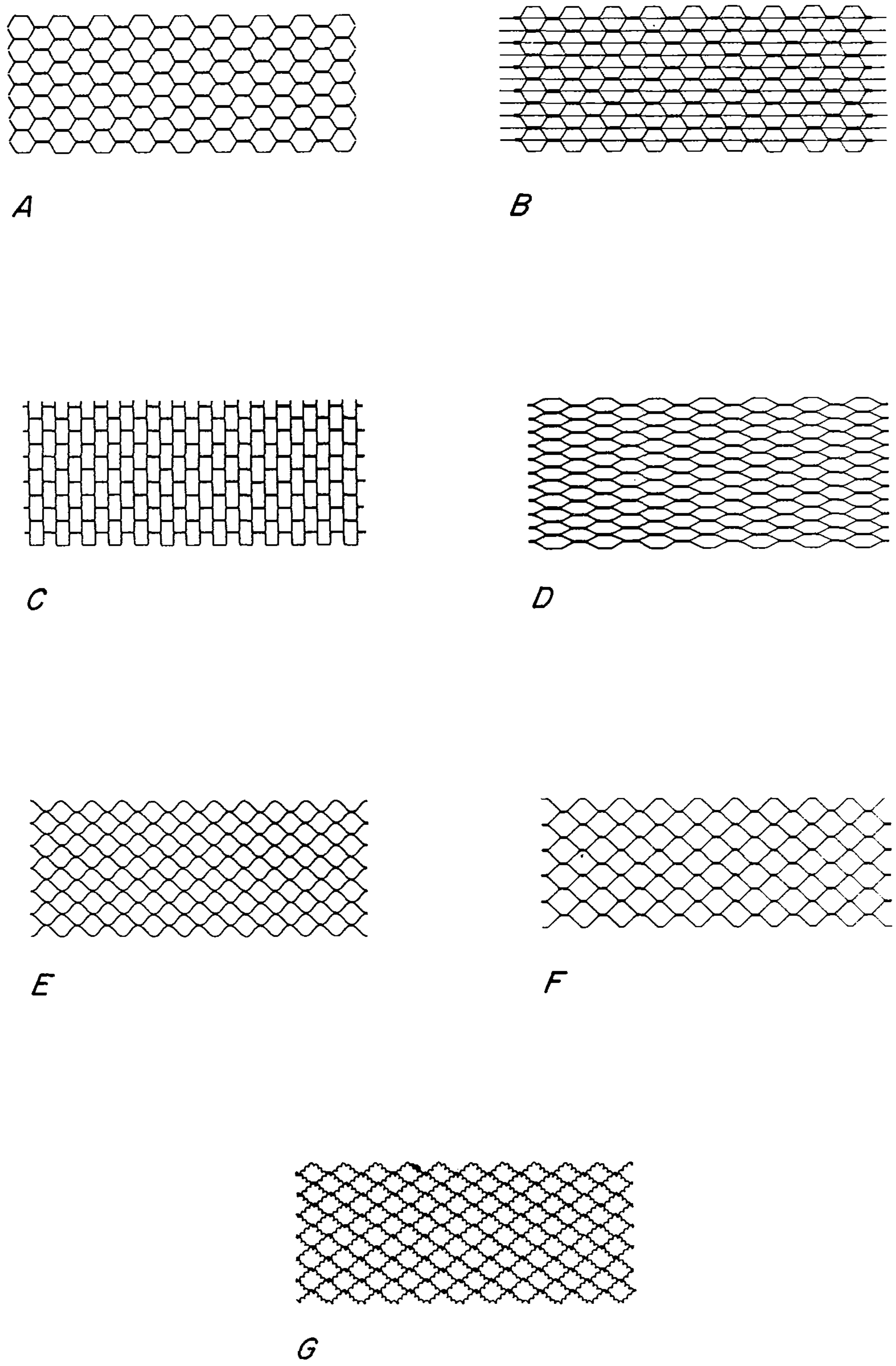
[4]Adherends of 0.050-in. type 301 stainless steel.

Table 2-9.--Strength of Adhesives in Sandwich with Honeycomb Core[1]

| Adhesive | Fillet strength[2] | | | Peel strength | | |
|---|---|---|---|---|---|---|
| | 73°F | 180°F | -67°F | 73°F | 180°F | -67°F |
| | Lb /in. | Lb /in. | Lb /in. | In.-lb /in. | In.-lb /in. | In.-lb /in. |
| Nitrile elastomer-phenolic plus modified epoxy film | 73 | 51 | 84 | 66 | 32 | 21 |
| Polyvinyl-phenolic | 42 | 35 | 49 | 25 | 22 | 14 |
| Epoxy-polyamide | 71 | 39 | 66 | 18 | 24 | 15 |
| Modified epoxy (350°F cure) | 62-86 | 27-65 | 61-87 | 16-97 | 13-82 | 12-49 |
| Modified epoxy (250°F cure) | 46-76 | 34-38 | 47-91 | 15-40 | 18-23 | 19-26 |
| Nitrile epoxide | 61 | 33 | 89 | 27 | 18 | 28 |

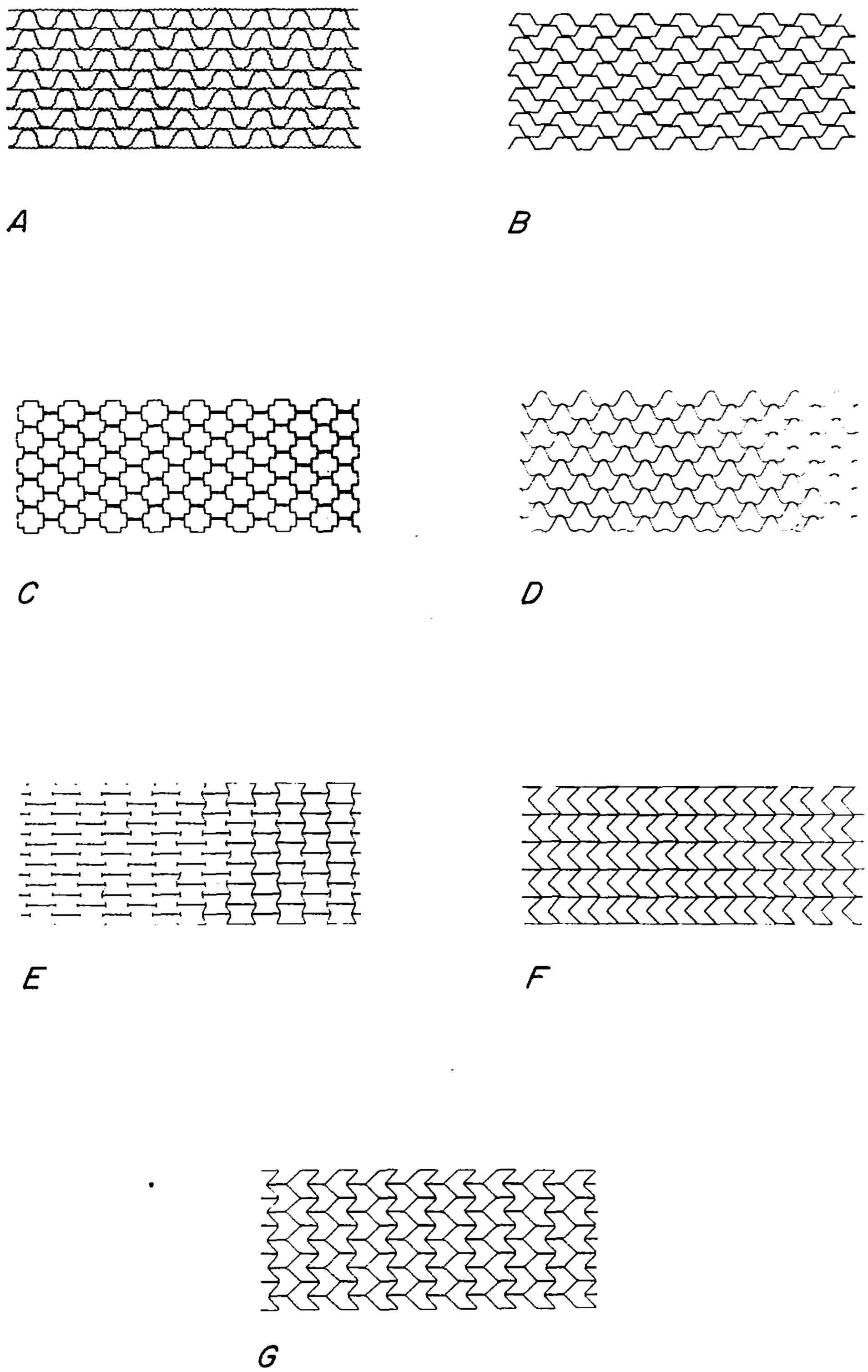
[1] Tests described in ref. 2-37.

[2] Analysis and application of ref. 2-29.




M 134 056

Figure 2-1.--Honeycomb core cell configurations.




M 134 055

Figure 2-2.--Cell configurations for formable honeycomb cores.

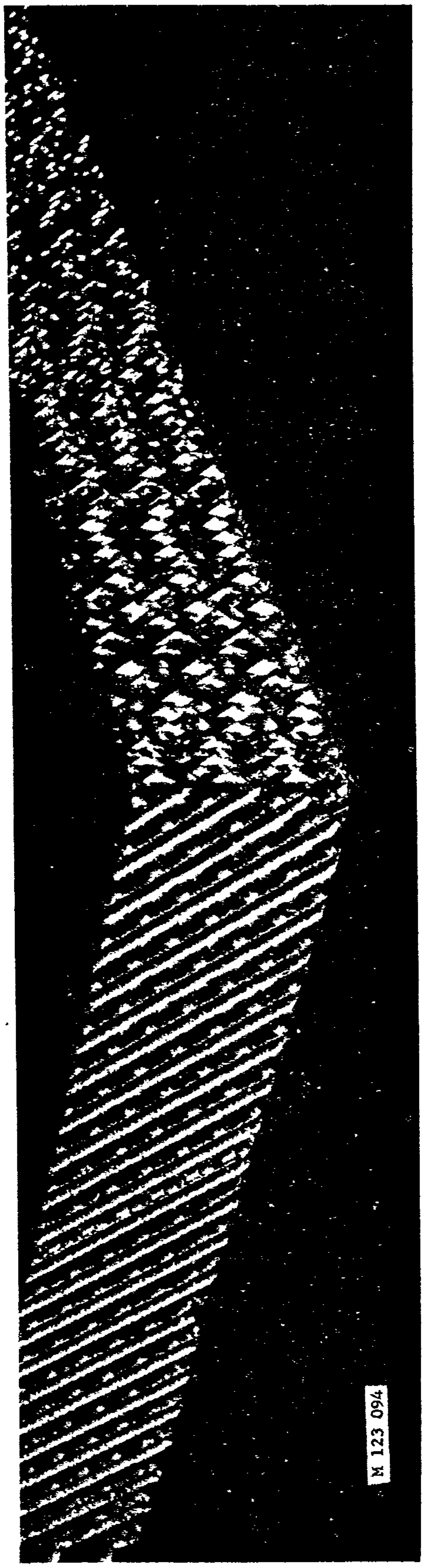
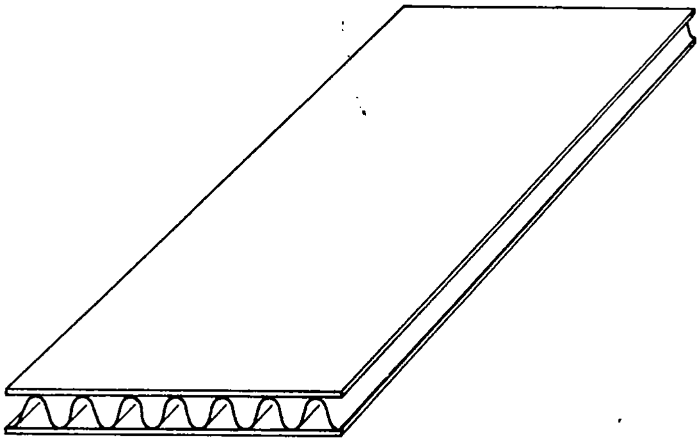
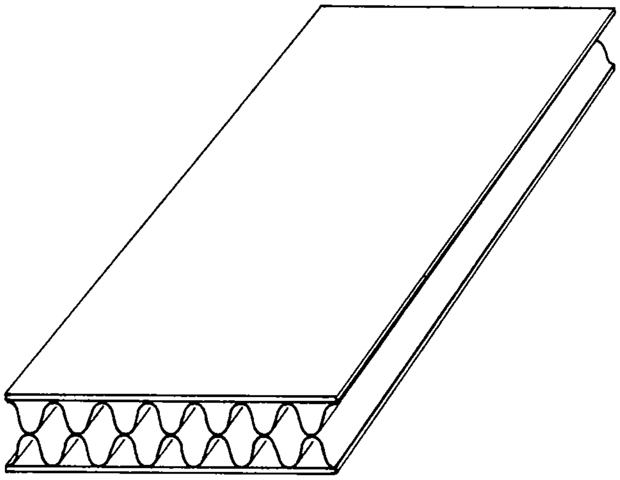



Figure 2-3.--Aluminum sandwich panel with crossbanded core.



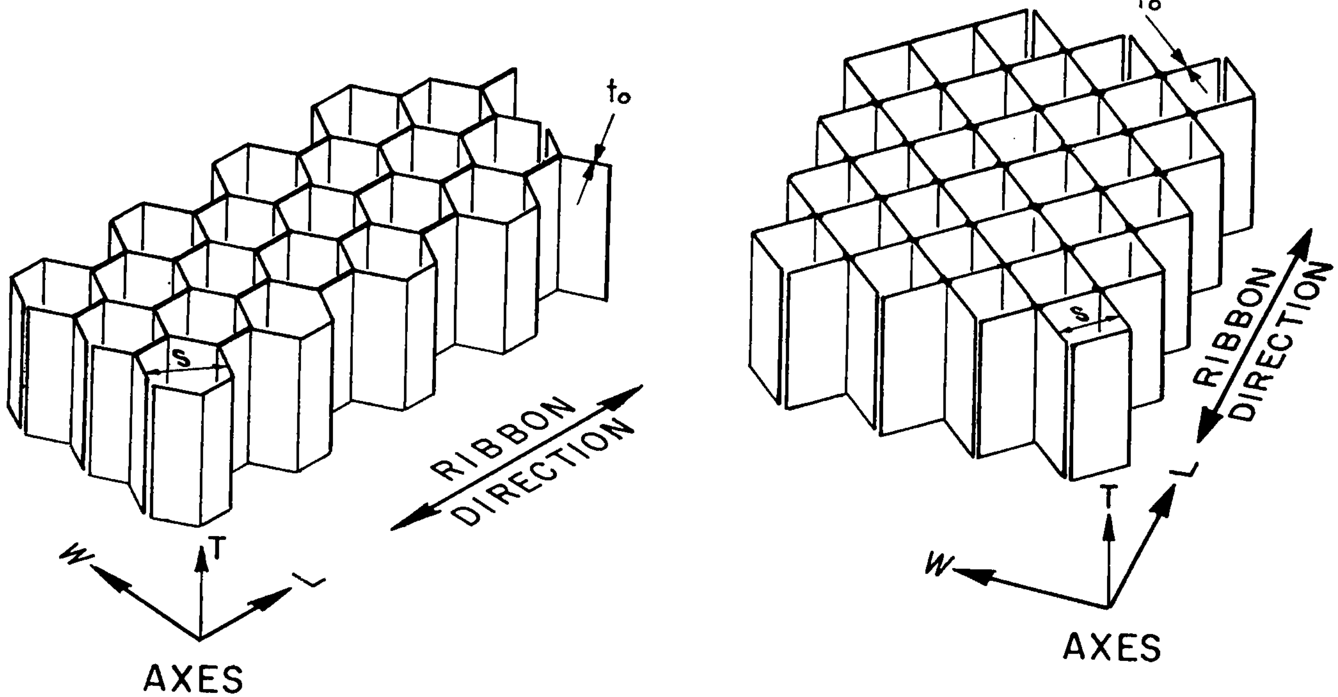
SINGLE ROW OF CORRUGATIONS



DOUBLE ROW OF CORRUGATIONS

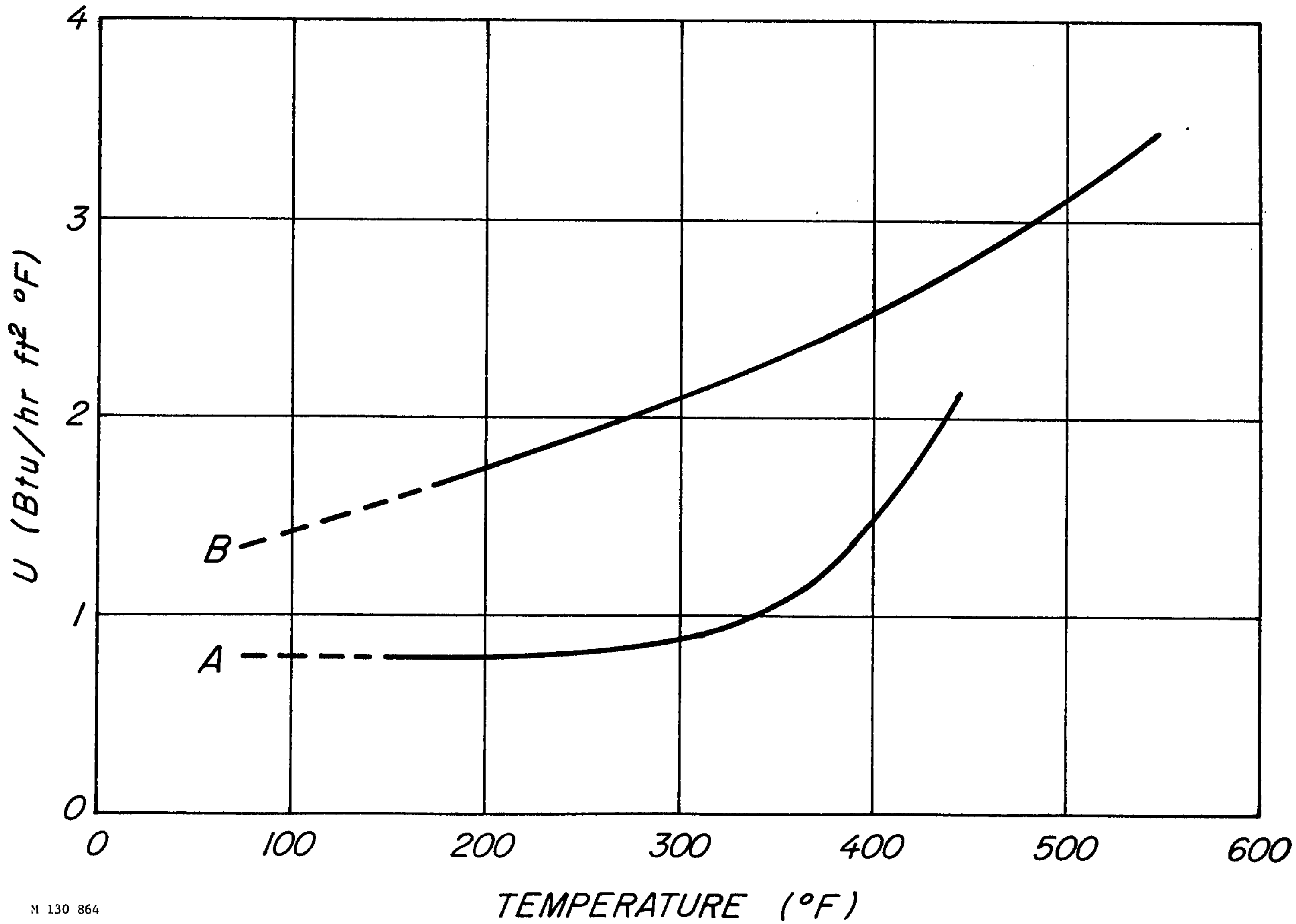
M 127 567

Figure 2-4. --Sandwich with corrugated cores.



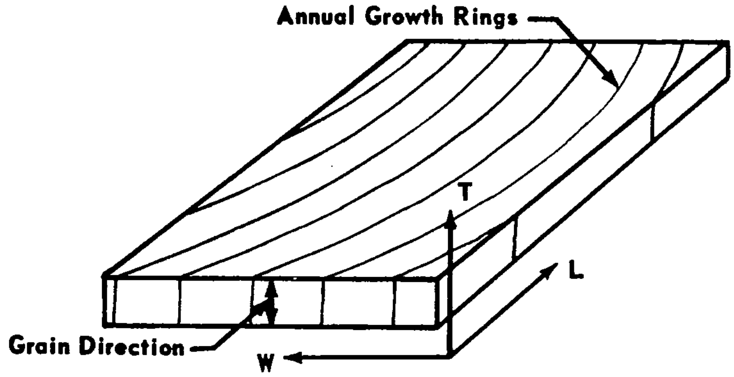

M 127 568,

Figure 2-5.--Honeycomb core notation.

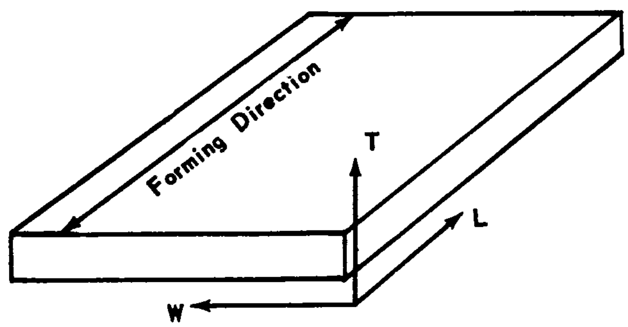



M 130 864

Figure 2-6.--Thermal conductivity, U, of sandwich panels 1/3 inch thick with 0.03-inch glass fabric-reinforced polyester resin facings and (A) foamed-in-place alkyd-isocyanate plastic core, 10 pounds per cubic foot density; (B) glass-fabric honeycomb core, phenolic resin, 9.9 pounds per cubic foot density.



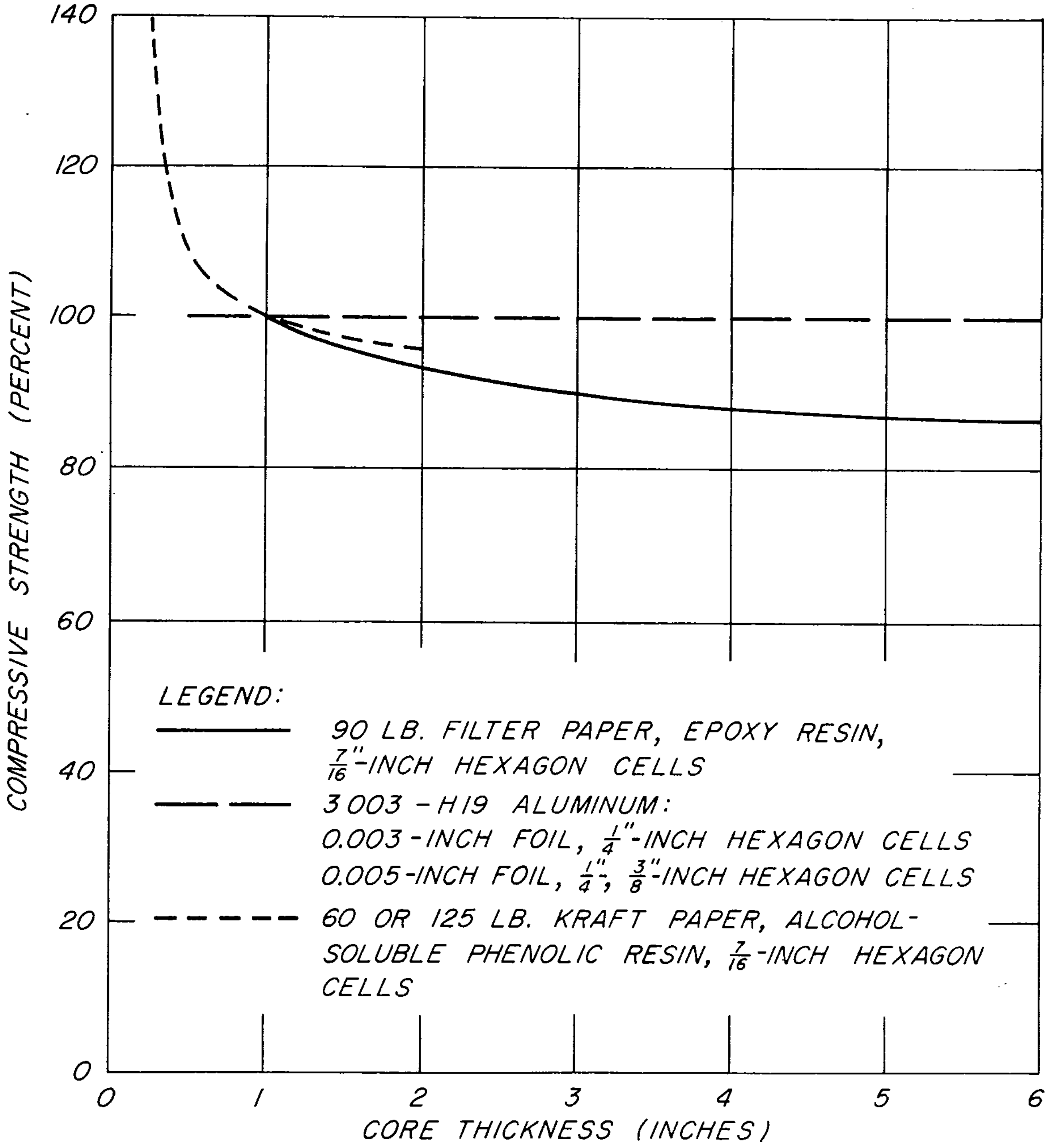

REFERENCE AXES FOR WOOD CORES




REFERENCE AXES FOR CELLULAR PLASTIC CORES

M 108 398

Figure 2-7.--Orthotropic axes notation for sandwich cores.




M 127 562

Figure 2-8.--Effect of core thickness on compressive strength.

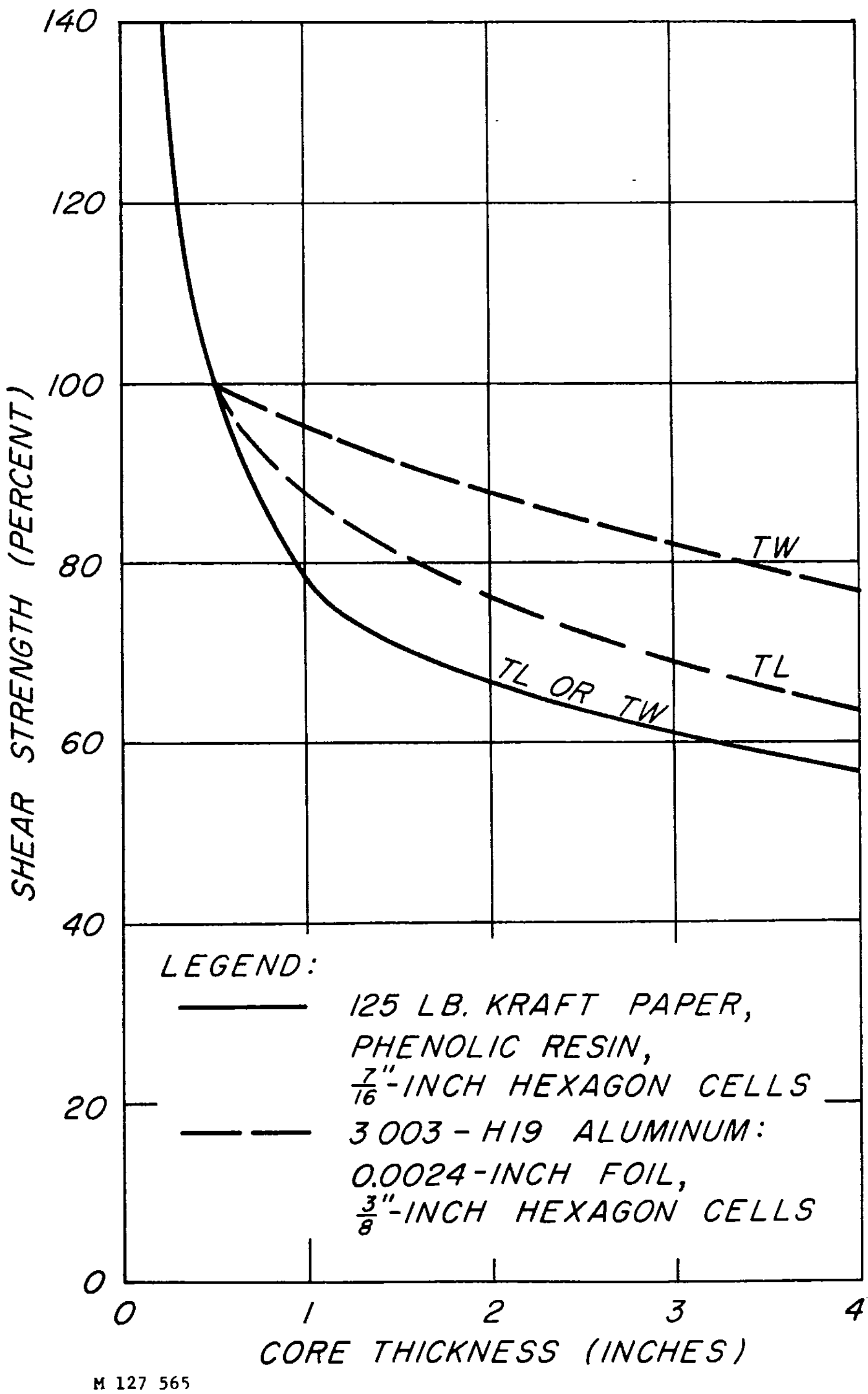
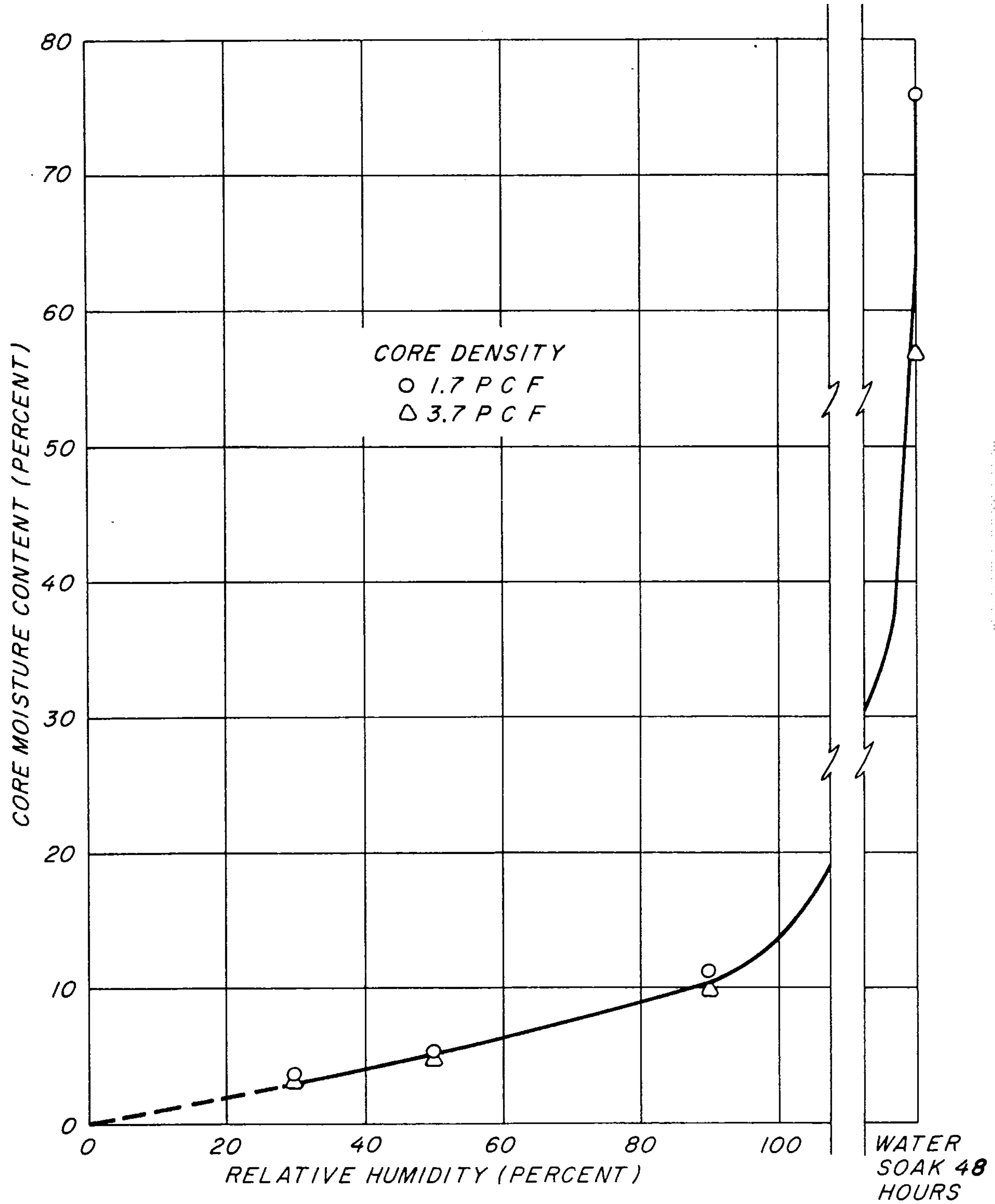
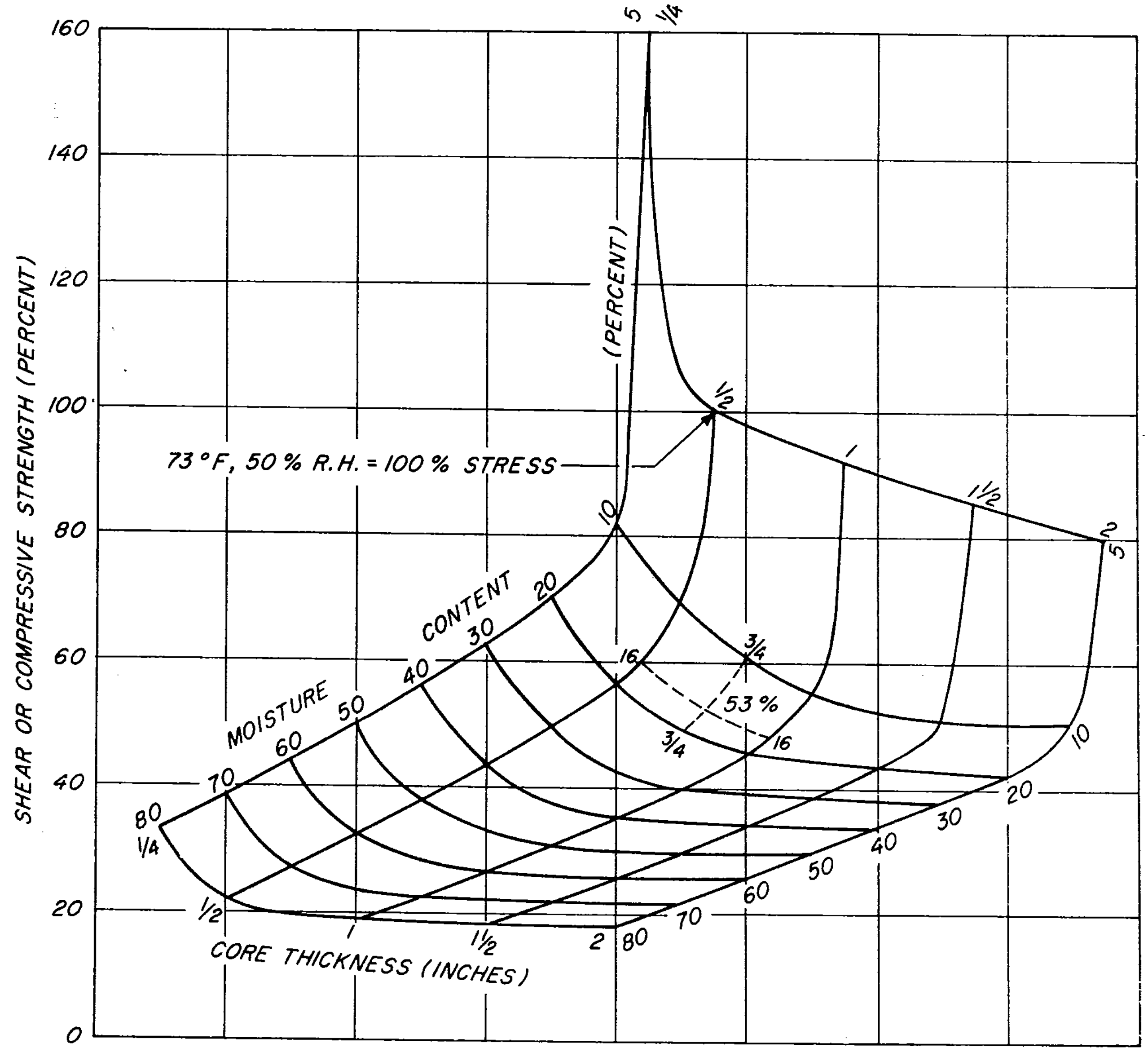



Figure 2-9.--Effect of core thickness on shear strength.



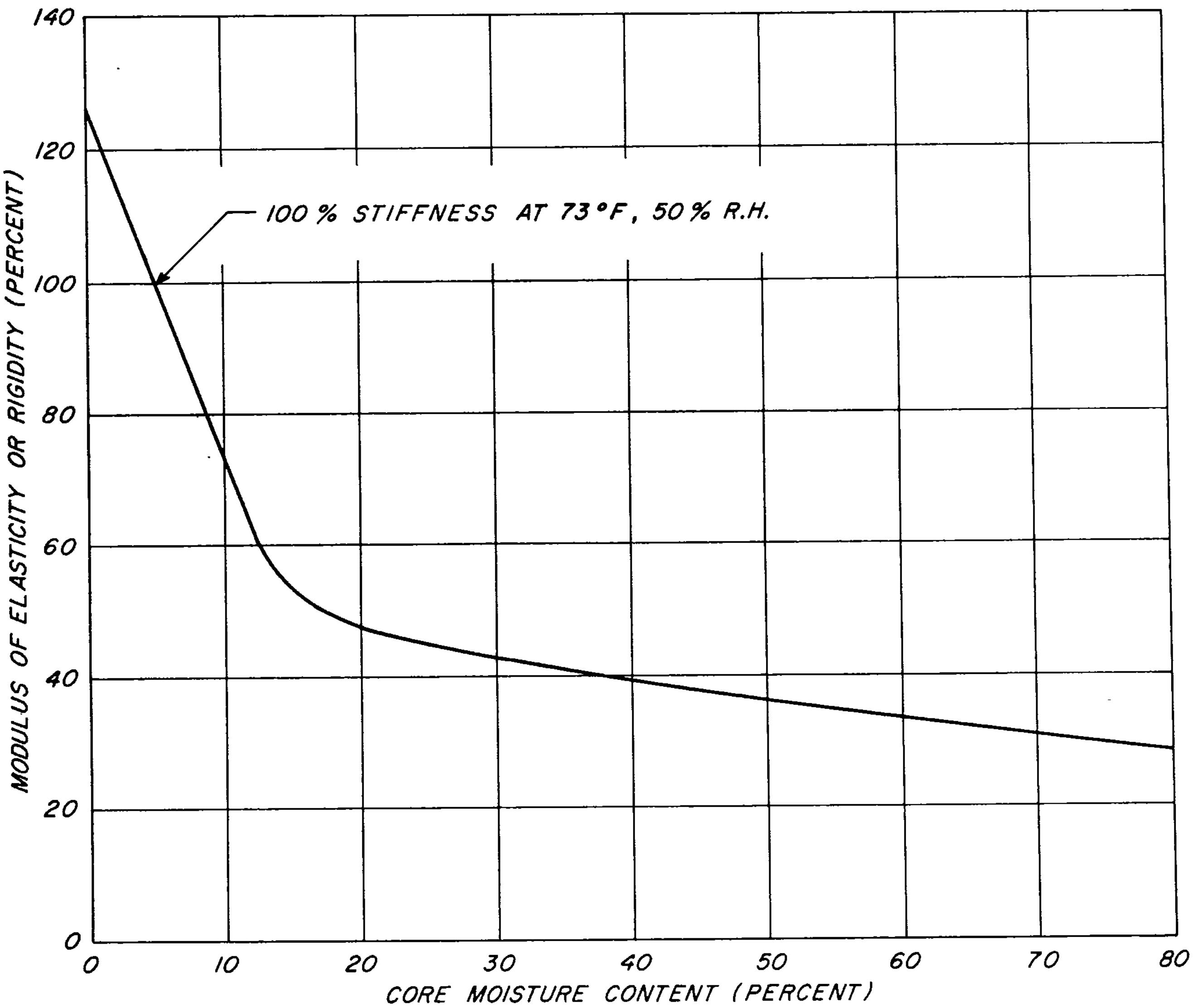

M 129 079

Figure 2-10. --Effect of relative humidity (at 80° F ) on equilibrium moisture content of resin-treated paper honeycomb core.



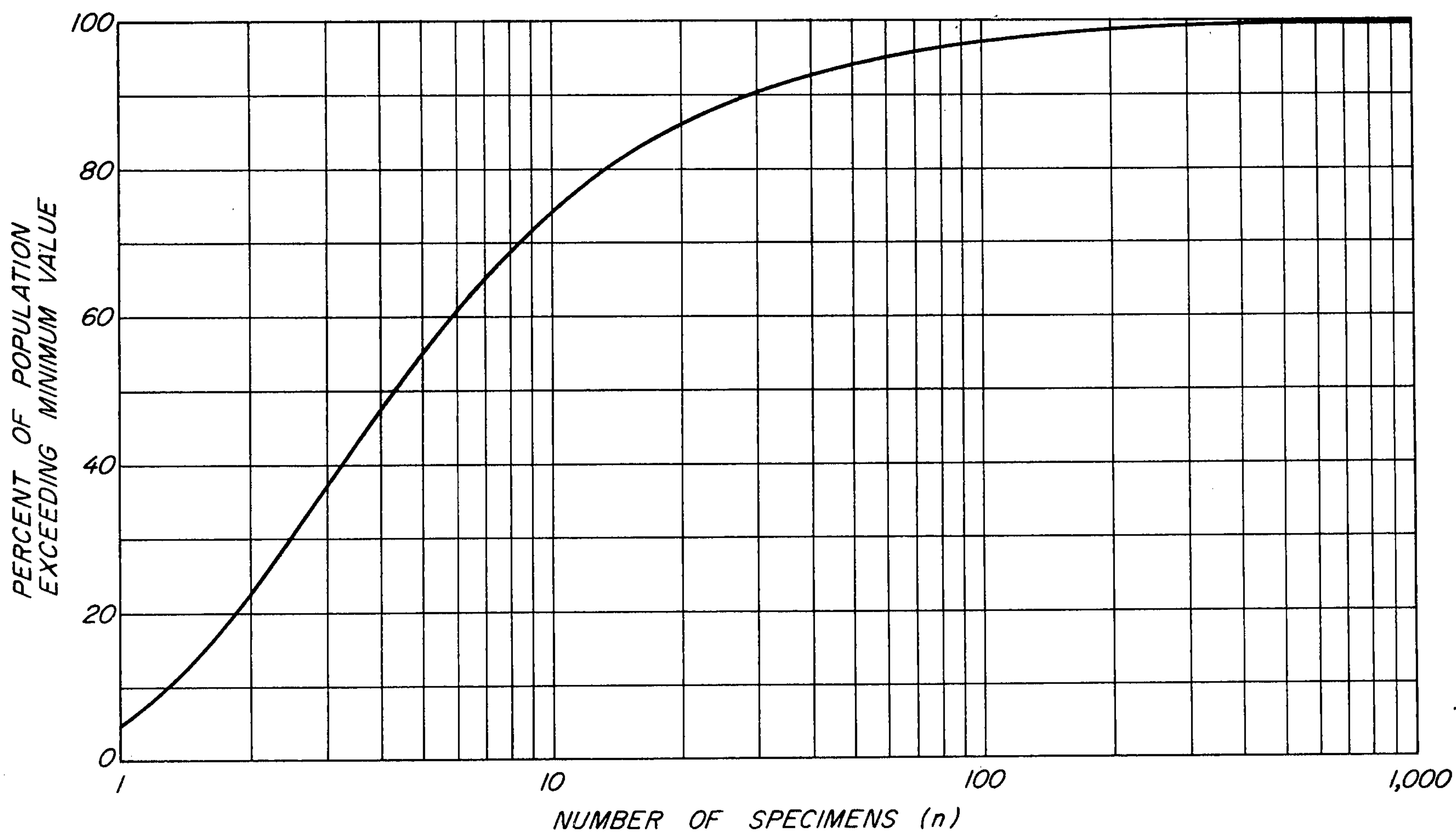

M 133 030

Figure 2-11.--Compressive or shear strength of resin-treated paper honeycomb core plotted as a function of core thickness and moisture content.

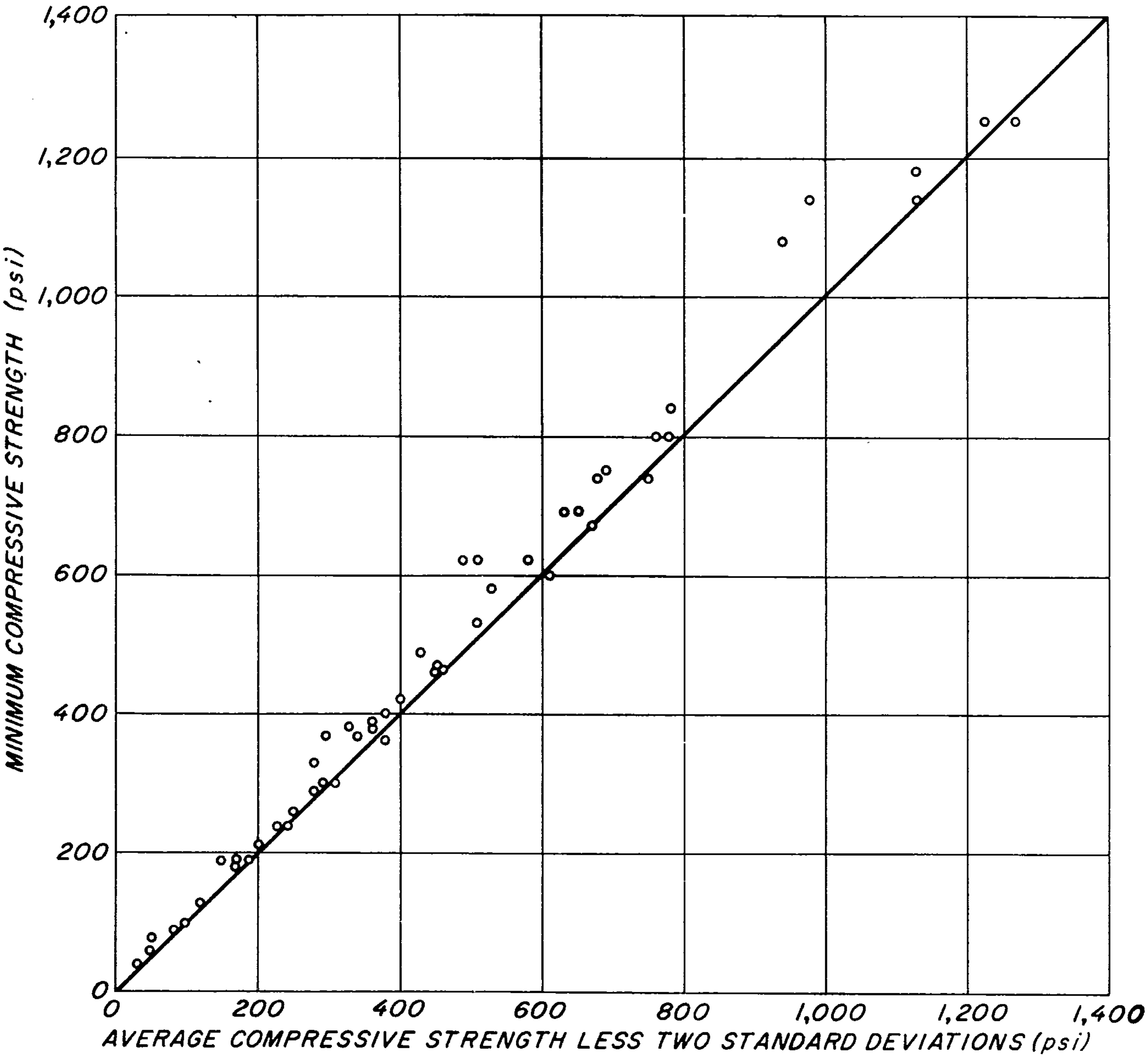



M 133 029

Figure 2-12.--Effect of core moisture content on shear and compressive stiffness of resin-treated paper honeycomb core.

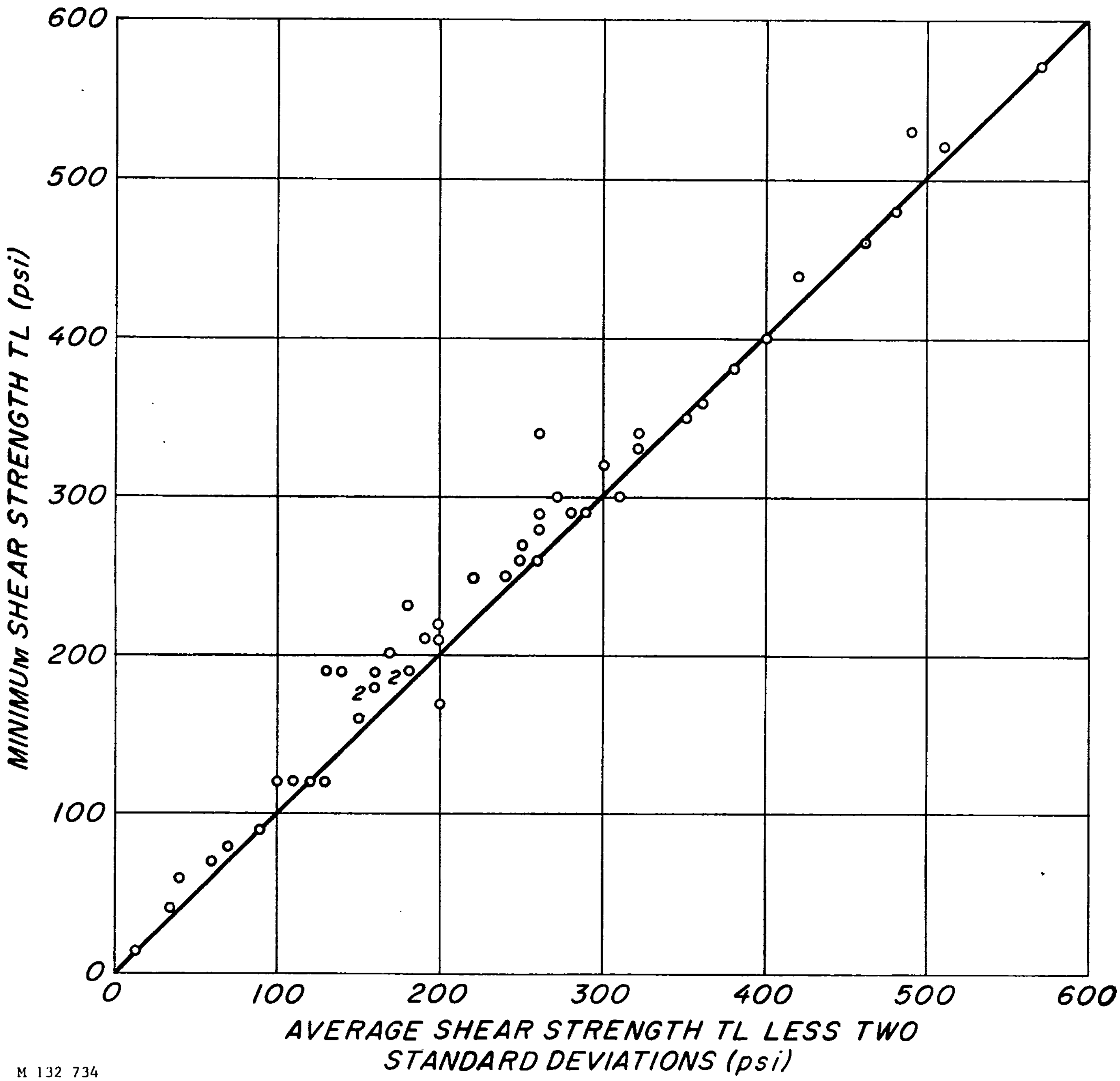



M 132 821 Figure 2-13.--Curve showing percent of population exceeding minimum value of a sample of n specimens with a probability of 0.95 (ref. 2-51).



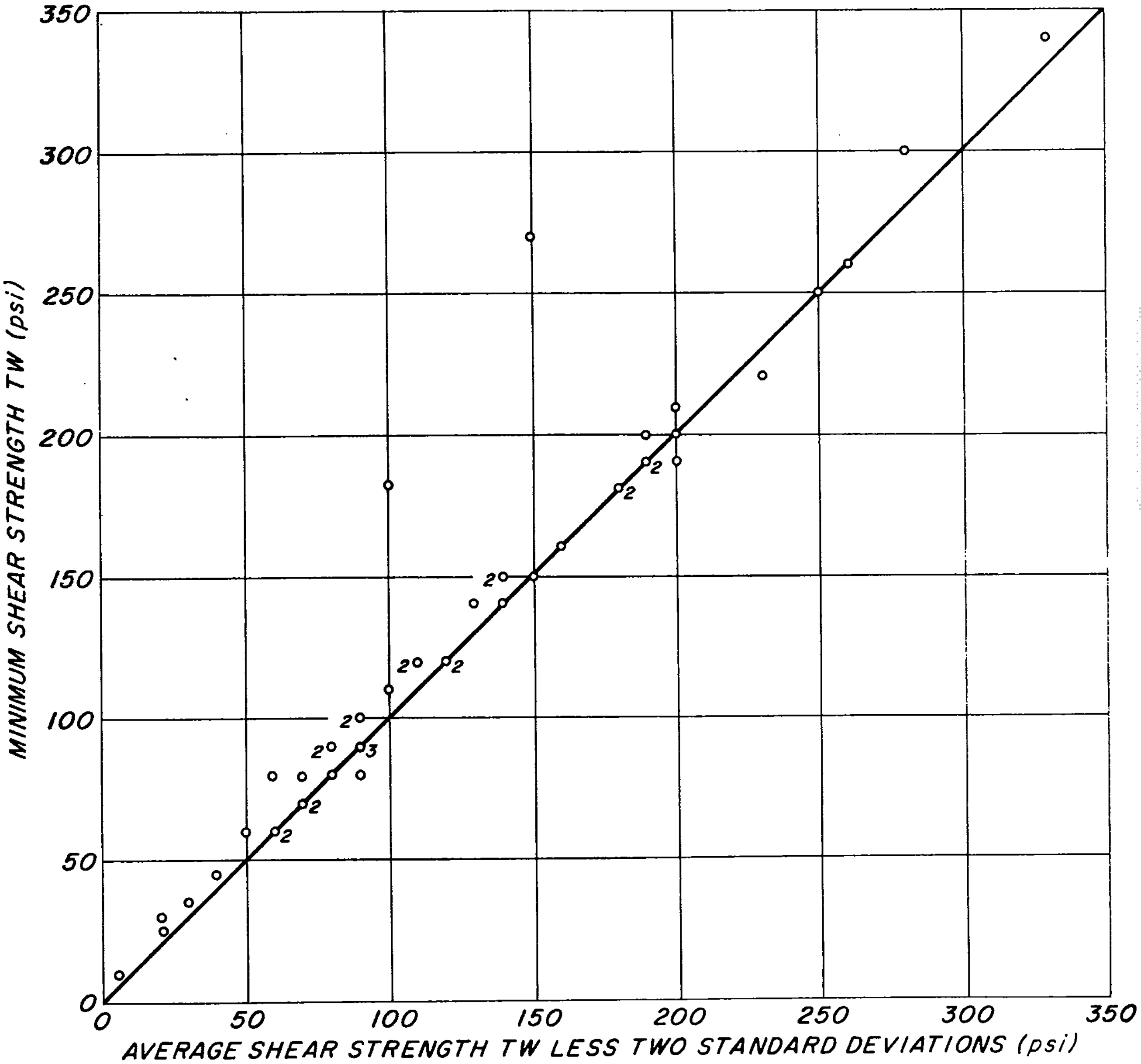

M 132 73?

Figure 2-14. --Graph of minimum compressive strength.



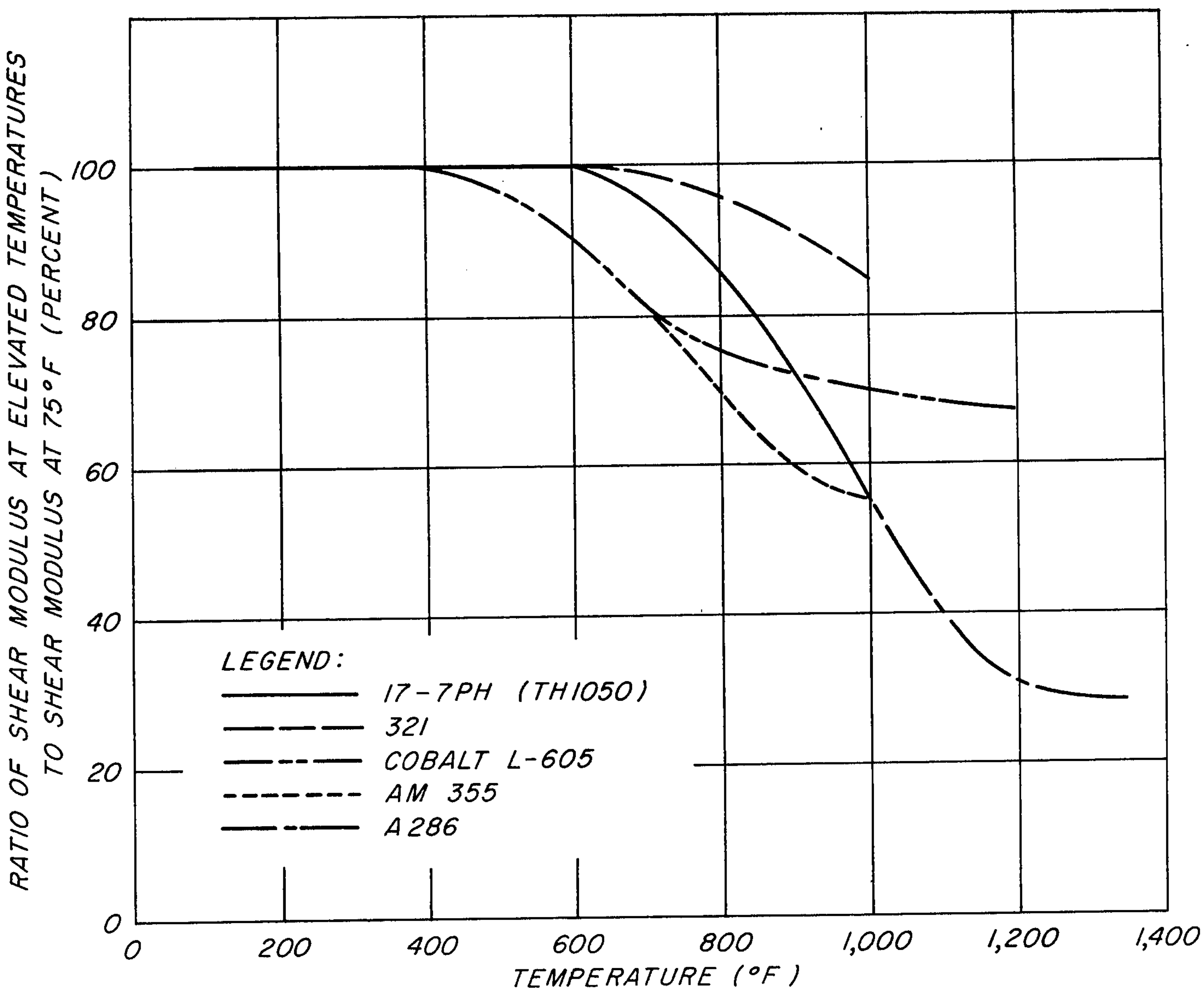

M 132 734

Figure 2-15. --Graph of minimum TL shear strength.




M 132 733

Figure 2-16.--Graph of minimum TW shear strength.




M 127 564

Figure 2-17.--Effect of elevated temperatures on the shear modulus of heat-resistant metal sandwich cores.

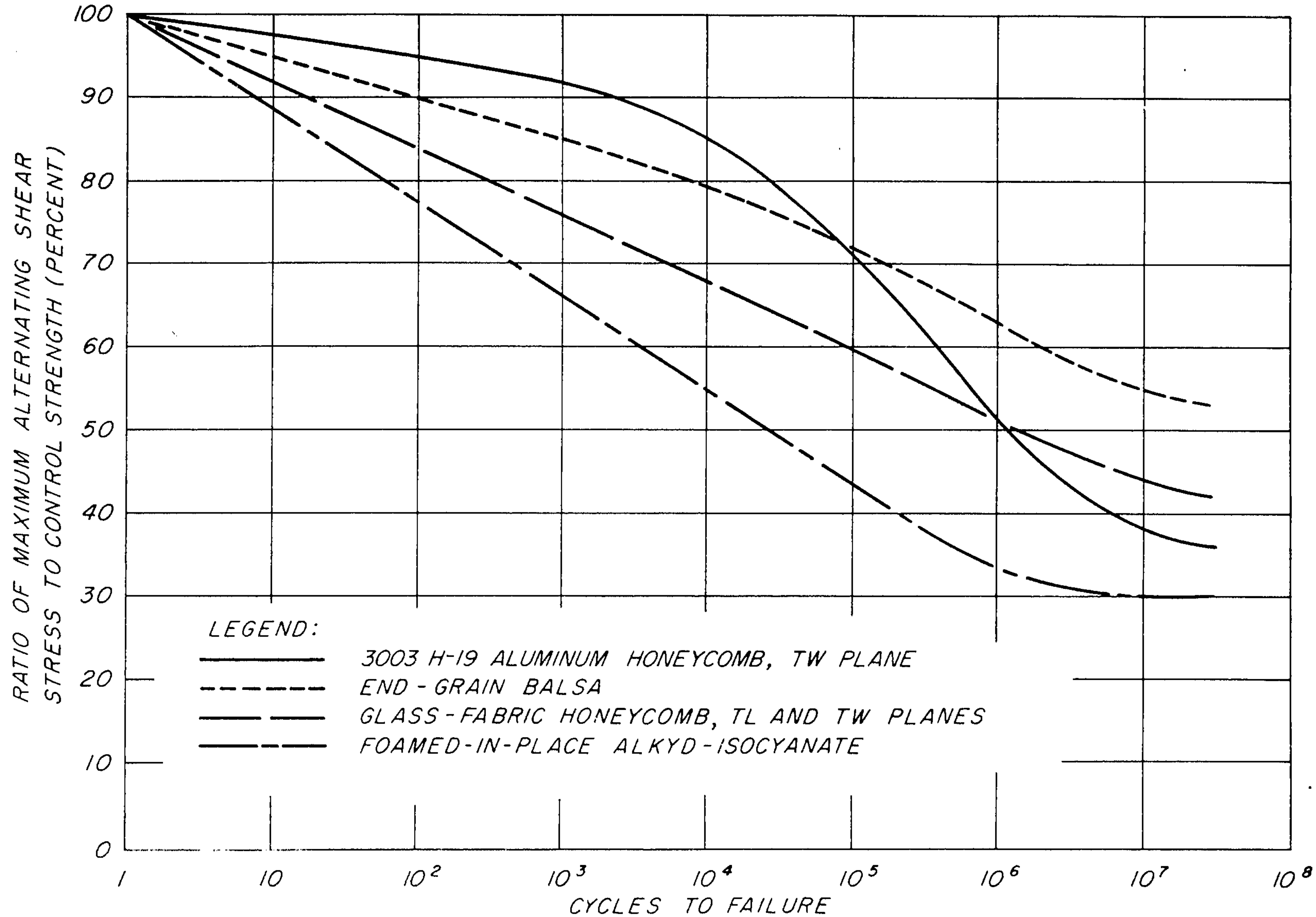



Figure 2-18. --Shear fatigue curves for low-density core materials. The ratio of minimum to maximum stress was 0.10.

(M 127 563)

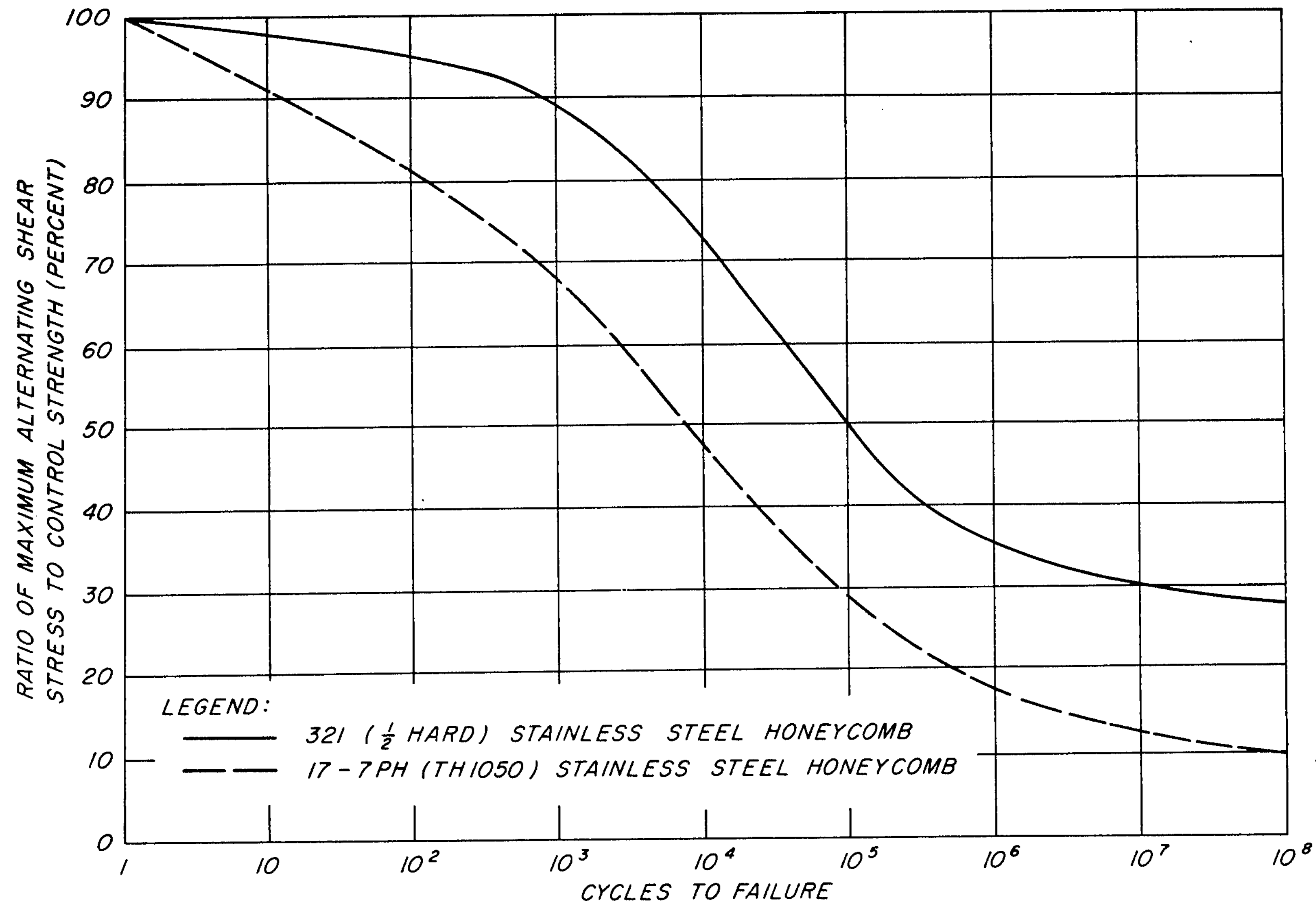



Figure 2-19.--Shear fatigue curves for stainless steel honeycomb cores. The ratio of minimum to maximum stress was 0.10.

(M 127 569)

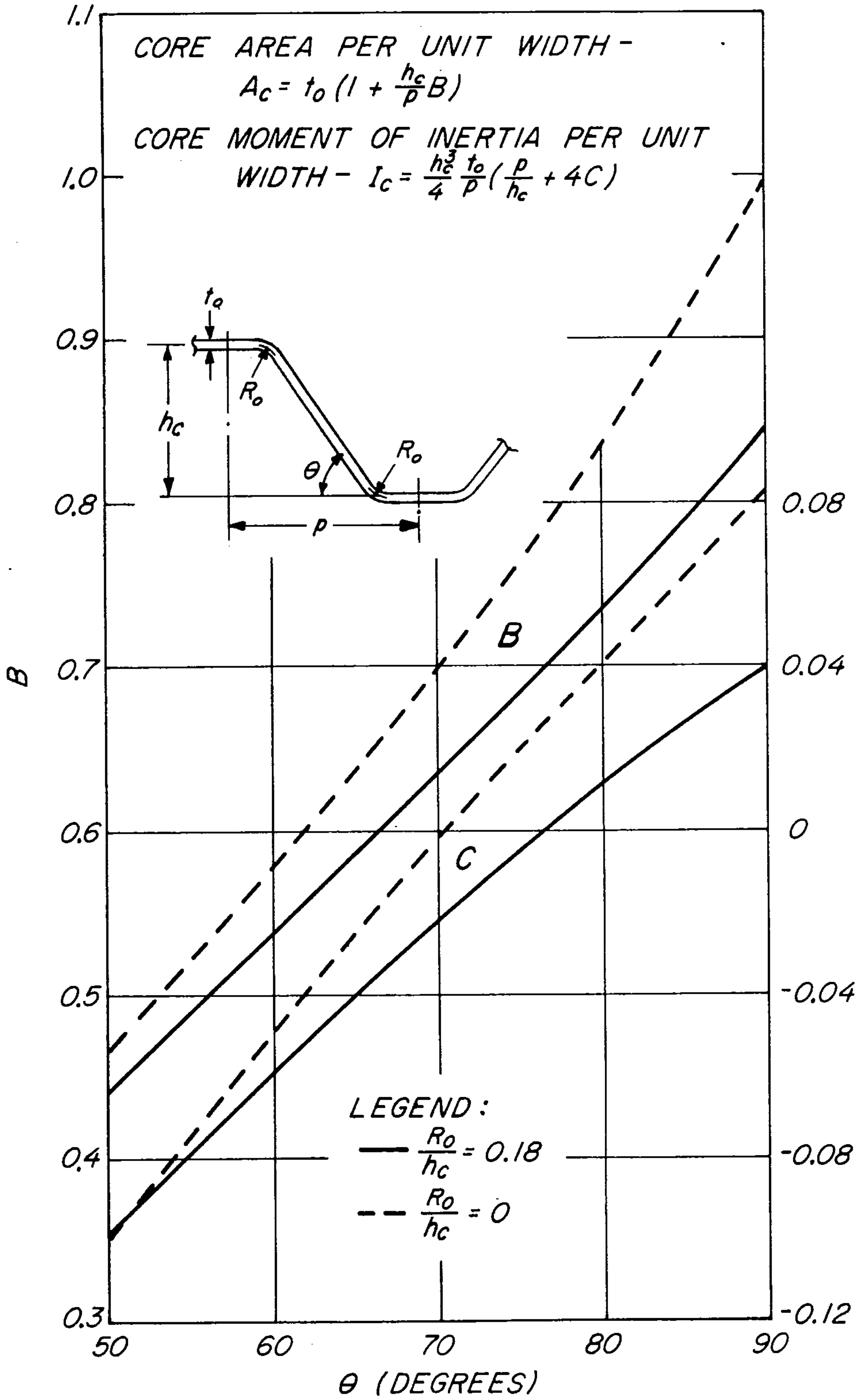



Figure 2-20.--Chart for determining core area and moment of inertia for core with single row of corrugations.

(M 130 865)

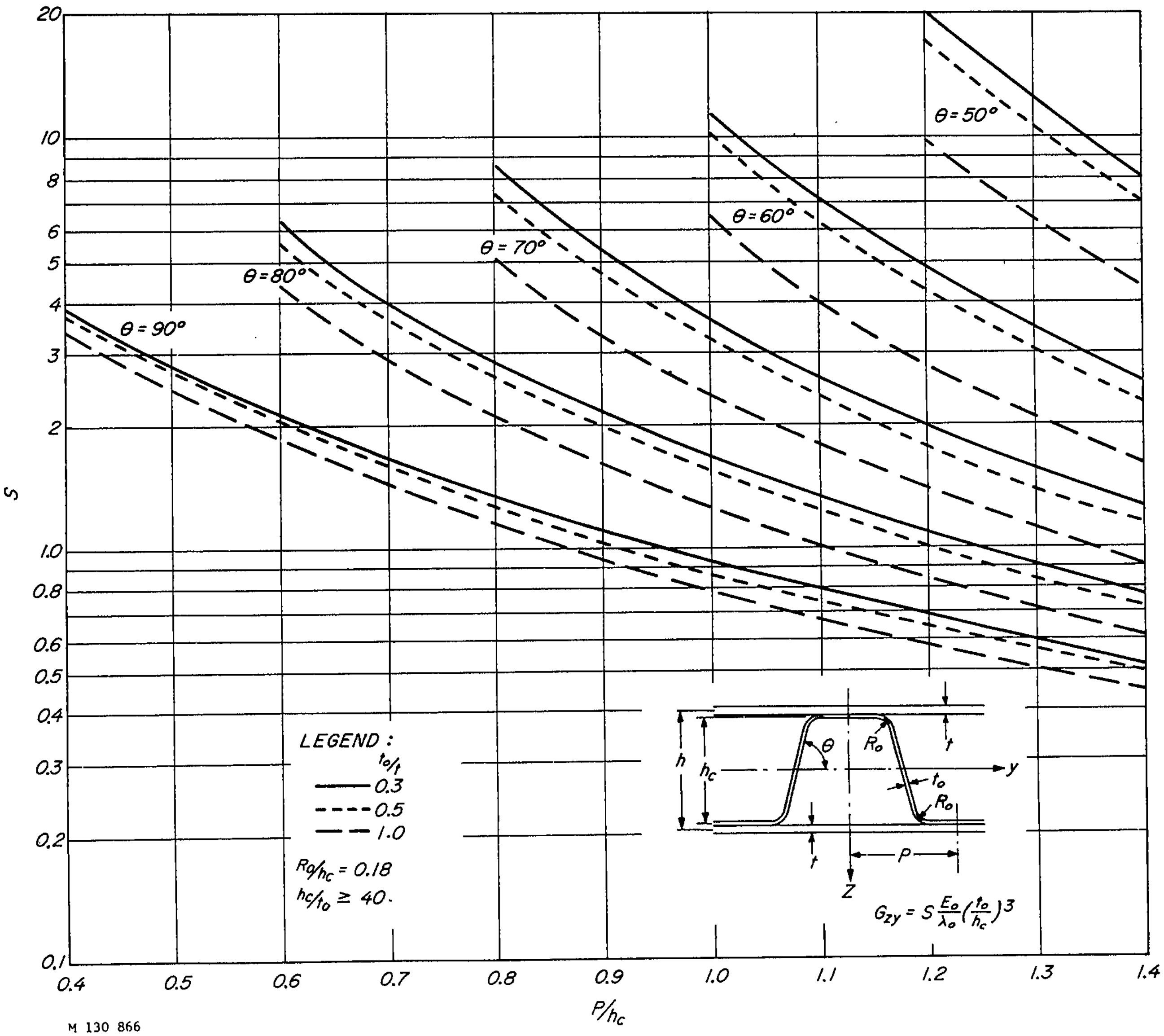



Figure 2-21. --Graph for determining core shear modulus for core with single row of corrugations.

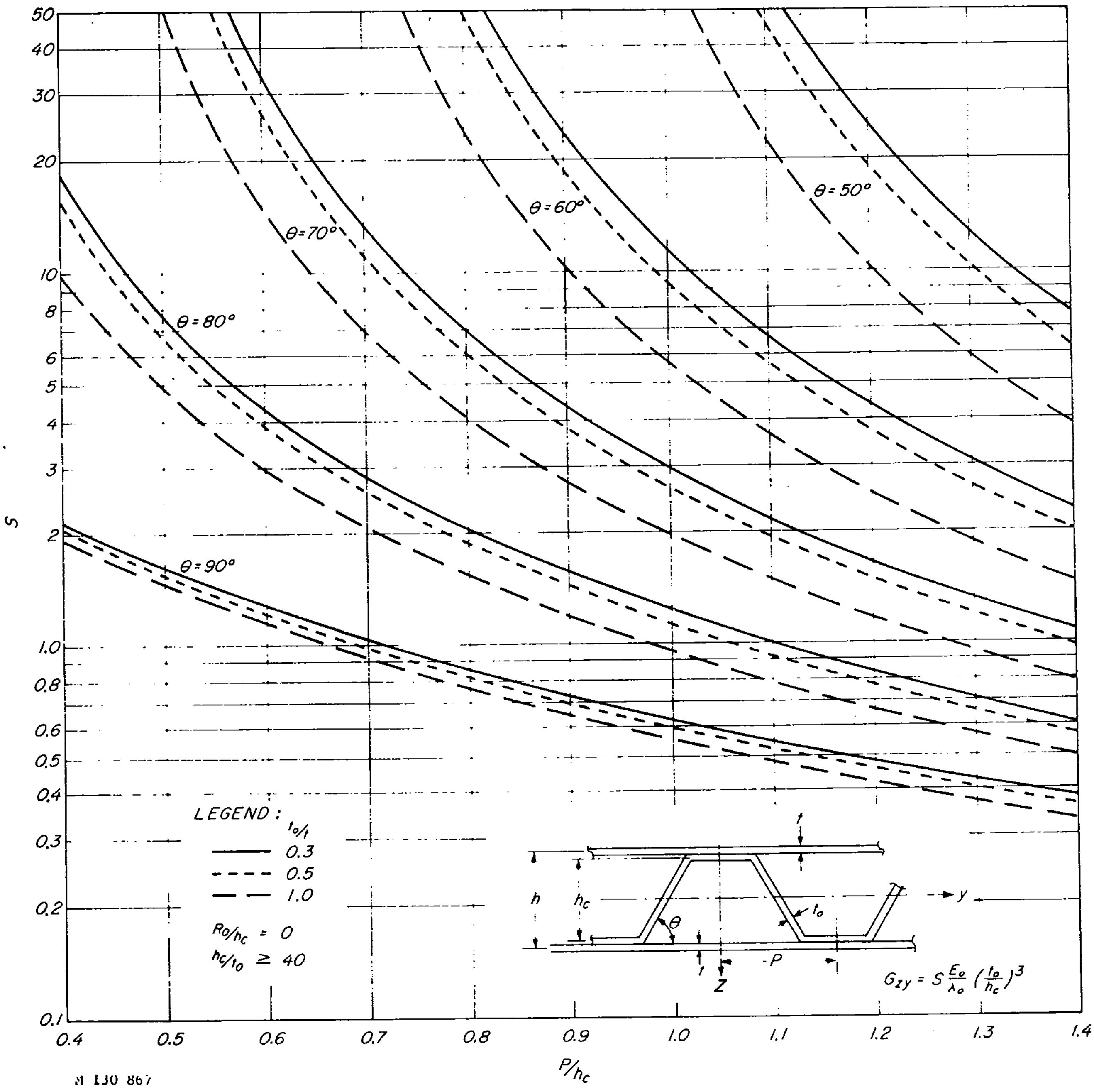
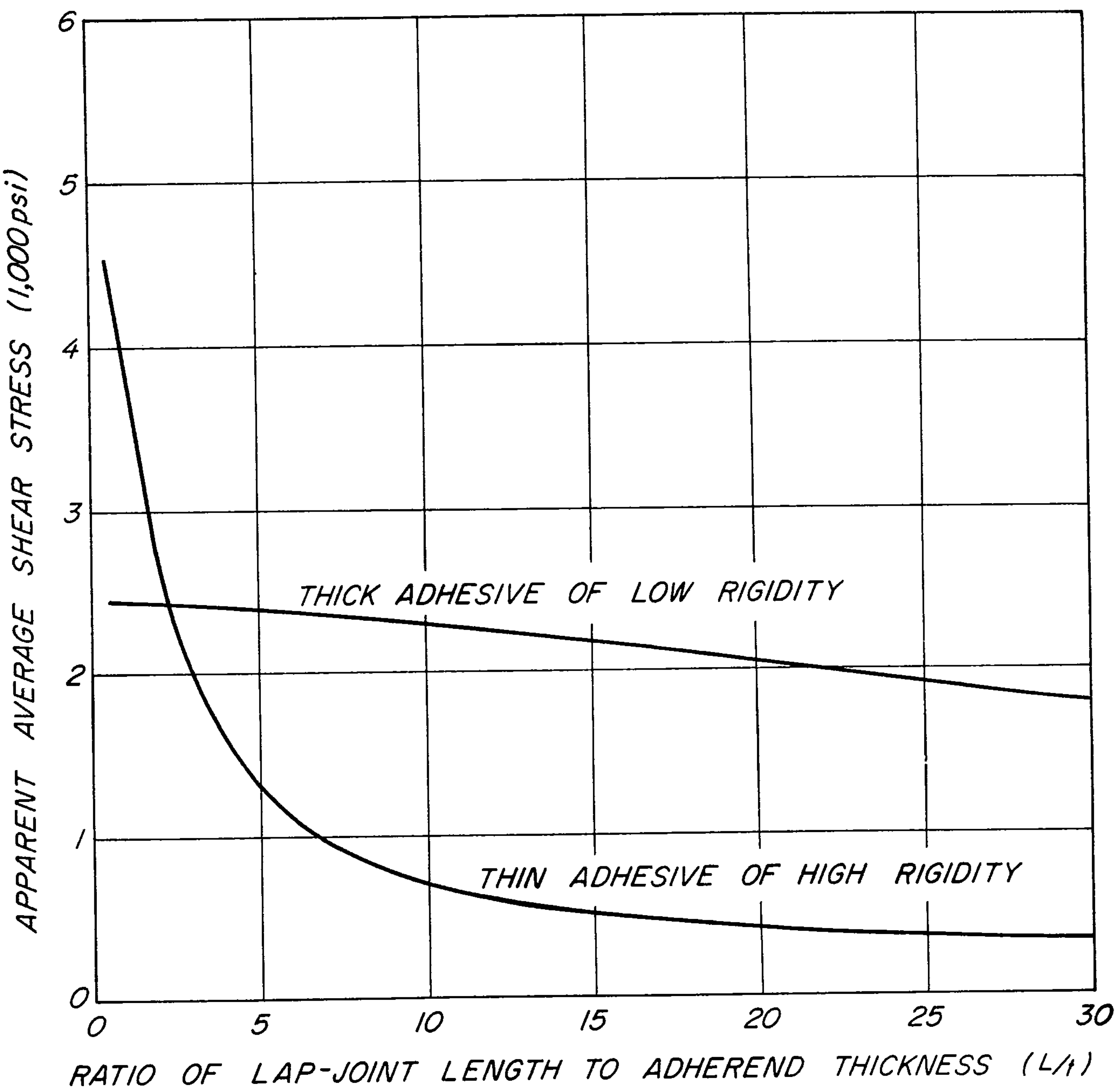



Figure 2-22. --Graph for determining core shear modulus for core with single row of corrugations.




M 132 822

Figure 2-23.--Dependence of average lap joint shear stress on ratio of lap length to adherend thickness.

# CHAPTER 3

## WRINKLING OF SANDWICH FACINGS UNDER EDGEWISE LOAD

### 3.1 BASIC PRINCIPLES

Wrinkling of sandwich facings, as shown in figure 1-1D of the Introduction, Chapter 1, may occur if a sandwich facing buckles as a plate on an elastic foundation. Analysis of this localized buckling behavior is complicated by unknown waviness of sandwich facings. Thus, the designer must, in effect, consider the buckling of a column (facing) that is supported on an elastic foundation (core) and that is not initially straight. The initial curvature or deflection (waviness) is not easily defined or easily measured, and attempts to correlate wrinkling data, including measured facing waviness, with theory have not been very successful. Growth of initial waves causes stresses in the core and in the bond between facings and core. Final failure may occur suddenly and the facing may buckle inward or outward, depending on the flatwise compressive strength of the core relative to the flatwise tensile strength of the bond between the facing and core. Information given here should not be used as a primary means of sandwich design, but should be used in conjunction with information on general buckling, deflection, etc. The final design should be checked to ascertain whether wrinkling of the sandwich facings might occur at design load. Because of uncertainties in analysis and values of material properties, it is recommended that the final design be checked by tests of a few small specimens (see refs. 3-1 and 3-6 for test methods).

The facings of a sandwich shall not wrinkle under design load. The information given here assumes that the facing and core properties and dimensions are known. The properties shall be values at the condition of use; that is, if application is at elevated temperature, then properties at elevated temperature shall be used in design. The facing modulus of elasticity is the effective value at the facing stress. If this stress is beyond the proportional limit value, an appropriate tangent, reduced, or modified compression modulus of elasticity shall be used (ref. 3-5).

The wrinkling stress formulas are given for two types of sandwich; sandwich with continuous cores and sandwich with honeycomb cores for which elastic moduli in the plane of the core are very small compared with the elastic modulus in a direction normal to the core plane.

## 3.2 SANDWICH WITH CORE SUPPORTING FACINGS CONTINUOUSLY

The stress at which wrinkling of sandwich facings on a continuous core will occur is given approximately by the formula (ref. 3-2):

$$F_w = Q\left(\frac{E' E_c G_c}{\lambda}\right)^{1/3} \tag{3:1}$$

where $F_w$ is facing wrinkling stress; E' is effective facing elastic modulus in the direction of the applied load; $\lambda$ is one minus the product of two Poisson's ratios; $E_c$ is core elastic modulus in a direction normal to the sandwich facings; $G_c$ is core shear modulus associated with shear distortion in the plane perpendicular to the facings and parallel to the direction of applied load; and Q is the relative minimum with respect to $\zeta$ of the expression

$$\frac{\dfrac{\zeta^2}{30q^2} + \dfrac{16q}{\zeta}\left(\dfrac{\cosh \zeta - 1}{11 \sinh \zeta + 5}\right)}{1 + 6.4K\zeta\left(\dfrac{\cosh \zeta - 1}{11 \sinh \zeta + 5}\right)} \tag{3:2}$$

where

$$q = \frac{t_c}{t} G_c \left(\frac{\lambda}{E' E_c G_c}\right)^{1/3} \tag{3:3}$$

$$K = \frac{\delta E_c}{t_c F_c} \tag{3:4}$$

and $t_c$ is core thickness; t is facing thickness; $\delta$ is initial deflection of facing waviness; and $F_c$ is flatwise sandwich strength (the lesser of flatwise core compression or sandwich flatwise tension). The parameter $\zeta$ is proportional to the fourth root of the ratio of the core elastic moduli and to the ratio of the core thickness to the ideal buckle wavelength (see ref. 3-2 for details).

A graphical presentation of Q (minimum values of formula 3:2) is given in figure 3-1. The graph can be entered at known values of the abscissa, q, and the ordinate, Q, determined after choosing an estimated K curve. Present state of the art does not permit a suitable choice for values of $\delta$. If test values of wrinkling stresses are known, the graph of figure 3-1 can be used to determine which K curve fits the data and then compute values of $\delta$ from formula (3:4). Changes in design for similar sandwich can then be made by assuming $\delta$ to be a constant for that particular type of sandwich and then using the graph of figure 3-1 to redesign.

Examples:

1. A sandwich has 0.067-inch facings on a 1-inch core. Core elastic properties are $E_c$ = 50,000 pounds per square inch and $G_c$ = 20,000 pounds per square inch. Facing elastic modulus is $(E/\lambda)$ = 10,000,000 pounds per square inch at a design stress of 43,000 pounds per square inch. Determine whether sandwich facings will wrinkle under this design stress. Values of Q and q were computed from formulas (3:1) and (3:3) to be 0.20 and 1.39, respectively. The graph of figure 3-1 shows the value of K to be about 1.2 and from the definition of K (formula 3:4), $\delta$ was computed to be 0.012 inch for $F_c$ = 500 pounds per square inch. This severe an amplitude of waviness for a 0.067-inch facing seems unlikely, hence wrinkling at design stress would be unlikely even though the formula is not exact.

2. Solution of formula (3:1) from test values results in Q = 0.32 and solution of formula (3:3) give q = 3.86. The graph of figure 3-1 shows that the curve K = 0.20 passes through the point designated by these values of Q and q. In order to increase the value of the wrinkling stress by 50 percent, the value of Q must increase from 0.32 to 0.48, and then the value of K must decrease to about 0.092 for the same value of q. Thus, the core or sandwich flatwise strength, $F_c$, would have to be increased by a factor of about 0.20/0.09 = 2.2 to raise the wrinkling stress by 50 percent. Another way to obtain an increase in wrinkling stress is to increase the facing thickness, t, without changing core or sandwich flatwise strength. This results in sliding up the K = 0.20 curve until Q = 0.48 at which point q = 1.75 and thus t increases by a factor of 3.86/1.75 = 2.2. This would be a bit conservative because it is assuming $\delta$ is the same for facings of different thickness. From formula (3:1) it is also obvious that an increase in elastic properties will also increase wrinkling stress provided Q is not decreased too much by an increase in q.

On the left side of figure 3-1, the curves terminate in a straight line represented by $Q = 1/2q$. Substitution of this into (3:1) and replacing q by (3:3) results in the formula

$$F_w = \frac{t_c G_c}{2t} \tag{3:5}$$

which is the same result as obtained for the "shear crimping" mode defined by a limit of the general buckling modes and illustrated in figure 1-1B of the Introduction, Chapter 1.

Figure 3-2 presents a graphical means for determining K values from the ratios $\delta/t_c$ and $F_c/E_c$. The graph is also useful in determining $\delta/t_c$ values from known values of $F_c/E_c$ and K.

## 3.3 SANDWICH WITH HONEYCOMB CORES

Solution of the general expressions for wrinkling of sandwich facings on honeycomb cores leads to somewhat different results because for honeycomb cores the elastic moduli in the plane of the core ($E_L$, $E_W$, $G_{WL}$) are very small compared with elastic moduli in a direction normal to the core plane ($E_T$, $G_{TL}$, $G_{TW}$). The stress at which wrinkling of sandwich facings on a honeycomb core will occur is given approximately by the formula (ref. 3-3)

$$F_w = \frac{0.82 \left( \frac{E_c t}{E' t_c} \right)^{1/2} E'}{1 + 0.64K} \tag{3:6}$$

where the symbols have the same meaning as given previously. A nondimensional graph of formula (3:6) is given in figure 3-3. Solution of the formula is carried out the same as for the sandwich with continuous cores.

The wrinkling of sandwich facings brazed to honeycomb cores has been investigated experimentally and analyzed statistically for hardened alloys of 17-7PH and PH15-7Mo steel (ref. 3-4). The resultant statistical formula for wrinkling stress was given as

$$F_w = 266,820 \log_{10} \left( \frac{F_{cy}}{1,000} \right) + 68,578 \log_{10} \rho_c + 17,175 \log_{10} \left( \frac{t_c}{t} \right) - 46,747 \log_{10} \left( \frac{s}{t} \right) - 454,978 \tag{3:7}$$

where $F_w$ is wrinkling stress of the facing in pounds per square inch; $F_{cy}$ is compressive yield stress of the facing in pounds per square inch; $\rho_c$ is core density in pounds per cubic foot; $t_c$ is core thickness; t is facing thickness; and s is core cell size. Direct use of formula (3:7) for materials other than those for which it was obtained is not recommended without test verification.

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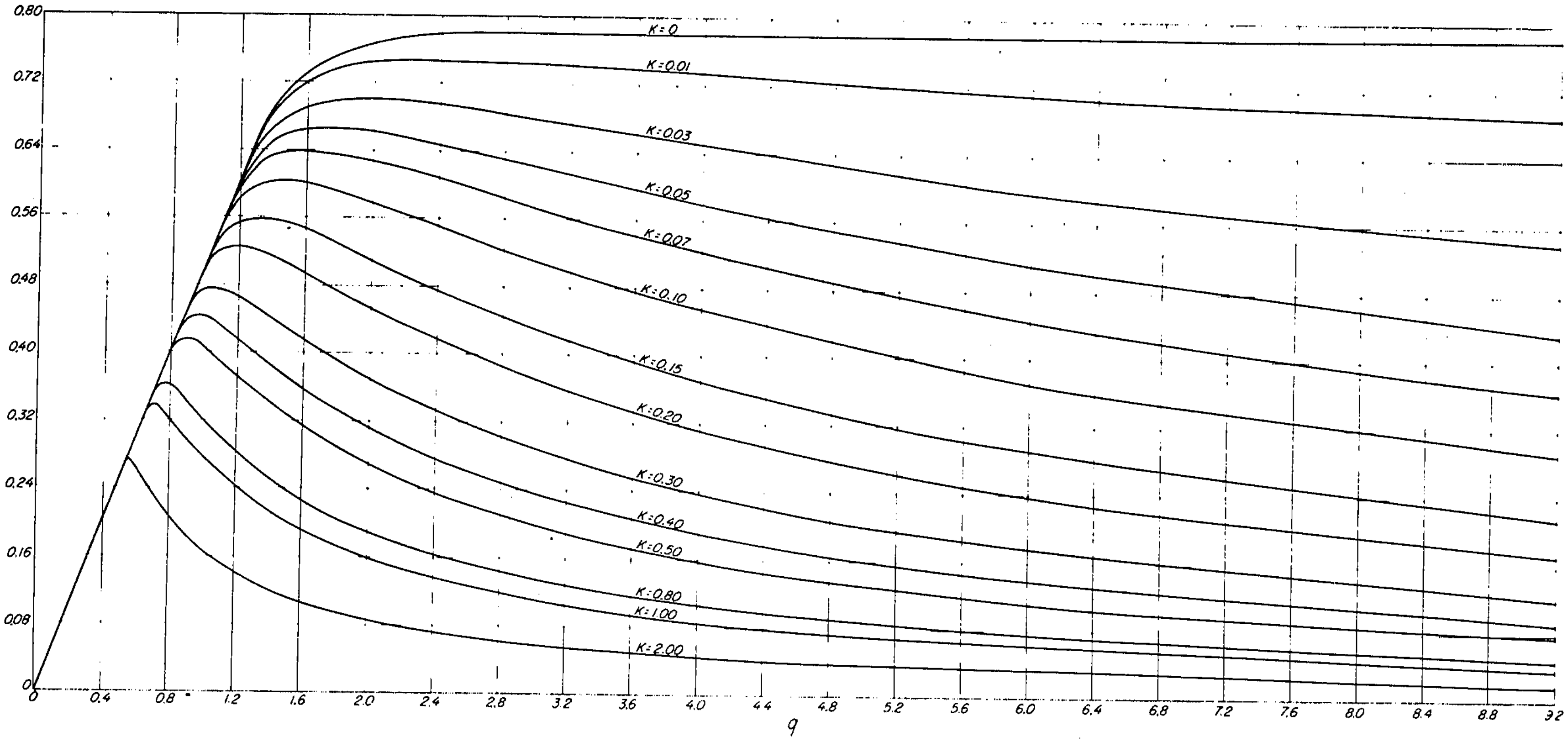


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Figure 3-1. --Parameters for determining wrinkling of facings of sandwich with continuous cores.

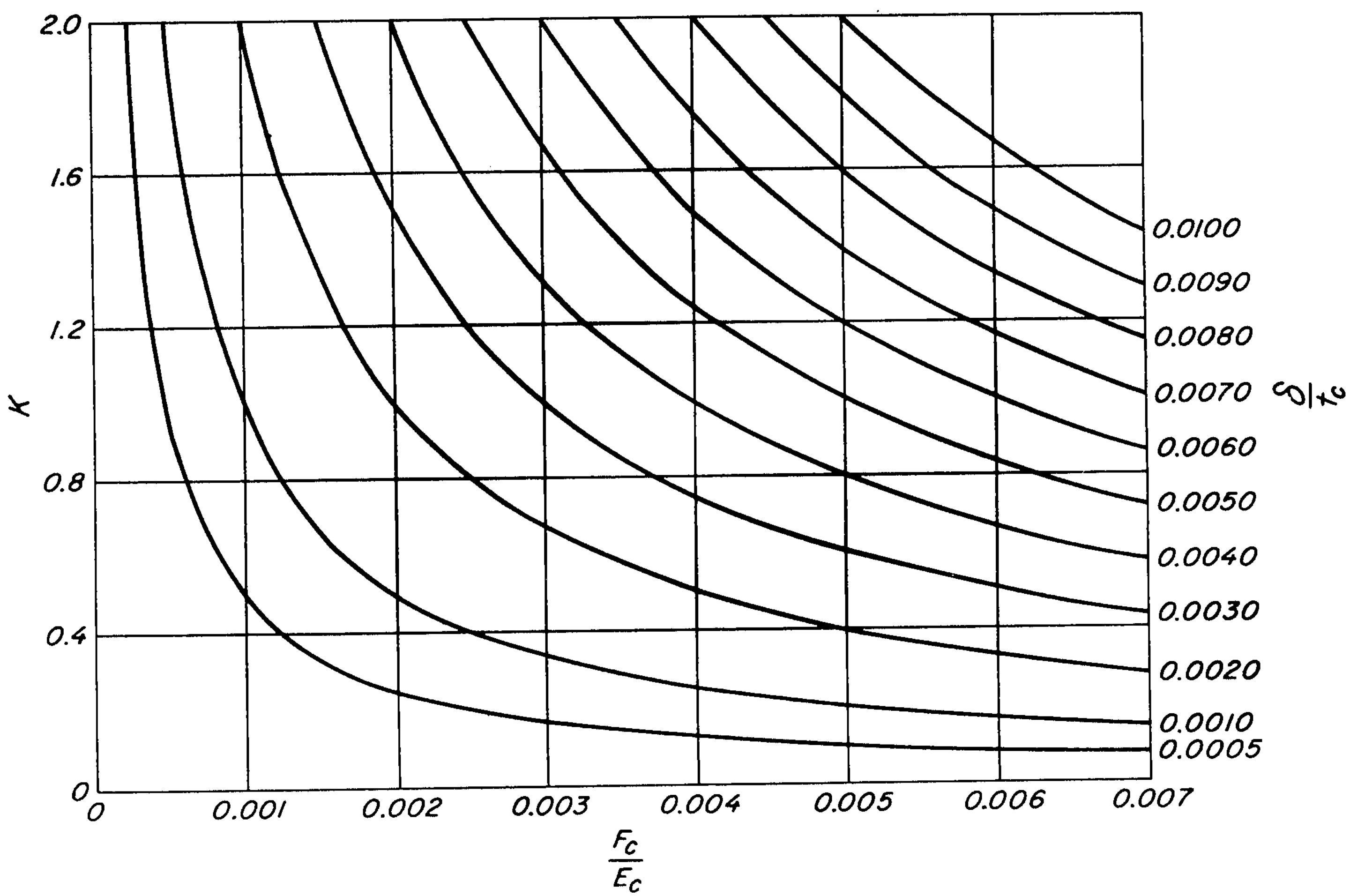


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Figure 3-2. --Relationship of K to core properties ($F_c/E_c$) and facing waviness ($\delta/t_c$).

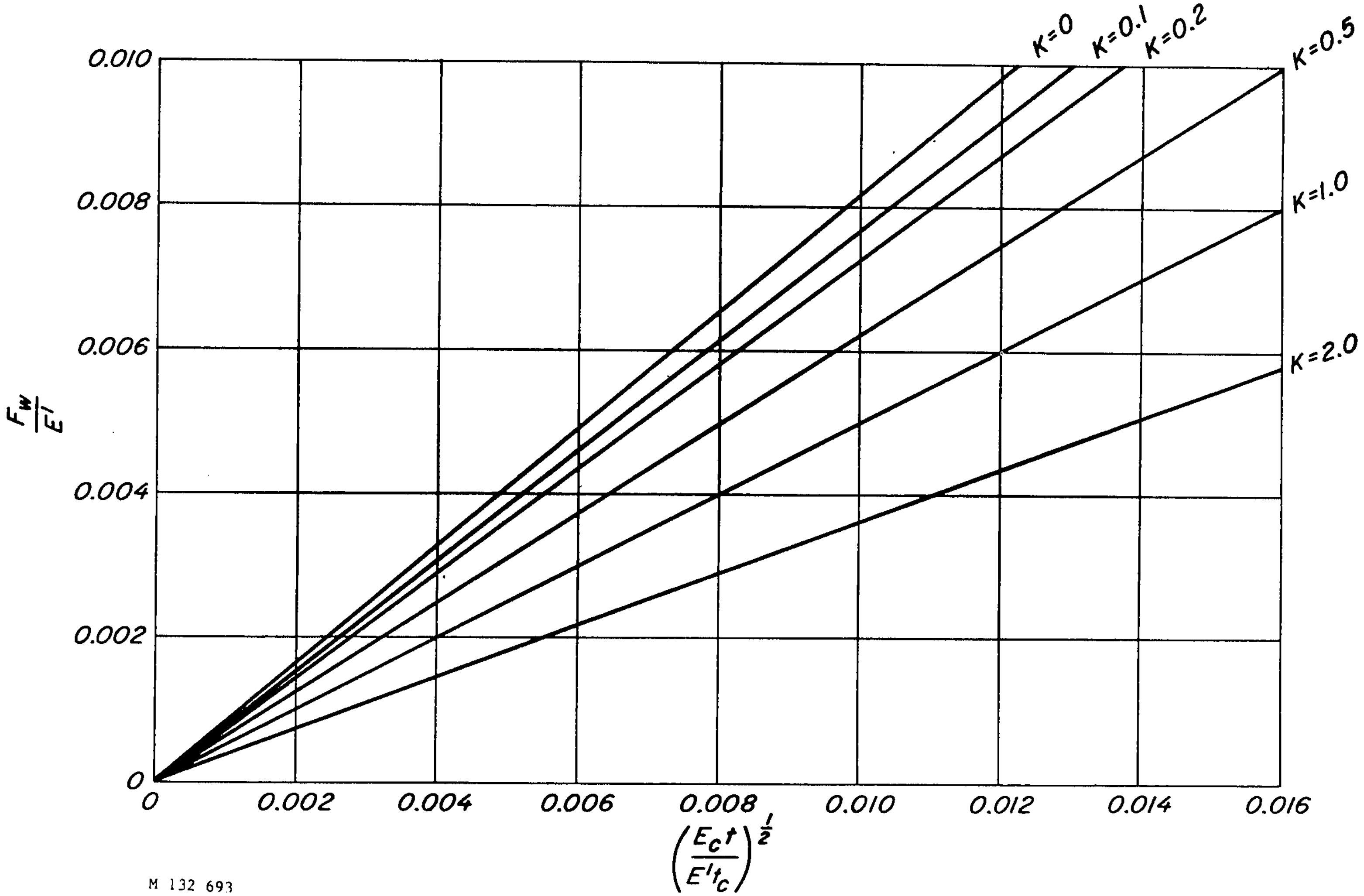


Figure 3-3. --Graph of formula (3:6) for the wrinkling stress of facings of sandwich with honeycomb cores.

# CHAPTER 4 -- DIMPLING OF SANDWICH FACINGS UNDER EDGEWISE LOAD

Page

# CHAPTER 4

## DIMPLING OF SANDWICH FACINGS UNDER EDGEWISE LOAD

### 4.1 BASIC PRINCIPLES

If the core of a sandwich construction is of cellular (honeycomb) or corrugated material, it is possible for the facings to buckle or dimple into the spaces between core walls or corrugations. Dimpling of the facings may not lead to failure unless the amplitude of the dimples becomes large and causes the dimples or buckles to grow across core cell walls and result in wrinkling of the facings. Dimpling that does not cause total structural failure may, of course, be severe enough so that permanent dimples remain after removal of load.

If dimpling of the facings is not permissible, the core cell size or corrugation spacing shall be small enough so that dimpling will not occur under design loads. It is assumed that failure in the facing-to-core bond cannot occur prior to dimpling. The design procedures also assume that a facing thickness (t) is known (facing thickness having been determined by consideration of design loads and chosen design compressive facing stresses); that facing compressive stress $F_c$ and effective compressive modulus of elasticity $E'$ are known; and that the core cell size or corrugation spacing is to be determined. The facing properties shall be values at the condition of use; that is, if application is at elevated temperature, then facing properties at elevated temperature shall be used in design. The facing modulus of elasticity is the effective value at the facing stress. If this stress is beyond the proportional limit value, an appropriate tangent, reduced, or modified compression modulus of elasticity shall be used (ref. 4-4).

Because of uncertainties in analysis and values of material properties, it is recommended that the final design be checked by tests of a few small specimens (see refs. 4-1 and 4-5 for test methods).

### 4.2 SANDWICH HAVING CELLULAR (HONEYCOMB) CORE

This section gives the procedure for determining the core cell size such that an isotropic sandwich facing will not dimple (ref. 4-3).

Supersedes Chapter 4 of 30 December 1968.

The facing stress at which dimpling of the sandwich facing will occur is given by the empirical formula

$$F_c = 2\,\frac{E'}{\lambda}\left(\frac{t}{s}\right)^2 \qquad (4:1)$$

where E' is effective compressive modulus of elasticity of the facing at stress $F_c$, $\lambda = 1 - \mu^2$ when $\mu$ is Poisson's ratio of facings, t is facing thickness and s is core cell size (diameter of inscribed circle).

Solving formula (4:1) for s results in

$$s = t\sqrt{2}\left(\frac{\lambda F_c}{E'}\right)^{-\frac{1}{2}} \qquad (4:2)$$

Determine maximum core cell size from formula (4:2) or by graphical solution using the chart in figure 4-1. If the core cell size is smaller than available, it is necessary to use a thicker facing and a lower stress in order that dimpling will occur at the same edge load. The chart of figure 4-1 can also be used to find facing thicknesses and stresses for dimpling of sandwich facings on cores of a particular cell size.

## 4.3 SANDWICH HAVING CORRUGATED CORE

This section gives the procedure for determining the spacing between core corrugations such that sandwich facing or core elements will not buckle (refs. 4-2, 4-7, and 4-8). For edge compression load in a direction parallel to the core axis, the design procedure is based on the buckling load of the unsupported facing or core element, whichever is the lower, although it may be possible to utilize a sandwich in which the core elements are buckled. For edge compression load in a direction perpendicular to the core axis, the design procedure is based on the buckling load of the unsupported facing element and the core is assumed to be rigid enough to cause rotational restraint at the ends of the facing element. If the core is double corrugated, it may not have sufficient flatwise strength to cause the facing elements to buckle as assumed.

The facing stress at which buckling of the facing element or core element will occur is given by the formula

$$F_c = k\,\frac{E'}{\lambda}\left(\frac{t}{b}\right)^2 \qquad (4:3)$$

where E' is the effective compressive modulus of elasticity of the facing at stress $F_c$; $\lambda = 1 - \mu^2$, $\mu$ being Poisson's ratio of the facing; t is facing thickness; b is unsupported width of facing element; and k is a coefficient dependent upon the ratio ($t_o/t$) of the corrugation thickness ($t_o$) to the facing thickness (t), tha angle ($\theta$) between the corrugation element and the facing, and the type of material, i.e., isotropic or orthotropic.

Solving formula (4:3) for b results in

$$b = t\sqrt{k}\left(\frac{\lambda F_c}{E'}\right)^{-\frac{1}{2}} \qquad (4:4)$$

Graphical solutions for formula (4:4) are given in charts of figures 4-2 to 4-12. All charts except that of figure 4-12 apply to sandwich in which the load is in a direction parallel to the core axis. The chart of figure 4-12 applies to sandwich with the load in a direction perpendicular to the core axis. Charts of figures 4-2 and 4-3 apply to sandwich with facings and core of the same isotropic material. Charts of figures 4-4 to 4-11 apply to sandwich of orthotropic materials such as glass fabric laminates* for which $\alpha$ = 2/3, 1, or 3/2, and $\beta$ = 0.6 as indicated on the charts. The values of $\alpha$ and $\beta$ depend upon the elastic properties as follows:

$$\alpha = \sqrt{\frac{E'_b}{E'_a}} \; ; \; \beta = \frac{\lambda}{\sqrt{E'_a E'_b}}\left[\frac{E'_b \mu_{ab}}{\lambda} + 2G'_{ab}\right]$$

where $E'_a$ and $E'_b$ are the moduli of elasticity parallel and perpendicular to the direction of loading, $G'_{ba}$ is the shear modulus associated with those directions, $\mu_{ab}$ is the Poisson's ratio of the contraction in the b direction to extension in the a direction due to a tensile stress in the a direction. $\mu_{ba}$ is similarly defined, and $\lambda = 1-\mu_{ab}\mu_{ba}$. Symbols subscripted with o such as $\alpha_o$, $\beta_o$, etc. indicated properties of the core material.

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*Laminates giving the following values of $\alpha$ and $\beta$ were of glass fabrics 112, 116, 120, 128, 143, 162, 164, 181, 183, and 184 (ref. 4-6)

After choosing θ and determining b from the charts, the geometry of the sandwich cross section is now fixed so that the distance, h, between the facing centroids is given by

$$h = (b/2) \tan \theta \text{ (single corrugated core)} \qquad (4{:}5)$$

$$h = b \tan \theta \text{ (double corrugated core)} \qquad (4{:}6)$$

Since the dimension h may be determined previously by sandwich stiffness or strength requirements, it will be necessary to determine b by solving formula (4:5) or (4:6). Graphical solutions for determining b from formula (4:5) or (4:6) are given in the lower portion of the charts of figures 4-2 to 4-12. The final design will be based on the value of b determined by solution of formula (4:5) or (4:6) and b shall be no greater than the solution of formula (4:4). By iteration, it is possible to choose θ so that values of b determined by charts for formula (4:4) are the same as determined by the charts for formula (4:5) or (4:6).

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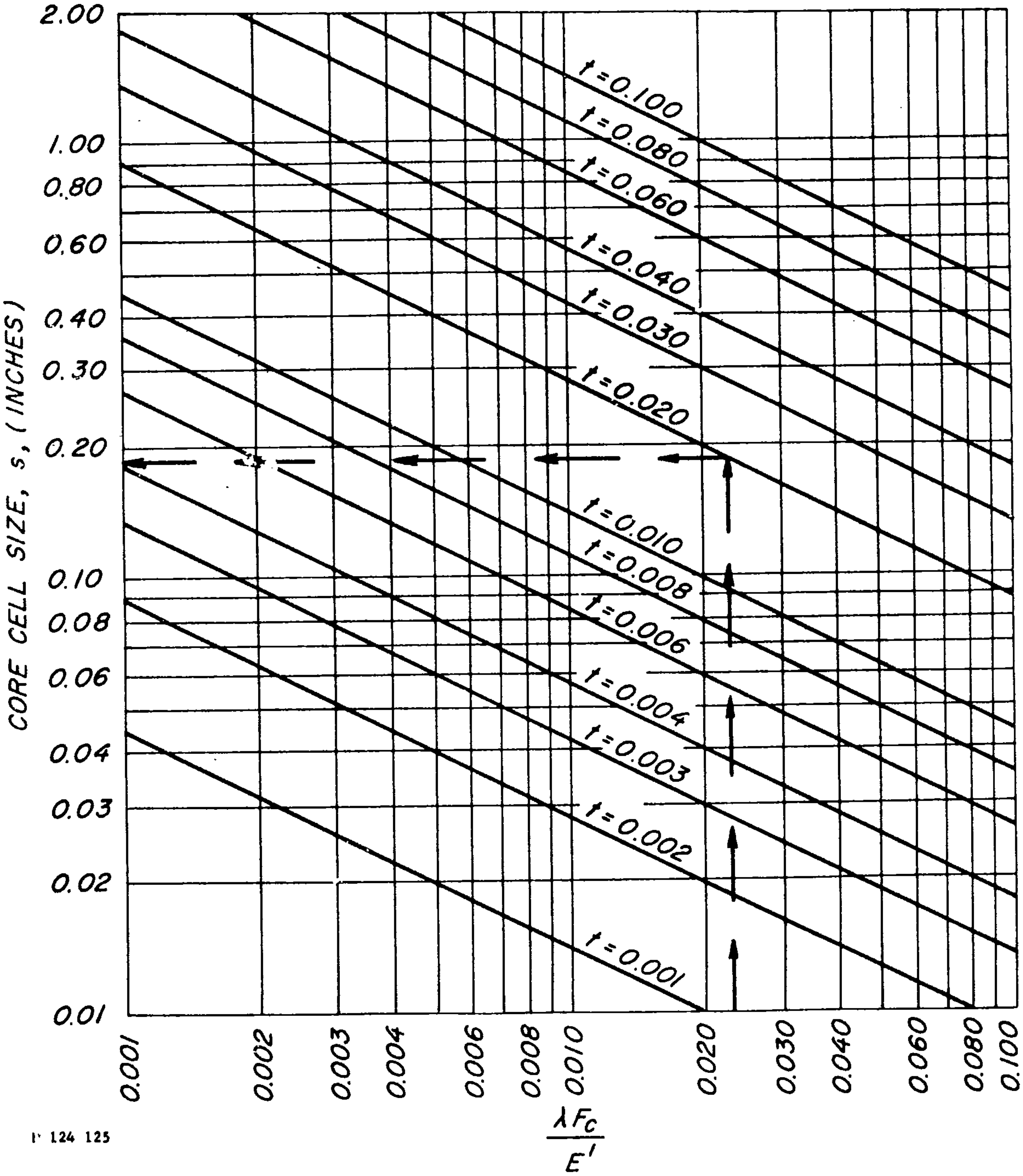


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Figure 4-1.--Chart for determining cellular core cell size such that dimpling (intracell buckling) of isotropic sandwich facing will not occur.

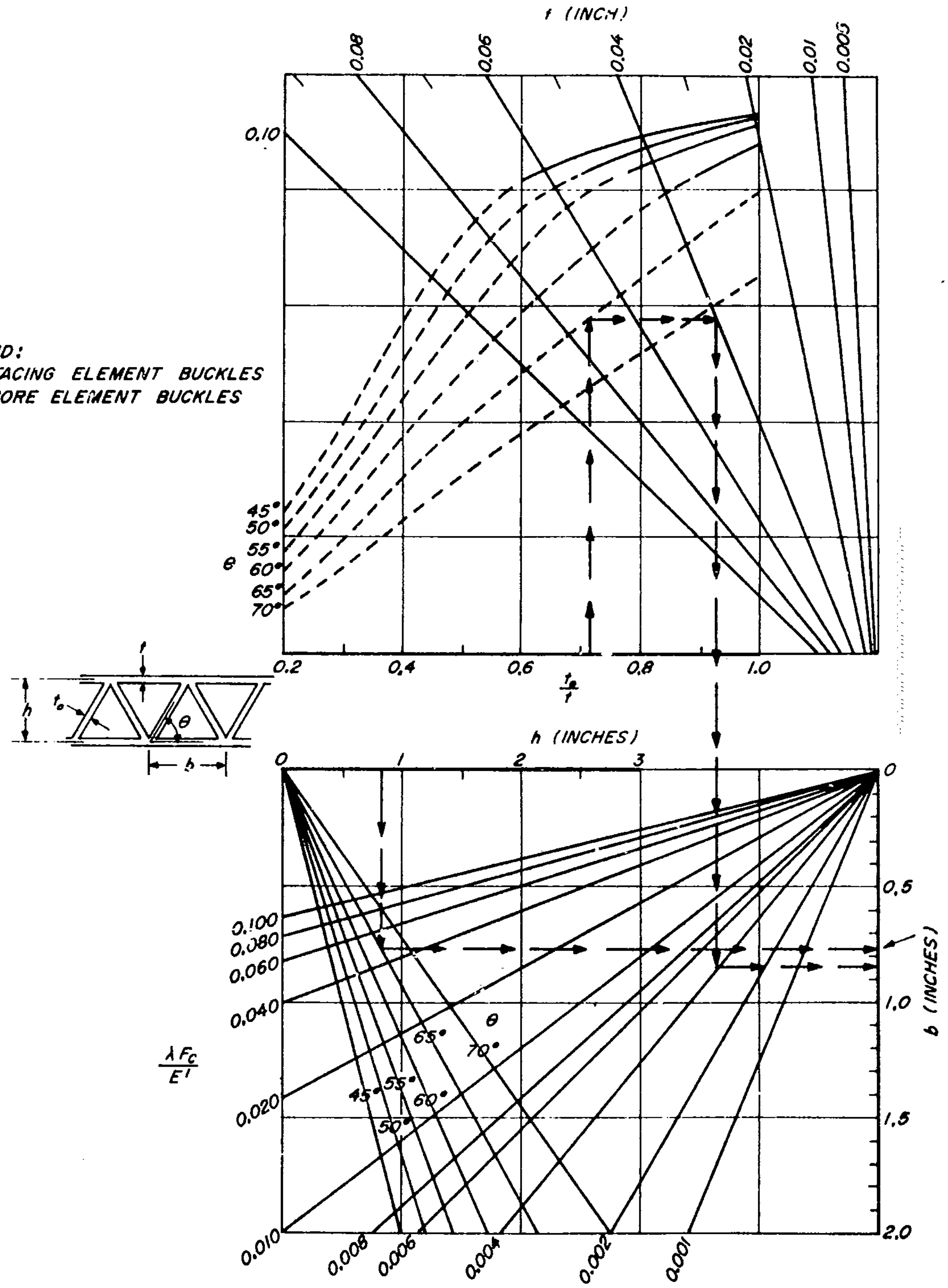


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Figure 4-2.--Chart for determining width, b, of facing element for isotropic corrugated-core sandwich under compression edge load in a direction parallel to core axis (single corrugated core).

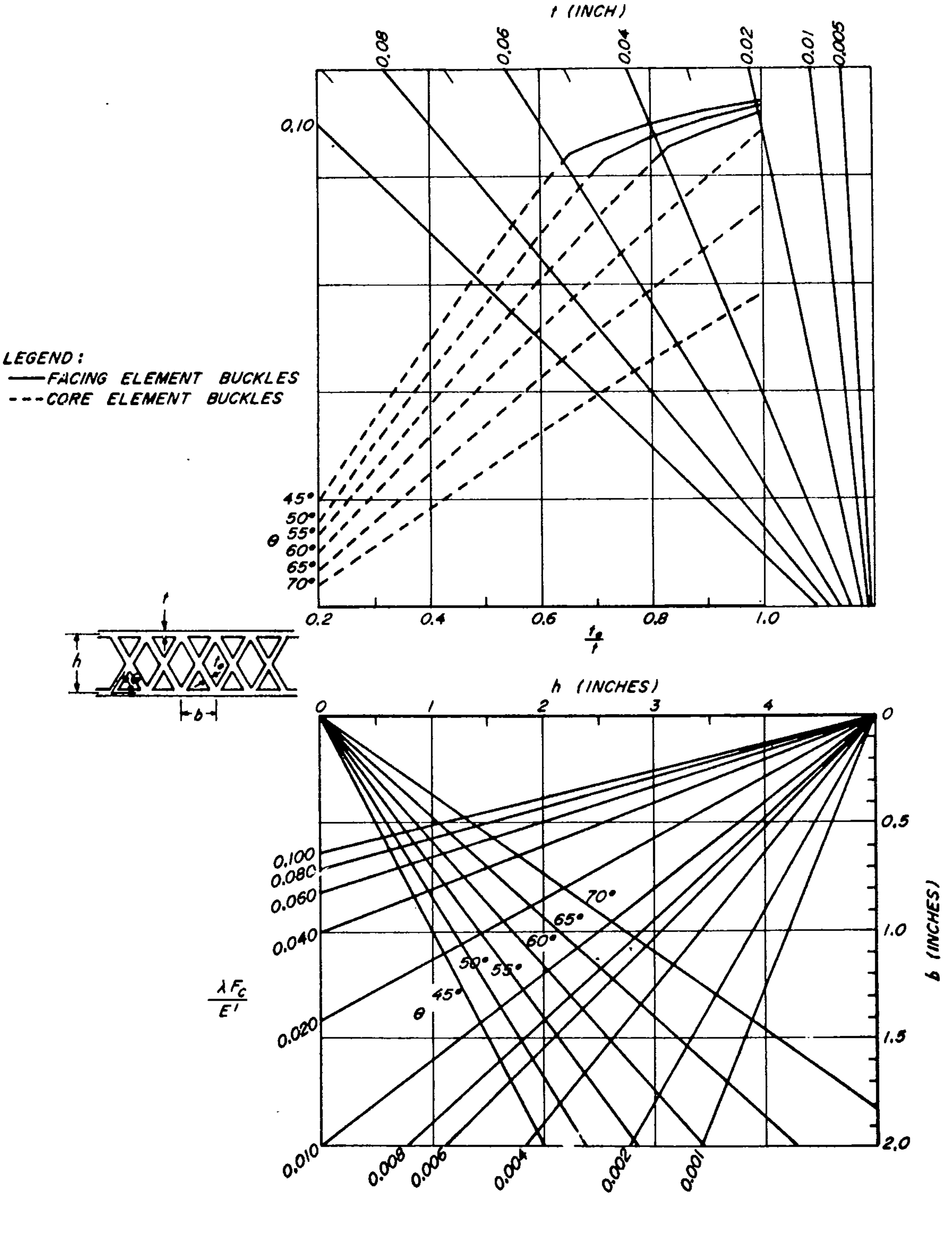


Figure 4-3.--Chart for determining width, b, of facing element for isotropic corrugated-core sandwich under compression edge load in a direction parallel to core axis (double corrugated core).

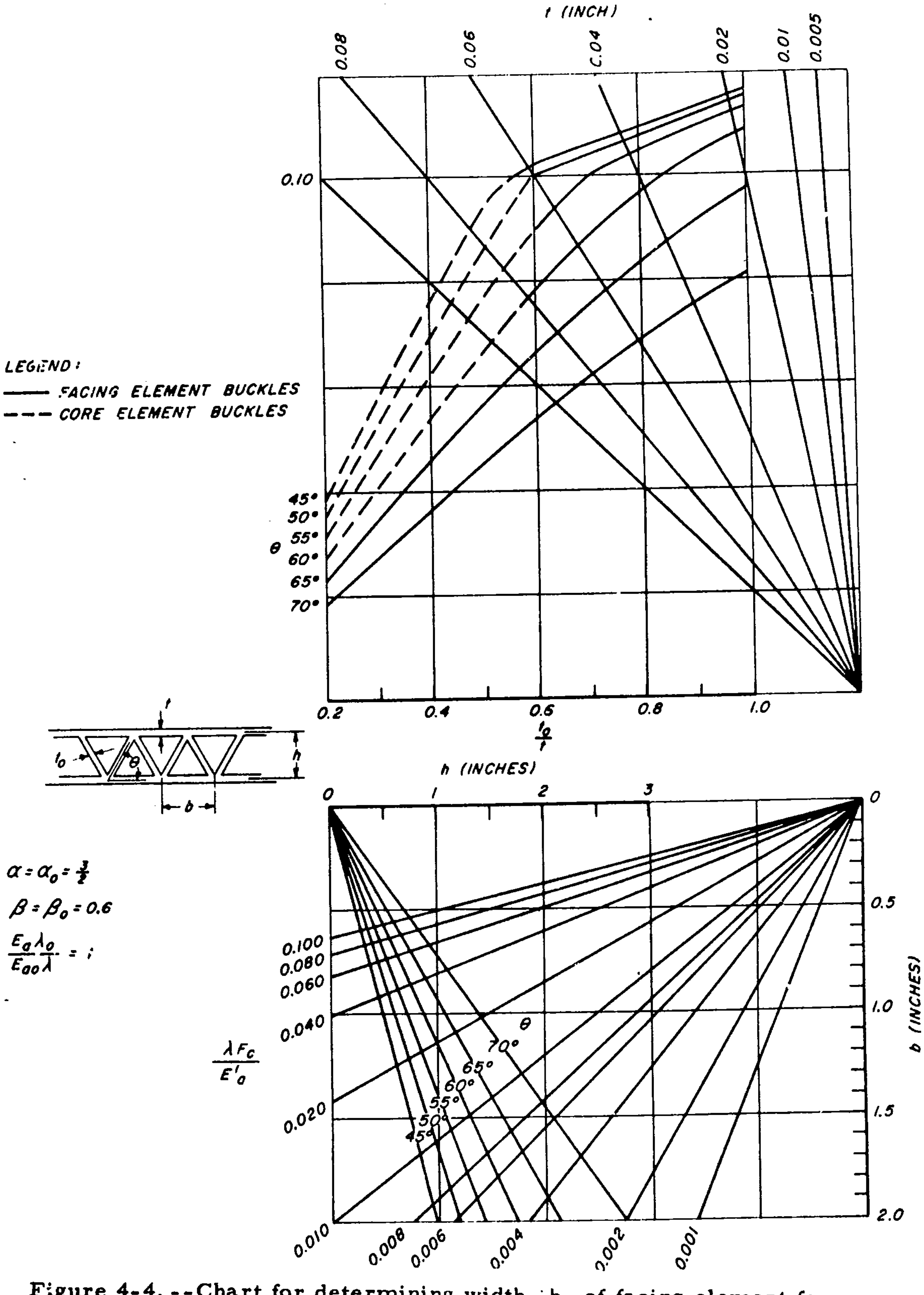


**Figure 4-4.**--Chart for determining width, b, of facing element for orthotropic corrugated-core sandwich under compression edge load in a direction parallel to core axis (single corrugated core). M 141 637

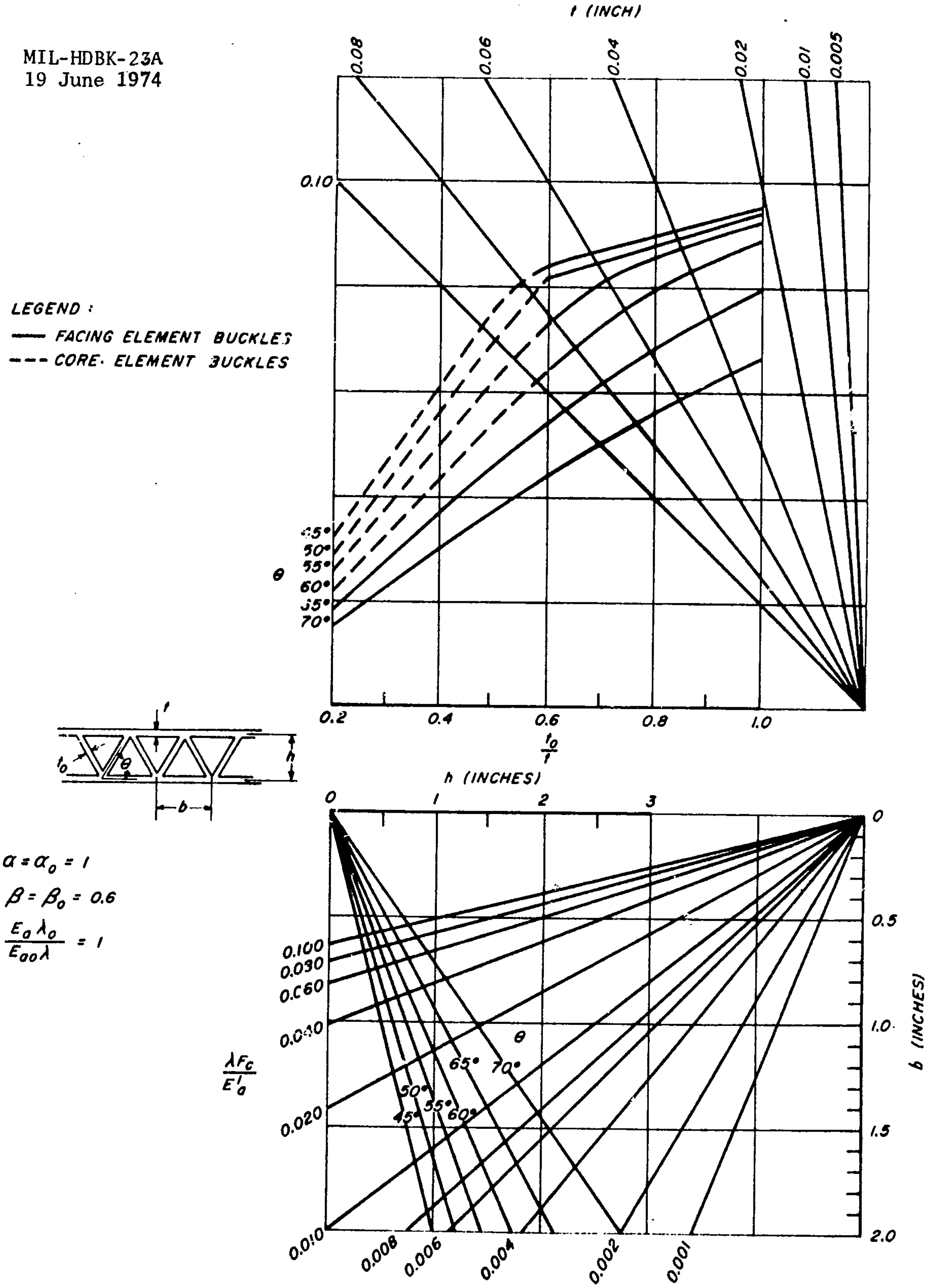


Figure 4-5.--Chart for determining width, b, of facing element for orthotropic corrugated-core sandwich under compression edge load in a direction parallel to core axis (single corrugated core). M 141 638

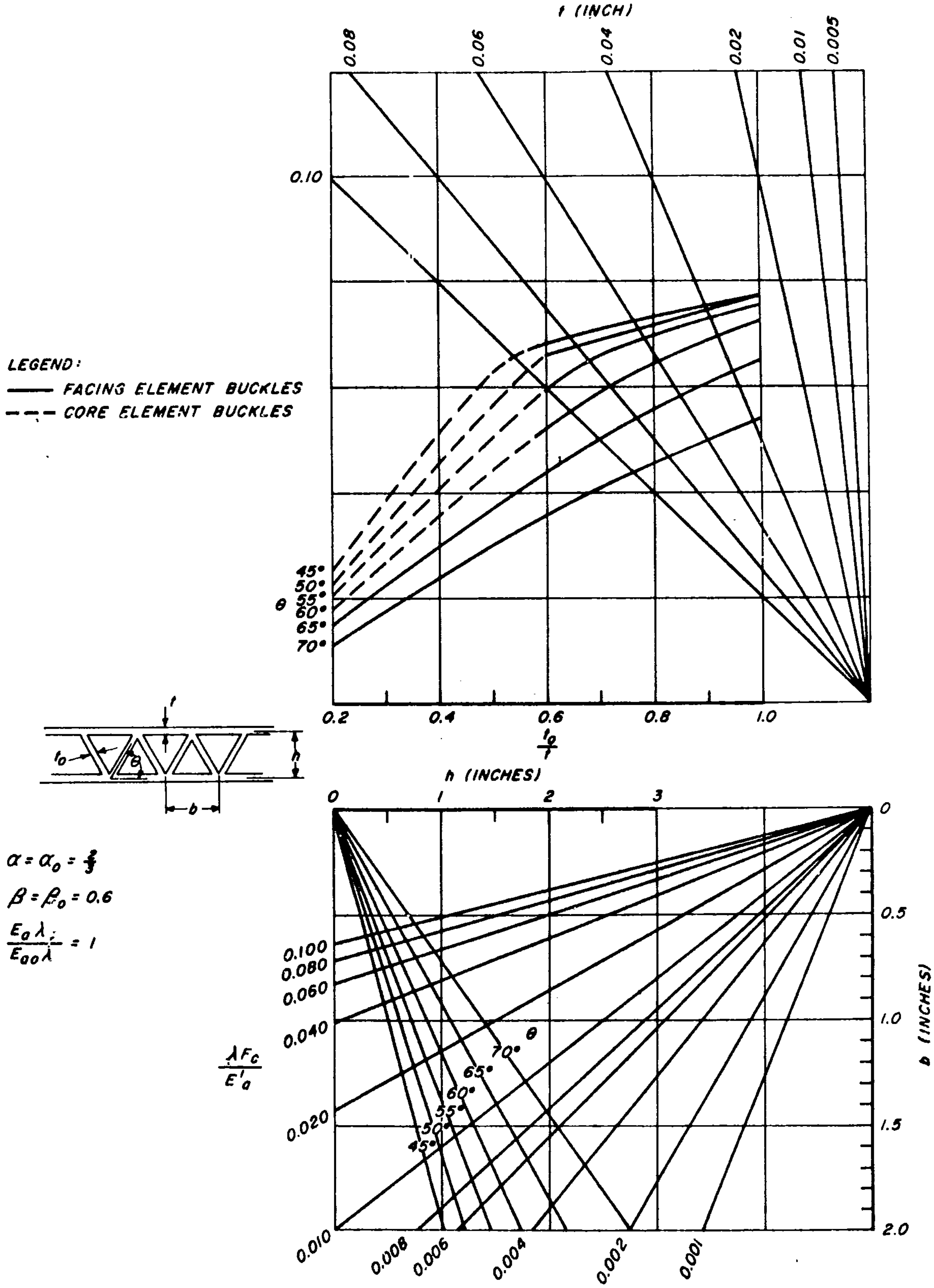


Figure 4-6.--Chart for determining width, b, of facing element for orthotropic corrugated-core sandwich under compression edge load in a direction parallel to core axis (single corrugated core). M 141 639

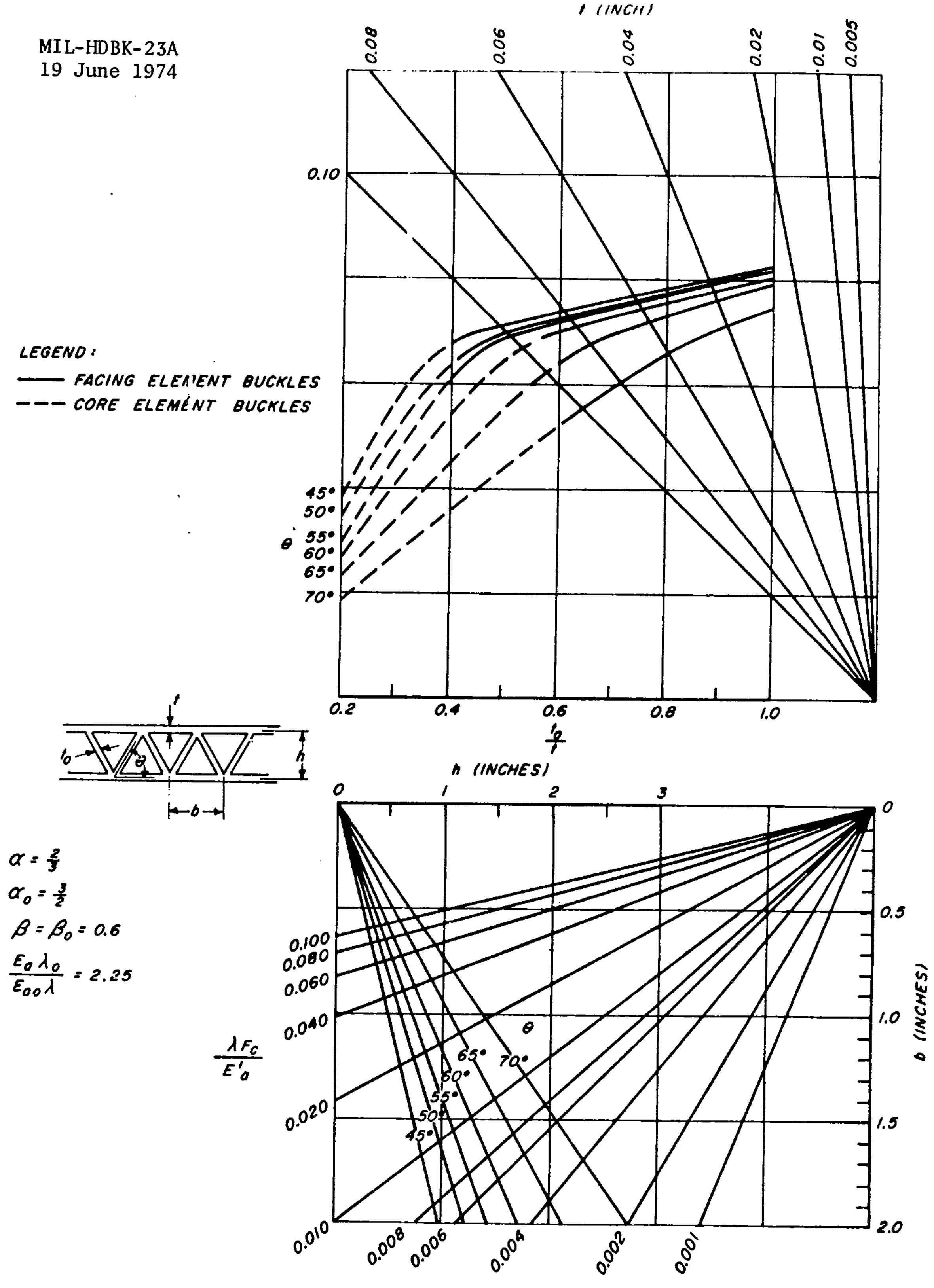


Figure 4-7.--Chart for determining width, b, of facing element for orthotropic corrugated-core sandwich under compression edge load in a direction parallel to core axis (single corrugated axis). M 141 640

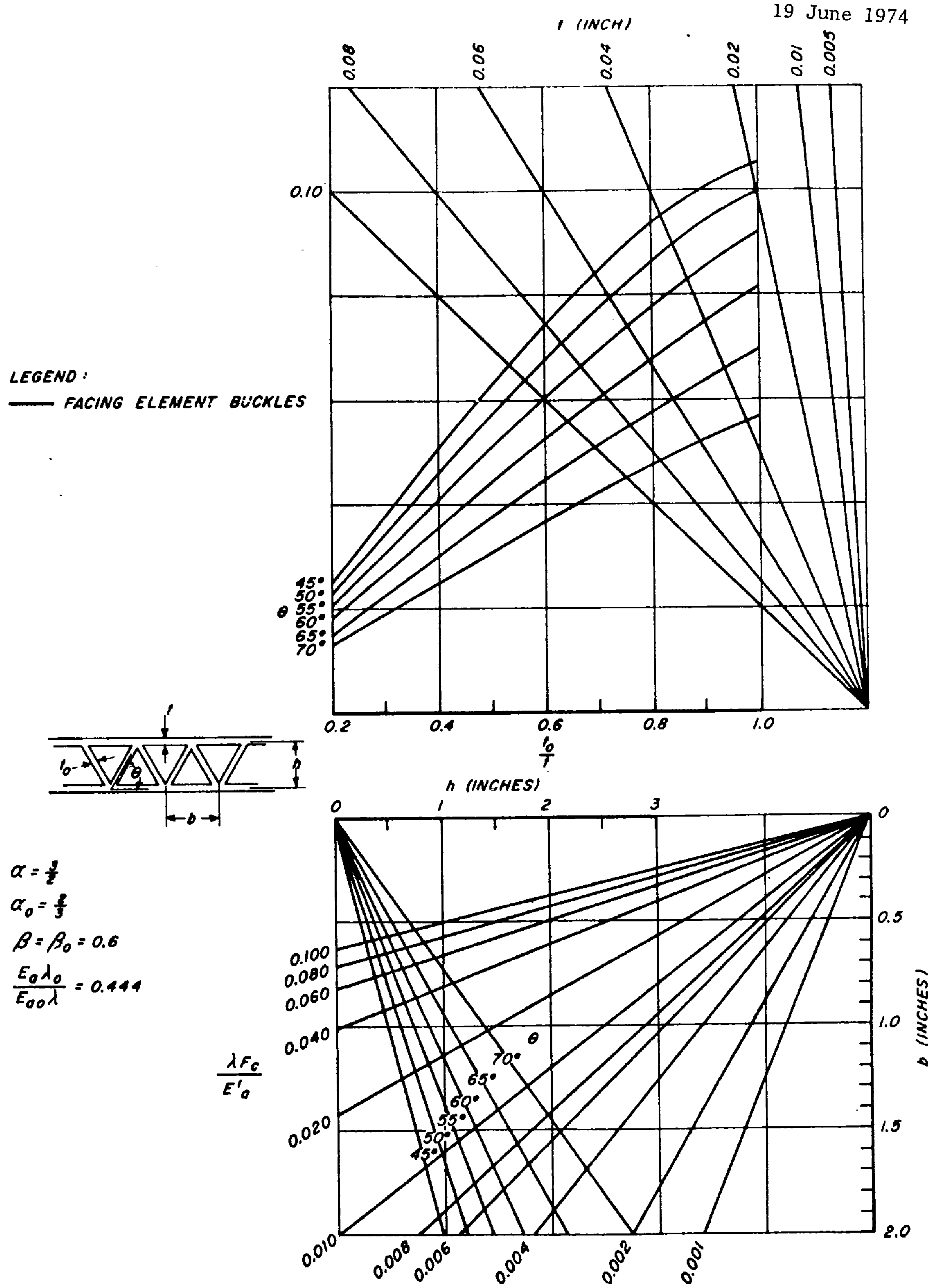


**Figure 4-8.--Chart for determining width, b, of facing element for orthotropic corrugated-core sandwich under compression edge load in a direction parallel to core axis (single corrugated core).** M 141 641

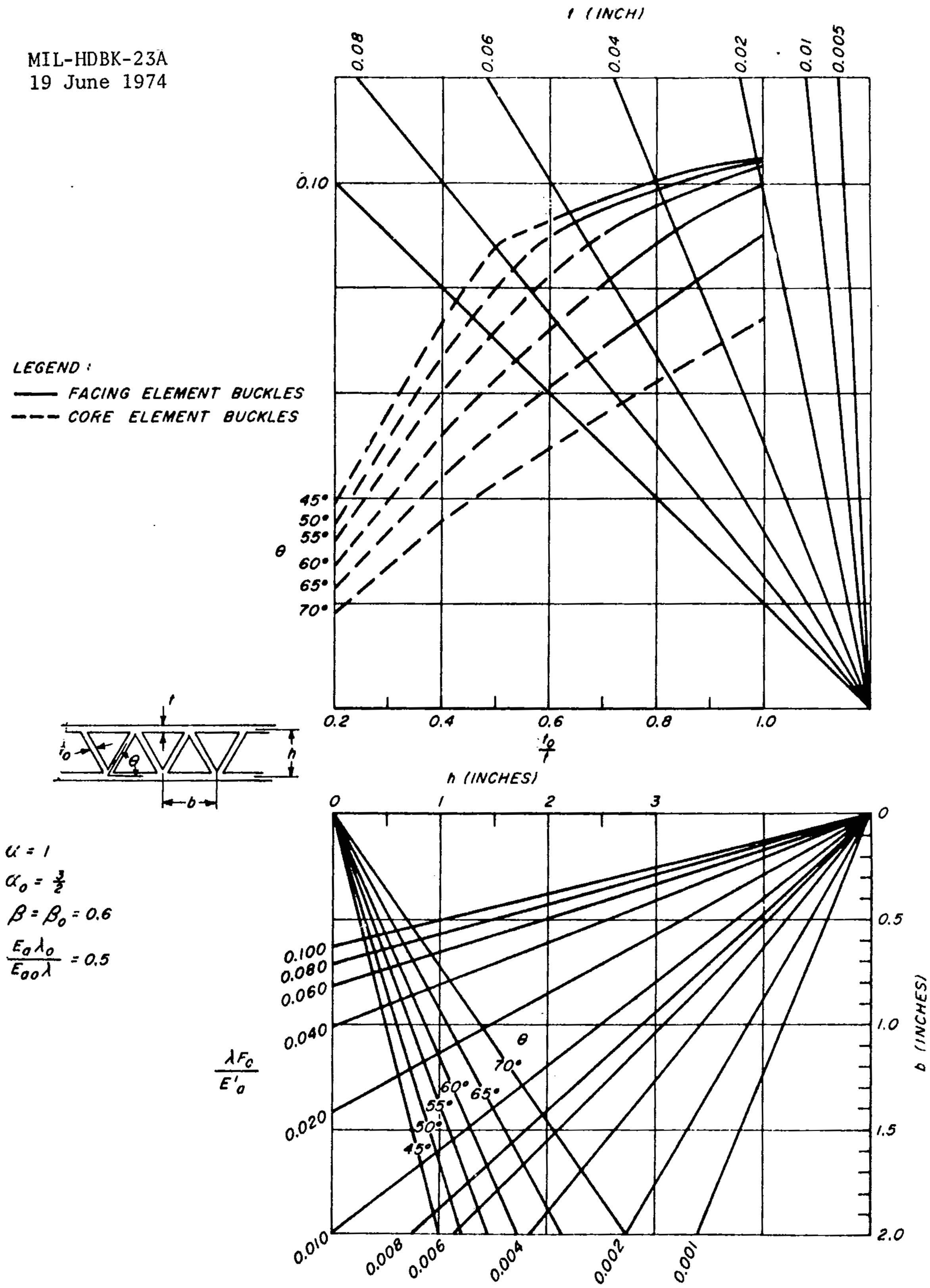


**Figure 4-9.--Chart for determining width, b, of facing element for orthotropic corrugated-core sandwich under compression edge load in a direction parallel to core axis (single corrugated core).** M 141 642

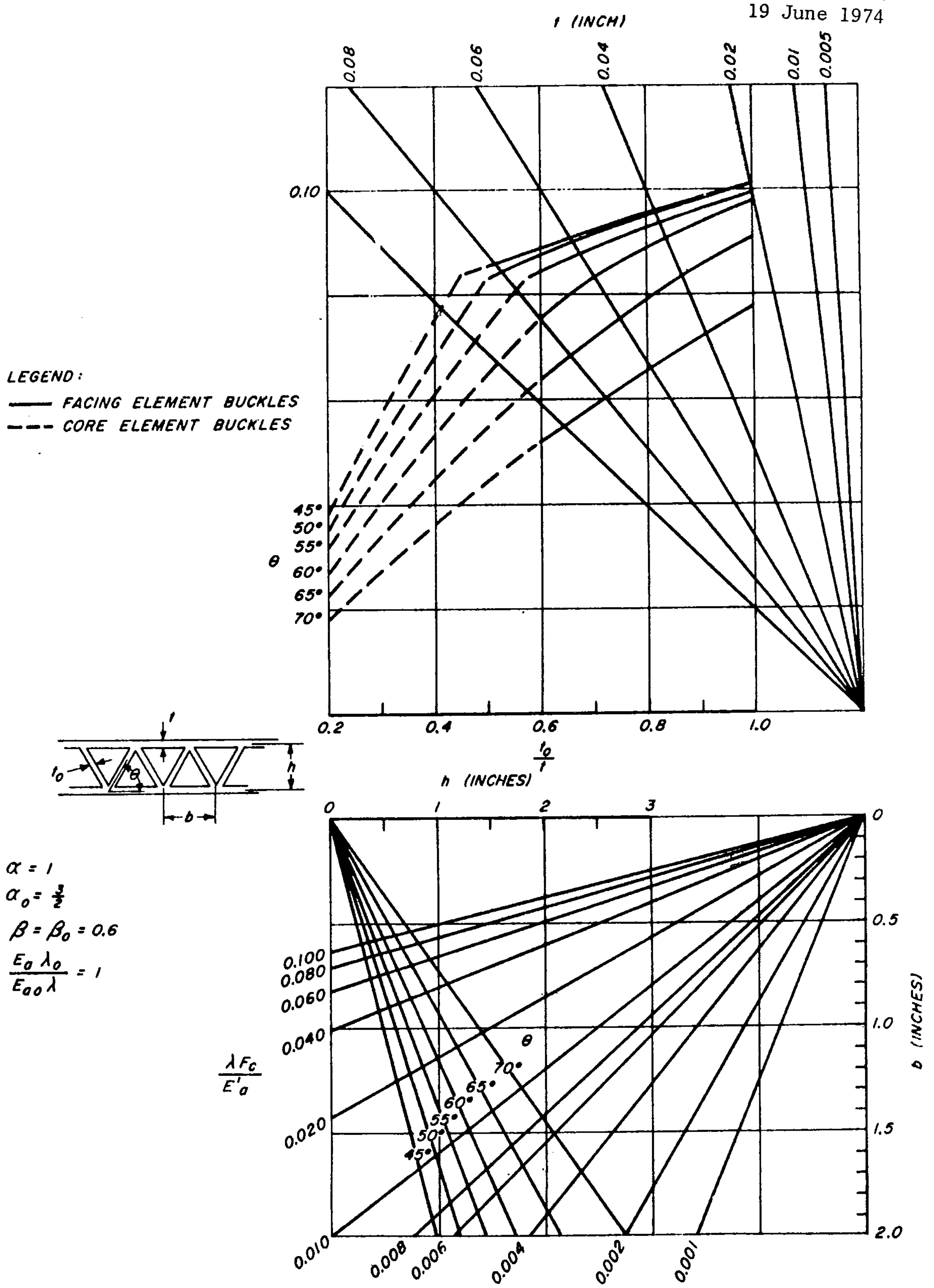


Figure 4-10.--Chart for determining width, b, of facing element for orthotropic corrugated-core sandwich under compression edge load in a direction parallel to core axis (single corrugated core). M 141 643

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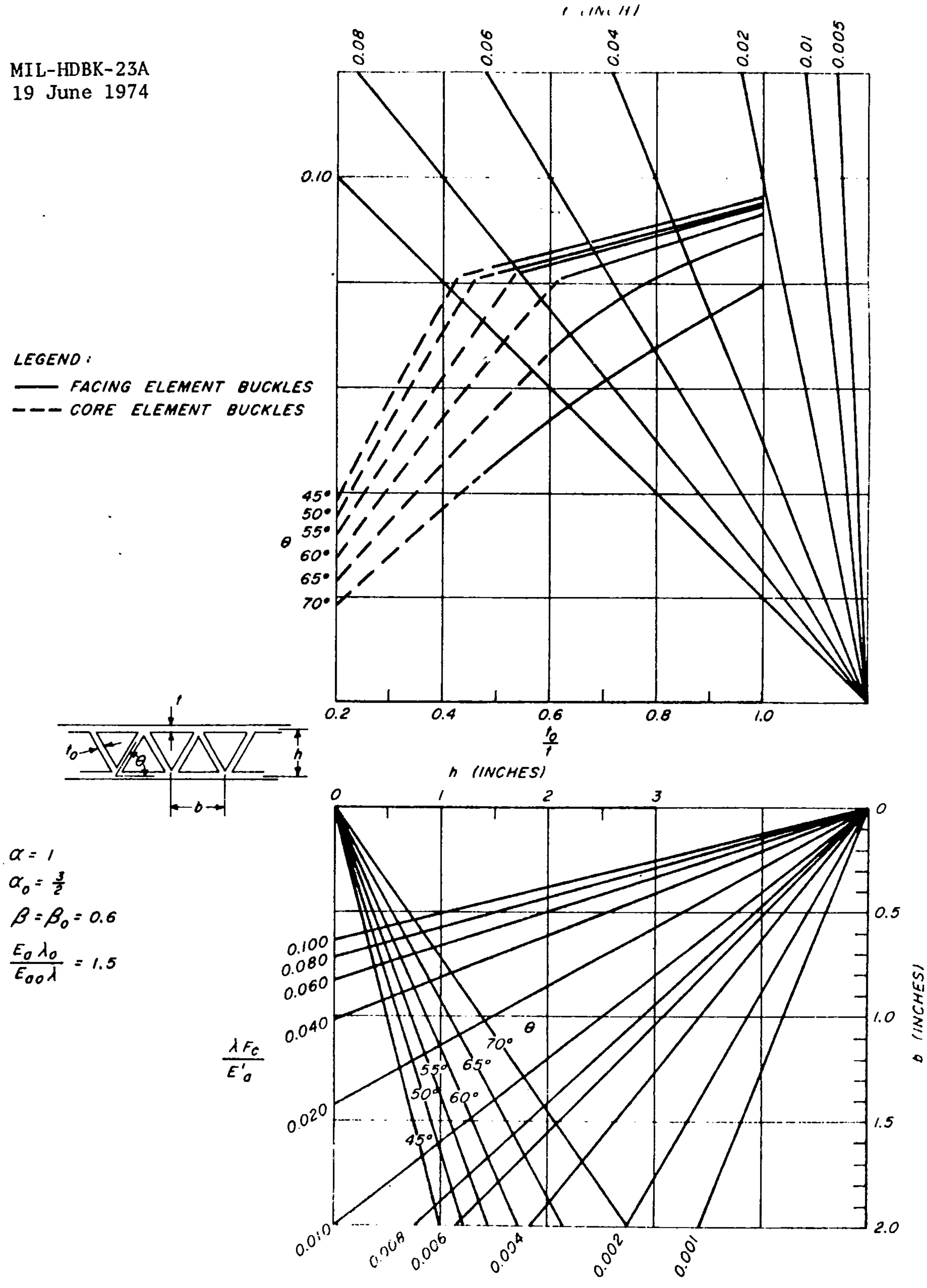


**Figure 4-11.--Chart for determining width, b, of facing element for orthotropic corrugated-core sandwich under compression edge load in a direction parallel to core axis (single corrugated core).** M 141 644

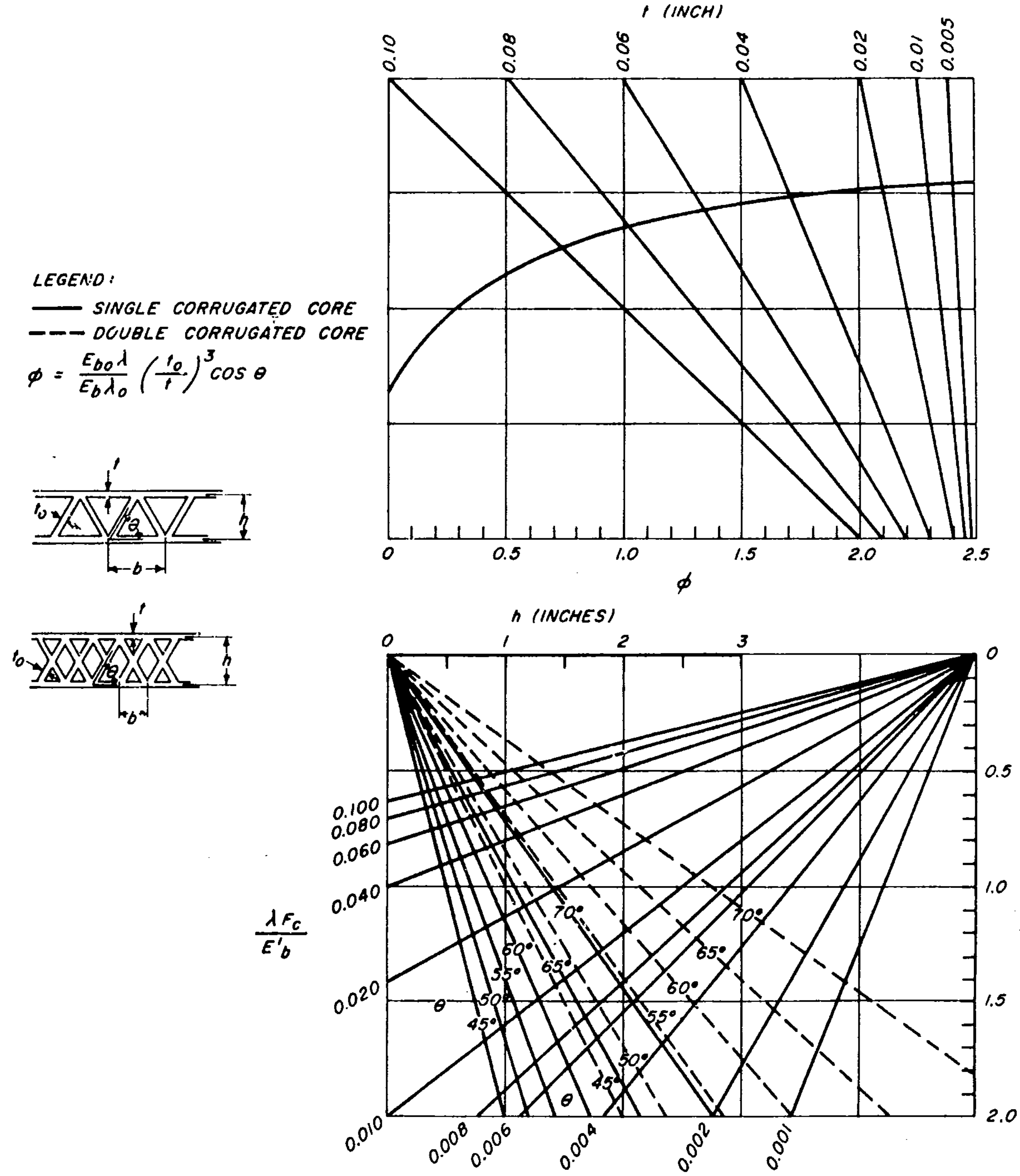


Figure 4-12.--Chart for determining width, b, of facing element for corrugated-core sandwich under compression edge load in a direction perpendicular to core axis. M 141 645

# CHAPTER 5

## DESIGN OF FLAT RECTANGULAR SANDWICH PANELS UNDER EDGEWISE COMPRESSION LOAD

### 5.1 BASIC PRINCIPLES

Assuming that a design begins with chosen design stresses and a given load to transmit, a flat rectangular panel of sandwich construction under edgewise compression load shall be designed to comply with the four basic design principles summarized in 1.2 of Introduction. These four conditions must be met.

Overall buckling of the sandwich or dimpling or wrinkling of the facings cannot occur without possible total collapse of the panel. Detailed procedures giving theoretical formulas and graphs for determining dimensions of the facings and core, as well as necessary core properties, are given in following paragraphs. Double formulas are given, one formula for sandwich with facings of different materials and thicknesses and another formula for sandwich with each facing of the same material and thickness. Facing modulus of elasticity, E', and stress values, $F_c$, shall be compression values at the conditions of use; that is, if application is at elevated temperature, then facing properties at elevated temperature shall be used in design. The facing modulus of elasticity is the effective value at the facing stress. If this stress is beyond the proportional limit value, an appropriate tangent, reduced, or modified compression modulus of elasticity shall be used (ref. ref. 5-5).

### 5.2 DETERMINING FACING THICKNESS

Facing stresses are related to the edge load by the equations:

$$t_1F_{c1} + t_2F_{c2} = N \quad \text{(for unequal facings)} \qquad (5:1)$$

$$t = \frac{N}{2F_c} \quad \text{(for equal facings)} \qquad (5:1a)$$

where t is facing thickness; $F_c$ is chosen design facing compressive stress; N is design compression load per unit length of panel edge; and 1, 2 are subscripts denoting facings 1 and 2.

In determining thicknesses of facings for sandwich with facings of different materials, equation (5:1) must be satisfied, but also the stresses $F_{c1}$ and $F_{c2}$ must be chosen so that $F_{c1}/E_{s1} = F_{c2}/E_{s2}$ (where $E_s$ is facing secant modulus of elasticity), thus avoiding overstressing of either facing. For example, if facing 1 is of a material such that the ratio $F_{c1}/E_{s1} = 0.005$ and facing 2 is of a material such that the ratio $F_{c2}/E_{s2} = 0.002$, the design must be based on a ratio of 0.002, otherwise facing 2 will be overstressed. In order to accomplish this, the chosen design stress for facing 1 must be lowered. For many combinations of facing materials it will be found advantageous to choose thicknesses such that $E_1t_1 = E_2t_2$. If the core can support edge load, N should be replaced by the quantity $(N - F_ct_c)$.

## 5.3 DETERMINING CORE THICKNESS AND CORE SHEAR MODULUS

This section gives procedures for determining core thickness and core shear modulus so that overall buckling of the sandwich panel will not occur (refs. 5-1, 5-2, and 5-3). The load per unit panel width at which buckling of a sandwich panel will occur is given by the theoretical formula:

$$N_{cr} = K \frac{\pi^2}{b^2} D$$

where D is sandwich bending stiffness. This formula, solved for the facing stress, becomes:

$$F_{c1,2} = \pi^2 K \frac{E_1' t_1 E_2' t_2}{\left(E_1' t_1 + E_2' t_2\right)^2} \left(\frac{h}{b}\right)^2 \frac{E_{1,2}'}{\lambda} \qquad (5:2)$$

$$F_c = \frac{\pi^2 K}{4} \left(\frac{h}{b}\right)^2 \frac{E'}{\lambda} \text{ (for equal facings)} \qquad (5:2a)$$

where E' is effective compressive modulus of elasticity of facing at stress $F_c$ (for orthotropic facings $E' = \sqrt{E'_a E'_b}$); $\lambda = 1 - \mu^2$; $\mu$ is Poisson's ratio of facings (in formula (5:2) it is assumed that $\mu = \mu_1 = \mu_2$); h is distance between facing centroids; b is length of loaded panel edge; $K = K_F + K_M$; $K_F$ is a theoretical coefficient dependent on facing stiffness and panel aspect ratio; and $K_M$ is a theoretical coefficient dependent on sandwich bending and shear rigidities and panel aspect ratio.

Solving equations (5:2) and (5:2a) for h/b gives:

$$\frac{h}{b} = \frac{1}{\pi\sqrt{K}} \sqrt{\frac{\lambda F_{c1,2}}{E'_{1,2}}} \left( \frac{E'_1 t_1 + E'_2 t_2}{\sqrt{E'_1 t_1 E'_2 t_2}} \right) \quad (5:3)$$

$$\frac{h}{b} = \frac{2}{\pi\sqrt{K}} \sqrt{\frac{\lambda F_c}{E'}} \quad \text{(for equal facings)} \quad (5:3a)$$

Therefore, if K is known, equation (5:3) or (5:3a) can be solved directly to eventually obtain h because all other quantities are known. After h is obtained, the core thickness, $t_c$, is computed from the formulas

$$t_c = h - \frac{t_1 + t_2}{2} \quad (5:4)$$

$$t_c = h - t \quad \text{(for equal facings)} \quad (5:4a)$$

As a first approximation, it will be assumed that $K_F = 0$, hence $K = K_M$. Values of $K_M$ depend upon the bending and shear rigidities of the sandwich as incorporated in the parameter

$$V = \frac{\pi^2 D}{b^2 U}$$

which can be written as:

$$V = \frac{\pi^2 t_c E'_1 t_1 E'_2 t_2}{\lambda b^2 G_c \left( E'_1 t_1 + E'_2 t_2 \right)} \qquad (5:5)$$

$$V = \frac{\pi^2 t_c E' t}{2\lambda b^2 G_c} \quad \text{(for equal facings)} \qquad (5:5a)$$

where U is sandwich shear stiffness; $G_c$ is the core shear modulus associated with the axes parallel to direction of loading (also parallel to panel side of length a) and perpendicular to the plane of the panel. As values of core shear modulus decrease, values of V increase and values of $K_M$ gradually decrease. For sandwich with corrugated core having corrugation flutes parallel to direction of loading the parameter V is replaced by the parameter

$$W = \frac{\pi^2 t_c E'_1 t_1 E'_2 t_2}{\lambda b^2 G_{cb} \left( E'_1 t_1 + E'_2 t_2 \right)} \qquad (5:6)$$

$$W = \frac{\pi^2 t_c E' t}{2\lambda b^2 G_{cb}} \quad \text{(for equal facings)} \qquad (5:6a)$$

where $G_{cb}$ is the core shear modulus associated with the axes perpendicular to direction of loading (parallel to panel side of length b) and perpendicular to the plane of the panel.

### 5.3.1 Determination of Minimum Values of h

A minimum value of h required will be determined by assuming V = 0 or W = 0 for a first approximation. The value of h is minimum because V = 0 or W = 0 only if the core shear modulus is infinite; for any actual core the shear modulus is not infinite, hence a thicker core must be used. The chart of figure 5-1 gives minimum values of h for sandwich panels with isotropic or orthotropic facings and core and for various edge conditions. Panels with clamped edges are included in the chart of figure 5-1, although truly clamped edges are not actually attainable.

The charts of figures 5-1 to 5-22 are applicable to sandwich with isotropic facings for which $\alpha = 1.0$; $\beta = 1.0$; $\gamma = 0.375$ and to sandwich with orthotropic facings such as glass fabric laminates* for which $\alpha = 1.0$; $\beta = 0.6$; $\gamma = 0.2$.

The constants $\alpha$, $\beta$, and $\gamma$ depend upon elastic properties of the facings as follows:

$$\alpha = \sqrt{\frac{E'_b}{E'_a}}; \quad \beta = \alpha\mu_{ab} + 2\gamma; \quad \gamma = \frac{\lambda G'_{ba}}{\sqrt{E'_a E'_b}}.$$

where $E'_a$ and $E'_b$ are the moduli of elasticity parallel and perpendicular to the direction of loading, $G'_{ba}$ is the facing shear modulus associated with those directions, $\mu_{ab}$ is the Poisson's ratio of the contraction in the b direction to extension in the a direction due to a tensile stress in the a direction. $\mu_{ba}$ is similarly defined, and $\lambda = 1 - \mu_{ab}\mu_{ba}$. For isotropic facings it was assumed that $\mu = 0.25$. For orthotropic facings it was assumed that $\mu_{ab} = \mu_{ba} = 0.2$, $E'_a = E'_b$, and $G'_{ba} = 0.21E_a$.

Parameters needed for use of the chart of figure 5-1 are:

1. Panel aspect ratio a/b or b/a
2. Facing properties $\dfrac{\lambda F_{c1,2}}{E'_{1,2}}$
3. Ratio of $E'_2t_2/E'_1t_1$.

The charts of figures 5-1 to 5-22 are also applicable to sandwich with dissimilar facings wherein facing 1 is isotropic ($\alpha_1 = 1.0$, $\beta_1 = 1.0$, and $\gamma_1 = 0.375$) and facing 2 is orthotropic ($\alpha_2 = 1.0$, $\beta_2 = 0.6$, and $\gamma_2 = 0.2$). For such a sandwich, linear interpolation is made between curves for sandwich with both facings isotropic and curves for sandwich with both facings orthotropic by means of the parameter

$$T = \frac{1}{1 + E'_2t_2/E'_1t_1}$$

*Laminates giving the following values of $\alpha$, $\beta$, and $\gamma$ were of glass fabrics 112, 116, 120, 128, 162, 164, 181, 182, 183, and 184 (ref. 5-2).

Values of T = 0 correspond to sandwich with both facings isotropic and T = 1 to sandwich with both facings orthotropic. This is demonstrated by substitution of these T values in the general expression for $K_M$ ( ref. 5-3). Thus for example: if T = 1/4, interpolation is at 1/4 of the distance from the curve for both facings isotropic toward the curve for both facings orthotropic.

5.3.2 Determination of Actual Values of h

Since actual core shear modulus values are not very large, a value of h somewhat greater than given on figure 5-1 must be used. Charts for determining h for sandwich with all edges simply supported are shown in figures 5-2, 5-3, 5-4, 5-5, and 5-6. These figures are entered with values of the panel aspect ratio and values of V as computed by equation (5:5) or (5:5a). Figure 5-2 applies to sandwich with isotropic cores for which the core shear modulus perpendicular to the direction of loading is equal to the core shear modulus parallel to the direction of loading. Figure 5-3 applies to sandwich with honeycomb cores for which the core shear modulus perpendicular to the direction of loading is equal to 0.40 times the core shear modulus parallel to the direction of loading. Figure 5-4 applies to sandwich with honeycomb cores for which the core shear modulus perpendicular to the direction of loading is 2.50 times the core shear modulus parallel to the direction of loading.

> NOTE: For honeycomb cores with core ribbons parallel to direction of loading, $G_c = G_{TL}$ and the shear modulus perpendicular to loading is $G_{TW}$. For honeycomb cores with core ribbons perpendicular to direction of loading $G_c = G_{TW}$ and the shear modulus perpendicular to loading is $G_{TL}$.

Figure 5-5 applies to sandwich with corrugated core having the core flutes perpendicular to the direction of loading. Figure 5-6 applies to sandwich with corrugated core having the core flutes parallel to the direction of loading and requires values of the parameter W given by equation (5:6) or (5:6a) instead of values of V.

In using figures 5-2, 5-3, 5-4, 5-5, and 5-6, it is necessary to iterate because V is directly proportional to the core thickness $t_c$. As an aid to finally determining $t_c$ and $G_c$, figure 5-7 presents a number of lines representing V for various values of $G_c$ with V ranging from 0.01 to 2 and $G_c$ ranging from 1,000 to 1,000,000 pounds per square inch. The following procedure is suggested:

1. Determine a core thickness $t_c$ from figure 5-2, 5-3, 5-4, 5-5, or 5-6 using a value of 0.01 for V or W.

2. Compute the constant relating V or W to $G_c$.

$$\left[\frac{\pi^2 t_c E'_1 t_1 E'_2 t_2}{\lambda b^2 \left(E'_1 t_1 + E'_2 t_2\right)}\right] \text{ or } \left[\frac{\pi^2 t_c E' t}{2\lambda b^2}\right] \text{(for equal facings)}$$

$$= VG_c \text{ or } WG_c$$

3. With this constant enter figure 5-7 and determine necessary $G_c$.

4. If the shear modulus is outside the range of values for materials available, slide up the appropriate line of figure 5-7 and pick a new value of V or W, for a reasonable value of core shear modulus.

5. Reenter figure 5-2, 5-3, 5-4, 5-5, or 5-6 with the new value of V or W and repeat previous steps 1, 2, and 3.

Charts of the type used in figures 5-2, 5-3, 5-4, 5-5, and 5-6 have not been prepared for panels with ends or sides clamped. True clamping at panel edges is never attained, particularly for sandwich constructions. It is suggested that each panel be designed as simply supported on all edges and then enter figure 5-1 to estimate any possible reduction that can be made in core thickness due to edge clamping.

### 5.3.3 Checking Procedure for Determining Buckling Stress, $F_{cr}$

The design shall be checked by using the graphs of figures 5-8 to 5-21 to determine values of $K_M$ for use in evaluating $K = K_F + K_M$ to substitute into formula (5:2) or (5:2a) to compute actual buckling stress, $F_{cr}$.

The figures apply to sandwich panels with edges simply supported and clamped and to sandwich with isotropic or certain orthotropic facings and cores (see 5.3.1).

For each value of the parameter V, there is a cusped curve giving values of $K_M$ for various values of the ratios a/b or b/a. These cusps are indicated by dotted lines for the top curve in each figure. The cusps show the sandwich panel buckling coefficients calculated for different values of n, the number of half waves into which the panel buckles. Only the portions of each cusped curve for which $K_M$ is a minimum are shown. Envelope curves indicate values of $K_M$ for use in design.

Values of $K_F$ shall be determined by the formula

$$K_F = \frac{\left(E_1' t_1^3 + E_2' t_2^3\right)\left(E_1' t_1 + E_2' t_2\right)}{12 E_1' t_1 E_2' t_2 h^2} K_{MO} \qquad (5:7)$$

$$K_F = \frac{t^2}{3h^2} K_{MO} \quad \text{(for equal facings)} \qquad (5:7a)$$

where $K_{MO}$ is determined from the chart of figure 5-22. ($K_{MO} = K_M$ when $V = 0$.) For panels with a/b ratios larger than shown on figure 5-22, it can be assumed that $K_F = 0$. Then K shall be computed as $K_F + K_M = K_M$ and equation (5:2) and (5:2a) solved for $F_{cr}$. It should be understood that if the desired $F_{cr}$ is above proportional limit values, the value of E' shall be an effective value, used in computing V and $F_{cr}$.

If the charts do not apply because ratios of core shear moduli are far different from what is given on the charts, or it is desired to check by a more accurate analysis, the formulas given in the following shall be used (refs. 5-1, 5-2, 5-3):

$$K_M = \frac{\psi_1 K_2 + \left(1 + \frac{R}{c_4}\right) B_2 V}{\psi_2 + \psi_3 Q_2 V + \frac{R}{c_4} B_2 V^2} \qquad (5:8)$$

$$K_i = \alpha_i c_1 + 2\beta_i c_2 + \frac{c_3}{\alpha_i} \qquad (5:9)$$

where

$$\psi_1 = T + (1 - T)\frac{K_1}{K_2} \cdot \frac{B_2}{B_1} \tag{5:10}$$

$$\psi_2 = T^2 + 2T(1 - T)\frac{B_{12}}{B_1} + (1 - T)^2 \frac{B_2}{B_1} \tag{5:11}$$

$$\psi_3 = T + (1 - T)\frac{Q_1}{Q_2} \cdot \frac{B_2}{B_1} \tag{5:12}$$

$$B_i = c_1 c_3 - \beta_i^2 c_2^2 + \gamma_i c_2 K_i \tag{5:13}$$

$$B_{12} = \left(\frac{\alpha_1^2 + \alpha_2^2}{2\alpha_1\alpha_2}\right) c_1 c_3 - \beta_1\beta_2 c_2^2 + \frac{c_2}{2}\left(\gamma_1 K_2 + \gamma_2 K_1\right) \tag{5:14}$$

$$Q_i = \alpha_i c_1 \frac{R}{c_4} + \left(1 + \frac{R}{c_4}\right)\gamma_i c_2 + \frac{c_3}{\alpha_i} \tag{5:15}$$

The parameters of these formulas are given by the following expressions:

$$T = \frac{A_1}{A_1 + A_2} \tag{5:16}$$

$$V = \frac{A_1 A_2}{A_1 + A_2} \frac{\pi^2 t_c}{b^2 G_{ca}} \tag{5:17}$$

$$R = \frac{G_{ca}}{G_{cb}} \tag{5:18}$$

$$A_i = \frac{t_i}{\lambda_1} \sqrt{E'_{ai} E'_{bi}} \tag{5:19}$$

where $G_{cb}$ and $G_{ca}$ are the moduli of transverse rigidity of the core associated with the directions of the loaded and unloaded edges of the panel.

The values of $c_1$, $c_2$, $c_3$, and $c_4$ depend upon the panel aspect ratio, b/a, the integral number of longitudinal half waves, n, into which the panel buckles, and the panel edge conditions. Values of n are chosen to produce minimum values of N.

For a panel with all edges simply supported:

$$c_1 = c_4 = \frac{a^2}{n^2 b^2}, \quad c_2 = 1, \quad \text{and } c_3 = \frac{n^2 b^2}{a^2}$$

For a panel with loaded edges simply supported and other edges clamped:

$$c_1 = \frac{16a^2}{3n^2 b^2}, \quad c_2 = \frac{4}{3}, \quad c_3 = \frac{n^2 b^2}{a^2}, \quad \text{and } c_4 = \frac{4a^2}{3n^2 b^2}$$

For a panel with loaded edges clamped and other edges simply supported:

$$\text{For } n = 1 \quad c_1 = c_4 \frac{3a^2}{4b^2}, \quad c_2 = 1, \quad c_3 = 4\frac{b^2}{a^2}$$

$$\text{For } n \geq 2 \quad c_1 = c_4 = \frac{a^2}{\left(n^2 + 1\right) b^2}, \quad c_2 = 1, \quad c_3 = \frac{n^4 + 6n^2 + 1}{n^2 + 1} \cdot \frac{b^2}{a^2}$$

For a panel with all edges clamped:

$$\text{For } n = 1 \quad c_1 = 4c_4 = 4\frac{a^2}{b^2}, \quad c_2 = \frac{4}{3}, \quad c_3 = 4\frac{b^2}{a^2}$$

$$\text{For } n \geq 2 \quad c_1 = 4c_4 = \frac{16a^2}{3\left(n^2 + 1\right) b^2}, \quad c_2 = \frac{4}{3}, \quad c_3 = \frac{n^4 + 6n^2 + 1}{n^2 + 1} \cdot \frac{b^2}{a^2}$$

Adaptations of these formulas to sandwich with corrugated core are made by considering core shear modulus infinite in the direction of the corrugation flutes (details in ref. 5-2). If the corrugation flutes are parallel to the direction of loading, they can carry load in proportion to their area and elastic modulus.

For panels with edges a not simply supported but supported by beams with low torsional rigidity but finite bending stiffness, the buckling coefficient may be much lower than for panels with simply supported edges (ref. 5-6). The buckling coefficient for such a panel is dependent upon the parameters $\zeta$ and $\phi$ in addition to the usual parameters where $\zeta$ and $\phi$ depend upon bending stiffness and cross sectional area of the beam supports. Charts showing effects of beam support stiffness and area on buckling coefficients are given in figures 5-23 and 5-24.

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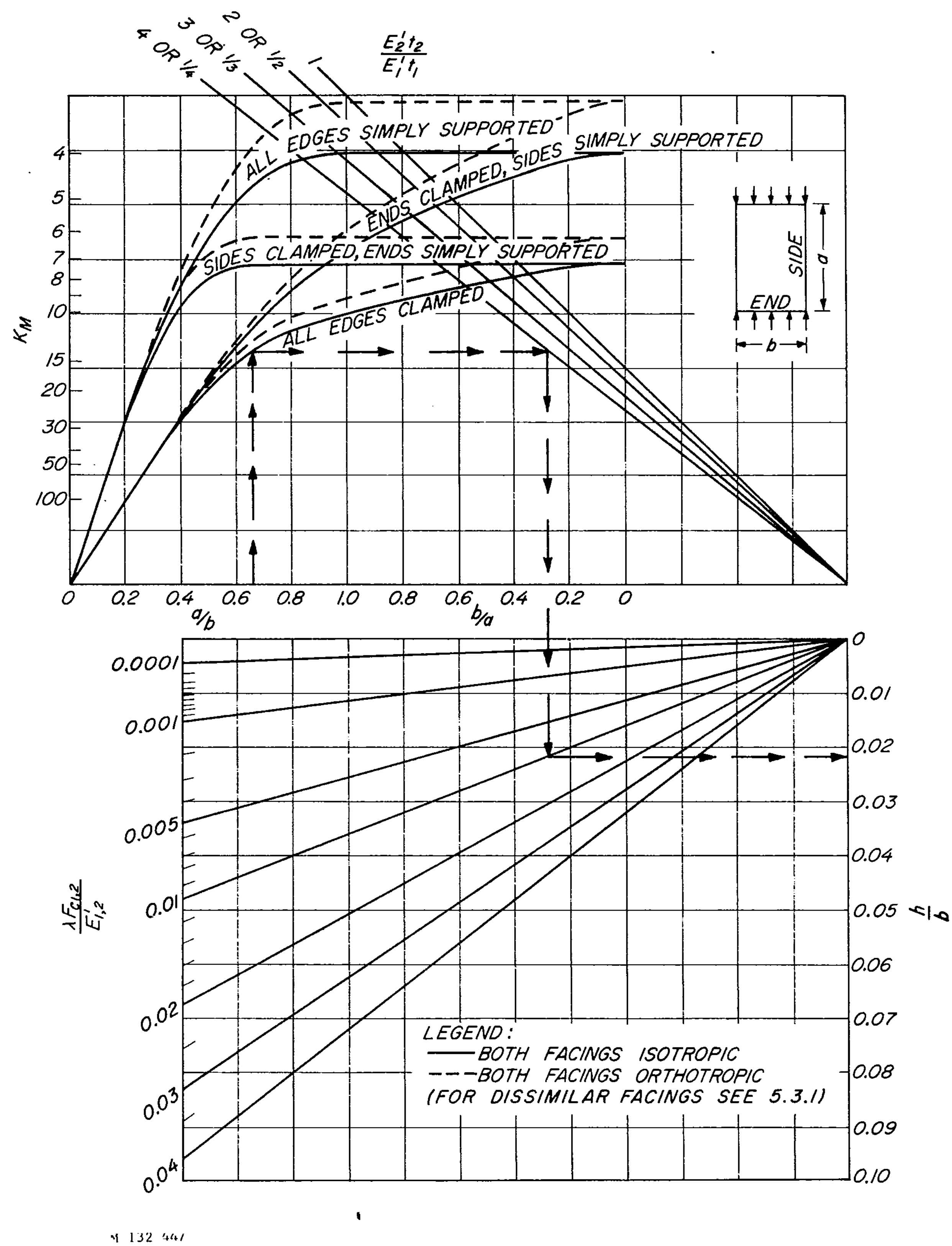


Figure 5-1.--Chart for determining h/b ratio (V = 0) such that a sandwich panel will not buckle under edgewise compression load.

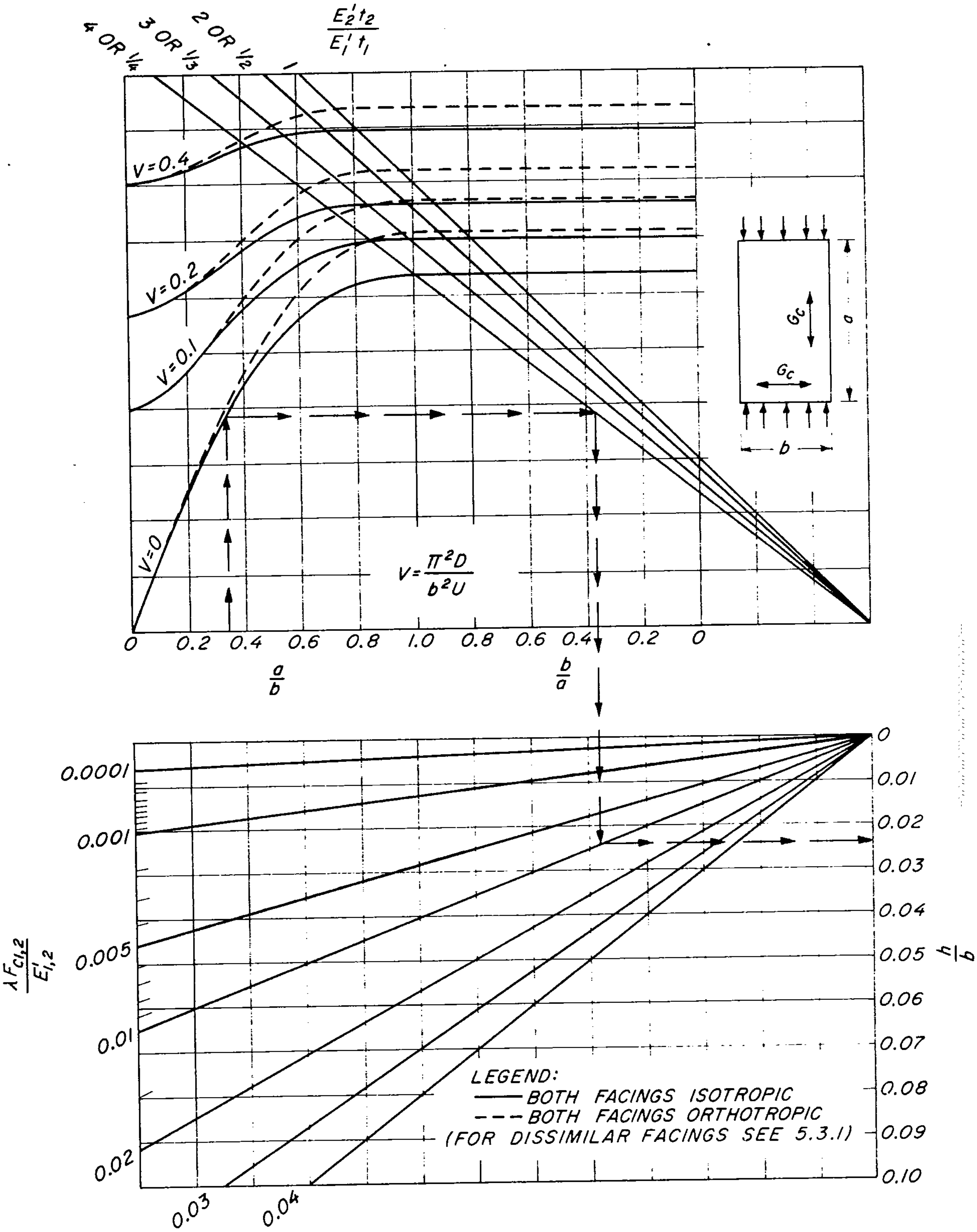


Figure 5-2. --Chart for determining h/b ratio such that a simply supported sandwich panel with isotropic core ($G_{cb} = G_{ca}$) will not buckle under edgewise compression load.

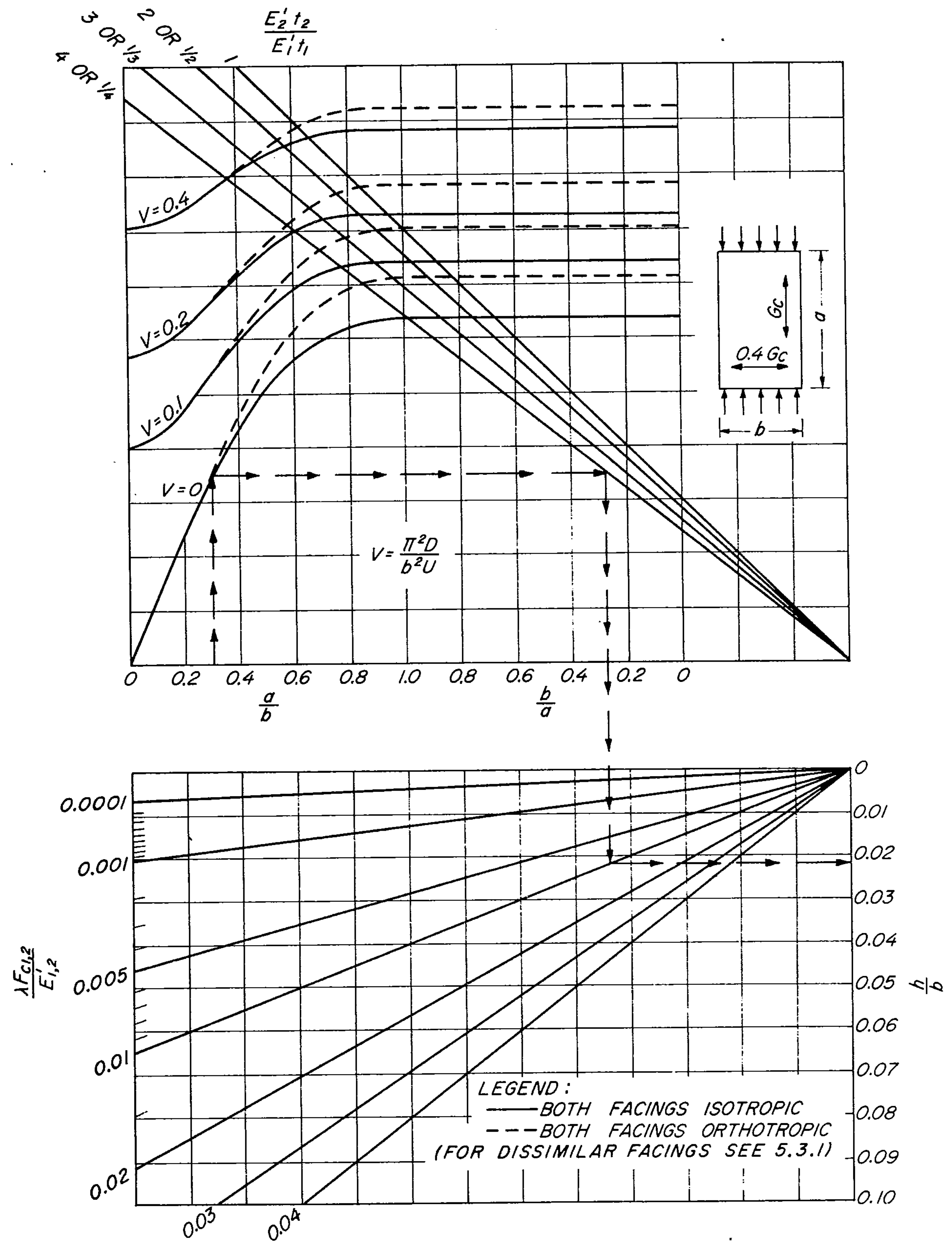


Figure 5-3. --Chart for determining h/b ratio such that a simply supported sandwich panel with orthotropic core ($G_{cb} = 0.4\ G_{ca}$) will not buckle under edgewise compression load.

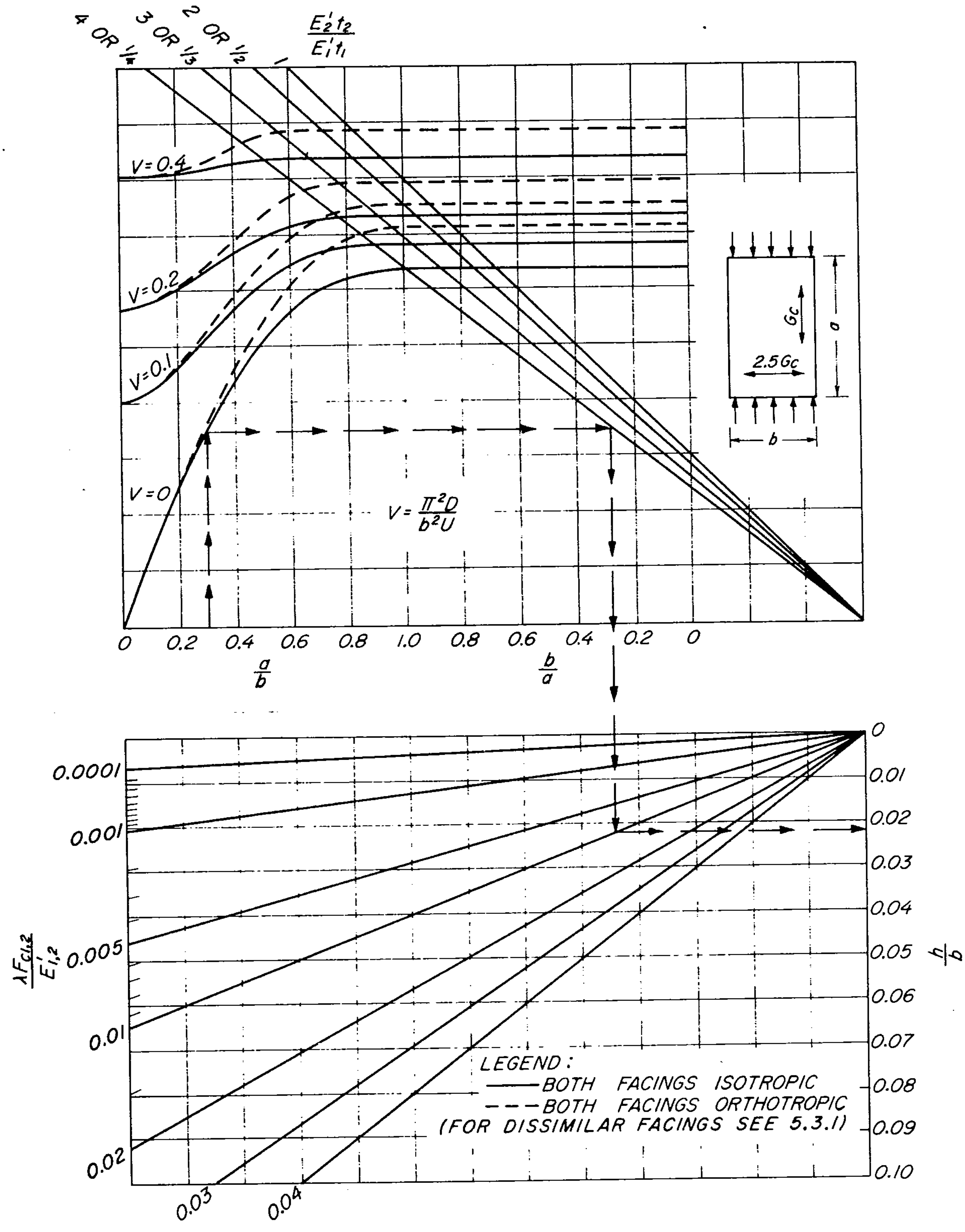


Figure 5-4.--Chart for determining h/b ratio such that a simply supported sandwich panel with orthotropic core ($G_{cb} = 2.5\ G_{ca}$) will not buckle under edgewise compression load.

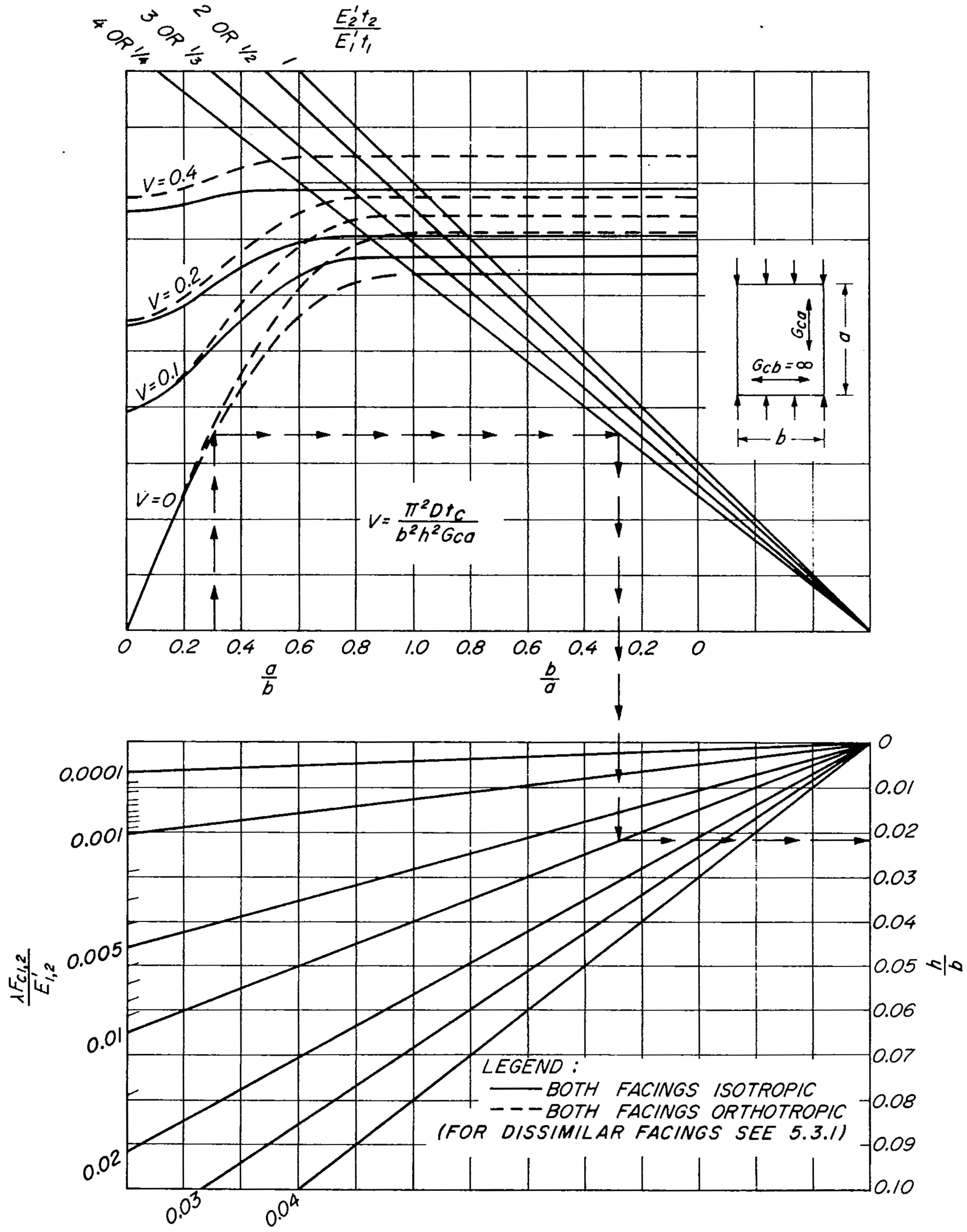


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Figure 5-5.--Chart for determining h/b ratio such that a simply supported sandwich panel with corrugated core will not buckle under edgewise compression load; core corrugation flutes perpendicular to load direction.

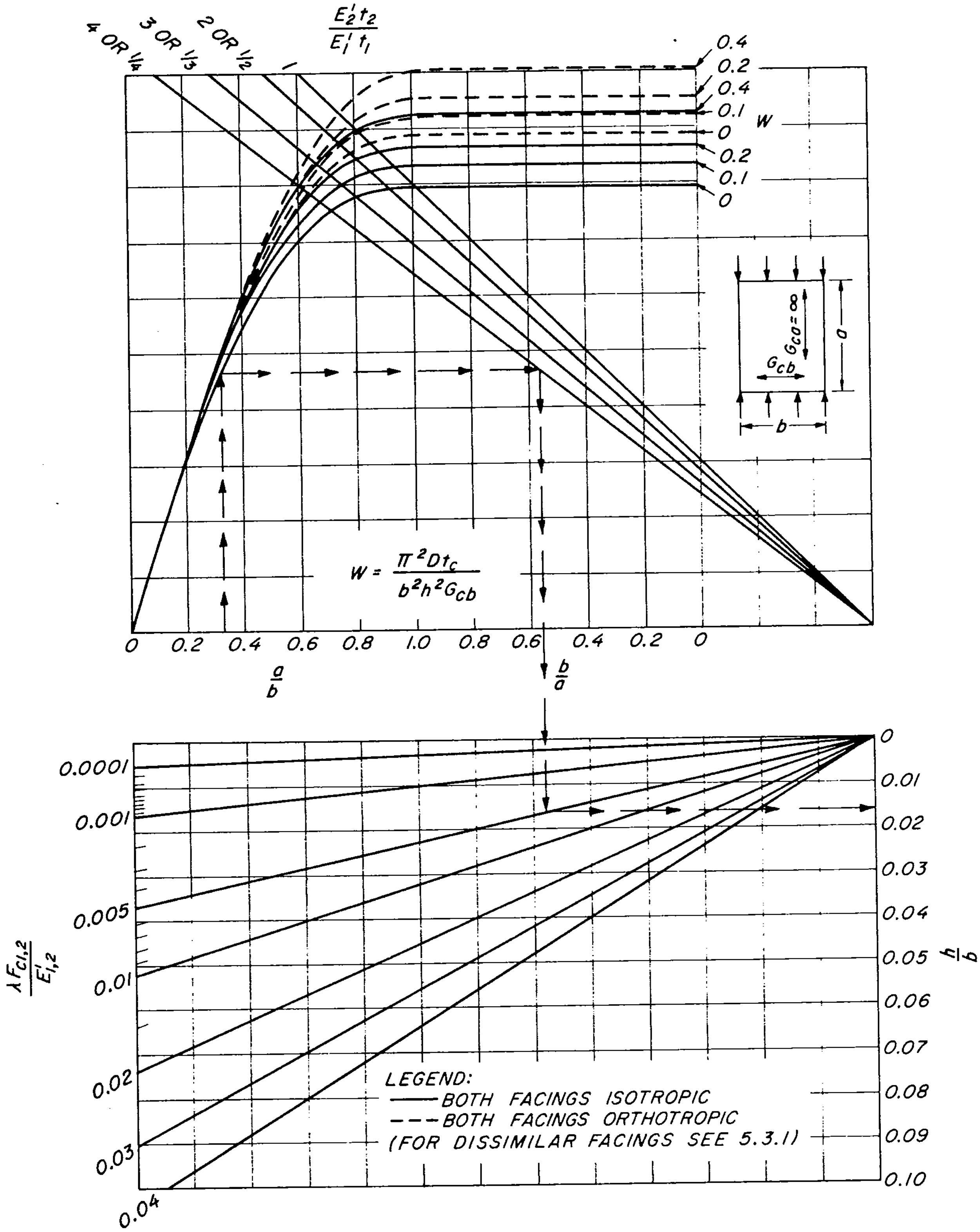


Figure 5-6. --Chart for determining h/b ratio such that a simply supported sandwich panel with corrugated core will not buckle under edgewise compression load; core corrugation flutes parallel to load direction.

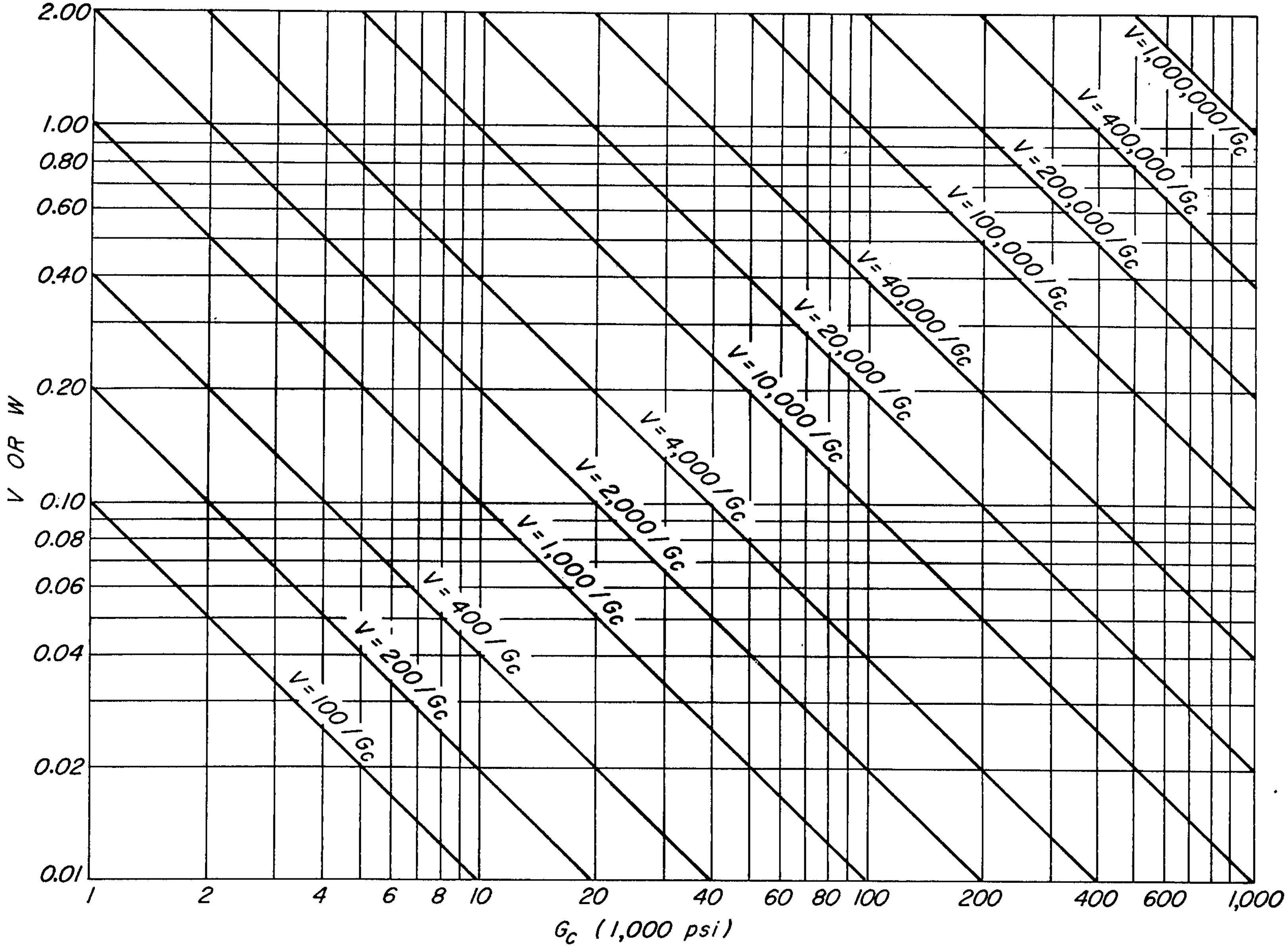


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Figure 5-7.--Chart for determining V or W and $G_c$ for sandwich in edgewise compression.

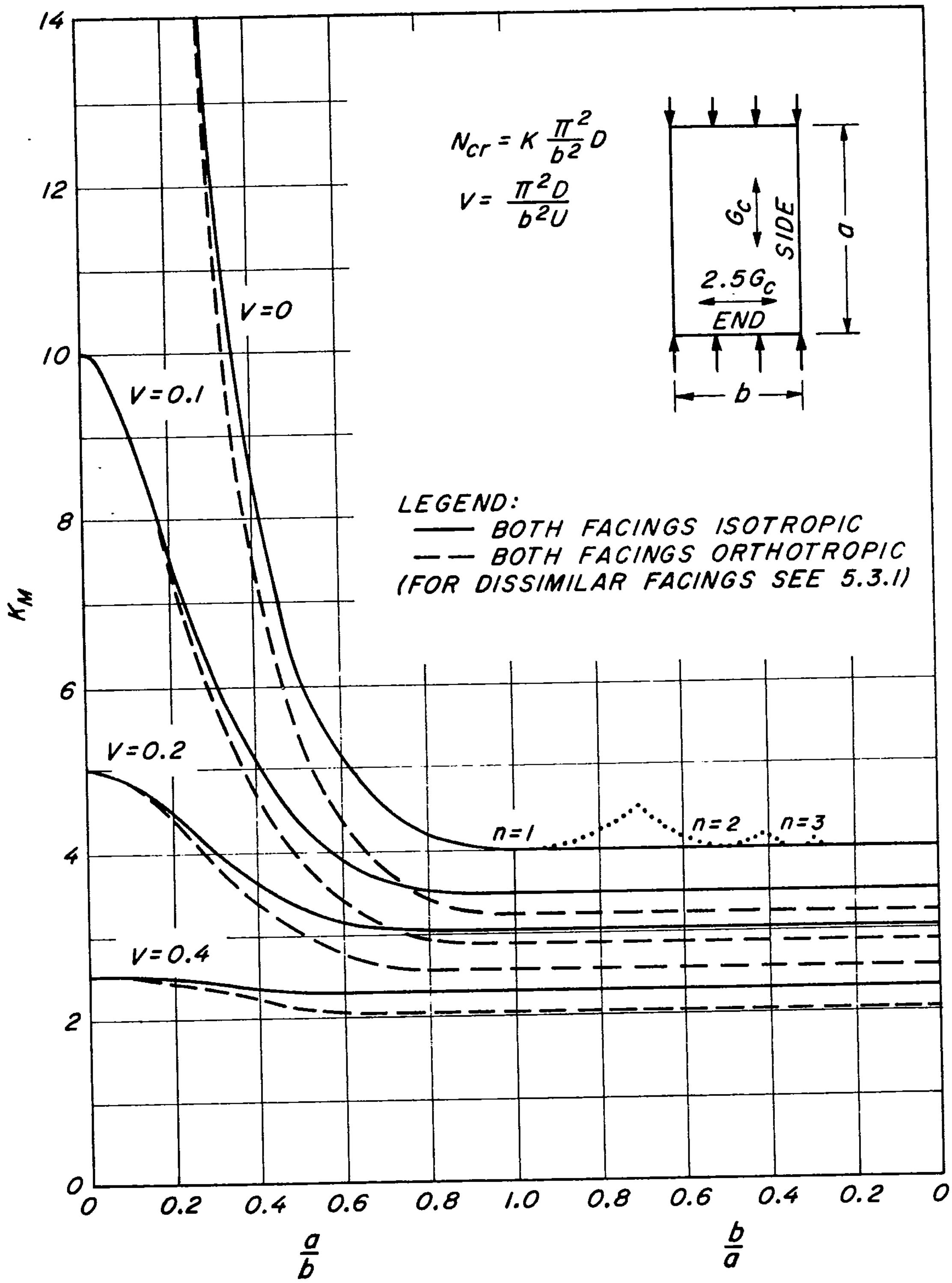


Figure 5-8.--$K_M$ for sandwich panel with ends and sides simply supported and orthotropic core. ($G_{cb} = 2.5\ G_{ca}$).

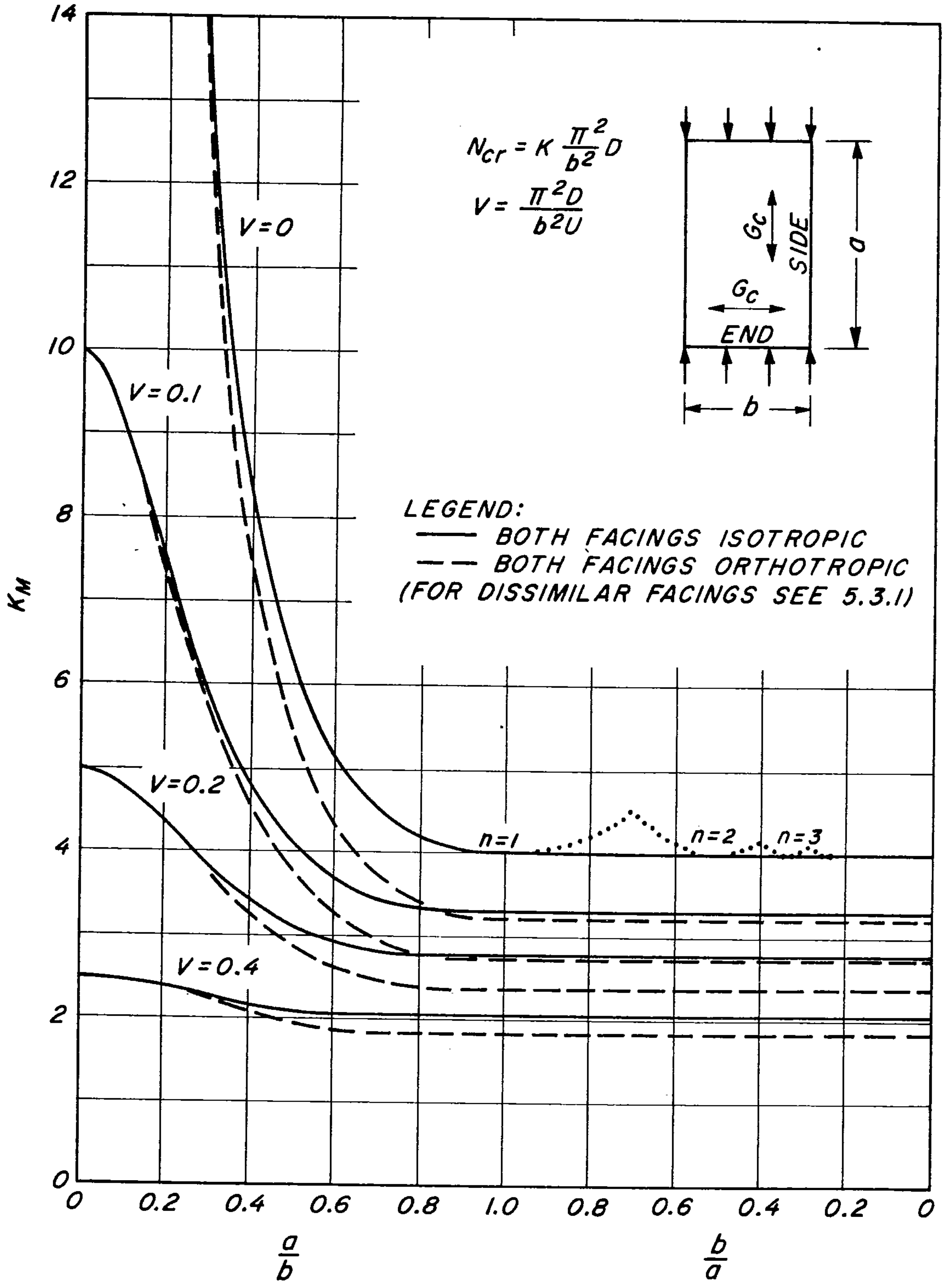


Figure 5-9.--$K_M$ for sandwich panel with ends and sides simply supported and isotropic core. ($G_{cb} = G_{ca}$).

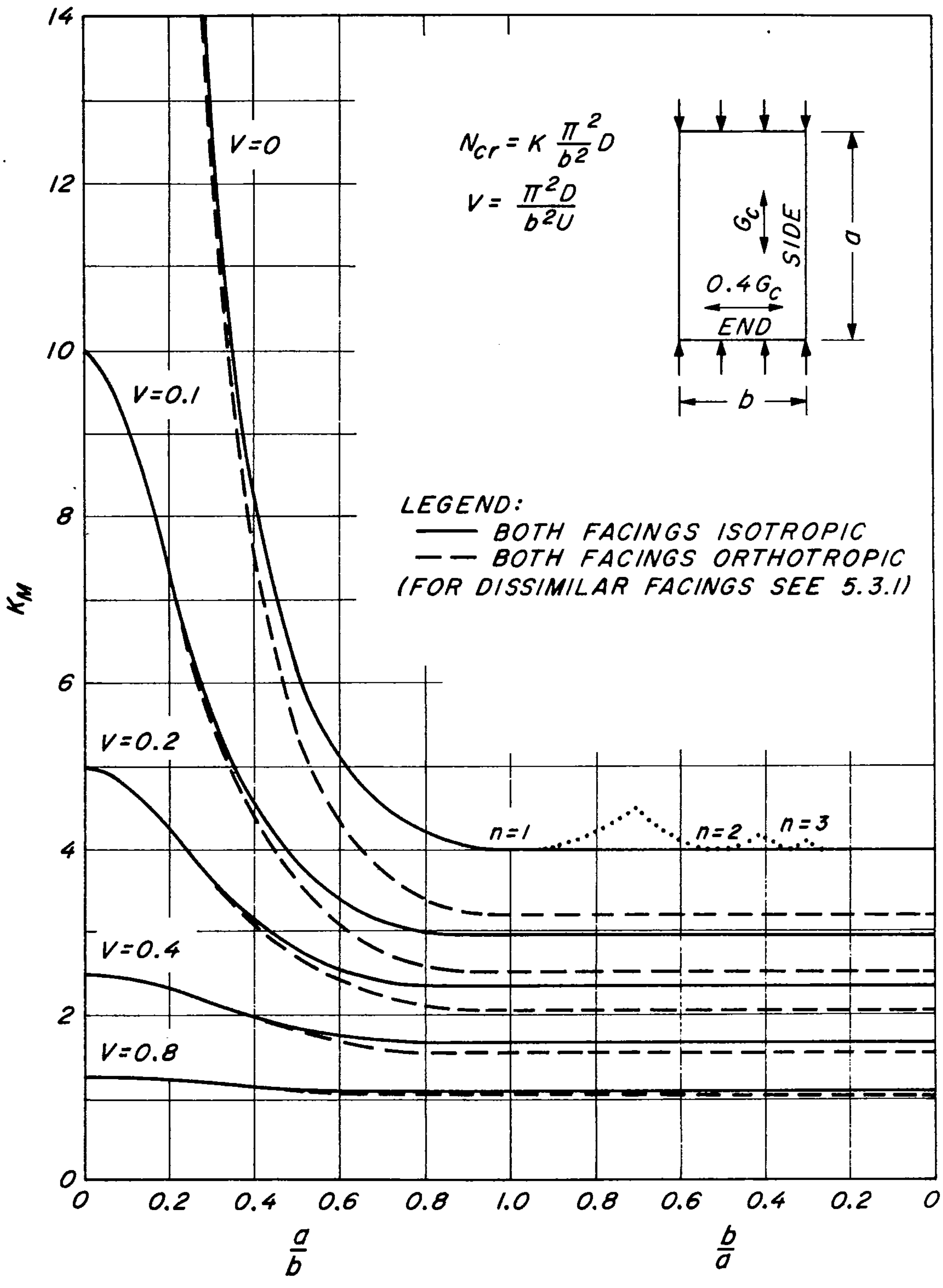


Figure 5-10.--$K_M$ for sandwich panel with ends and sides simply supported and orthotropic core. ($G_{cb} = 0.4\, G_{ca}$).

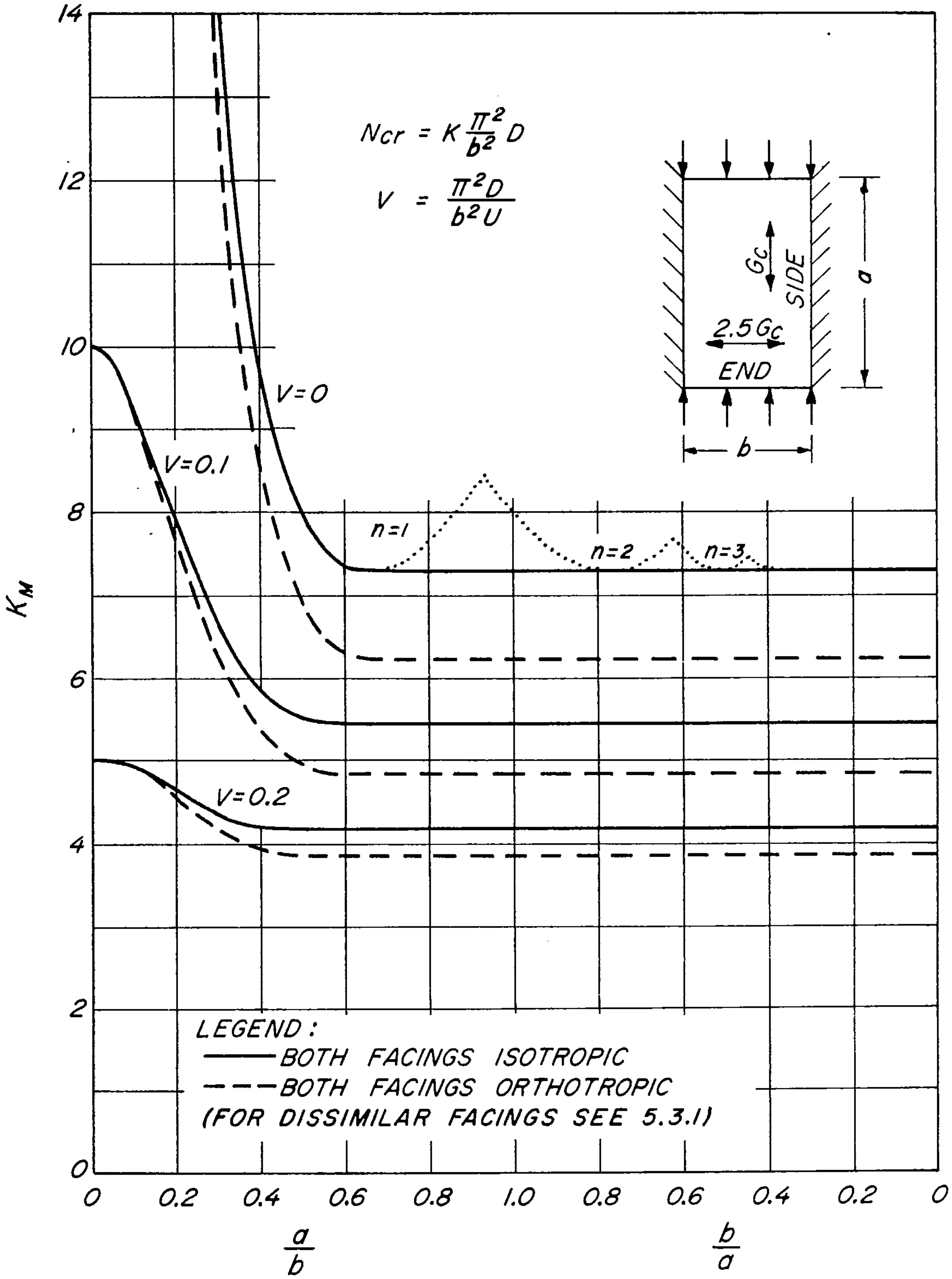


Figure 5-11.--$K_M$ for sandwich panel with ends simply supported and sides clamped, and orthotropic core. ($G_{cb} = 2.5\ G_{ca}$).

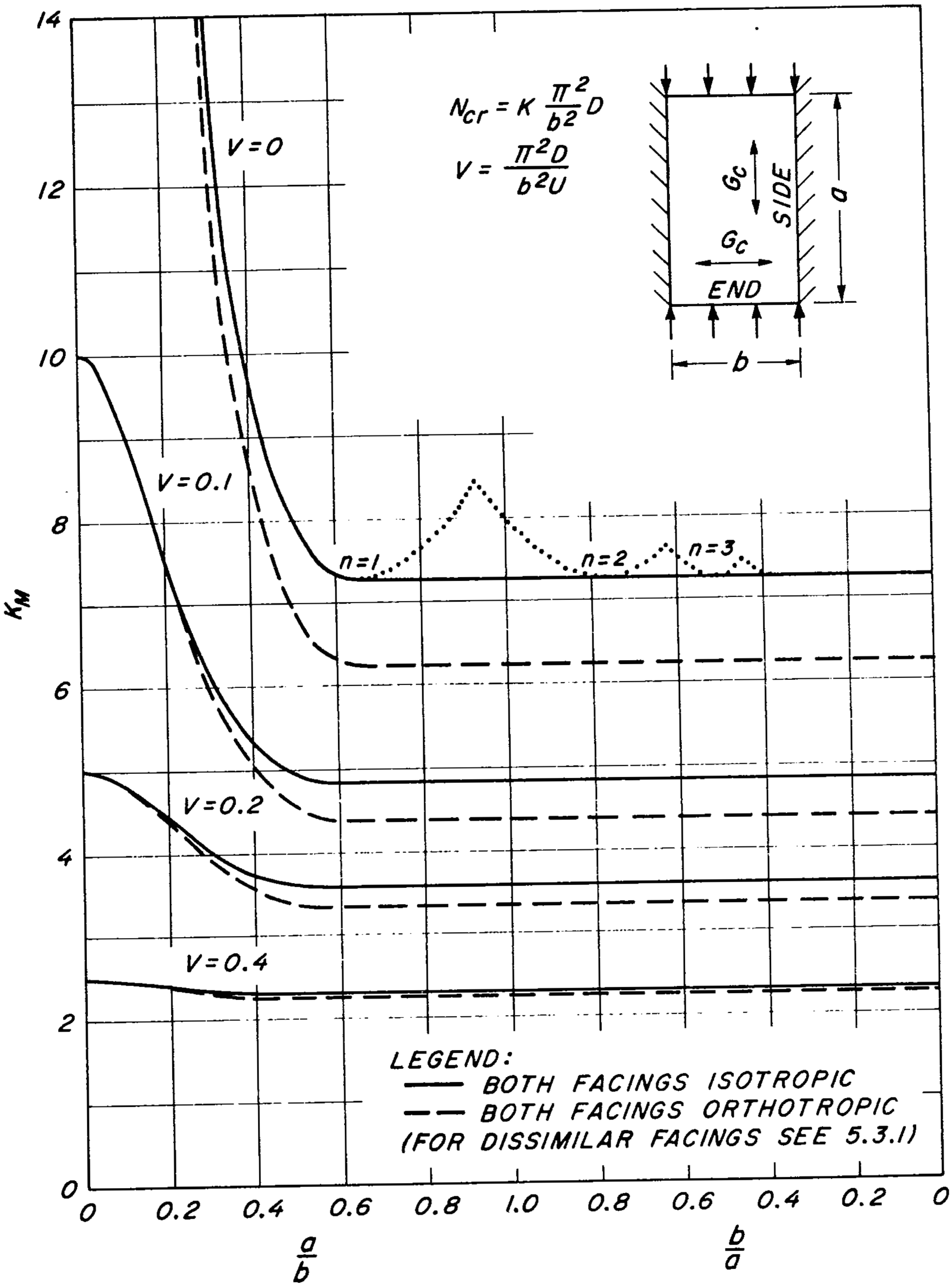


Figure 5-12.--$K_M$ for sandwich panel with ends simply supported and sides clamped, and isotropic core. ($G_{cb} = G_{ca}$).

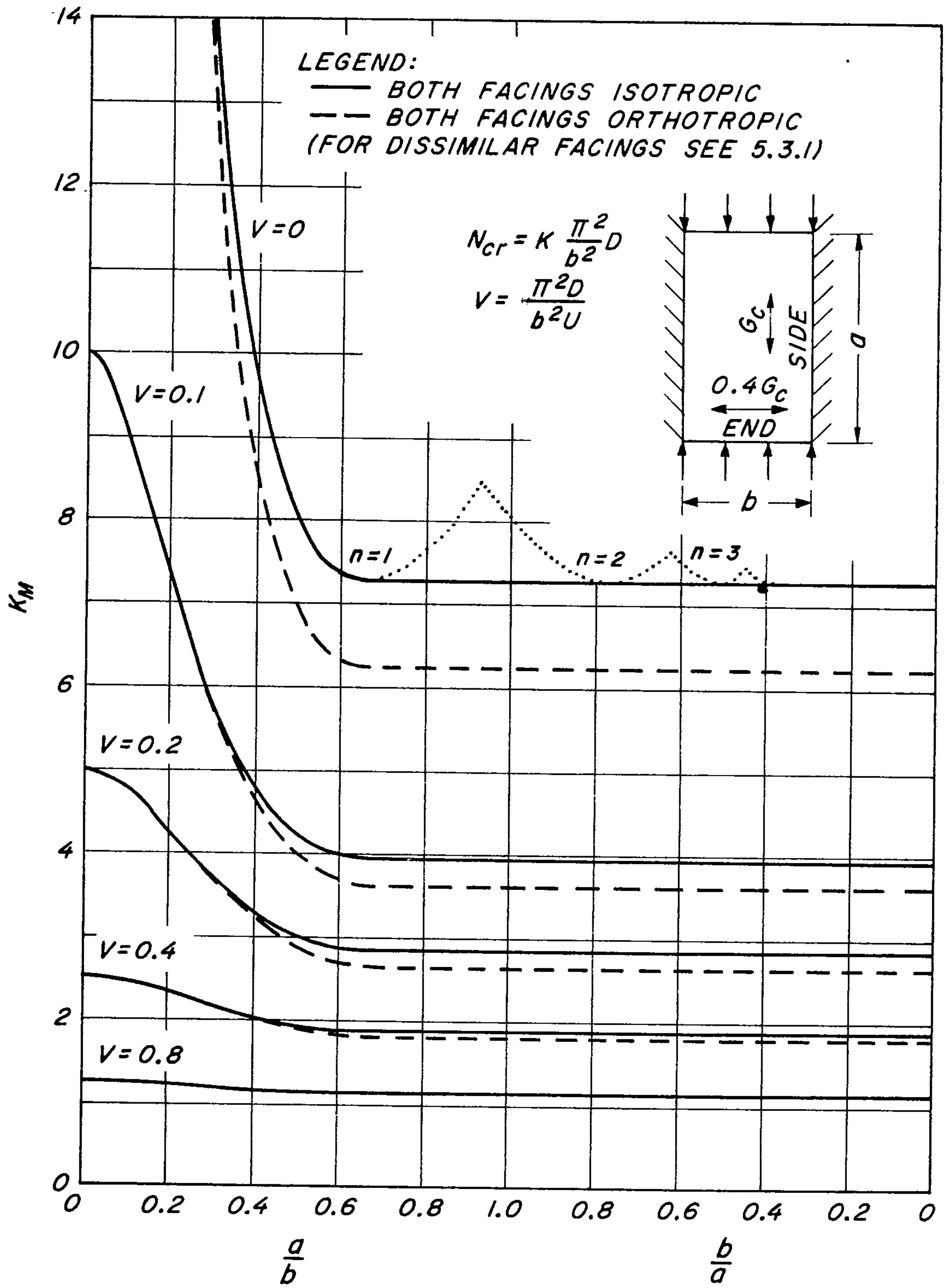


Figure 5-13.--$K_M$ for sandwich panel with ends simply supported and sides clamped, and orthotropic core. ($G_{cb} = 0.4\ G_{ca}$).

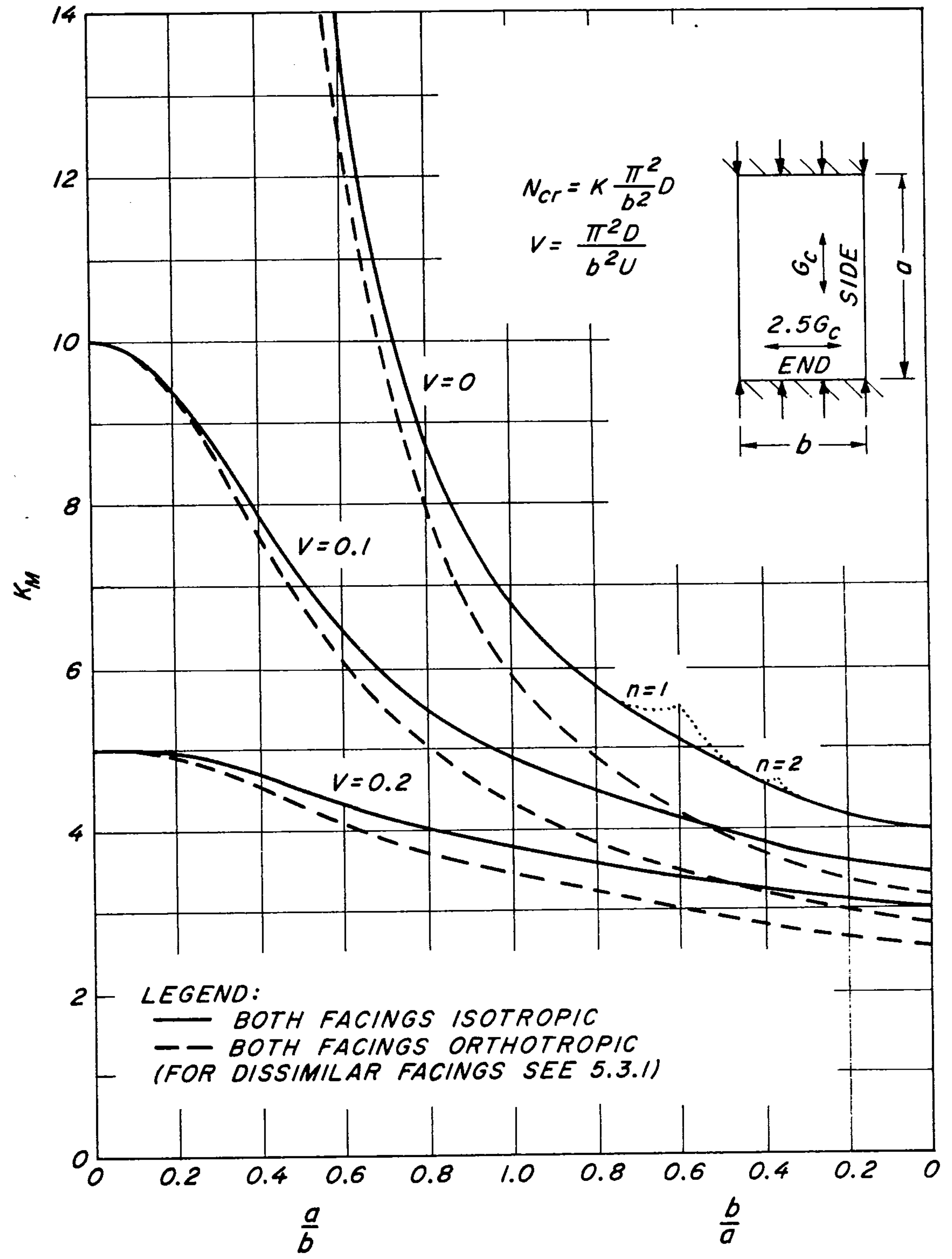


Figure 5-14. --$K_M$ for sandwich panel with ends clamped and sides simply supported, and orthotropic core. ($G_{cb} = 2.5\ G_{ca}$).

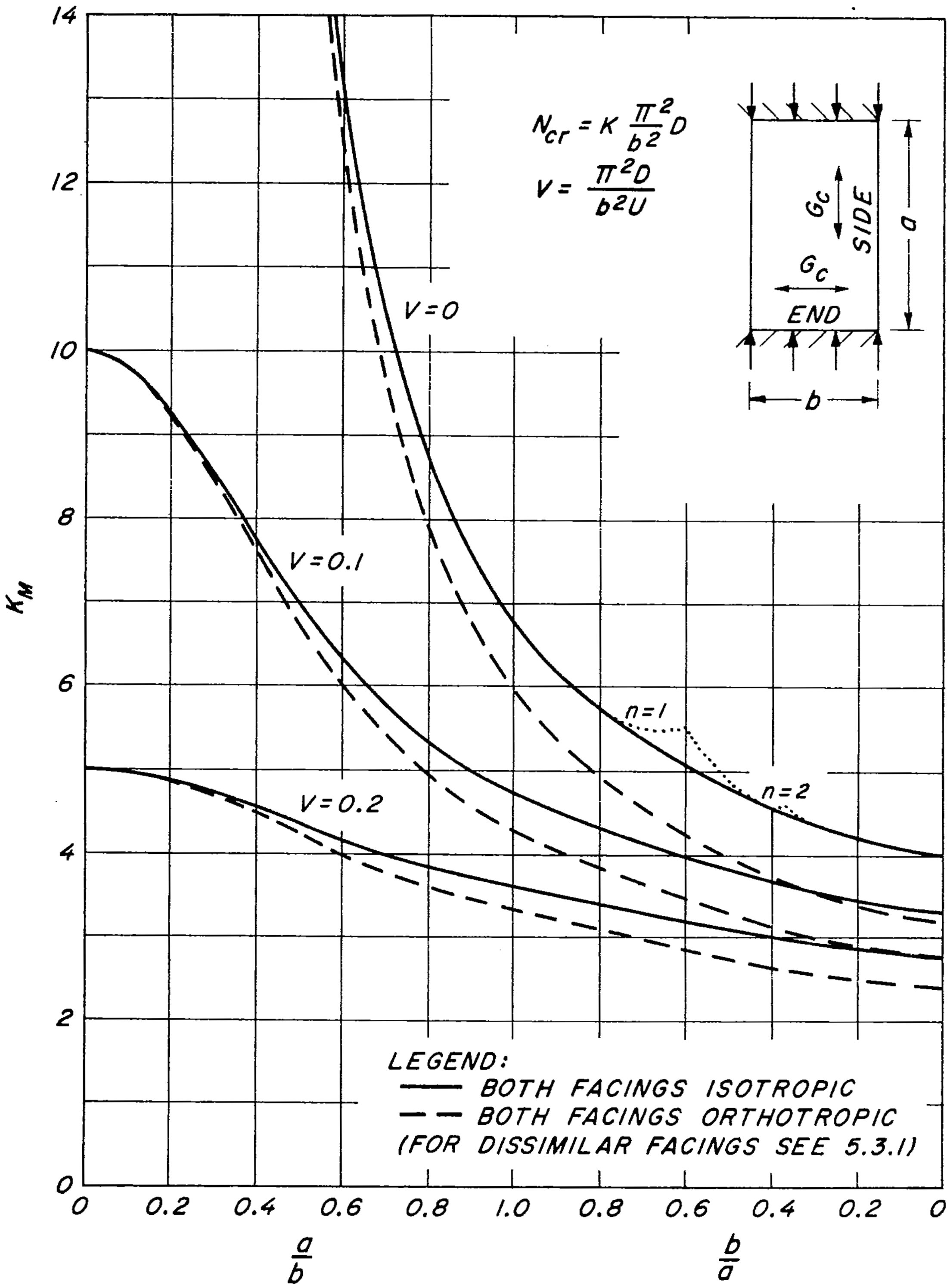


Figure 5-15.--$K_M$ for sandwich panel with ends clamped and sides simply supported, and isotropic core. $(G_{cb} = G_{ca})$.

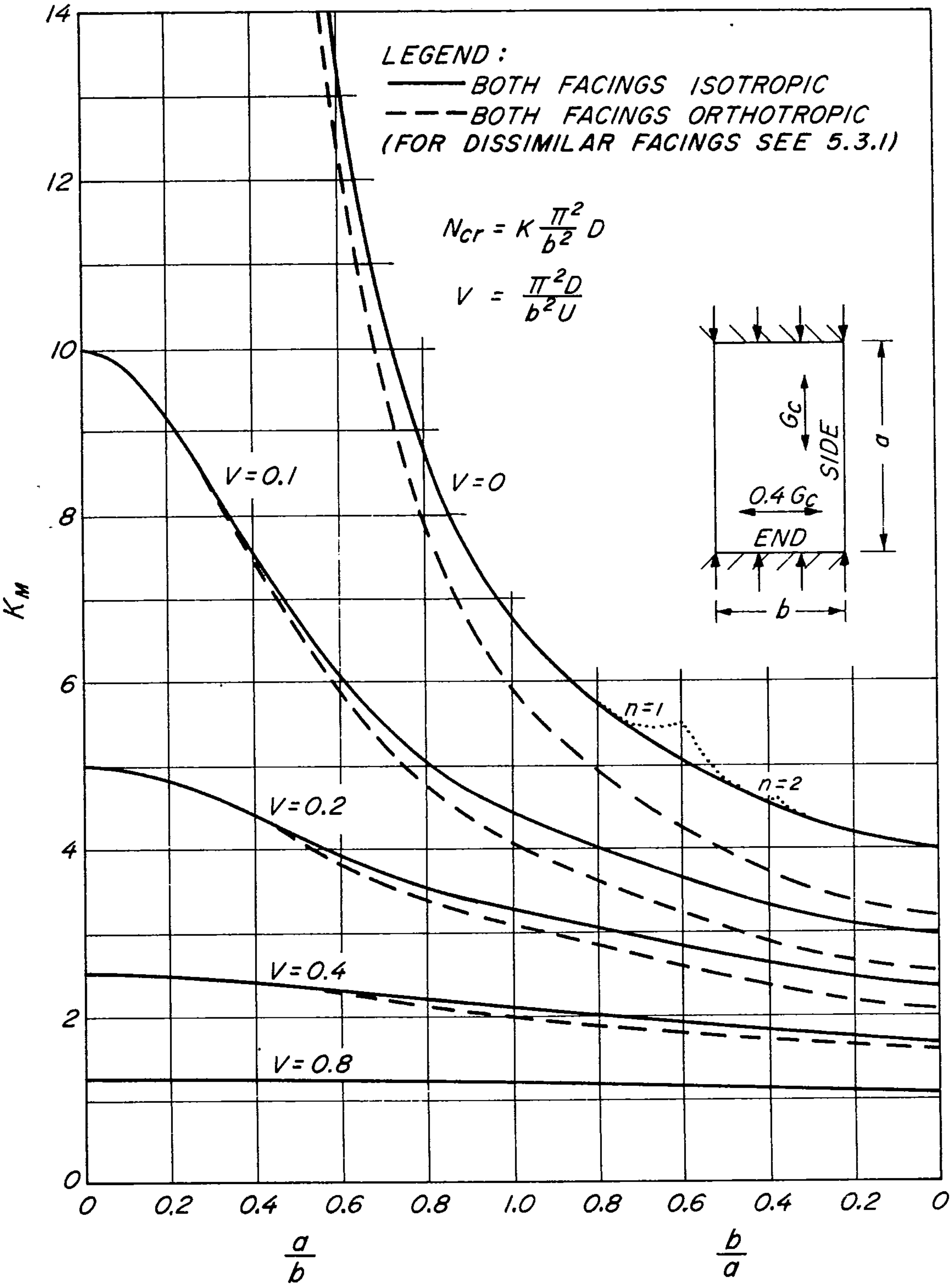


Figure 5-16.--$K_M$ for sandwich panel with ends clamped and sides simply supported, and orthotropic core. ($G_{cb} = 0.4\ G_{ca}$).

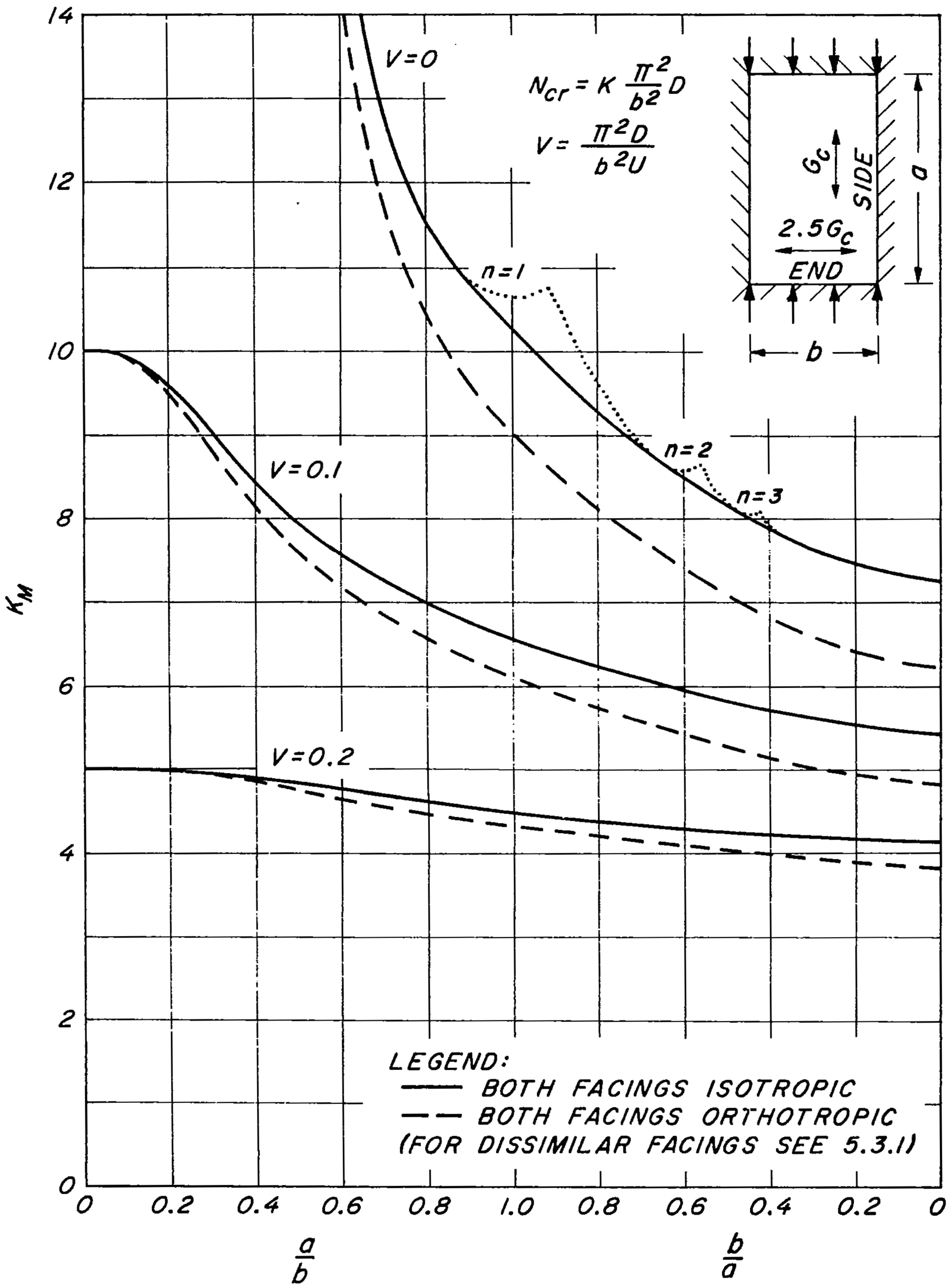


Figure 5-17.--$K_M$ for sandwich panel with ends and sides clamped, and orthotropic core. ($G_{cb} = 2.5\ G_{ca}$).

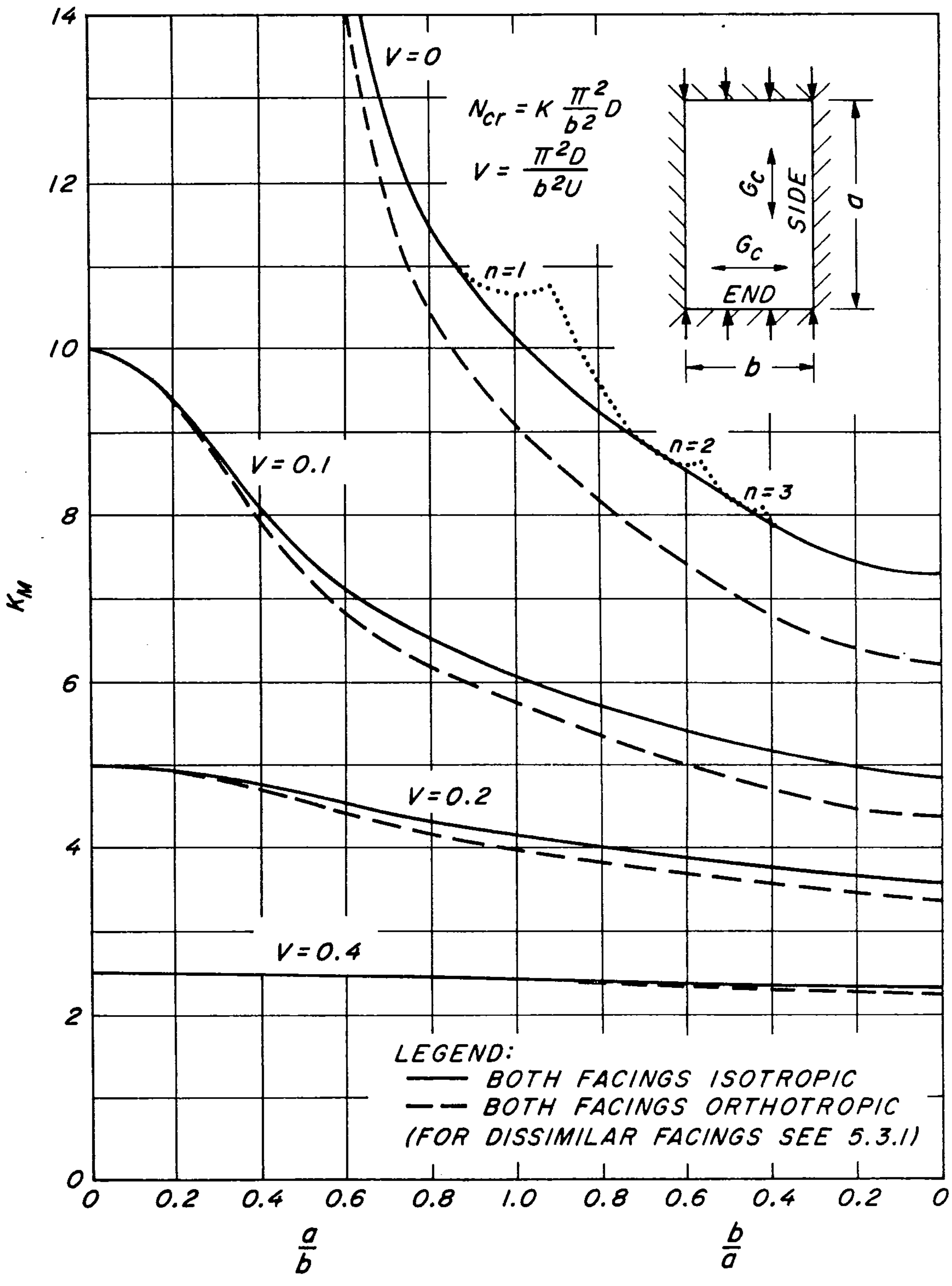


**Figure 5-18.** --$K_M$ for sandwich panel with ends and sides clamped, and isotropic core. ($G_{cb} = G_{ca}$).

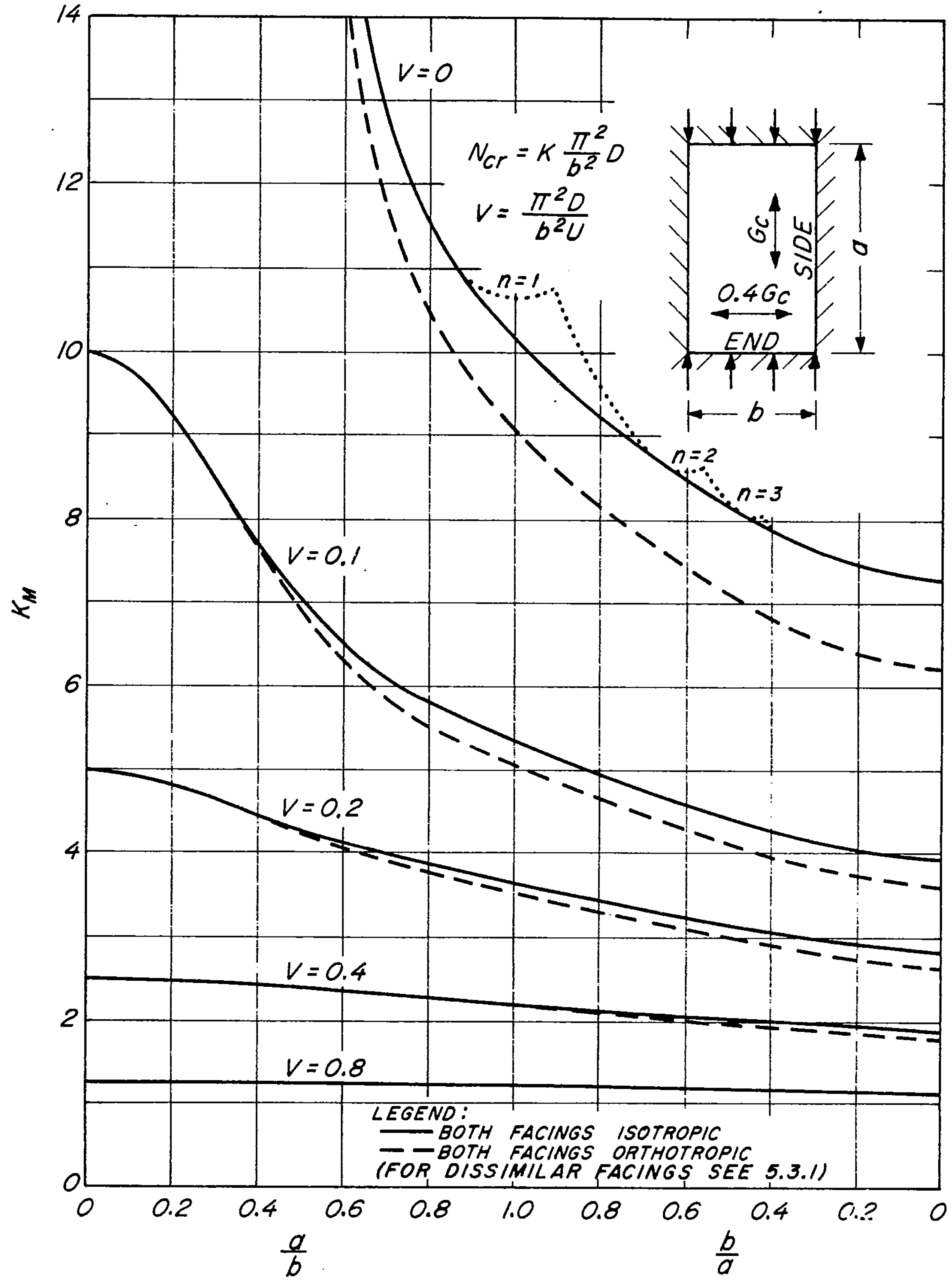


Figure 5-19.--$K_M$ for sandwich panel with ends and sides clamped, and orthotropic core. ($G_{cb} = 0.4\ G_{ca}$).

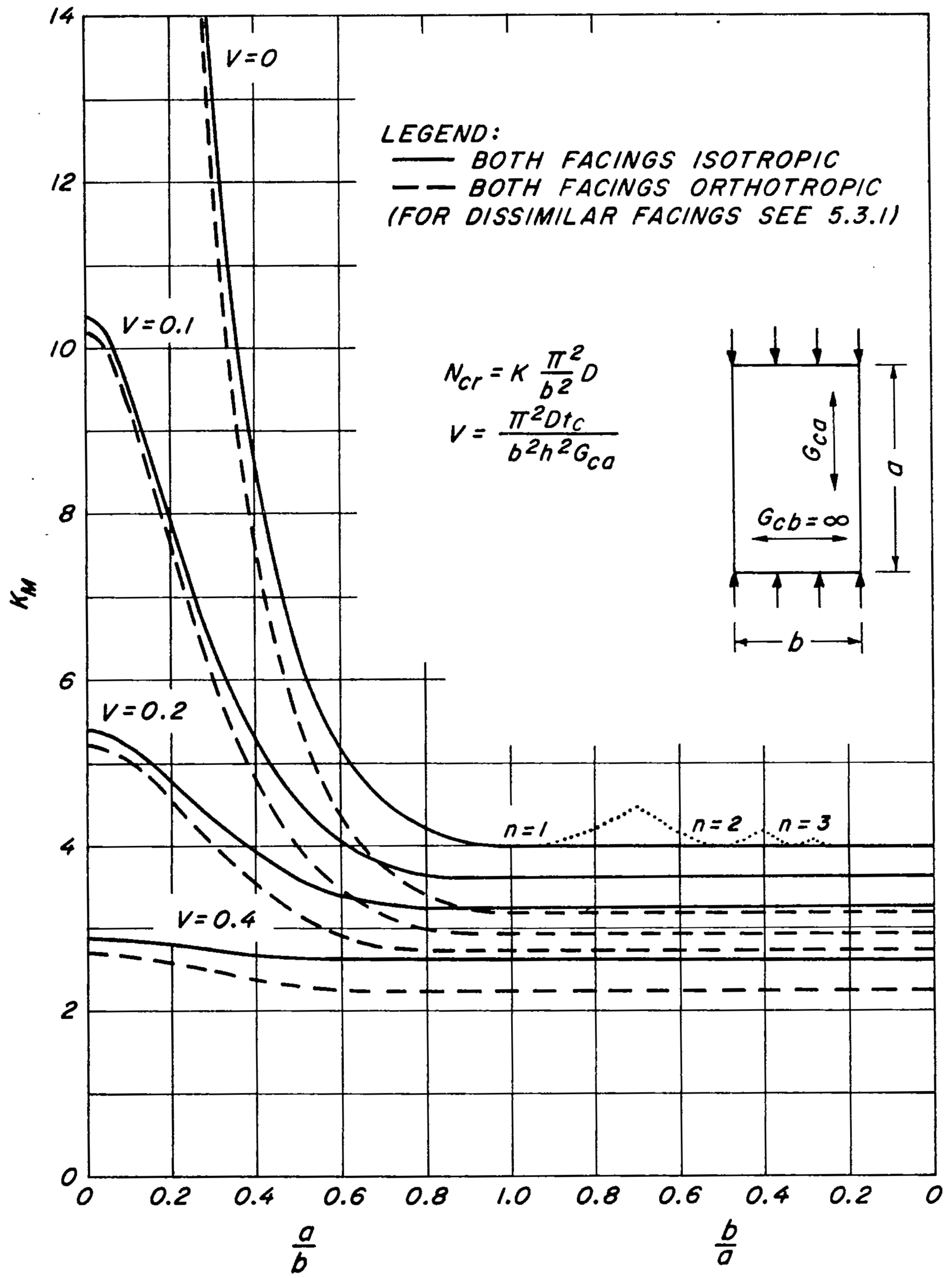


Figure 5-20. --$K_M$ for simply supported sandwich panel having a corrugated core. Core corrugation flutes perpendicular to load direction.

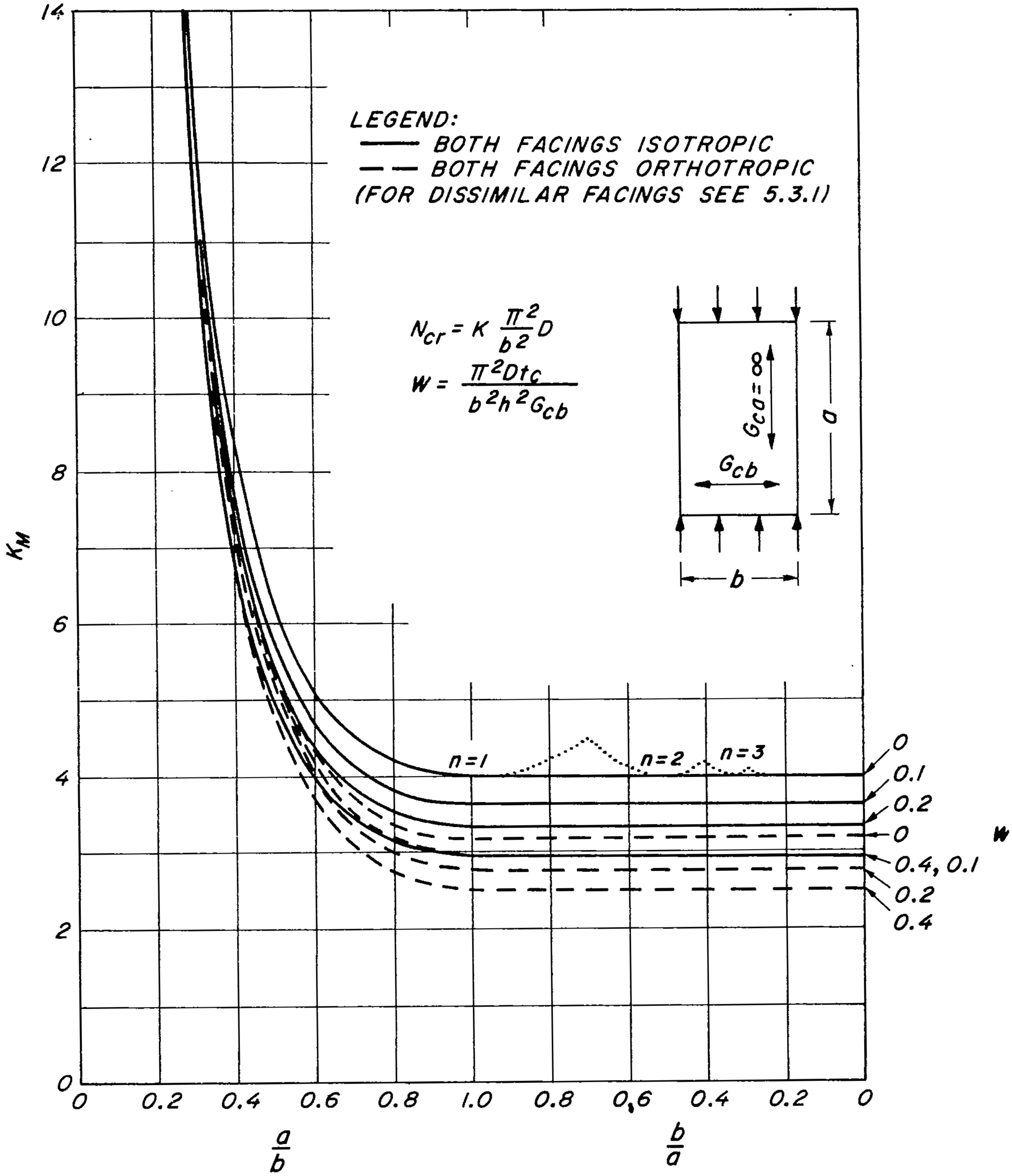


Figure 5-21.--$K_M$ for simply supported sandwich panel having a corrugated core. Core corrugation flutes parallel to load direction.

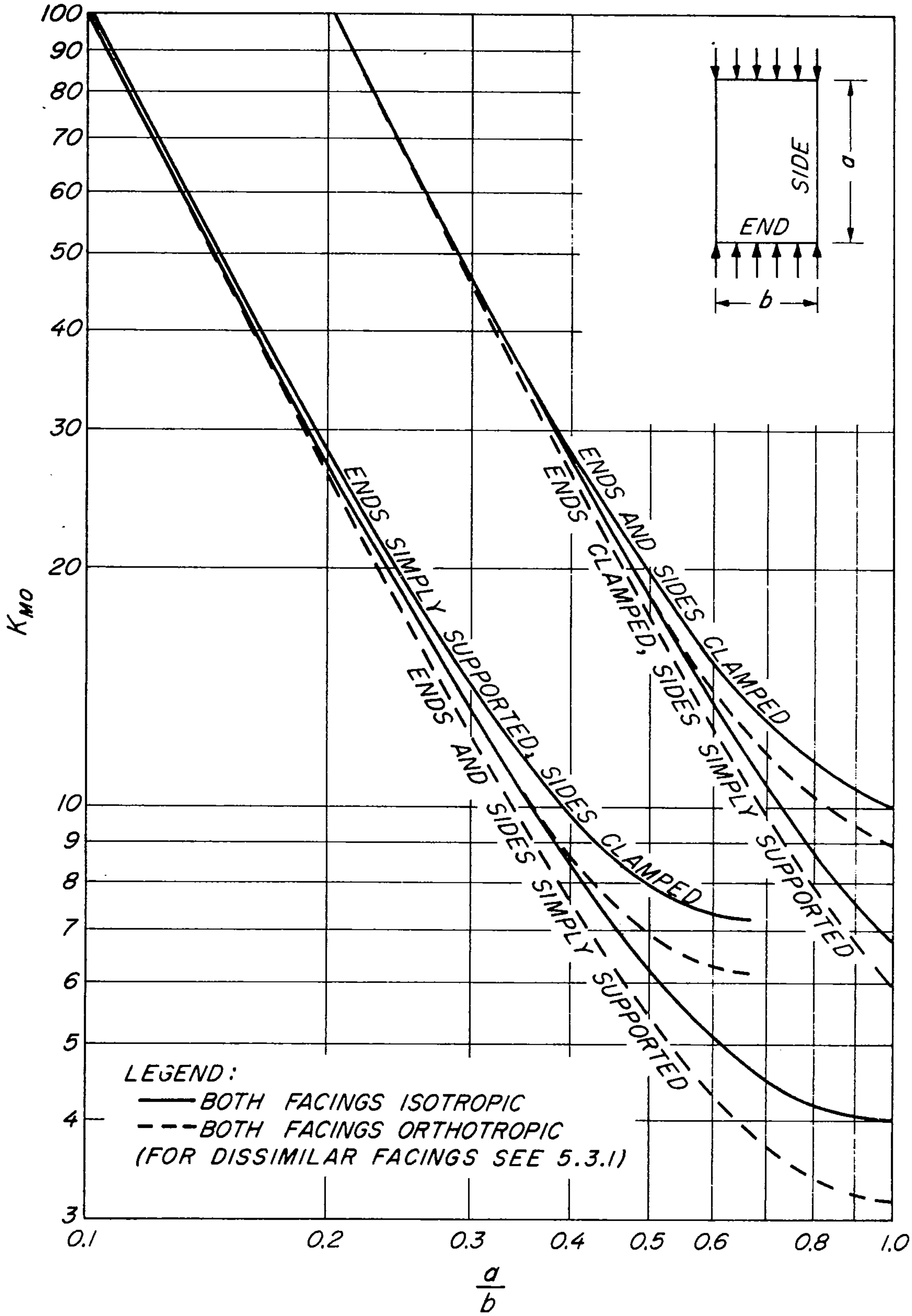


Figure 5-22. --Values of $K_{MO}$ for sandwich panels in edgewise compression.

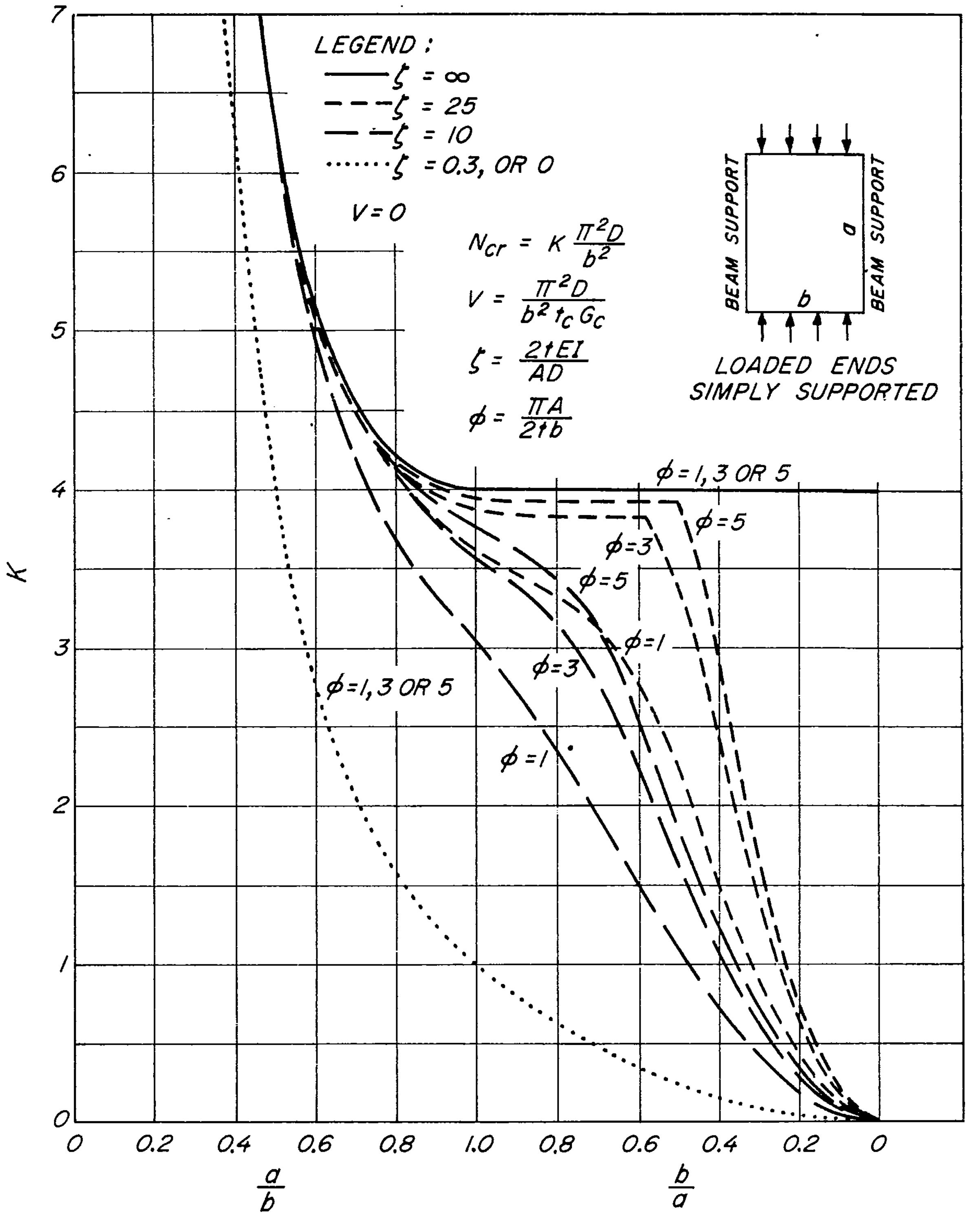


Figure 5-23.--Edgewise compressive buckling coefficients for flat, isotropic, sandwich panels with loaded ends simply supported and sides supported by beams; $\mu = 0.3$; $V = 0$.

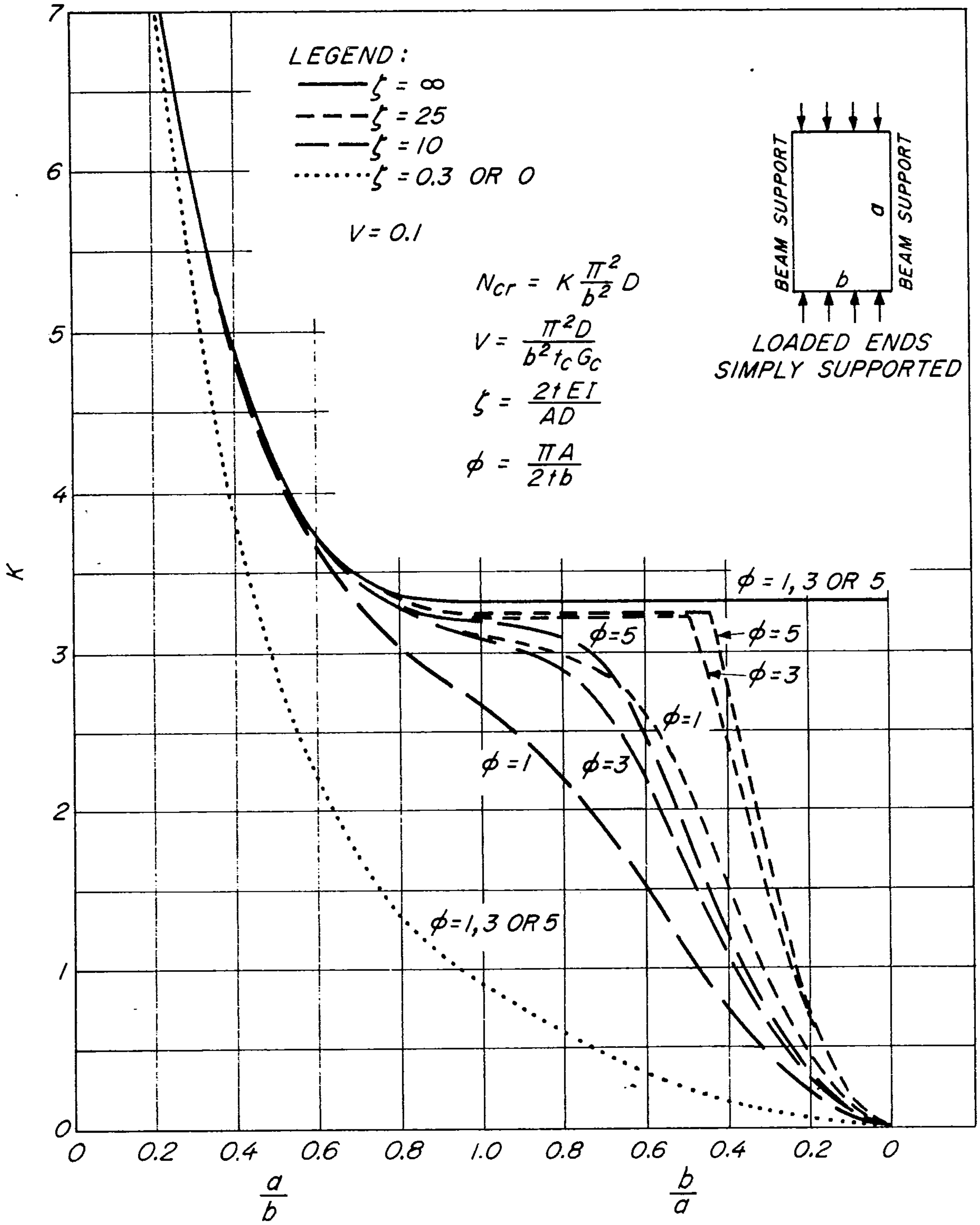


Figure 5-24.--Edgewise compressive buckling coefficients for flat, isotropic, sandwich panels with loaded ends simply supported and sides supported by beams; $\mu = 0.3$; $V = 0.1$.

# CHAPTER 6

## DESIGN OF FLAT RECTANGULAR SANDWICH PANELS UNDER EDGEWISE SHEAR LOAD

### 6.1 BASIC PRINCIPLES

Assuming that a design begins with chosen design stresses and a given load to transmit, a flat rectangular panel of sandwich construction under edgewise shear load shall be designed to comply with the four basic design principles summarized in 1.2 of Introduction. These four conditions must be met.

Overall buckling of the sandwich or dimpling or wrinkling of the facings cannot occur without possible total collapse of the panel. Detailed procedures giving theoretical formulas and graphs for determining dimensions of the facings and core, as well as necessary core properties, are given in following paragraphs. Double formulas are given, one formula for sandwich with facings of different materials and thicknesses and another formula for sandwich with each facing of the same material and thickness. Facing modulus of elasticity, E'; shear modulus, G'; and stress values $F_s$, shall be values at the conditions of use; for example, if application is at elevated temperature, then facing properties at elevated temperature shall be used in design. The facing shear modulus or modulus of elasticity is the effective value at the facing stress. If this stress is beyond the proportional limit value, an appropriate tangent, reduced, or modified value shall be used (ref. 6-4).

### 6.2 DETERMINING FACING THICKNESS

$$t_1F_{s1} + t_2F_{s2} = N_s \quad \text{(for unequal facings)} \tag{6:1}$$

$$t = \frac{N_s}{2F_s} \quad \text{(for equal facings)} \tag{6:1a}$$

where t is facing thickness; $F_s$ is chosen design facing shear stress; $N_s$ is design shear load per unit length of panel edge; and 1, 2 are subscripts denoting facings 1 and 2.

In determining thicknesses of facings for sandwich with facings of different materials, equation (6:1) must be satisfied, but also the stresses $F_{s1}$ and $F_{s2}$ must be chosen so that $F_{s1}/G_{s1} = F_{s2}/G_{s2}$ (where $G_s$ is facing secant shear modulus), thus avoiding overstressing of either facing. For example, if facing 1 is a material such that $F_{s1}/G_{s1} = 0.005$, and facing 2 is a material such that $F_{s2}/G_{s2} = 0.002$, the design must be based on a ratio of $F_{s1}/G_{s1} = F_{s2}/G_{s2} = 0.002$, otherwise facing 2 will be overstressed. In order to accomplish this, the chosen design stress for facing 1 must be lowered. For many combinations of facing materials it will be found advantageous to choose thicknesses such that $G_1t_1 = G_2t_2$ or $E_1t_1 = E_2t_2$.

## 6.3 DETERMINING CORE THICKNESS AND CORE SHEAR MODULUS

This section gives procedures for determining core thickness and core shear modulus so that overall buckling of the sandwich panel will not occur (refs. 6-1 and 6-2). The load per unit panel width at which buckling of a sandwich panel will occur is given by the formula:

$$N_{scr} = K \frac{\pi^2}{b^2} D$$

where D is sandwich bending stiffness. This formula solved for the facing stress becomes:

$$F_{s1,2} = \pi^2 K \frac{E'_1 t_1 E'_2 t_2}{(E'_1 t_1 + E'_2 t_2)^2} \left(\frac{h}{b}\right)^2 \frac{E'_{1,2}}{\lambda} \qquad (6:2)$$

$$F_s = \frac{\pi^2 K}{4} \left(\frac{h}{b}\right)^2 \frac{E'}{\lambda} \qquad \text{(for equal facings)} \qquad (6:2a)$$

where E' is effective modulus of elasticity of facing at stress $F_s$; $\lambda = 1 - \mu^2$; $\mu$ is Poisson's ratio of facings (in formula (6:2) it is assumed that $\mu = \mu_1 = \mu_2$); h is distance between facing centroids; b is width of panel; $K = K_F + K_M$; $K_F$ is a theoretical coefficient dependent on facing stiffness and panel aspect ratio; $K_M$ is a theoretical coefficient dependent on sandwich bending and shear rigidities and panel aspect ratio.

Solving equations (6:2) and (6:2a) for h/b gives

$$\frac{h}{b} = \frac{1}{\pi\sqrt{K}}\sqrt{\frac{\lambda F_{s1,2}}{E'_{1,2}}\left(\frac{E'_1 t_1 + E'_2 t_2}{\sqrt{E'_1 t_1 E'_2 t_2}}\right)} \qquad (6:3)$$

$$\frac{h}{b} = \frac{2}{\pi\sqrt{K}}\sqrt{\frac{\lambda F_s}{E'}} \qquad \text{(for equal facings)} \qquad (6:3a)$$

Therefore, if K is known, equations (6:3) or (6:3a) can be solved directly to eventually obtain h because all other quantities are known. After h is obtained, the core thickness, $t_c$, is computed from the formulas

$$t_c = h - \frac{t_1 + t_2}{2} \qquad (6:4)$$

$$t_c = h - t \qquad \text{(for equal facings)} \qquad (6:4a)$$

As a first approximation, it will be assumed that $K_F = 0$, hence $K = K_M$. Values of $K_M$ depend upon the bending and shear rigidities of the sandwich as incorporated in the parameter $V = \frac{\pi^2 D}{b^2 U}$, which can be written as:

$$V = \frac{\pi^2 t_c E'_1 t_1 E'_2 t_2}{\lambda b^2 G_c (E'_1 t_1 + E'_2 t_2)} \qquad (6:5)$$

$$V = \frac{\pi^2 t_c E' t}{2\lambda b^2 G_c} \quad \text{(for equal facings)} \qquad (6{:}5a)$$

where U is sandwich shear stiffness; $G_c$ is the core shear modulus associated with the axes parallel to panel side of length a and perpendicular to the plane of the panel. As values of core shear modulus decrease, values of V increase and values of $K_M$ gradually decrease.

For sandwich with corrugated core having corrugation flutes parallel to the edge of length a, the parameter V is replaced by the parameter

$$W = \frac{\pi^2 t_c D}{b^2 h^2 G_{cb}}$$

which can be written as:

$$W = \frac{\pi^2 t_c E_1' t_1 E_2' t_2}{\lambda b^2 G_{cb}(E_1' t_1 + E_2' t_2)} \qquad (6{:}6)$$

$$W = \frac{\pi^2 t_c E' t}{2\lambda b^2 G_{cb}} \quad \text{(for equal facings)} \qquad (6{:}6a)$$

where $G_{cb}$ is the core shear modulus associated with the axes parallel to the edge of length b and perpendicular to the plane of the panel (ref. 6-1).

## 6.3.1 Determination of Minimum Values of h

A minimum value of h required will be determined by assuming V = 0 or W = 0, for a first approximation. The value of h is minimum because V = 0 or W = 0 only if the core shear modulus is infinite; for any actual core the shear modulus is not infinite, hence a thicker core must be used. The curves for V = 0 or W = 0 in the charts of figures 6-1 to 6-5 give minimum values of h for sandwich panels with isotropic, orthotropic, or corrugated cores and with simply supported edges. Panels with clamped edges are not included in the design charts because truly clamped edges are not actually attainable. Approximate curves for checking clamped sandwich are included and discussed in 6.3.3.

The charts of figures 6-1, 6-2, and 6-3 are applicable to simply supported sandwich with isotropic facings for which $\alpha = 1.0$; $\beta = 1.0$; $\gamma = 0.375$, and to sandwich with orthotropic facings such as glass fabric laminates* for which $\alpha = 1.0$; $\beta = 0.6$; and $\gamma = 0.2$.

The constants $\alpha$, $\beta$, and $\gamma$ depend upon the elastic properties of the facings, as follows:

$$\alpha = \sqrt{\frac{E'_b}{E'_a}}; \quad \beta = \alpha\mu_{ab} + 2\gamma; \quad \gamma = \frac{\lambda G'_{ba}}{\sqrt{E'_a E'_b}}$$

where $E'_a$ and $E'_b$ are the moduli of elasticity parallel to sides a and b, respectively; $G'_{ba}$ is the facing shear modulus associated with those directions; $\mu_{ab}$ is the Poisson's ratio of the contraction in the b direction to extension in the a direction due to a tensile stress in the a direction; $\mu_{ba}$ is similarly defined; and $\lambda = 1 - \mu_{ab}\mu_{ba}$. For isotropic facings it was assumed that $\mu = 0.25$. For orthotropic facings it was assumed that $\mu_{ab} = \mu_{ba} = 0.2$, $E'_a = E'_b$, and $G'_{ba} = 0.21\ E_a$.

Parameters needed for the use of the charts in figures 6-1, 6-2, and 6-3 are:

1. Panel aspect ratio b/a
2. Facing properties $\frac{\lambda F_{s1,2}}{E'_{1,2}}$
3. Ratio $\frac{E'_2 t_2}{E'_1 t_1}$

The charts of figures 6-1, 6-2, and 6-3 are also applicable to sandwich with dissimilar facings wherein facing 1 is isotropic ($\alpha_1 = 1.0$, $\beta_1 = 1.0$, $\gamma_1 = 0.375$) and facing 2 is orthotropic ($\alpha_2 = 1.0$, $\beta_2 = 0.6$, $\gamma_2 = 0.2$). For such a sandwich, linear interpolation is made between curves for sandwich with both facings isotropic and both facings orthotropic by means of the parameter:

*Laminates giving the following values of $\alpha$, $\beta$, and $\gamma$ were of glass fabrics 112, 116, 120, 128, 162, 164, 181, 182, 183, and 184 (ref. 6-3).

$$T = \frac{1}{1 + \frac{E'_2 t_2}{E'_1 t_1}}$$

Values of T = 0 correspond to sandwich with both facings isotropic and T = 1 to sandwich with both facings orthotropic. This is demonstrated by substitution of these T values in the general expression for $K_M$ (ref. 6-2).

Thus, for example: If T = 1/4, interpolation is at 1/4 of the distance from the curve for both facings isotropic toward the curve for both facings orthotropic.

## 6.3.2 Determination of Actual Values of h

Since actual core shear modulus values are not very large, a value of h somewhat greater than given by the curves for V = 0 or W = 0 in figures 6-1 to 6-5 must be used. These figures are entered with values of the panel aspect ratio and values of V or W as computed by equations (6:5), (6:5a), (6:6), or (6:6a). Figure 6-1 applies to sandwich with isotropic cores for which the core shear modulus perpendicular to the panel length is equal to the core shear modulus parallel to the panel length. Figure 6-2 applies to sandwich with honeycomb cores for which the core shear modulus perpendicular to the panel length is 0.40 times the core shear modulus parallel to the panel length. Figure 6-3 applies to sandwich with honeycomb cores for which the core shear modulus perpendicular to the panel length is 2.50 times the core shear modulus parallel to the panel length.

> NOTE: For honeycomb cores with core ribbons parallel to the panel length, $G_c = G_{TL}$ and the shear modulus perpendicular to panel length is $G_{TW}$. For honeycomb cores with core ribbons perpendicular to the panel length, $G_c = G_{TW}$ and the shear modulus perpendicular to the panel length is $G_{TL}$.

Figure 6-4 applies to sandwich having isotropic facings and a corrugated core with the corrugation flutes parallel to the edge of length a. The parameter W, given by equations (6:6) and (6:6a), is used instead of V. Figure 6-5 applies to sandwich having isotropic facings and a corrugated core with the corrugation flutes parallel to the edge of length b. Solution of the charts gives the ratio h/b.

In using the curves of figures 6-1 to 6-5 for values of V or W other than zero, it is necessary to iterate because V and W are directly proportional to the core thickness $t_c$. As an aid to finally determining $t_c$ and $G_c$, figure 6-6 presents a number of lines representing V or W for various values of $G_c$, with V and W ranging from 0.01 to 2 and $G_c$ ranging from 1,000 to 1,000,000 pounds per square inch. The following procedure is suggested.

1. Determine a core thickness $t_c$ from figures 6-1 to 6-5, using a value of 0.01 for V or W.

2. Compute the constant relating V or W to $G_c$:

$$\left[\frac{\pi^2 t_c E_1' t_1 E_2' t_2}{\lambda b^2 (E_1' t_1 + E_2' t_2)}\right] \text{ or } \left[\frac{\pi^2 t_c E' t}{2\lambda b^2}\right] = VG_c \text{ or } WG_c$$

3. With this constant enter figure 6-6 and determine necessary $G_c$.

4. If the shear modulus is outside the range of values for materials available, slide up the appropriate line of figure 6-6 and pick a new value of V or W for reasonable value of core shear modulus.

5. Reenter figures 6-1 to 6-5 with the new value of V or W and repeat previous steps 1, 2, and 3.

Charts of the type used in figures 6-1 through 6-5 have not been prepared for panels with ends or sides clamped. True clamping at panel edges is never attained, particularly for sandwich constructions. It is suggested that each panel be designed as simply supported on all edges and consult section 6.3.3 to estimate any possible reduction that can be made in core thickness due to edge clamping.

## 6.3.3 Checking Procedure of Determining Buckling Stress, $F_{cr}$

The design shall be checked by using the graphs of figures 6-7 to 6-11 to determine values of $K_M$ for use in evaluating $K = K_F + K_M$ to substitute into formula (6:2) or (6:2a) and compute actual buckling stress, $F_{cr}$. The figures apply to sandwich panels with edges simply supported and isotropic or certain orthotropic facings and cores. Curves in figures 6-7, 6-8, and 6-9 for isotropic facings and $V \neq 0$ were derived on the assumption that $\mu = 1/4$; and in figures 6-10 and 6-11 that $\mu = 0.3$.

Values of $K_F$ shall be determined by the formula

$$K_F = \frac{(E'_1 t_1^3 + E'_2 t_2^3)(E'_1 t_1 + E'_2 t_2)}{12 E'_1 t_1 E'_2 t_2 h^2} \; K_{MO} \qquad (6{:}7)$$

$$K_F = \frac{t^2}{3h^2} \; K_{MO} \qquad \text{(for equal facings)} \qquad (6{:}7a)$$

where $K_{MO}$ is determined from the curve for V = 0 or W = 0 of figures 6-7 to 6-11.

It should be understood that if the desired $F_{cr}$ is above proportional limit values, the value of E' shall be an effective value, used in computing V from equation (6:5) or (6:5a) or W from equation (6:6) or (6:6a) and $F_{cr}$ from equation (6:2) or (6:2a).

If the charts do not apply because ratios of core shear moduli are far different from what is given on the charts, or it is desired to check by a more accurate analysis, the formulas given in references 6-1 and 6-2 shall be used.

Graphs of $K_M$ for sandwich panels having isotropic facings and isotropic or orthotropic core with all edges clamped are presented in figures 6-12, 6-13, and 6-14. Curves for clamped sandwich panels with orthotropic cores are approximate because they were obtained by multiplying buckling coefficients for simply supported orthotropic sandwich by the ratio of clamped to simply supported buckling coefficients for isotropic sandwich. Values of $K_M$ from these figures may be used to compute the facing stress $F_s$ from equation (6:2) or (6:2a) or to solve equation (6:3) or (6:3a) for h/b. The values of h/b so obtained may then be compared with the values obtained for simply supported panels given by the design charts of figures 6-1 to 6-5 to determine possible reductions in core thickness due to edge clamping.

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1959. Stability of Flat, Simply Supported Corrugated Core Sandwich Plate Under Combined Longitudinal Compression and Bending, Transverse Compression and Bending, and Shear. North American Aviation, Inc., Missile Div., Rep. STR 67.

(6-2) KUENZI, E.W., ERICKSEN, W.S., and ZAHN, J.J.
1962. Shear Stability of Flat Panels of Sandwich Construction. U.S. Forest Prod. Lab. Rep. 1560.

(6-3) NORRIS, CHARLES B.
1958. Compressive Buckling Curves for Simply Supported Sandwich Panels with Glass-Fabric-Laminate Facings and Honeycomb Cores. U.S. Forest Prod. Lab. Rep. 1867.

(6-4) U.S. DEPARTMENT OF DEFENSE
Current Metallic Materials and Elements for Aerospace Vehicle Structures. Military Handbook 5. Available from U.S. Gov. Printing Office, Washington, D.C.

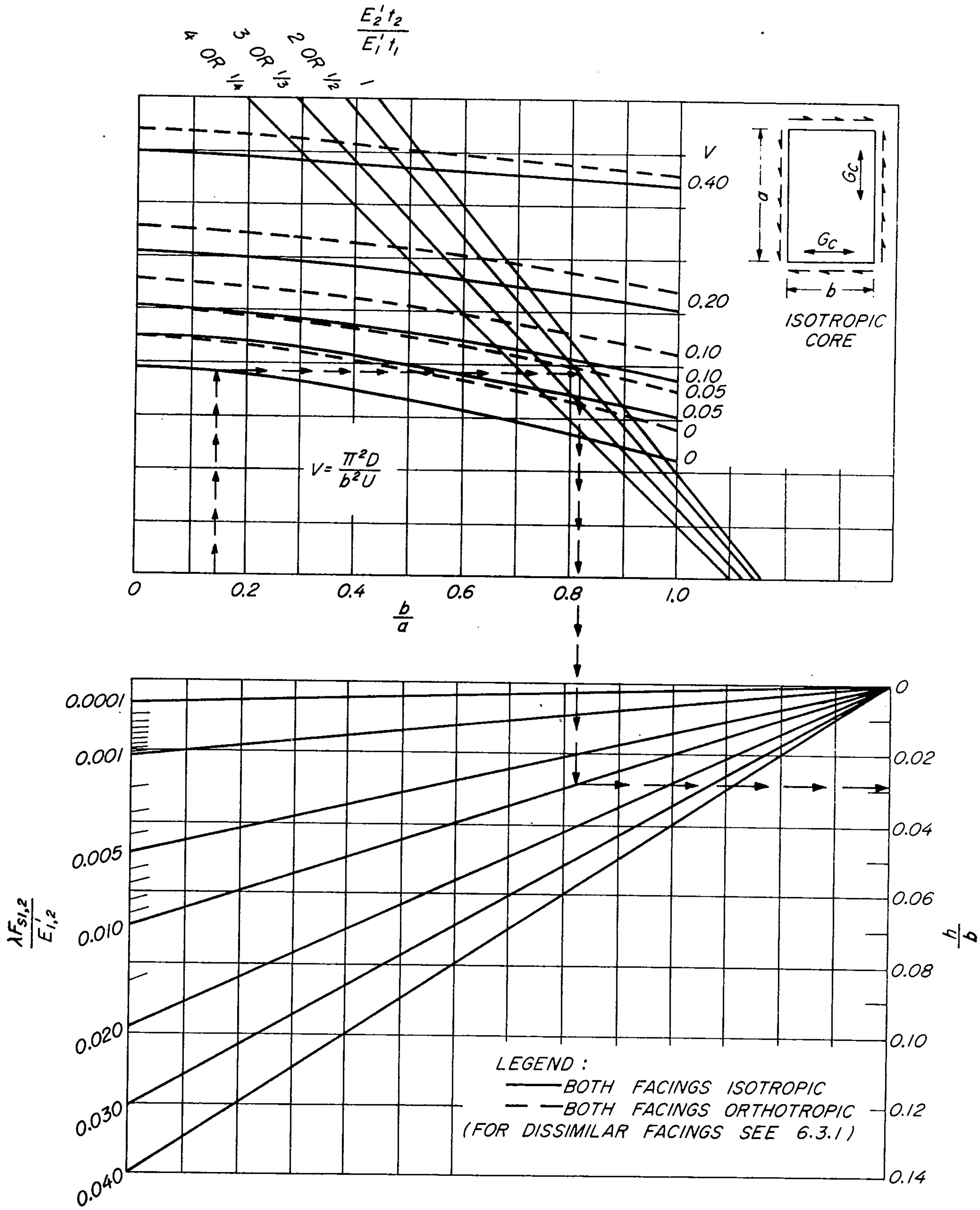


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Figure 6-1. --Chart for determining h/b ratio such that a simply supported sandwich panel with isotropic core will not buckle under edgewise shear load.

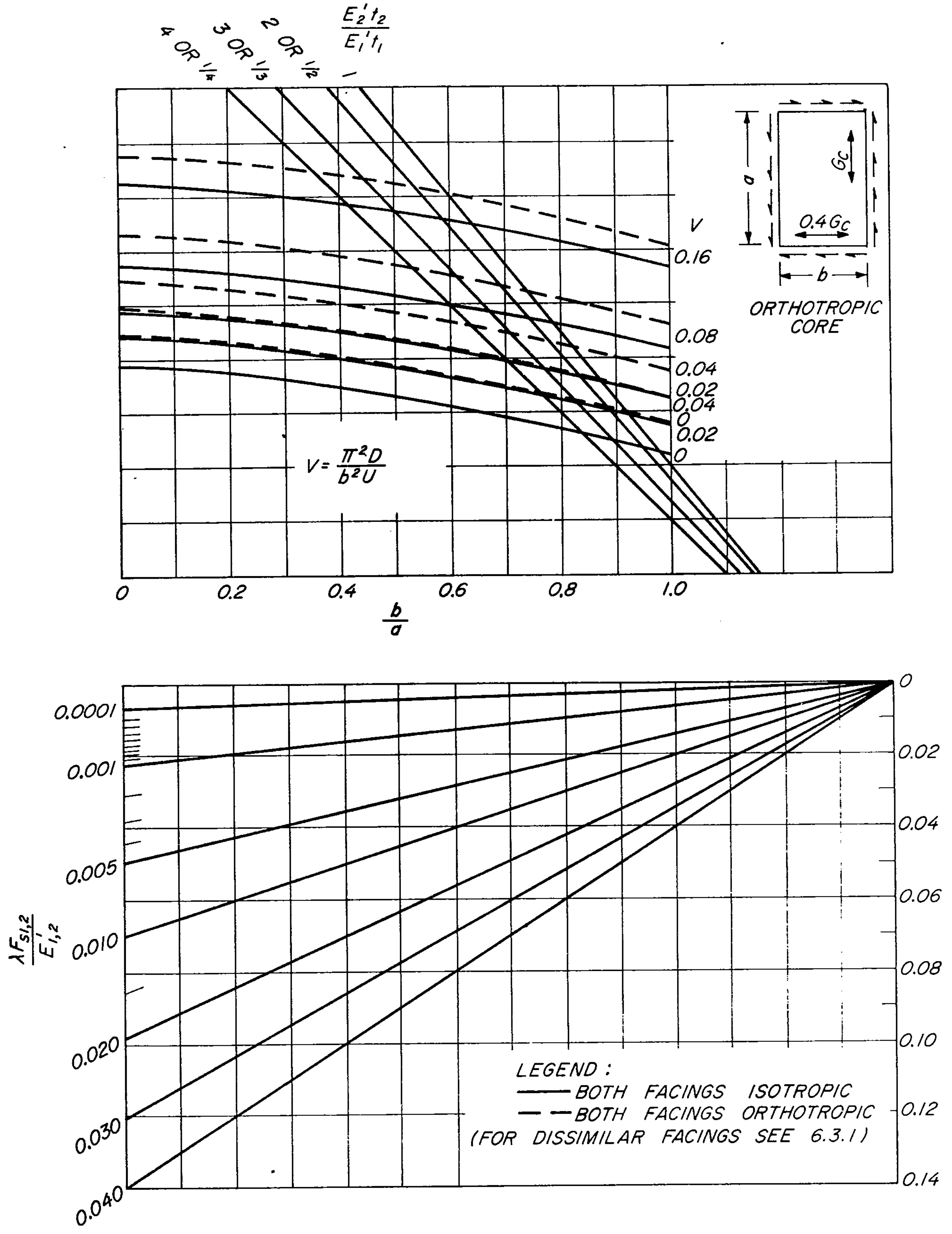


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Figure 6-2.--Chart for determining h/b ratio such that a simply supported sandwich panel with orthotropic core will not buckle under edgewise shear load. ($G_{cb} = 0.4\ G_{ca}$).

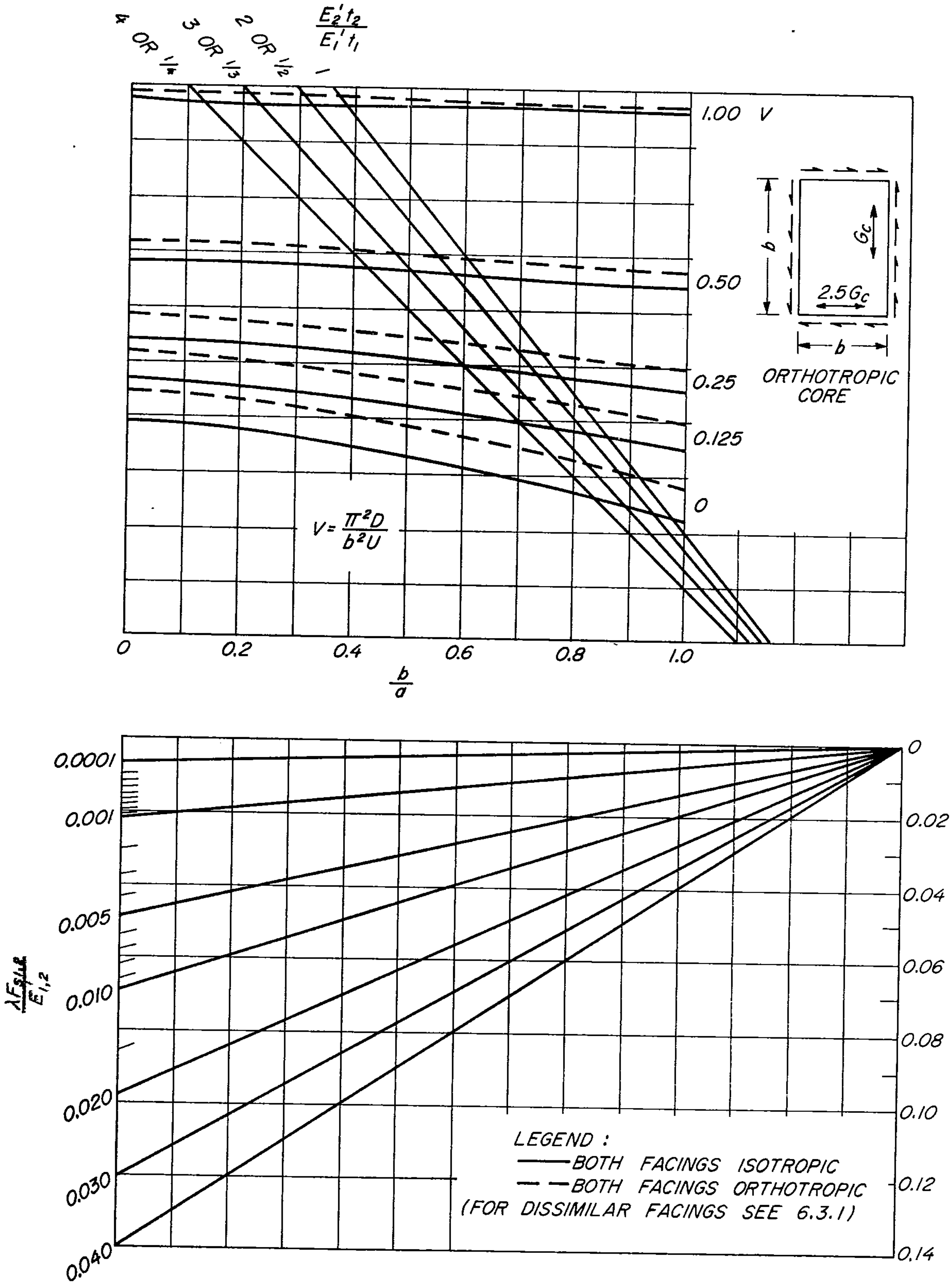


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Figure 6-3.--Chart for determining h/b ratio such that a simply supported sandwich panel with orthotropic core will not buckle under edgewise shear load. ($G_{cb}$ = 2.5 $G_{ca}$).

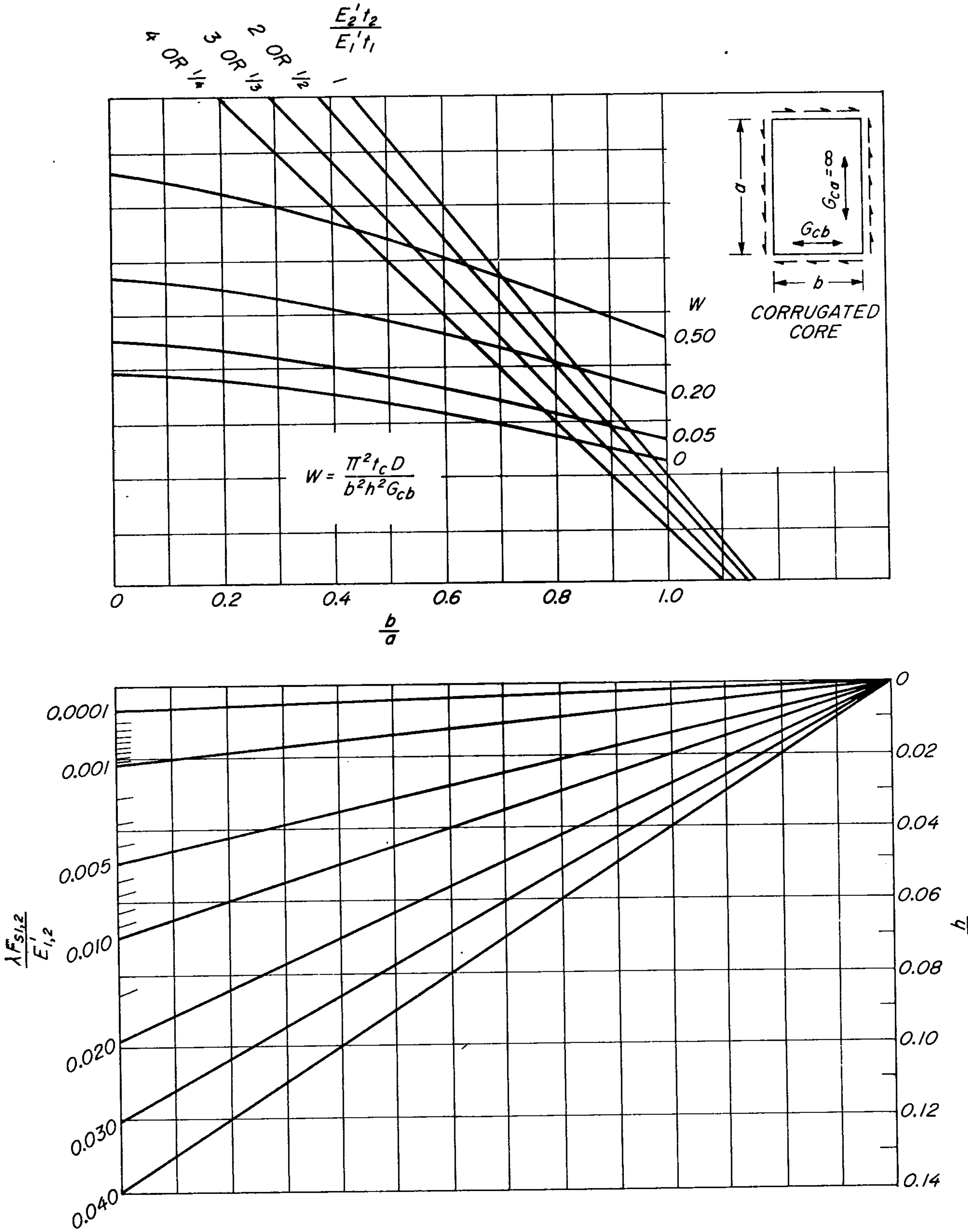


Figure 6-4.--Chart for determining h/b ratio such that a simply supported sandwich panel with isotropic facings and a corrugated core will not buckle under edgewise shear load. Core corrugation flutes parallel to edge a.

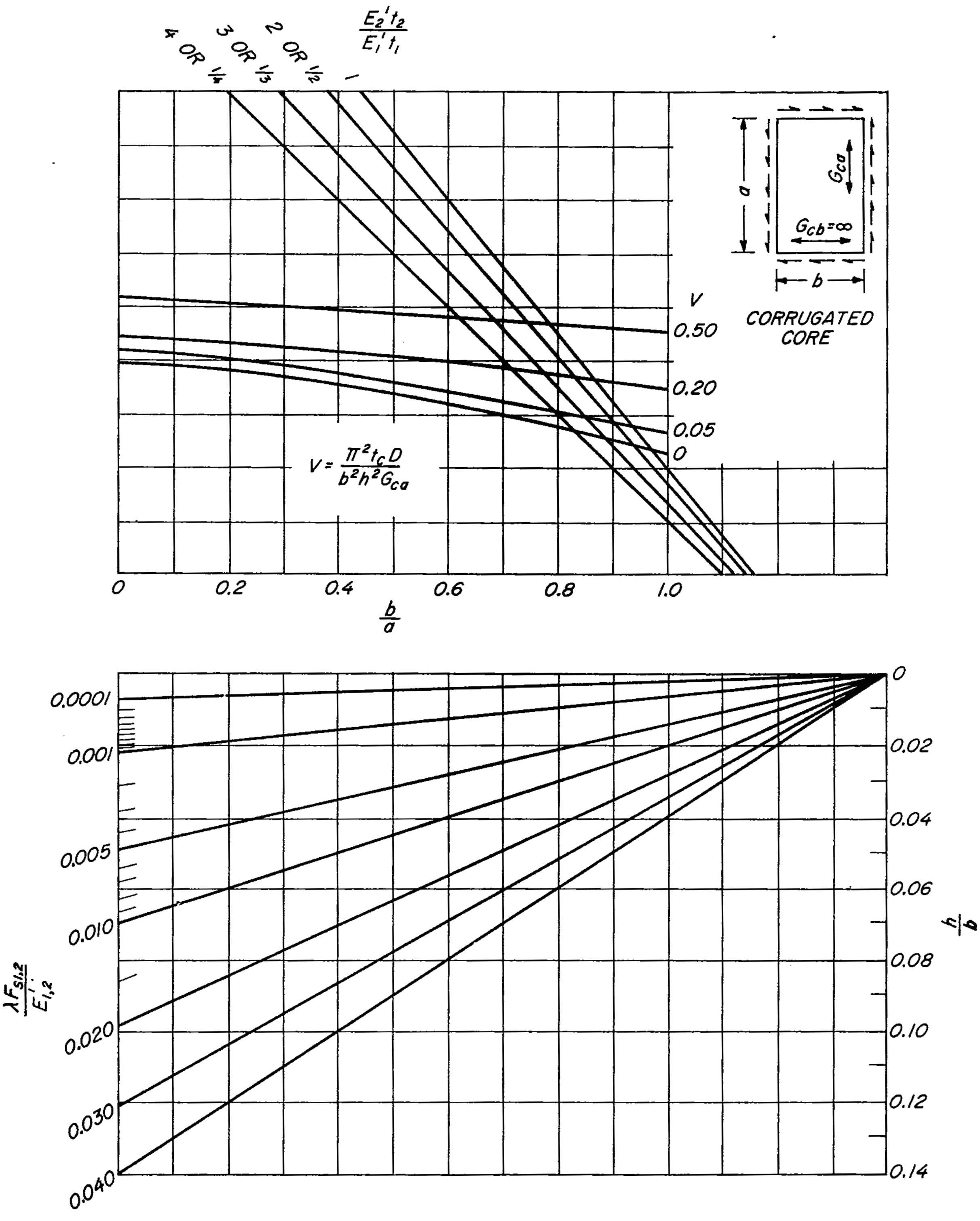


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Figure 6-5. --Chart for determining h/b ratio such that a simply supported sandwich panel with isotropic facings and a corrugated core will not buckle under edgewise shear load. Core corrugation flutes parallel to edge b.

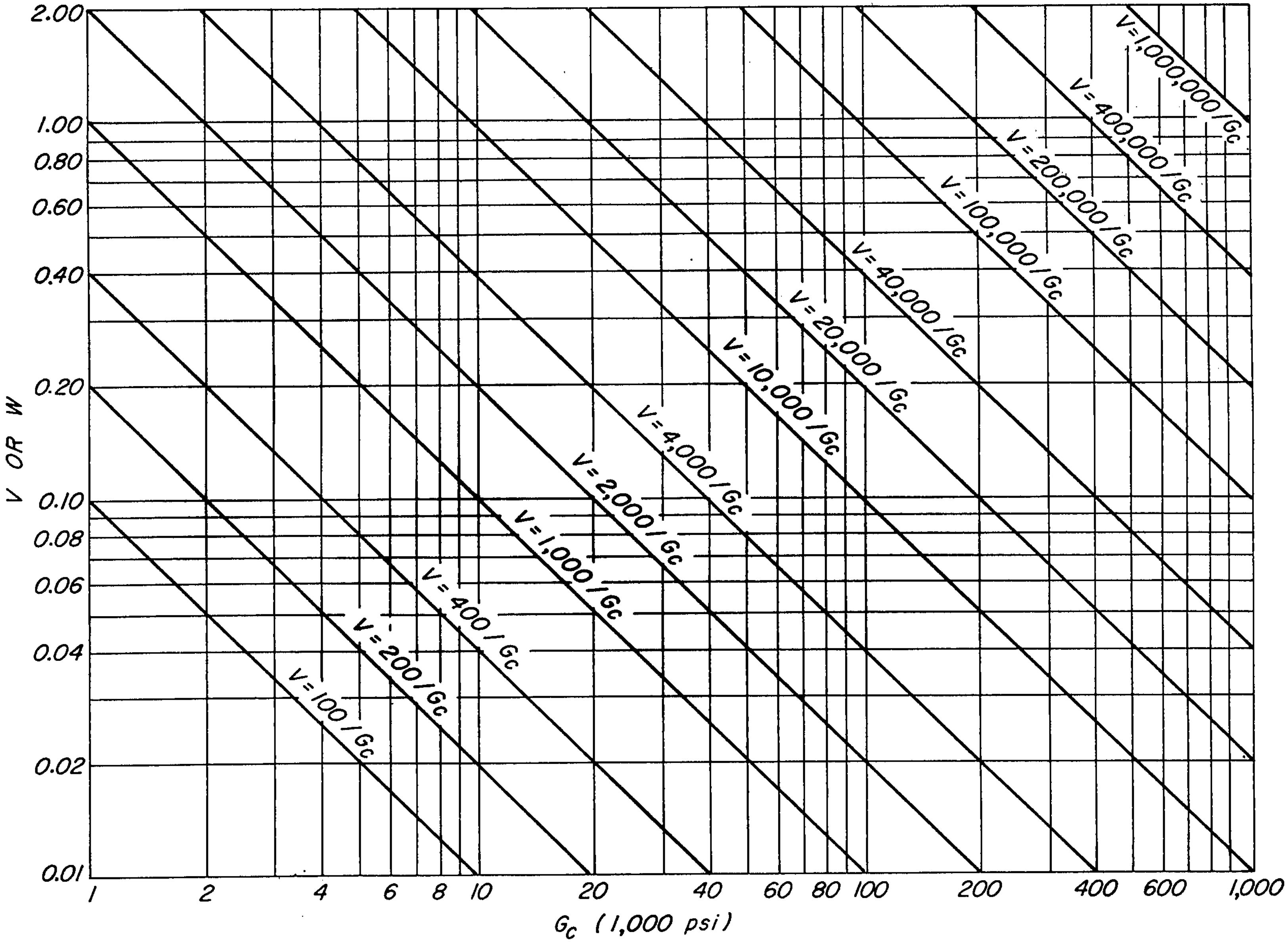


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Figure 6-6.--Chart for determining V or W and $G_c$ for sandwich in edgewise shear.

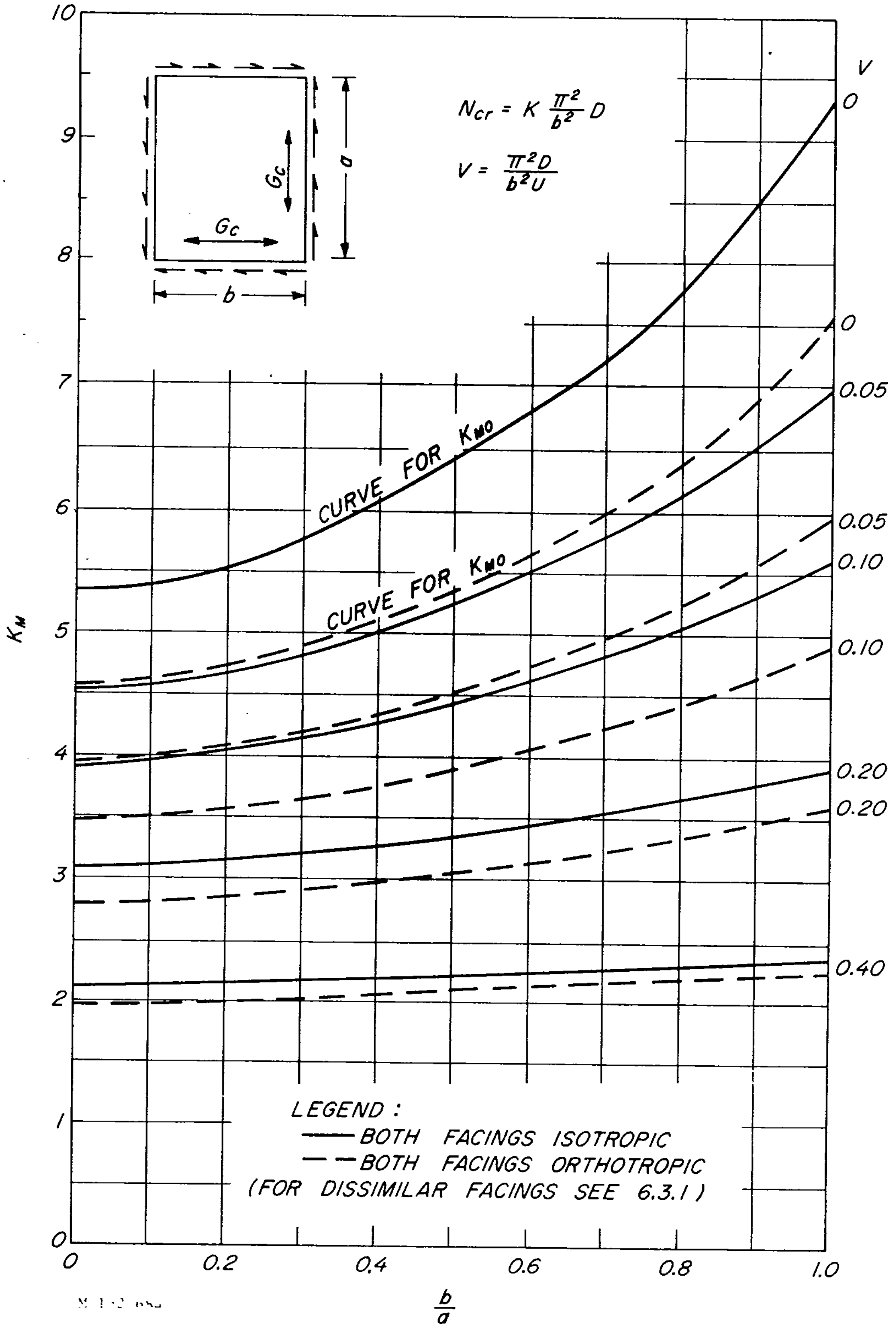


Figure 6-7. --$K_M$ for sandwich panel with all edges simply supported, and isotropic core.

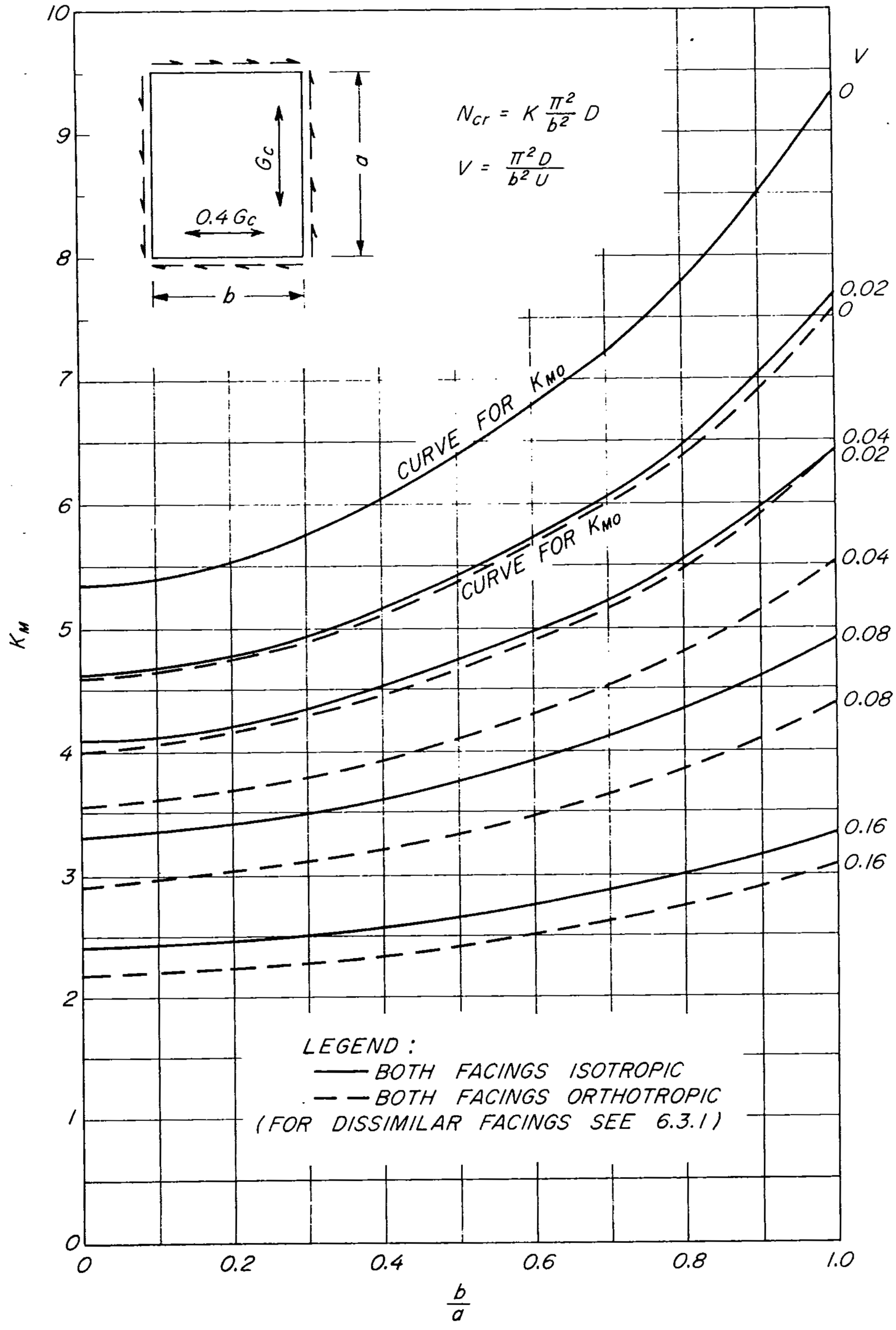


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Figure 6-8.--$K_M$ for sandwich panel with all edges simply supported, and orthotropic core. ($G_{cb} = 0.4\ G_{ca}$).

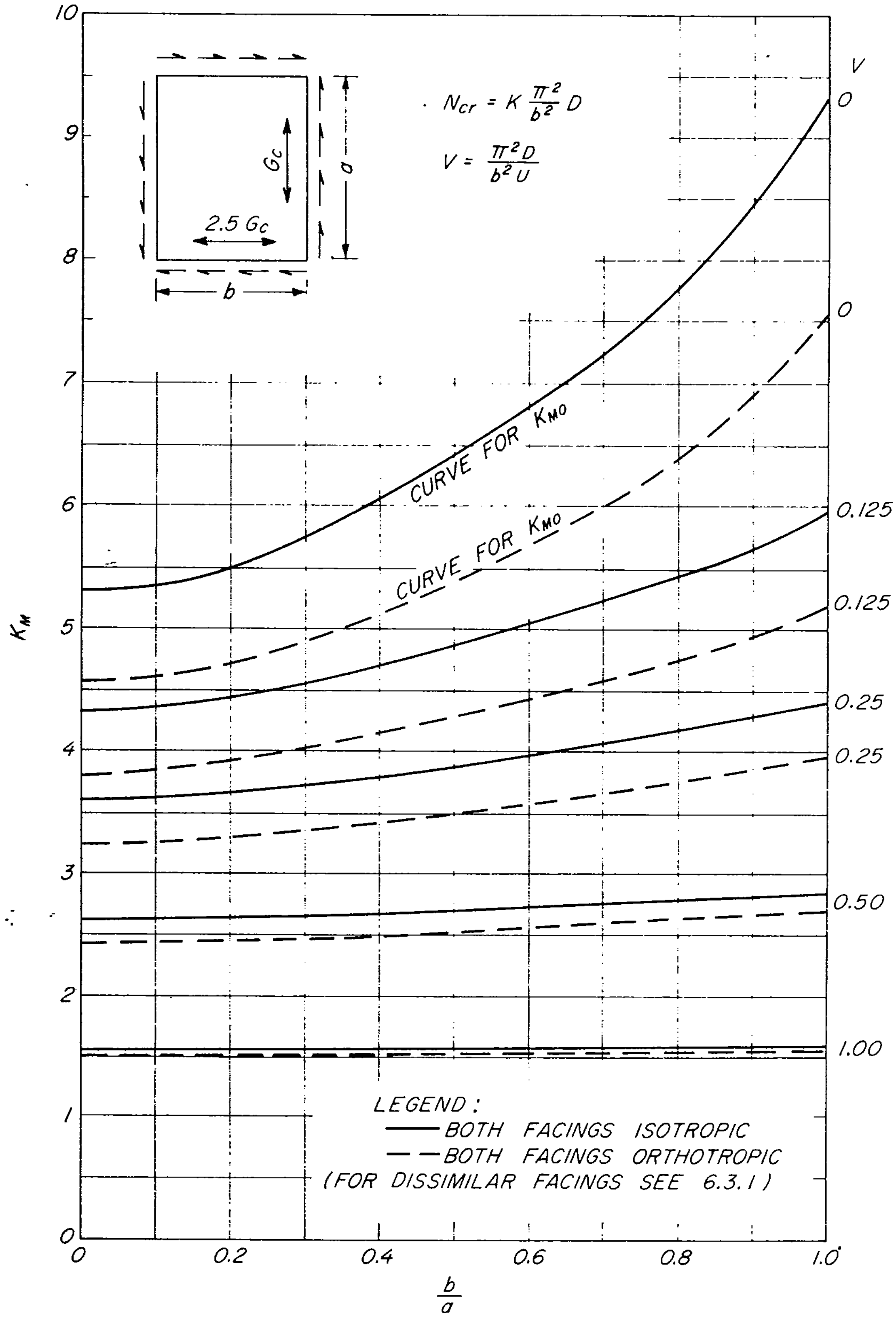


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Figure 6-9.--$K_M$ for sandwich panel with all edges simply supported, and orthotropic core. ($G_{cb}$ = 2.5 $G_{ca}$).

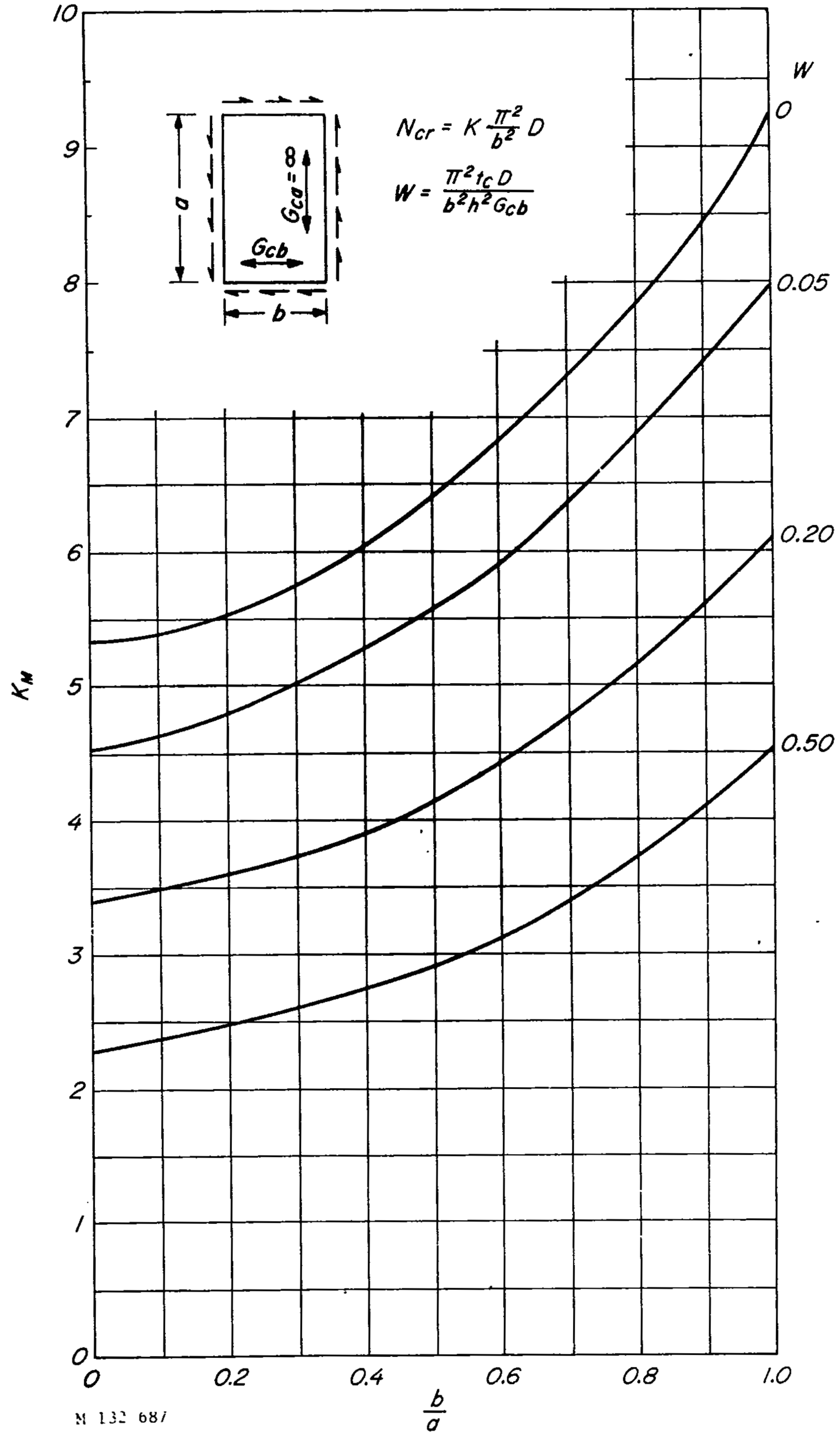


Figure 6-10. --$K_M$ for sandwich panel with all edges simply supported, isotropic facings and corrugated core. Core corrugation flutes parallel to side a.

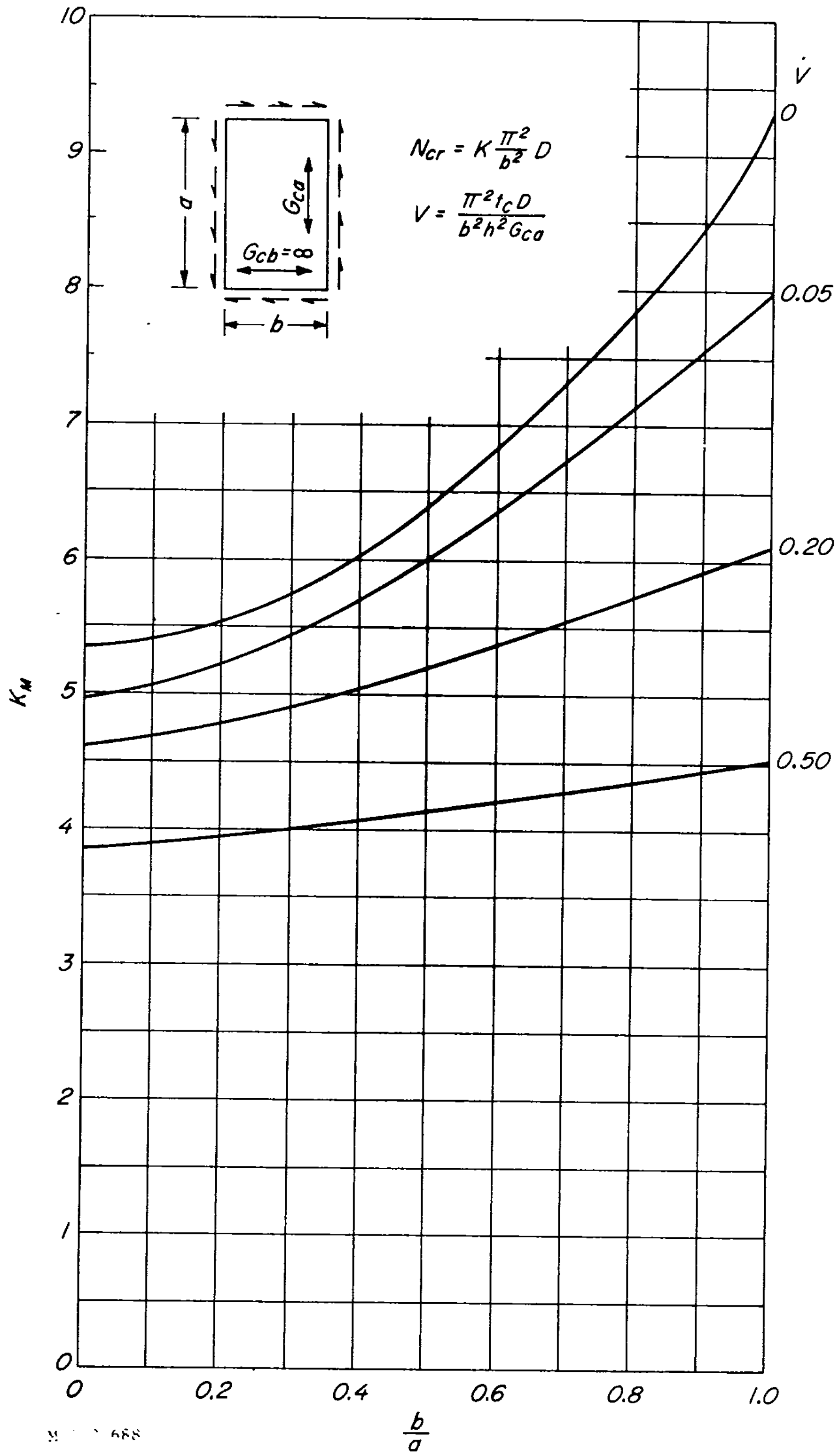


Figure 6-11.--$K_M$ for sandwich panel with all edges simply supported, isotropic facings and corrugated core. Core corrugation flutes parallel to side b.

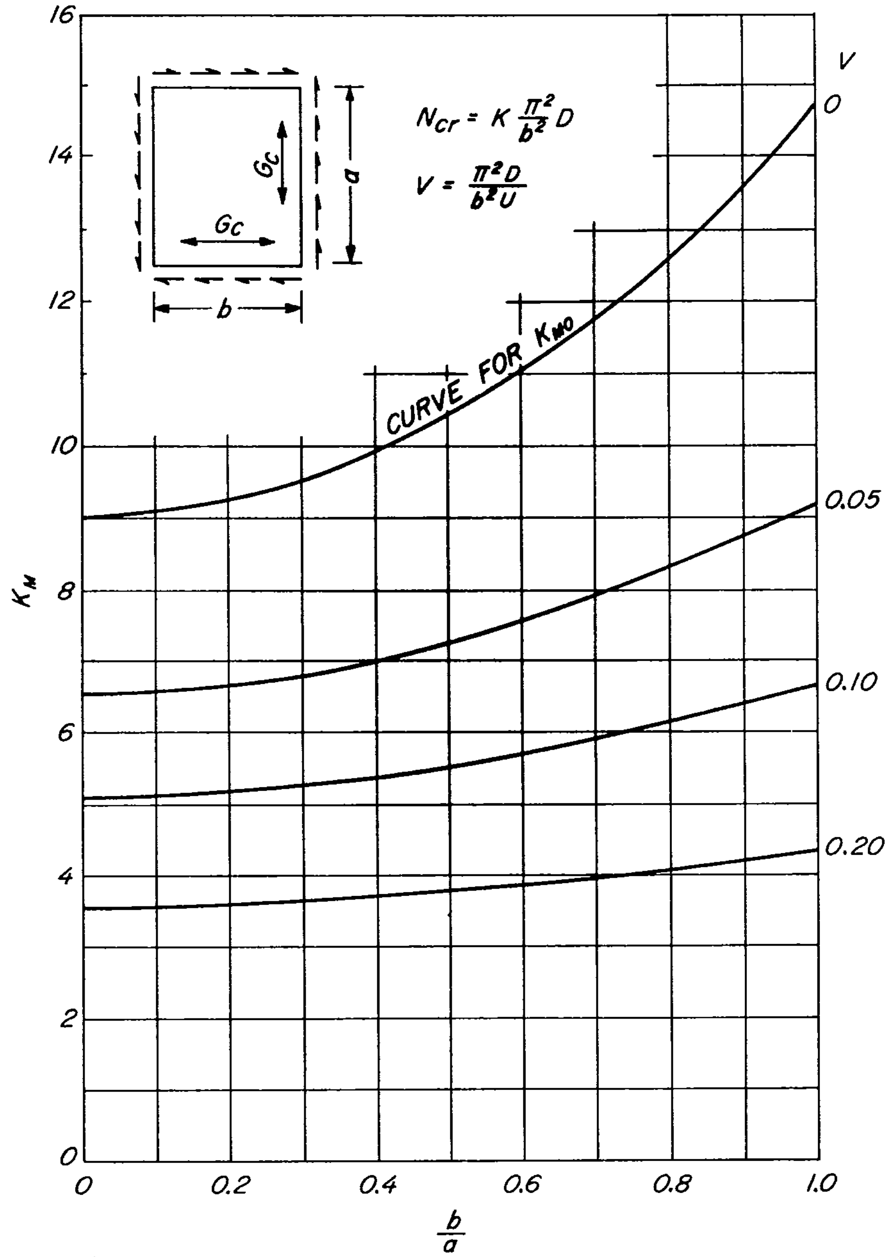


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Figure 6-12.--$K_M$ for sandwich panel with all edges clamped, isotropic facings and isotropic core.

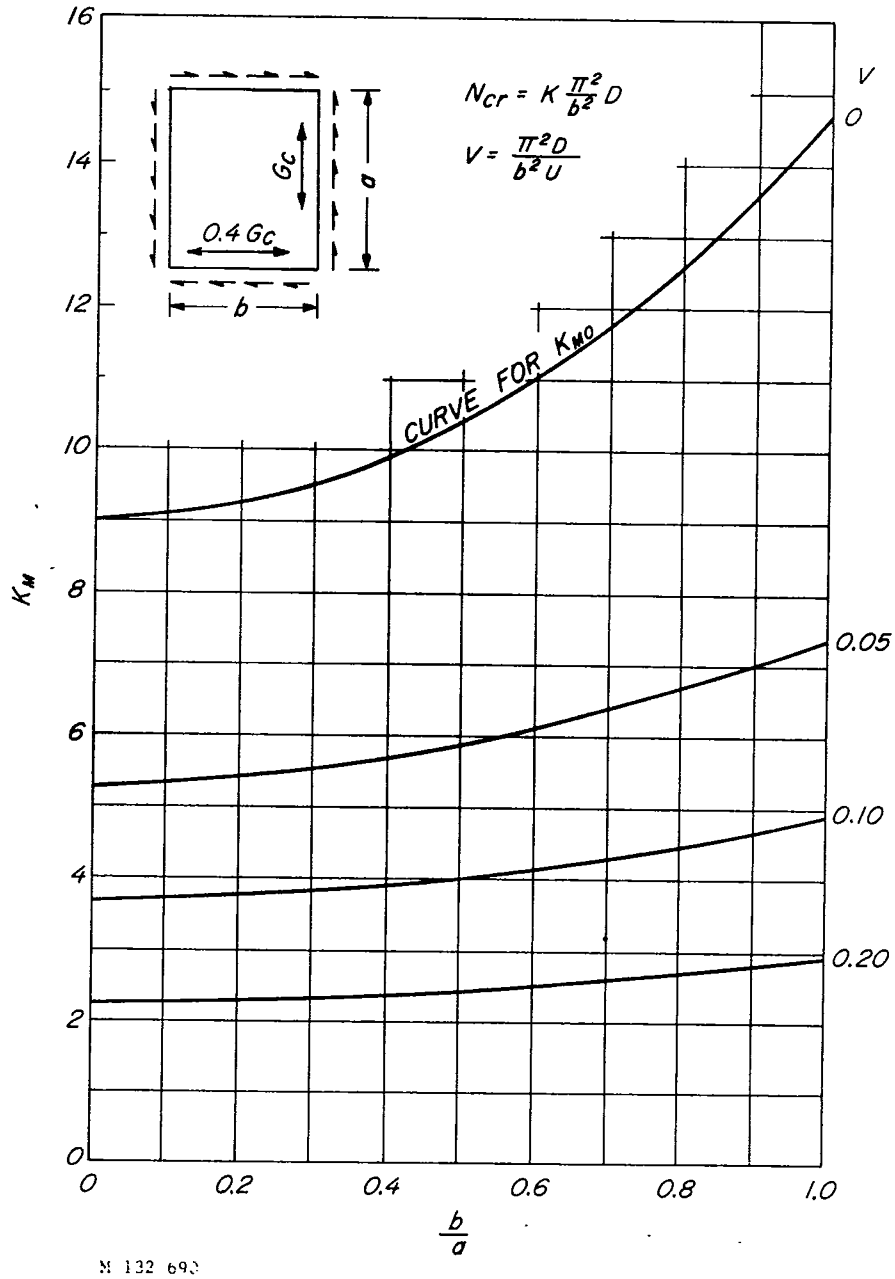


Figure 6-13.--$K_M$ for sandwich panel with all edges clamped, isotropic facings and orthotropic core. ($G_{cb} = 0.4\ G_{ca}$).

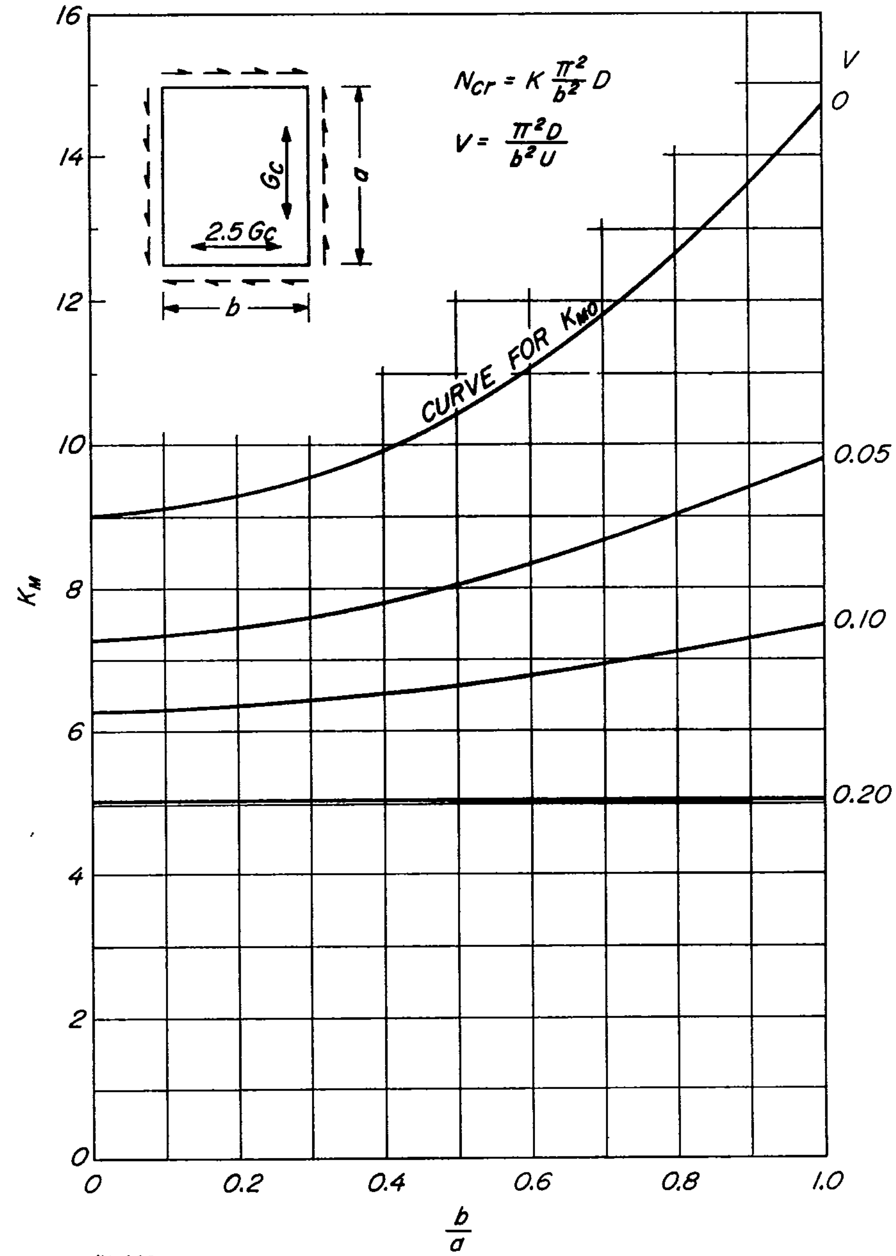


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Figure 6-14.--$K_M$ for sandwich panel with all edges clamped, isotropic facings and orthotropic core. ($G_{cb}$ = 2.5 $G_{ca}$).

# CHAPTER 7

## DESIGN OF FLAT RECTANGULAR SANDWICH PANELS UNDER EDGEWISE BENDING MOMENT

### 7.1 BASIC PRINCIPLES

Assuming that a design begins with chosen design stresses and a given load to transmit, a flat rectangular panel of sandwich construction under edgewise bending moment shall be designed to comply with the four basic design principles summarized in 1.2 of Introduction. These four conditions must be met.

Overall buckling of the sandwich or dimpling or wrinkling of the facings cannot occur without possible total collapse of the panel. Detailed procedures giving theoretical formulas and graphs for determining dimensions of the facings and core to prevent elastic buckling, as well as necessary core properties, are given in following paragraphs. Double formulas are given, one formula for sandwich with isotropic facings of different materials and thicknesses and another formula for sandwich with each isotropic facing of the same material and thickness. Because edgewise bending moment causes variation in facing stress across the panel width, extrapolation to buckling beyond the elastic range of facing stresses cannot be done by substituting an effective elastic modulus, such as a tangent modulus, in the buckling formulas. Proper extrapolation to stresses beyond the elastic range must consider the variation of effective elastic modulus across the panel width associated with the stress variation. The information given here is thus strictly applicable only to buckling at facing stresses within the elastic range. Facing modulus of elasticity, E, and stress values, $F_c$, shall be compression values at the conditions of use; that is, if application is at elevated temperature, then facing properties at elevated temperature shall be used in design.

### 7.2 DETERMINING FACING THICKNESS

Edgewise bending moment applied to a simply supported, flat rectangular sandwich panel produces the loading shown in the sketch in figure 7-1. Half of the panel is in edgewise tension, which is a stable condition, but the other half is in edgewise compression. The edge compression load, varying from zero at the neutral axis to a maximum value, N, at the panel edge, can produce buckling.

The value of N at the panel edge is determined by the formula

$$N = \frac{6M}{b^2} \qquad (7{:}1)$$

where N is load per unit edge width, M is edgewise bending moment, and b is panel width.

The formulas for buckling in edgewise bending are similar to those for edgewise compression buckling, but the critical edge load, $N_{cr}$, is higher for edgewise bending.

Facing stresses are related to the edge load by the equations:

$$t_1F_{c1} + t_2F_{c2} = N \quad \text{(for unequal facings)} \qquad (7{:}2)$$

$$t = \frac{N}{2F_c} \quad \text{(for equal facings)} \qquad (7{:}2a)$$

where t is facing thickness; $F_c$ is chosen design facing compressive stress; N is design compression load per unit length of panel edge; and 1, 2 are subscripts denoting facings 1 and 2.

In determining thicknesses of facings for sandwich with facings of different materials, equation (7:2) must be satisfied, but also the stresses $F_{c1}$ and $F_{c2}$ must be chosen so that $F_{c1}/E_1 = F_{c2}/E_2$ (where E is facing modulus of elasticity), thus avoiding overstressing of either facing. For example, if facing 1 is of a material such that the ratio $F_{c1}/E_1 = 0.005$ and facing 2 is of a material such that the ratio $F_{c2}/E_2 = 0.002$, the designs must be based on a ratio of 0.002; otherwise facing 2 will be overstressed. In order to accomplish this, the chosen design stresses for facing 1 must be lowered. For many combinations of facing materials, it will be found advantageous to choose thicknesses such that $E_1t_1 = E_2t_2$. If the core can support edge load, N should be replaced by $(N - F_ct_c)$.

## 7.3 DETERMINING CORE THICKNESS AND CORE SHEAR MODULUS

This section gives procedures for determining core thickness and core shear modulus so that overall buckling of the sandwich panel will not occur (refs. 7-1 and 7-2).

The load per unit panel width at the panel edge at which buckling of a sandwich panel will occur is given by the theoretical formula: $N_{cr} = K \frac{\pi^2}{b^2} D$, where D is the sandwich bending stiffness. This formula solved for the facing stress becomes:

$$F_{c1,2} = \pi^2 K \frac{E_1 t_1 E_2 t_2}{(E_1 t_1 + E_2 t_2)^2} \left(\frac{h}{b}\right)^2 \frac{E_{1,2}}{\lambda} \qquad (7:3)$$

$$F_c = \frac{\pi^2 K}{4} \left(\frac{h}{b}\right)^2 \frac{E}{\lambda} \quad \text{(for equal facings)} \qquad (7:3a)$$

where E is modulus of elasticity of facing; $\lambda = 1 - \mu^2$; $\mu$ is Poisson's ratio of facings (in formula (7:3) it is assumed that $\mu = \mu_1 = \mu_2$); h is distance between facing centroids; b is length of loaded panel edge; $K = K_F + K_M$; $K_F$ is a theoretical coefficient dependent on facing stiffness and panel aspect ratio; and $K_M$ is a theoretical coefficient dependent on sandwich bending and shear rigidities and panel aspect ratio.

Solving equations (7:3) and (7:3a) for h/b gives:

$$\frac{h}{b} = \frac{1}{\pi\sqrt{K}} \sqrt{\frac{\lambda F_{c1,2}}{E_{1,2}} \left(\frac{E_1 t_1 + E_2 t_2}{\sqrt{E_1 t_1 E_2 t_2}}\right)} \qquad (7:4)$$

$$\frac{h}{b} = \frac{2}{\pi\sqrt{K}} \sqrt{\frac{\lambda F_c}{E}} \quad \text{(for equal facings)} \qquad (7:4a)$$

Therefore, if K is known, equation (7:4) or (7:4a) can be solved directly to eventually obtain h because all other quantities are known. After h is obtained, the core thickness, $t_c$, is computed from the formulas:

$$t_c = h - \frac{t_1 + t_2}{2} \qquad (7:5)$$

$$t_c = h - t \quad \text{(for equal facings)} \qquad (7:5a)$$

As a first approximation, it will be assumed that $K_F = 0$, hence $K = K_M$. Values of $K_M$ depend upon the bending and shear rigidities of the sandwich as incorporated in the parameter $V = \frac{\pi^2 D}{b^2 U}$ which can be written as:

$$V = \frac{\pi^2 t_c E_1 t_1 E_2 t_2}{b^2 \lambda (E_1 t_1 + E_2 t_2) G_c} \qquad (7:6)$$

$$V = \frac{\pi^2 t_c Et}{2b^2 \lambda G_c} \quad \text{(for equal facings)} \qquad (7:6a)$$

where U is sandwich shear stiffness; $G_c$ is the core shear modulus associated with the axes parallel to the direction of loading (also parallel to panel side of length a) and perpendicular to the plane of the panel. As values of core shear modulus decrease, values of V increase and values of $K_M$ gradually decrease. For sandwich with corrugated core having corrugation flutes parallel to the direction of loading, the parameter V is replaced by the parameter:

$$W = \frac{\pi^2 t_c E_1 t_1 E_2 t_2}{b^2 \lambda (E_1 t_1 + E_2 t_2) G_{cb}} \qquad (7:7)$$

$$W = \frac{\pi^2 t_c Et}{2b^2 \lambda G_{cb}} \quad \text{(for equal facings)} \qquad (7:7a)$$

where $G_{cb}$ is the core shear modulus associated with the axes perpendicular to direction of loading (parallel to panel side of length b) and perpendicular to the plane of the panel.

### 7.3.1 Determination of Minimum Values of h

A minimum value of h required will be determined by assuming V = 0 or W = 0 for a first approximation. The value of h is minimum because V = 0 or W = 0 only if the core shear modulus is infinite; for any actual core, the shear modulus is not infinite, hence a thicker core must be used. The minimum value of h may be found using V = 0 or W = 0 in any of the charts in figure 7-1 through 7-4. These charts apply to simply supported sandwich panels having isotropic facings and isotropic, orthotropic, or corrugated cores.

Parameters needed for use of the charts are:

1. Panel aspect ratio a/b or b/a
2. Facing properties $\frac{\lambda F_{c1,2}}{E_{1,2}}$
3. Ratio of $E_2t_2/E_1t_1$

### 7.3.2 Determination of Actual Values of h

Since actual core shear modulus values are not very large, a value of h somewhat greater than that determined by assuming V = 0 or W = 0 must be used. Charts for determining h for sandwich with all edges simply supported are shown in figures 7-1, 7-2, 7-3, and 7-4. The figures are entered with values of the panel aspect ratio and values of V as computed by equation (7:6) or (7:6a) or values of W as computed by equation (7:7) or (7:7a). Figure 7-1 applies to sandwich with isotropic cores for which the core shear modulus perpendicular to the direction of loading is equal to the core shear modulus parallel to the direction of loading. Figure 7-2 applies to sandwich with honeycomb cores for which the core shear modulus perpendicular to the direction of loading is equal to 0.40 times the core shear modulus parallel to the direction of loading. Figure 7-3 applies to sandwich with honeycomb core for which the core shear modulus perpendicular to the direction of loading is 2.50 times the core shear modulus parallel to the direction of loading.

Note: For honeycomb cores with core ribbons parallel to direction of loading, $G_c = G_{TL}$ and the shear modulus perpendicular to loading is $G_{TW}$. For honeycomb cores with core ribbons perpendicular to direction of loading, $G_c = G_{TW}$ and the shear modulus perpendicular to loading is $G_{TL}$.

Figure 7-4 applies to sandwich with corrugated core having the core flutes parallel to the direction of loading.

In using figures 7-1, 7-2, 7-3, and 7-4, it is necessary to iterate because V and W are directly proportional to the core thickness $t_c$. As an aid to finally determining $t_c$ and $G_c$, figure 7-5 presents a number of lines representing V for various values of $G_c$ with V ranging from 0.01 to 2 and $G_c$ ranging from 1,000 to 1,000,000 pounds per square inch. The following procedure is suggested:

1. Determine a core thickness $t_c$ from figure 7-1, 7-2, 7-3, or 7-4 using a value of 0.01 for V or W.

2. Compute the constant relating V or W to $G_c$.

$$\left[\frac{\pi^2 t_c E_1 t_1 E_2 t_2}{b^2 \lambda (E_1 t_1 + E_2 t_2)}\right] \text{ or } \left[\frac{\pi^2 t_c E t}{2 b^2 \lambda}\right] \text{ (for equal facings)} = VG_c \text{ or } WG_c$$

3. With this constant, enter figure 7-5 and determine necessary $G_c$.

4. If the shear modulus is outside the range of values for materials available, slide up the appropriate line of figure 7-5 and pick a new value of V or W, for a reasonable value of core shear modulus.

5. Reenter figure 7-1, 7-2, 7-3, or 7-4 with the new value of V or W and repeat previous steps 1, 2, and 3.

### 7.3.3 Checking Procedure for Determining Buckling Stress, $F_{cr}$

The design shall be checked by using the graphs of figures 7-6 to 7-9 to determine values of $K_M$ for use in evaluating $K = K_F + K_M$ to substitute into formula (7:3) or (7:3a) to compute actual buckling stress, $F_{cr}$. The figures apply to sandwich panels with edges simply supported and with isotropic or certain orthotropic cores (see 7.3.2).

For each value of the parameter V or W, there is a cusped curve giving values of $K_M$ for various values of the ratio a/b or b/a. These cusps are indicated by dotted lines for the top curve in each figure. The cusps show the sandwich panel buckling coefficients calculated for different values of n, the number of half waves into which the panel buckles. Only the portions of each cusped curve for which $K_M$ is a minimum are shown. Envelope curves indicate values of $K_M$ for use in design.

Values of $K_F$ shall be determined from the formula:

$$K_F = \frac{(E_1t_1^3 + E_2t_2^3)(E_1t_1 + E_2t_2)}{12E_1t_1E_2t_2h^2} K_{MO} \qquad (7:8)$$

$$K_F = \frac{t^2}{3h^2} K_{MO} \quad \text{(for equal facings)} \qquad (7:8a)$$

where $K_{MO} = K_M$ when V = 0 or W = 0 and thus can be obtained from the graphs of figures 7-6 to 7-9. For panels with a/b ratios $\geqq 0.4$, it can be assumed that $K_F = 0$. Then K shall be computed as $K_F + K_M = K_M$ and equation (7:3) or (7:3a) solved for $F_{cr}$.

If the charts do not apply because ratios of core shear moduli are far different from what is given on the charts, or it is desired to check by a more accurate analysis, the formulas given in references 7-1 and 7-2 shall be used.

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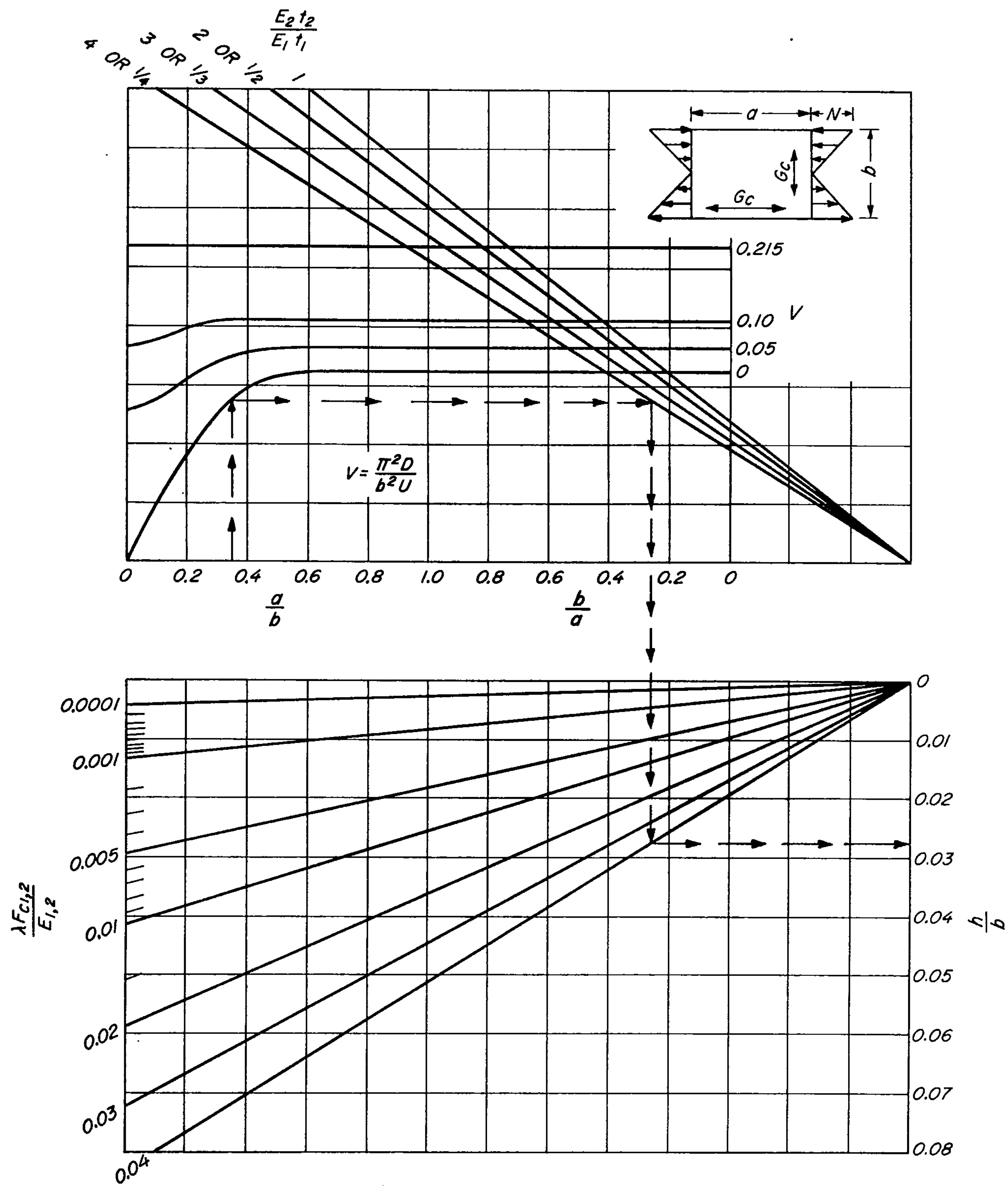
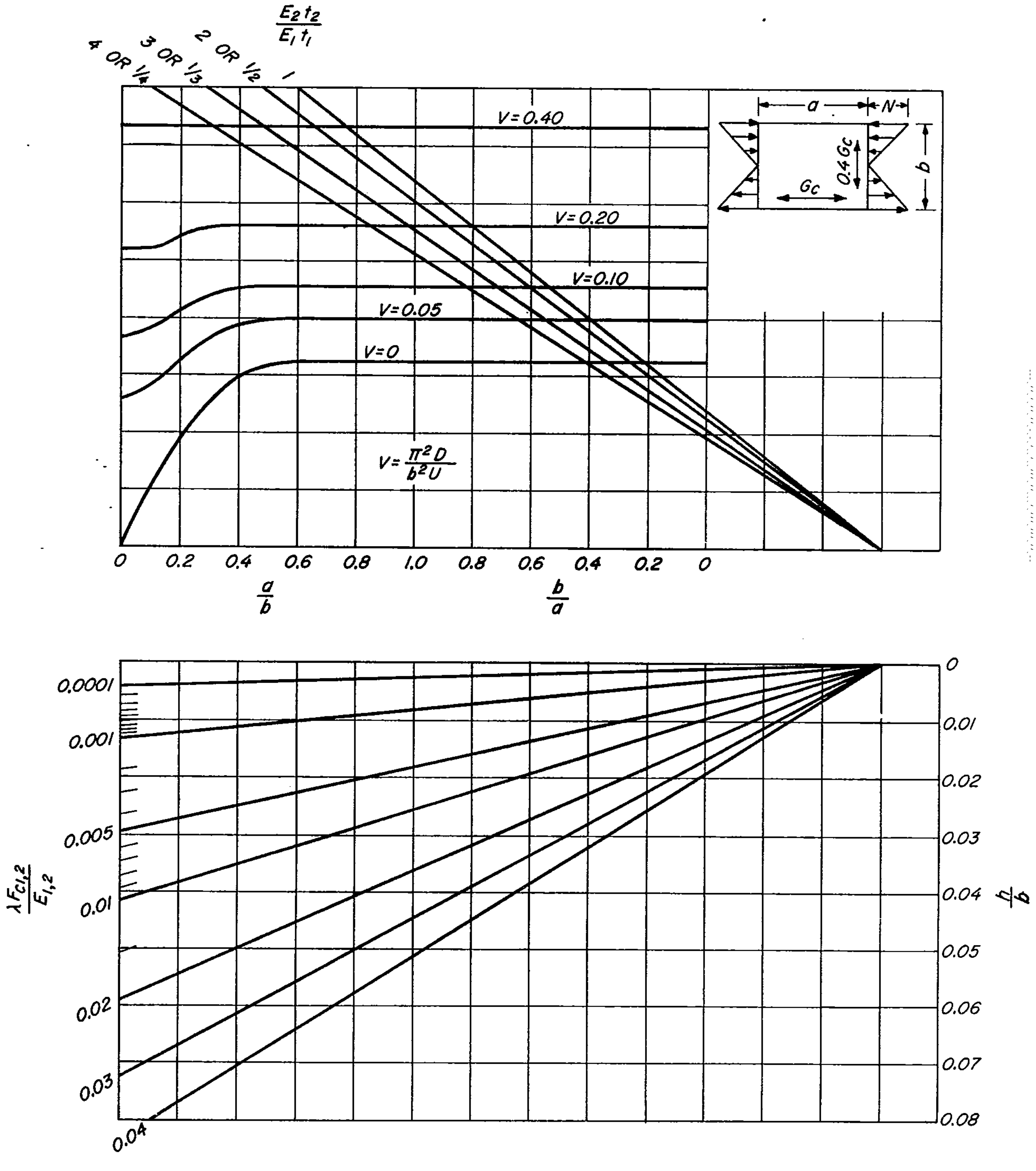


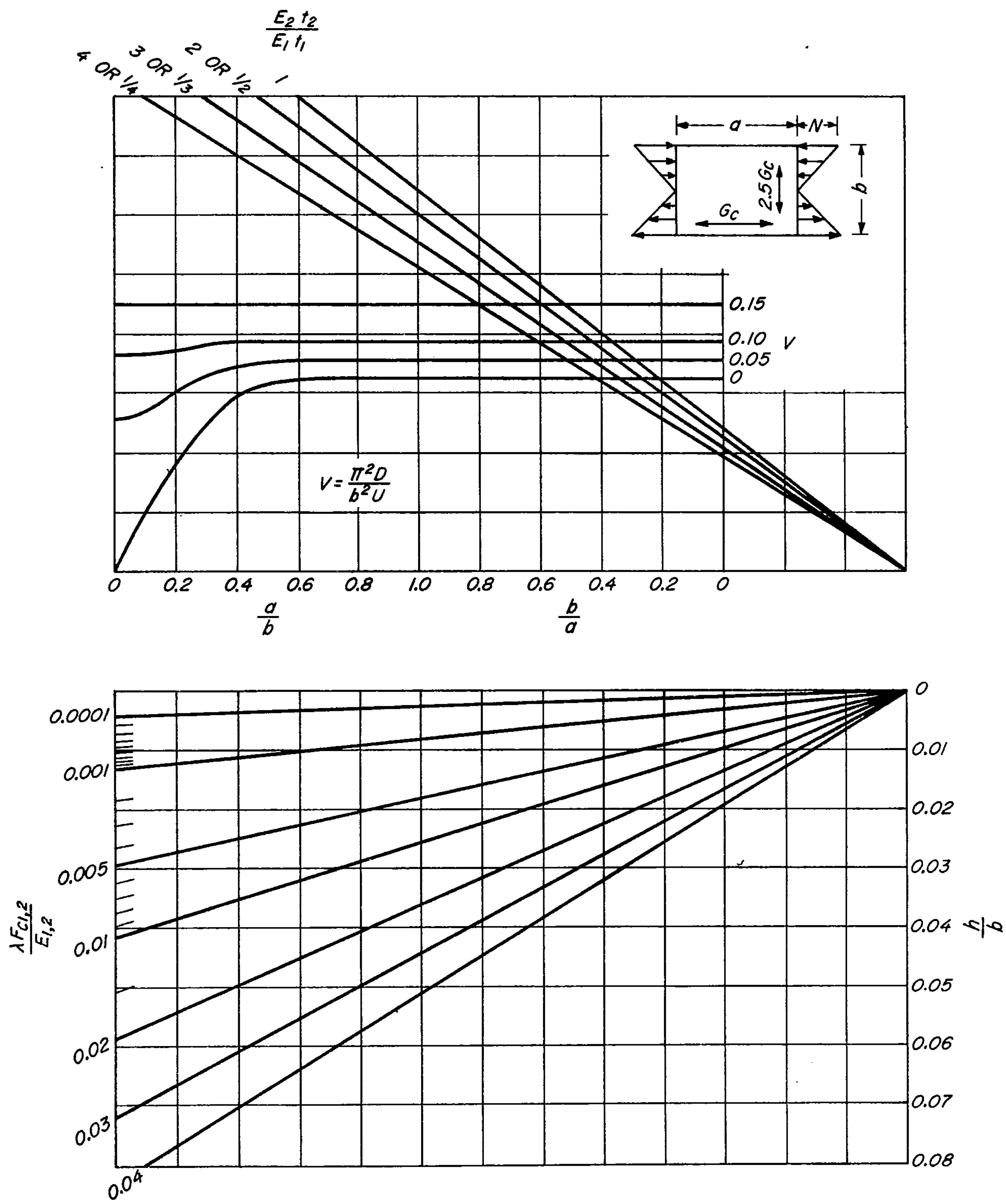

M 132 949

Figure 7-1.--Chart for determining h/b ratio such that a simply supported sandwich panel with isotropic facings and isotropic core will not buckle elastically under edgewise bending load. ($G_{cb} = G_{ca}$).



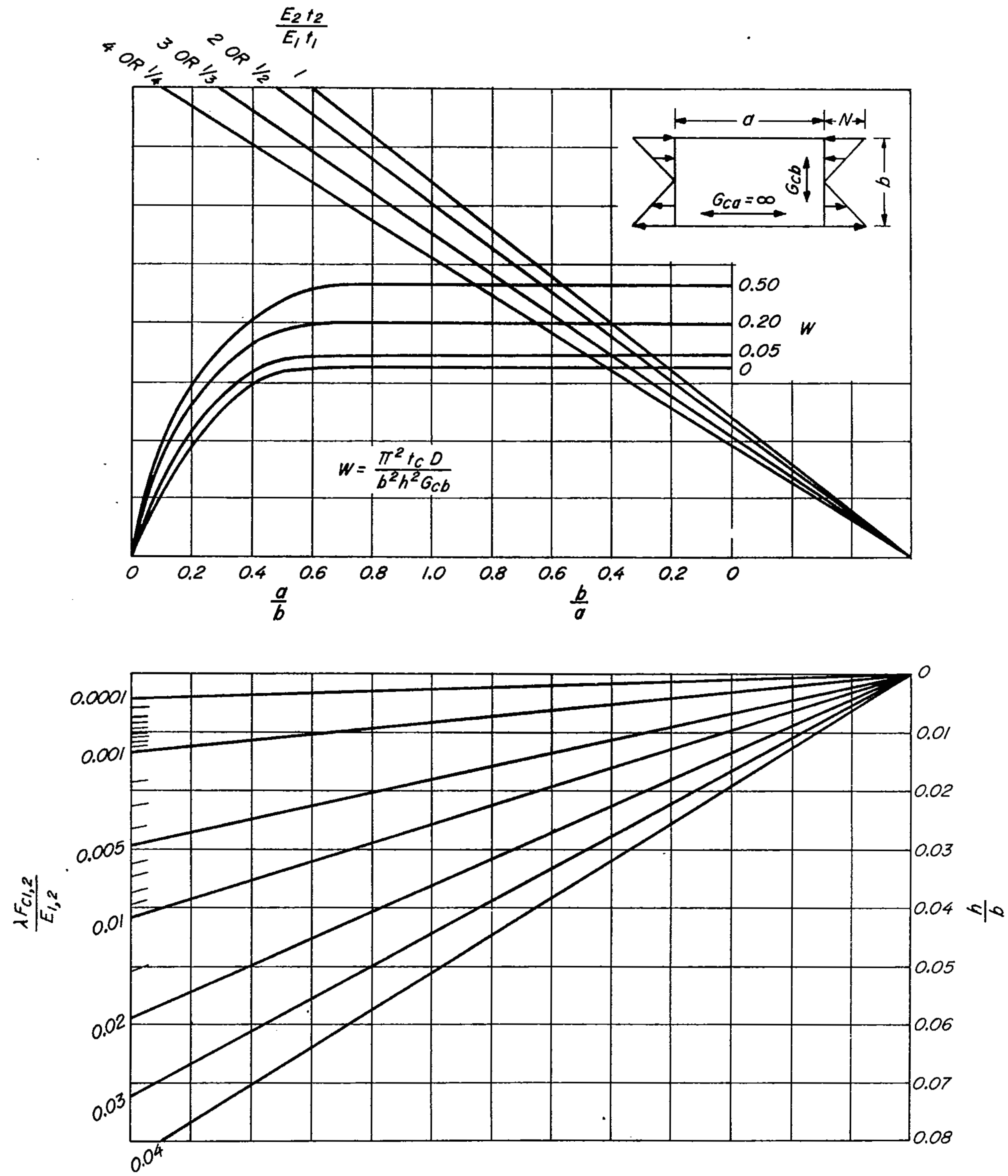

M 132 953

Figure 7-2. --Chart for determining h/b ratio such that a simply supported sandwich panel with isotropic facings and orthotropic core will not buckle elastically under edgewise bending load. ($G_{cb}$ = 0.4 $G_{ca}$).



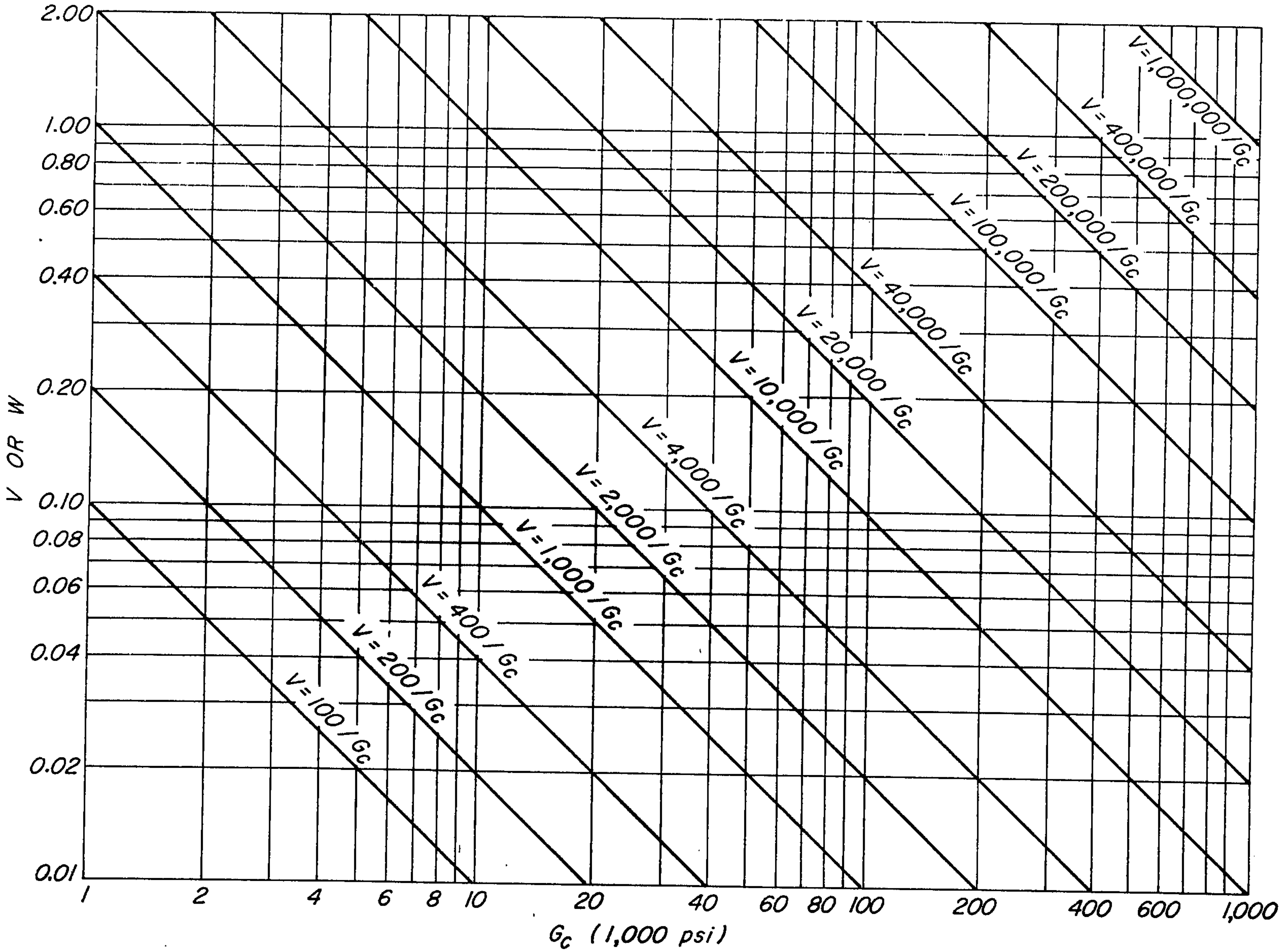

M 132 955

Figure 7-3.--Chart for determining h/b ratio such that a simply supported sandwich panel with isotropic facings and orthotropic core will not buckle elastically under edgewise bending load. ($G_{cb}$ = 2.5 $G_{ca}$).



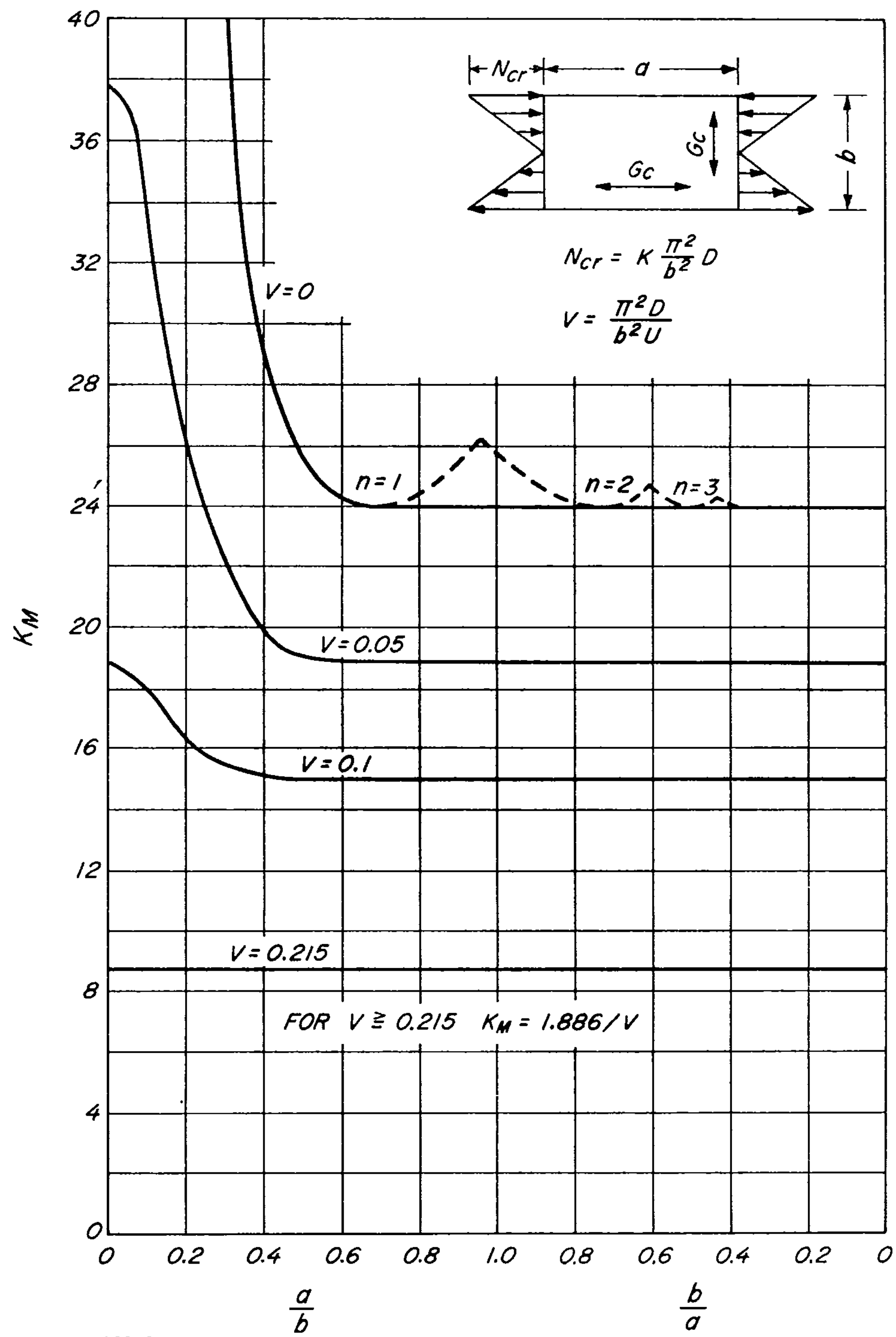

M 132 948

Figure 7-4.--Chart for determining h/b ratio such that a simply supported sandwich panel with isotropic facings and a corrugated core will not buckle elastically under edgewise bending load. Core corrugation flutes parallel to side a.



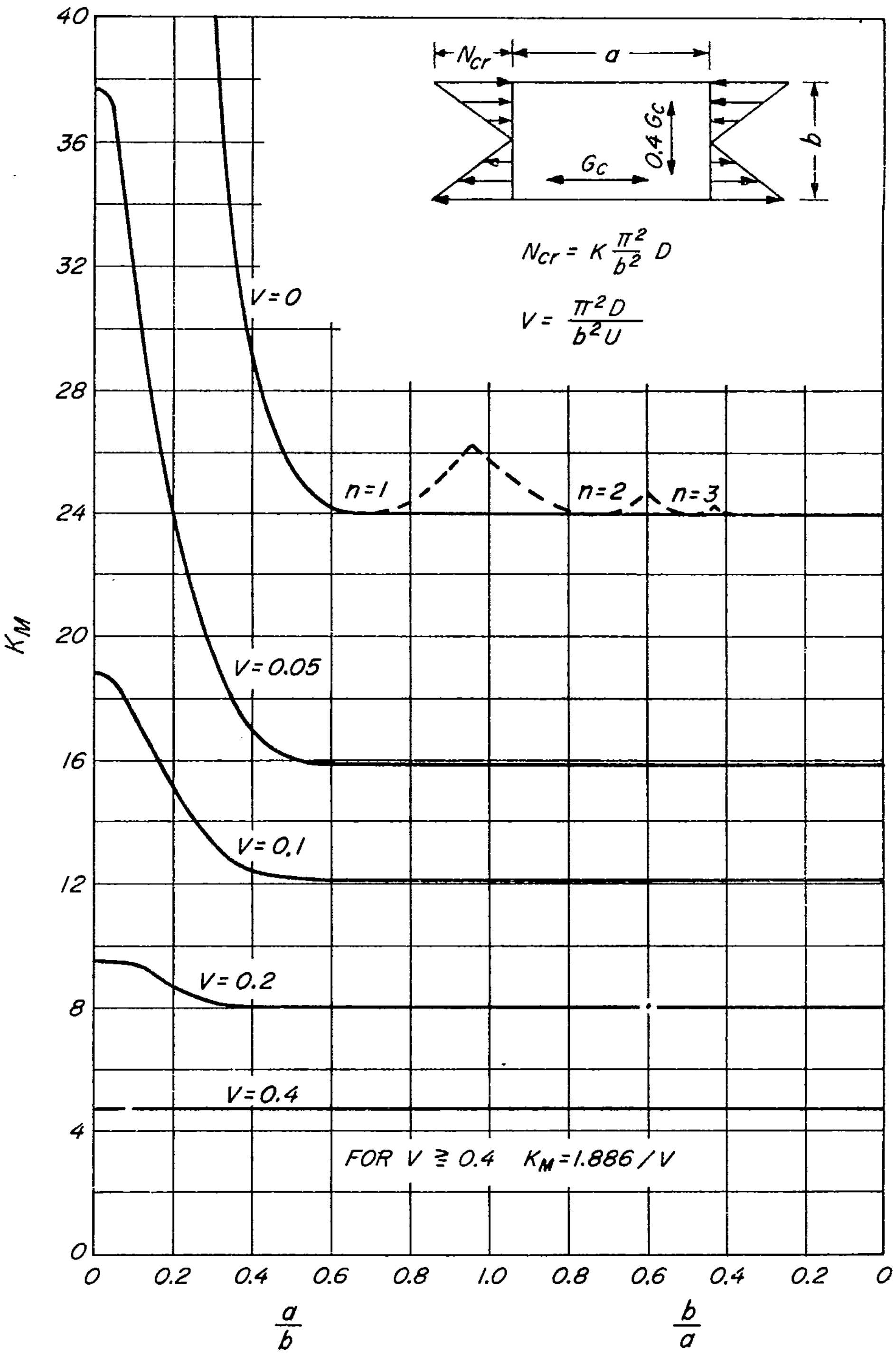

M 132 669

Figure 7-5.--Chart for determining V or W and $G_c$ for sandwich in edgewise bending.




M 132 951

Figure 7-6.--$K_M$ for simply supported sandwich panel with isotropic core. ($G_{cb} = G_{ca}$).




M 132 952

Figure 7-7.--$K_M$ for simply supported sandwich panel with orthotropic core. ($G_{cb} = 0.4\ G_{ca}$).

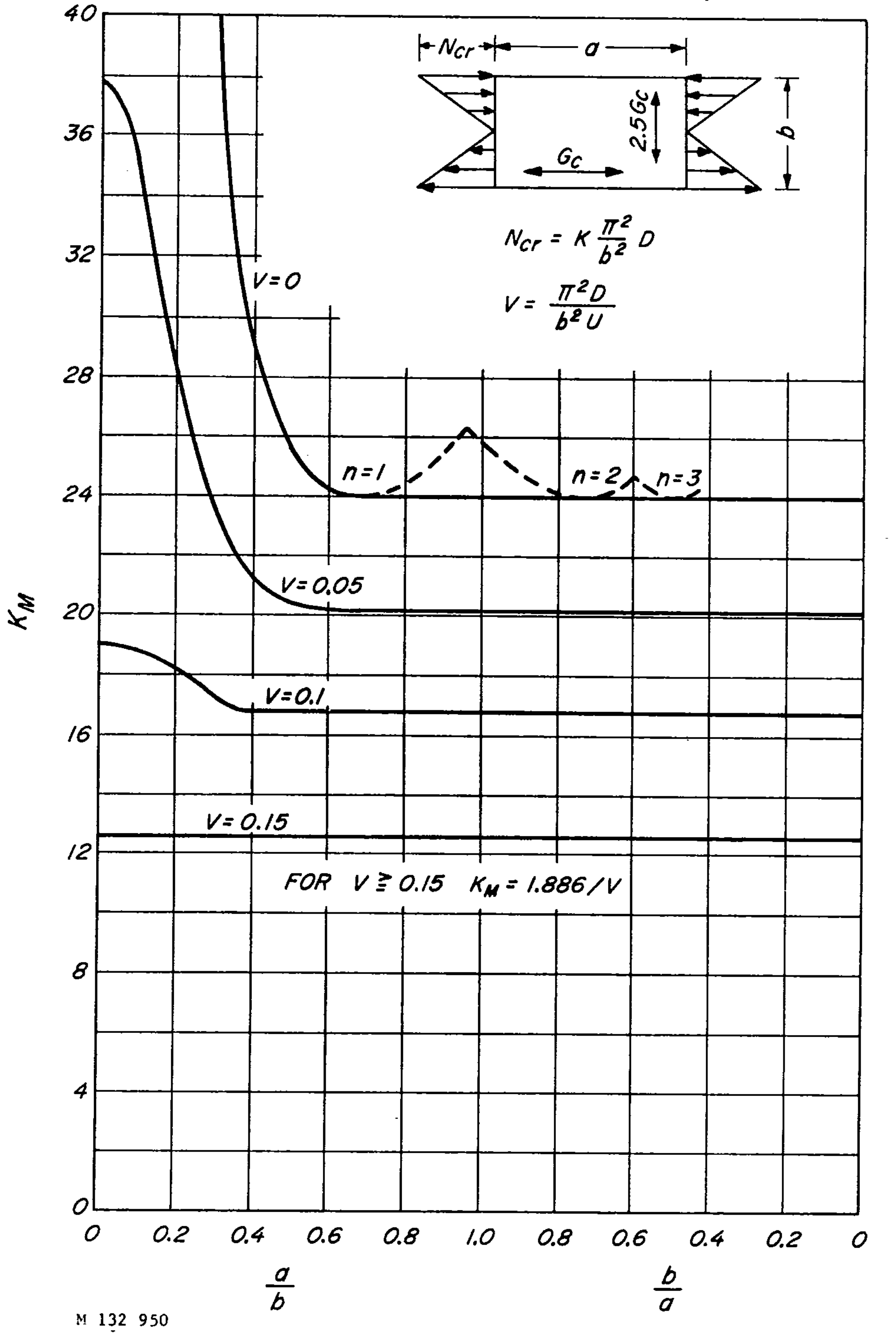



Figure 7-8. --$K_M$ for simply supported sandwich panel with orthotropic core. ($G_{cb}$ = 2.5 $G_{ca}$).

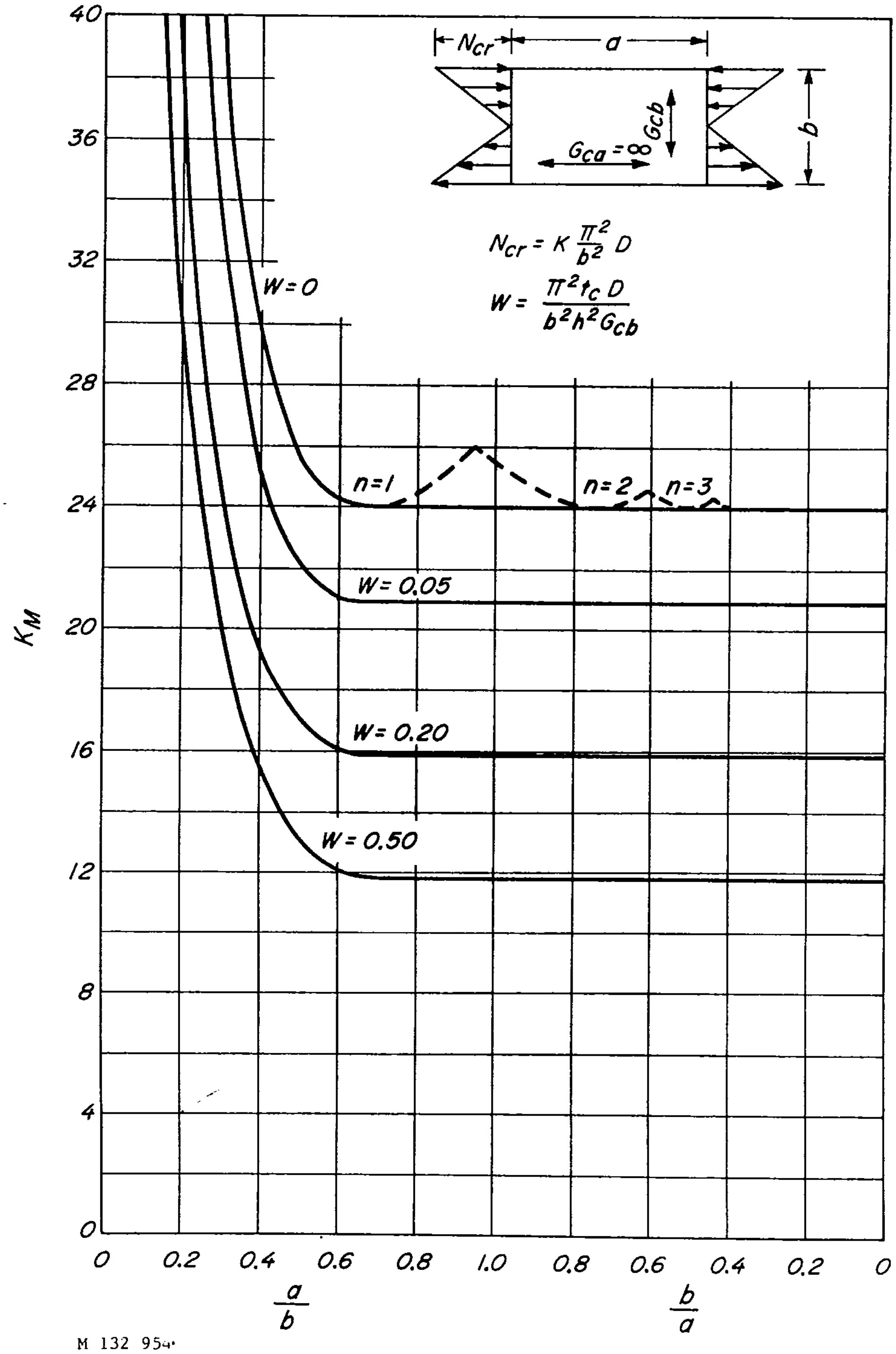



Figure 7-9.--$K_M$ for simply supported sandwich panel with corrugated core. Core corrugation flutes parallel to side a.

# CHAPTER 8

# DESIGN OF FLAT RECTANGULAR SANDWICH PANELS UNDER COMBINED LOADS

## 8.1 BASIC PRINCIPLES

Assuming that a design begins with chosen design stresses and a given design load to transmit, a flat rectangular panel of sandwich construction under edgewise loads with or without loads directed normal to the plane of the sandwich shall be designed to comply with the four basic design principles summarized in 1.2 of the Introduction.

Facing stresses shall be determined for each load applied separately (see appropriate Chapters) and the effects of combining the loads and stresses shall be assessed by appropriate interaction formulas for the facing materials as given in references (8-8) and (8-9) wherein design values of these stresses are established.

Overall buckling of the sandwich or dimpling or wrinkling of the facings cannot occur without possible total collapse of the panel. Local failure by wrinkling of the facings under loads other than uniaxial compression are not given and it is necessary to determine this behavior of the sandwich by testing small specimens if estimates based on information given in Chapter 3 show that failure by wrinkling of facings could be expected. Dimpling of facings under combined loads is not given; however, the information given in Chapter 4 can be combined with interaction formulas for buckling of the individual facing sheets as are given in references (8-1) and (8-8) to obtain some estimates that can be confirmed by tests of small specimens.

Overall buckling of sandwich panels under combined loads is given by interaction formulas in terms of the ratios, R, wherein R denotes the ratio of the applied stress or load under combined loading to the buckling stress or load under separate loading ($R = N/N_{cr}$). Appropriate subscripts are given to R to denote stress or load and direction.

## 8.2 BIAXIAL COMPRESSION

Overall buckling of sandwich panels under biaxial compression can be estimated by the interaction formula

$$R_{cx} + R_{cy} = 1 \qquad (8:1)$$

This formula is correct for square, isotropic sandwich panels for which $V \approx 0$. It can be exceedingly conservative for long panels and for panels with $V >> 0$. For more accurate analyses including sandwich with corrugated core consult references (8-1), (8-2), (8-4), (8-5), and (8-7).

## 8.3 BENDING AND COMPRESSION

Overall buckling of sandwich panels under edgewise bending and compression applied at the panel ends can be estimated by the interaction formula

$$R_{cx} + (R_{Bx})^{3/2} = 1 \qquad (8:2)$$

Approximate values which may be conservative can be obtained from formula (8:2). For more accurate analyses including sandwich with corrugated core see references (8-2), (8-3), and (8-7).

## 8.4 COMPRESSION AND SHEAR

Overall buckling of sandwich panels under edgewise compression and shear can be estimated by the interaction formula

$$R_c + (R_s)^2 = 1 \qquad (8:3)$$

References (8-2), (8-5), and (8-7) contain more complete information.

## 8.5 BENDING AND SHEAR

Overall buckling of sandwich panels under edgewise bending and shear can be closely approximated by the interaction formula

$$(R_B)^2 + (R_s)^2 = 1 \qquad (8:4)$$

Details of the analysis leading to these interaction curves are given in references (8-2) and (8-3).

## 8.6 EDGE LOADS COMBINED WITH NORMAL LOADS

The combination of edge loads with loads directed normal to the plane of a sandwich panel can greatly magnify deflections and stresses due to the normal load only (design information for panels under normal load only is given in Chapter 9). The deflections and stresses under combined loads can be closely approximated by the formula

$$\psi = \frac{\psi_0}{1 - \frac{N}{N_{cr}}} \qquad (8:5)$$

where $\psi$ is deflection or stress due to edgewise load combined with normal load; $\psi_0$ is deflection or stress due to normal load only; N is edgewise loading (single or combined); and $N_{cr}$ is overall edgewise buckling load (single or combined). Details concerning formula (8:5) are given in references (8-6) and (8-7).

## REFERENCED DOCUMENTS

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# CHAPTER 9

## DESIGN OF FLAT SANDWICH PANELS UNDER UNIFORMLY DISTRIBUTED NORMAL LOAD

### 9.1 BASIC PRINCIPLES

Assuming that a design begins with chosen design stresses and deflections and a given load to transmit, a flat rectangular or circular panel of sandwich construction under uniformly distributed normal load shall be designed to comply with the four basic design principles summarized in 1.2 of the Introduction.

Detailed procedures giving theoretical formulas and graphs for determining dimensions of the facings and core, as well as necessary core properties, for simply supported panels are given in the following paragraphs. Double formulas are given, one formula for sandwich with isotropic facings of different materials and thicknesses and another formula for sandwich with each isotropic facing of the same material and thickness. Facing moduli of elasticity, $E_{1,2}$, and stress values, $F_{1,2}$, shall be compression or tension values at the condition of use; that is, if application is at elevated temperature, then facing properties at elevated temperature shall be used in design. For many combinations of facing materials it will be found advantageous to choose thicknesses such that $E_1t_1 = E_2t_2$. The following procedures are restricted to linear elastic behavior.

Supersedes Chapter 9 of 30 Dec 1968.

## 9.2 DETERMINING FACING THICKNESS, CORE THICKNESS, AND CORE SHEAR MODULUS FOR SIMPLY SUPPORTED FLAT RECTANGULAR PANELS

This section gives procedures for determining sandwich facing and core thicknesses and core shear modulus so that chosen design facing stresses and allowable panel deflections will not be exceeded (ref. 9-2, 9-3). The facing stresses, produced by bending moment, are maximum at the center of a simply supported panel under uniformly distributed normal load. If restraint exists at panel edges, a redistribution of stresses may cause higher stresses near panel edges. The procedures given apply only to panels with simply supported edges. Because facing stresses are caused by bending moment, they depend not only upon facing thickness but also upon the distance the facings are spaced, hence core thickness. Panel stiffness, hence deflection, is also dependent upon facing and core thickness.

If the panel is designed so that facing stresses are at chosen design levels, the panel deflection may be larger than allowable, in which case the core or facings must be thickened and the design facing stress lowered in order to meet deflection requirements. A solution is presented in the form of charts with which, by iterative process, the facing and core thicknesses and core shear modulus can be determined.

The average facing stress, F (stress at facing centroid), in the b direction[1] is given by the theoretical formula:

$$F_{1,2} = K_2 \frac{pb^2}{ht_{1,2}} \quad \text{(for unequal facings)} \qquad (9:1)$$

$$F = K_2 \frac{pb^2}{ht} \quad \text{(for equal facings)} \qquad (9:1a)$$

[1] For sandwich with orthotropic cores having greater rigidity in the a direction than in the b direction, the facing stress may be greater in the a direction than the b direction, for panels nearly square (b/a > 0.4), and this stress is dependent upon $K_2'$ given in figures 9-16, 9-17, and 9-18.

where p is the intensity of the distributed load; b is the panel width, h is the distance between facing centroids; t is facing thickness; 1 and 2 are subscripts denoting facings 1 and 2; and $K_2$ is a theoretical coefficient dependent on panel aspect ratio, and sandwich bending and shear rigidities. If the core is isotropic (shear moduli alike in the two principal directions), $K_2$ values depend only upon panel aspect ratio. The values of $K_2$ for sandwich with orthotropic core are dependent not only on panel aspect ratio but also upon sandwich bending and shear rigidities as incorporated in the parameter $V = \frac{\pi^2 D}{b^2 U}$ which can be written as:

$$V = \frac{\pi^2 t_c E_1 t_1 E_2 t_2}{\lambda b^2 G_c (E_1 t_1 + E_2 t_2)} \qquad (9{:}2)$$

$$V = \frac{\pi^2 t_c E t}{2\lambda b^2 G_c} \quad \text{(for equal facings)} \qquad (9{:}2a)$$

where U is sandwich shear stiffness, E is modulus of elasticity of facing; $\lambda = 1 - \mu^2$; $\mu$ is Poisson's ratio of facings (in formula 9:2 it is assumed that $\mu = \mu_1 = \mu_2$); and $G_c$ is the core shear modulus associated with axes parallel to panel side of length a and perpendicular to the plane of the panel. The core shear modulus associated with axes parallel to panel side of width b and perpendicular to the plane of the panel is denoted by $(RG_c)$. For sandwich with corrugated core having corrugation flutes parallel to panel side of length a the parameter V is replaced by the parameter

$$W = \frac{\pi^2 t_c E_1 t_1 E_2 t_2}{\lambda b^2 G_{cb} (E_1 t_1 + E_2 t_2)} \qquad (9{:}3)$$

$$W = \frac{\pi^2 t_c E t}{2 \lambda b^2 G_{cb}} \quad \text{(for equal facings)} \qquad (9:3a)$$

where $G_{cb}$ is the core shear modulus associated with the axes perpendicular to the direction of the corrugation flutes (parallel to panel side of length b) and perpendicular to the plane of the panel.

Solving equations (9:1) and (9:1a) for $\frac{h}{b}$ gives

$$\frac{h}{b} = \sqrt{K_2} \frac{\sqrt{\frac{p}{F_{1,2}}}}{\sqrt{\frac{t_{1,2}}{h}}} \qquad (9:4)$$

$$\frac{h}{b} = \sqrt{K_2} \frac{\sqrt{\frac{p}{F}}}{\sqrt{\frac{t}{h}}} \quad \text{(for equal facings)} \qquad (9:4a)$$

A chart for solving formulas (9:4) and (9:4a) graphically is given in figures 9-1, 9-2, and 9-3. The formulas and charts include the ratio t/h, which is usually unknown, but by iteration satisfactory ratios of t/h and h/b can be found.

The deflection, δ, of the panel center is given by the theoretical formula:

$$\delta = \frac{K_1}{K_2} \cdot \frac{\lambda F_{1,2}}{E_{1,2}} \left(1 + \frac{E_{1,2} t_{1,2}}{E_{2,1} t_{2,1}}\right) \frac{b^2}{h} \qquad (9:5)$$

$$\delta = 2 \frac{K_1}{K_2} \cdot \frac{\lambda F}{E} \cdot \frac{b^2}{h} \quad \text{(for equal facings)} \qquad (9:5a)$$

where $K_1$ is a coefficient dependent upon panel aspect ratio and the value of V or W and in sandwich with corrugated core on the ratio between the sandwich bending stiffness parallel and perpendicular to the corrugation flutes.

Solving equations (9:5) and (9:5a) for $\frac{h}{b}$ gives

$$\frac{h}{b} = \frac{\sqrt{\frac{K_1}{K_2}}\sqrt{\frac{\lambda F_{1,2}}{E_{1,2}}}\sqrt{1 + \frac{E_{1,2}t_{1,2}}{E_{2,1}t_{2,1}}}}{\sqrt{\frac{\delta}{h}}} \qquad (9:6)$$

$$\frac{h}{b} = \frac{\sqrt{\frac{2K_1}{K_2}}\sqrt{\frac{\lambda F}{E}}}{\sqrt{\frac{\delta}{h}}} \quad \text{(for equal facings)} \qquad (9:6a)$$

Charts for solving formulas (9:6) and (9:6a) are given in figures 9-4, 9-5, 9-6, 9-7, and 9-8. Use of the equations and charts beyond $\delta/h = 0.5$ is not recommended.

## 9.2.1 Use of Design Charts

The sandwich must be designed by iterative procedures and the charts enable rapid determination of the various quantities sought. For panel with isotropic and honeycomb core the charts were derived for a Poisson's ratio of the facings of 0.3, and can be used with small error for facings having other values of Poisson's ratio. For panels with corrugated core they were derived for a Poisson's ratio of the facings of 0.25.

As a first approximation, it will be assumed that V or W = 0. If the design is controlled by facing stress criteria, as may be determined, this assumption will lead to an exact value of h if the core is isotropic; to a minimum value of h if the core is orthotropic with a greater core shear modulus across the panel width than lengthwise; and to too large a value of h if the core is orthotropic with a smaller core shear modulus across the panel width than lengthwise. If the design is controlled by deflection requirements, the assumption that V = 0 will produce a minimum value of h. The value of h is minimum because V = 0 if the core shear modulus is infinite. For any actual core, the shear modulus is not infinite; hence a thicker core must be used.

The following procedure is suggested:

(1) Enter figures 9-1, 9-2, or 9-3 with desired values for the parameters b/a and $\frac{p}{F_{1,2}}$, using the curve for V or W = 0. Assume a value for $\frac{t_{1,2}}{h}$ and determine h/b. Compute h and $t_{1,2}$. Modify ratio $\frac{t_{1,2}}{h}$ if necessary and determine more suitable values for h and $t_{1,2}$. Check stress in a direction as per footnote 1.

(2) Enter figure 9-4, 9-7, or 9-8 with desired values for the parameters b/a, $\frac{E_2 t_2}{E_1 t_1}$, $\frac{\lambda F_2}{E_2}$, using the curve for V or W = 0. Assume a value of $\delta/h$ and determine h/b. Compute h and $\delta$. Modify ratio $\delta/h$ if necessary and determine more suitable values for h and $\delta$.

(3) Repeat steps (1) and (2), using lower chosen design facing stresses, until h determined by step (2) is equal to, or a bit less than, h determined by step (1).

(4) Compute the core thickness, $t_c$, using the formulas

$$t_c = h - \frac{t_1 + t_2}{2} \qquad (9:7)$$

$$t_c = h - t \text{ (for equal facings)} \qquad (9:7a)$$

The first approximation was based on a core with an infinite shear modulus. Since actual core shear modulus values are not very large, a value of $t_c$ somewhat larger must be used. Successive approximations can be made by entering figures 9-1 to 9-8 with values of V or W as computed by equations (9:2) and (9:3). Figures 9-1, 9-2, and 9-3 include curves for sandwich with isotropic and certain orthotropic cores. Figure 9-4 applies to sandwich with isotropic core (R = 1). Figure 9-5 applies to sandwich with orthotropic cores for which the shear modulus associated with the panel width is 0.4 of the shear modulus associated with the panel length (R = 0.4). Figure 9-6 applies to sandwich with orthotropic cores for which the shear modulus associated with the panel width is 2.5 times the shear modulus associated with the panel length (R = 2.5).

NOTE: For honeycomb cores with core ribbon parallel to panel length a, $G_c = G_{TL}$ and the shear modulus parallel to panel width b is $G_{TW}$. For honeycomb cores with core ribbons parallel to panel width b, $G_c = G_{TW}$ and the shear modulus parallel to panel length b is $G_{TL}$.

Figure 9-7 applies to sandwich with corrugated core having the core flutes perpendicular to the panel edge of length a. Figure 9-8 applies to sandwich with corrugated core having the core flutes parallel to the panel edge of length a and requires values of the parameter W given by equation (9:3) or (9:3a) instead of values of V.

In using figures 9-1 to 9-8 for V or W $\neq 0$ it is necessary to iterate because V or W is directly proportional to the core thickness $t_c$. As an aid to finally determining $t_c$ and $G_c$, figure 9-9 presents a number of lines representing V or W for various values of $G_c$ with V or W ranging from 0.01 to 2 and $G_c$ ranging from 1,000 to 1,000,000 pounds per square inch. The following procedure is suggested:

(a) Determine a core thickness using a value of 0.01 for V or W.

(b) Compute the constant relating V or W to $G_c$ or $G_{cb}$:

$$\left[\frac{\pi^2 t_c E_1 t_1 E_2 t_2}{\lambda b^2 (E_1 t_1 + E_2 t_2)}\right] \text{ or } \left[\frac{\pi^2 t_c E t}{2\lambda b^2}\right] \text{ (for equal facings)} = VG_c \text{ (or } WG_{cb}\text{)}$$

(c) With this constant, enter figure 9-9 and determine necessary $G_c$ or $G_{cb}$.

(d) If the shear modulus is outside the range of values for materials available, slide up the appropriate line of figure 9-9 and pick a new value of V or W, for reasonable value of core shear modulus.

(e) Reenter figures 9-1 to 9-8 with the new value of V or W and repeat all previous steps.

## 9.3 DETERMINING CORE SHEAR STRESS

This section gives the procedure for determining the maximum core shear stress of a flat rectangular sandwich panel under uniformly distributed normal load. The core shear stress is maximum at the panel edges, at midlength of each edge. The maximum shear stress, $F_{cs}$, is given by the formula:

$$F_{cs} = K_3 p \frac{b}{h} \qquad (9:8)$$

where $K_3$ is a theoretical coefficient dependent upon panel aspect ratio and the parameter V. If the core is isotropic, values of V do not affect the core shear stress.

The charts of figures 9-10, 9-11, and 9-12 present a graphical solution of (9:8). The chart should be entered with values of thicknesses and other parameters previously determined.

## 9.4 CHECKING PROCEDURES

The design shall be checked by using the graphs of figures 9-13 through 9-24 to determine theoretical coefficients $K_2$, $K_2'$, $K_1$, and $K_3$ to compute facing stresses, deflection, and core shear stresses. If the graphs do not apply to honeycomb core because ratios of core shear moduli are far different from those given on the graphs, or it is desired to check by a more accurate analysis, the formulas given in reference (9-2) shall be used. The graphs for panels having corrugated core apply to panels where the ratio of bending stiffnesses, $(D_a/D_b)$, is equal to 1.

If the core corrugations contribute significantly to the panel bending stiffness $(D_a/D_b \neq 1)$ the graphs given in reference (9-3) should be used.

## 9.5 DETERMINING FACING THICKNESS, CORE THICKNESS, AND CORE SHEAR MODULUS FOR SIMPLY SUPPORTED FLAT CIRCULAR PANELS

This section gives procedures for determining sandwich facing and core thicknesses and core shear modulus so that chosen design facing stresses and allowable panel deflections will not be exceeded (ref. 9-1). The facing stresses, produced by bending moment, are maximum at the center of a simply supported circular panel under uniformly distributed normal load. If restraint exists at panel edges, a redistribution of stresses may cause higher stresses near panel edges. The procedures given apply only to panels with simply supported edges, isotropic facings, and isotropic cores. A solution is presented in the form of charts with which, by iterative process, the facing and core thicknesses and core shear modulus can be determined.

The average facing stress, F (stress at facing centroid), is given by the theoretical formula:

$$F_{1,2} = \frac{3+\mu}{16} \frac{pr^2}{t_{1,2}h} \qquad (9:9)$$

$$F = \frac{3+\mu}{16} \frac{pr^2}{th} \quad \text{(for equal facings)} \qquad (9:9a)$$

where $\mu$ is Poisson's ratio of facings (in formula 9:9 it is assumed that $\mu = \mu_1 = \mu_2$); r is the radius of the circular panel; and other quantities are as previously defined (see section 9.2).

Solving equations (9:9) and (9:9a) for $\frac{h}{r}$ gives

$$\frac{h}{r} = \frac{\sqrt{3+\mu}\sqrt{\frac{p}{F_{1,2}}}}{4\sqrt{\frac{t_{1,2}}{h}}} \qquad (9:10)$$

$$\frac{h}{r} = \frac{\sqrt{3+\mu}\sqrt{\frac{p}{F}}}{4\sqrt{\frac{t}{h}}} \quad \text{(for equal facings)} \qquad (9:10a)$$

A chart for solving formulas (9:10) and 9:10a) graphically is given in figure 9-25. The formulas and chart include the ratio t/h, which is usually unknown, but by iteration satisfactory ratios of t/h and h/r can be found.

The deflection, $\delta$, of the panel center is given by the theoretical formula:

$$\delta = K_4 \left(1 + \frac{E_{1,2}t_{1,2}}{E_{2,1}t_{2,1}}\right) \frac{\lambda F_{1,2}}{E_{1,2}} \frac{r^2}{h} \qquad (9:11)$$

$$\delta = 2K_4 \frac{\lambda F}{E} \frac{r^2}{h} \quad \text{(for equal facings)} \qquad (9:11a)$$

where $K_4$ depends on the sandwich bending and shear rigidities as incorporated in the parameter $V = \frac{\pi^2 D}{(2r)^2 U}$ which can be written as

$$V = \frac{\pi^2 t_c E_1 t_1 E_2 t_2}{4\lambda r^2 G_c (E_1 t_1 + E_2 t_2)} \qquad (9:12)$$

$$V = \frac{\pi^2 t_c Et}{8\lambda r^2 G_c} \quad \text{(for equal facings)} \qquad (9:12a)$$

where r is panel radius and all other terms are as previously defined in section 9.2.

Solving equations (9:11) and (9:11a) for $\frac{h}{r}$, gives

$$\frac{h}{r} = \frac{\sqrt{K_4}\sqrt{\frac{\lambda F_{1,2}}{E_{1,2}}}\sqrt{1 + \frac{E_{1,2}t_{1,2}}{E_{2,1}t_{2,1}}}}{\sqrt{\frac{\delta}{h}}} \qquad (9:13)$$

$$\frac{h}{r} = \frac{\sqrt{2K_4}\sqrt{\frac{\lambda F}{E}}}{\sqrt{\frac{\delta}{h}}} \quad \text{(for equal facings)} \qquad (9:13a)$$

A chart for solving formulas (9:13) and (9:13a) is given in figure 9-26. Use of the equations and charts beyond $\delta / h = 0.5$ is not recommended.

## 9.5.1 Use of Design Charts

The sandwich must be designed by iterative procedures and the charts enable rapid determination of the various quantities sought. The charts were derived for a Poisson's ratio of the facings of 0.3 and can be used with small error for facings having other values of Poisson's ratio.

As a first approximation, it will be assumed that V = 0. If the design is controlled by facing stress criteria, as may be determined, this assumption will lead to an exact value of h. If the design is controlled by deflection requirements, the assumption that V = 0 will produce a minimum value of h. The value of h is minimum because V = 0 if the core shear modulus is infinite. For any actual core, the shear modulus is not infinite; hence a thicker core must be used.

The following procedure is suggested:

(1) Enter figure 9-25 with the desired value for the parameter $\frac{p}{F_{1,2}}$. Assume a value for $\frac{t_{1,2}}{h}$ and determine h/r. Compute h and $t_{1,2}$. Modify ratio $\frac{t_{1,2}}{h}$ if necessary and determine more suitable values for h and $t_{1,2}$.

(2) Enter figure 9-26 with desired values of the parameters $\frac{E_2 t_2}{E_1 t_1}$ and $\frac{\lambda F_2}{E_2}$ and assume V = 0. Assume a value for δ/h and determine h/r. Compute h and δ. Modify ratio δ/h if necessary and determine more suitable values for h and δ.

(3) Repeat steps (1) and (2), using lower chosen design facing stresses, until h determined by step (2) is equal to, or a bit less than, h determined by step (1).

(4) Compute the core thickness $t_c$, using the formulas

$$t_c = h - \frac{t_1 + t_2}{2}$$

$$t_c = h - t \qquad \text{(for equal facings)}$$

This first approximation was based on a core with an infinite shear modulus. Since actual core shear modulus values are not very large, a value of $t_c$ somewhat larger must be used. Successive approximations can be made by entering figure 9-26 with values of V as computed by equations (9:12) and (9:12a).

In using figure 9-26 for $V \neq 0$ it is necessary to iterate because V is directly proportional to the core thickness $t_c$. As an aid to finally determining $t_c$ and $G_c$, figure 9-9 can again be used. The constant relating V to $G_c$ may be computed from the formula

$$VG_c = \left[\frac{\pi^2 t_c E_1 t_1 E_2 t_2}{4\lambda r^2 (E_1 t_1 + E_2 t_2)}\right] \text{ or } \left[\frac{\pi^2 t_c E t}{8\lambda r^2}\right] \text{ (for equal facings)}$$

With this constant, figure 9-9 may be entered. Use of the figure is as described in section 9.2.1.

## 9.6 DETERMINE CORE SHEAR STRESS

This section gives the procedure for determining the maximum core shear stress of a flat circular sandwich panel under uniformly distributed normal load. The core shear stress is maximum at the panel edge. The maximum shear stress, $F_{cs}$, is given by the formula:

$$F_{cs} = \frac{pr}{2h} \tag{9:14}$$

## 9.7 CHECKING PROCEDURE

The design shall be checked by computing the facing stresses by equation (9:9) and the deflection by equation (9:11). The value of $K_4$ to be used in equation (9:11) is given by

$$K_4 = \frac{16}{\pi^2(3+\mu)}\left[\frac{(5+\mu)\pi^2}{64(1+\mu)} + V\right] \tag{9:15}$$

which reduces to $K_4 = 0.309 + 0.491V$ when $\mu = 0.3$. Values of V may be computed by equation (9:12).

An alternate method for computing the deflection at the panel center is given by the formula:

$$\delta = K_5 \left(1 + \frac{E_{1,2}t_{1,2}}{E_{2,1}t_{2,1}}\right) \frac{\lambda p r^4}{\pi^2 E_{1,2} t_{1,2} h^2} \qquad (9:16)$$

$$\delta = 2K_5 \frac{\lambda p r^4}{\pi^2 Eth^2} \qquad (9:16a)$$

where

$$K_5 = \frac{(5 + \mu)\pi^2}{64(1 + \mu)} + V$$

which reduces to $K_5 = 0.629 + V$ when $\mu = 0.3$.

The core selected for the panel should be checked to be sure that it has a core shear modulus value, $G_c$, at least as high as that assumed in computing the deflection in equation (9:11) and that the core shear strength is sufficient to withstand the maximum core shear stress calculated from equation (9:14).

If it is desired to check by a more accurate analysis, the formulas given in reference (9-1) shall be used.

## REFERENCED DOCUMENTS

(9-1) ERICKSEN, WILHELM S.
1960. The Bending of a Circular Sandwich Panel Under Normal Load. U.S. Forest Prod. Lab. Rep. 1828.

(9-2) RAVILLE, MILTON E.
1962. Deflection and Stresses in a Uniformly Loaded, Simply Supported, Rectangular Sandwich Plate. U.S. Forest Prod. Lab. Rep. 1847.

(9-3) ALLEN, H. G.
1968. Graphs for the Analysis of Simply Supported Rectangular Sandwich Plates Under Uniform Transverse Pressure. Report CE/21/68. Dept. Civil Eng., Southampton Univ., England.

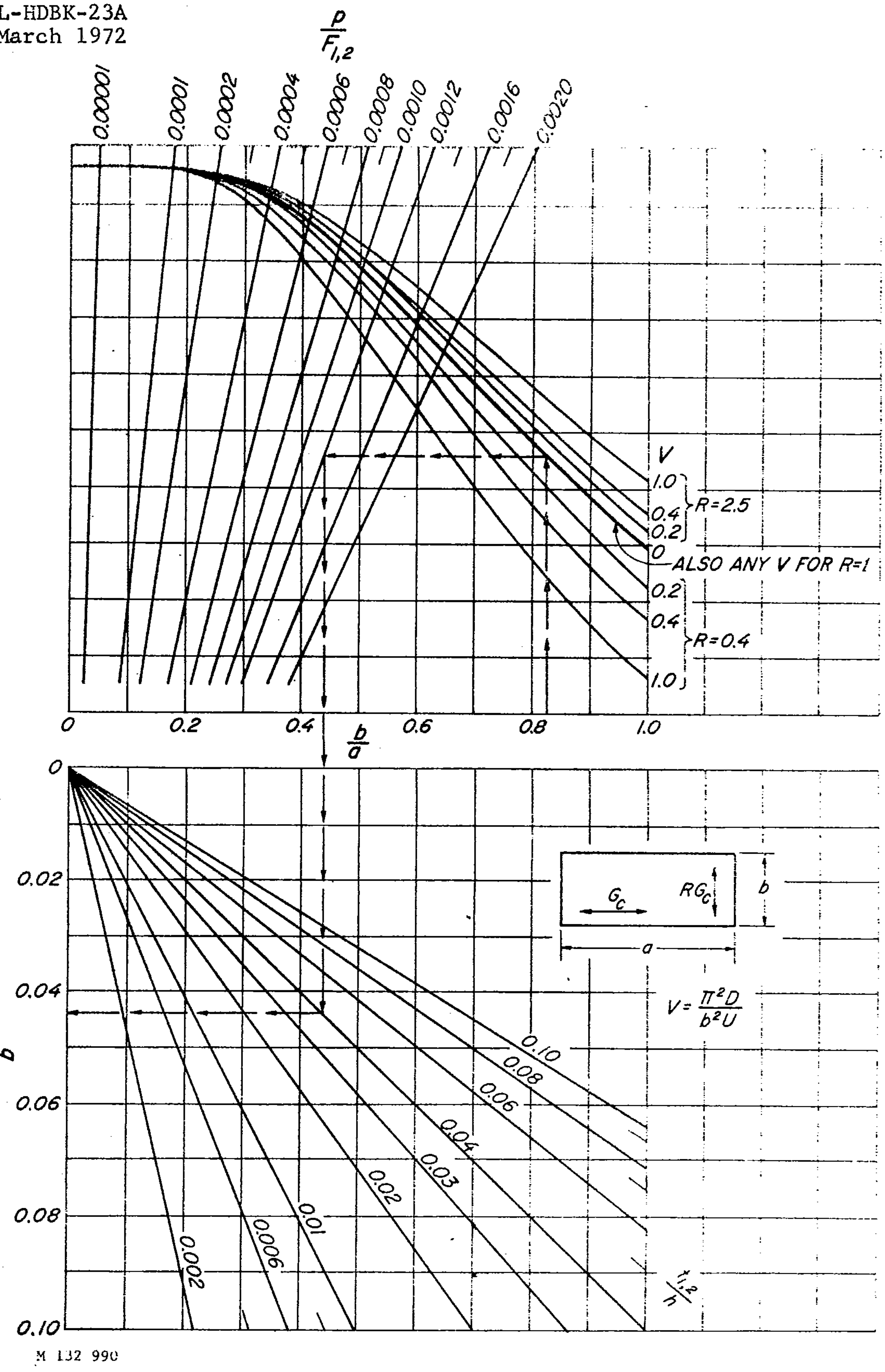


Figure 9-1.--Chart for determining h/b ratio for flat rectangular sandwich panel, with isotropic facings, under uniformly distributed normal load so that facing stress will be $F_{1,2}$.

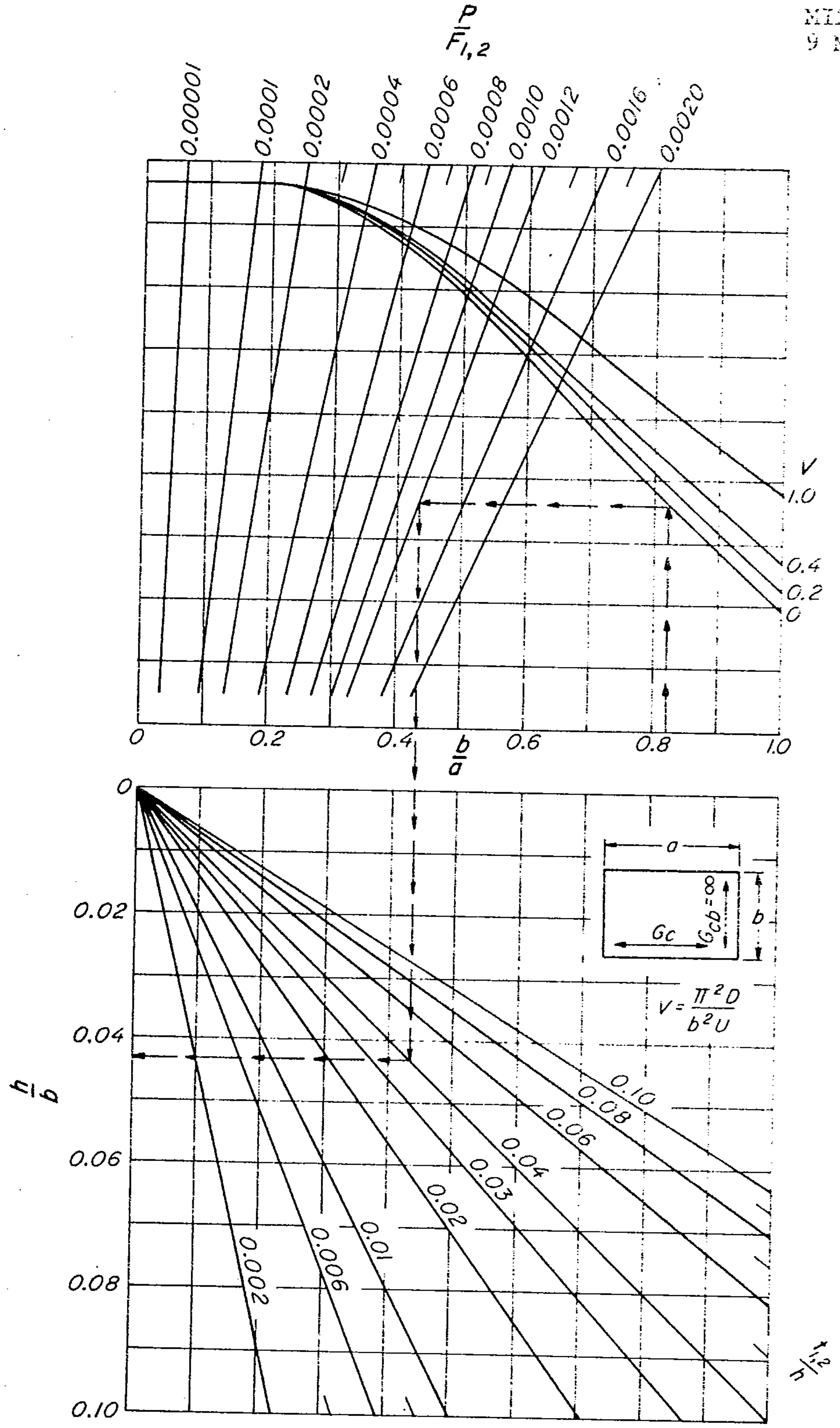


Figure 9-2. --Chart for determining h/b ratio for flat rectangular sandwich panel, with isotropic facings and a corrugated core, under uniformly distributed normal load so that facing stress will be $F_{1,2}$.

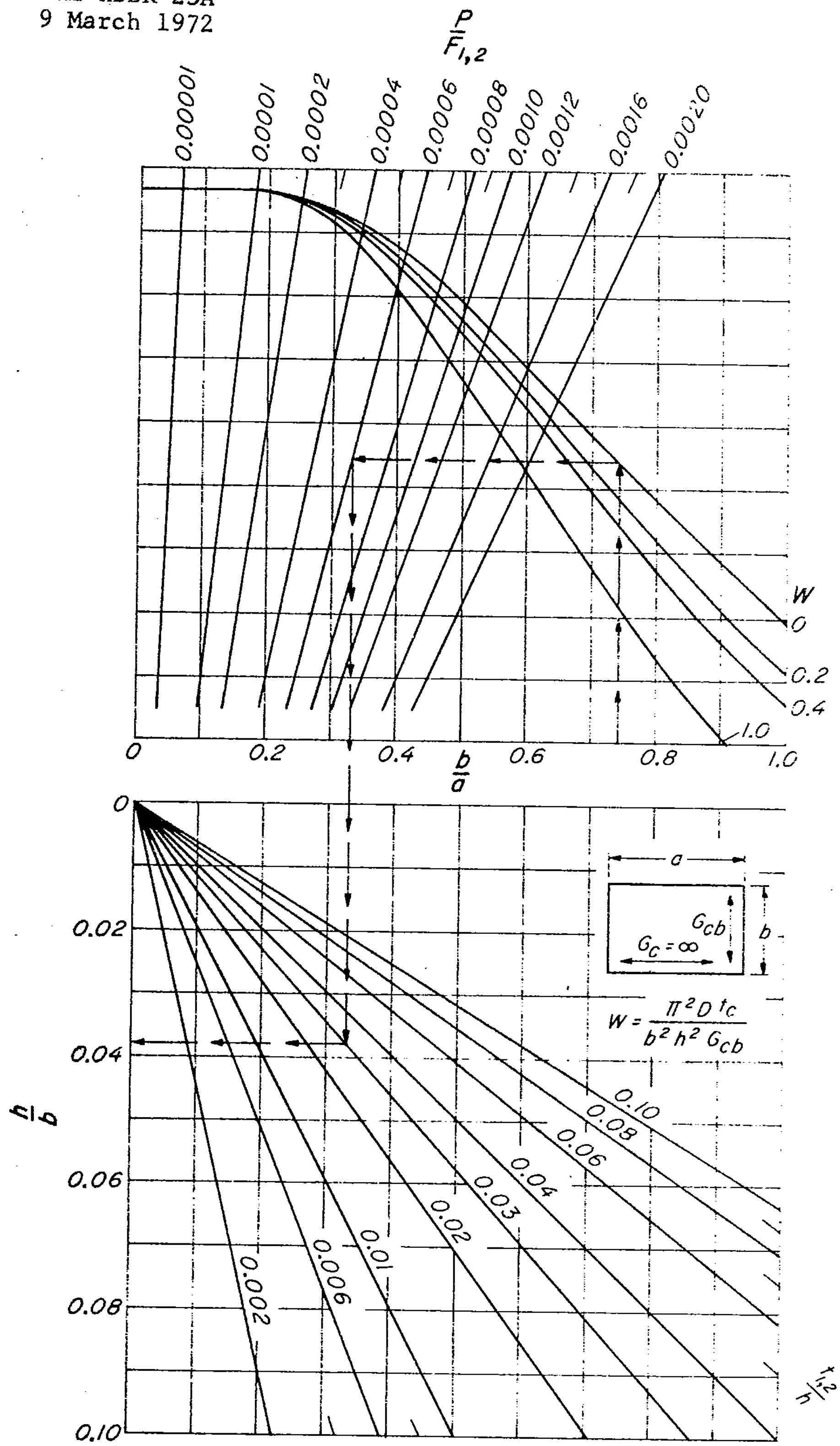


Figure 9-3. --Chart for determining h/b ratio for flat rectangular sandwich panel, with isotropic facings and a corrugated core, under uniformly distributed normal load so that facing stress will be $F_{1,2}$.

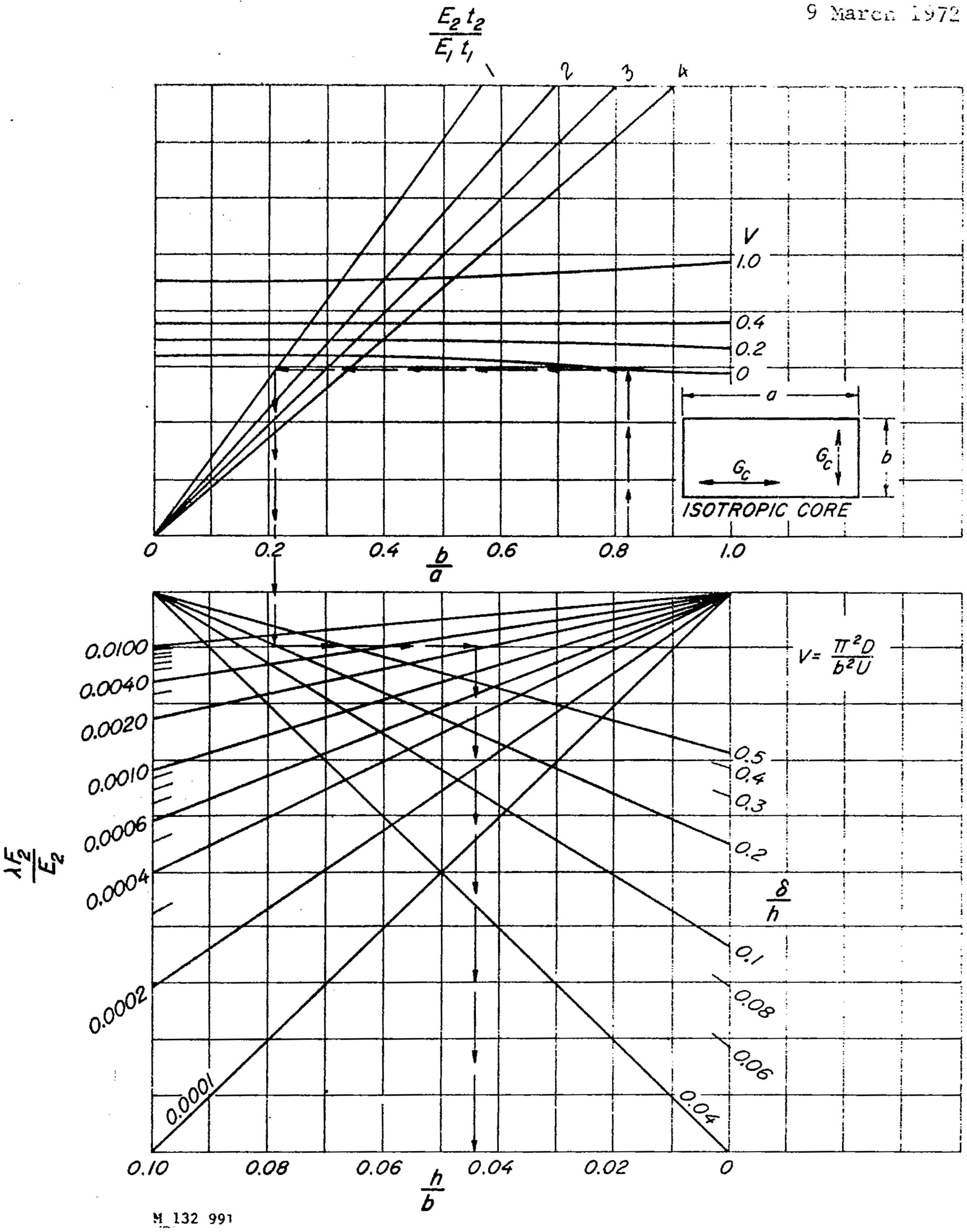


Figure 9-4.--Chart for determining h/b ratio for flat rectangular sandwich panel, with isotropic facings and isotropic core, under uniformly distributed normal load producing deflection ratio δ/h.

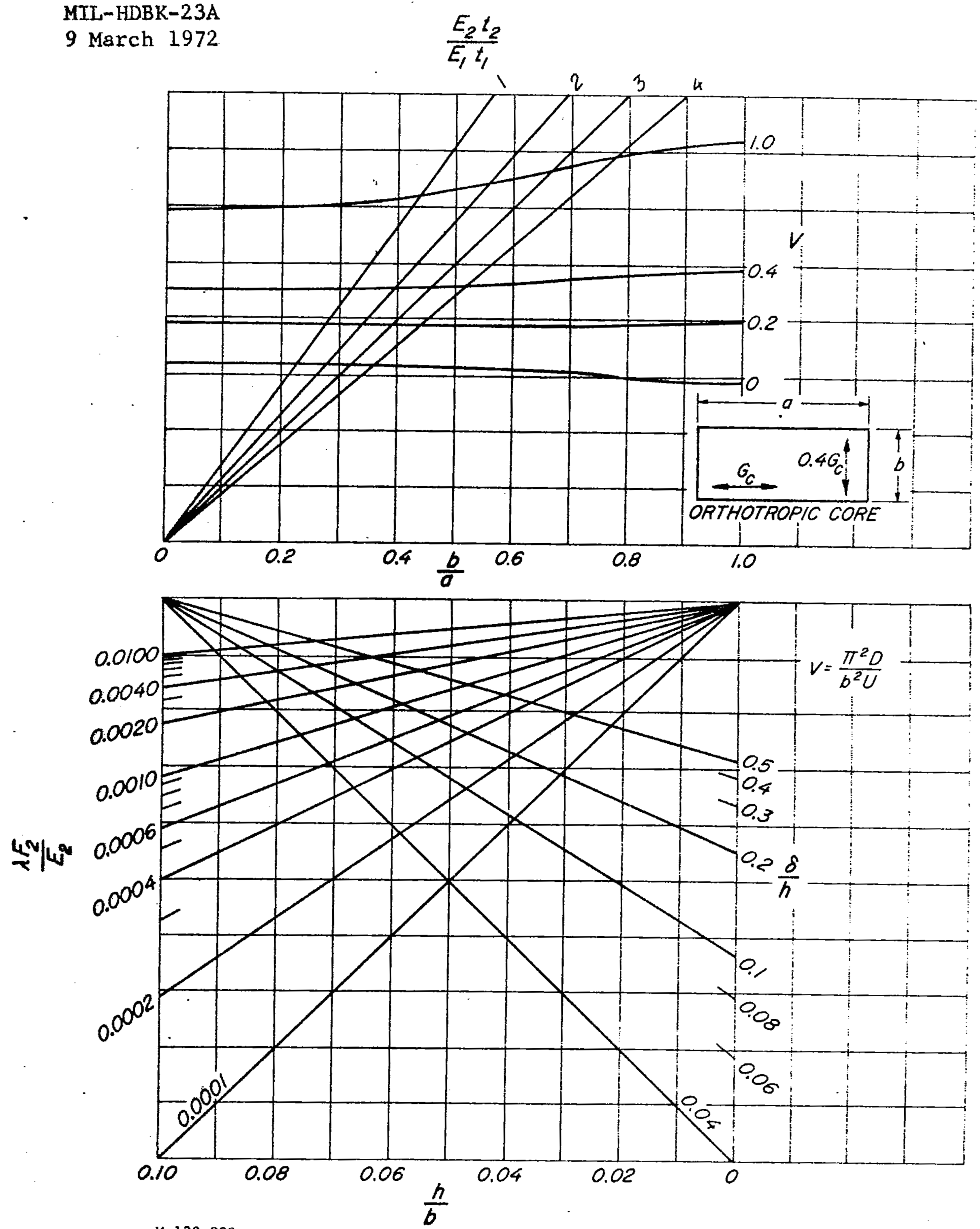


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Figure 9-5.--Chart for determining h/b ratio for flat rectangular sandwich panel, with isotropic facings and orthotropic (see sketch) core, under uniformly distributed normal load producing deflection ratio δ/h.

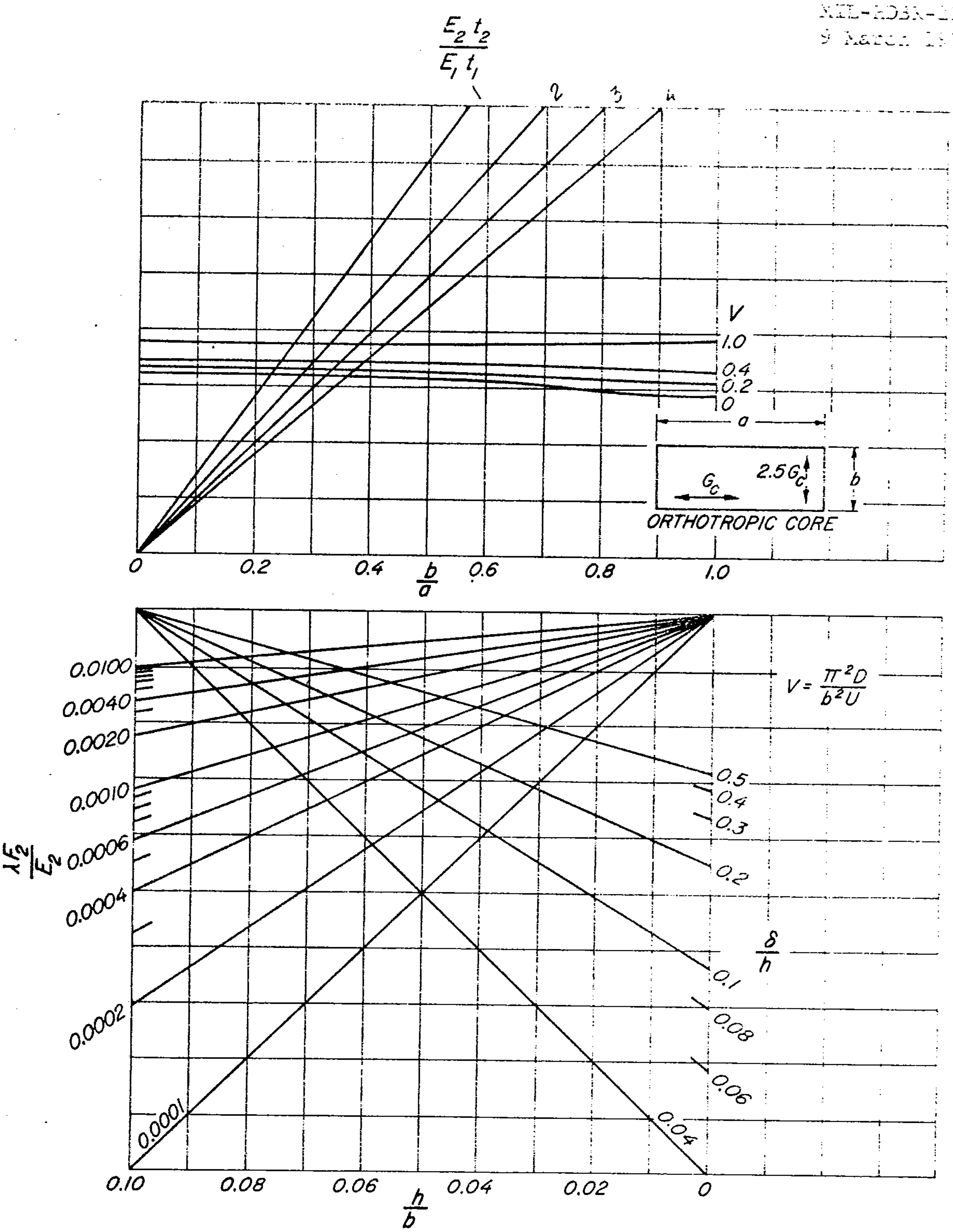


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Figure 9-6.--Chart for determining h/b ratio for flat rectangular sandwich panel, with isotropic facings and orthotropic (see sketch) core, under uniformly distributed normal load producing deflection ratio δ/h.

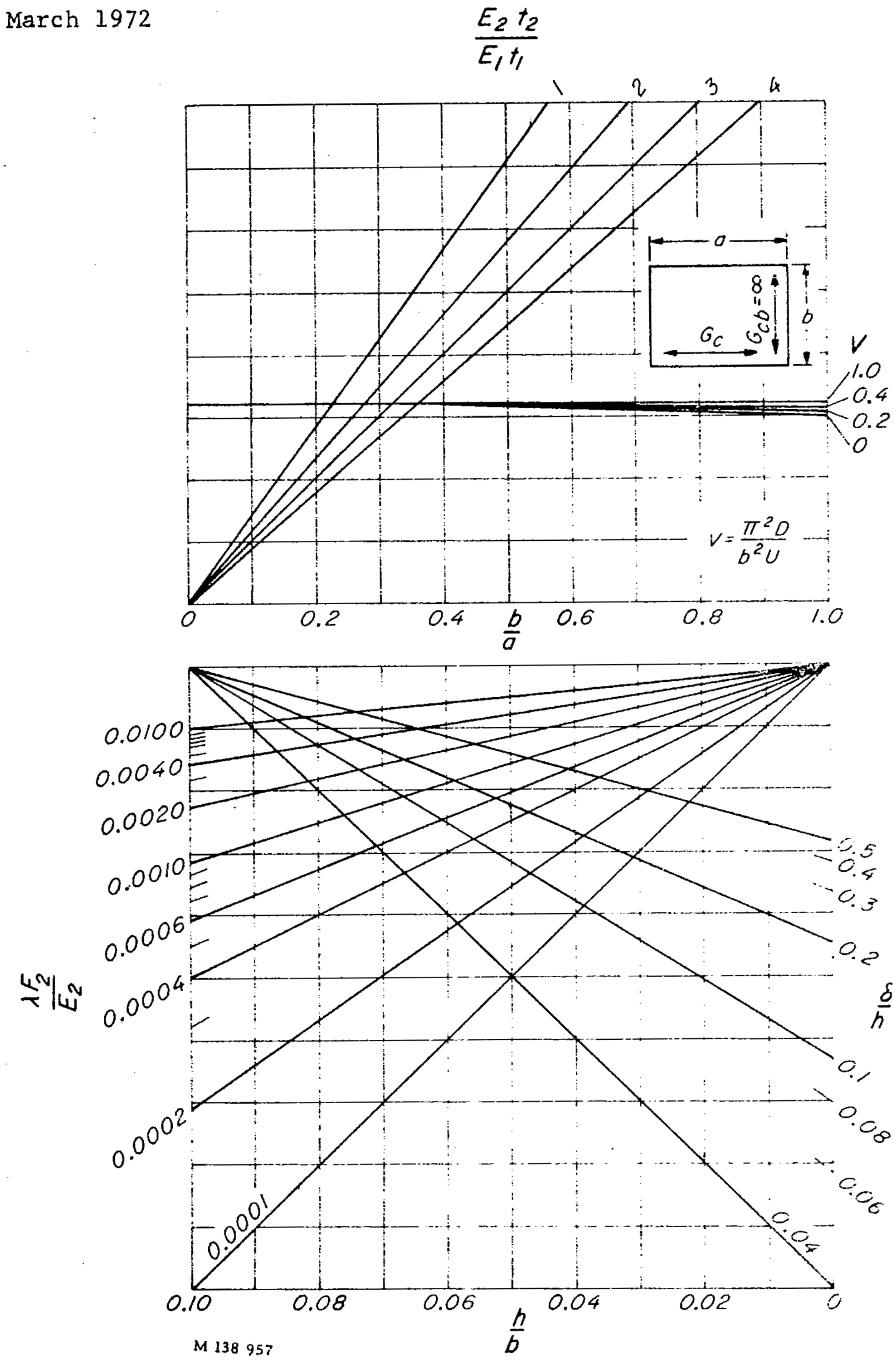


Figure 9-7. --Chart for determining h/b ratio for flat rectangular sandwich panel, with isotropic facings and corrugated core, under uniformly distributed normal load producing deflection ratio $\delta/h$.

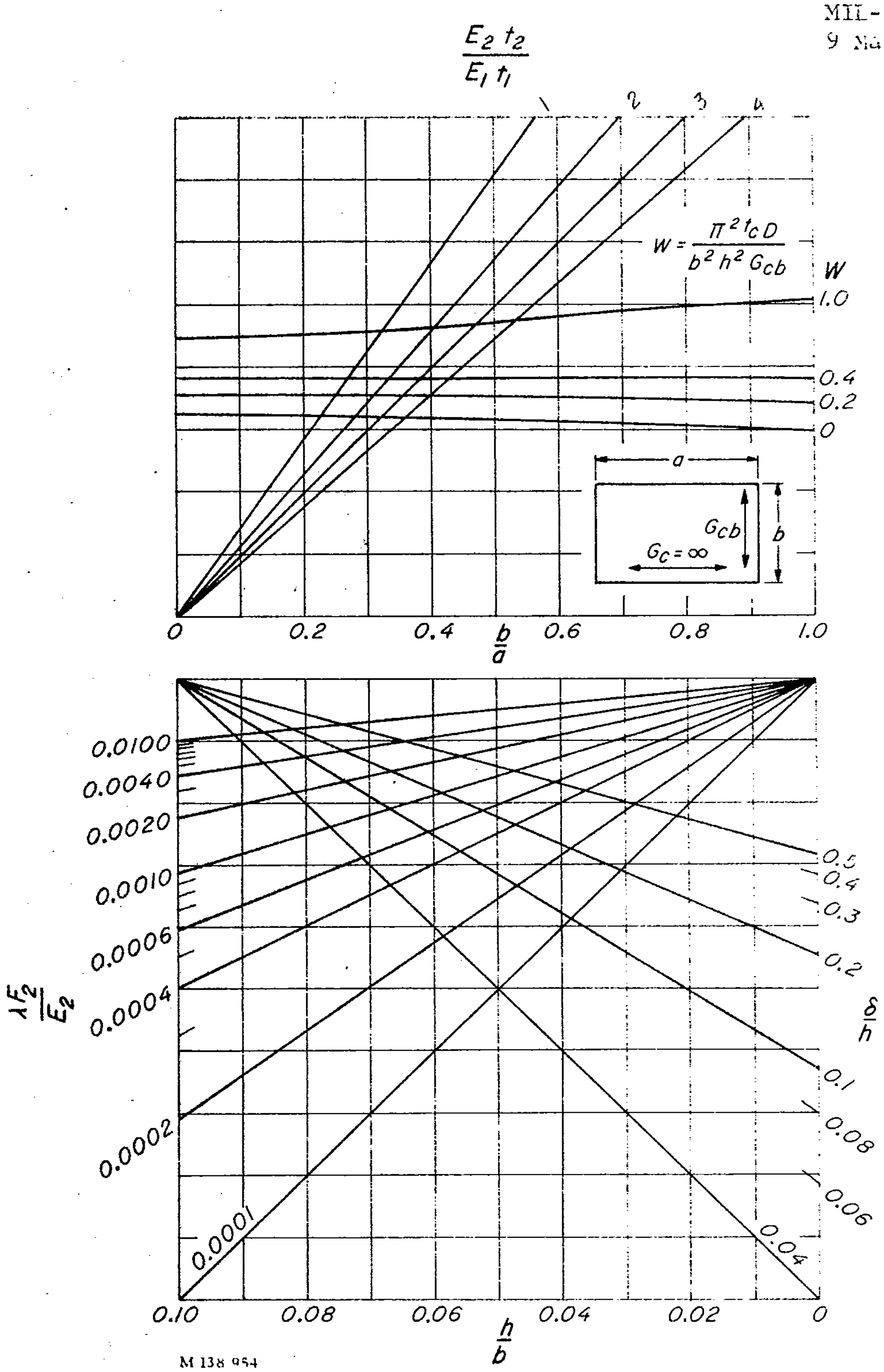


Figure 9-8.--Chart for determining h/b ratio for flat rectangular sandwich panel, with isotropic facings and corrugated core, under uniformly distributed normal load producing deflection ratio δ/h.

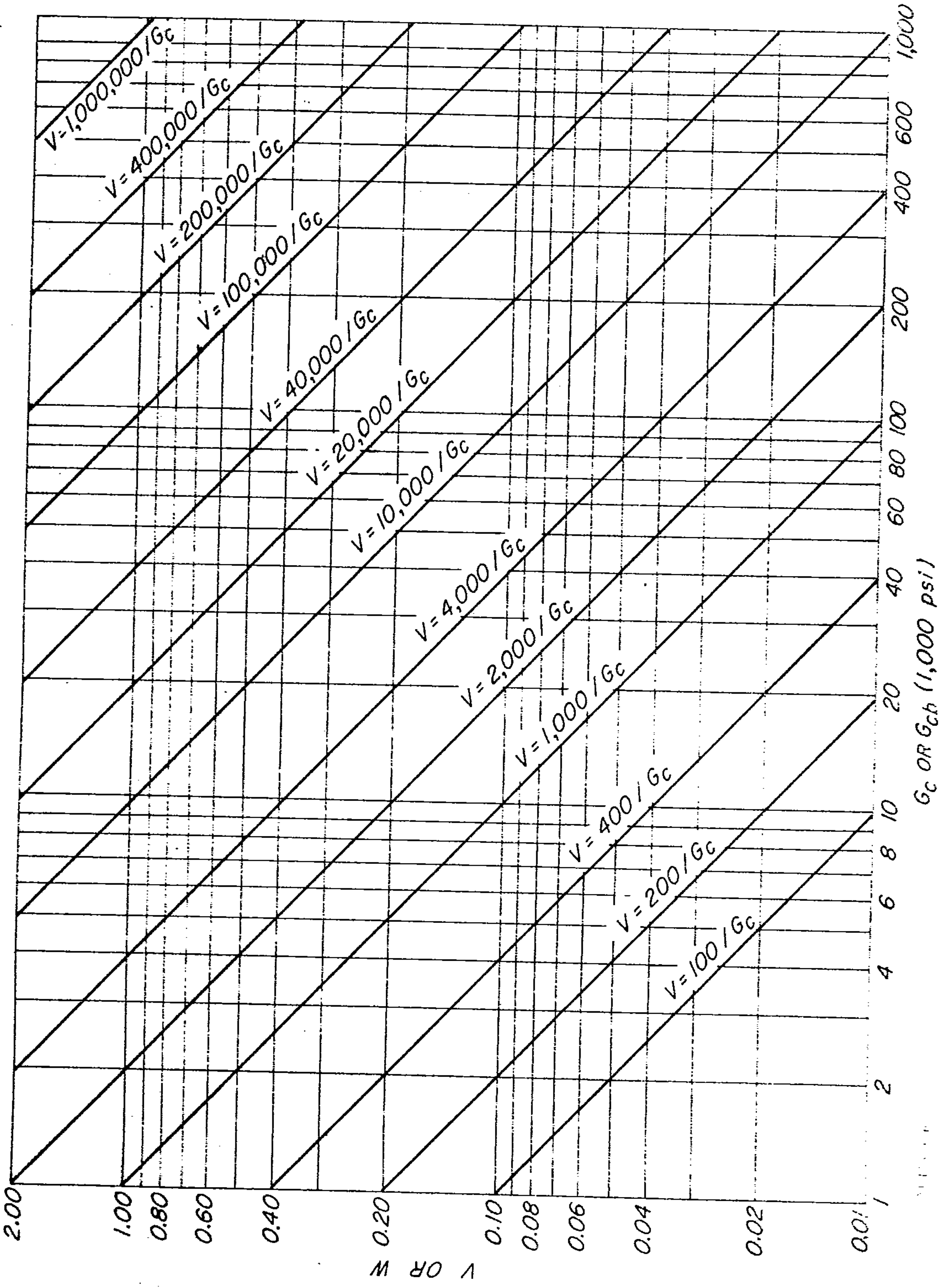


Figure 9-9. --Chart for determining V or W and $G_c$ or $G_{cb}$ for sandwich under uniformly distributed normal load.

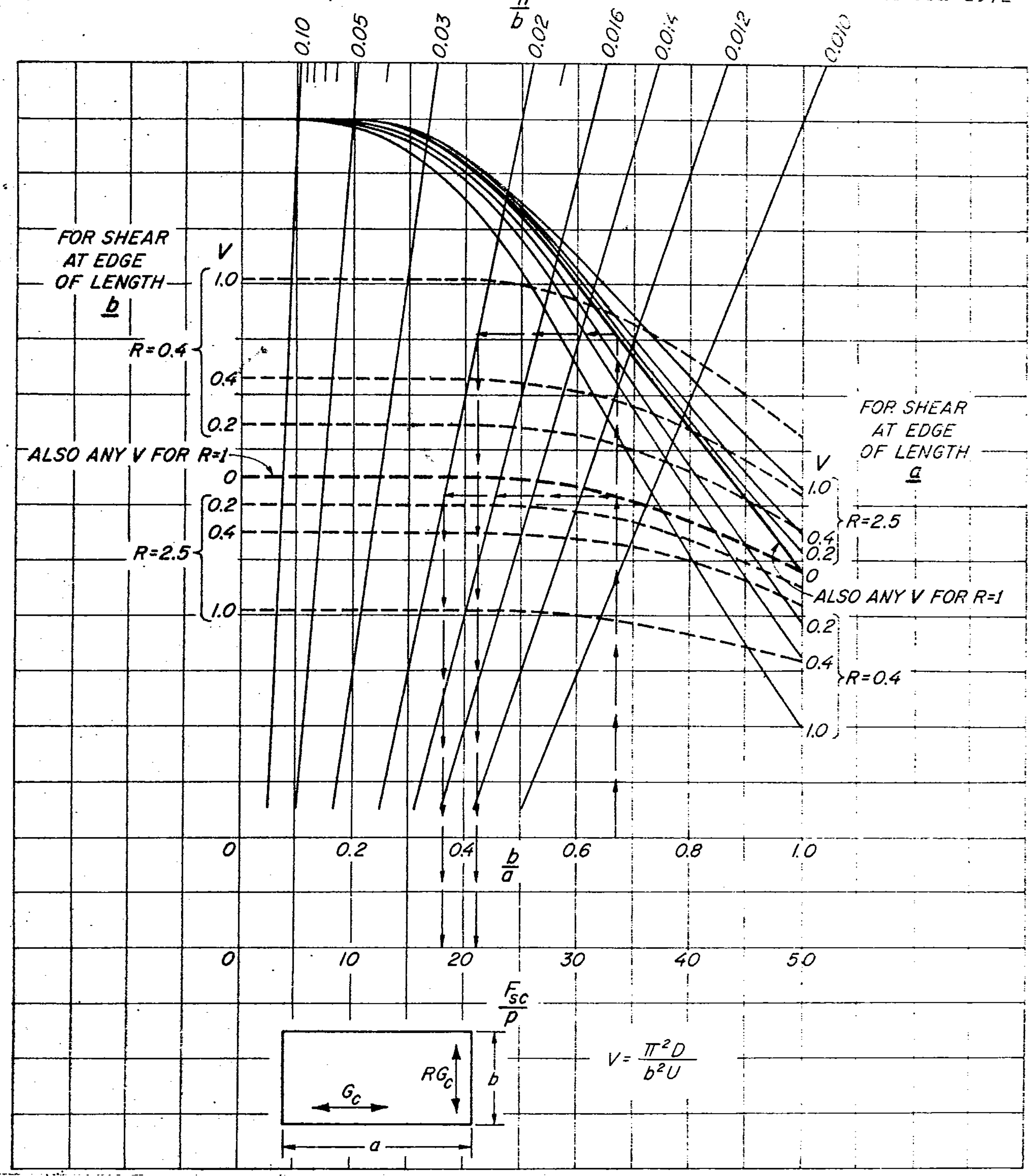


Figure 9-10. --Chart for determining core shear stress ratio $\frac{F_{sc}}{p}$ for flat rectangular sandwich panel, with isotropic facings, under uniformly distributed normal load.

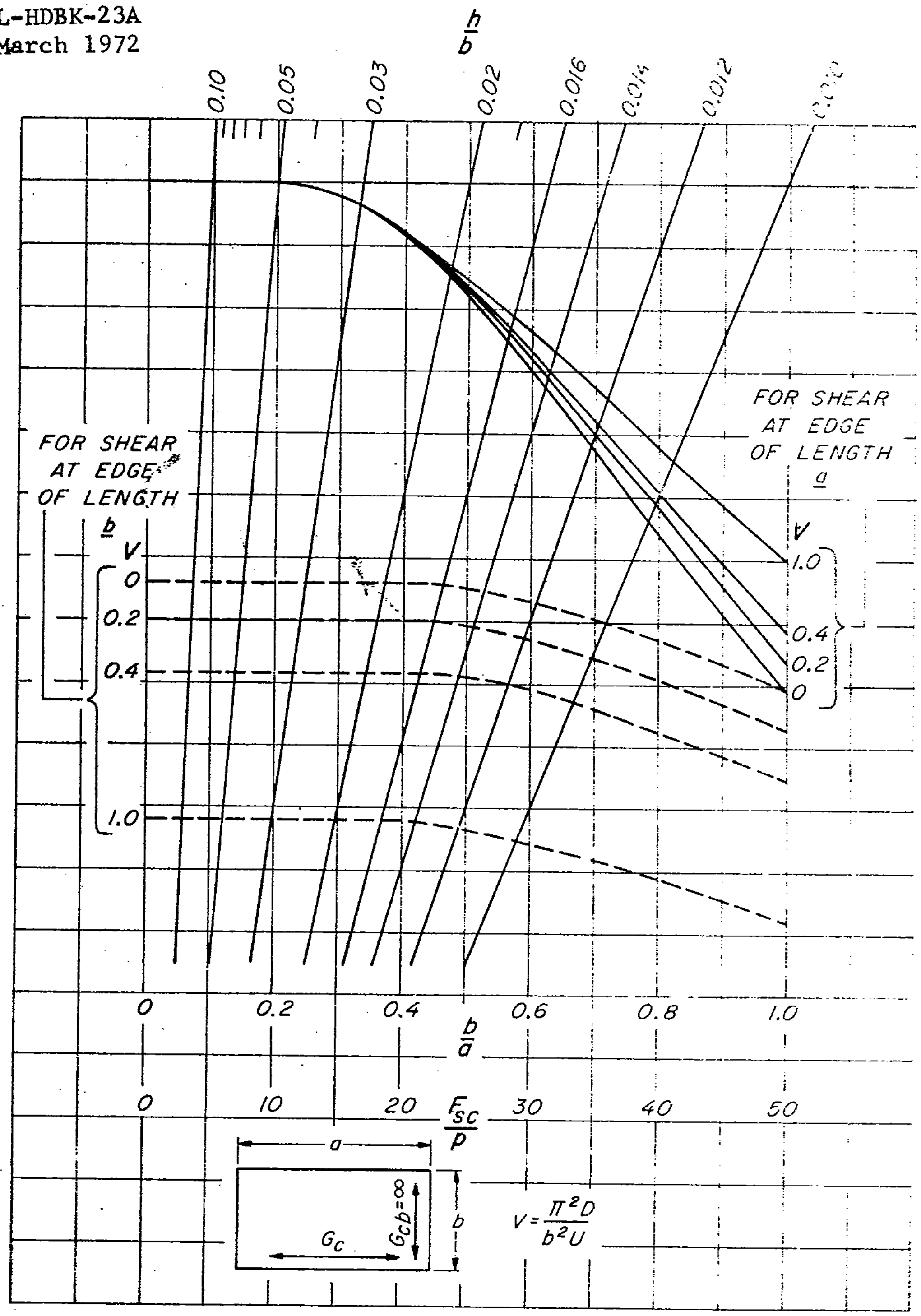


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Figure 9-11. --Chart for determining core stress ratio $\frac{F_{sc}}{p}$ for flat rectangular sandwich panel, with isotropic facings and corrugated core, under uniformly distributed load.

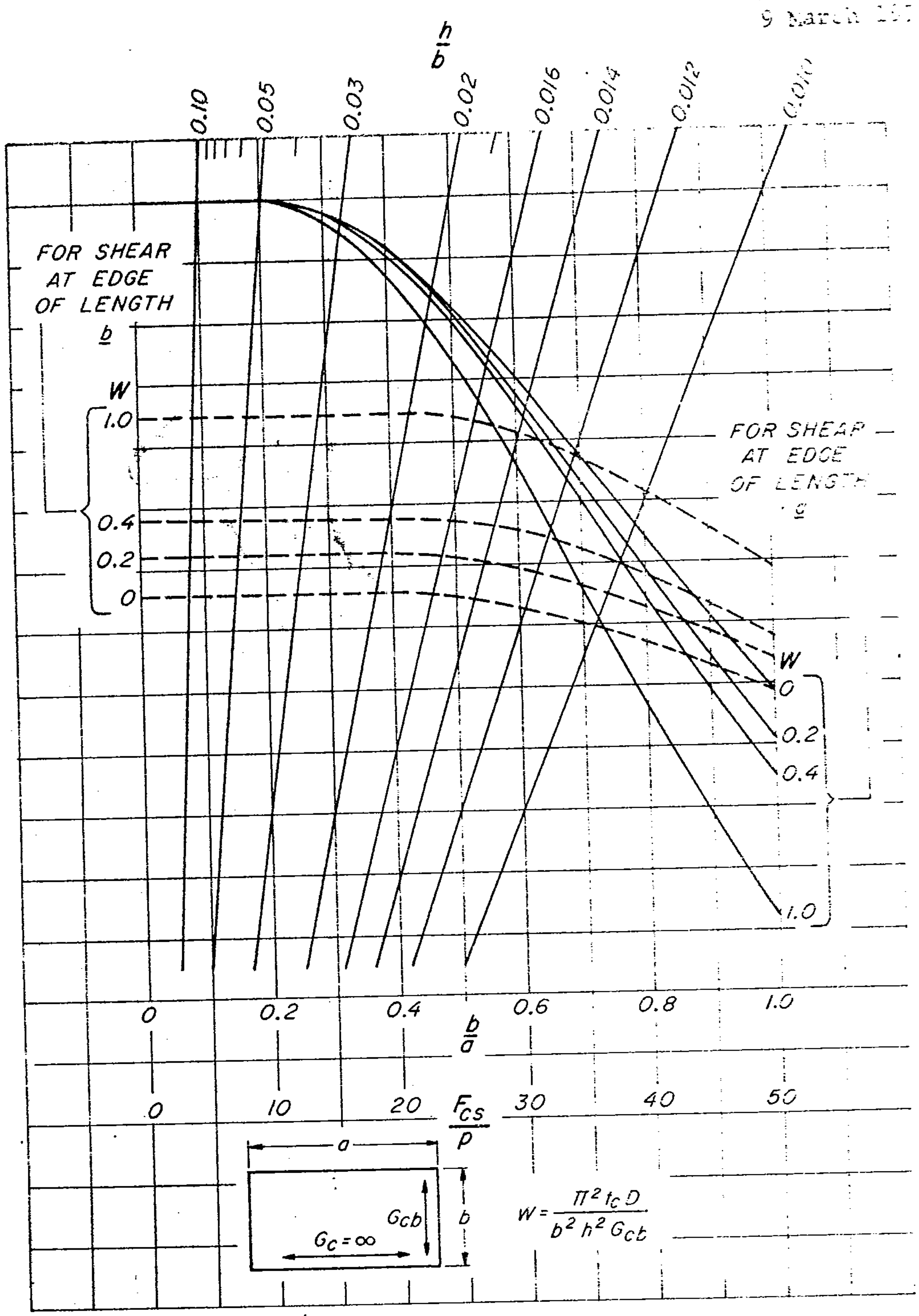


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Figure 9-12. --Chart for determining core shear stress ratio $\frac{F_{sc}}{p}$ for flat rectangular sandwich panel, with isotropic facings and corrugated core, under uniformly distributed normal load.

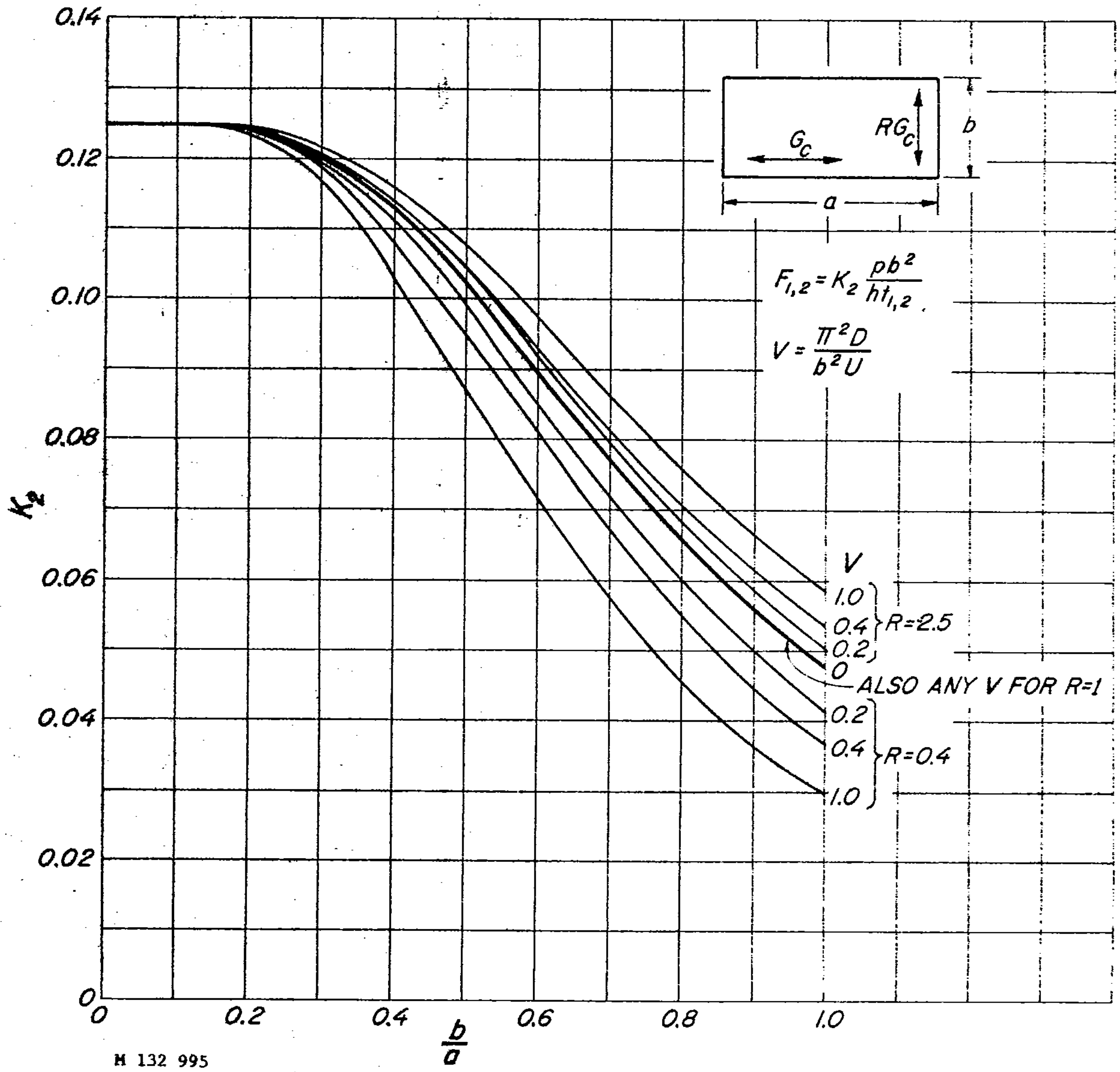



Figure 9-13.--$K_2$ for determining facing stress, F, in b direction of flat rectangular sandwich panels, with isotropic facings and isotropic or orthotropic core (see sketch), under uniformly distributed normal load.

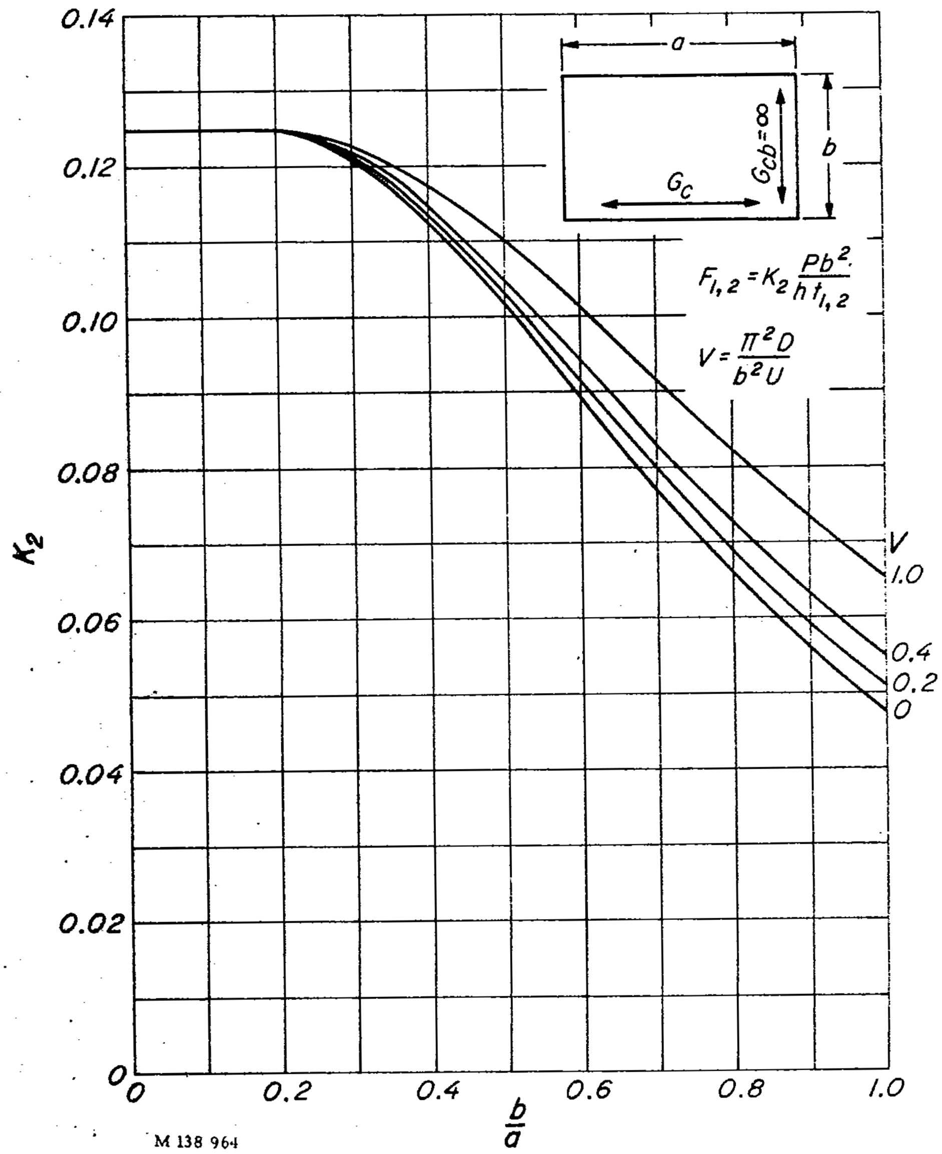



Figure 9-14.--$K_2$ for determining facing stress, F, in b direction of flat rectangular sandwich panels, with isotropic facings and corrugated core (see sketch), under uniformly distributed load.

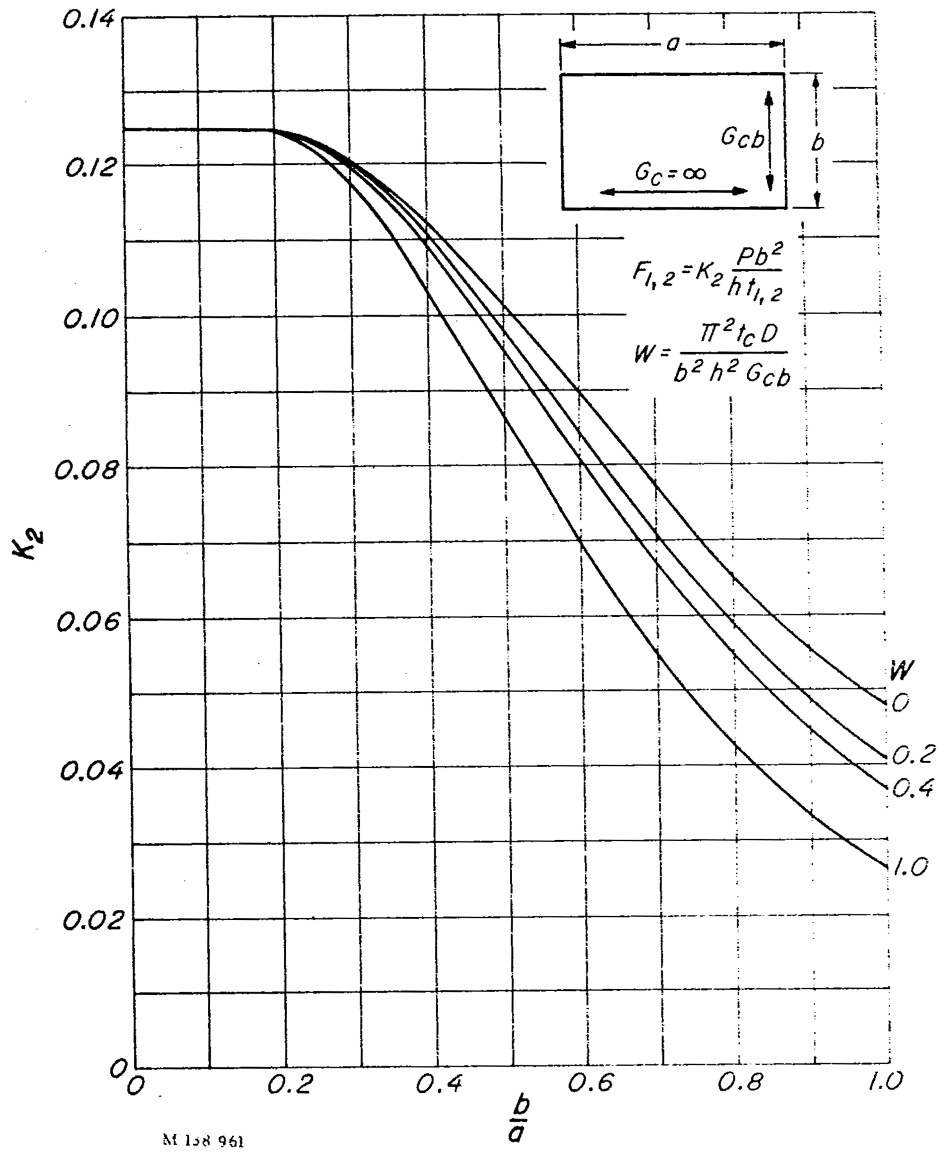



Figure 9-15.--$K_2$ for determining facing stress, F, in the b direction of flat rectangular sandwich panels, with isotropic facings and corrugated core (see sketch), under uniformly distributed load.

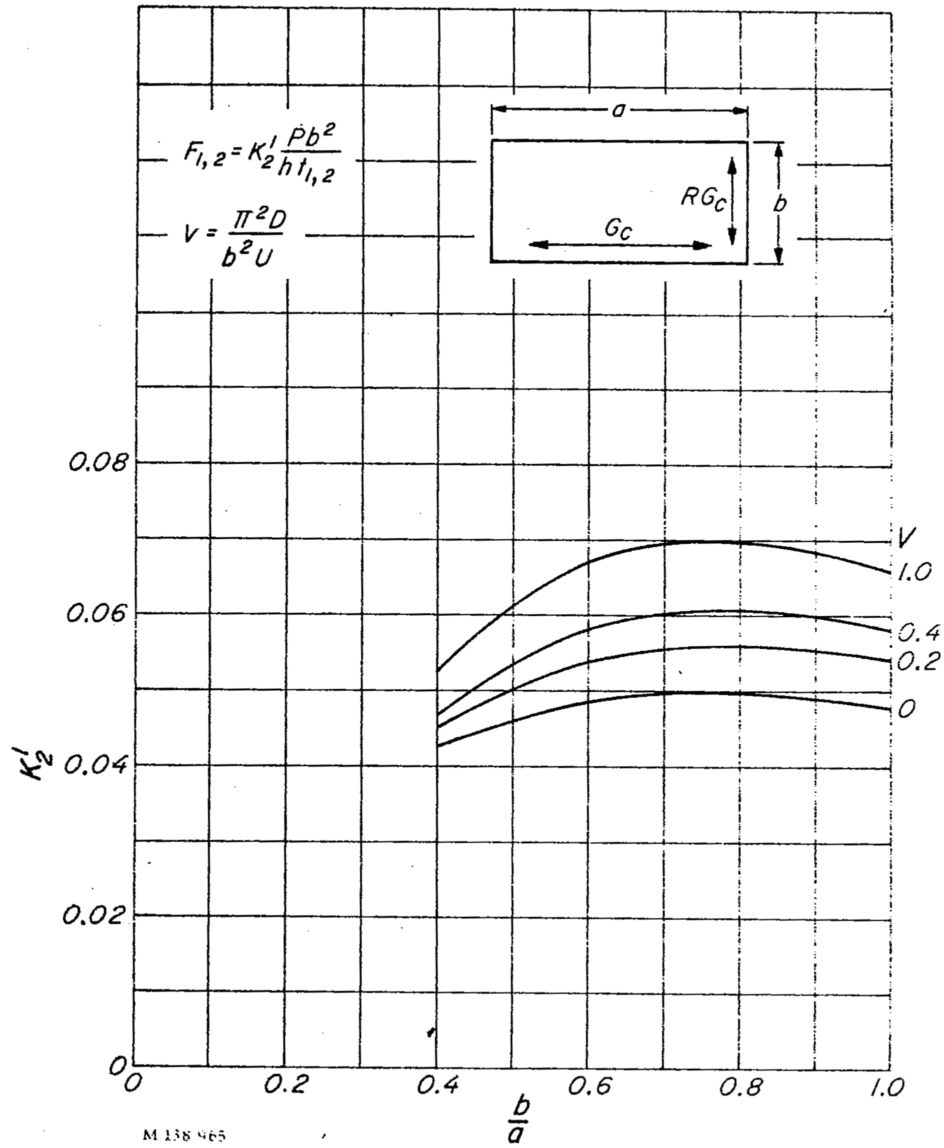



Figure 9-16.--$K_2'$ for determining facing stress, F, in the a direction of flat rectangular sandwich panels, with isotropic facings and orthotropic core (see sketch) R = 0.4, under uniformly distributed load. For R = 1 and R = 2.5 the maximum stress is given by $K_2$ of Fig. 9-13.

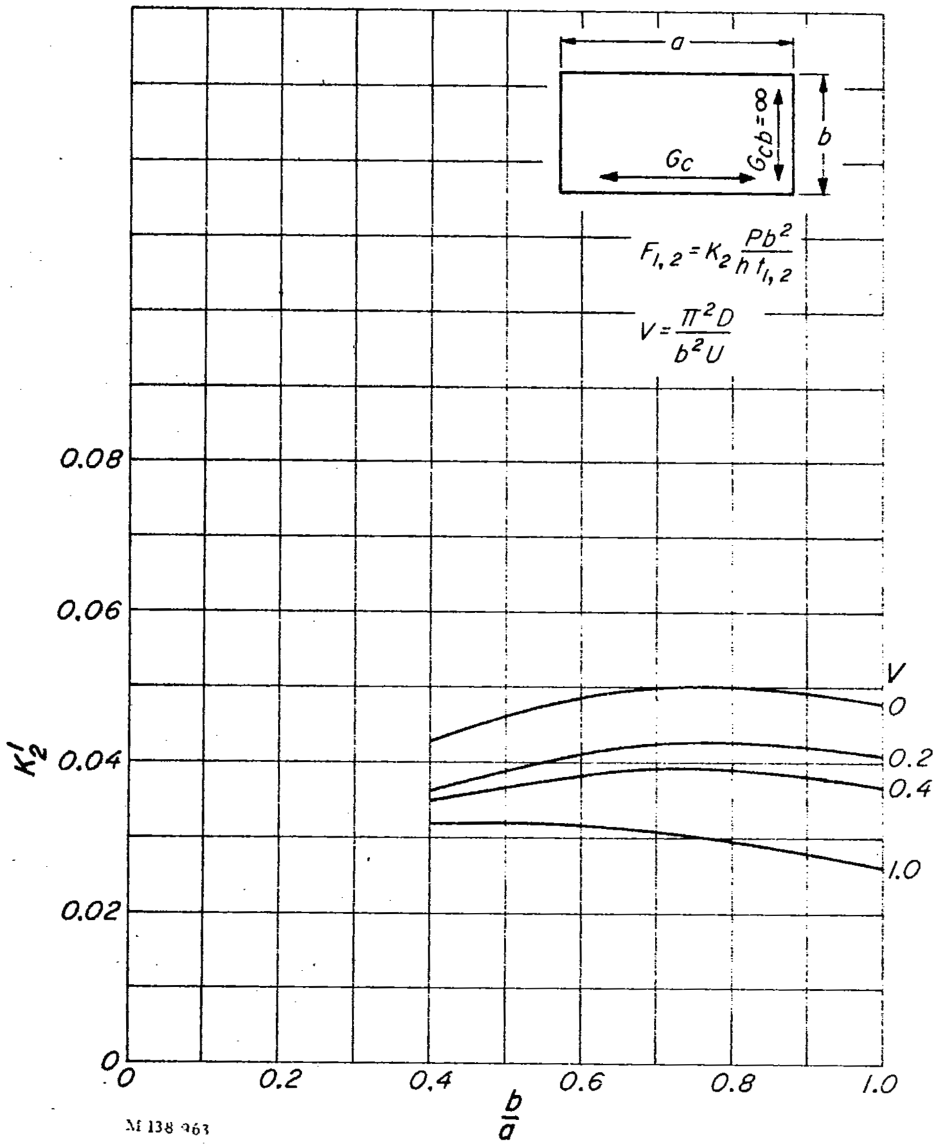



Figure 9-17.--$K_2'$ for determining facing stress, F, in a direction of flat rectangular sandwich panels, with isotropic facings and corrugated core (see sketch), under uniformly distributed load.

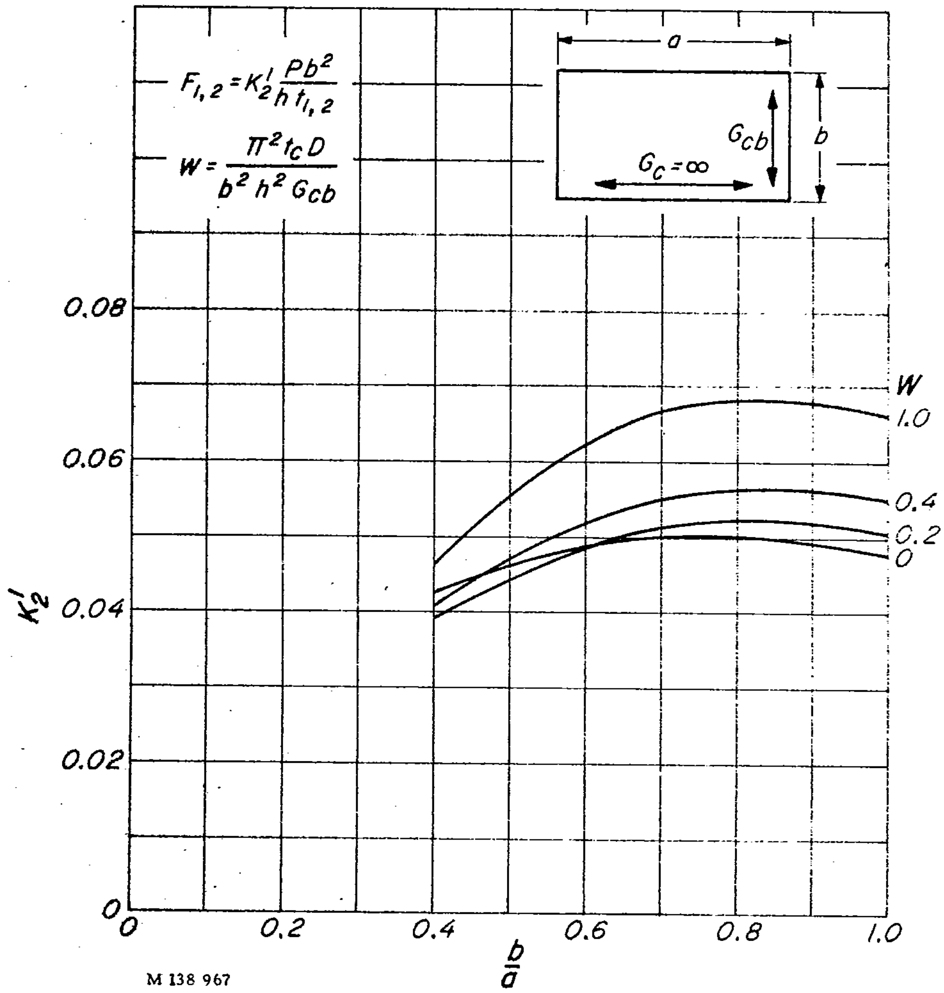



Figure 9-18.--$K_2'$ for determining facing stress, F, in a direction of flat rectangular sandwich panels, with isotropic facings and corrugated core (see sketch), under uniformly distributed load.

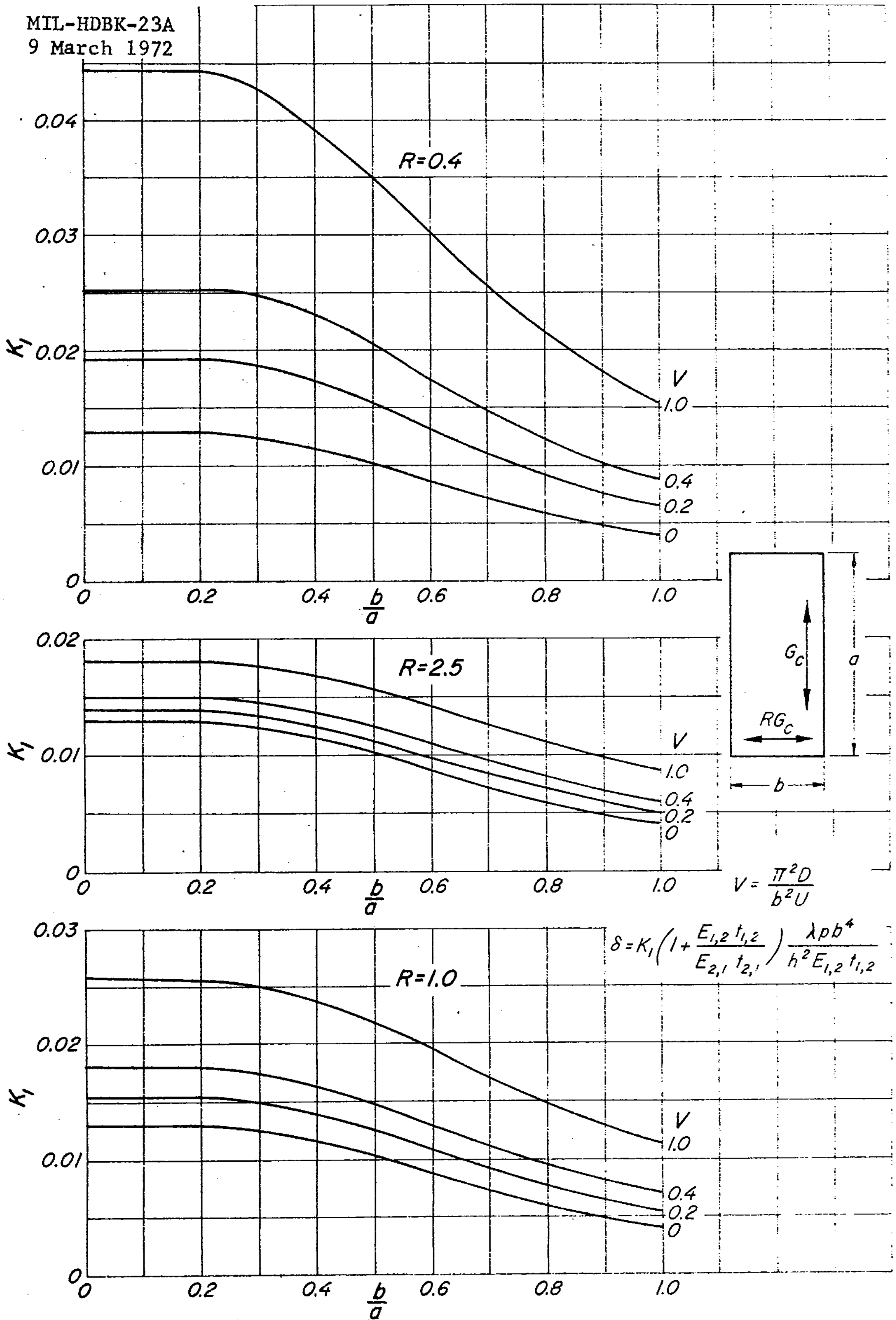



Figure 9-19.--$K_1$ for determining maximum deflection, $\delta$, of flat rectangular sandwich panels, with isotropic facings and isotropic or orthotropic core (see sketch), under uniformly distributed normal load.

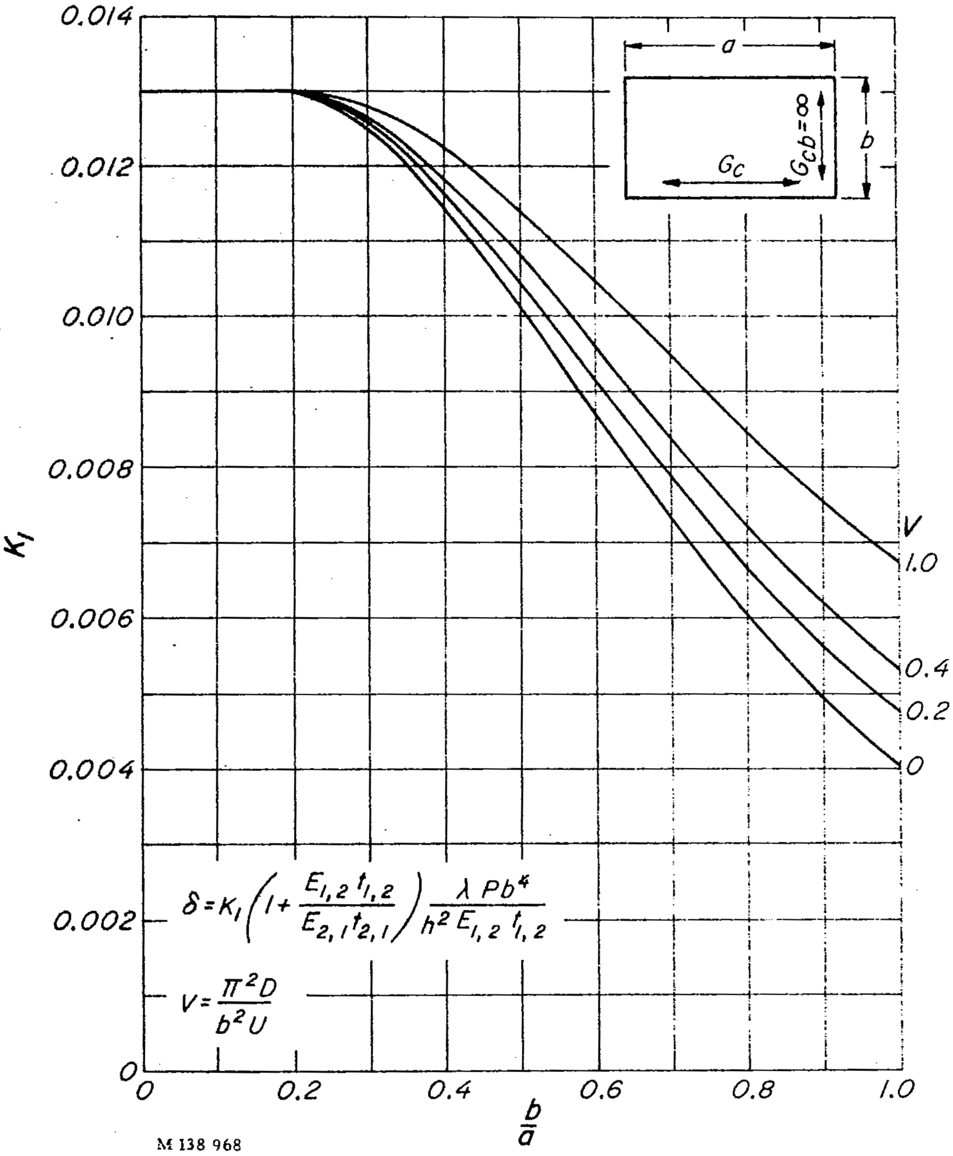



Figure 9-20.--$K_1$ for determining maximum deflection, $\delta$, of flat rectangular sandwich panels, with isotropic facings and corrugated core (see sketch), under uniformly distributed load.

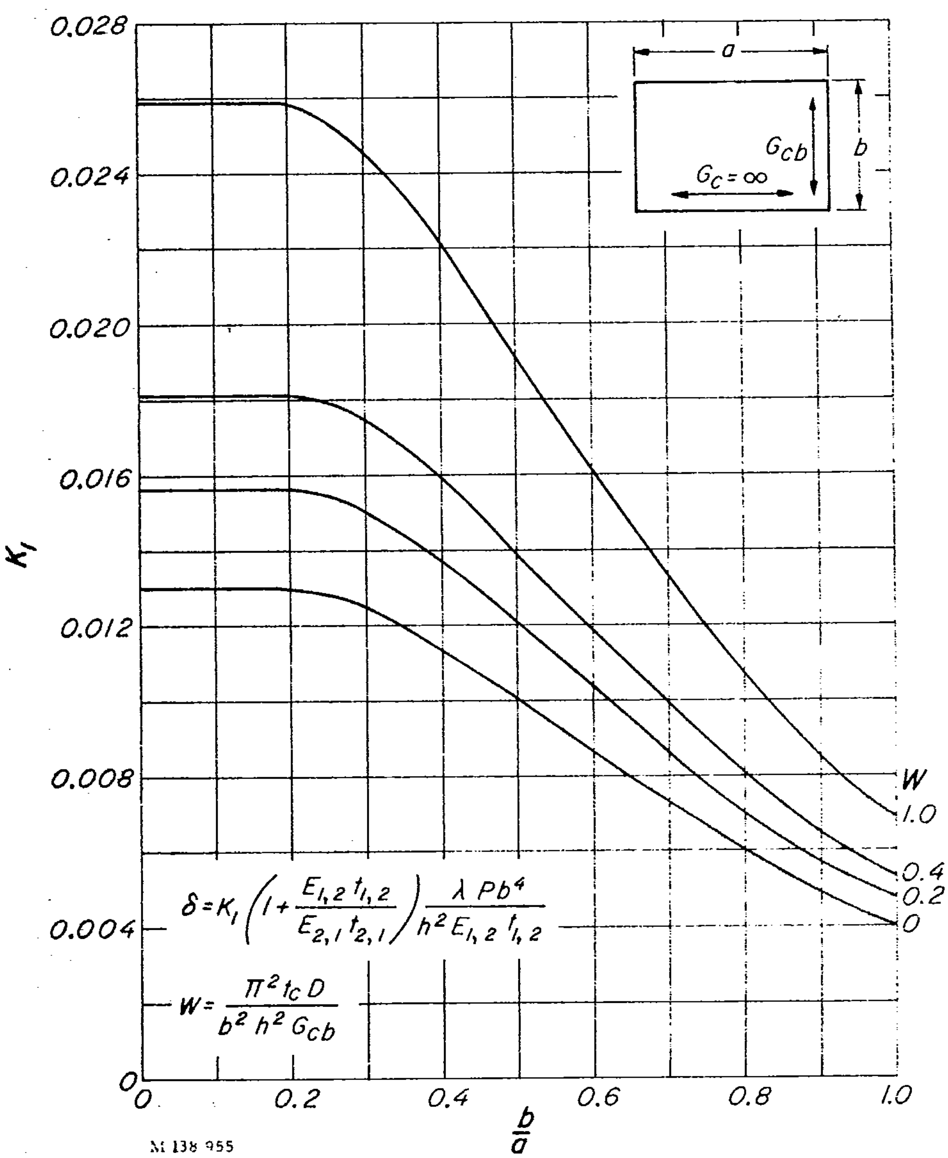
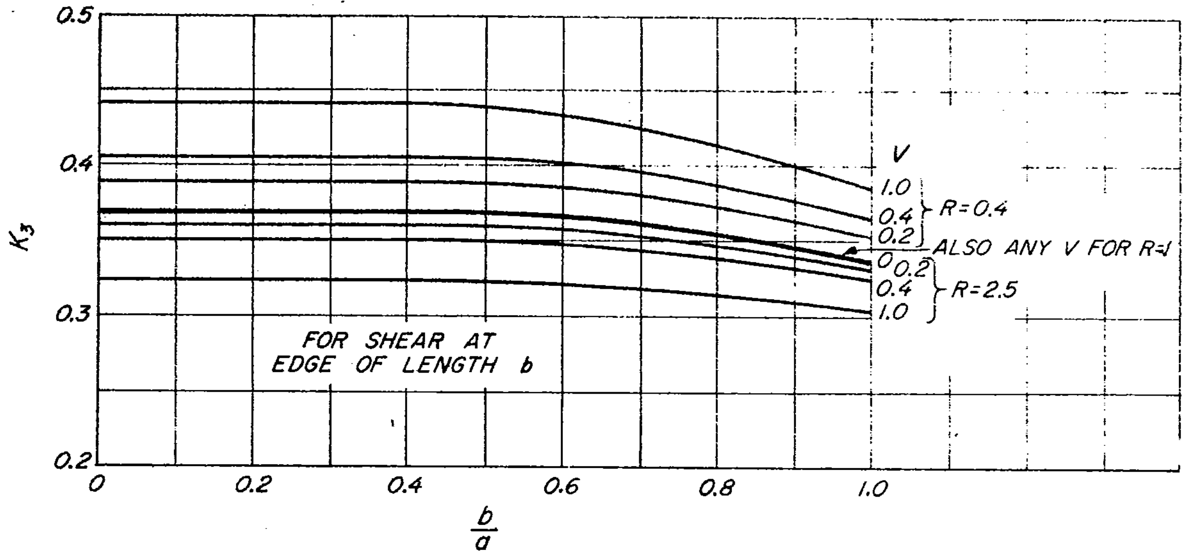
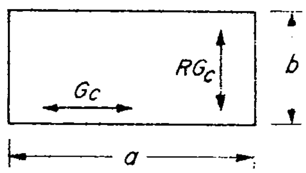



Figure 9-21.--$K_1$ for determining maximum deflection, δ, of flat rectangular sandwich panels, with isotropic facings and corrugated core (see sketch), under uniformly distributed normal load.




$$F_{sc} = K_3 p \frac{b}{h}$$

$$V = \frac{\pi^2 D}{b^2 U}$$



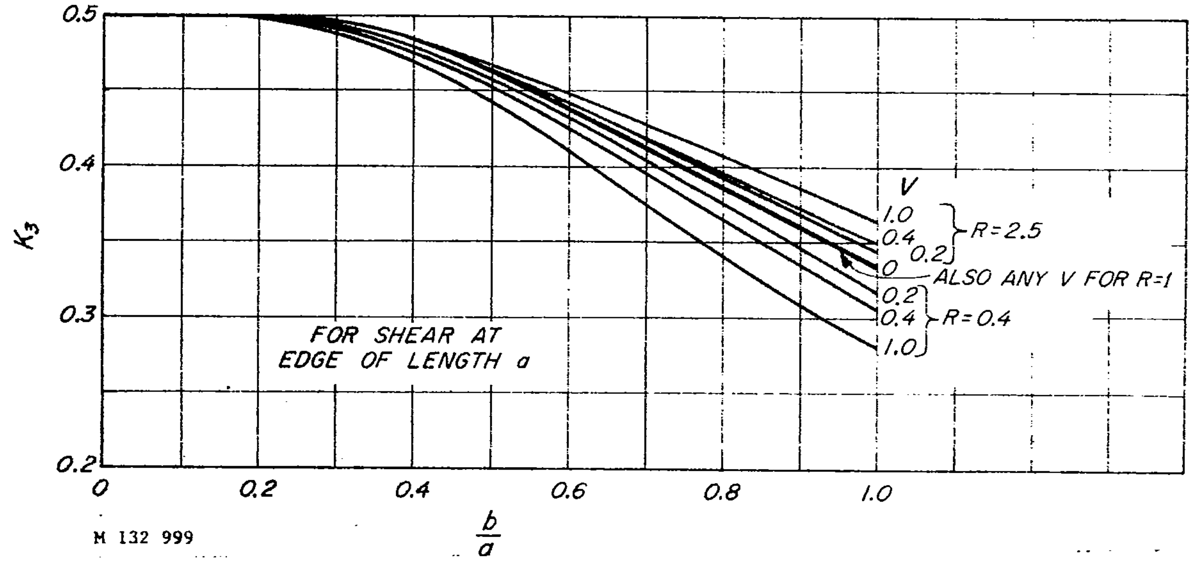




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Figure 9-22.--$K_3$ for determining maximum core shear stress, $F_{sc}$, for flat rectangular sandwich panels, with isotropic facings and isotropic or orthotropic core (see sketch), under uniformly distributed normal load.

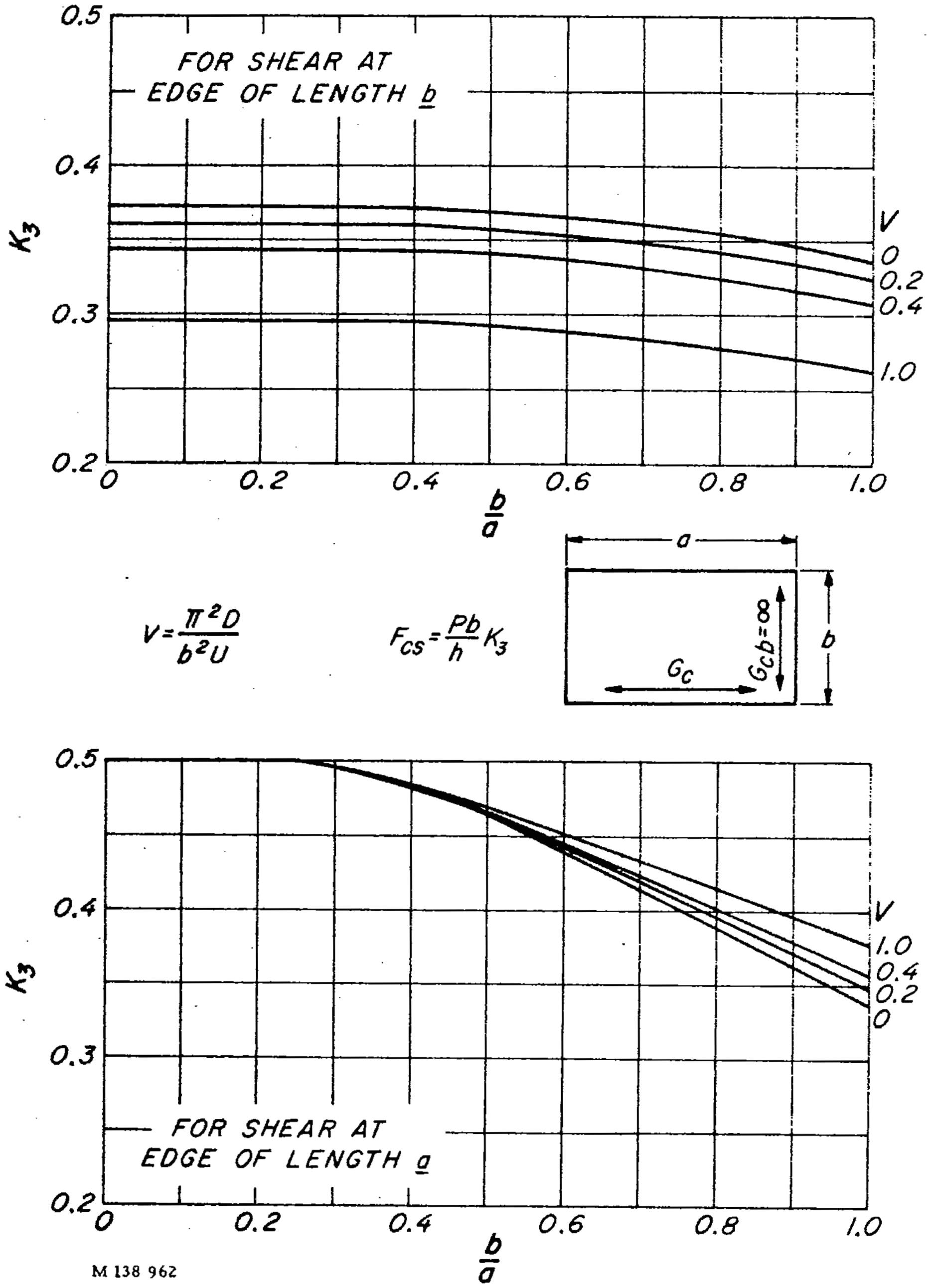
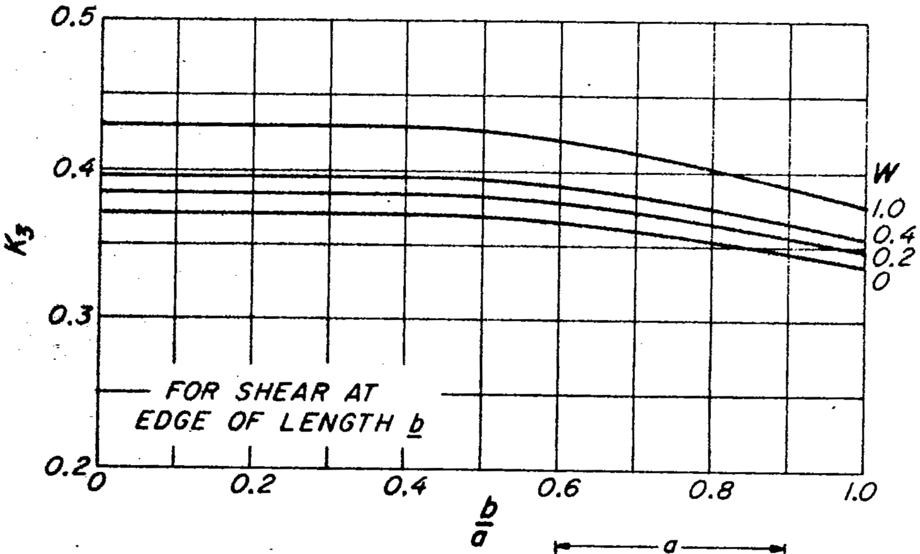
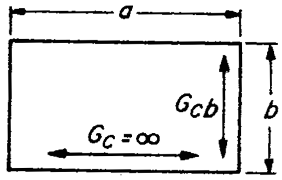



Figure 9-23.--$K_3$ for determining maximum core shear stress, $F_{cs}$, for flat rectangular sandwich panels, with isotropic facings and corrugated core (see sketch), under uniformly distributed load.




$$W = \frac{\pi^2 t_c D}{b^2 h^2 G_{cb}}$$

$$F_{cs} = \frac{Pb}{h} K_3$$



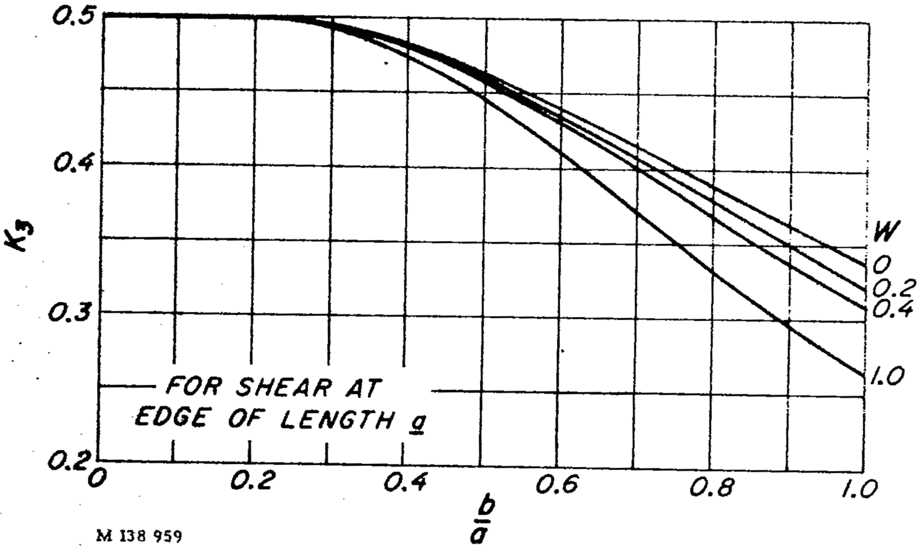




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Figure 9-24.--$K_3$ for determining maximum core shear stress, $F_{cs}$, for flat rectangular sandwich panel, with isotropic facings and corrugated core (see sketch), under uniformly distributed load.

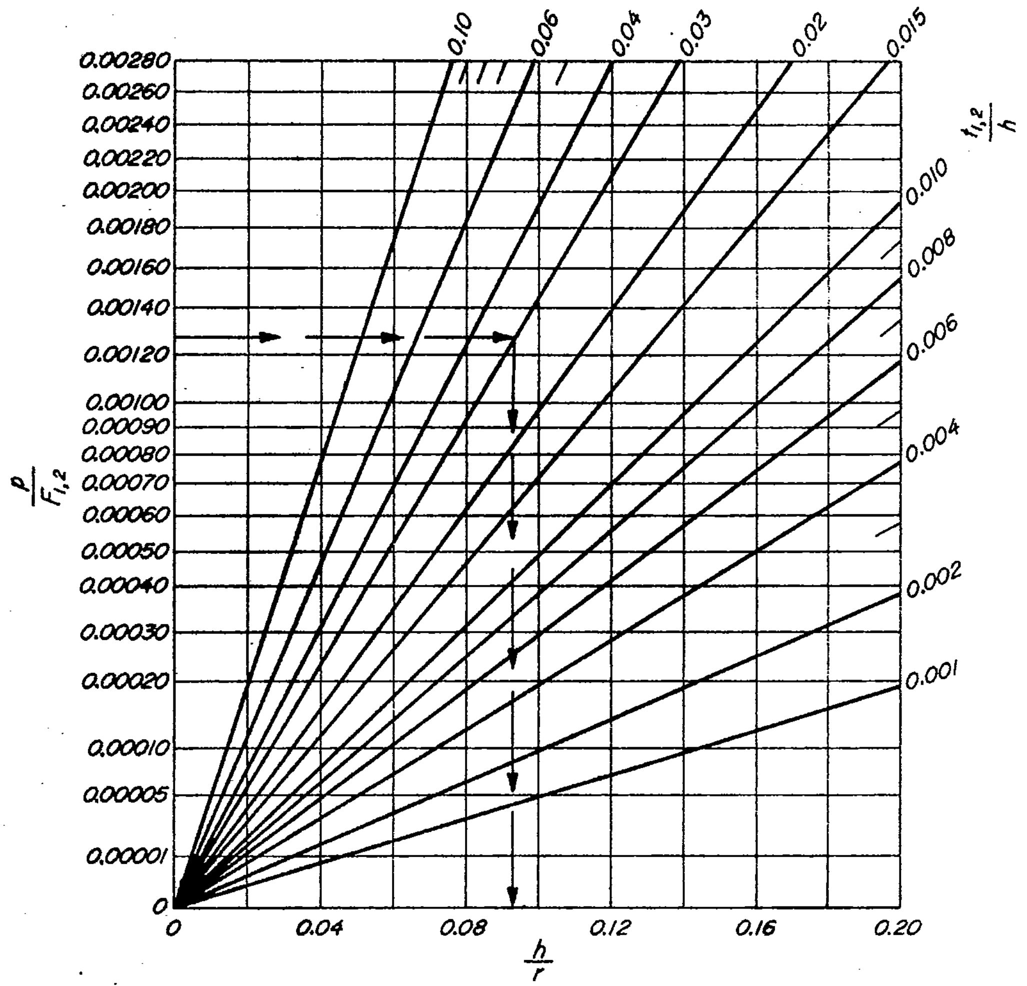


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Figure 9-25.--Chart for determining h/r ratio for flat circular sandwich panel, with isotropic facings and core, under uniformly distributed normal load so that facing stress will be $F_{1,2}$; $\mu = 0.3$.

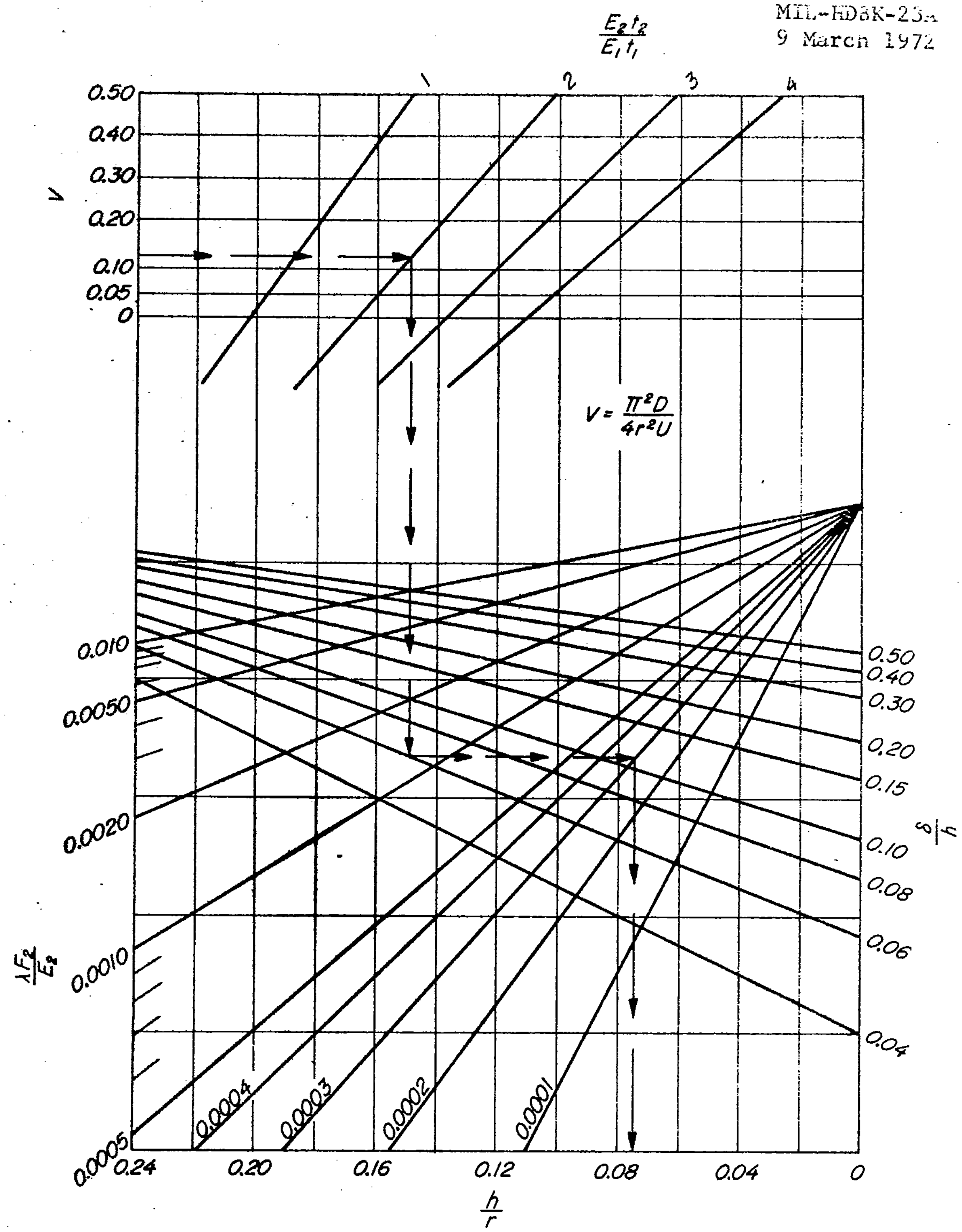


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Figure 9-26.--Chart for determining h/r ratio for flat circular sandwich, with isotropic facings and core, under uniformly distributed normal load producing center deflection ratio δ/h.

# CHAPTER 10

## DESIGN OF SANDWICH CYLINDERS UNDER EXTERNAL RADIAL PRESSURE

### 10.1 BASIC PRINCIPLES

Assuming that a design begins with chosen design stresses and a given external radial pressure (no axial load), a circular cylinder with walls of sandwich construction shall be designed to comply with the four basic design principles summarized in section 1.2 of the Introduction. These four conditions must be met.

Overall buckling of the sandwich walls or dimpling or wrinkling of the sandwich facings cannot occur without possible collapse of the cylinder. Detailed procedures, theoretical formulas, and graphs for determining dimensions of the facings and core, as well as necessary core properties, are given in following paragraphs. Double formulas are given, one formula for sandwich with facings of different materials and thicknesses and another for sandwich with both facings of the same material and of equal thickness.

Facing modulus of elasticity, $E'$, and stress values, $F_c$, shall be compression values at the conditions of use; that is, if application is at elevated temperature, then facing properties at elevated temperature shall be used in design. The facing modulus of elasticity is the effective value of the facing stress. If the stress is beyond proportional limit values, an appropriate tangent, reduced, or modified compression modulus of elasticity shall be used (ref. 10-3).

## 10.2 DETERMINING FACING THICKNESS, CORE THICKNESS, AND CORE SHEAR MODULUS FOR SANDWICH CYLINDERS UNDER EXTERNAL RADIAL PRESSURE

This section presents formulas, theoretical equations, and a design procedure to determine the sandwich facing thickness, core thickness, and core shear modulus such that overall buckling of a sandwich cylinder will not occur at the chosen facing design stresses. The equations and procedure presented apply to sandwich cylinders having facings of isotropic materials and an isotropic or orthotropic core. Ends of the cylinder are assumed to be simply supported on rigid plates that hold the ends circular. The facing stresses are related to the applied external radial pressure (no axial load) by the equation:

$$t_1 F_{c1} + t_2 F_{c2} = rp \qquad (10:1)$$

$$t = \frac{rp}{2F_c} \qquad \text{(for equal facings)} \qquad (10:1a)$$

where t is facing thickness, $F_c$ is chosen design hoop compressive facing stress, p is the design value of external radial pressure, r is the mean radius of cylinder, and 1, 2 are subscripts denoting facings 1 and 2.

In determining thickness of facings for sandwich with facings of different materials, equation 10:1 must be satisfied, but also the stresses $F_{c1}$ and $F_{c2}$ must be chosen so that $F_{c1}/E_{s1} = F_{c2}/E_{s2}$ (where $E_s$ is facing secant modulus of elasticity), thus avoiding overstressing of either facing. For example, if facing 1 is a material such that the ratio $F_{c1}/E_{s1} = 0.005$ and facing 2 is a material such that the ratio $F_{c2}/E_{s2} = 0.002$, the design must be based on a ratio of 0.002; otherwise facing 2 will be overstressed. In order to accomplish this, the chosen design stress for facing 1 must be lowered. For many combinations of facing materials, it will be found advantageous to choose thicknesses such that $E_1't_1 = E_2't_2$. If the core can support hoop compression loads, rp should be replaced by $(rp - F_c t_c)$.

The load per inch of length due to an applied external radial pressure at which buckling of a sandwich cylinder occurs is given by the theoretical equation (ref. 10-1):

$$rp = \left(\frac{E'_1 t_1}{\lambda_1} + \frac{E'_2 t_2}{\lambda_2}\right) K \quad (10:2)$$

$$rp = \frac{2E't}{\lambda} K \quad \text{(for equal facings)} \quad (10:2a)$$

where E' is effective compression modulus of elasticity of the facings, $\lambda = 1 - \mu^2$, $\mu$ is Poisson's ratio of the facings, and K is a theoretical coefficient. Substitution of (10:1) into (10:2) with the provision that strain in facing 1 equals strain in facing 2 results in

$$\frac{F_{c1,2}\lambda_{1,2}}{E'_{1,2}} = K \quad (10:3)$$

$$\frac{F_c \lambda}{E'} = K \quad \text{(for equal facings)} \quad (10:3a)$$

The coefficient K is dependent upon cylinder dimensions and sandwich bending and shear rigidities. Convenient nondimensional parameters for determining K are h/r, L/r, $E'_1 t_1 / E'_2 t_2$, and $V = \frac{D}{r^2 U}$ where h is distance between facing centroids, L is cylinder length, D is sandwich bending stiffness, and U is sandwich shear stiffness. Substitution of expressions for D and U into the parameter V results in

$$V = \frac{E'_1 t_1 E'_2 t_2 h}{\left(E'_1 t_1 + E'_2 t_2\right) \lambda r^2 G_c} \quad (10:3)$$

$$V = \frac{E' th}{2\lambda r^2 G_c} \quad \text{(for equal facings)} \quad (10:3a)$$

where $G_c$ is the core shear modulus associated with shear distortion in the radial and circumferential directions.

### 10.2.1 Determination of Minimum Values of h

A minimum value of h required will be determined by assuming V = 0 for a first approximation. The value of h is minimum because V = 0 only if the core shear modulus is infinite; for any actual core the shear modulus is not infinite; hence a thicker core must be used.

The chart of figure 10-1 gives minimum values of h/r for sandwich with isotropic facings.

Parameters needed for use of the chart are:

1. Facing properties $\frac{F_{c1,2}\lambda_{1,2}}{E'_{1,2}}$
2. Cylinder length-to-radius ratio L/r.
3. Ratio of $\frac{E'_1 t_1}{E'_2 t_2}$.

From the value of h the core thickness is computed by the formula

$$t_c = h - \frac{t_1 + t_2}{2} \qquad (10:4)$$

$$t_c = h - t \qquad \text{(for equal facings)} \qquad (10:4a)$$

## 10.3 FINAL DESIGN

The final sandwich design is arrived at by assuming a slightly thicker core than determined in 10.2.1 and using the checking curves of figures 10-2 for V = 0, 10-3 for V = 0.05, and 10-4 for V = 0.10. The final design shall be based on a buckling coefficient of 0.95 times the values given by figures 10-2 to 10-4 (ref. 10-2). Several iterations may be necessary because the parameter V is dependent upon sandwich thickness and core shear modulus as given in formula (10:3). Interpolation for values of V other than those given in the figures can be done graphically.

The family of curves on figure 10-2 can be approximated very closely by a single curve for cylinders of short and moderate length. This single curve shown in figure 10-5 is obtained by modifying the coordinate axes of figure 10-2. For very long cylinders the single curve branches into a family of lines of steeper slope, as shown in the upper right-hand portion of figure 10-5. This family of lines is dependent upon the ratio r/h as well as the graph abscissa. If the value of the abscissa is such that the branched lines are shown, the value of the ordinate shall be picked from the branched lines rather than the bottom straight line. Thus for an abscissa of $10^5$ and a value of 100 for the parameter $\frac{(E_1't_1 + E_2't_2)\sqrt{\lambda}}{\sqrt{E_1't_1E_2't_2}}\frac{r}{h}$ the proper value of the ordinate to produce the least buckling pressure would be $3.05 \times 10^2$, not $1.64 \times 10^2$.

If a more accurate determination of K is desired, the approximate formula given in reference 10-1 can be solved. This formula is

$$K = \frac{\psi^2(n^2-1)\left(3+\frac{n^2L^2}{\pi^2r^2}\right)\left[\left(\frac{n^2L^2}{\pi^2r^2}-\frac{1}{3}\right)\left(n^2-1+\frac{\pi^2r^2}{L^2}\right)-\frac{2}{3}\right]+\frac{8}{9}\left[1+\left(n^2+\frac{\pi^2r^2}{3L^2}\right)V\right]}{\left[\left(\frac{n^2L^2}{\pi^2r^2}+1\right)^2(n^2-1)+\frac{1}{3}\right]\left[1+\left(n^2+\frac{\pi^2r^2}{3L^2}\right)V\right]} \qquad (10:5)$$

$$\text{where} \quad \psi^2 = \frac{E_1't_1E_2't_2h^2}{\left(E_1't_1 + E_2't_2\right)^2 r^2} \qquad (10:6)$$

$$\psi^2 = \frac{h^2}{4r^2} \quad \text{(for equal facings)} \qquad (10:6a)$$

Values of the number of circumferential buckles, n, are chosen to produce minimum values of K. This approximate formula does not contain terms with core shear moduli in the radial-axial directions because these terms have little influence on cylinders longer than about one diameter. Thus the curves given approximate the behavior of cylinders with orthotropic as well as isotropic cores.

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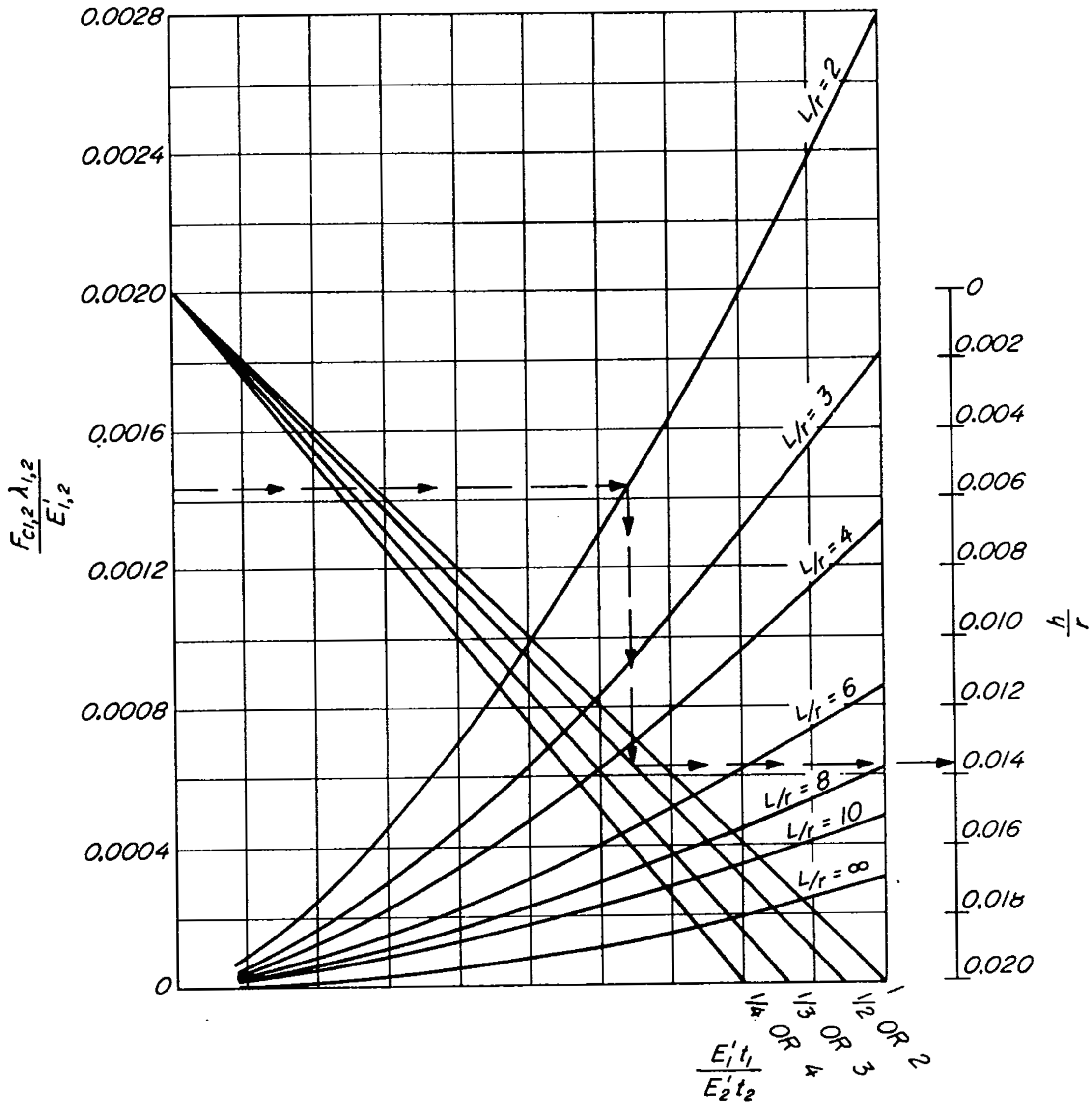


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Figure 10-1.--Chart for determining minimum h/r ratio (V = 0) such that the walls of a sandwich cylinder with isotropic facings will not buckle under external radial pressure (no axial load).

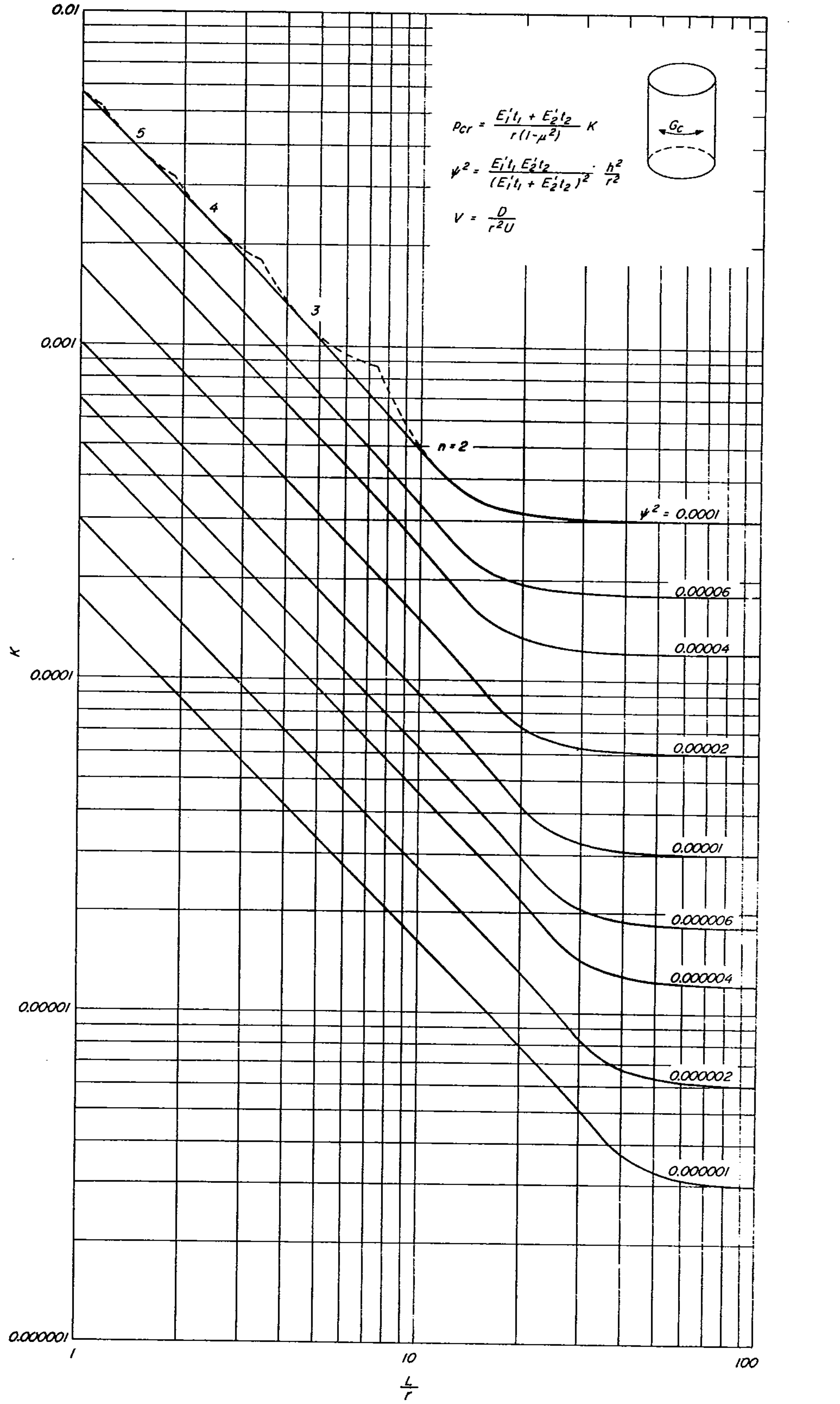


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Figure 10-2.--Buckling coefficient K for sandwich cylinder under **external radial pressure.** Isotropic facings; isotropic or orthotropic core; V = 0.

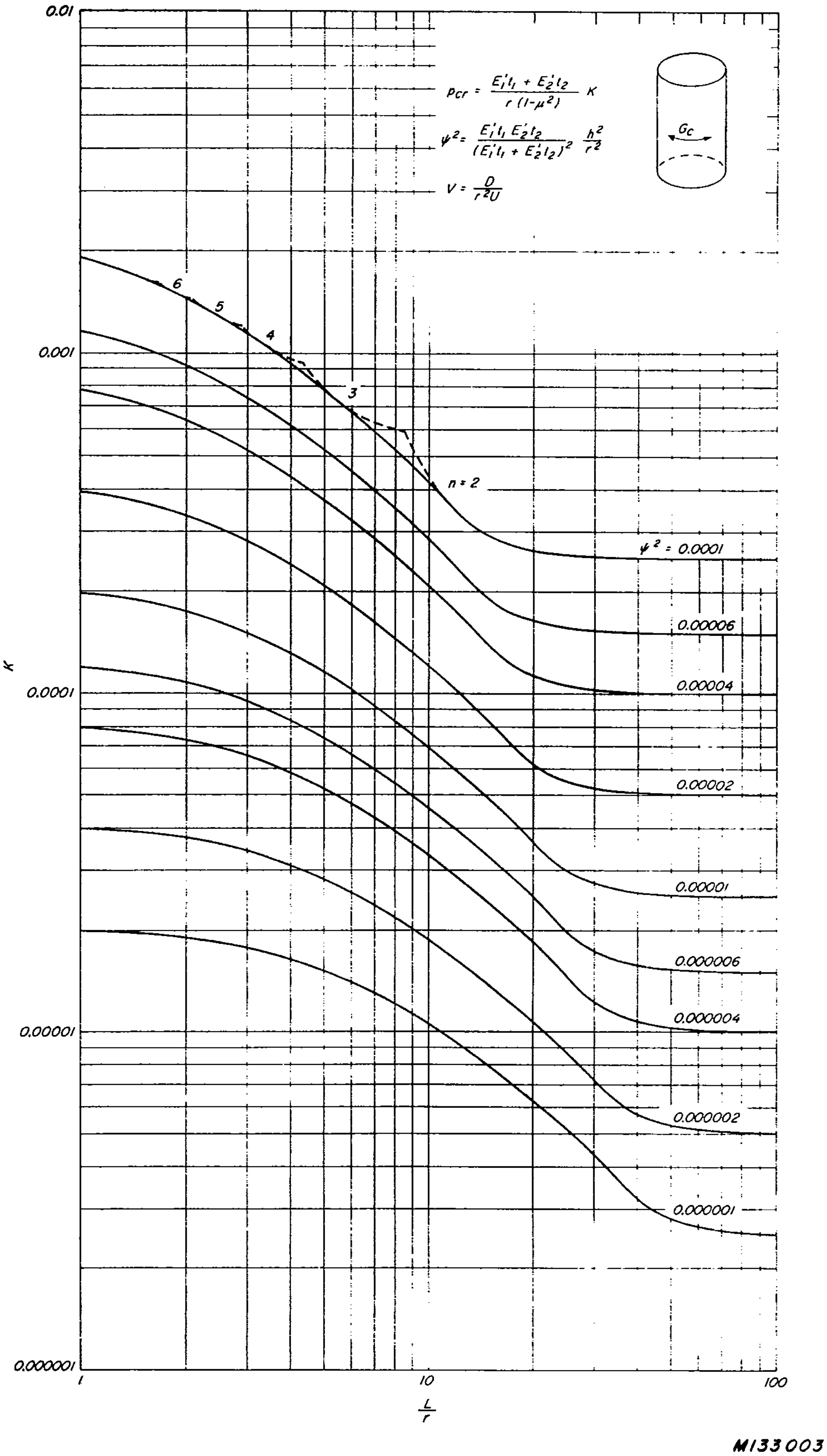


Figure 10-3.--Buckling coefficient K for sandwich cylinders under external radial pressure. Isotropic facings; isotropic or orthotropic core; V = 0.05.

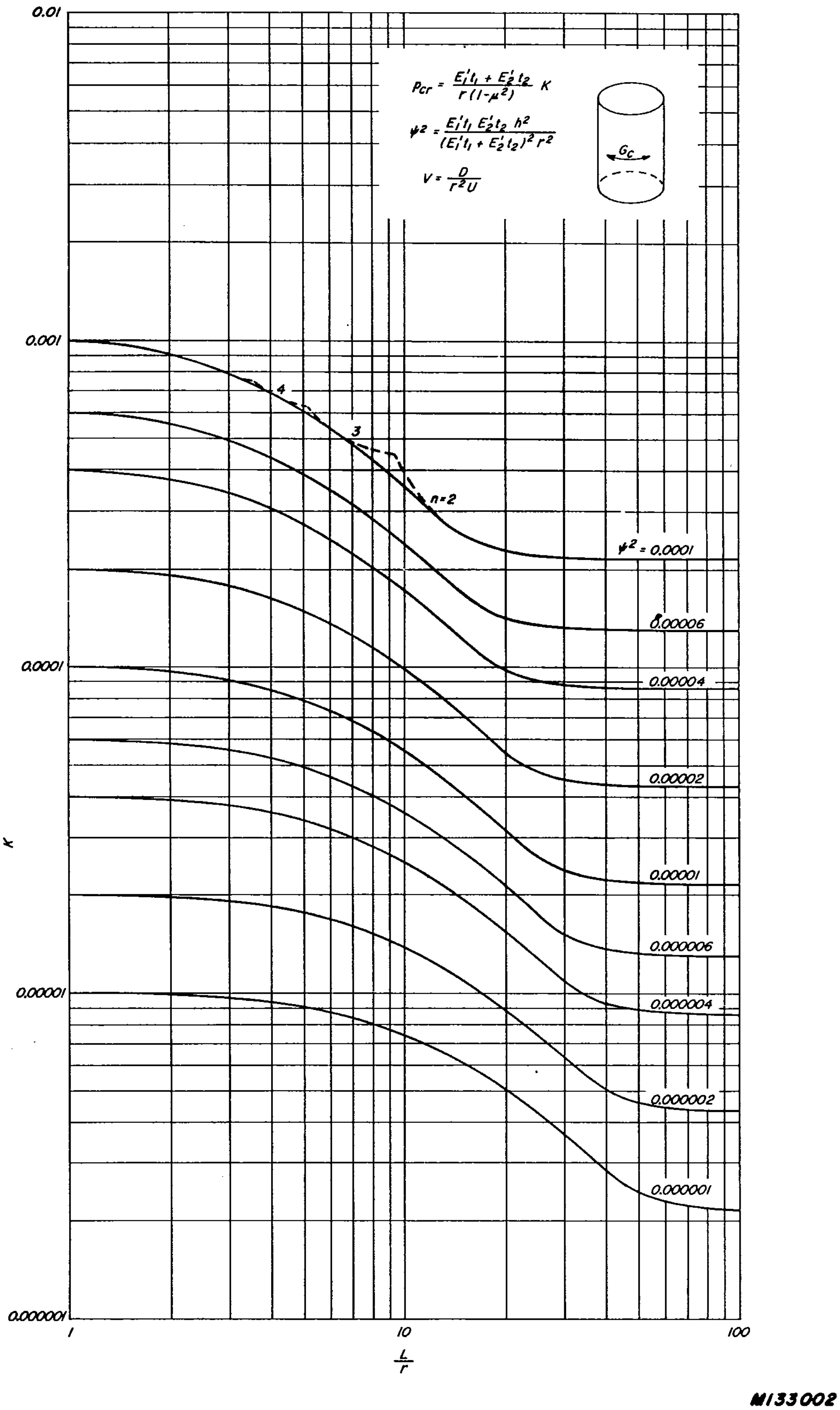


Figure 10-4.--Buckling coefficient K for sandwich cylinders under external radial pressure. Isotropic facings; isotropic or orthotropic core; V = 0.10.

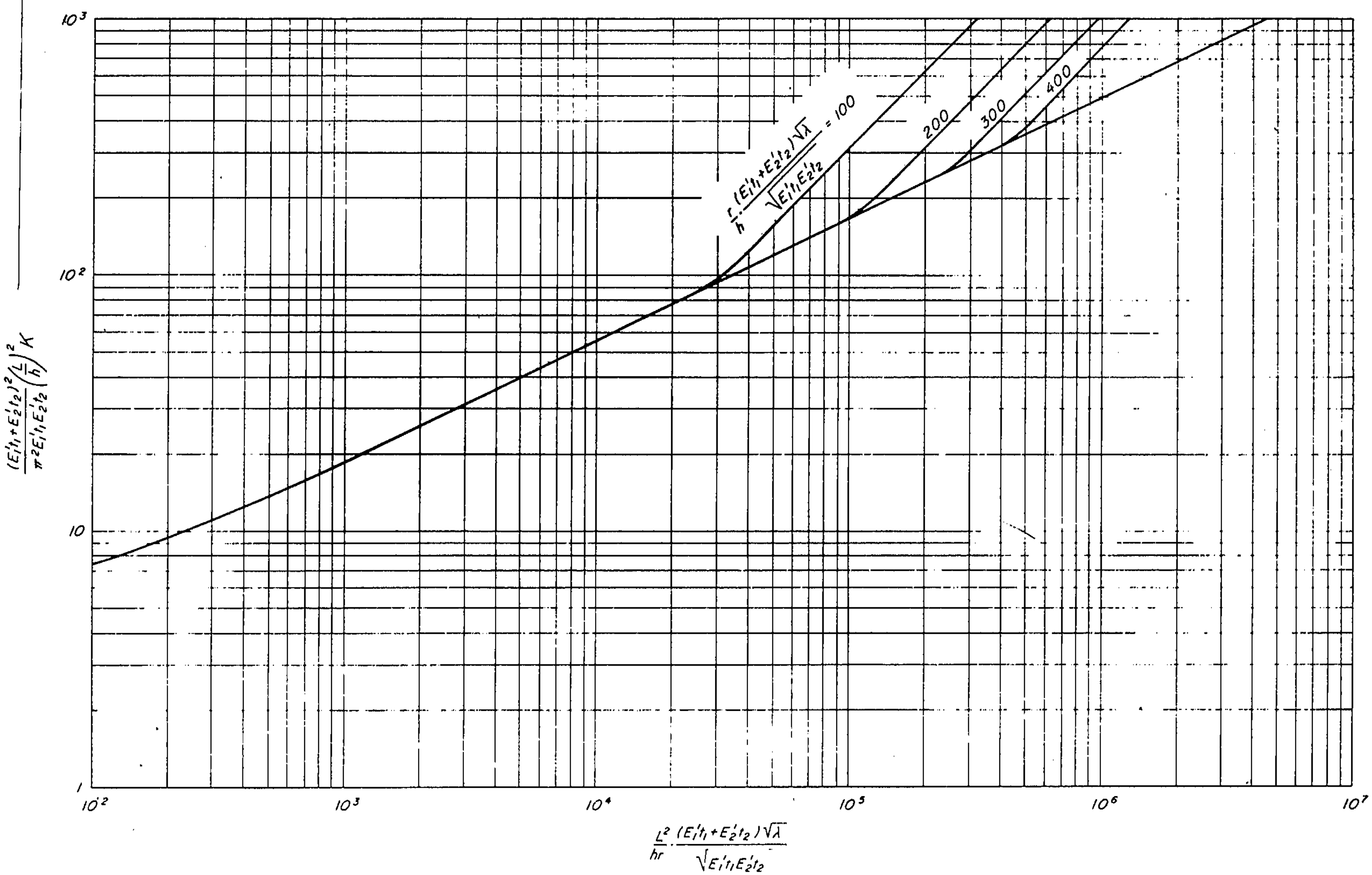


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Figure 10-5.--Modified buckling coefficient for sandwich cylinders under external radial pressure. Isotropic facings; isotropic or orthotropic core; V = 0.

# CHAPTER 11

## DESIGN OF SANDWICH CYLINDERS

## UNDER TORSION

### 11.1 BASIC PRINCIPLES

Assuming that a design begins with chosen design stresses and a given load to transmit, a cylinder, with walls of sandwich construction, under torsion load shall be designed to comply with the four basic design principles summarized in 1.2 of the Introduction. In addition, if the cylinder is extremely long, it shall have sufficient bending stiffness so that sideways buckling will not occur. These five conditions must be met.

Buckling of the sandwich walls, dimpling or wrinkling of the facings, or sideways buckling of the cylinder cannot occur without possible total collapse of the cylinder. Detailed procedures giving theoretical formulas and graphs for determining dimensions of the facings and core, as well as necessary core properties, are given in the following paragraphs. Double formulas are given, one formula for sandwich with facings of different materials and thicknesses and another formula for sandwich with each facing of the same material and thickness. Facing modulus of elasticity, E'; shear modulus, G'; and stress values, $F_s$, shall be values at the condition of use; that is, if application is at elevated temperature, then facing properties at elevated temperature shall be used in design. The effective elastic modulus shall be the lower of either the compressive or tensile value of the facing material in a direction at 45° to the cylinder axis. (The compression and tension stresses, $F_c$ and $F_t$, are equal to the shear stress, $F_s$ for a tube in torsion.) If the stress is beyond the proportional limit value, an appropriate, tangent, reduced, or modified modulus of elasticity or shear modulus shall be used (ref. 11-5).

## 11.2 DETERMINING FACING THICKNESS

Facing stresses are related to the applied torsion load by the equations:

$$t_1F_{s1} + t_2F_{s2} = N \quad \text{(for unequal facings)} \qquad (11:1)$$

$$t = \frac{N}{2F_s} \quad \text{(for equal facings)} \qquad (11:1a)$$

where t is facing thickness, $F_s$ is chosen design facing shear stress, N is design shear load per unit length of cylinder circumference, and 1,2 are subscripts denoting facings 1 and 2. N is determined from the design torque, T, by the formula

$$N = \frac{T}{2\pi r^2} \qquad (11:2)$$

where r is mean radius of curvature of the sandwich cylinder walls.

In determining thickness of facings for sandwich with facings of different materials, equation (11:1) must be satisfied, but also the stresses $F_{s1}$ and $F_{s2}$ must be chosen so that $F_{s1}/G_{s1} = F_{s2}/G_{s2}$ (where G is facing secant shear modulus), thus avoiding overstressing of either facing. For example, if facing 1 is a material such that $F_{s1}/G_{s1} = 0.005$, the facing 2 is a material such that $F_{s2}/G_{s2} = 0.002$, the design must be based on a ratio of $F_{s1}/G_{s1} = F_{s2}/G_{s2} = 0.002$; otherwise facing 2 will be overstressed. In order to accomplish this, the chosen design stress for facing 1 must be lowered. For many combinations of facing materials it will be found advantageous to choose thicknesses such that $G_1t_1 = G_2t_2$ or $E_1t_1 = E_2t_2$.

If the cylinder is long and slender and the radius is limited, the facing thicknesses may have to be increased in order to prevent sideways buckling, as covered by section 11.4.

## 11.3 DETERMINING CORE THICKNESS AND CORE SHEAR MODULUS

This section gives procedures for determining core thickness and core shear modulus so that overall buckling of the sandwich walls of the cylinder will not occur (ref. 11-1, 11-2, 11-3). The facing stress at buckling is given by the formula:

$$F_{s1,2} = KE'_{1,2} \frac{d}{r} \qquad (11:3)$$

$$F_s = KE' \frac{d}{r} \quad \text{(for equal facings)} \qquad (11:3a)$$

where E' is effective facing elastic modulus at stress $F_s$; d is sandwich thickness; r is mean radius of curvature; and K is a theoretical buckling coefficient dependent on cylinder dimensions and sandwich bending and shear rigidities.

Values of the coefficient K are given by ordinates of the curves in the upper portion of figures 11-1 to 11-6 for sandwich with isotropic facings and isotropic or orthotropic cores. Determination of the coefficients was based on the assumption that the Poisson's ratio of the facings was 0.25. Figures 11-1, 11-2, and 11-3 are for sandwich with thin facings ($t_c/d = 1$) and figures 11-4, 11-5, and 11-6 for sandwich with moderately thick facings ($t_c/d = 0.7$). The curves give approximate values for cylinders of sandwich with corrugated cores. More accurate data for such sandwich cylinders are given in references (11-1) and (11-2). Final design values of K shall be 0.75 times the values given by figures 11-1 to 11-6 (ref. 11-4).

Solving equations (11:3) and (11:3a) for d/r gives:

$$\frac{d}{r} = \frac{F_{s1,2}}{E'_{1,2}} \left(\frac{1}{K}\right) \qquad (11:4)$$

$$\frac{d}{r} = \frac{F_s}{E'} \left(\frac{1}{K}\right) \quad \text{(for equal facings)} \qquad (11:4a)$$

Therefore, if K is known, equation (11:4) or (11:4a) can be solved directly to eventually obtain d because all other quantities are known. After d is obtained, the core thickness, $t_c$, is computed from the formulas

$$t_c = d - (t_1 + t_2) \qquad (11:5)$$

$$t_c = d - 2t \quad \text{(for equal facings)} \qquad (11:5a)$$

Values of K depend upon the bending stiffness, D, and shear stiffness, U, of the sandwich as incorporated in the parameter

$$V = \frac{D}{r^2 U}$$

which can be written as:

$$V = \frac{E_1' t_1 E_2' t_2 h}{\left(E_1' t_1 + E_2' t_2\right) \lambda r^2 G_c} \qquad (11:6)$$

$$V = \frac{E' th}{2\lambda r^2 G_c} \quad \text{(for equal facings)} \qquad (11:6a)$$

where h is distance between facing centroids, $\lambda = 1 - \mu^2$, $\mu$ is Poisson's ratio of facings, and $G_c$ is core shear modulus associated with shear distortion in the radial and axial directions. Values of K are also dependent upon the cylinder geometry as represented conveniently by dimensionless parameters L/r, d/r, and $J = L^2/dr$.

11.3.1 Determination of Minimum Values of d

A minimum value of d required will be determined by assuming V = 0 for a first approximation. The value of d is minimum because V = 0 only if the core shear modulus is infinite; for any actual core the shear modulus is not infinite; hence, a thicker core must be used.

The charts of figures 11-1 to 11-3 give values for d/r for sandwich with thin, equal, isotropic facings or for sandwich with thin isotropic facings such that $E_1' t_1 = E_2' t_2$. The charts of figures 11-4 to 11-6 apply to similar sandwich with moderately thick facings. Minimum values of d/r are obtained from the curves for V = 0. The upper portion of the charts is entered with the appropriate straight line represented by the known value of a parameter

$$\frac{F_s/E'}{(L/r)^2} \tag{11:7}$$

The intersection of this appropriate line with the curve for V = 0 in the upper graph occurs at an abscissa value of J which is solved graphically for any particular L/r ratio to give the minimum d/r ratio in the lower graph of the figures.

## 11.3.2 Determination of Actual Values of d

Since actual core shear modulus values are not very large, a value of d somewhat greater than given in 11.3.1 must be used. The figures 11-1 to 11-6 are entered at curves with values of V as computed by equation (11:6) or (11:6a). Figures 11-1 and 11-4 apply to sandwich with isotropic cores for which the circumferential shear modulus is equal to the axial shear modulus. Figures (11-2, 11-5) and (11-3, 11-6) apply to sandwich with orthotropic cores for which the circumferential shear modulus is equal to 0.40 and 2.50 times, respectively, the axial shear modulus.

NOTE: For honeycomb cores with core ribbons parallel to the cylinder axis, $G_c = G_{TL}$ and the circumferential shear modulus is $G_{TW}$. For honeycomb cores with core ribbons circumferential, $G_c = G_{TW}$ and the circumferential shear modulus is $G_{TL}$.

In using figures 11-1 to 11-6 it is necessary to iterate because V is directly proportional to the core thickness, $t_c$. As an aid to finally determining $t_c$ and $G_c$, figure 11-7 presents a number of lines representing V for various values of $G_c$ with V ranging from 0.01 to 2 and $G_c$ ranging from 1,000 to 1,000,000 pounds per square inch. The following precedure is suggested:

1. Determine a thickness d from figures 11-1 to 11-6 using a value of 0.01 for V.

2. Compute the constant relating V to $G_c$.

$$\left[\frac{E_1' t_1 E_2' t_2 h}{\left(E_1' t_1 + E_2' t_2\right) \lambda r^2}\right] \quad \text{or} \quad \left[\frac{E' t h}{2 \lambda r^2}\right] \text{ (for equal facings)} = V G_c$$

3. With this constant enter figures 11-7 and determine necessary $G_c$.

4. If the shear modulus is outside the range of values for the materials available, slide up the appropriate line of figure 11-7 and pick up a new value of V, for a reasonable value of core shear modulus.

5. Reenter figures 11-1 to 11-6 with the new value of V and repeat previous steps 1, 2, and 3.

### 11.3.3 Checking Procedure for Determining Buckling Stress, $F_{scr}$

The design shall be checked by using the graphs of figures 11-1 to 11-6 to determine values of K to substitute into formula (11:3) or (11:3a) to compute actual buckling stress, $F_{scr}$.

## 11.4 CHECK TO DETERMINE WHETHER SIDEWAYS BUCKLING WILL OCCUR

If the sandwich cylinder is fairly long it may buckle sideways similar to the way a column buckles under end compression. The load per unit length of circumference at which sideways buckling will occur is given approximately by the formula:

$$N_{cr} = \frac{\pi \left(E_1' t_1 + E_2' t_2\right) r}{2L} \tag{11:8}$$

$$N_{cr} = \frac{\pi E' t r}{L} \quad \text{(for equal facings)} \tag{11:8a}$$

If the value of $N_{cr}$ as computed by formula (11:8) is less than the design load, the cylinder will have to be redesigned by using a larger radius, shorter length, or stiffer facings. Formula (11:8) was derived for thin-walled cylinders and is about 3 percent in error for $h/r = 0.2$. For $h/r < 0.2$, the error is less than 3 percent.

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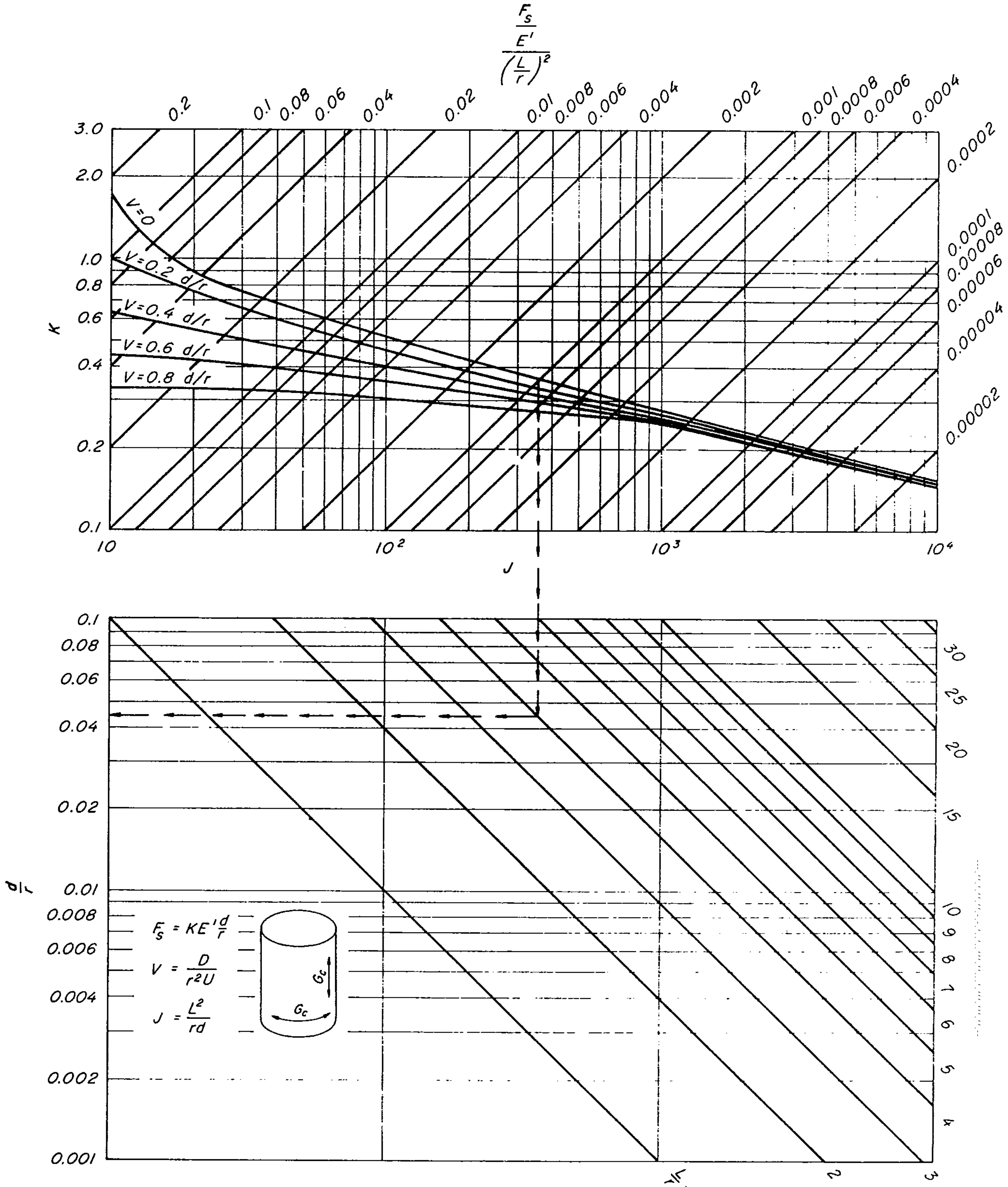


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Figure 11-1.--Chart for determining a $\frac{d}{r}$ ratio such that a sandwich cylinder with isotropic core will not buckle; $\frac{t_c}{d} = 1$.

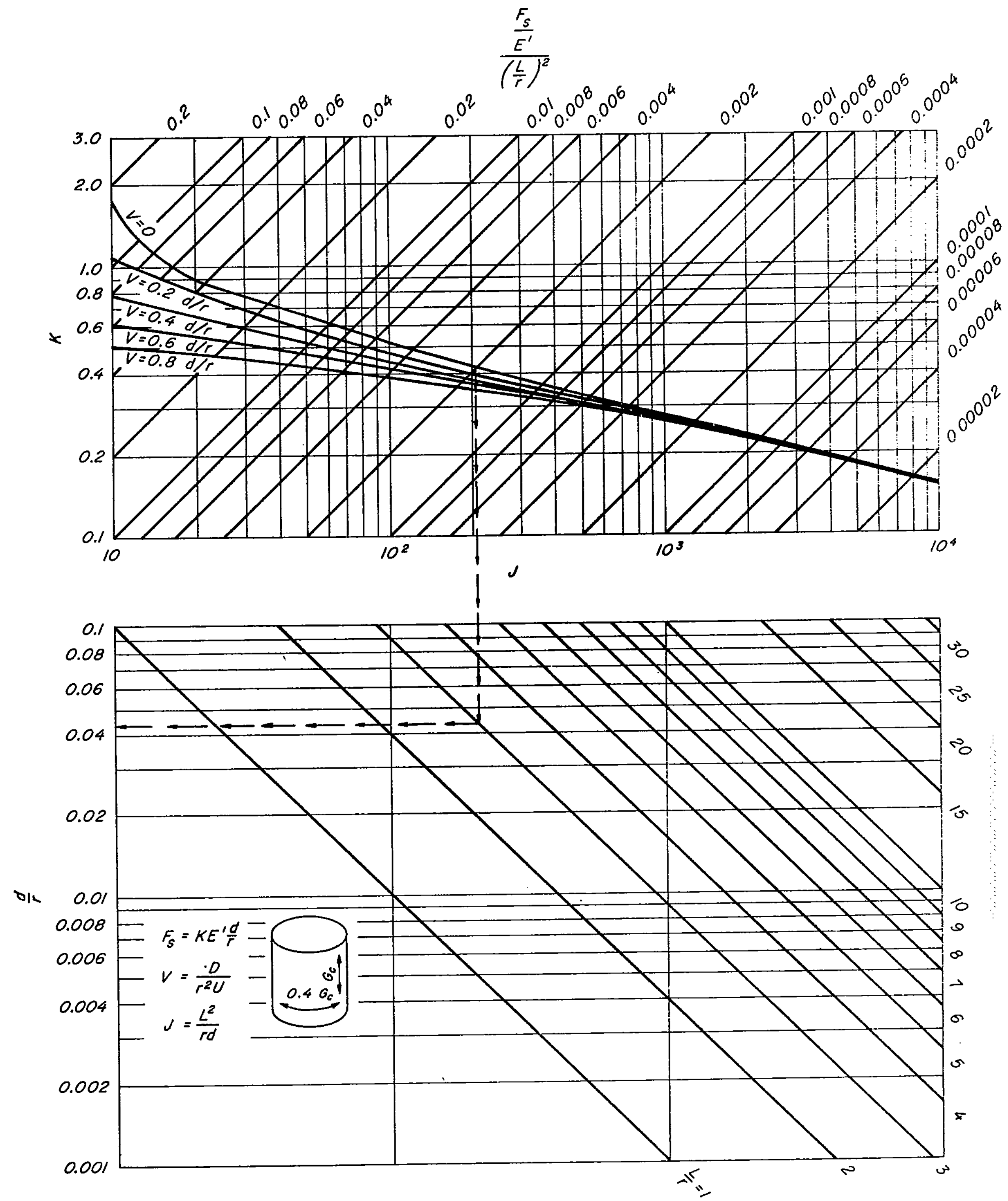


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Figure 11-2.--Chart for determining a $\frac{d}{r}$ ratio such that a sandwich cylinder with orthotropic core will not buckle; $\frac{t_c}{d} = 1$.

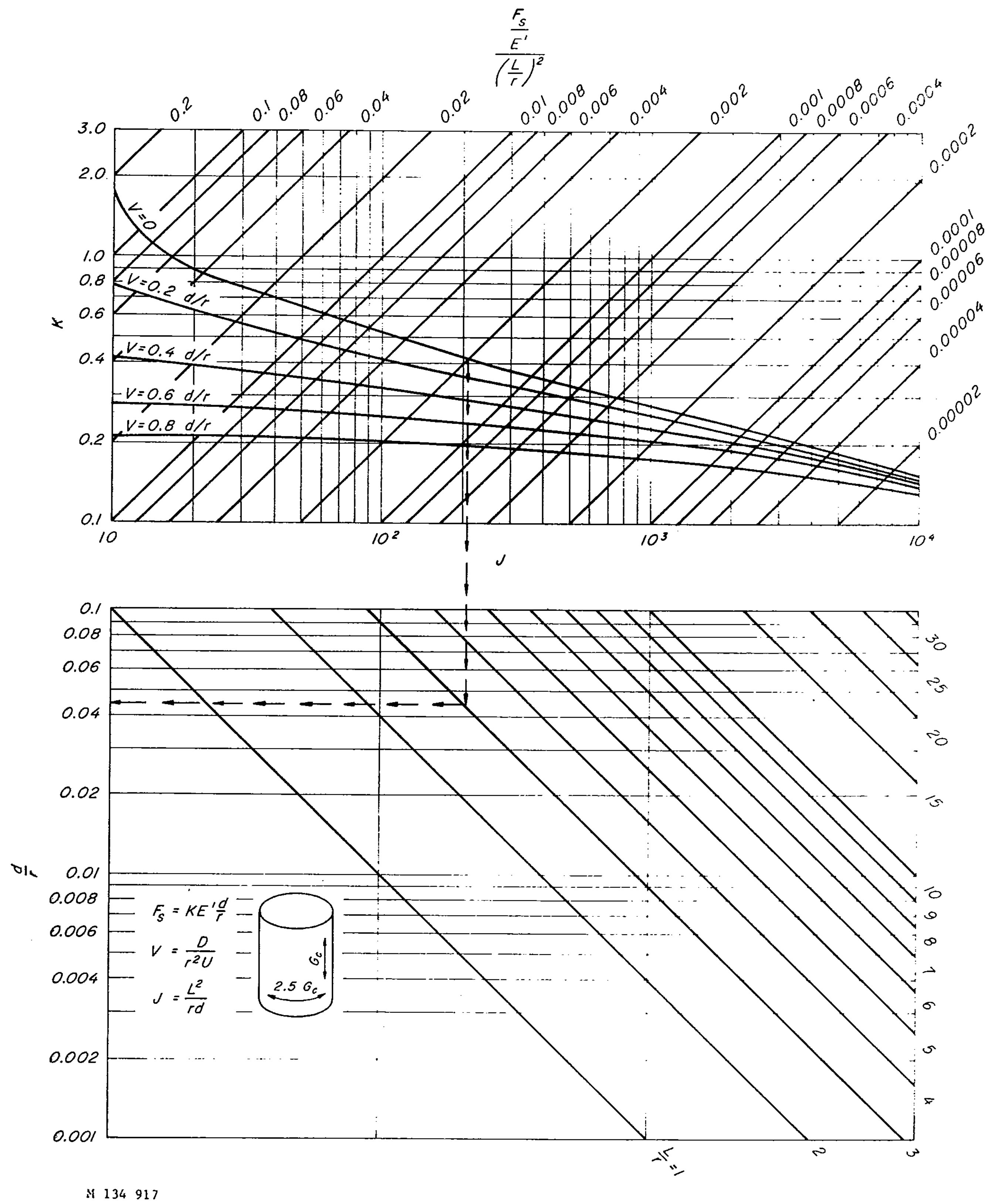


Figure 11-3.--Chart for determining a $\frac{d}{r}$ ratio such that a sandwich cylinder with orthotropic core will not buckle; $\frac{t_c}{d}$ = 1.

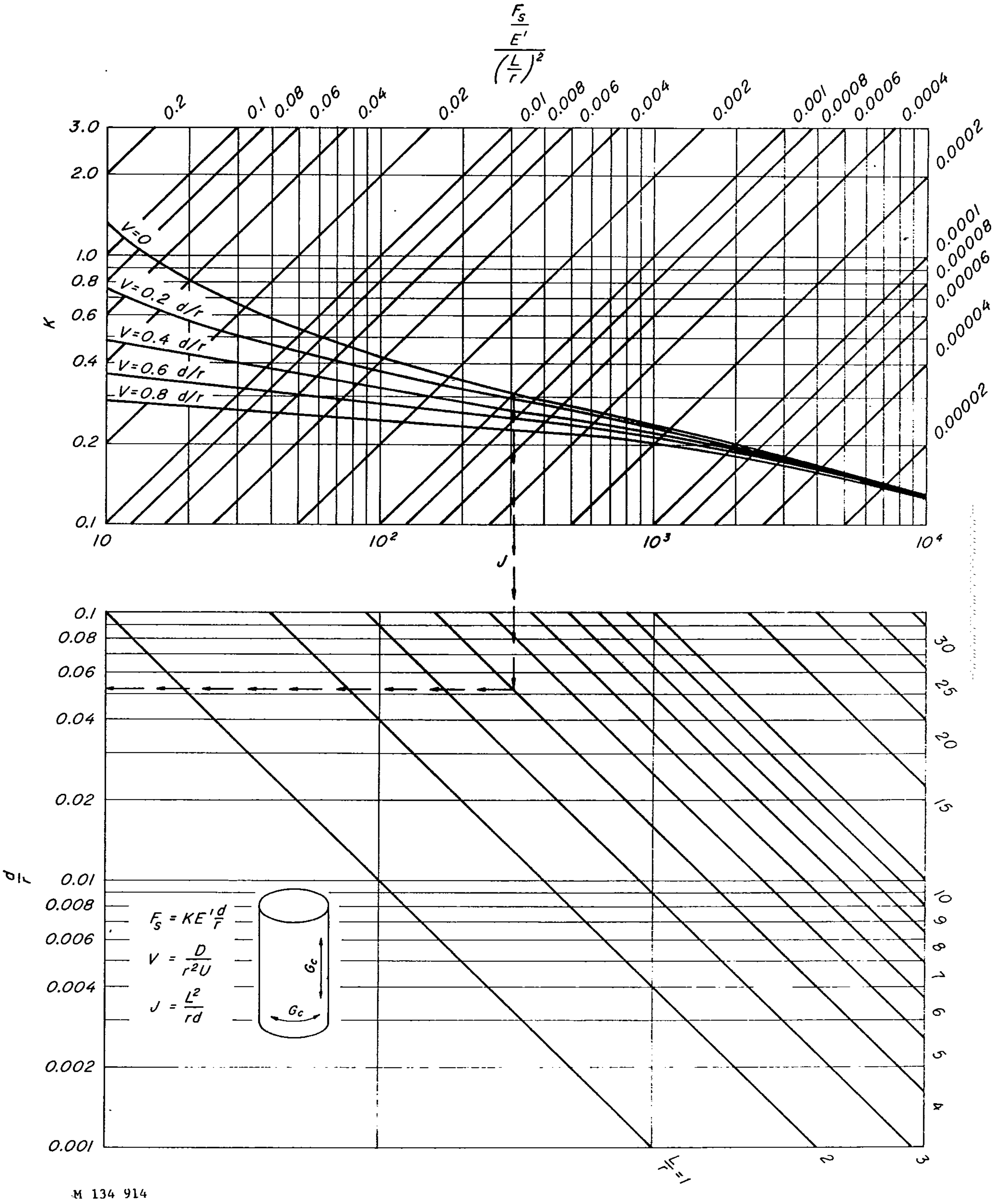


Figure 11-4.--Chart for determining a $\frac{d}{r}$ ratio such that a sandwich cylinder with isotropic core will not buckle; $\frac{t_c}{d}$ = 0.7.

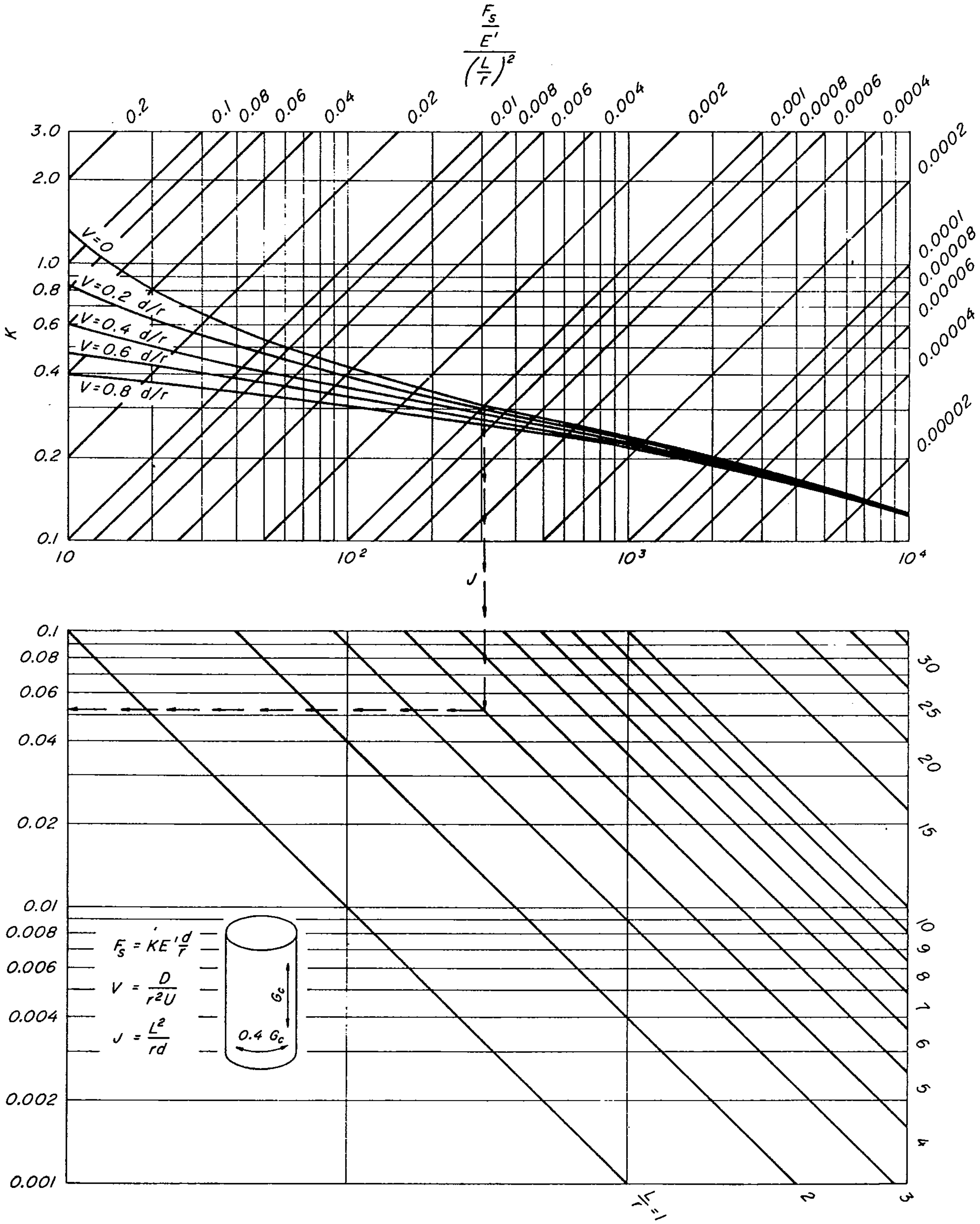


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Figure 11-5.--Chart for determining a $\frac{d}{r}$ ratio such that a sandwich cylinder with orthotropic core will not buckle; $\frac{t_c}{d}$ = 0.7.

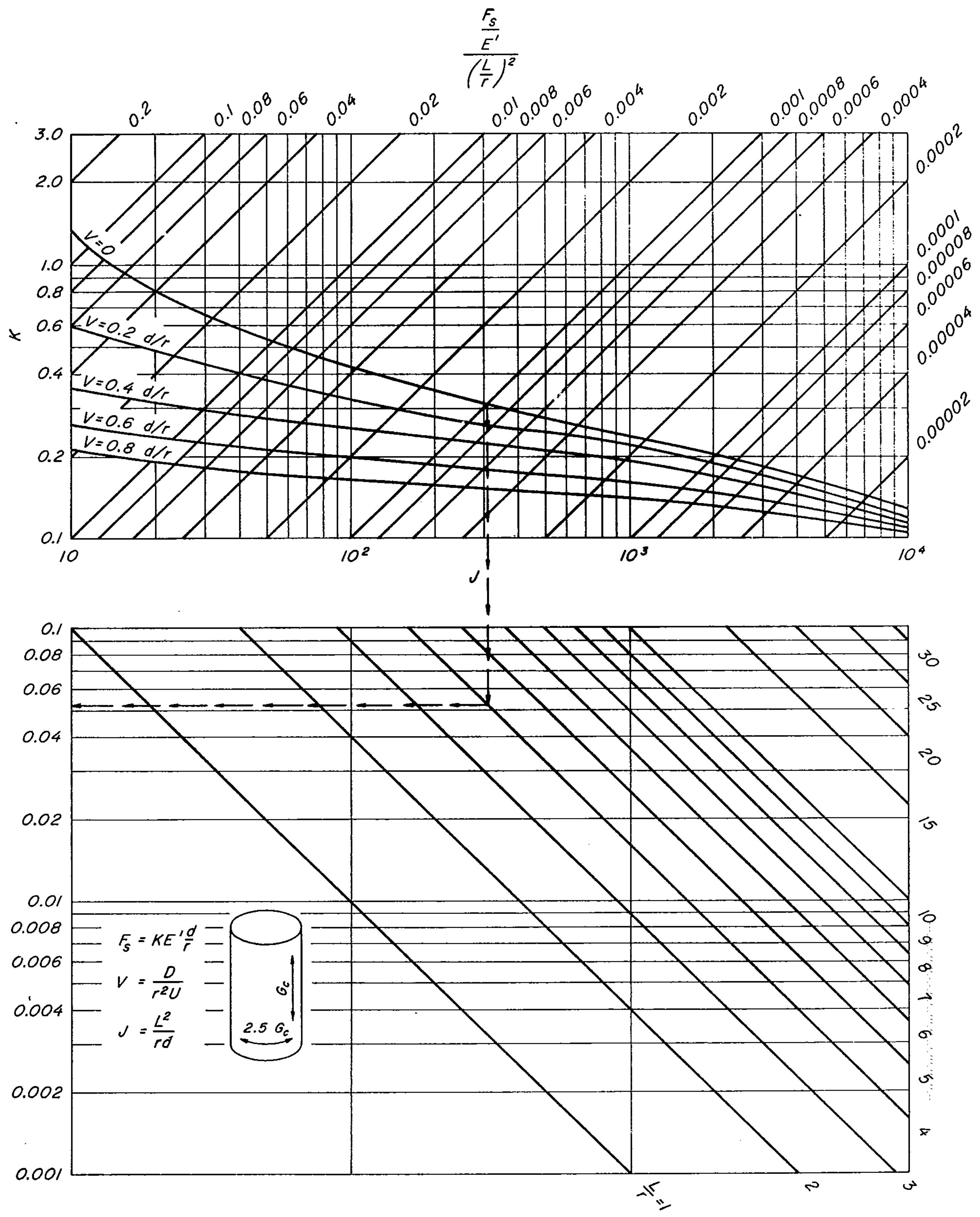


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Figure 11-6.--Chart for determining a $\frac{d}{r}$ ratio such that a sandwich cylinder with orthotropic core will not buckle; $\frac{t_c}{d} = 0.7$.

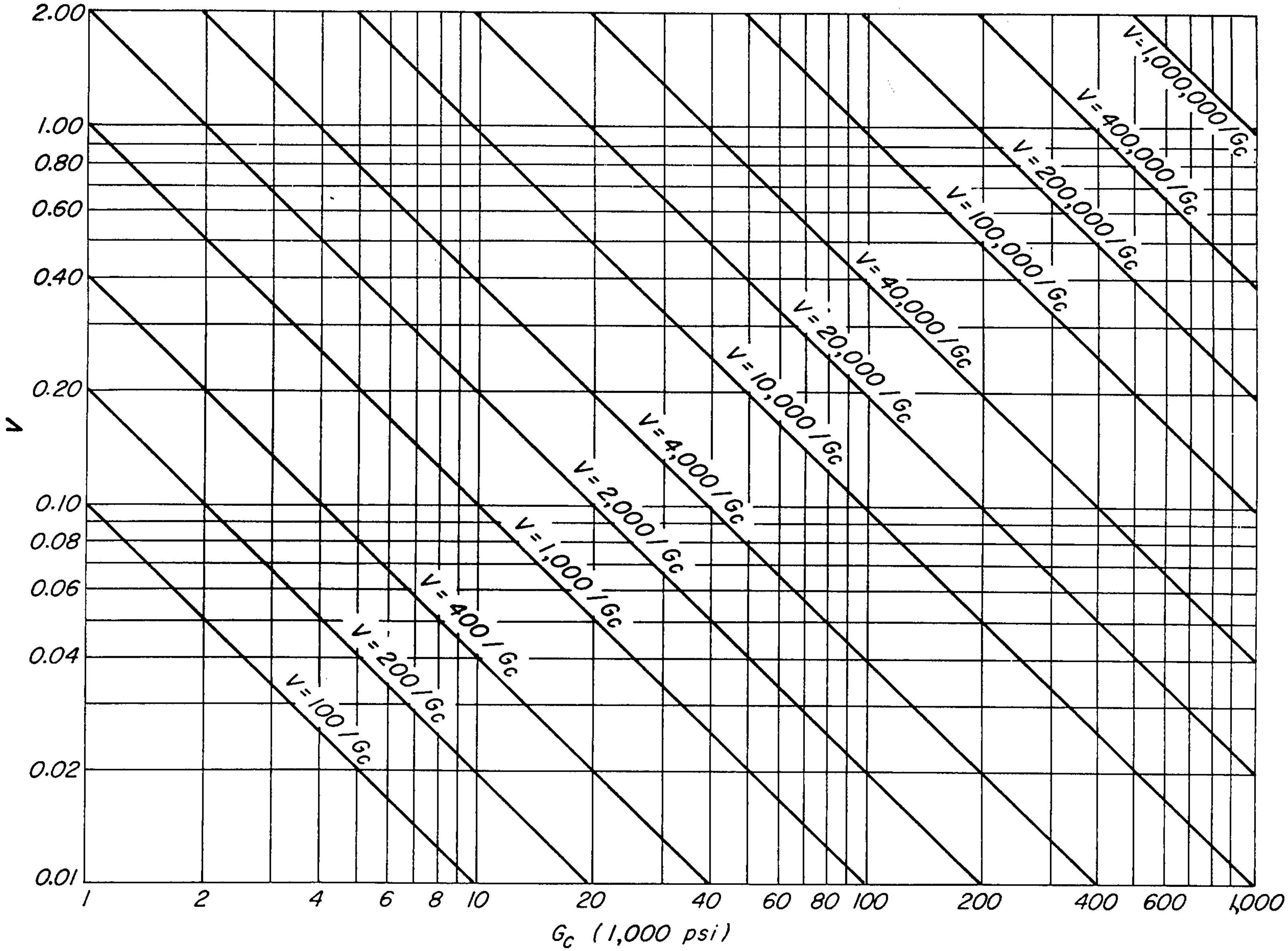


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Figure 11-7.--Chart for determining V and $G_c$ for sandwich cylinders under torsion load.

# CHAPTER 12

## DESIGN OF SANDWICH CYLINDERS UNDER AXIAL COMPRESSION OR BENDING

### 12.1 BASIC PRINCIPLES

Assuming that a design begins with chosen design stresses and a given load to transmit, a cylinder with walls of sandwich construction under axial compression or bending load shall be designed to comply with the four basic design principles summarized in 1.2 of the Introduction. In addition, if the cylinder is compressed axially, the entire cylinder shall have sufficient bending stiffness so that buckling as a long column will not occur.

Overall buckling of the cylinder or the sandwich walls or dimpling or wrinkling of the facings cannot occur without possible total collapse of the cylinder. Detailed procedures giving theoretical formulas and graphs for determining dimensions of the facings and core, as well as necessary core properties, are given in following paragraphs. Double formulas are given, one formula for sandwich with facings of different materials and thicknesses and another formula for sandwich with each facing of the same material and thickness. Facing modulus of elasticity, $E'$, and stress values, $F_c$, shall be compression values at the condition of use; that is, if application is at elevated temperature, then facing properties at elevated temperature shall be used in design. The facing modulus of elasticity is the effective value at the facing stress. If this stress is beyond the proportional limit value, an appropriate tangent, reduced, or modified compression modulus of elasticity shall be used (ref. 12-8).

### 12.2 DETERMINING FACING THICKNESSES

Facing stresses are related to the axial load by the equations:

$$t_1 F_{c1} + t_2 F_{c2} = N \quad \text{(for unequal facings)} \qquad (12:1)$$

$$t = \frac{N}{2F_c} \quad \text{(for equal facings)} \qquad (12:1a)$$

where t is facing thickness, $F_c$ is chosen design facing compressive stress, N is design compression load per unit length of cylinder circumference, and 1,2 are subscripts denoting facings 1 and 2. If the load is produced by bending moment the relationship between maximum N and bending moment, M, for a cylinder of mean radius, r, is given by $N = M/\pi r^2$.

In determining thicknesses of facings of different materials, equation (12:1) must be satisfied, but also the stresses $F_{c1}$ and $F_{c2}$ must be chosen so that $F_{c1}/E_{s1} = F_{c2}/E_{s2}$ (where $E_s$ is facing secant modulus of elasticity), thus avoiding overstressing of either facing. For example, if facing 1 is a material such that the ratio $F_{c1}/E_{s1} = 0.005$ and facing 2 is a material such that the ratio $F_{c2}/E_{s2} = 0.002$, the design must be based on a ratio of 0.002, otherwise facing 2 will be overstressed. In order to accomplish this, the chosen design stress for facing 1 must be lowered. For many combinations of facing materials, it will be found advantageous to choose thicknesses such that $E_1 t_1 = E_2 t_2$. If the core can support edge load, N should be replaced by the quantity $(N - F_c t_c)$.

If an axially compressed cylinder is long and slender and the radius is limited, the facing thicknesses may have to be increased in order to prevent column buckling, as covered by section 12.5.

## 12.3 DETERMINING CORE THICKNESS AND CORE SHEAR MODULUS

This section gives procedures for determining core thickness and core shear modulus so that overall buckling of the sandwich walls of the cylinder will not occur (refs. 12-1, 12-2, 12-3, 12-4, 12-7, and 12-10).

Theoretical formulas are based on buckling load for classical sine-wave buckling. The theory defines the parameters involved rather than determines exact coefficients for computing buckling loads. Large discrepancies exist between theory and tests and unfortunately the test values for buckling of thin-walled cylinders in axial compression or bending are much lower than expected by theory (refs. 12-5, 12-6). Previous design information (ref. 12-9) based on a large-deflection theory and diamond-shaped buckles gave results less than one-half the buckling loads given by classical theory. Continued efforts in shell analysis have shown that the post-buckling behavior tends to approach much lower limits.

Until sufficient test data are available, reduction factors must be applied to theoretical buckling coefficients. These reduction factors attempt to account for effects of initial shell irregularities, and thicker shells have less reduction from classical theory than thinner shells (refs. 12-4 and 12-5). Reduction factors, k, which are 95% of factors given in ref. 12-4, are presented in figure 12-1 as a function of the ratio of mean cylinder radius, r, to the cylinder wall radius of gyration, $\rho$.

The following procedures are applicable to cylinders longer than the length of one ideal buckle, such as would form in the wall of a long cylinder. Generally, the ideal buckle length is about equal to the radius of the cylinder if the core shear modulus is high. It becomes shorter than the radius as the core shear modulus decreases.

The load per unit cylinder circumference at which buckling of the sandwich wall will occur is given by the formula:

$$N_{cr} = 2kK \frac{\sqrt{\left(E'_1 t_1 + E'_2 t_2\right) D}}{r} \qquad (12:2)$$

where k is a reduction factor given in figure 12-1, D is the sandwich bending stiffness, r is mean radius of curvature, and K is a theoretical buckling coefficient dependent on sandwich bending and shear rigidities. This formula solved for the facing stress becomes:

$$F_{c1,2} = \frac{kKE'_{1,2}}{\sqrt{\lambda}} \frac{2\sqrt{E'_1 t_1 E'_2 t_2}}{E'_1 t_1 + E'_2 t_2} \left(\frac{h}{r}\right) \qquad (12:3)$$

$$F_c = \frac{kKE'}{\sqrt{\lambda}} \frac{h}{r} \quad \text{(for equal facings)} \qquad (12:3a)$$

where $E'$ is effective compressive modulus of elasticity at stress $F_c$; $\lambda = 1 - \mu^2$; $\mu$ is Poisson's ratio of facings (in formulas given here it is assumed $\mu = \mu_1 = \mu_2$); and h is distance between facing centroids.

Values of the coefficient K are given by the following approximate formulas:

For sandwich with isotropic or honeycomb core or corrugated core with flutes circumferential--

$$K = 1 - \left(\frac{1+R}{2\sqrt{R}}\right)\left(\frac{r}{h}\right) V \qquad (12:4)$$

$$K = 1 - \left(\frac{r}{h}\right) V \quad \text{(for equal facings)} \qquad (12:4a)$$

for $\left(\frac{1+R}{2\sqrt{R}}\right)\left(\frac{r}{h}\right) V \leq \frac{1}{2}$

$$K = \frac{1}{4\left(\frac{1+R}{2\sqrt{R}}\right)\left(\frac{r}{h}\right) V} \qquad (12:5)$$

$$K = \frac{1}{4\left(\frac{r}{h}\right) V} \quad \text{(for equal facings)} \qquad (12:5a)$$

for $\left(\frac{1+R}{2\sqrt{R}}\right)\left(\frac{r}{h}\right) V > \frac{1}{2}$

For sandwich with corrugated core having flutes axial--

$$K = 1 - \frac{1}{4}\left(\frac{1+R}{2\sqrt{R}}\right)\left(\frac{r}{h}\right) W \qquad (12:6)$$

$$K = 1 - \frac{1}{4}\left(\frac{r}{h}\right) W \quad \text{(for equal facings)} \qquad (12:6a)$$

where $R = \frac{E'_2 t_2}{E'_1 t_1}$

$$V = \frac{E'_1 t_1 E'_2 t_2 \, h}{\lambda r^2 \left(E'_1 t_1 + E'_2 t_2\right) G_c} \qquad (12:7)$$

$$V = \frac{E' th}{2\lambda r^2 G_c} \quad \text{(for equal facings)} \qquad (12:7a)$$

$$W = \frac{E_1't_1E_2't_2\ h}{\lambda r^2 \left(E_1't_1 + E_2't_2\right) G_c'} \qquad (12:8)$$

$$W = \frac{E'th}{2\lambda r^2 G_c'} \quad \text{(for equal facings)} \qquad (12:8a)$$

$G_c$ is the core shear modulus associated with the directions axial to the cylinder and perpendicular to the wall of the cylinder and $G_c'$ is the core shear modulus associated with the directions circumferential to the cylinder and perpendicular to the wall of the cylinder. As values of core shear modulus decrease, values of V or W increase and values of K gradually decrease.

Solution of formula (12:3) for h/r after substitution of expressions for K from formulas (12:4) and (12:6) result in

$$\frac{h}{r} = \left(\frac{1 + R}{2\sqrt{R}}\right) \left[\frac{F_{c1,2}\lambda_{1,2}}{kE_{1,2}'} + V\right] \qquad (12:9)$$

$$\frac{h}{r} = \frac{F_{c}\lambda}{kE'} + V \quad \text{(for equal facings)} \qquad (12:9a)$$

or

$$\frac{h}{r} = \left(\frac{1 + R}{2\sqrt{R}}\right) \left[\frac{F_{c1,2}\lambda_{1,2}}{kE_{1,2}'} + \frac{W}{4}\right] \qquad (12:10)$$

$$\frac{h}{r} = \frac{F_{c}\lambda}{kE'} + \frac{W}{4} \quad \text{(for equal facings)} \qquad (12:10a)$$

To determine values of h it is necessary to iterate because k and V or W are dependent upon h. A first iteration to determine a minimum value of h can be made from formula (12:9) or (12:10) and the graph of figure 12-1 by assuming V = 0 or W = 0. This value of h is a minimum because V = 0 or W = 0 only if the core shear modulus is infinite; for any actual core the shear modulus is not infinite, hence a thicker core must be used. Values of V or W are also dependent upon core shear modulus, $G_c$ (see formulas 12:7 and 12:8). As an aid to finally determining h and $G_c$, figure 12-2 presents lines representing V or W for various values of $G_c$.

The following procedure is suggested:

1. Assume V or W equal to zero, k equal to 0.6, and compute a value of h from formula (12:9) or (12:10).

2. Enter figure 12-1 with a value of $r/\rho$ based on the computed value of h and determine a new value of k. ($\rho$ is defined in figure 12-1.)

3. Recompute a value of h from formulas (12:9) or (12:10) using the value of k determined in Step 2.

4. Repeat Steps 2 and 3 until the value of h computed in Step 3 agrees with that used in Step 2.

5. Assume a small value of V or W and repeat previous steps to determine a somewhat larger value of h.

6. Compute the constant relating V or W to $G_c$:

$$\left[\frac{E_1' t_1 E_2' t_2 h}{\lambda r^2 \left(E_1' t_1 + E_2' t_2\right)}\right] = VG_c \text{ or } WG_c$$

$$\left[\frac{E' th}{2\lambda r^2}\right] = VG_c \text{ or } WG_c \quad \text{(for equal facings)}$$

7. With this constant, enter figure 12-2 and determine necessary $G_c$.

8. If the shear modulus is outside the range of values for materials available, slide up the appropriate line of figure 12-2 and pick a new value of V or W for a reasonable value of core shear modulus.

9. Recompute h with a new value of V or W and repeat previous steps until the value of h is obtained.

10. Calculate core thickness $t_c$ from the equations

$$t_c = h - \frac{t_1 + t_2}{2} \qquad (12:11)$$

$$t_c = h - t \quad \text{(for equal facings)} \qquad (12:11a)$$

## 12.4 CHECKING PROCEDURE FOR DETERMINING CYLINDER WALL BUCKLING STRESS, $F_{cr}$

The design shall be checked by using the graph of figure 12-1 to obtain k values and formulas (12:4), (12:5), or (12:6) to obtain K to substitute into formula (12:3) or (12:2) to compute the buckling stress $F_{cr}$ or end load $N_{cr}$. The formulas apply to sandwich cylinders having isotropic facings and isotropic honeycomb, or corrugated cores as noted. It should be understood that if the desired $F_{cr}$ is above proportional limit values, the value of E' shall be an effective value used in computing V and in computing $F_{cr}$.

## 12.5 CHECK TO DETERMINE WHETHER COLUMN BUCKLING WILL OCCUR

If an axially compressed sandwich cylinder is fairly long, it may buckle as a column. The facing stress at which Euler column buckling will occur, if the ends of the cylinder are hinged, is given by the formula:

$$F_{e1,2} = \frac{\pi^2 r^2 E'_{1,2}}{2L^2} \qquad (12:12)$$

where L is the unsupported column length and e denotes Euler. The load per unit length of circumference of the cylinder is given by:

$$N_e = \frac{\pi^2 r^2 \left(E'_1 t_1 + E'_2 t_2\right)}{2L^2} \qquad (12:13)$$

$$N_e = \frac{\pi^2 r^2 E' t}{L^2} \quad \text{(for equal facings)} \qquad (12:13a)$$

If the value of $N_e$ as computed by formula (12:13) is less than the design load, the cylinder will have to be redesigned by using a longer radius, shorter length, or stiffer facings. The formulas (12:12) and (12:13) were derived for thin-walled cylinders and are about 3 percent in error for $\frac{h}{r} = 0.2$. For $\frac{h}{r} < 0.2$, the error is less than 3 percent.

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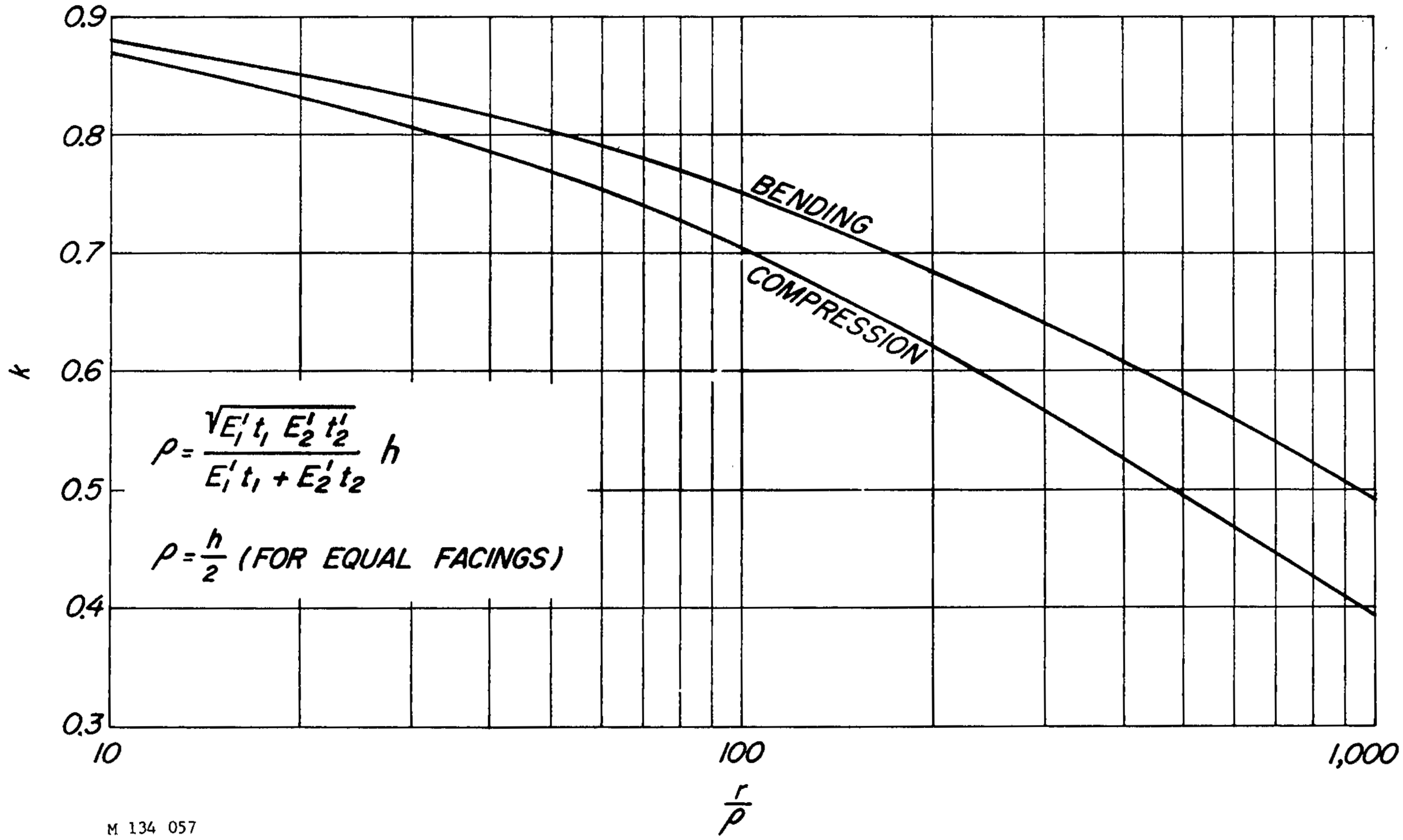


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Figure 12-1.--Reduction factor, k, for the buckling of sandwich cylinders in axial compression or bending.

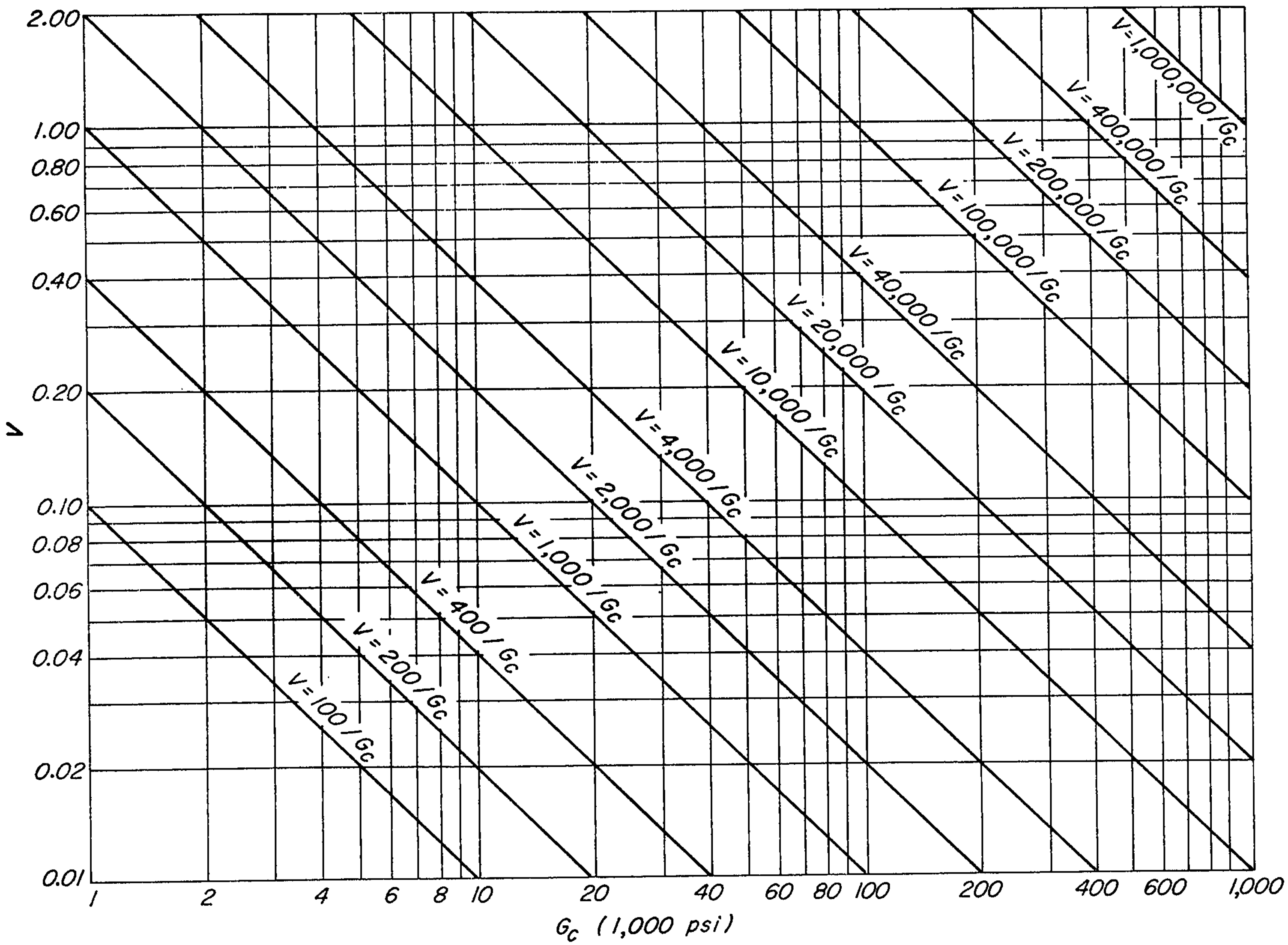


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Figure 12-2.--Chart for determining V and $G_c$ for sandwich cylinders under axial compression or bending load.

# CHAPTER 13

## DESIGN OF SANDWICH CYLINDERS UNDER COMBINED LOADS

### 13.1 BASIC PRINCIPLES

Assuming that a design begins with chosen design stresses and given design loads to transmit, a circular cylinder with walls of sandwich construction shall be designed with the four basic design principles summarized in section 1.2 of the Introduction. These four conditions must be met.

Facing stresses shall be determined for each load applied separately (see appropriate chapters) and the effects of combining the loads and stresses shall be assessed by appropriate interaction formulas for the facing materials as given in references 13-6 and 13-7 wherein design values for these stresses are established.

Overall buckling of the sandwich walls or dimpling or wrinkling of the facings cannot occur without possible total collapse of the cylinder. Local failure by wrinkling of the facings under loads other than uniaxial compression are not given, and it is necessary to determine this behavior of the sandwich by testing small specimens if estimates based on information given in Chapter 3 show that failure by wrinkling of facings could be expected. Dimpling of facings under combined loads is not given; however, the information given in Chapter 4 can be combined with interaction formulas for buckling of the individual facing sheets as given in references 13-2 and 13-6 to obtain some estimates that can be confirmed by tests of small specimens.

Overall buckling of the sandwich walls of cylinders under combined loads is given by interaction formulas in terms of the ratios, R, wherein R denotes the ratio of the applied stress or load under combined loading to the buckling stress or load under separate loading ($R = N/N_{cr}$). Appropriate subscripts are given to R to denote stress or load and direction.

## 13.2 AXIAL COMPRESSION AND EXTERNAL LATERAL PRESSURE

Overall buckling of the sandwich walls of a circular cylinder under axial compression and external lateral pressure can be estimated by the interaction formula

$$R_{cx} + R_{py} = 1 \qquad (13:1)$$

This formula is usually somewhat conservative for most sandwich cylinders. It can be exceedingly conservative for sandwich with $V >> 0$. For more accurate analyses, including sandwich walls with corrugated core, consult references 13-1, 13-3, 13-4, and 13-5.

## 13.3 AXIAL COMPRESSION AND TORSION

Overall buckling of the sandwich walls of a circular cylinder under axial compression and torsion can be estimated by the interaction formula

$$R_c + R_s = 1 \qquad (13:2)$$

This formula is conservative for short and thick-walled cylinders for which the torsion $(R_s)$ term should have an exponent of 2. The formula can be very conservative for sandwich with $V >> 0$. For more accurate analysis of sandwich walls with corrugated core consult references 13-1 and 13-3.

## 13.4 TORSION AND LATERAL EXTERNAL OR INTERNAL PRESSURE

Overall buckling of the sandwich walls of a circular cylinder under torsion and external or internal pressure can be estimated by the interaction formula

$$R_p + R_s^2 = 1 \qquad (13:3)$$

For external pressure $R_p$ is positive and for internal pressure $R_p$ is negative. Details of the derivation and resultant interaction curves are given in references 13-1 and 13-3.

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# CHAPTER 14

# FABRICATION

## 14.1 FABRICATION OF CORES

### 14.1.1 Preparation for Use

From the position of the sandwich fabricator, the core as received is a raw material, and therefore the manufacture of the core stock will not be considered in this manual. All core materials described in chapter 2 must be prepared for use by the sandwich fabricator. This preparation consists of machining in some manner or, in isolated cases, of mixing, pouring, or expanding the raw materials. Some of the more common means of preparing core materials for use in sandwich structures are presented here.

#### 14.1.1.1 Aluminum Honeycomb

Aluminum honeycomb is received in the form of blocks or in slices cut to proper thicknesses. These core blocks can be sliced on a metal-cutting bandsaw. High cutting speeds and fine-tooth blades are desirable for best results (fig. 14-1). Dimensional tolerances are normally held to ±0.005 inch.

For sawing expanded honeycomb blocks, a special honeycomb cutting blade has been developed. With this honeycomb cutting blade, very good surface finishes can be achieved. The optimum speeds of the blade and feeding vary with cell size and foil gage combinations.

Specially designed contouring machines such as the horizontal bandsaw shown in figure 14-2 are sometimes used for quantity production of contoured cores of aluminum honeycomb. Compound contouring is easily performed with proper tooling.

Aluminum honeycomb cores must often be routed at specific locations for doublers. This operation is normally performed using a high-speed traveling bed router, with a cutter usually referred to as a "valve stem" cutter. An operation of this type and some typical cutters are shown in figure 14-3. Sometimes the cutter is shielded with a "chipper," which breaks up the waste (the material removed) into chips for convenient removal. By modifying the details of the cutter and the chipper, the same procedure can be used for cutting stainless steel honeycomb, or for contouring metal honeycomb cores.

Precut blocks of honeycomb core, ready for use in an assembly, should be handled with extreme care to avoid contamination. The use of clean white cotton gloves and reusable containers to protect the delicate precut cores, as shown in figure 14-4, is recommended.

### 14.1.1.2 Stainless Steel Honeycomb

When required, stainless steel honeycomb core can be rough cut to a tolerance of ±0.006 to 0.010 inch by friction band sawing. For final finishing to close tolerances, either electrolytic surfacing or disk cutting are most commonly used.

Electrolytic surfacing (fig. 14-5) is a method of electrical-discharge grinding that combines two methods of metal removal--spark erosion and mechanical abrasion. A process used to advantage for surfacing stainless steel honeycomb core involves utilization of an electrolyte as a dielectric and coolant in combination with electrical circuitry, which includes the honeycomb core as the anode and the electrolytic grinder as the cathode. The cutter is a conductor with a random dispersion of a resin-bonded abrasive nonconductor on the working surface. The surfacing operation is accomplished by rotating the cutter cathode while gradually advancing it across the surface of the honeycomb. As the wheel rotates, alternately a conducting area and a nonconductive abrasive area contacts the core material, thereby creating a spark that breaks down the electrolyte and dislodges metal from the honeycomb surface. The metal in turn is washed away by the flow of electrolyte. The nonconductive abrasive in the cutting wheel maintains the spark gap and makes and breaks the current.

In disk cutting, disk, valve-stem, or "baloney-slicer" cutters, equipped with feather edges of Stellite or other hard facing material, have been developed that will cut stainless core burr-free to tolerances of ±0.002 inch. Usual procedure when this equipment is used is to take a series of thin cuts until the requisite amount of material has been removed. Stabilization of the core material, either by filling the cells with water and freezing to a refrigerated platen, or filling with some other material such as plastic foam, polyethylene glycol, or other water-soluble compound, is practically essential when this technique is used.

On surfaces that are adequately stabilized, surface grinding tools coated with special abrasives also have been used successfully to produce an acceptable surface free of burring or layover.

Another technique for finishing stainless core is the Elox electrical method. In this relatively slow but very accurate process, the core material is eroded to the desired thickness by sparking or burning.

### 14.1.1.3 Glass-Fabric Honeycomb

Blocks of glass-fabric honeycomb core material may be cut to finished thickness on a bandsaw. A variety of metal-cutting bandsaw blades, running at speeds from 1,500 to 9,000 feet per minute, have been found to give satisfactory results. The fabrication application may require a long fiber being exposed after cut, which can be achieved with a four-tooth blade running forward at about 4,500 feet per minute. A very smooth cut can be achieved with a six-tooth bandsaw blade running backward at 5,500 feet per minute. Slight variations in these blades or speeds may be necessary for particular cell sizes and densities. The optimum cutting conditions can probably best be achieved by trial and error for the specific application. Thickness tolerances of ±0.005 inch should be maintained (fig. 14-6). The slightly fuzzy character of the sawn surface is shown in figure 14-7.

Precautions must be taken to remove the fine resin and glass dust that results from the sawing operation. Dust removal may be accomplished by drilling holes in the fence near the saw and applying suction to the far side to draw up the dust, as shown in figure 14-8. In addition, an adequate respirator or dust filter should be worn by the operator when large quantities are cut.

For convenience in handling when large flat parts are being fabricated, the slices of glass-fabric honeycomb core may be edge bonded in the usual manner by hand pressure and the glue cured by high-frequency dielectric heating. Glass-fabric honeycomb is used for radome applications and therefore must be tailored very carefully to fit the curvature of the mold. This requires smaller pieces, which are cut from the sawn slices.

Typical joints between individual pieces of glass-fabric honeycomb core are shown in figure 14-9. For maximum strength the interlock type of joint is preferred. Most types of glass-fabric honeycomb will interlock very uniformly if they are overlapped about one cell diameter and crushed into each other by means of a mallet or a compression block. Tightly fitted butt joints usually give adequate strength properties, particularly if they are bonded together so as to develop a high percentage of the shear strength of the unjointed core material. Open butt joints are generally not allowed for structural parts; they are permissible only when stresses are low, and facings are thick enough to carry the shear.

Glass-fabric plastic honeycomb of the forming grade can be preformed to simple or compound curvatures by heating and molding in the proper radius. Some of the honeycomb manufacturers specialize in supplying preformed honeycomb cores.

Immediately before use, the pieces of glass-fabric honeycomb core are sometimes treated with the same resin that is to be used in the facings. The pieces may be dipped in a thin solution (normally about 20 percent) of the resin in acetone and used as soon as the acetone has evaporated, or unthinned resin may be roller-coated on the surfaces. Either method supplies additional resin at the interface between the core and the facings, and thus provides increased bond strength and, in addition, a tacky surface that aids in laying up complicated shapes.

### 14.1.1.4 Foamed-in-Place Cores

Foamed-in-place core materials are based upon the reaction of an unsaturated alkyd resin with an isocyanate, resulting in the liberation of carbon dioxide gas. The reaction is exothermic and the mixture must be controlled within a temperature range of 75° to 85° F. If the temperature exceeds 85° F , the reaction will proceed to completion without control on the quality of foam produced. The resin and isocyanate are not readily miscible and require about one-half hour to mix thoroughly. The other two component systems furnished by several suppliers are readily miscible and require somewhat less time for mixing to a homogeneous blend. Because of the nature of the compounds used, the mixing equipment should be placed under a hood, and workers should be protected by gloves and fresh-air hoods. When the liquid is thoroughly mixed, the liquid is poured into the mold and heated to the desired temperature until expansion ceases. Temperatures varying from room temperature to 200° F have been used for this step. After expansion ceases, the core material is given a final cure for about 2 hours at a slightly higher temperature.

### 14.1.1.5 Lost Wax Process

A technique sometimes referred to as the lost wax process, has found application for producing a special type of core through which hot air can be fed for de-icing purposes. This type of construction is sometimes used as a cap over the portion of a radome, or may be used (if properly constructed) as a self de-icing sandwich. Extruded bars of a specially prepared wax formulation are helically wrapped with a ribbon of glass fabric as shown in figure 14-10. These wrapped extruded bars are somewhat flexible and can be formed to the desired shape and encased within glass-fabric facings. A section from a typical sandwich part made by the lost wax process is shown in figure 14-11. After the part is partially cured at a carefully controlled temperature (slightly below the melting point of the special wax), the temperature is raised to allow the special wax to melt and run out. The part is then cured at a higher temperature to produce optimum strength properties. The wax is then reused in the extrusion machine.

### 14.1.1.6 Balsa

Two methods of core preparation are in use for balsa: (1) Bandsawing end-grain slabs from large bonded billets and sanding to finished thickness, or (2) sawing end-grain slabs to finished thickness from planks, followed by edge bonding to the proper core size. Both methods require that the selected balsa planks be accurately jointed and planed to a rectangular or square cross section. Conventional woodworking machinery, such as a jointer, rip saw, and cabinet planer, may be used.

### 14.1.1.7 Paper Honeycomb

The small-cell type with high resin content can be sawed on a circular saw into smoothly cut slabs having thickness tolerances of ±0.008 inch if the block is less than 3 inches thick. It may also be cut on a bandsaw into slices having slightly roughened surfaces and somewhat larger tolerances. The large-cell type with low resin content is usually cut on a bandsaw.

## 14.2 FABRICATION OF BONDED CONSTRUCTION

In bonding sandwich construction, including bonds between metal facings and the metal fittings, reinforcing plates, and other inserts, carefully controlled fabrication techniques are required in using resin adhesives.

## 14.2.1 Preparation for Bonding

This section outlines the general methods of preparing the metal facings for bonding, and the general fabrication procedures used in bonding the sandwich components together with resin adhesives.

### 14.2.1.1 Surface Preparation of Metals for Bonding

It is essential in good bonding practice that greases, waxes, oils, loose oxides, and other contaminants be removed from the metal surfaces, and the surface then kept clean until the adhesives are applied. Metal preparation for bonding is now thought to be more than merely cleaning the surface. It is known that the chemical nature of the metal surface at the time of bonding influences not only the initial degree of adhesion, but probably also the permanence of the bonds (particularly at elevated temperatures in service) and the permanence of the metal itself under corrosive conditions. With some metals, etching of the surfaces prior to application of the adhesive has been found essential to obtain the highest quality bonds. With other metals that corrode easily, special protective coatings must be applied to the surfaces prior to bonding when it is difficult to apply these protective treatments to the parts after fabrication. Several extensive reports (ref. 14-3, 14-5, and 14-9) have been prepared on investigations of surface treatments for metals prior to bonding. Adhesive suppliers usually specify procedures for preparation of various metal surfaces for bonding with their adhesives.

In the use of the various chemical solutions, particularly alkaline solutions, care should be taken that these solutions do not dry on the sheets, as they are often difficult to remove when dry. The final treatment of an aluminum surface should never be done with an alkaline solution, and when alkaline solutions are used in degreasing, a chromic acid or similar acid solution must be used as the final treatment. A thorough rinsing of all chemical solutions from the sheets is normally required in order to obtain optimum bonding results. It is likewise very important that cleaned metal surfaces be handled carefully to avoid further contamination before the adhesive is applied. Generally adhesives should be applied as soon after the metal has been prepared as is practical.

14.2.1.1.1 Surface Preparation of Cores.--Cellular aluminum core materials with adhesive-bonded nodes and similar stainless steel core materials with adhesive-bonded or spot-welded nodes should receive careful surface preparation before being bonded or brazed to facings to form sandwich constructions. All core materials, after being cut or otherwise formed into the desired size, shape, or contour, should receive a degrease treatment. A suitable method is liquid or vapor immersion in stabilized trichloroethylene. This may be followed by a chemical treatment.

Chemical treatments are somewhat specific for types of steel core used. Satisfactory treatments used for sheet steel-to-steel bonds may be used for steel core materials because they do not etch and remove metal as fast as do etch treatments for aluminum alloys. Certain treatments with mild detergent and strong acid are suitable and are summarized under surface preparation of metals.

### 14.2.1.2 Inspection of Treated Metal Surfaces

To determine if a metal surface has been sufficiently cleaned of greases, waxes, and oils to be bonded, many fabricators use the water-film test. This test consists of running cold water over the surface, allowing the excess water to run off, and then inspecting the surfaces for areas where the water film breaks due to the presence of greases, oils, and waxes (fig. 14-12). Portable instruments have also been developed for use in determining contact angles between the water drop and metal surface. Surfaces that show areas with such breaks in the water film or high contact angles should be recleaned before bonding.

Since metal preparation requires treatments other than simple degreasing, it cannot be assumed that metal surfaces will be satisfactory for bonding if there are no areas that show water breaks in the water-film test. There has been some evidence that poor adhesion has been obtained to "nonbreak" surfaces because of thin films or stains from the cleaning solutions, loose oxides, or particles on the surface or that the metal may require an etching of the surface in addition to being free of impurities.

### 14.2.1.3 Handling and Storage of Treated Metal Surfaces

After metal surfaces have been prepared for bonding, they should not be handled with bare hands or placed in contact with other contaminating sources in any subsequent operation until the final bonding has been completed. Clean, white cotton gloves should be used as prescribed in Military Specification MIL-A-9067 (ref. 14-10). After proper surface treatment has been made, no longer than one 8-hour shift shall elapse before bonding, unless an approved primed surface has been applied. Even if such approved prime systems are used, tests should be conducted by the fabricator to determine the maximum allowable period of storage.

14.2.1.4 Aluminum Surface Preparation

As much of the adhesive bonding of metals has involved the use of clad aluminum alloy, surface preparation methods for this metal have become more standardized than for the other metals. It is the general practice to wipe the aluminum sheets with a clean cloth saturated with a solvent such as acetone, naphtha, toluene, or lacquer thinner to partially remove identification markings. These sheets may then be vapor degreased in trichloroethylene vapor degreaser. After the vapor degreasing, the sheets are etched in sulfuric acid-sodium dichromate solution, rinsed in warm-water spray, and then dried. Military Specification MIL-A-9067 (ref. 14-10) suggests that aluminum for bonding be degreased with organic solvent and then immersed for 10 minutes at 150° to 160° F. in a solution of:

1 part by weight of sodium dichromate
10 parts by weight concentrated sulfuric acid (specific gravity 1.84)
30 parts water by weight

The aluminum is rinsed in water and then air-dried for 30 minutes. Other methods are to be used only when approved by the procuring agency.

Some modifications and special precautions have been adopted by fabricators using these general cleaning methods. A hot alkaline sodium-metasilicate cleaning and warm-water rinse is used by some fabricators, in place of, or in addition to, the vapor degreasing method. Other fabricators have increased the ratio of sodium dichromate to sulfuric acid in the etch solution in order to increase the useful life of this solution. Also some structural adhesives produce better and more permanent bonds with higher concentrations of sodium dichromate. The use of the higher concentration of sodium dichromate, which is normally considered to have inhibiting action in the solution may result, however, in less etching if the same time and temperature are used with the solution. Sulfuric acid-chromic acid solutions having similar composition to the sulfuric acid-sodium dichromate solution have also been used for preparing aluminum surfaces for bonding.

The spray rinse is considered to be important in obtaining optimum results with the sulfuric acid-dichromate etch treatment. Precautions are taken by some fabricators in areas where tap water has high mineral content to use steam condensate or deionized water for the rinse. The temperature of this rinse water is usually controlled at less than 150° F as there are indications that higher temperature water may result in sealing of the etched surface to produce an undesirable hydrated oxide and therefore result in low bonding characteristics.

Other types of surface preparation for aluminum are also used in special applications. Bare aluminum alloys given chromic acid or sulfuric acid anodizing treatments can be bonded, but sealing treatments for these anodized coatings to protect the metals themselves should be done after bonding because such seal treatments prior to bonding greatly reduce the strength of bonds (ref. 14-3) that can be obtained to these surfaces. Bonding must be done in some instances to surfaces that have been treated by proprietary surface treatments approved for surfaces in contact with aircraft fuels. Strength of bonds obtained to these surfaces are not usually as high as those obtained to aluminum surfaces prepared with the sulfuric acid-sodium dichromate solution, but may be considered satisfactory.

There are applications where it is not practical to use hot sodium dichromate-sulfuric solution for preparing the aluminum surface such as for secondary bonding to parts already containing adhesive bonds, and for repair of assembled parts. Solvent cleaning or washing with warm alkaline cleaning solutions, followed by mild acid neutralizing, may be sufficient in such cases.

High-strength bonds have also been made to metal surfaces prepared with "mild" surface treatments utilizing detergents or wetting agents. Considerable experimentation should be done by each fabricator prior to the use of these treatments in production. In general, detergents of the nonionic type should be used on aluminum alloys and anionic type should be used on stainless steel. Furthermore, only certain detergents within these types are effective. Mild detergent metal treatments are particularly adapted to metal honeycomb cores. Strong acid surface treatments reduce foil thickness and may damage the node-to-node bonds.

One specific detergent cleaning method is: 92.5 percent by weight of water, 1.0 percent by weight of concentrated sulfuric acid, 6.0 percent by weight of sodium dichromate, and 0.1 percent commercial wetting agent of the nonionic type, Pluronic F-68 or equivalent.

Abrading of the surfaces with aluminum wool or iron-free abrasive cloth is used in repair work and for removing corroded areas from sheets prior to regular cleaning. Care should be taken that the abrasives do not include other metals, such as iron, that are likely to set up electrolytic forces later to cause corrosion of the sheet. Chromate compounds, usually based on chromic and phosphoric acid, and certain other proprietary compounds have also been used at room temperatures in preparing the aluminum surfaces for bonding when the warm sodium dichromate-sulfuric acid solutions cannot be used. In repair work, where care must be taken to prevent the solutions from getting down into the panels, pastes made of acid solutions can be used. These acid pastes may be prepared of cold mixtures of sodium dichromate-sulfuric acid solution with inert powders and fiber such as barium sulfate, potters clay, vermiculite, asbestos fibers, and ground glass fibers. Any residue must be washed and rinsed off the panel later.

14.2.1.5 Magnesium Surface Preparation

Magnesium surfaces are easily corroded, and therefore in applications for airframes these surfaces are usually prepared for paint coatings by chemical seal methods such as are described in Military Specification MIL-M-3171 (ref. 14-11), and by anodize coatings (ref. 14-2) and then coated with zinc chromate paints such as are prescribed in MIL-P-8585 (ref. 14-12).

Much of the experience in adhesive bonding to magnesium has been with surfaces treated by the methods prescribed in MIL-M-3171, Type I (Chrome Pickle Treatment) and Type III (Dichromate Treatment) or anodize methods used in combination with a zinc chromate prime coat before bonding. Bond strengths to such a primed surface have always been lower with standard high-strength adhesives (1,800 to 2,400 pounds per square inch on 1/2-inch lap joint of 0.064-inch thick metal), than is usually obtained in bonds to aluminum. It is, however, possible to design the bonds to compensate for this lower strength. Bonding to magnesium with these treatments can usually be improved by lighter application of the metal treatments and of the prime coat, and by baking the prime coat prior to bonding. Additional protective coats can then be applied after bonding.

Exceptionally uniform bonding to magnesium alloys, including good performance in high humidity and salt-water spray conditions, has been obtained in studies (ref. 14-4) when using a light acid anodize treatment. Bonding is then directly to this anodize coating, with any protective chromate primers applied after bonding. The best performance to this anodize coating has generally been obtained with flexible adhesives of the acrylonitrile-modified phenolic type.

14.2.1.6 Stainless Steel Surface Preparation

Satisfactory adhesive bonding can be accomplished to many stainless steel surfaces by merely degreasing. However, for best performance when bonds are to be exposed to elevated temperatures, chemical treatments are also used in preparing the stainless steel surfaces. Several methods have been used in etching stainless steel for bonding. One method consists of etching for 10 minutes at 140° to 150° F in a solution by weight of:

50 parts of concentrated hydrochloric acid (specific gravity 1.19),
2 parts of 30 percent hydrogen peroxide,
10 parts of 40 percent formalin solution, and
45 parts water

After a water rinse, the stainless steel is immersed for 5 minutes at 140° to 150° F in the sulfuric acid-sodium dichromate solution, (such as is used for etching aluminum) to remove the light "smut" formed during etching.

Other alternative methods include: (1) Treatment for 15 minutes at 120° F in a solution composed of:

35 milliliters of sodium dichromate solution (saturated at room temperature)
1 liter of concentrated sulfuric acid (specific gravity 1.84)

(2) etch for 10 minutes at 150° F in a solution of:

10 percent by volume concentrated sulfuric acid (specific gravity 1.84)
0.5 percent of a commercial liquid wetting agent of the anionic type, Triton X200 or equivalent
89.5 percent water

water rinse and then immerse for 10 minutes at room temperature in a solution of:

10 percent by volume of concentrated nitric acid (specific gravity 1.42)
2 percent by volume of concentrated hydrofluoric acid (60 percent)
88 percent water

or (3) etch for 2 minutes from 180° to 200° F in a solution of:

841 milliliters of hydrochloric acid (specific gravity 1.19)
89 milliliters of phosphoric acid (specific gravity 1.69)
49 milliliters of hydrofluoric acid (60 percent).

Adequate water rinsing and drying should follow each of these methods.

Vapor blasting has been used successfully in preparing stainless steel surfaces, particularly in the fabrication of helicopter blades. Care must be taken, however, that the abrasive materials do not contaminate the surfaces being treated. It is recommended when possible that suitable chemical treatments, as listed above, be used following the vapor blast treatment. Dry sandblasting is not recommended because it distorts the sheets, and there are also indications (ref. 14-9) that it lowers the salt-spray resistance of the bonds made with certain adhesives.

Heat-treated 17-7PH stainless steel usually has scale on the surface. Prolonged treatments with one of the above etching treatments may be necessary to remove this scale.

14.2.1.7 Titanium Surface Preparation

Satisfactory adhesive bonding to titanium surfaces can sometimes be accomplished by simple abrasive blasting or acid etching. This simple cleaning treatment is not sufficient when bonds are to be exposed to elevated temperatures or high humidity. Surface preparation for these environments must include a chemical or anodic seal.

Like aluminum, titanium is a very reactive metal which depends upon the formation of a chemically inert natural oxide film for its very high corrosion resistance. Titanium differs from aluminum and many other metals in that the oxidation process depends on the reaction between oxygen and titanium occurring at the metal-metal oxide interface; i.e., the oxygen rather than the metal diffuses through the oxide scale. This diffusion process results in the formation of a non-adherent inner layer of scale, and is greatly accelerated when surfaces which are not completely sealed from oxygen contact are subjected to elevated temperatures or high humidity.

General surface cleaning is usually accomplished by wiping with a non-chlorinated solvent, followed by immersion in a hot alkaline cleaner of the type normally used for steel. (Vapor degreasing is not recommended, due to the danger of trichloroethylene residues on the surface causing stress corrosion during any subsequent exposure at temperatures above 600° F.)

Abrasive blasting can be used to remove the non-adherent natural oxide layer, and to increase the area of the surface in order to improve the mechanical bonding of the adhesive. Abrasive blast cleaning may be accomplished either wet or dry, generally using 180- to 325-mesh aluminum oxide or garnet to avoid excessive roughening or contamination of the titanium. In order to avoid excessive build-up of the non-adherent natural oxide layer, titanium parts must be adhesive bonded, primed, or chemically sealed within 2 hours after blasting.

Acid etching is used to remove heat treat scale, the natural oxide layer and the top layer of oxygen-contaminated titanium (alpha case). This produces a very smooth surface which is chemically clean and very reactive. Surfaces must be bonded, primed, or chemically sealed within 2 hours after etching. Etching is generally accomplished by immersing for 10 minutes in the following solution:

2-8 ounces per gallon of hydrofluoric acid (HF)
30-65 ounces per gallon of nitric acid ($HNO_3$)
10:1 minimum ratio $HNO_3$:HF
0.0025-0.0050 etch rate (inches per side per hour)
120° - 135° F temperature

Titanium surfaces may be sealed either chemically or anodically. The seal coating reaction is essentially a controlled corrosion reaction in which a corrosion-preventing, reaction-product film is formed. The reaction product, itself intimately adherent to the metal, serves to seal titanium from contact with oxygen and makes a good base for bonding. The chemical sealing solutions are acidic and contain an attacking agent ($P^-$), a film-forming agent ($CrO_4^{--}$ or $PO_4^{---}$), and sometimes a moderating agent ($NO_3^-$). The anodic sealing solutions contain a chelating agent or an active acid to attack the titanium, and an acidic or alkaline electrolyte to increase conductivity. Anodic sealing serves to electrolytically oxidize the titanium at the metal-metal oxide interface with no significant part growth. Anodic coatings are not good barriers against further oxidation, and generally require sealing with a silane primer prior to bonding.

A chemical seal which is fairly effective in preventing loss of strength when bonds are exposed to elevated temperature (up to 600° F with the proper adhesive) or high humidity, is a 15 to 30 minute treatment with a solution containing 50 to 70 percent by volume of Pasa-Jell 107C in water. This is a solution containing nitric, chromic, and fluosilicic acids. The solution etch rate is normally maintained at 0.02 to 0.04 mil per side per hour by additions of the make up liquid or hydrofluoric acid.

A chemical seal which is somewhat less effective in preventing thermal or humid degradation of bonds is a 1 to 3 minute treatment in the following solution:

6.3 - 6.7 ounces per gallon of sodium phosphate dodecahydrate
2.5 - 4.0 ounces per gallon of potassium fluoride dihydrate
2.0 - 2.8 ounces per gallon of hydrofluoric acid (as HF)
Balance water

After sealing, titanium surfaces should be thoroughly rinsed in water containing less than 6 parts per million of chlorides, and then air dried. Properly applied seal coatings will prevent reoxidation of titanium surfaces during storage for 16 hours or more. Nevertheless, bonding should be accomplished as soon as possible after sealing.

## 14.2.2 Method of Applying Adhesives

After the cores and facings have been properly prepared for bonding, the adhesives are applied. The method of application will depend on the form of the adhesive, and the adhesive manufacturer's recommendations should be closely followed. General requirements with respect to the applying of the adhesive are given in Military Specification MIL-A-9067 (ref. 14-10). The thinner solutions are formulated for use as sprayable primers or for application in multiple coats by spraying. The more viscous solutions are designed for application by brush, hand roller, scraper, roll glue spreader, and by direct extrusion of the adhesive. The powdered and solid epoxy-resin adhesives are applied by sprinkling or rubbing on over heated (200° F) metal surfaces. The film or tape adhesives are simply laid in place, and if necessary can be tacked in position at several places by momentarily touching a hot iron to the film or tape, or by moistening with solvent followed by air or forced air drying.

### 14.2.2.1 Application by Spraying

Spraying is generally used in applying thin solvent solutions of adhesive to a uniform spread, particularly over large assemblies that may involve thin facings or complicated curved shapes. This method is usually limited to applying adhesives on facings or on solid cores, but several fabricators have also used spraying methods to apply adhesives to honeycomb cores. However, the spraying techniques with the various adhesives will vary slightly depending on the chemical types of resins and solvents used; the thinning of the adhesive and spraying should be done as recommended by the adhesive manufacturer.

Pressure-cup spray equipment is frequently used in applying adhesives in production work. It is then possible to keep the adhesive in larger quantities in a separate pressurized tank and feed the spray gun atomizer through flexible hoses connected to the tank. More viscous types of adhesives can also be more successfully sprayed by using pressure-cup equipment.

Many of the adhesive primers used in combination with film and tape adhesives are also applied by spraying. These adhesive primers are usually applied in a single thin coat to maintain the surface cleanliness of the metal sheets, and to provide good "wetting" between the adhesive on the film and tapes and the surfaces of the adherend.

When possible, surfaces should be turned between coats so that successive coats can be applied at right angles to each other to minimize irregular adhesive films.

The application of adhesive by spraying generally results in a uniform film with a minimum of such surface defects as pin holes, blisters, and runs. With certain adhesives that have good flow characteristics while curing under pressure, some surface defects can be tolerated. The defects encountered in spraying are sometimes characteristic of the adhesive formulation being sprayed, but some defects may have additional causes, as follows:

1. Excessive cobwebbing of the adhesive spray may be from using a high air-to-adhesive ratio for the gun, using low-boiling point solvents, or holding the spray gun too far from the work. Using the gun at excessive distances from the work results in the solvent volatilizing too much before the spray strikes the surface.

2. Orange-peel effect and wrinkling of the surface film may be due to high air pressures, excessive adhesive application, holding the gun too close to the work, incomplete atomizing of the adhesive, or to the use of adhesive solutions that do not contain enough high-boiling solvents to allow sufficient flow for the surface to smooth out before drying.

3. Pinholes and bubbles in the adhesive film may be due to the use of too heavy an application of adhesive, the use of adhesive formulations that have been thinned excessively with low-boiling solvents, or to the application of successive adhesive coats over adhesive coats that have not dried sufficiently.

4. Blushing (a dull, cloudy effect on the sprayed surface) of the adhesive film may be due to the condensation of moisture on the surface during spraying or to the inclusion of moisture in the adhesive. Condensed moisture is often due to the cooling of the atmosphere above the work by the rapid evaporation of the adhesive solvents. Factors that contribute to condensation are high temperatures and relative humidities in the spray room, low temperatures of the materials being coated, adhesive solvents with excessively low boiling points, and high rate of air flow across the drying film. A number of the regularly formulated adhesives for spraying can be used in atmospheric conditions of 55° to 75° F , provided the relative humidity is 55 percent or less. Spraying can be done at temperatures as high as 100° F, but then the relative humidity should not exceed 30 percent. Some adhesives, because of the composition of the resin or solvents used, are less sensitive to atmospheric moisture conditions, and can be sprayed at higher humidities.

5. Running of the adhesive film may be caused by overthinning, using high-boiling solvents that do not volatilize rapidly enough, or applying too much adhesive.

6. Lifting or blistering of the adhesive film is said to be caused when a heavy coat of adhesive is applied over an adhesive prime coat that has not been allowed to air-dry long enough.

7. Irregular particles in the adhesive film may be caused by improper mixing and thinning of the adhesive, over-aged adhesive, blocked air passages in the gun, moisture and impurities entering the gun from the air supply, dried adhesive particles being deposited by using the gun too far from the work, too high an air-to-adhesive ratio for the gun, or by the use of a low-boiling solvent.

14.2.2.2 Application by Other Methods

Ordinary brushing of the adhesive can be used if the areas are small and difficult to mask, if the adhesive is viscous and thinning is not recommended, or if spraying equipment is not available. Hand rollers and conventional roll glue spreaders are frequently used when applying liquid adhesives to the cores of sandwich construction. One company has also developed an extrusion method by which a wet film of the adhesive can be extruded directly upon the core or facings of the sandwich panel. This method is said to produce good "filleting" action to honeycomb-type cores. The adhesive formulated for application by these methods is generally of higher viscosity than those intended for spray application.

Film and tape adhesives are simply laid in place, sometimes after first priming of the core and facings with a liquid primer. While not generally recommended, heat "tacking" (temperature should be below curing temperature for adhesive) or solvent "tacking" may be used to insure that the adhesive film will stay in place during any operations prior to bonding. After solvent "tacking" sufficient air or forced-air drying should be used to insure solvent release. If these solvents are retained within the assembly, poor core-to-facing bonds or blistering may occur when the assembly is removed from the bonding presses.

### 14.2.2.3 Amounts of Adhesive Applied

The amount of adhesive applied is dependent upon a number of factors, such as the type of adhesive used, the type and fit of the surfaces being bonded, and the degree of adhesive flow during the formation of the joints. The adhesive manufacturers generally recommend that, when bonding metal to metal with the liquid adhesives, sufficient adhesive be applied to result in a final bond-line thickness of 0.002 to 0.005 inch. Adhesives supplied in film form range in thickness from 0.003 to 0.030 inch (0.015 to 0.180 pounds per square foot) with the thicker supported films or combinations of the thinner films generally being used when bonding panels of honeycomb cores. When liquid adhesives are used for bonding to honeycomb cores, it is generally desirable to apply the adhesive to the core so that the adhesive will cover the core surface, extend down into core, and surround the ends of the cell walls for 1/32 to 1/16 inch. Roller coating, spraying, or extrusion procedures as outlined under section 14.2.2.2 are satisfactory methods for applying these priming adhesives to the honeycomb cores. Most manufacturers of sandwich construction try to control the total amount of adhesive applied in bonding the sandwich panels to a dry weight of 0.15 to 0.25 pounds per square foot of sandwich panel; this control gives economy and low panel weights, except when the heaviest of the film adhesives are being used.

### 14.2.2.4 Assembly Period in Bonding

The assembly period, which is the time between spreading and application of the pressure and curing temperature, must be controlled to allow volatile solvents to escape from the film and to obtain some initial setting of the adhesive. This setting must not be so advanced that there will be inadequate flow and wetting of the entire adherend surfaces during the final pressing. This assembly period may be either in open assembly or with the surfaces placed together in position for bonding. Open assembly periods are generally used when bonding nonporous metal-to-metal or sandwich panels.

The adhesive manufacturer's recommendations regarding the assembly periods to be used with each formulation of adhesive should be closely followed. With the liquid epoxy-resin adhesives and the other adhesives formulated for rapid curing at or near normal shop temperatures, maximum assembly period should be short; usually less than 30 minutes, depending on the adhesive formulation and room temperatures, so that the assembly can be made and pressure applied before there is partial setting of the adhesive. With the elevated-temperature-setting adhesives that contain volatile solvents, it is necessary to air dry the adhesive, after it is spread, to remove excess solvents that might otherwise cause excessive flow or blistering of the final bond. Assembly periods of 8 to 24 hours after applying the adhesive are frequently used with the elevated-temperature-settting metal-bonding adhesives. With some of these adhesives, assembly periods of several months have been successfully used, when the adhesive surface is protected from contamination.

When it is more convenient to use short assembly periods (1 to 8 hours), precuring of the adhesive film (at a temperature below the curing temperature of the adhesive and without pressure) is often used to adequately remove the solvents and to provide the desired degree of flow during the actual precuring operation. With some adhesives, precuring is required even following open assembly periods of 8 to 24 hours because of the slow rate of evaporation of solvents from the adhesive film. The amount of precuring should be carefully controlled, following the adhesive manufacturer's recommendations, as excessive precuring often results in weak bonds because of inadequate flow of the adhesive during final cure. In addition to reducing flow and blistering tendencies during cure, adequate precuring will, with certain adhesives, improve the bond strengths at elevated temperatures. Precuring conditions vary from drying in a forced-air oven for 30 minutes to 2 hours at temperatures from 180° to 230° F, to precuring on the platens of a press without pressure or at low pressures (3 pounds per square inch) for 5 to 15 minutes until the normal curing temperature from 300° to 335° F is reached, releasing pressure momentarily, and then applying full curing pressure.

If the adhesive film blisters when precured, the application of the adhesives has probably been too heavy, the air-drying period prior to precuring has been too short, or the precuring temperature being used is too high.

### 14.2.2.5 Curing Time and Temperature Considerations

The final chemical reaction of curing of the components of the adhesive into a strong film requires the application of elevated temperatures. The selection of the curing time and temperature, and even the rate of heating required, are dependent on the adhesive formulation, the type of joint, and the service condition expected for the bond. The adhesive manufacturer's recommendations should be carefully considered in establishing the curing conditions to be used in fabrication of the bonded assemblies. Details on the type of equipment used in obtaining the proper curing temperatures in the bond assemblies are described in section 14.4.1.1.4.

The elevated-temperature-setting adhesives are usually cured by maintaining bond-line temperature at 325° to 350° F for 30 minutes to 2 hours. Some of these high-temperature-setting adhesives show practically no evidence of cure at temperatures lower than 300° F ; others are said to cure partially at temperatures as low as 250° F if the curing period is greatly increased. Certain formulations of the epoxy-resin adhesives can be cured at 180° to 200° F and moderately strong bonds are obtainable with some special formulations of this type of adhesive when cured at normal shop temperatures.

Post-curing of panels bonded with heat-resistant adhesives is being done to a limited extent. This postcuring is done at elevated temperatures, after the panels are removed from the press, to obtain higher heat-resistance properties of the adhesive bond.

### 14.2.2.6 Bonding Pressure

Adequate pressure must be maintained during the final cure of the adhesive bond to (1) obtain uniformly thin adhesive bond lines, (2) overcome viscosity of adhesive film at the curing temperature, (3) overcome internal pressure exerted by release of adhesive solvents, and (4) overcome the surface imperfections (within limits) between mating surfaces or the lack of flatness in the skin materials. The pressure required for bonding is not a constant for any one adhesive, nor is it a constant for all assemblies. Pressure is rather a function of a size of the bonded parts, the perfection of the mating surfaces, the viscosity of the adhesive at curing temperature, and internal pressure due to solvent vapors.

In bonding facings to core materials, bonding pressures up to the maximum pressure that the core material can withstand at the bonding temperature can be used. Pressures of approximately 14 pounds per square inch, normal vacuum pressure, are frequently used in bonding to honeycomb cores. A rough factor of 10 times the core density in pounds per cubic foot may be used as the maximum curing pressure in pounds per square inch for aluminum alloy cores. Pressures up to 200 pounds per square inch are recommended for making metal-to-metal bonds. In bonding sandwich panels containing metal inserts and edgings, it is frequently necessary to design special fixtures so that the higher pressures can be applied in the areas of the metal-to-metal bonding. Bonding of sandwich panels by pressing to stops can also be done if care is taken to see that there is no crushing of the core. The maximum pressures for the various core materials and details on methods of applying bonding pressures on sandwich parts are discussed in section 14.4.1.

## 14.3 BRAZED OR WELDED SANDWICH CONSTRUCTION

Metallic sandwich construction for use at elevated temperatures can be fabricated by brazing or welding facings to a core (ref. 14-1, 14-7). Constructions being made today comprise facings and core of heat-resistant stainless steel, usually the 17-7PH, PH15-7Mo, or AM350 alloys; nickel-base and titanium alloys, and alloys of refractory metals such as molybdenum and columbium. Core pieces are best assembled by tack welding.

All sandwich components, core, facings, and braze are cleaned by degreasing, followed by etching if necessary.

Brazing of sandwich must be done in a reducing atmosphere, inert atmosphere, or in a vacuum; otherwise, thin core foils and thin facings will corrode severely. Successful sandwich has been made by using a dry hydrogen atmosphere (dew point at -40° F ) or atmospheres of helium or argon. Care must be taken to purge properly the chamber or envelope containing the sandwich before it is heated to brazing temperatures. Cooling must be done in a controlled atmosphere or vacuum so as to prevent corrosion. A pressure differential is maintained between the brazing retort and the envelope containing the sandwich, so that the sandwich components will be held in contact. Brazing temperatures are dependent upon the braze alloy and, with proper selection of braze alloy, compatible brazing and heat-treating cycles can be utilized. Heat treating must also be done in an atmosphere or vacuum.

Several brazing alloys have been used to bond facings to cores. Early attempts were on copper that was plated on the core, or sheets of nickel braze composed of 82.5 percent nickel, 4.5 percent silicon, 2.9 percent boron, 7.0 percent chromium, and 3.0 percent iron. Silver alloys. such as 85 percent silver, and 15 percent manganese, or 92.5 percent silver 7 percent copper. and 0.5 percent lithium, have been used successfully.

Facings can also be welded to cores. Corrugated cores, waffle cores, or flanged honeycomb cores have been spot-welded to facings. Some success has also been had with a projection weld between a honeycomb core and facings. This weld can be obtained by placing a fine wire screen between the core and facing or by using facings on which a grid is etched.

Inspection of brazed sandwich can be aided by ultrasonic inspection and X-ray photographs that show whether brazing is or is not uniform between facings and core, local areas of crushed core, open core joints, and other defects that may be present.

## 14.4 SANDWICH PRODUCTION TECHNIQUES

Sandwich constructions currently in use in airframes, or in the experimental stages of fabrication, are of many combinations of cores and facings.

The combination of facing materials and cores to make sandwich constructions for specific applications is almost infinite. Figure 14-13 illustrates two of the combinations that are finding limited use for highly specialized applications. The socalled multi-core sandwich is composed of layers of core material in the form of cured foam, interleaved by single layers of glass fabric and resin. Constructions of this type are sometimes used for highly specialized dielectric applications. The second construction illustrated in figure 14-13 is sometimes referred to as a "fluted core sandwich." It is made by the lost wax process, and offers opportunity of transmitting a fluid in each of the tiers of core for purposes of heating or cooling.

Sandwich parts in airframes are of any configuration from flat to severe compound curvature; consequently, a fabrication technique must be chosen that can be adapted most readily to the specific core-facing combination and configuration.

Fabrication techniques may be divided into classes according to curvature of product, type of facing or core, equipment required, method of applying pressure, or according to some other characteristic. For the purposes of this discussion, techniques are classed principally according to the method used to apply pressure.

In the fabrication of sandwich panels and the bonding of attachment fittings, it is sometimes necessary to subject some of the adhesive bonds to several curing cycles. These repeated cures, within the normal curing temperature range for the adhesives, do not deteriorate the quality of bonds made with the structural type of metal-bonding adhesives. Tests (ref. 14-8) made at 350° F on adhesive bonds generally showed better strengths after being aged for 192 and 1,000 hours at 350° F than when tested after the original curing cycle.

## 14.4.1 Means of Applying Pressure

### 14.4.1.1 Fluid Pressure

The molding of sandwich parts by means of fluid pressure applied through flexible bags or blankets of impermeable material has found increasing application in making sandwich parts of various degrees of curvature in the last five years. Typical parts include all combinations of single and compound curvature, cylinders, paraboloids, portions of a sphere--in short, any piece for which a mold can be made and later separated from the finished product.

The fundamental procedure of molding with fluid pressure is the same for all processes on common use. In principle, the technique consists of attaching temporary super-imposed layers of facings and core in a mold of the desired shape, and molding these into a unit structure by the application of heat and fluid pressure through a bag or blanket. The fluid may be air, steam, steam-air mixture, or an inert gas. Processes are relatively simple and provide a means by which sandwiches can be produced of single or compound curvature, and of constant or varying thickness in any arrangement of facings and core. Flat sandwich parts can also be made by fluid pressure molding, but can normally be produced more economically by other means. The fluid-pressure technique is largely limited in use to the production of parts that can be manufactured by no other practical means. In general, parts that fall in this category will have one or more of the following characteristics: Appreciable compound curvature, variable thickness, single-curvature bends approximating or exceeding 180°, parts too large to be made practicably by mating dies, or quantity too small to justify mating dies.

The processes permit the use of thermosetting resins and metal-to-metal adhesives with long assembly periods. Pressures within the range of 10 to 75 pounds per square inch are common. Figure 14-14 illustrates diagrammatically three basic processes in use at present: A, the vacuum bag process; and B and C, techniques capable of employing higher pressures by means of an autoclave or a pressure chamber respectively.

14.4.1.1.1 Autoclave Molding.--The use of autoclave (sometimes called pressure cylinders or tanks), such as are shown diagrammatically in figure 14-14B, has greatly increased in the past five years.

Many of these applications require high temperature-curing metal-to-metal adhesives, and therefore employ relatively high temperatures (400° to 500° F ) in the curing cycle. The direct injection of steam as a heating medium is often impractical at these temperatures, and impossible if the pressure required is relatively low (25 to 50 pounds per square inch). Air, heated by means of electric resistance heaters or Dowtherm units, is therefore often used as the pressure- and heat-transfer fluid. Many problems arise with the use of a gas such as air as a heating medium. All gases have low heat-transfer properties, therefore it is necessary to create rapid movement within the autoclave to improve heat transfer. The liberal use of thermocouples at typical locations on the part being molded is recommended.

CAUTION

Extreme caution should be exercised in the operation of autoclaves since very serious and sometimes unexplained fires have been experienced by several fabricators. Electric heating of any kind may be a potential fire hazard due to defective wiring and connections. The combination of compressed hot air and combustible materials (such as rubber or plastic bags or blankets, oil vapors from the compressor, and solvent vapors from the adhesive that may be squeezed through a defective bag or blanket) is exceedingly dangerous and may be a potential explosion hazard. The maintenance of a vacuum pump on the vent from the bonding fixture (although not usually done) would lessen the latter hazard considerably.

In planning such an operation, all known safety precautions and regulations should be observed. The air compressor should always be equipped with an adequate after-cooler, an oil-vapor filter, and a device commonly used in mines to warn of explosive mixtures. The lubricating oil in the compressor should have a high flash point so that a minimum of vapor is given off. All precautions should be taken to eliminate any sparks in a cylinder charged with hot air that contains some oil vapor, as a dangerous explosion could result.

Numerous fires have been reported in autoclaves when operating under conditions described above. Therefore, it is strongly recommended that an inert gas be used in place of air for the pressure and heating medium. Several inert gases are possibilities, such as nitrogen, carbon dioxide, argon, helium, or superheated steam. However, in all cases the autoclave should be equipped with an oxygen detector to warn the operator of an oxygen content that could support combustion or produce an explosion. Naturally the use of an inert gas in place of air involves additional expense, however, in some localities it is reported that nitrogen containing a slight amount of impurities can be obtained at low cost. This might also be true of carbon dioxide. Because the autoclave is charged with air at atmospheric pressure at the time the door is closed, it must be purged before each pressure cycle to reduce the oxygen content to a safe level. Although most of the inert gas required to charge the autoclave can be reused, provided adequate equipment is installed, there is some loss of inert gas in each use.

14.4.1.1.2 Molds.--The forming of any piece by means of fluid pressure requires some type of mold. These molds, sometimes called forms or dies, are broadly classified as male or female. Male molds have the desired shape on the convex surface while female molds (fig. 14-14, A, B, and C) have the desired shape on the concave surface. Female molds are used almost exclusively for all curved aircraft sandwich panels, as smoothness of the convex surface on the finished part is important. The surface of the sandwich next to the mold is always smoother and has a more precise contour than the surface exposed to the bag or blanket.

Metal molds are usually made of sheet steel, aluminum alloys, or cast iron. Alloys having relatively low melting points are also reported to be in limited use. Molds of single or slight compound curvature are made of sheet material 1/16 to 1/4 inch thick. A typical mold of thin sheet steel adequately supported by a steel framework is shown in figure 14-15. Two well-designed bleeder inlets are shown on the surface, attached to a common bleeder connection extending from the end. Molds of severe compound curvature, such as for radomes, are often cast. Thin sheet metal molds have the advantage of rapid heat transfer, while heavy cast metal molds heat more slowly. For any kind of externally heated mold, the rate of heating is affected by the heating medium of which steam is faster than air or inert gas. Metal molds in continuous use may require cooling before they can be used for the next lay-up. This is particularly true of small molds of considerable thickness. Large molded pieces require a longer time for removal; consequently, the mold may be sufficiently cooled before it is again ready for use.

Molds of the type shown in figure 14-14C, are heated internally. They may be of cast iron and be cores for steam heating, or may be of a low-melting alloy poured around a network of copper heating tubes. Laminated plastic molds with internal metal heating tubes are also used. Cooling, if necessary, may be done with cold-water circulation. One application of this type of mold is for producing sandwich skins for helicopter blades.

Female metal molds have recently been successfully made by means of an electrodepositing process on reusable cast phenolic male forms. Molds of this type are normally about one-quarter inch thick, being deposited from nickel, a nickel alloy, iron, or copper, sometimes with nickel or chrome faces. The process is particularly adaptable to molds of compound curvature. Molds several feet in width and length have been made by this process.

Female metal molds are sometimes heated by means of flexible steam coils that are metal-sprayed in position on the outside surface. The proper spacing and configuration of the coils must be determined with care to avoid excessive temperature variation. If the sandwich part being molded is unusually thick (more than one-half inch) it may be necessary to provide for supplemental heating on the inside (blanket side). This may be done with electric heaters and fans under a portable canopy in vacuum bag molding, or by use of an electrically heated blanket if the molding is done in an autoclave using inert gas as a pressure medium.

One of the most efficient means of molding with an autoclave and fluid pressure, when many parts of the same size are required, is the use of a self-heated mold and unheated air (for pressure). The mold in this case is usually of metal or glass-fiber-reinforced plastic, with the heat being supplied by means of electric resistance wires embedded in the plastic or electric heating units attached to the metal mold. It is reported that, using this system, the temperature of the air in the autoclave rises only 15° to 20° above room temperature with a mold surface temperature of 300° to 400° F.

Wood or plaster molds are sometimes used for exploratory work where only a few pieces fabricated at room temperature are required.

<u>14.4.1.1.3 Bags or Blankets</u>.--The purpose of the bag or blanket is to provide a flexible impermeable barrier between the fluid under pressure and the mold. The piece being molded is pressed between this flexible bag and the rigid surface of the mold; therefore, the full fluid pressure is applied at right angles to the surface of the part regardless of the shape. The pressure at certain points within curved parts may, however, be slightly less than the full fluid pressure by the amount necessary to shape or force the facings or core into place.

Bags are classified as full bags or blankets. A full bag is a complete envelope of impervious flexible material, completely closed and having only a tube or bleeder connection for inflation or evacuation. A blanket is a sheet that normally fits the mold without wrinkling and is sealed by some temporary means to its edges (fig. 14-14, A, B, and C). The bleeder may be attached either to the mold or to the blanket.

The useful life of a bag depends on the type of material, the heating medium used, the temperature of the cycle, and the care used in handling. The type of bag material depends largely on the molding process, the temperature, and the heating medium. The use of steam requires bags made of specially compounded natural or synthetic rubber. When hot air is used, polyvinyl-alcohol film, polyester film, or cellophane may be used and discarded after one operation. Soft aluminum foil and stainless steel foil have been successfully used as bag materials in some elevated-temperature molding operations.

Whenever a steam-air mixture is used and the air is introduced under pressure from a compressor, an adequate after cooler and air filter should be installed between the compressor and the cylinder. The life of a rubber bag is considerably increased when all traces of oil in the form of vapor or small drops are removed from the air.

When a rubber bleeder hose is employed, it must not collapse and close when external pressure is exerted upon it during the molding cycle. Collapse of the bleeder hose within the cylinder is difficult to observe. Emission of a slight amount of air or steam from the bleeder does not guarantee that it is functioning properly. Flexible metal hose, a copper tube, or a suitably reinforced rubber hose is recommended for the bleeder.

In using the method shown in figure 14-14B, careful attention should be given to the inside surface of the bleeder fitting in the bag. If this fitting is very smooth and flat it may make an airtight fit and stop the bleeder from functioning. Grooves in this fitting, or a piece of coarse burlap or screen bonded to it, will usually suffice.

14.4.1.1.4 Pressure and Temperature Equipment.--All pressure equipment for use with fluid-pressure molding should be hydraulically tested to a pressure of at least double that of the maximum working pressure to be used or in accordance with state or local codes. An adequate safety valve should always be installed if the steam or air is drawn from a supply line that is in excess of the pressure at which the cylinder was tested.

The devices placed within the pressure cylinder for controlling and recording conditions should be carefully installed. Heavily jacketed controls will lag and therefore will not record the actual cylinder temperature during the rapid heating period. A jacketed thermometer was found to be as much as 20° to 30° F below the reading on a bare thermocouple in heating a cylinder 2 feet in diameter and 6 feet long to 250° F in 5 minutes with a steam-air mixture. The lag would be much greater if a poorer heating medium such as dry air or an inert gas was used.

If temperature stratification exists in the cylinder, a temperature recording bulb at the top of the cylinder may read 30° F or more above the temperature at the bottom of the cylinder. Therefore, in order to minimize temperature stratification, and to keep thermometer readings more accurate, some means of circulation should be provided. A good check on uniformity of temperature may be obtained by inserting bare thermocouples in the top and bottom of the cylinder.

14.4.1.1.5 Amount of Pressure.--The pressures used in fluid-pressure molding of sandwiches vary from a vacuum drawn on the bag to a maximum of about 75 pounds per square inch. Vacuum alone normally produces sufficient pressure for sandwich constructions involving contact-pressure laminating resins, but is insufficient for operations such as bonding aluminum facings on end-grain balsa cores. Sufficient pressure should be used to insure contact between core and face sheet. In determining the proper pressure, consideration should be given to the pressure limitations of the core as given in table 14-1. These values were obtained between rigid surfaces and therefore are integrated or average values; whereas with the uniform distribution, characteristic of fluid pressure, the weaker spots in the core fail first. Considering the unavoidable nonuniformity of all core materials, fluid molding pressures should not exceed approximately 50 percent of the proportional-limit pressures of table 14-1.

When fluid pressure is used, all variations in thickness of core, facings, or adhesive spread result in nonuniformities or waviness in the facing next to the blanket. Under some forms of loading, the stresses on the core-to-facing bond are proportional to the magnitude of these irregularities; therefore, it is imperative to keep these irregularities to a minimum.

14.4.1.1.6 Fluid Pressure Assembly Jigs.--Complex sandwich parts are sometimes assembled from subassemblies by means of bonding in fluid-pressure assembly jigs. These jigs are often fabricated from welded steel construction and heated electrically or by means of electrically heated flexible blankets. A typical fluid-pressure assembly jig of this type for a portion of a sandwich wing is shown diagrammatically in figure 14-16, where it is shown that because of the variation of materials being assembled, the jig is so made that widely different pressures (compatible with the materials being assembled) are employed in the same fixture.

14.4.1.2 Rigid Dies

Molding or bonding pressure is often applied to sandwich panels by pressing them between surfaces made of metal or some other rigid material. The force is normally applied by a hydraulic piston or screw threads, and stops may be used in some cases to obviate crushing of the core. In using stops, core tolerances and bonding pressures should be carefully considered to insure the integrity of the completed part.

The simplest form of rigid-die application is the conventional hydraulic press. Stops between the platens are sometimes necessary to avoid or control compression of some of the weaker stops, but many of these flat panels have an edge banding of denser material that serves the same purposes as stops.

CAUTION

In using a multiple-opening hot press, the panels in each of the openings must be identical in size, shape, and pressure requirements; furthermore, they must be located in the same position as identical assemblies in all of the other openings in use in one press load.

To avoid nonuniform pressure on flat sandwich panels, the platens of a hot press must be exceedingly accurate, and the thickness tolerances of all of the component parts in the sandwich must be within close limits. Because this is often impractical, it is sometimes necessary to insert tooling to supply fluid pressure to one side of the sandwich being molded. One method of doing this is shown in figure 14-17, which involves the use of a thin, oil-filled metal bladder. The use of oil, or some other high-boiling-point liquid, is preferred over air because the liquid is noncompressible and transmits heat much more effectively than air. The essential steps in fabricating an oil-filled metal bladder are also shown in figure 14-17.

A set of mating rigid dies for a curved sandwich part normally represents a considerable investment because of the accuracy of fit required. In addition they may become distorted from repeated use and temperature changes. Consequently, they are used only for large quantities of parts for which exact specifications as to size, thickness, and shape have been established. To expedite production, heated dies are common and, if production schedules dictate, cooling of the dies may be required in some cases. The method of heating will depend upon the size of the dies, rate of heating required, or availability of equipment and may be supplied externally by conduction in a hot press, or internally by steam, hot water, or electricity. Cast aluminum dies having external copper heating tubes, metal-sprayed in place, have also been used.

The actual magnitude of the pressure applied on any point in a sandwich part between a set of curved dies is subject to so many variables that it is seldom known. Curvature of the part, thickness uniformity, modulus of elasticity of the core material, and accuracy of the dies all affect the pressure applied at any specific point. Optimum conditions may be determined by careful inspection and destructive testing of several exploratory parts made at calculated pressures ranging from inadequate contact to definite crushing of the core.

Production experience with rigid die bonding has indicated that its successful use requires extremely accurate tooling, (and subsequent checking for accuracy) and close thickness tolerances on the component parts forming the sandwich assembly being bonded; therefore its use is not generally recommended on structural sandwich assembly.

14.4.1.3 Semirigid Dies

Platens or dies having one or both mating surfaces somewhat resilient are sometimes used to simulate fluid-pressure molding. The resilient surfaces provide a more uniform distribution of pressure than do rigid surfaces, without resorting to the use of a fluid under pressure. The hardness of the resilient liner or caul is determined by the characteristics of the sandwich part being pressed. If it is too hard or soft, it will not produce the desired results. The most suitable material can usually be determined only by trial. For example, a soft-textured wool blanket was found satisfactory for pressing glass-fabric facings on end-grain balsa cores at 15 pounds per square inch, while 1/8-inch cotton-duck pads were necessary for bonding aluminum facings to end-grain balsa core at 300 pounds per square inch. Rubber, chipboard, paper, and felt have also found use.

A resilient pad used on only one side of a sandwich results in one smooth surface (next to the die), and in one irregular surface that conforms roughly to the thickness variations of the core. Resilient pads used on both surfaces result in slight irregularities in both surfaces of the part. For sandwich parts exposed to the air stream, smooth surfaces are essential, and, therefore only one resilient pad can be used; whereas, for internal sandwich structures, such as floors, partitions, or shear webs, one or two pads may be used.

A process similar to "hydropressing" of metal might be used for slightly curved sandwich parts by forcing a soft rubber plug of the proper shape into a heated die.

14.4.1.4 Expanding Cores

Pressure is applied by the core itself when foamed-in-place cores are used. These sandwiches require no externally applied pressure but instead a restraining mold that supplies the required heat to expand and cure the core.

With laminated facings of glass fabric and foamed-in-place cores, the facings are molded first, usually on a set of male and female heated dies employing fluid pressure applied through a bag or blanket. With the facings in place, the uncured liquid core mixture is poured into the female mold and the male mold is quickly lowered and clamped in place. The core material then expands and is finally cured by application of heat to form the bond between the core and facings. To insure a good bond between facings and core, the facings must be clean and free from any contamination, such as mold-release agents. One method commonly used is to sand the facings lightly, but care must be exercised to insure that the glass fibers are not exposed. A cross-sectional sketch of a set of dies of this type is shown in figure 14-18.

14.4.2 Techniques for Curved Parts

Parts of single or compound curvature are sometimes made by the same methods as are used on flat parts but, for certain combinations and degrees of curvature, special techniques are required.

14.4.2.1 Single Curvature

Parts with only slight single curvature can readily be molded by merely draping the core and facings in a concave mold and later applying pressure by means of a blanket or a mating die. An assembly of this kind, utilizing a thin steel mold and fluid pressure exerted through a bag, is shown in figure 14-14B.

As the curvature becomes more severe, it becomes more difficult to bend the core to shape and to draw it down firmly to the mold surfaces. The anticlastic (saddle-shaped) curvature, which most core materials tend to assume upon bending, causes some difficulty even at moderate curvature. This characteristic is particularly noticeable with honeycomb cores. The limitations imposed on curvatures of core materials by their tendency to assume an anticlastic curvature vary with the thickness and type of core and have not been fully investigated.

Often the severity of curvature to which a panel can be molded by the "draping method," or one-step molding process, is limited by breakage of the core material in bending. An attempt to evaluate this limitation was made by determining the approximate breaking radius of 1-inch-wide strips of four typical core materials in a variety of thicknesses from one-eighth to one-half inch. If a factor of safety against breakage of about 2 would be applied to these radii, it was believed that reasonably safe working radii would result. These working radii have been investigated in an exploratory manner by bending larger sheets of core material between thin sheets of aluminum, and results are listed below. This tabulation may be used in estimating an approximately safe working radius for typical core materials in fabricating curved parts by the draping method.

| Thickness of core in inches | Radius in inches |
|---|---|
| 1/8 | 6 |
| 3/16 | 11 |
| 1/4 | 18 |
| 5/16 | 24 |
| 3/8 | 32 |
| 7/16 | 40 |
| 1/2 | 50 |

If it is desired to make curved sandwich panels having radii smaller than the safe working radii listed above, special means of forming the core must be employed. Some of the suppliers of core material can supply preformed core to specifications. Some core materials, such as paper honeycomb, lend themselves somewhat to postforming while hot. Another method, perhaps less cumbersome, is to bond or laminate one facing to the core in the first operation, to bend the assembly to approximately the proper shape (with the faced side as the convex side), and then bond the inner facing to the core in a second molding operation. A similar alternate procedure is illustrated in figure 14-19. Fundamentally, this process is the same as that used in steam-bending wood with a metal tension band. The core material to be bent is positioned between two stops on the tension sheet and bent over a form of the proper shape so that the metal sheet takes all of the tension stresses and the core is deformed by compression.

### 14.4.2.2 Compound Curvature

The amount of compound curvature that can be formed in a sandwich part without resorting to special techniques is limited by the facings, the core, or both. In addition, the relation of the respective curvatures in intersecting planes may have an effect on the details and relative ease of fabrication; in general, panels having appreciable compound curvature present difficult fabricating problems. Certain combinations of materials, such as glass-fabric facings wet-laminated to a glass-fabric honeycomb core, accommodate compound curvature more readily than do others, such as aluminum facings bonded to honeycomb cores.

Parts having only a very moderate amount of compound curvature may be made by the one-step process in the same manner as flat parts or parts having moderate single curvature. If possible, the core should be prepared as a single sheet and laid in place between the facings; but if the stiffness of the core is the limiting factor, it may be tailored in place from small pieces. No tests, other than by trial, are available for guidance as to the maximum curvature feasible.

For severe compound curvatures, one-, two-, or three-step fabricating processes may be indicated. Glass-fabric facings on glass-fabric honeycomb cores can normally be laid and molded in a single operation, unless for some reason, such as to minimize air bubbles in the facings, it is necessary to mold the facings separately. When foamed-in-place cores are used, the fabrication is in two steps: (1) Facings, usually of glass-fabric-reinforced plastic, are formed on male or female molds or between mating dies, and (2) core is poured and cured between the facings (held in proper position by dies as shown in figure 14-18) thus forming the sandwich part. Other combinations, such as aluminum facings on balsa core, require a three-step process: (1) Forming the facings, (2) preforming the core, and (3) bonding the facings to the core. Aluminum facings may be formed by a carefully controlled stretching technique. Balsa cores of compound curvatures are produced by building up the desired shape, or by dampening one surface, and then drying the core in the properly curved position.

### 14.4.3 Mold-Release Agents

Some means of insuring easy removal of the part from the mold must be provided to avoid damage to the part being formed and to the mold.

Metal facings next to mold or caul surfaces of metal present no problem if both surfaces are clean and free from adhesive squeeze-out. However, if the metal facings include joints, adhesive may squeeze through and form a bond unless adequate mold treatment is provided. In this case, a very thin film of wax applied directly by wiping or in a solution is adequate protection against sticking.

To minimize warping and distortion of large aluminum-faced sandwich panels formed on steel molds, a mold-release agent or lubricant is beneficial and is sometimes a necessity. Extreme caution should be exercised in using silicone release agents in production shops because of the possibility of undetected transfer and contamination.

Glass-fabric facings of compound curvature require the use of mold-release coatings, rather than sheets, in order to avoid the imprints of unavoidable wrinkles. Parts are sometimes released from polished metal molds without the use of a coating, but for insurance against sticking, a coating is recommended. Mold-release coatings of various types are being used, and no general recommendations can be made for all resin and mold combinations. The final choice can best be made after a few exploratory tests. This is a list of commonly used mold-release coatings;

Liquid or paste wax
Silicone resin
Vegetable lecithin
Methyl cellulose
Polyvinyl alcohol lacquer
Cellulose acetate butyrate dope
Aluminum or zinc stearate
Polyvinyl fluorides

Since most of these coatings are applied as very thin films to avoid possible contamination of the resin, the molds must be highly polished to obviate mechanical adhesion. In some cases a combination of two coatings has been found necessary. Where the surface is subsequently to be painted with rain-erosion-resistant coating or other protective coating, mold-release agents containing silicone should not be used. In parts that are to be subsequently processed, such as premolded faces for sandwich, any mold-release agent must be completely removed to insure an adequate bond.

## 14.4.4 Attachment Details

All sandwich parts must be attached to the framework of the airframe and often to other similar parts; therefore, means for transferring the concentrated stresses imposed at these attachments must be provided. Occasionally, on very lightly stressed parts, unreinforced bolt holes or subsequently inserted reinforcements will suffice, but in most structural applications local reinforcements must be incorporated during fabrication.

### 14.4.4.1 Edge Reinforcements and Doublers

Sandwich parts are normally joined over a framing member, and it is common practice to incorporate a continuous-edge reinforcement to facilitate the transfer of stresses. There are many ways of accomplishing satisfactory edge reinforcing so that such details as loads to be transferred, type of facings and core, attachment fittings, and importance of smoothness of surface, should be considered before selection is made. Typical edge reinforcements for aluminum-faced and glass-fabric-faced parts are shown in figure 14-20. Areas of crushed low-density honeycomb core should be resin stabilized to prevent disintegration under sonic environment.

Some edge treatments serve as an effective moisture seal in addition to providing reinforcement. Others depend upon edge coating to seal out moisture and miscellaneous airframe fluids (ref. 14-6). High-strength inserts may be of a variety of materials, including end-grain mahogany or spruce, plywood (flat or on edge), or reinforced plastics. Additional bolt-bearing area may be provided by reinforcements or by increasing face thickness.

### 14.4.4.2 Doublers and Inserts

The design of a sandwich structure may be such that loads must be transferred to or from individual parts at points other than at their edges. Inserts in the part are required at these attachment points if the loads are of appreciable magnitude, such as over wing ribs or fuselage bulkheads. Typical inserts are presented in figure 14-21. These may be in the form of strips, inserted continuously across the panel, or as local reinforcements under individual bolt fittings. Shear loads on attachment bolts may require additional reinforcement, as shown in figure 14-21B, to provide adequate bolt-bearing area. Figure 14-22A shows one method of densification of metal honeycomb by means of inserts. Densification by compressing the core of metal honeycomb, as shown in figure 14-22B, is another method sometimes employed.

### 14.4.4.3 Cut-Outs

Openings in sandwich parts for inspection, filler holes, or adjustment of fittings must often be provided. Tests have demonstrated that, with certain ratios of opening to panel size, there is a concentration of stress around the cut-outs that may require consideration in design. Experience has shown that these increased stresses can often be carried by high-strength core inserts or edge treatments around the opening, as shown in figure 14-20. If the cut-out requires a cover, the means of attachment must be considered in choosing the proper edge reinforcement around the cut-out.

### 14.4.4.4 Joints in Facings

Part sizes in excess of available facing widths make joints in the facings a necessity. This presents no particular difficulty with glass fabric, as the individual sheets may be overlapped slightly during lay-up. Overlaps should be staggered so that no more than one is present in any cross section, including any joints in the core.

Facing materials of the sheet type, such as metal, must be joined when large sizes are required. Since the type and quality of joint is dictated by the application, some must of necessity be flush while others will permit a projection from the surface. Some joints are illustrated in figure 14-23 where both A and B may be used for metal facings and differ only in the location of the butt plate. Internal butt plates are required for all exterior facings exposed to the air stream, while exterior butt plates are preferred, because of simplicity, for all unexposed surfaces.

### 14.4.4.5 Attachment Fittings

Sandwich parts are attached by means of bolts or screws. Accessories, such as shelves, fittings, and mounting brackets, are often fastened to the parts by the same means. Inspection-door covers are sometimes fastened by means of special quick-opening fittings. Most of these attachment fittings require holes through the panel, usually specially prepared to fit the attachment or adaptor.

A few miscellaneous types of attachment fittings for metal-faced sandwich parts are shown in figure 14-24. Whenever inserts, sleeves, or bushings are employed, tolerances on the part thickness must be carefully maintained to insure proper fit.

It is generally considered good practice to use attachement fittings that distribute the load to both facings rather than those that attach to one facing only. Lightly stressed attachments on nonstructural parts are exceptions, as are attachments so designed that they apply no cleavage stresses to the facing. Occasionally, attachment fittings of the latter type are bonded to one facing by a metal-to-metal adhesive. Figure 14-25 shows a fitting of this type.

Some of the attachment methods shown in figure 14-24 may also be employed on sandwich panels having glass-cloth facings; however, because of the characteristics of these facings, special types of attachments that employ bonded joints are often preferred.

### 14.4.5 Trimming

Parts, after fabrication, often require trimming and subsequent cleaning to achieve final dimensions and to remove rough edges, adhesive squeeze-out, or resin flash. The trimmed parts require careful handling to protect sharp corners and edges from damage. Figure 14-26 illustrates one method of protecting corners of trimmed parts before final assembly on the aircraft.

Countersunk bolts are often not sufficiently smooth for high-speed performance. Bolts of this type are machined after fabrication by shaving with a special tool.

### 14.4.6 Safety Precautions

The fabrication of sandwich constructions requires many operations that, if not properly supervised, could be hazardous. In general, the safety precautions specified and employed by the paint and varnish industry should be followed, but where local codes exist they should be observed whenever applicable. Each operation must be analyzed, and protection provided, if necessary, against fumes, vapors, dust, skin infections, fire, and explosion.

Solvents such as benzene, toluene, methyl alcohol, carbon tetrachloride, and trichloroethylene that are used in cleaning metals, thinning adhesives, and washing equipment are toxic, and adequate ventilation must be provided to reduce the concentration of solvent vapors to less than 200 parts per million parts of air. Fumes or mists from chemical cleaning solutions should be drawn into hoods so that these chemicals cannot be inhaled or come in contact with the skin.

Commonly used resins of the phenolic and polyester types are not considered generally toxic, but certain individuals seem to be allergic to these materials, as evidenced by skin eruptions, sinus infections, or running eyes, and must be relieved of any contact with the aggravating material.

Dusts that are formed as a result of machining plastic parts should be removed by an effective exhaust system; in addition, respirators should be worn when dust particles capable of causing lung infection are present. Some of the dusts from glass-fabric and phenolic laminates are irritating to the skin and require the use of protective skin creams to prevent irritation. Dermatitis may also be caused from contact with some of the solvents and adhesives; therefore, rubber gloves should be worn when experience has demonstrated the need for protection.

Emphasis should be placed on personal cleanliness as a general precaution against discomfort from skin infection. Clothes should be changed after each shift and hands washed frequently to remove dangerous accumulations of irritating materials.

Many of the solvents employed are highly inflammable; therefore, standard precautions for storage and use of inflammable materials must be enforced. Benzoyl peroxide, a catalyst used with many of the polyester-type resins, is also highly inflammable in the dry powder form and care should be taken that this chemical is stored in a cool place and that it is not subjected to any heat, such as the friction of grinding.

**WARNING**

Tests have shown that paint removers used on bonded panels will diffuse into the edges of the bonds and disintegrate most structural adhesives.

## 14.4.7 Specifications

The fabrication of completed sandwich parts can best be controlled by means of clear, concise process and material specifications. Since the size and use to which sandwich constructions are put vary widely, it is essential that the specifications should control all stages of manufacturing, define plus or minus limits where they are required, and specify acceptable materials to be used directly or indirectly in the fabrication process.

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Table 14-1.--Compressive strength of four core materials as determined in a heated press on specimens 1/2 inch thick

| Core material | Temperature | Density | Approximate proportional limit | Load at 0.050-inch compression |
|---|---|---|---|---|
| | °F | Pounds per cubic foot | Pounds per square inch | Pounds per square inch |
| Balsa | 300 | 6.19 | More than 400 | [1]400 |
| Phenolic and polyester-paper honeycomb | Room | 5.79 | 550 | [2]550 |
| | 225 | 5.76 | 120 | 170 |
| | 250 | ........... | 110 | 160 |
| | 275 | 5.80 | 90 | 160 |
| | 300 | 4.71 | 90 | 140 |
| Phenolic glass-cloth honeycomb (1/4-inch cell size) | Room | 6. | 950 | ........... |
| | 225 | 6. | 260 | 150 |
| | 250 | 6. | 225 | 150 |
| | 275 | 6. | 220 | 125 |
| | 300 | 6. | 180 | 125 |
| Aluminum honeycomb (1/4-inch cell size) | Room | 6. | 550 | 600 |
| | 250 | 6. | 250 | 250 |

[1]Load at 0.010-inch compression.

[2]Load at 0.027-inch compression.

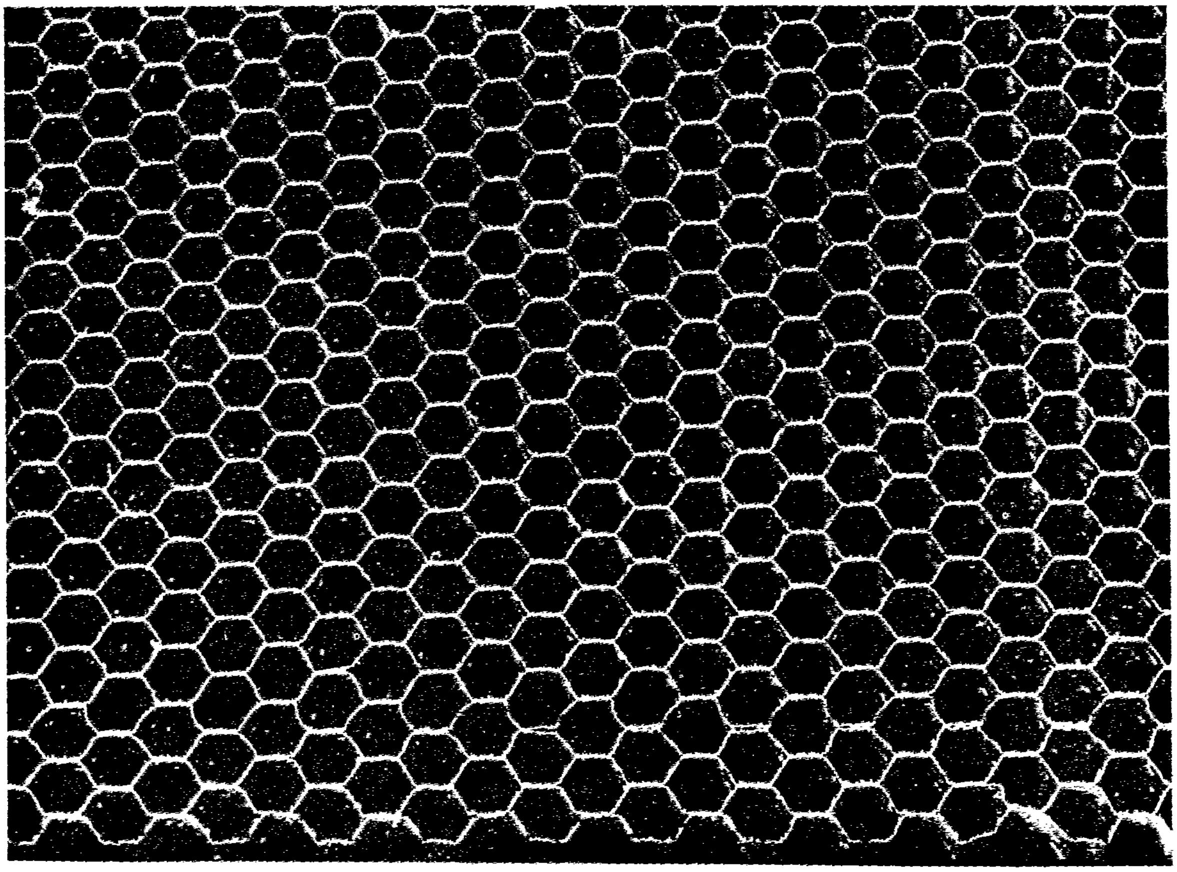

Figure 14-1.--Typical core section of aluminum honeycomb fabricated from precorrugated perforated aluminum foil.

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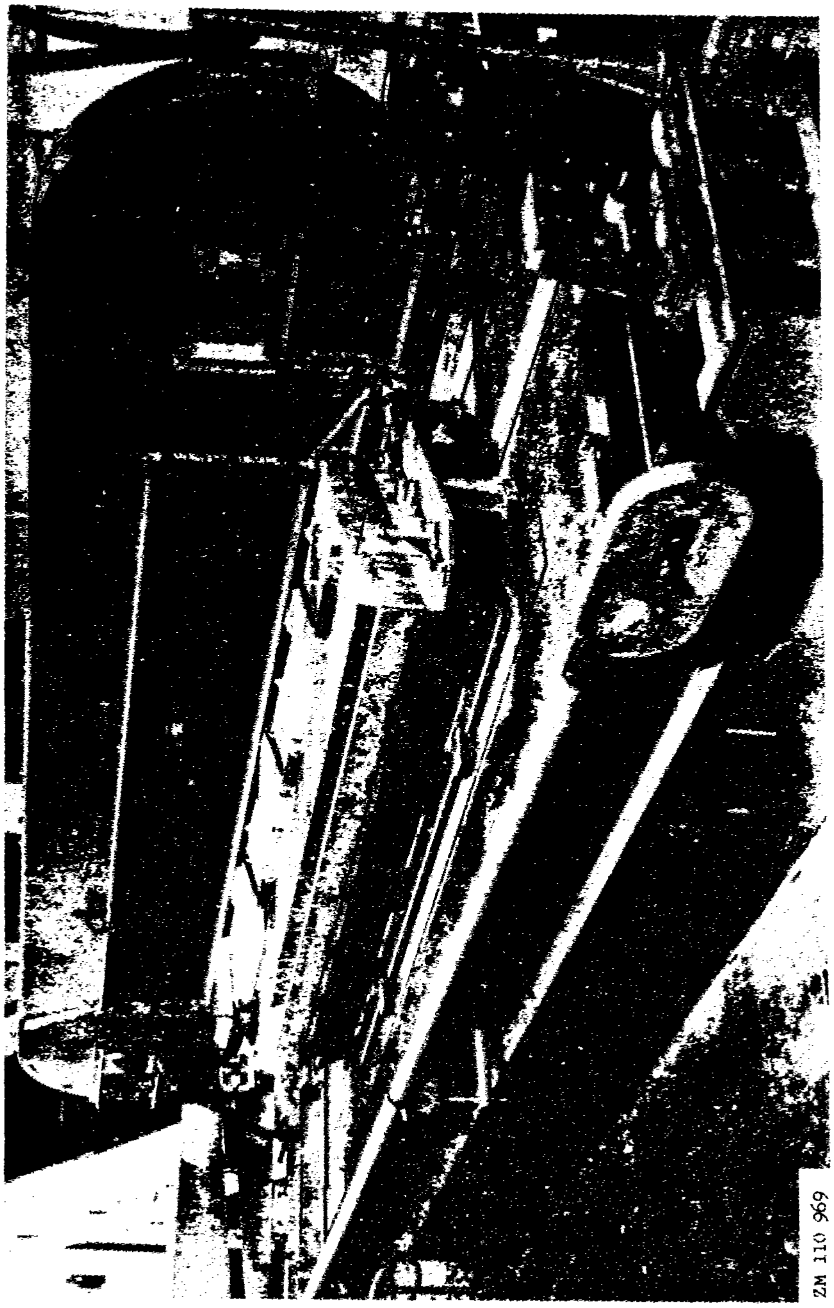


Figure 14-2.--Specially designed horizontal bandsaw used for cutting aluminum honeycomb cores to contour.

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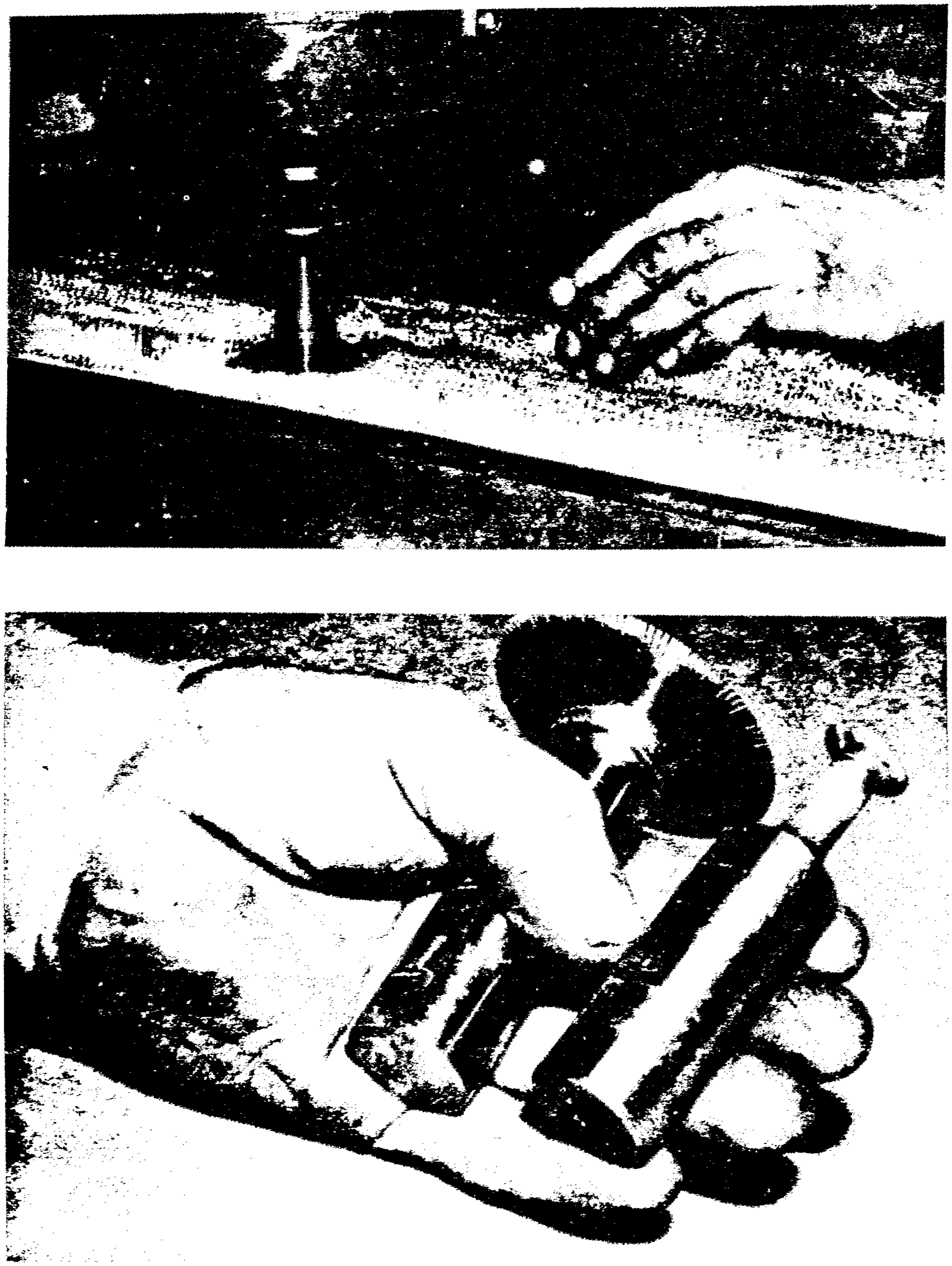

Figure 14-3.--Upper, high speed router shown cutting aluminum honeycomb cores; lower, cutters used for the undercutting of aluminum honeycomb cores.

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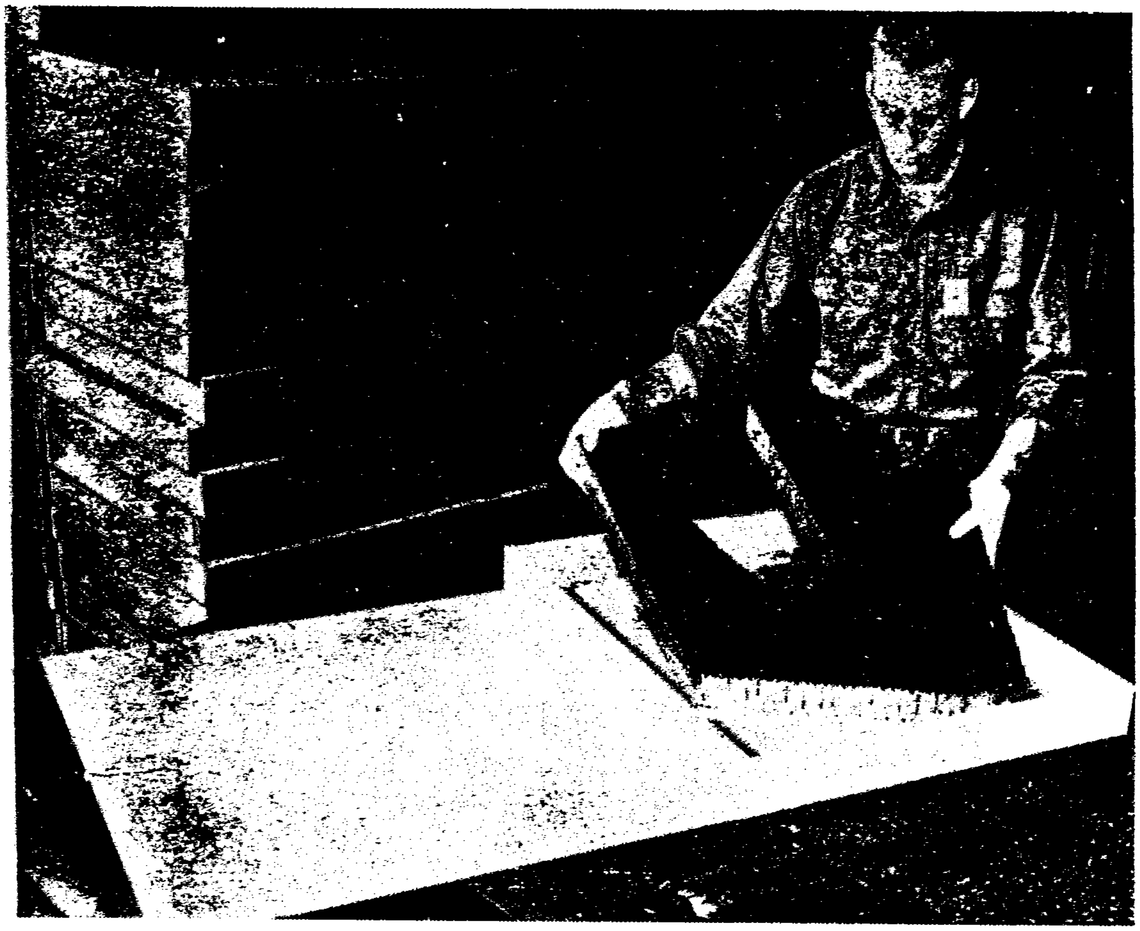

Figure 14-4.--Precut blocks of metal honeycomb core being placed in reusable containers for temporary storage.

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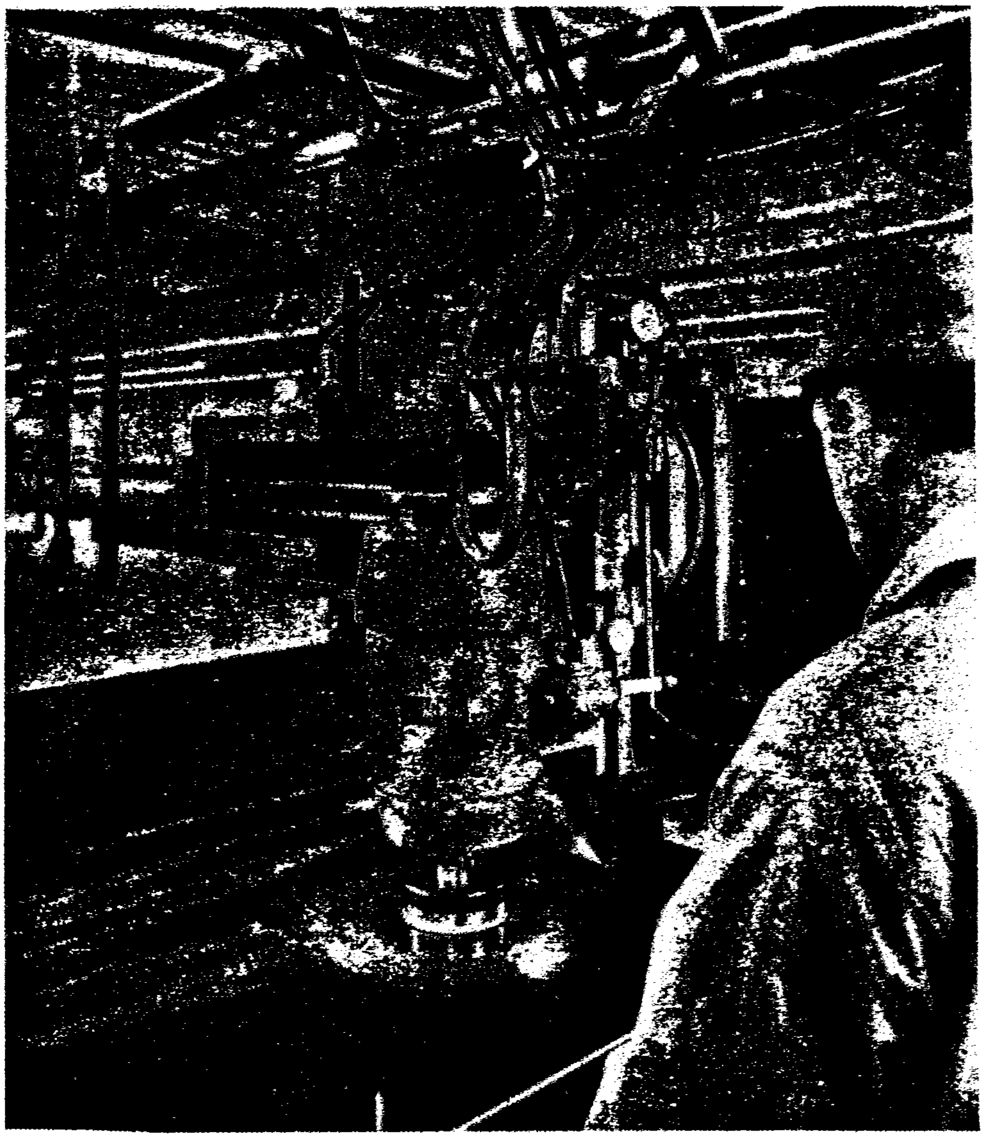

Figure 14-5.--An electrolytic discharge surfacing operation in action. The wheel does not actually touch the stainless steel honeycomb core. The operation is similar to plating except in reverse; the electrolyte disintegrates the metal. A planer modified as shown can be used to advantage in the surfacing operation. The finished surface is burr-free and the thickness tolerance can be held to ± 0.002 inch.

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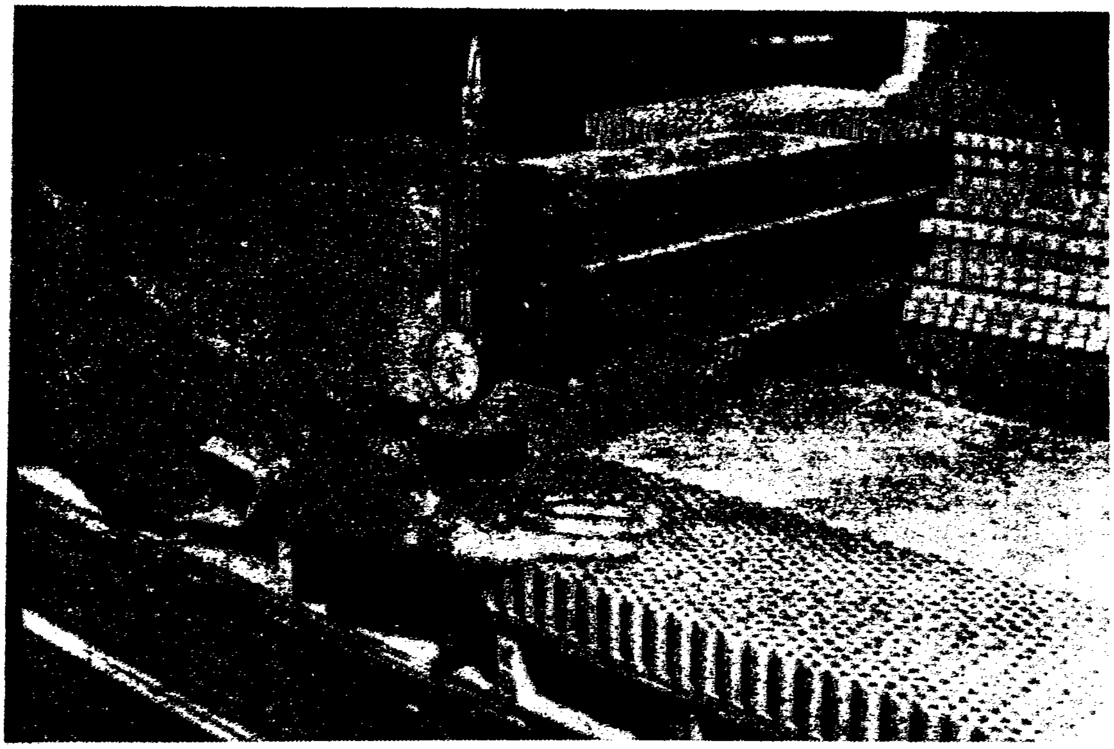

Figure 14-6.--Dial indicator with special base affords a convenient means of checking the thickness of honeycomb cores. Sometimes a roller is used in place of the anvil, with equivalent results.

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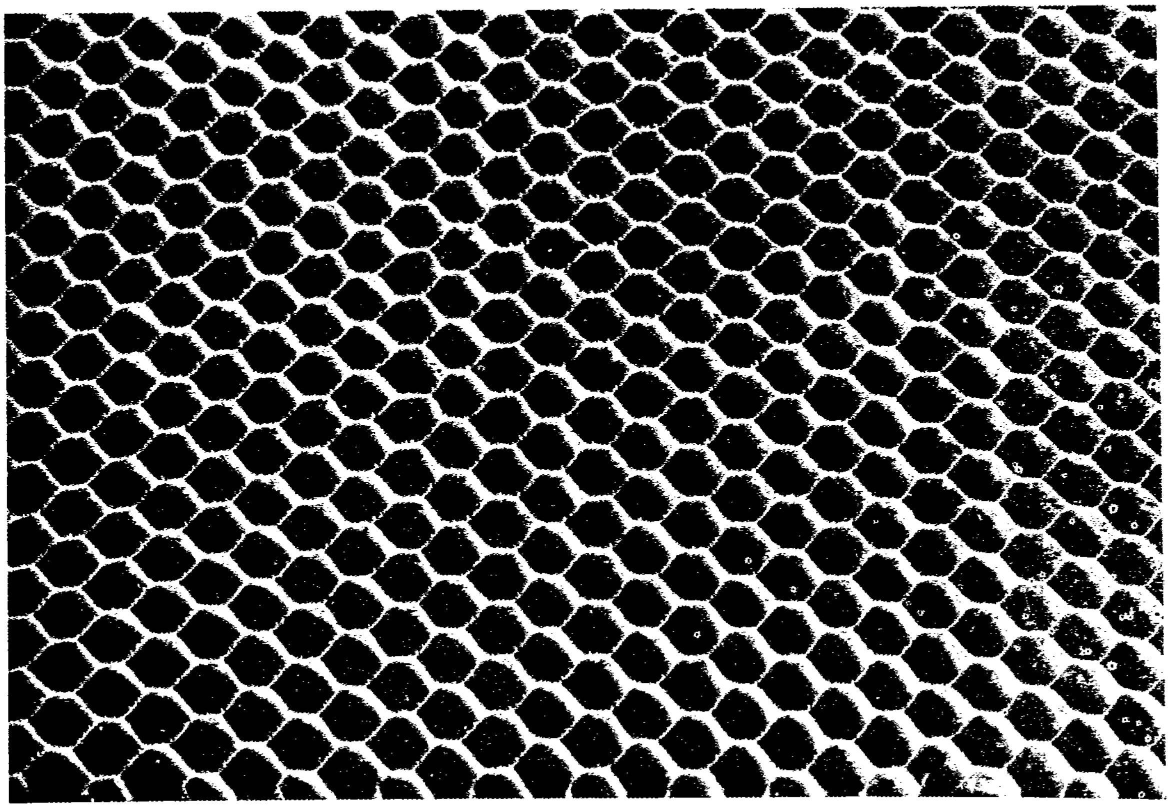

Figure 14-7.--Resin-impregnated glass-fabric honeycomb showing fuzzy surfaces caused by bandsaw cutting.

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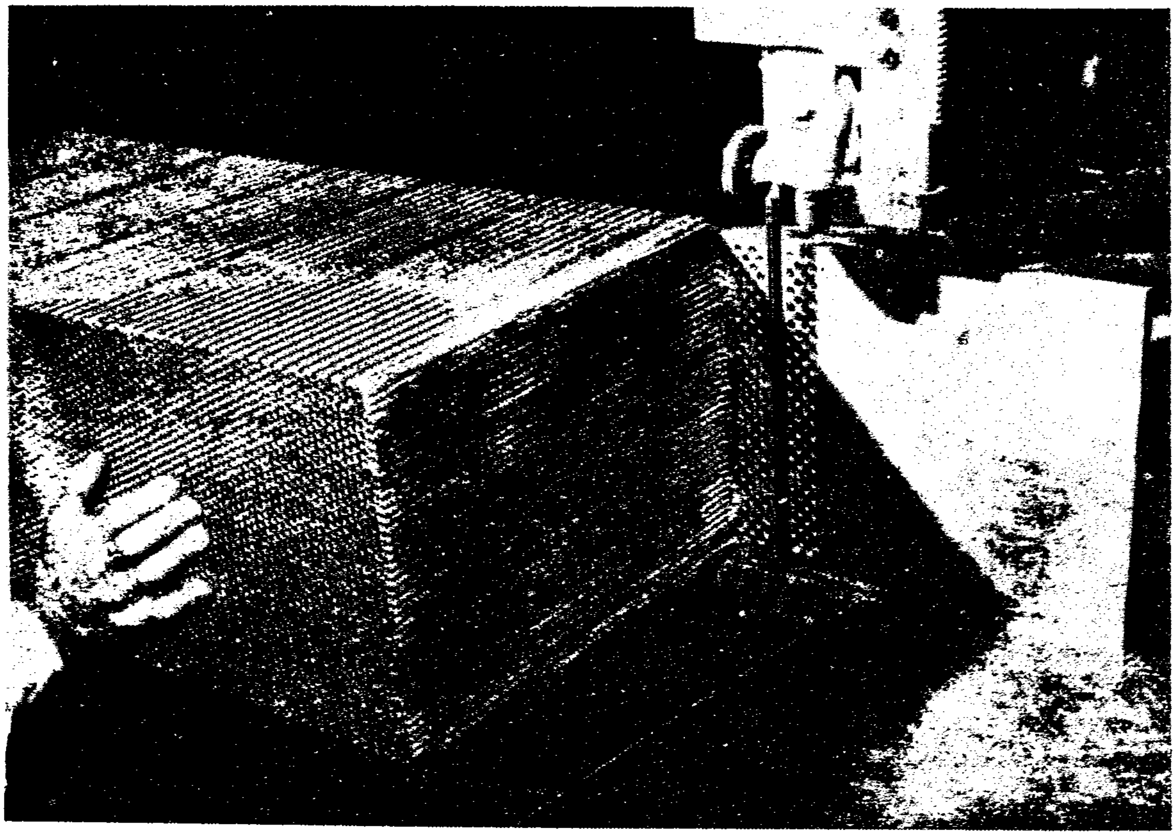

Figure 14-8.--Exhaust hose connected to the holes in the guide fence as a precautionary measure to remove fine resin and glass dust.

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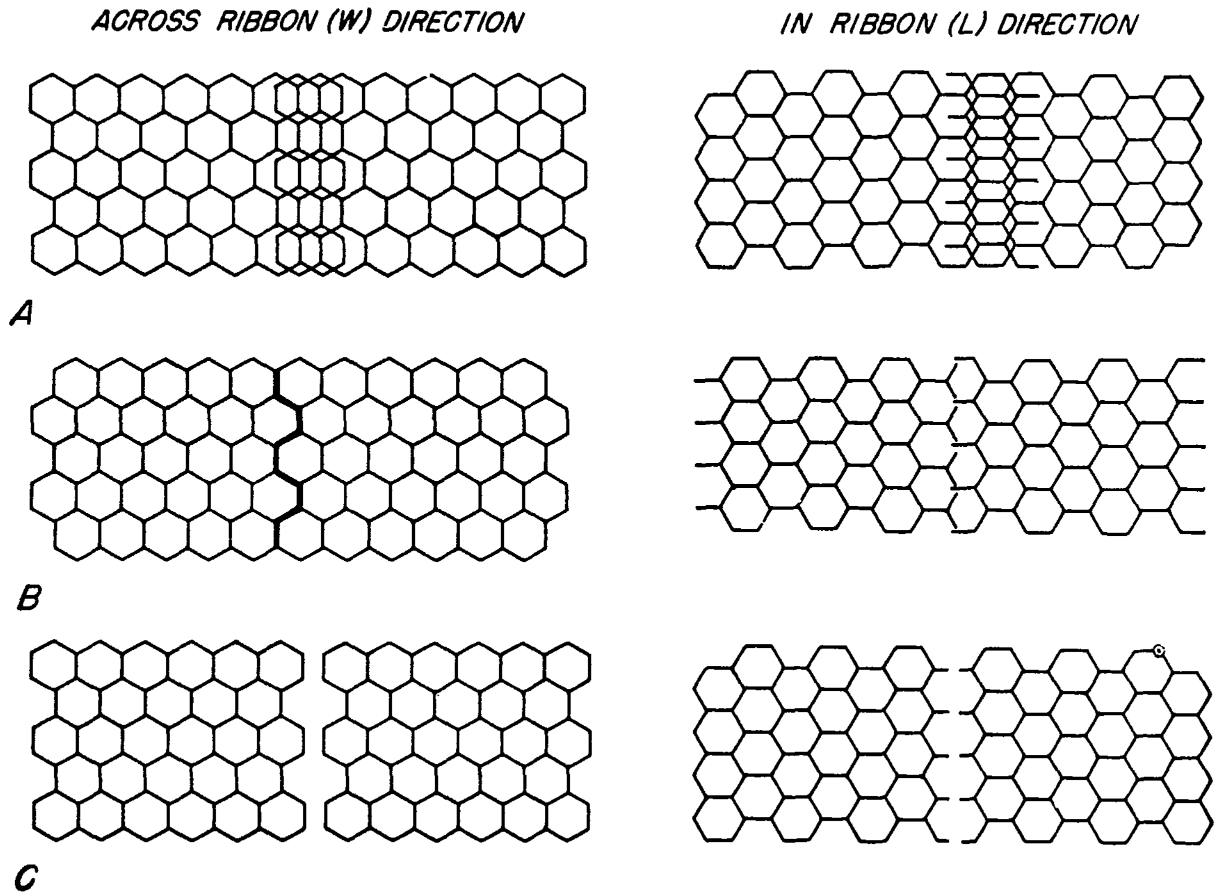


Figure 14-9.--Typical joints between glass-fabric honeycomb core segments; A, interlocked joints, overlapped and compressed; B, butt joints; C, open butt joints (limited by specification, usually not over 1/2 cell in width).

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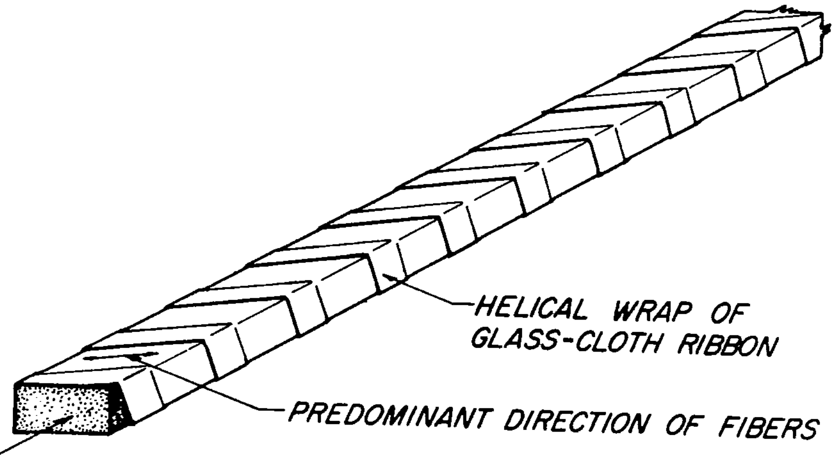


Figure 14-10.--Extruded bar of specially prepared wax formulation wrapped with glass fabric, to be used in the lost wax process.

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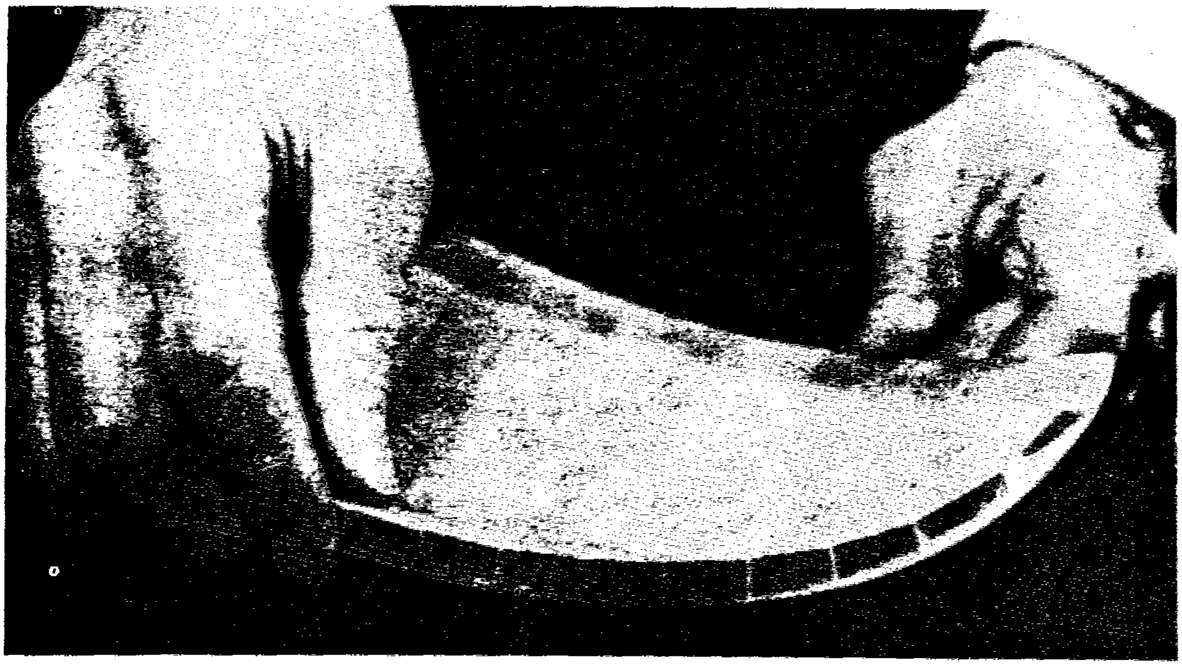

Figure 14-11.--Section of typical curved plastic sandwich part made by the lost wax process.

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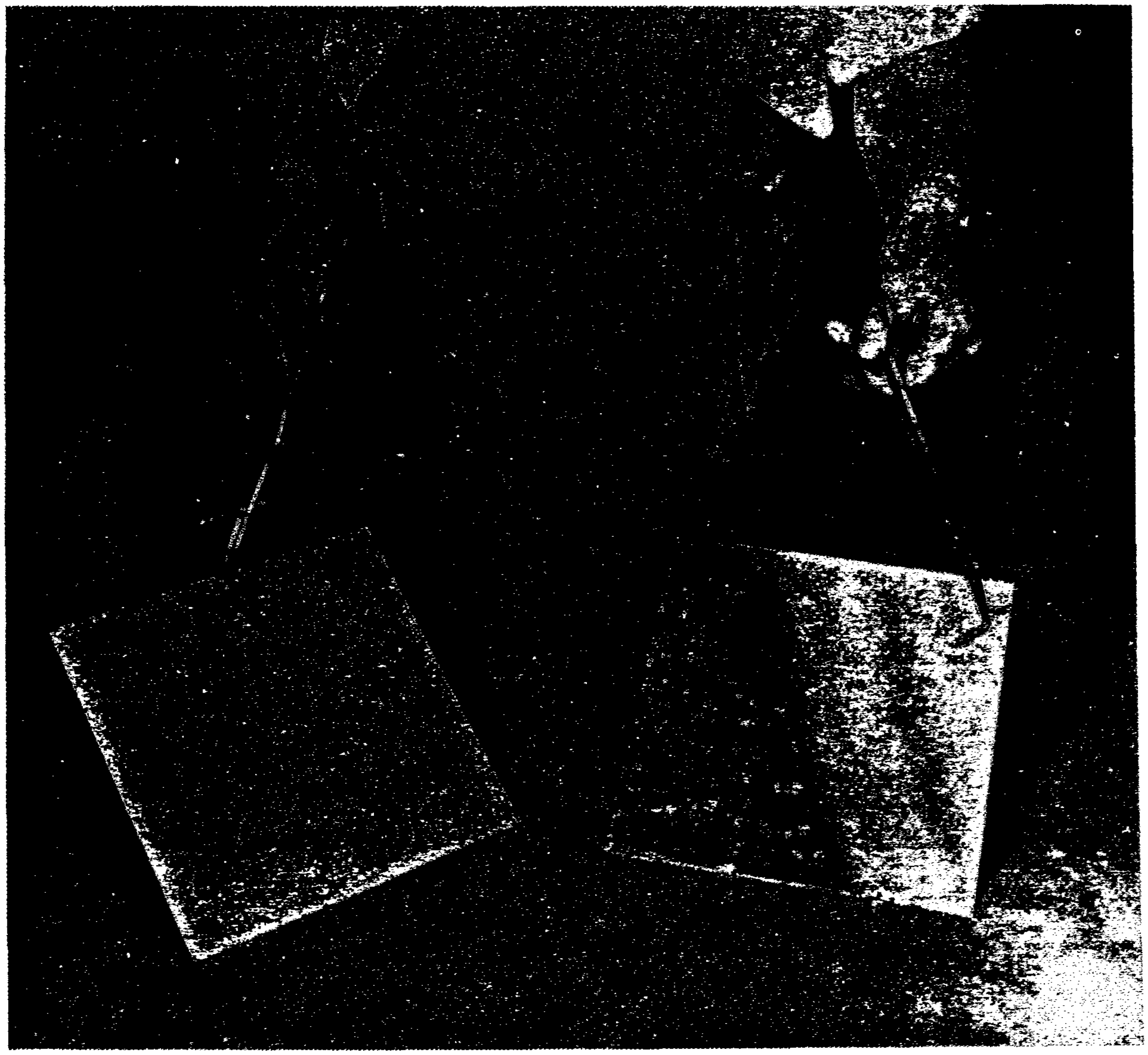

Figure 14-12.--Appearance of water film on a metal surface that is free from grease (left) and on a metal surface that has not been degreased (right). Note the continuous water film on the cleaned surface (left) and the nearly complete absence of a water film on the greasy surface (right).

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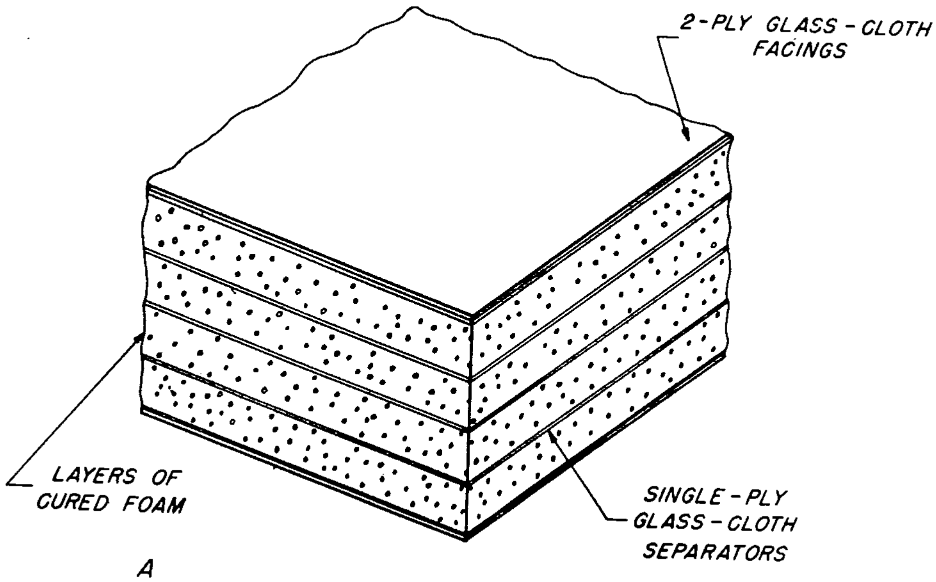


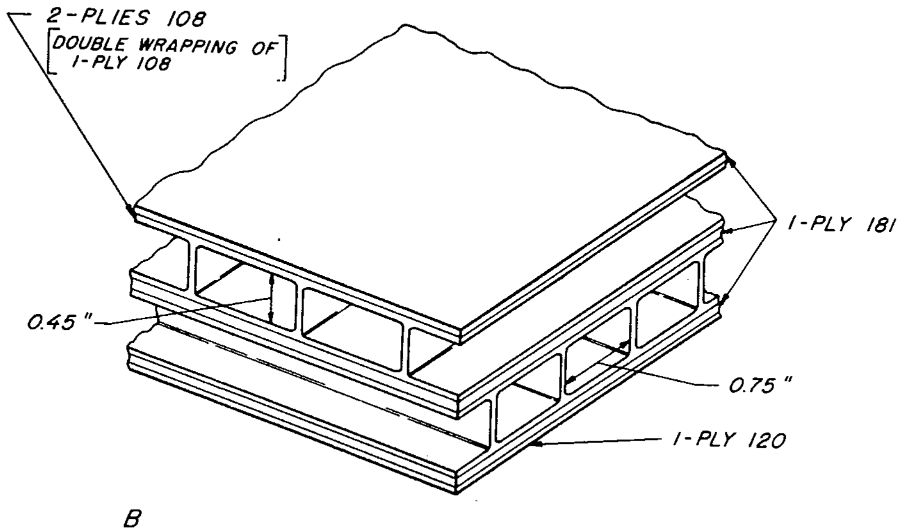


Figure 14-13.--Two examples of "multi-core sandwich" for use in specialized applications.

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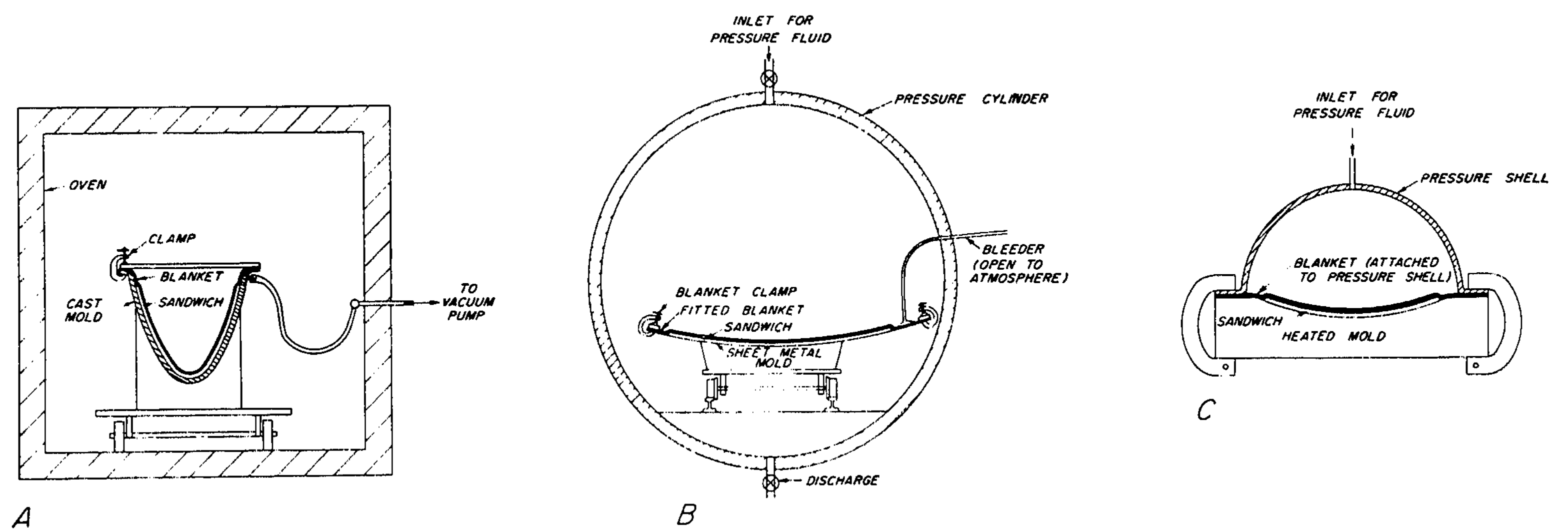


Figure 14-14. --Three basic methods of applying fluid pressure.

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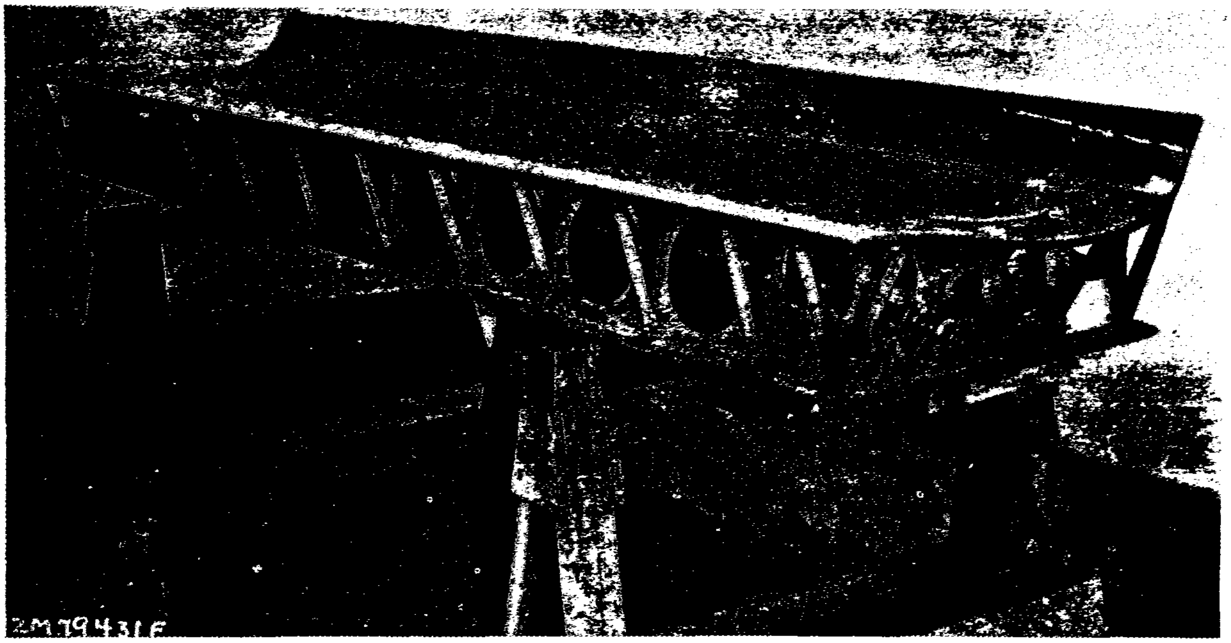


Figure 14-15.--Typical mold of thin sheet metal supported by steel framework suitable for fluid pressure molding of aircraft sandwich in an autoclave.

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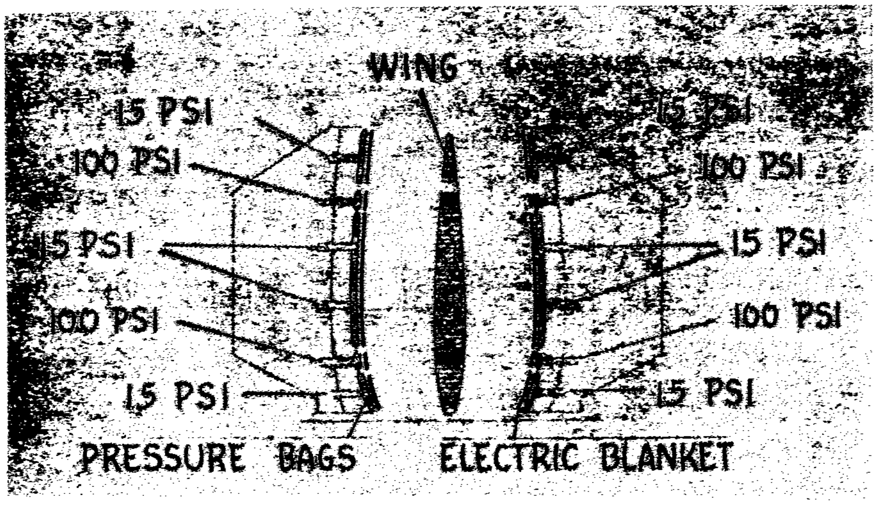


Figure 14-16.--Schematic diagram showing fluid-pressure assembly jig containing part of a sandwich wing. The jigs hold the component parts when they are being bonded together into final form.

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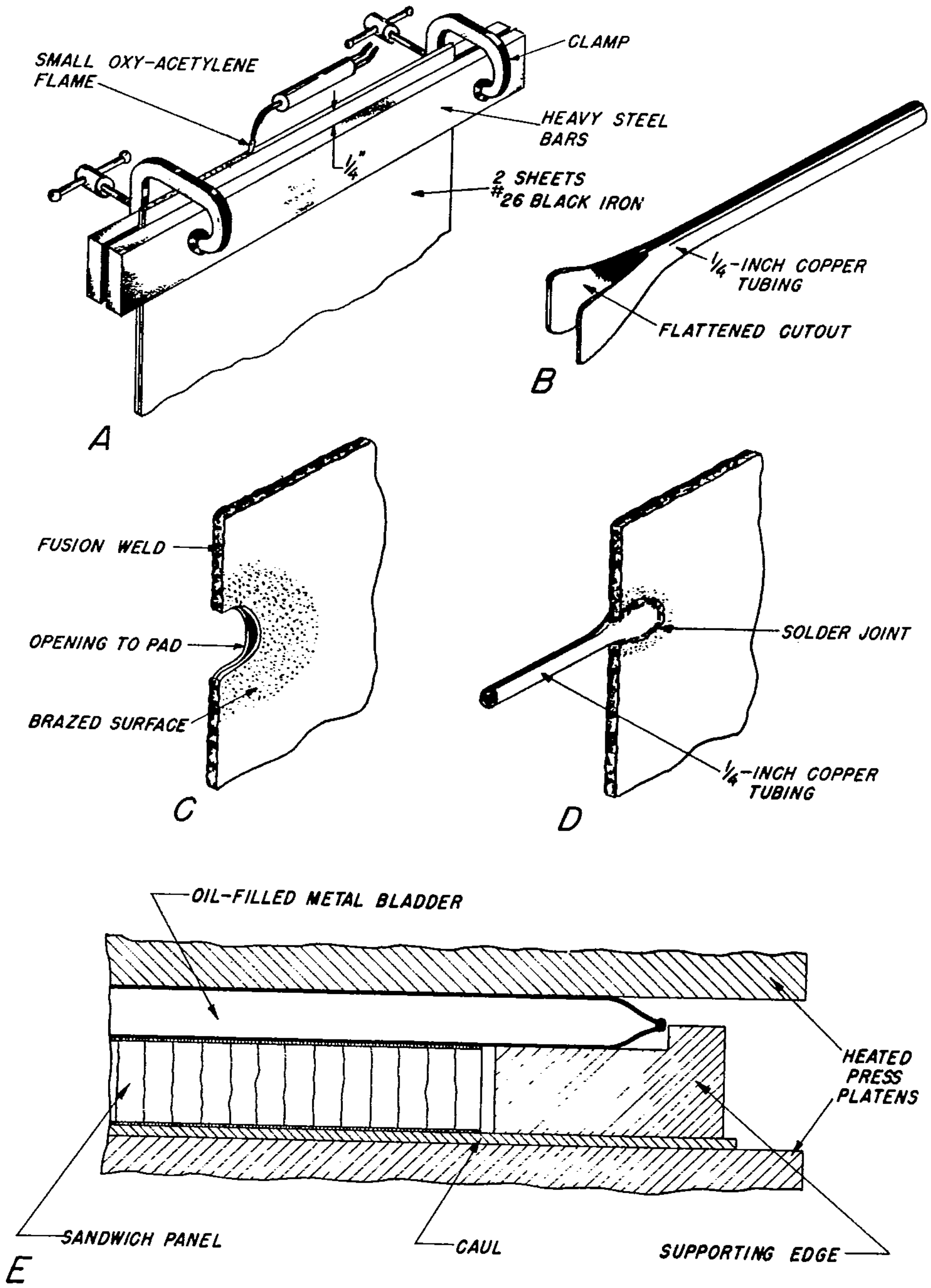


Figure 14-17.--Steps in fabricating the oil-filled metal bladder as shown in E.

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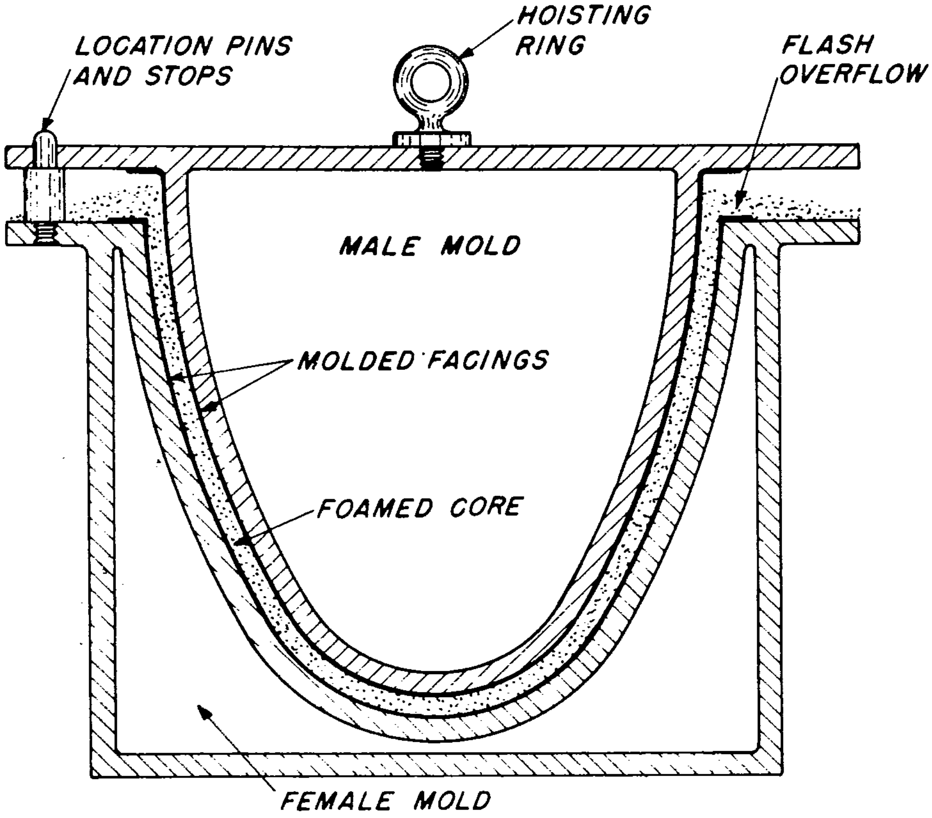


Figure 14-18.--Diagrammatic sketch of a heated mold for use with poured cores.

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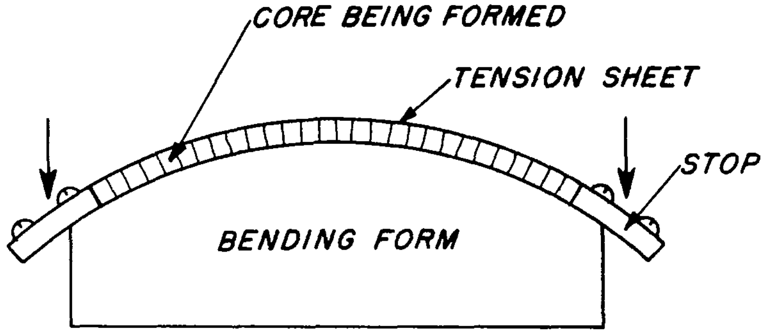


Figure 14-19.--Core being formed by means of a tension sheet.

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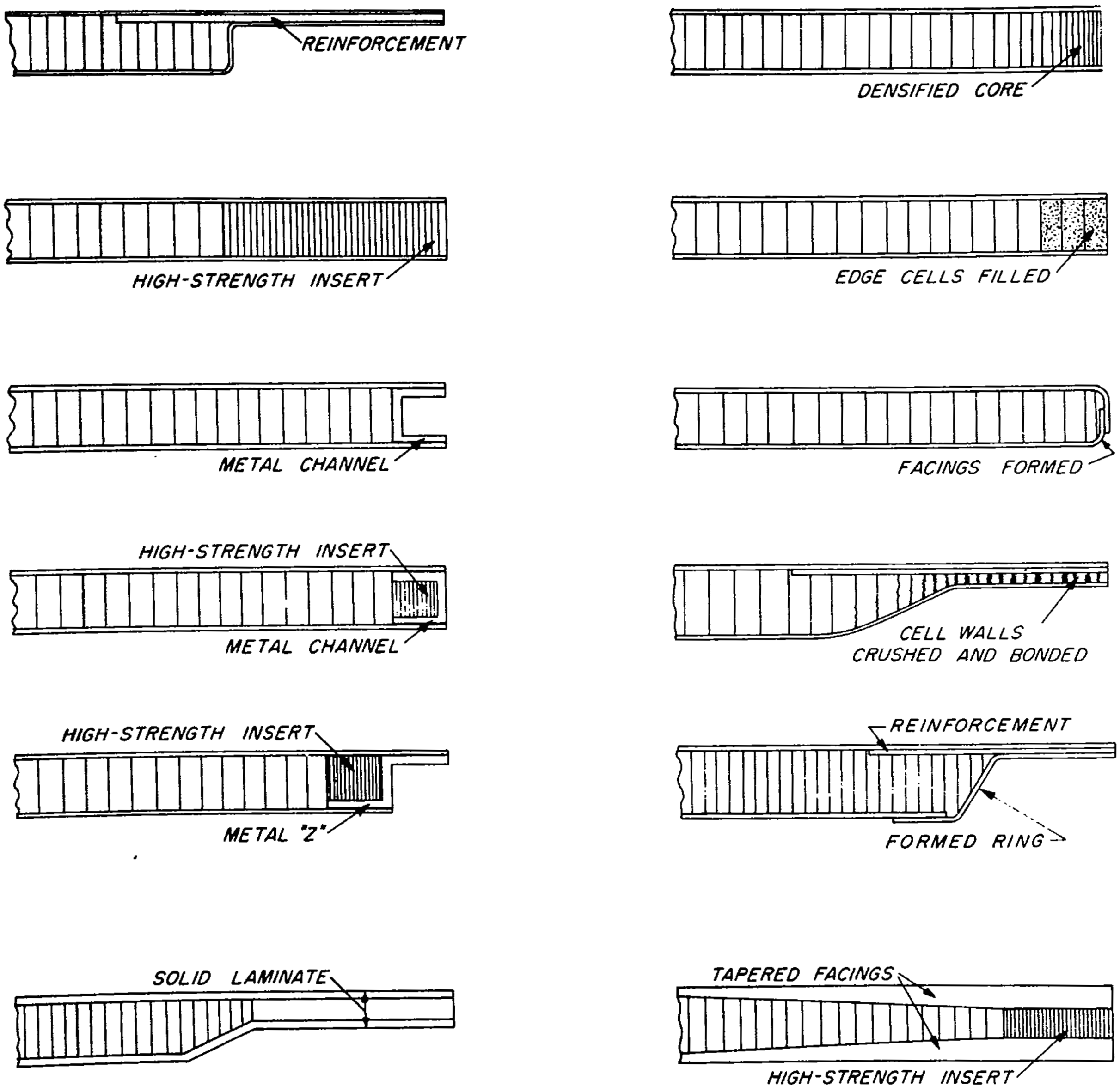


Figure 14-20.--Edge treatments.

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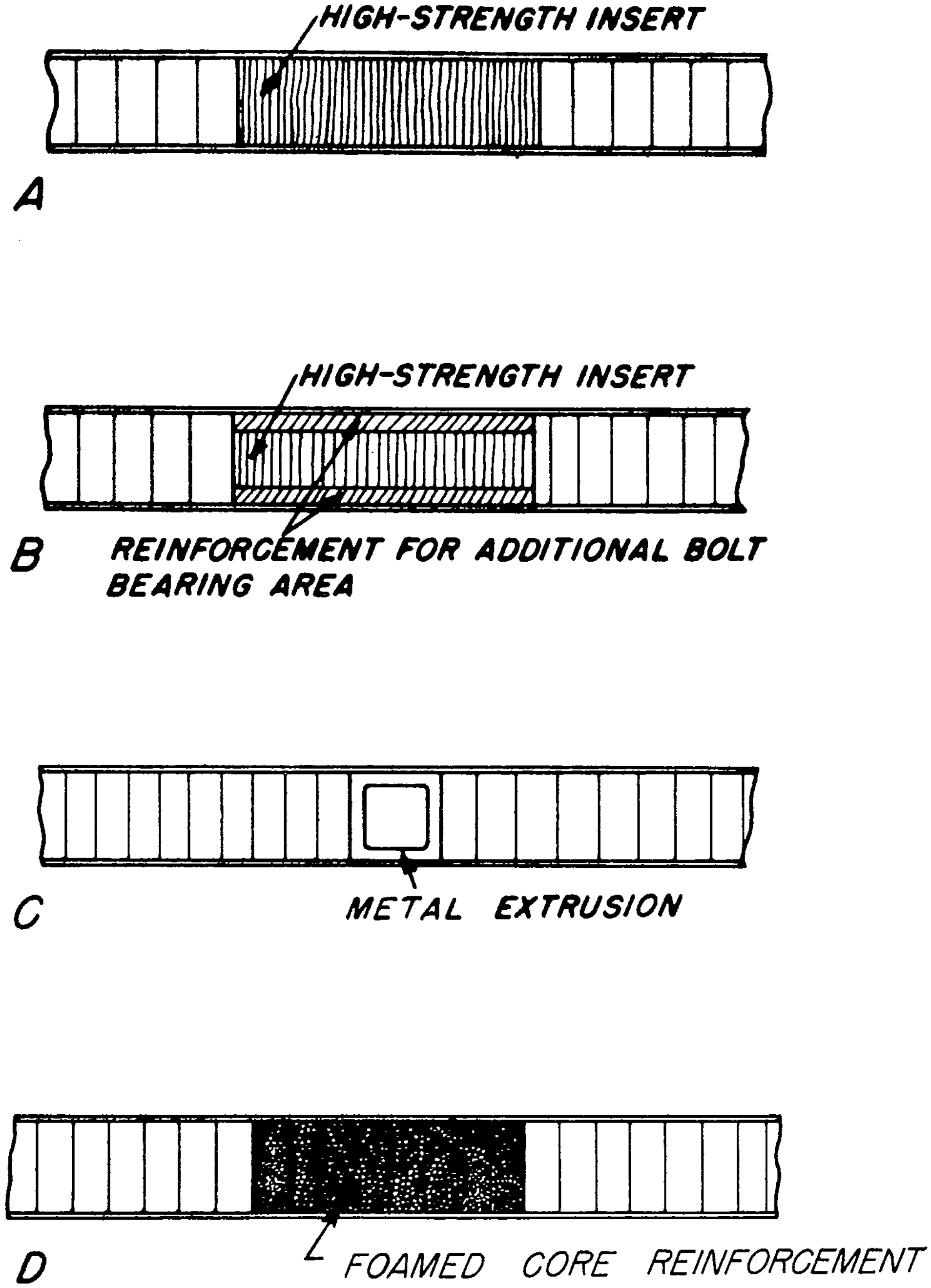


Figure 14-21.--High-strength inserts installed during fabrication.

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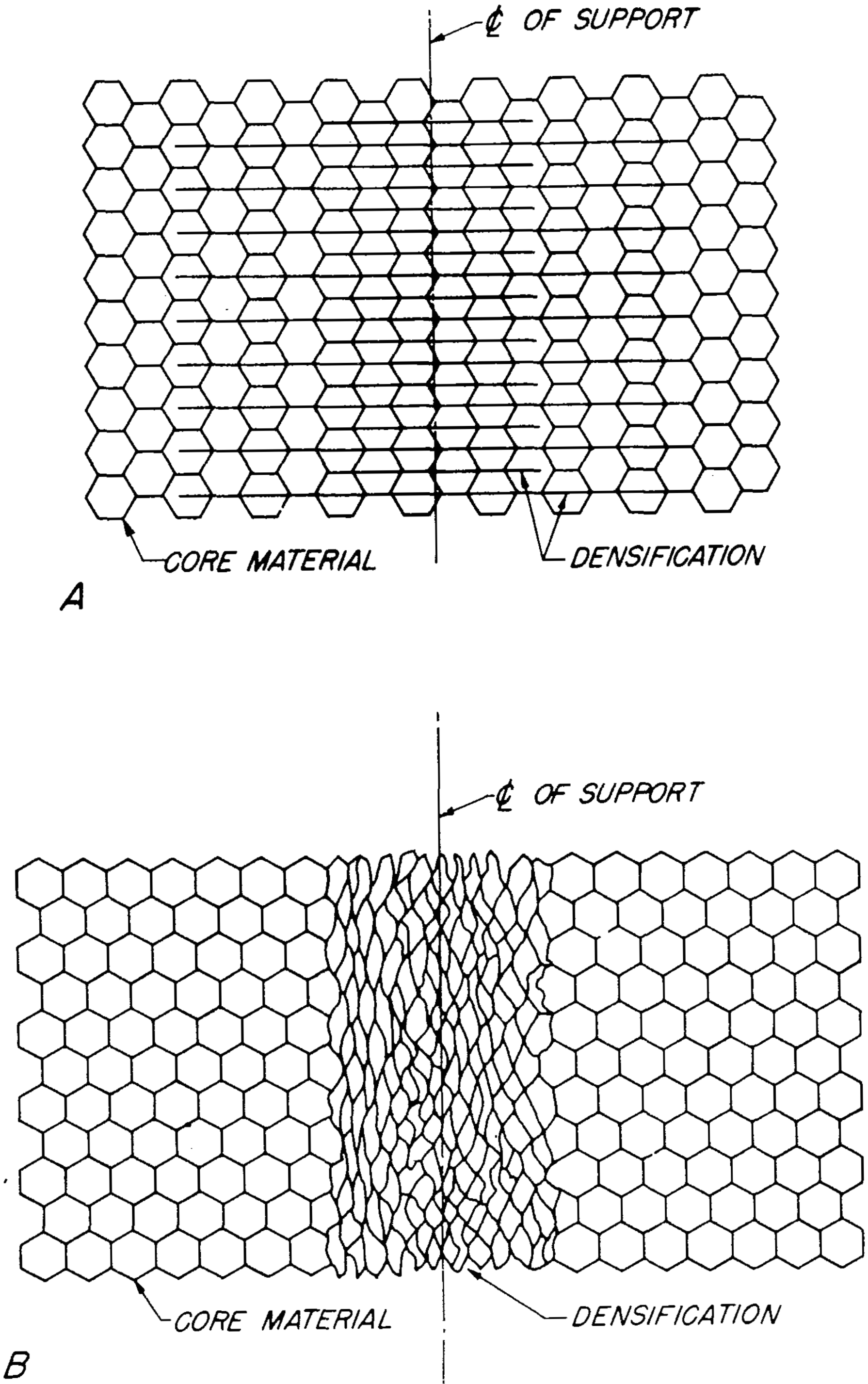


Figure 14-22.--Core densification by inserts and compression.

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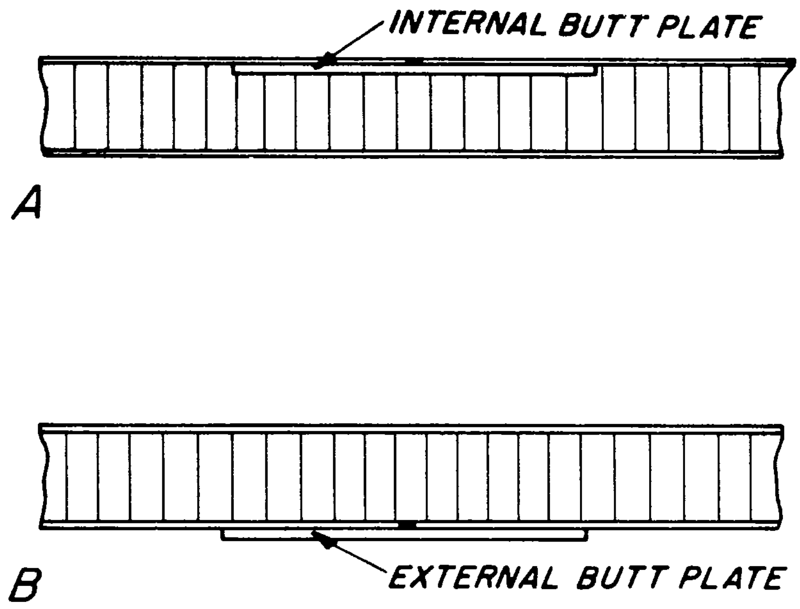


Figure 14-23.--Joints in sandwich facings.

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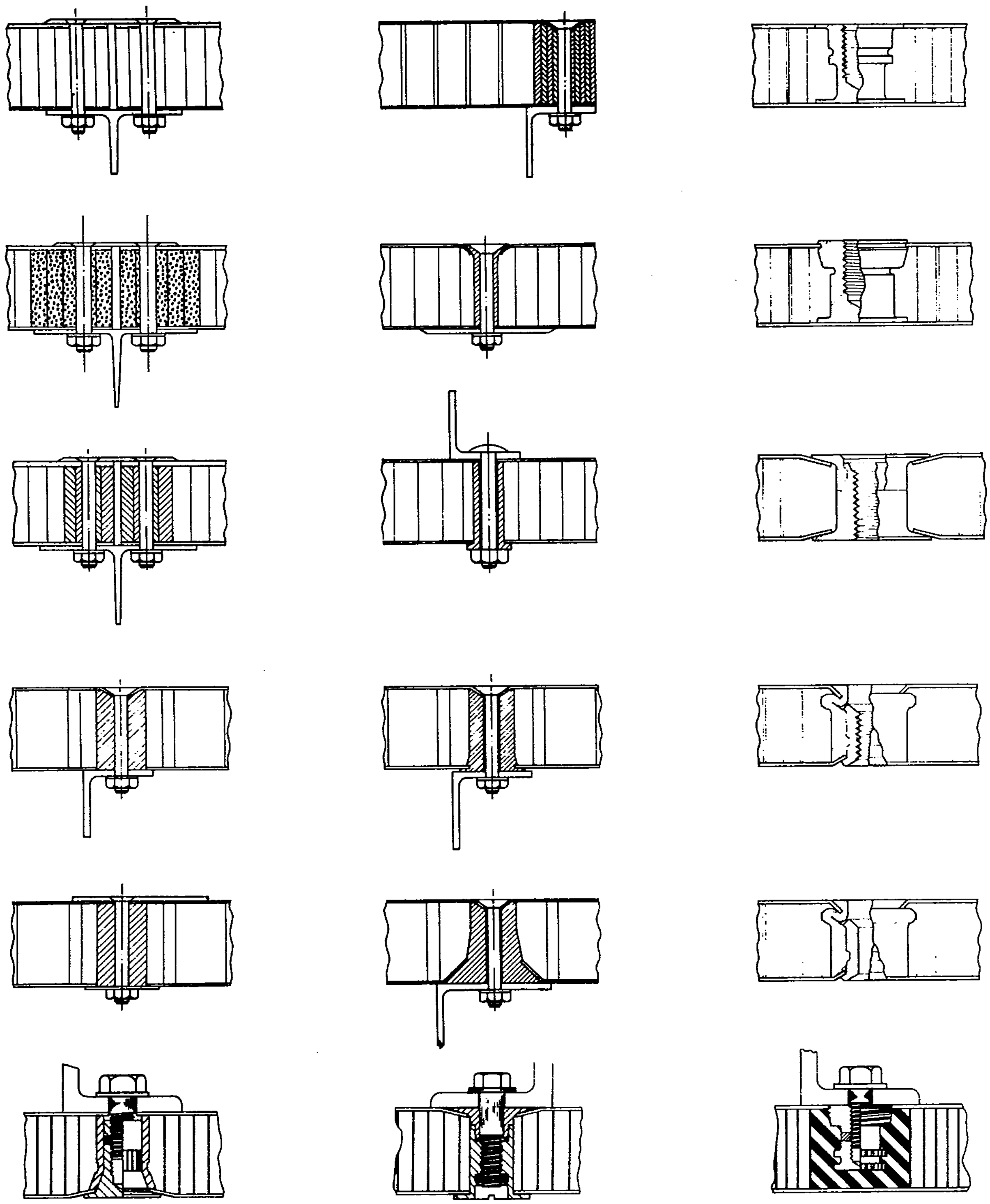

Figure 14-24.--Attachment fittings for metal-faced parts.

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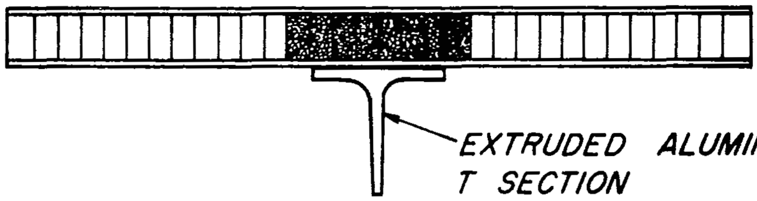


Figure 14-25.--T-section bonded to one facing of an aluminum-faced sandwich.

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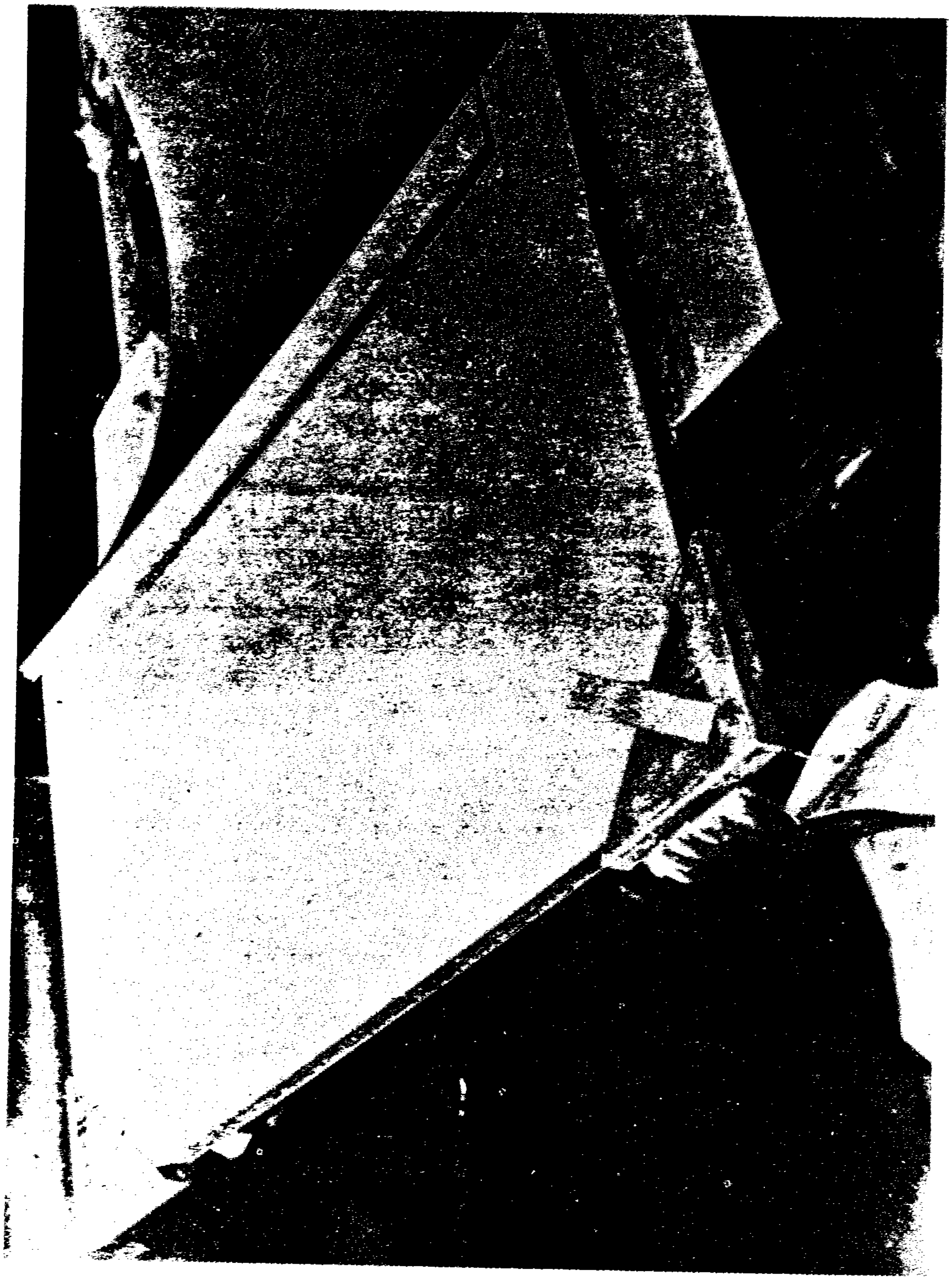

Figure 14-26.--Temporary metal corner guards used to protect sandwich part during handling.

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# CHAPTER 15

# INSPECTION AND TEST METHODS

## 15.1 INSPECTION OF RAW MATERIALS

Once fabricated, it is exceedingly difficult to determine the quality of sandwich construction parts. Carefully controlled systematic inspection of raw materials must be made in accordance with rigid materials specifications, and the fabrication must be controlled by strict adherence to rigid process specifications.

Oftentimes the only way of determining conformance to these process specifications is through use of nondestructive inspection methods. Nondestructive tests are an essential component of production processes as well as end product inspection. If necessary they can be applied to all processes, components, and assemblies. Most nondestructive indications are qualitative, not quantitative, and their interpretation involves judgment based on considerable experience. The relations between discontinuities and the performance capabilities of materials and systems are critically dependent upon the intended service conditions and operating environments. The significance of these indications should be initially verified by destructive means to assist in later evaluation of similar indications.

Although a detailed inspection procedure for all materials is beyond the scope of this manual, a brief discussion of the inspection methods employed on some of the key materials is presented for guidance.

## 15.1.1 Cores

Specifications normally designate acceptable density ranges and minimum strength properties for core materials. The acceptance of material for use therefore depends on careful inspection for weight and strength consistency. Natural core materials, such as balsa and mahogany, vary over a wider weight range than synthetic core materials making inspection for density conformance of prime consideration. Tensile, compressive, or other tests, as mentioned in section 15.5.1 are sometimes made as part of the inspection. Their purpose is either to insure proper strength requirements or as a check on other properties, such as the proper cure of the resin in a resin-impregnated glass fabric or paper honeycomb core. Some of the common characteristics of typical core materials that require investigation by inspection are presented in table 15-1.

## 15.1.2 Facings

Materials employed for facings, such as various metal alloys and glass-fabric-reinforced plastic, present no unusual inspection problems. Metals must normally conform to applicable military specifications and must be free from contamination, corrosion, and wrinkles. Before impregnation glass fabric must be clean, properly treated, and of a definite and uniform weave pattern.

## 15.1.3 Adhesives and Resins

Adhesives must first be evaluated for their suitability and performance in the type of application for which their use is intended. Some specifications require that bond tests be made at specific intervals to determine that there has not been any deterioration of the adhesive. Once a particular adhesive has been selected, inspection must be made to determine that the various batches as received are the same quality as the original samples, and that the adhesives are not used when the quality of their performance has been reduced by overaging or improper storage. Tests of bond strength have been widely used as a means of originally selecting the adhesive, determining the conditions under which the adhesive can be used, and as a means of inspecting the uniformity of the adhesive. Other tests, such as physical appearance, pH, viscosity, specific gravity, and solids content, have also been used to aid in inspecting the uniformity and storage characteristics of adhesives.

Inspection of parts for size, prior to bonding, is extremely important in preventing voids in the finished product. Tolerances on bonding fixtures are equally important for the same reason.

15.1.3.1 Adhesive Bond Strength Tests

Sandwich fabricators, in evaluating and controlling the quality of adhesives, use the test methods outlined in section 15.5.

In evaluating adhesives for their processes, fabricators may use several types of specimens to obtain preliminary information. Such information may concern the strength of the adhesive in joints of the material of the type to be bonded; the allowable bonding conditions under which the adhesive can be used, the performance of the adhesive joints when subjected to conditions simulating actual service, such as exposures at high and low temperatures and humidities, soaking in various fluids, and when subjected to fatigue and long-time loading.

Bond strength tests to check the quality of the various batches of adhesive or the quality of adhesive after storage are usually made with a lap-joint specimen. These tests are often made at room temperatures, but some fabricators believe that tests at low or at elevated temperatures are more sensitive in indicating deterioration in the quality of the adhesive.

When adhesives are intended primarily for bonding sandwich constructions, these adhesives should be accepted on the basis of specified acceptance tests.

15.1.3.2 Other Adhesive Inspection Tests

In inspecting adhesives to control the quality of the materials being used in the fabrication of sandwich construction, the adhesives should first be examined to see that the color and uniformity of mix are the same as observed in previously acceptable batches of the adhesive. Most fabricators then use some additional tests, such as viscosity, pH, specific gravity, or solids content, to establish further that the batch of adhesive under test is of the same formulation as batches of the adhesive previously used and accepted. As these quality-control tests are merely a comparison of the properties of the sample under test with those properties previously obtained on acceptable samples of the adhesive, any method of determining viscosity, pH, specific gravity, or solids content that gives reproducible results will prove satisfactory. When any of the foregoing tests indicate that the properties of the adhesive are not the same as those obtained with other samples of this adhesive, rejection is usually dependent on whether or not the sample gives satisfactory results in joint strength tests.

With certain film-type adhesives, flow tests are made to indicate if there has been any reduction in this property of the adhesive film during storage. A specified area of the film is cured under specified pressure-temperature-time conditions, and the ratio of the final area of the film to its original area is used to indicate the flow property of the adhesive film.

## 15.2 INSPECTION OF COMPLETED PARTS

Sandwich parts are inspected for conformance to dimension, weight, configuration, uniformity, and strength requirements of the applicable specification. The relative importance and tolerances allowable for each characteristic depend upon the application. Radar-antenna housings require panels of uniform and exact thickness, while structural panels require primarily, certification of adequate bond strength. Secondary structural parts are less critical, but must be of proper size and shape.

Radomes, after visual inspection for conformance to dimensional requirements, are often inspected for electrical transmission efficiency and possible distortion of signal, by a scanning apparatus that simulates conditions in actual use.

Structural parts must be critically inspected for areas of questionable bond between facings and core. Areas having no bond are usually readily detectable by several of the common inspection methods, but areas having merely subnormal bond strength are exceedingly difficult to locate by inspection or nondestructive test methods.

Many nondestructive test methods that may be useful in sandwich inspection are outlined in (ref. 15-7).

Testing of production samples or test coupons of various parts to destruction can be useful in providing information on manufacturing techniques and consistency, process control, and structural integrity.

### 15.2.1 Visual Inspection

Visual examination made immediately after a sandwich panel has been removed from the press or bag, where it was cured with heat, often reveals unbonded areas as blisters. These blisters remain extended for a short period only, or until the drop in panel temperature reduces the internal pressure of the panel. During this short interval in which the blisters are visible, they may be outlined with an approved marking pen for future location and possible repair.

Visual inspection methods appear to have only limited usefulness. If a part has blisters upon removal from the press or bag, the presence of defective areas is demonstrated and the part can be rejected or marked for salvage immediately. If no blisters are visible, however, the absence of defective areas is not proved and the part must be subjected to further tests by a more dependable method. Glass-fabric facings, particularly void-free laminates, permit inspection of the core and sometimes aid in detecting poor bonds.

The use of lights has been tried for determining faulty areas of blisters in various types of sandwich construction, but mainly in panels with glass-fabric facings. By varying the arrangement and angle of lighting some blistered areas can be detected, but not with any degree of reliability. Poorly bonded areas cannot be detected by means of lights.

## 15.2.2 Tapping

Tapping is one of the simplest and most effective methods in use for testing for voids in the adhesive bond between the facings and the core of a sandwich part. The only equipment necessary for this test is a small metal piece such as a coin or a small, light hammer.

During inspection by tapping, parts should be freely supported, as on three padded points, to eliminate sound interference from the support. A well-bonded area will produce a clear tone, while an unbonded area usually produces a lower tone or a dull thud.

This method has been found to be reasonably satisfactory for detecting areas where the facings of the sandwich are not firmly attached to the core. It has been found, however, that if there is intimate contact between the facing and the core, no difference in tone quality can be detected between these areas and those that are well bonded. Poorly bonded areas, therefore, cannot be differentiated from well-bonded areas by means of tapping. Tests have shown that very light tapping is more selective than are heavy blows. Considerable experience is required to locate defective areas consistently, because parts of different construction give off different tones and the tones on a single part vary with the position on the part. Variation in tone is especially noticeable within a few inches of the edge.

## 15.2.3 Spur Wheel

A refinement on the tapping hammer is the use of a "spur wheel," which is similar to the dressmaker's transfer wheel. In use the wheel is run at a uniform rate across the sandwich part and the operator listens for a change in tone. The teeth on the wheel should be accurately spaced so that the wheel itself does not produce a variation in tone. The spur wheel is sometimes connected to a sound-amplifying system to make its use more practical where relatively high background noise is prevalent.

## 15.2.4 Ultrasonic Inspection

Metal products, such as steel castings, forgings, and sheet stock, are sometimes inspected by the use of ultrasonic vibrations. Hidden flaws, voids, and other defects can usually be located by their attenuating effect upon high-frequency vibrations. Several ultrasonic instruments which are useful in nondestructive testing of sandwich are described (refs. 15-3, 15-4, 15-5, 15-9, 15-10, 15-11, 15-15, 15-17, 15-21, 15-22, and 15-30).

## 15.2.5 Radiographic Inspection

For metal sandwiches, brazed sandwich in particular, it is reported that radiographic inspection offers the most thorough and dependable method of nondestructive inspecting for internal quality. X-ray will reveal unbrazed areas, core defects, evidence of contamination, and mismatched parts. X-ray techniques have also been found valuable for detecting the presence of moisture in metal sandwiches after exposure. Other defects that can be located by X-ray are incorrect core ribbon direction, deformed cell pattern or incompletely expanded core, mislocation or shifting of core blocks, and ruptured bonds between the honeycomb ribbons (ref. 15-30). Stereo radiography can be employed for determining depth of fillets of adhesive or braze.

## 15.2.6 Vibrator - Amplifier Inspection

A nondestructive method of testing metal-to-metal bonds operates by introducing a controlled vibration from a "door-bell type" buzzer at a localized point directly underneath a small roller. A sensing unit consisting of a phonograph "pick-up," an amplifier, and earphones are used to detect the vibration by placing the pick-up in contact with the bonded assembly.

The operator rolls the vibrator over the bond to be tested, and listens through earphones for a change in tone as detected by the sensing unit. A change in tone indicates a discrepancy in the bond at the point of contact beneath vibrator roller. As defective areas are found, they can be outlined.

The apparatus works well on irregular or slightly corroded surfaces, in production lines, and in areas where background noise is prevalent. This apparatus, however, will only indicate voids, and does not indicate any variation in bond quality that may exist.

### 15.2.7 Thermographic Inspection

Disturbance of expected uniformly distributed thermal conductivity of sandwich panels can be indicative of unbonded areas or inclusions. Detection of these areas is possible by use of thermocouple readings, infrared sensing photographic or television cameras, or color changes in liquid crystal coatings as uniformly distributed heating is applied to the opposite sandwich facing (refs. 15-6, 15-8, 15-20, and 15-28). Inversely, the frost pattern immediately formed when a cooled sandwich panel is brought into a warm, moist atmosphere may also show unbonded areas.

## 15.3 PROOF LOADING DEVICES

### 15.3.1 Exposure to Vacuum

The force exerted by vacuum-induced air pressure in the core may be used to apply a moderate load on the bond between facings and core in sandwich parts, provided the facing and the core materials are relatively impervious to air. Internal pressure can be caused by placing panels in a vacuum in an autoclave or vacuum box. Observations are made through windows in the autoclave. The magnitude of this force is dependent entirely upon the rate of air flow through the facings and core of the part, but under ideal conditions cannot exceed atmospheric pressure, or about 14 pounds per square inch.

Tests made by this method on aluminum-faced parts indicated that areas having a poor bond could not be detected, and areas having no bond were difficult to locate unless they were large or the facings were very thin. Defects of this type can be located more easily and with greater degree of accuracy by tapping; therefore, testing by vacuum appears to have little value.

Panels can be tested at higher internal pressures if their edges are sealed and pressure is supplied by air pump.

Sensitive detection of unbonded or weakly bonded areas can be aided by application of brittle lacquer or bi-refrigent photoelastic coatings. The coatings are observed by ordinary light or polarized light as the internal pressure is increased. Unbonded areas appear at fairly low pressures even though fairly heavy facings may be used (ref. 15-29).

### 15.3.2 Vacuum-Induced Concentrated Load Tester

The tester consists of a dish-shaped casting, approximately 10 inches in diameter, with a rubber gasket around the outside rim to form a pressure seal between the tester and the sandwich panel. A central rubber-covered steel foot is pressed against the panel as the dish-shaped cavity is evacuated. Foot sizes of different diameters are supplied so that various ratios of core compression to core shear stress can be applied. A vacuum gage is attached to the casting to measure the applied load.

In use, the tester is operated by placing it on a sandwich panel, adjusting the positions of the foot until the panel contacts both the foot and the rubber gasket, and drawing a partial vacuum on the casting until failure occurs or until some desired proof load, determined by the setting on the poppet valve, is reached.

The tester appears to be a fairly reliable detection device on flat sandwich constructions having aluminum honeycomb, glass-fabric honeycomb, or balsa cores. Poor bonds between facings and core in flat panels having cores of aluminum-foil honeycomb, glass-fabric honeycomb, or balsa can be detected by proper use of the tester.

The sensitivity of the tester is about equal to the sensitivity of flexure tests for determining poor bonds, but neither is as sensitive as the flatwise tension test.

### 15.3.3. Multiple Proof Loader

Essentially, a multiple proof loader is a replica of one side of a curved or flat panel. The device is best adapted to use in testing flat or single-curved sandwich constructions.

Use of the multiple proof loader will cause failure of poor bonds in a panel being tested. Its controlled use on panels properly bonded will not cause failure of the bonds.

The sensitivity of the multiple proof loader in differentiating between poorly bonded areas and well-bonded areas was found to be better than a short edge-compression test, equal to that of the flexure test, and less than that of either a tension or peel test.

The proof loader base is fabricated of resin-impregnated glass fabric and is rigid enough to retain its shape when the base is subjected to the stresses of the vacuum test. (Other rigid materials can also be used for the base.) The mold from which the sandwich panels are made is also used to form the proof loader base, figure 15-1. For example, a multiple proof loader base used for testing wing skins can be formed from the wing skin molds.

After the wing skin is fabricated and is to be tested, it is rested on contact buttons on the concave side of the proof loader (for curved panels). The buttons are placed in checkerboard fashion to produce the desired proof load. When properly positioned, the wing skin panel will be situated within a rubber gasket, which is located along the edge of the proof loader base on the concave side. A vacuum gage is mounted on the convex side of the proof loader base.

A predetermined partial vacuum is applied to the enclosure between the vacuum base and the sandwich panel. If a faulty bond is present between facing and core on either side of the core, a sharp audible crack will be heard before the predetermined vacuum is reached and the part is classed as not acceptable.

## 15.4 SPECIFICATIONS

None of the inspection or nondestructive test methods in use at present appear to be an entirely dependable means of inspecting sandwich parts for quality of joints. Also, any such inspection method could at best detect poor panels after fabrication, and cannot be considered a replacement for quality control during processing. Therefore, adherence to adequate material and process specifications, supplemented by sufficient destructive tests, is necessary to insure uniform high-quality joints in sandwich panels.

## 15.5 TEST METHODS

Experience in testing sandwich constructions has been sufficiently extensive to establish some procedures. They are described in Military Standard MIL-STD-401 (refs. 15-2 and 15-23).

### 15.5.1 Test Methods for Core Materials

Core materials are sometimes difficult to test because they may not have sufficient rigidity or hardness to support strain gages or because they may be available only in thin sheets. A number of methods of test have been devised. They are described in detail in Military Standard MIL-STD-401 (15-2 and 15-23).

### 15.5.2 Test Methods for Adhesives and for Bonded Joints

Many types of test specimens and destructive test methods have been developed for evaluating the quality of adhesive bonds in metal-to-metal (ref. 15-27) and in sandwich construction (refs. 15-24 and 15-25). The results obtained from these tests are usually for the purpose of comparing the quality of adhesive bonding, as it is difficult with many of the tests to apply the values directly to the design of bonded parts.

### 15.5.3 Lap-Joint Metal-to-Metal Shear Test

A lap-joint specimen of two thin sheets of metal overlapped for a short distance at the ends has been widely used in the evaluation and control testing of adhesives for metal-to-metal and sandwich bonding. This specimen and its method of tests are described in Federal Specification MMM-A-132 (ref. 15-27) and in ASTM Standard D-1002 (ref. 15-1).

Clad aluminum alloy (0.064 inch) sheets with an overlap distance of 0.5 inch have frequently been used in fabricating this type of specimen. One-inch-wide specimens are then cut from bonded panels, or prepunched sheets may be used to eliminate sawing near the bond line. Other metals such as magnesium, stainless steel, and titanium, have also been used in this type of specimen.

When the lap-joint specimen is stressed by applying a tension load, bending also occurs within the specimen, such as shown in figure 15-2. Therefore, in addition to the complicated distribution of shear stress along the bond line because of differences in the moduli of elasticity of adherend and adhesive, there are tearing stresses normal to the bond line. The distribution of these shear and tearing stresses is dependent on the length of overlap, modulus of elasticity and thickness of the adherend, modulus of elasticity, modulus of rupture, and thickness of the adhesive (refs. 15-16 and 15-18). Examples of relationships of shear stress, normal stress, and the apparent average shear stress value are shown in figure 15-3 as computed (ref. 15-18) for adhesives with low and high elastic modulus. As the apparent average shear strength values computed for the bond area are dependent on the several properties of both adherend and adhesive, these average shear values can be used for direct comparisons only when identical types of specimens are used for all tests.

The variability of bond tests made with lap-joint specimens under conditions believed to be identical has usually been considered to be fairly high. In a survey study made (ref. 15-12), among fabricators of bonded joints, the coefficient of variation of this type of test was found to be 6 to 10 percent in laboratory and adhesive acceptance tests and 10 to 16 percent in production control tests.

The variability in these lap-joint bond tests can be attributed to many possible causes such as variations in:

The bonding characteristics of metal sheets furnished by different manufacturers.

The smoothness of the edge of the sheet being bonded. In clipped metal edges, the orientation of the burred edge is believed to influence the failing strength of the joint.

The contaminates on the surfaces and the effectiveness of the prebonding treatments in preparing the metal surface for bonding.

The drying conditions after prebonding treatments and before the adhesive is applied to the surface.

The temperature, humidity, and other conditions under which the adhesives are applied.

The formulation of the adhesives and changes during aging of the adhesive sample.

A bonded panel in the bonding conditions and methods, such as amount of adhesive applied, precure and cure conditions, and uniformity of pressure.

The heat and vibration that specimens are subjected to during the cutting operation.

The testing technique, including the distance between jaws, alinement of jaws and test specimens, temperature control, and rate of loading.

One must allow for these variables, not only when using lap-joint specimens, but also when one applies other types of tests to the metal-bonding adhesives.

Careful process control is necessary to reduce the variations indicated above as required by the various military specifications.

### 15.5.4 Lap-Joint Shear Test at Various Temperatures

The lap-joint shear test is frequently used to indicate the performance of adhesive bonds over a wide temperature range. Tests are made by heating or cooling the bond line of the specimen to the required temperature in circulating-air chambers, or by the use of thermostatically controlled small cylindrical ovens that will maintain the temperature within ±2° F of the required temperature. Radiant heat ovens are also used in this type of testing. Thermocouples attached to both faces of the lap area are used to indicate the temperature. When radiant heating is used, the thermocouple junctions should be shielded to prevent error in reading the temperatures.

Variations in the results of these tests may be obtained, depending on the time required to bring the specimen to the required temperature for testing. This time may vary, depending on the heat capacity of the test chamber and whether the test jaws are located within or outside of the test chamber.

The procedures as established in Federal Specifications such as MMM-A-132 (ref. 15-27) should be followed.

## 15.5.5 Lap-Joint Shear Test After Exposure

The durability and overall performance of metal-bonding adhesives are often evaluated by preparing lap-joint panels with the adhesives and then subjecting these panels or specimens cut from these panels to various types of exposures. After exposure, these specimens are tested to failure by the regular methods as described in section 15.5.3.

## 15.5.6 Lap-Joint Specimens in Fatigue Testing

The lap-joint test specimen (section 15.5.3) can also be used to determine the fatigue characteristics of the metal-bonding adhesives. Stresses are applied in cycles varying from the maximum selected stress to 10 percent of this maximum stress.

Curves showing stress number of cycles to failure can be established for the adhesive by stressing specimens to failure, using selected maximum stresses. A typical stress number of cycles to failure curve is shown in figure 15-4.

Fatigue tests can be made over a wide temperature range by using ovens and conditioning chambers surrounding the test specimens. Fatigue tests on lap joints of aluminum at low temperatures (-67° F ), however, have generally shown fatigue strengths of the bonds equal to or greater than those obtained at room temperatures, and even with the short 3/8-inch overlap specimen, metal tension failures frequently were noted rather than adhesive failures.

## 15.5.7 Use of Lap-Joint Specimens in Long-Time Loading

The lap-joint specimen (section 15.5.3) is also used to determine the long-time load and creep properties of adhesives (ref. 15-27). Applied loads are selected so that the length of time to failure for the specimens will range over the interval from 0.1 to 200 hours. The stress-time to failure curve can be established, and the point where this curve intercepts the 200-hour ordinate is considered the long-time load strength. A typical stress-time to rupture curve is shown in figure 15-5. Tests may be made over a wide range of temperatures from room temperature up to the maximum temperature the adhesive will withstand.

Measurements are also made during the long-time loading to indicate the deformation of the adhesive film. Scribe marks are made across each of the two edges of the overlapped area at distances of 1/32 inch from the ends of the overlap and also at the center of the overlap. The deformation of each of these lines is then measured, using a traveling microscope after various intervals of the loading period. A camera arranged with automatic timing devices can be used for obtaining the creep deformations. Test results indicated (ref. 15-19) that the deformation at the ends of the lap joint is frequently greater than obtained at the center. The typical load time-deformation curve shown in figure 15-6 presents extensive information on the creep of adhesive-bonded joints under constant load.

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Table 15-1.--Principal core material characteristics that require inspection

| Core material | Characteristics (in order of importance) |
|---|---|
| Balsa and mahogany | Density, defects,[1] slope of grain, moisture content |
| Paper honeycomb | Cure, configuration, bonding, density |
| Metal honeycomb | Bonding, alloy, configuration, perforation, density |
| Glass-fabric honeycomb | Configuration, bonding, resin content, density, dielectric properties |
| Foamed-in-place | Foaming characteristics, uniformity of foam, density |

[1]Common defects are knots, rot, wormholes, wane, checks, and splits.

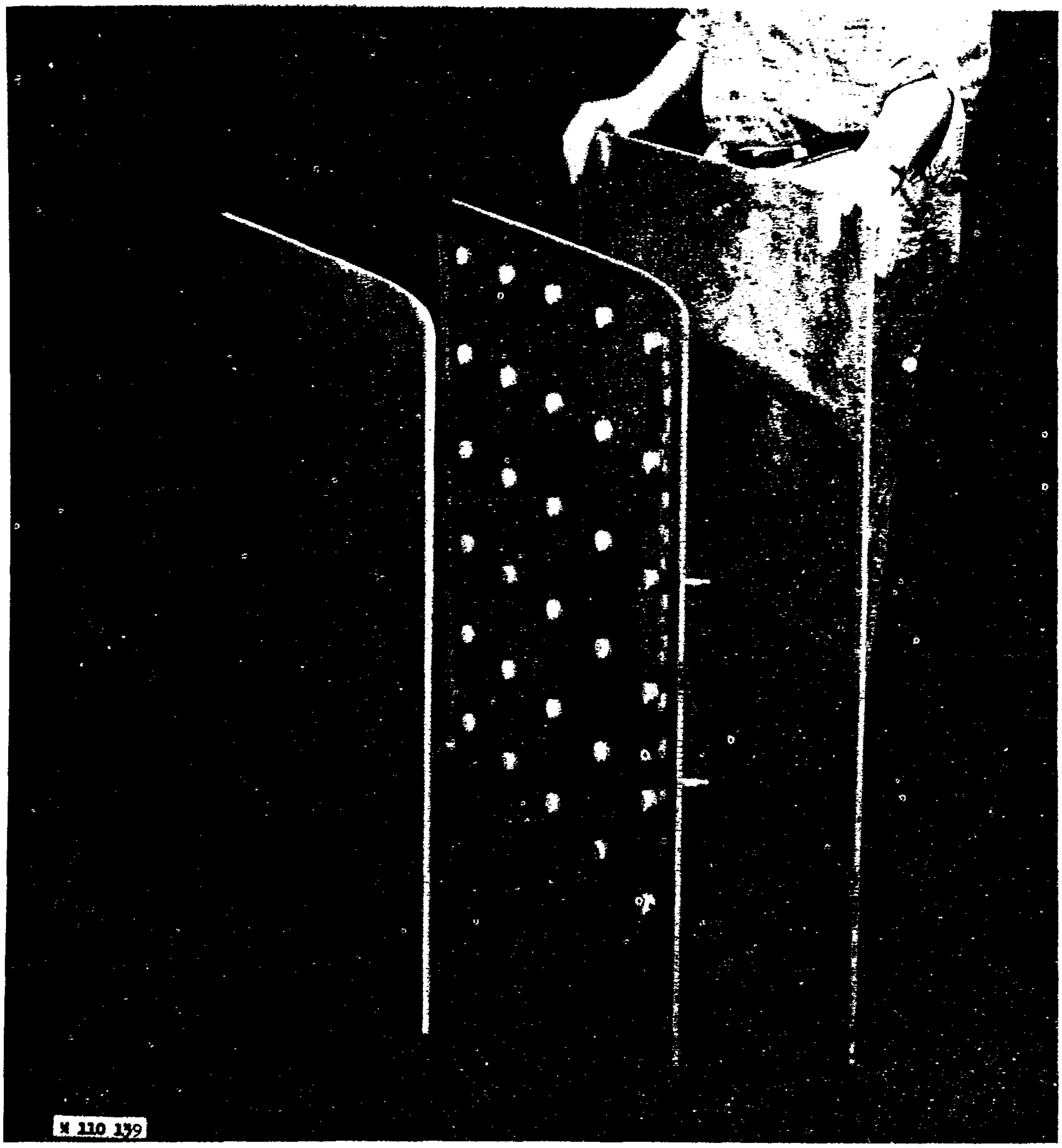



Figure 15-1.--The mold (right) from which the proof loader base (center) and the sandwich test panel (left) were formed. The base is shown with the rubber rim gasket, contact buttons, and vacuum gage connections.

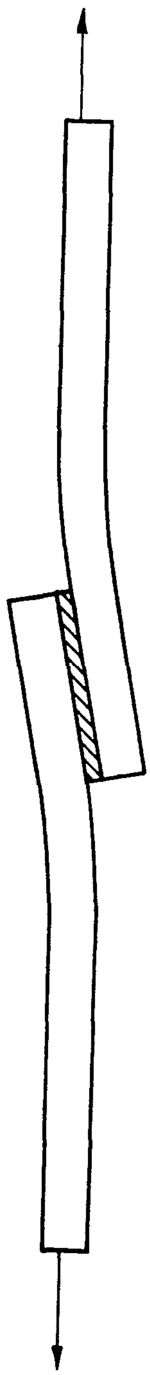
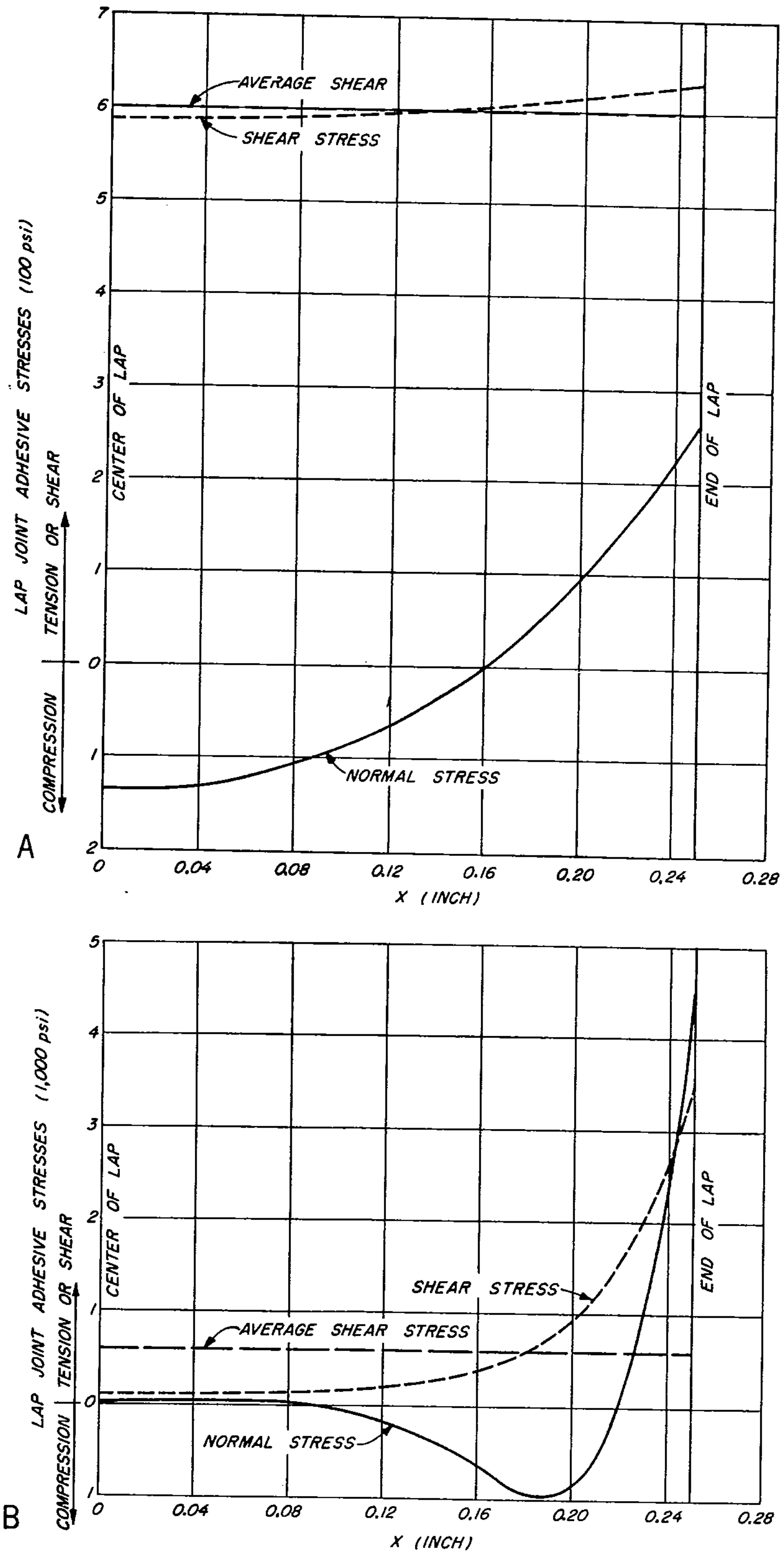
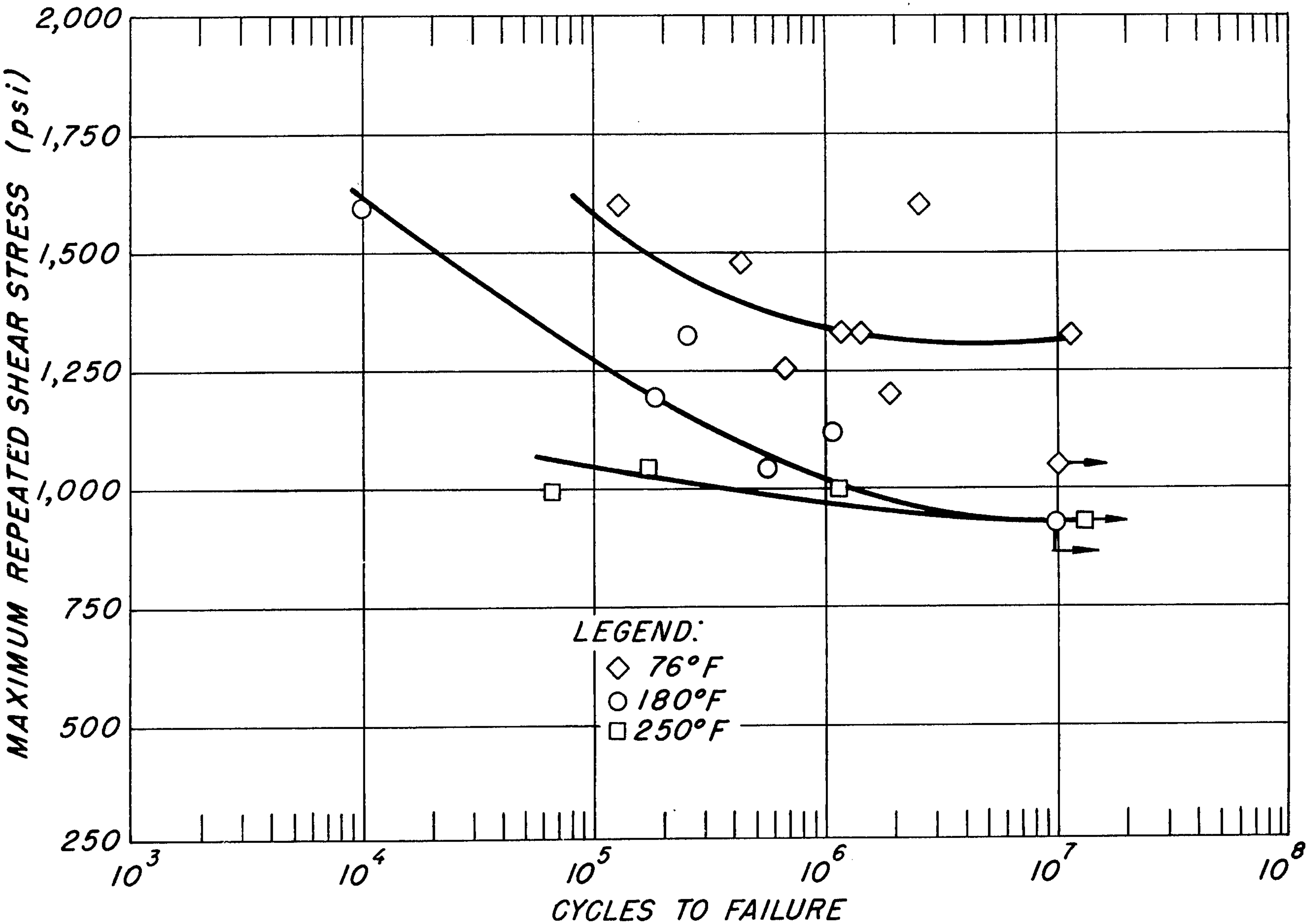



Figure 15-2.--Type of bending that occurs in singlelap-joint specimen when loaded in tension.



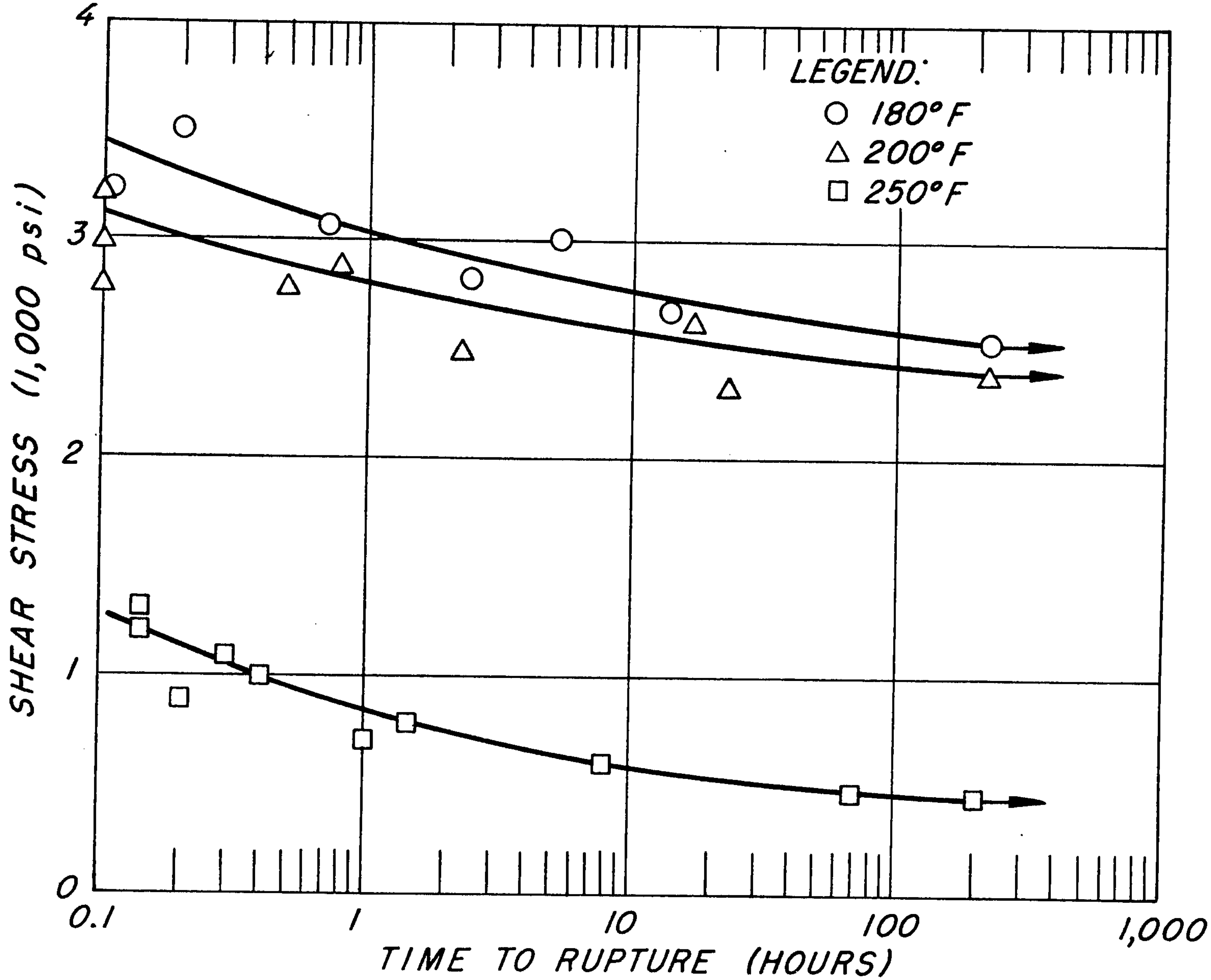

M 134 962

Figure 15-3.--Theoretical relationship of shear and normal stresses in 1/2-inch lap-joint specimen of 0.064-inch clad 2024-T3 aluminum, loaded with 300 pounds per inch of width; A, when bonded with an adhesive of low elastic modulus; B, when bonded with an adhesive of high elastic modulus.



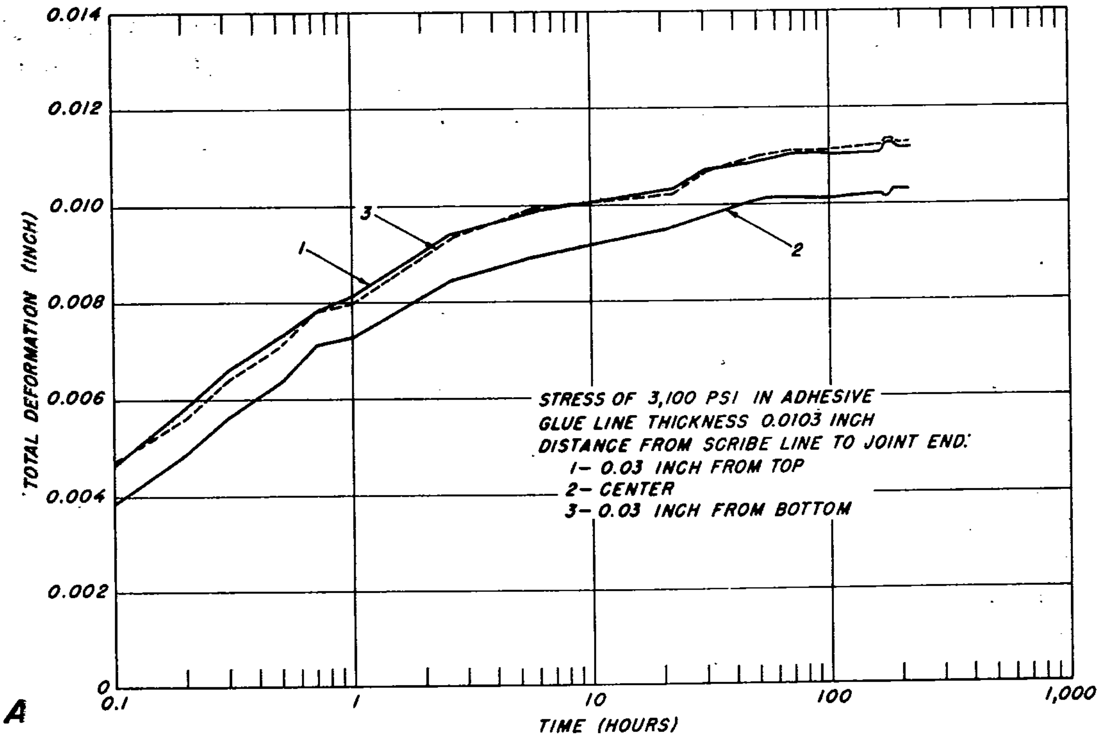

M 113 232

Figure 15-4.--Typical S-N (stress-number of cycles of failure) fatigue curve for bonded lap joints.

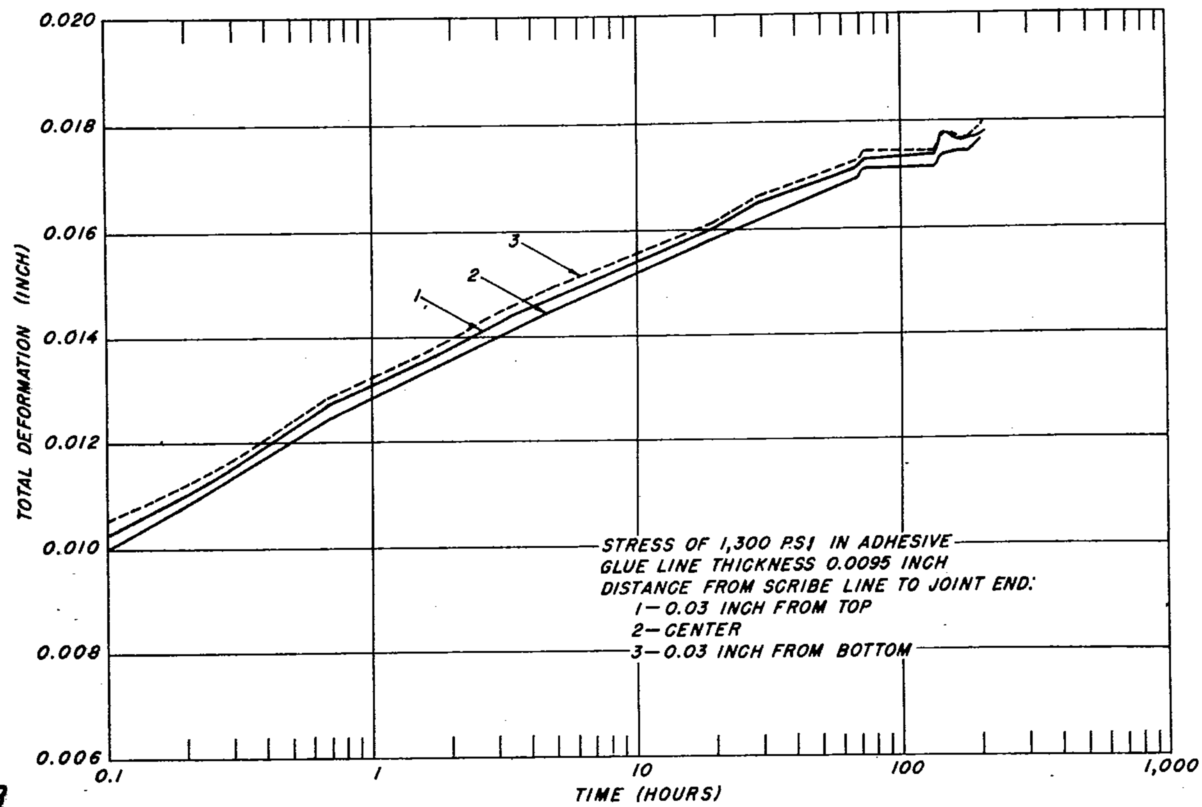



ZM 113 228

Figure 15-5.--Typical stress-time to rupture curves for adhesive-bonded lap-joint specimens




A




B

Figure 15-6.--Typical load time-deformation curve, during creep-rupture test for lap-joint specimen bonded with: A, adhesive of high rigidity; B, adhesive of low rigidity.

# CHAPTER 16

## REPAIR

### 16.1 GENERAL

With the application of sandwich construction, as with any other type of construction, it is inevitable that a certain amount of damage will occur. During the manufacturing stages, where hazards of dropped tools and equipment are encountered, serious damage to sandwich parts may be eliminated by protecting exposed corners and by using temporary protective covers. Proper precautions will minimize damages; but when damage does result, acceptable methods of repair must be available.

The possibility of combining many materials in a variety of sandwich constructions precludes the presentation of detailed repair procedures for all material combinations. Repair methods that have been used to give reasonable results are presented in the following sections for some of the typical sandwich combinations. Inclusion of this information on repairs does not provide authorization for any repairs of defects in new parts. Requirements for such repairs are given in specifications or contracts.

### 16.2 PRINCIPLES OF REPAIR

Repair procedures are developed with the objective of equaling, as nearly as possible, the strength of the original part with a minimum of increase in weight or change in aerodynamic characteristics and electrical properties where applicable. This can only be accomplished by replacing damaged material with identical material or an approved substitute. In order to eliminate dangerous stress concentrations, abrupt changes in cross-sectional areas must be avoided whenever practicable by tapering joints, by making small patches round or oval-shaped instead of rectangular, and by rounding corners of all large repairs. Smoothness of outside surfaces of high-speed aircraft is a necessity for proper performance, and consequently patches that project above the orginal surface must be avoided if at all possible. When this is impossible, the edges must be generously tapered to fair the repair into the original contour. Uniformity of thickness of core and facings is exceedingly important in the repair of the critical areas in radomes. Repairs of punctured facings and fractured cores in these areas, therefore, necessitate removal of all the damaged material, followed by its replacement with the same type of material and in the same thickness and resin-glass ratio as the original.

Repairs referred to in this Handbook are field repairs, and major repairs are not allowed on new parts. Even minor repairs on new parts are discouraged and can only be used in accordance with the provisions of applicable military specifications.

Attempts have been made to simplify the repair techniques presented in this Handbook without sacrificing strength of the part. Even so, it is realized that personnel with little or no experience with the materials and techniques involved in making repairs to structural sandwich parts may have difficulty in immediately interpreting the procedure and in making acceptable repairs in the first attempt. It is therefore recommended that inexperienced personnel be certified on each type of repair they may be required to make in service aircraft before they are allowed to repair actual aircraft parts for later service use. This certification may be accomplished in various ways, among which are the following:

a. Repairs to simulated damages in flat sandwich panels of a construction similar to the parts to be later repaired. If equipment is available the repairs can be tested in this manner: Tension specimens about 1 inch wide or wider are cut across the repair and tested; the resulting strength values are compared to similar tests on unrepaired material from the same panel. If failures occur at the specimen grips it will be necessary to use a necked specimen, and possibly to use hardwood inserts in the core at the grips. Edgewise compression or flexure tests are sometimes used for evaluation of repairs.

b. Repairs to actual parts (of the type later to be repaired) that have been rejected for further use because of excessive damage or some other reason. These repairs may then be carefully inspected by experienced personnel and can be later torn apart to observe the quality of the joints or of replacement material.

## 16.3 CLASSES OF REPAIR

It is sometimes necessary or more convenient to install a temporary repair over minor damage and later replace it by a permanent repair. These temporary or emergency repairs are normally devised to fit the application and therefore are not considered in this Handbook. The repairs shown for fractures completely through the part may be further subdivided according to accessibility of the part from both sides or from one side. Radomes are usually removed for repair unless they are readily accessible from both sides. However, structural panels such as wing surfaces, sandwich floors, and bulkheads must often be repaired in place, and sometimes by working from one side only. The repairs shown in this Handbook for radomes are based on the presumption that both sides of the sandwich radome are accessible. Some of the repairs to structural sandwich panels, however, were designed so that the repair can be completed when only one side of the part is accessible. If both sides are accessible, the same procedure can be followed; however, additional optional techniques are shown for alternate use.

For convenience in presentation and for efficiency in designating repairs to sandwich constructions, damages are divided into groups or classes according to severity and possible effect upon the structure. The following classes are used in presentation of the repair techniques in this Handbook.

Class 1: Dents, scars, scratches, or erosion in the facings, not accompanied by a puncture or a fracture.

Class 2: Punctures or fractures in one facing only, possibly accompanied by damage to the core but without damage to the opposite facing.

Class 3: Holes or damage extending completely through the sandwich, affecting both facings and the core.

Class 4: Extensive damage requiring replacement of a complete sandwich part or parts.

# 16.4 REPAIR OF PLASTIC SANDWICH PARTS (ref. 16-1)

## 16.4.1 Repair Materials

### 16.4.1.1 Glass Fabric

The facings of radome sandwiches are made of several layers of glass fabric impregnated and bonded together with a low-pressure, thermosetting laminating resin. A variety of glass-fabric weaves are employed; however, the repair of practically all constructions can be accomplished with combinations of the following fabrics:

The thicker fabrics, such as 181, 162, and 164, are normally used for the body of the facings with one or more layers of a finer-weave fabric, such as 112 or 128, on the surface. In all repairs it is important to determine the direction of the threads in the original facings so that the direction of the threads in the replacement layers can be made to match in each ply.

Glass fabric should be heat cleaned and treated with one of the finishes that prevent serious loss in strength when the part is later subjected to prolonged moist conditions.

### 16.4.1.2 Resins

Specifications for radomes allow a selection of approved resins, normally of polyester type; but regardless of the resin used in the original fabrication of a radome, a repair can be accomplished with any one of the approved resins of the same type if the electric properties of the repaired part are satisfactory. These resins can be made to cure at different temperatures by adjusting the amount and type of catalyst. Elevated temperatures are commonly used in curing the resin in the fabrication of radomes, as these temperatures reduce the time required for complete cure. Elevated-temperature curing facilities may not be readily available at repair stations; therefore catalysts must be chosen that will promote complete cure at room temperature in a reasonably short time. The combinations of resins (of various viscosities) and catalyst systems given in reference (16-1) are suggested; however, there are other combinations that will give equally good results.

In working with polyester resins, catalysts, promoters, and such solvents as acetone (necessary to clean equipment), local safety regulations as to fire and health hazards must be followed. The resins should be stored in closed metal containers in a cool place. Catalysts, promoters, and solvents are very reactive and should be stored in the original tight containers, isolated from one another in a cool place.

**WARNING**

Never mix the catalyst and promoter together as they are explosively reactive as a mixture. Always mix the promoter with the resin first and then add the catalyst to the mixture. Do not inhale the fumes during mixing.

## 16.4.2 Preparing Parts for Repair

### 16.4.2.1 Radomes

Radomes represent the principal application of plastic sandwich in aircraft. They are normally removed from the aircraft prior to cleaning and preparing the part for the repair. On radomes that cannot be removed, the area immediately around the damage must be cleaned while the radome is in place.

### 16.4.2.2 Blankets and Seals

On large repairs it is necessary to apply a uniformly distributed pressure to insure contact. This is best accomplished by using a thin, impervious blanket of polyvinyl alcohol sheet, vinylite, or cellophane. The first two materials can be stretched and made to conform to surfaces of compound curvature, whereas the last cannot and therefore can only be used on single curvatures. The seal around the edges of blankets can be provided by using pressure-sensitive cellophane tape or a thin rope of a soft sealing compound. The sealing compound is most practicable if the edges of the blanket are likely to be wrinkled. It can be removed and reused.

16.4.2.3 Parting Films and Compounds

When it is necessary to use a mold to rebuild a portion of a plastic sandwich, the surface of the mold must be treated in some manner to prevent adhesion of the resin. If the mold surface is of double curvature, several coatings of a good parting compound will give the desired results.

On the convex side of compound-curvature molds of polyvinyl alcohol or vinylite parting film can often be stretched wrinkle-free, and cellophane works very well on molds of single-curvature. If the repair is done in place, care must be exercised to avoid paint removers and stripping compounds normally used on the metal part of the plane for removing finish. Some of these materials have been found to penetrate the facing of the radome and may possibly have an adverse effect on its dielectric properties or strength. Parts that are removed for repair must be handled with care to avoid abrasive and puncture damage from contact with metal objects, parts removed from the aircraft for repair, or from stacking on a rough concrete floor. Radomes should always be supported on padded supports or should be supported from the mounting holes provided for that purpose.

The area to be repaired is first cleaned with soap and warm water. After it is dry, the area is carefully inspected for excessive layers of paint. The paint is removed by wet or dry sanding methods; or if equipment is available, by light seed blasting.

16.4.3 Repair Techniques

16.4.3.1 Class 1 Repairs

Scars, scratches, surface abrasion, or rain erosion may be repaired as follows: Apply one or more coats of resin, catalyzed to room temperature, to the abraded surface (number of coats depends upon the severity of the abrasion). Small fractures may be filled with a putty made from room-temperature-setting resin and short glass fibers. Over this coated surface apply a sheet of cellophane that extends 2 or 3 inches beyond the painted surface; after it is taped in place, work out all air bubbles and excessive resin with the hand or a rubber squeegee. The resin can then be allowed to cure at room temperature, or, if necessary, the cure can be hastened by the use of infrared bulbs or hot sandbags. Occasionally, on small parts, the whole part can be put in an oven set at 100° C (212° F) to hasten the cure. After the resin has been cured, the cellophane is removed, the excess resin is sanded off, and the whole repaired area is lightly sanded preparatory to refinishing.

If the surface abrasions, scratches, or scars are deep enough to seriously affect the strength of the facing (usually to more than the first ply of fabric), they should be repaired in the following manner: Sand the damaged area either by hand or with a flexible disk sander to a smooth contour as shown in figure 16-1. Sand to a distance of at least 100 times the depth of material removed. Coat the sanded area with one coat of room-temperature-setting resin and apply pieces of glass fabric soaked in resin to a resin content of about 50 percent. Lay these pieces of fabric in place in the sanded depression as shown in figure 16-1. Tape cellophane in place over the repair and work out excess resin. After the resin has cured, the surface of the repair is sanded down to the original surface of the facing.

16.4.3.2 Class 2 Repairs

Damages that extend completely through one facing of the sandwich and into the core require removal of the damaged core and replacement of the damaged facing in such a manner that normal stresses can be carried over the area. Figure 16-2 shows one method for accomplishing this type of repair. The damaged portion is carefully trimmed out to a circular or oval shape and the core removed completely to the opposite facing. Caution must be exercised not to damage the opposite facing or to start delaminations between that facing and the core around the damage. The damaged facing around the trimmed hole is then scarfed back carefully by using a flexible disk sander, a belt or rotating pad sander, or by hand, to a distance of at least 100 times the facing thickness. This scarfing operation must be done accurately to a uniform taper and usually takes a little practice before acceptable scarfs are obtained. Contour lines produced by the individual plies of fabric in the sanding operation can be used to judge the accuracy of the scarfed surface.

WARNING

> The sanding operation on laminates reinforced with glass fabric gives off a fine dust that may cause skin irritation. In addition, breathing an excessive amount of this dust may be injurious; therefore precautions as to skin and respiration protection must be observed.

A piece of replacement core material (or a suitable substitute) equal in thickness to the original core material is cut to fit snugly in the trimmed hole.

The glass-fabric laminations for the facing repair are then prepared, with the largest piece being cut to the exact shape of the outside of the scarfed area. The smallest piece is cut so that it overlaps the scarfed area by its proportionate amount, depending on the number of plies in the repair, and the intermediate pieces are cut to have equal overlaps. A convenient means of preparing these pieces is to brush-spread the resin on the pieces of fabric and sandwich the spread fabric between two sheets of colored cellophane. The pieces are then cut to shape without the usual fraying at the edges. The resin content of the fabric should be about 50 percent.

When all of the pieces are ready for assembly, the opening from which the damaged core was removed is coated on all sides and bottom with room-temperature-setting resin. The piece of core that is to be inserted is likewise coated on all sides, including top and bottom surfaces, and inserted in the hole. The pieces of fabric are then laid in place by first removing the cellophane sheet from one side of the fabric, placing the exposed fabric in position on the repair, and then removing the second cellophane sheet. The whole area is then covered by a piece of cellophane and carefully worked down to remove as much excess resin and air as possible. Light pressure is applied to the cellophane by means of sandbags, taping (if the repair is on a convex area), or a vacuum blanket, if facilities permit.

After the repair has cured, it is lightly sanded to contour it to the original shape, and it is then ready for refinishing.

An alternate method that may be used for class 2 repairs is the "stepped-joint" method, described under class 3 repairs.

### 16.4.3.3 Class 3 Repairs

Damages that are completely through the sandwich may be repaired by two methods: (1) The scarf-joint method (similar to that described for class 2 damage), and (2) the stepped-joint method described later. The scarfed method is normally used on small punctures up to 3 or 4 inches in maximum dimension, and in facings made of thin fabrics (which are difficult to peel). The stepped-joint method is often employed on larger repairs to facings composed of thick fabrics.

The details of the scarfed method are shown in figure 16-3. They consist of trimming out the damaged portion and proceeding as with class 2 damage, except that the opposite side of the sandwich is provided with a temporary mold or block to hold the core in place during the first step. After the first facing repair is cured completely, the mold and the shim (which temporarily replaced the facing on the opposite side) are removed and the repair is completed by repeating the procedure used in the first step. Typical steps in making this type of repair are shown in figure 16-3.

By using the stepped-joint method shown in figure 16-4, the damaged portion is trimmed as before to a round or oval shape or to a rectangular or square shape (preferably having rounded corners). The thicknesses of the individual plies in the facings are determined, for choice of replacement fabrics, from the portions removed; the total overlap of the stepped joint is computed from the number of plies in one facing, minus one, times 1-1/2 inches. This overall size is then marked on the sandwich. The marking can be done with cellophane tape or by lightly scratching the surface. The outer layer of fabric only is then cut with a sharp knife or a specially prepared cutter along these lines.

**CAUTION**

Do not cut through more than one layer. If the layer of fabric underneath is scratched, the strength of the repair will suffer.

Using a knife blade, the outer fabric layer can be lifted and carefully peeled away from the layer underneath until the entire sheet is removed; this leaves a clean-cut step round the area. The process is then repeated, with the cut being made at a distance of 1-1/2 inches inside the original step, as shown in figure 16-4. Each consecutive layer of glass-fabric lamination shall be removed in this manner except the last one (bonded to the core), which is exposed for an area approximately 1-1/2 inches wide around the trimmed hole. This surface is then lightly sanded. A piece of core material of identical thickness to that in the sandwich is prepared of the same material (or an approved substitute) and of a size to provide a snug fit in the trimmed hole. Glass-fabric sheets of appropriate thickness are then cut slightly too large (approximately an inch or two oversize) for each of the steps in the repair. A mold and shim combination is now prepared for the opposite side of the sandwich to preserve the contour while the first facing is being repaired.

After the mold and shim have been temporarily secured in place by clamping, propping, or lashing, the damaged area is ready for the first step in rebuilding. The replacement core piece is coated with resin on all edges and the top surface only, leaving the bottom surface (next to the temporary shim) uncoated. It is then inserted in place above the temporary shim. The glass-fabric sheets for repairing the facing are now impregnated with resin to a resin content of about 50 percent, and the smallest one is laid in place over the replaced core. It is then trimmed with scissors to the exact shape of the trimmed hole. After the trimmed portion has been removed, successive plies of glass fabric are laid in place and trimmed, just as was done for the first ply. An extra layer of 112 cloth is then applied over the repair and trimmed so that it laps about 1/2 inch over the undamaged facing. The area is then covered with cellophane, and the excess resin and air are worked out as described earlier.

### 16.4.4 Special Considerations

Sandwich parts in aircraft are ordinarily thought of as being uniform in thickness and having a core of honeycomb material, or a natural core such as balsa. Some parts, however, have a foamed-in-place core; the parts, in addition to being very irregular in shape, may vary in thickness. These parts, because of the nature of their use, are built to very exacting tolerances on both the facing and the overall thickness. Sandwiches of this type sometimes develop voids or delaminations at the interface between the facing and the foamed-in-place core, caused by a blow from a blunt object. These voids may be repaired by injecting a small quantity of room-temperature-catalyzed resin by means of a hypodermic needle and syringe. Two 1/32-inch holes are drilled in the facing at diametrically opposite sides of the void area. The resin is injected into one hole until it starts to exude from the other. Slight pressure is then applied by means of a hot sandbag over the void to remove excess resin and to insure contact between the facing and the core while the resin is curing.

There are a few applications of plastic-faced sandwiches in which access for repair is possible only from the outside. In these parts "blind repairs" must be employed in the repair of class 3 damages. Repairs of this type have been made by using a plastic backing plate and a technique for its attachment similar to that discussed later for the repair of metal-faced sandwiches. The backing plate should be about 0.060 inch thick, and it can be made of glass fabric and room-temperature-curing resin by working out the excess resin from the impregnated fabric while it is under a cellophane cover sheet. If the part to be repaired is curved, the backing plate should be laminated on a cellophane-covered surface of the proper curvature near the damaged area or at the same location on a similar undamaged part. It should be noted that the damage must be trimmed to an oval shape so that the backing plate can be inserted through the trimmed hole. After the backing plate has been bonded in place with resin, the core and surface patch can be fabricated as shown in figure 16-2.

## 16.5 REPAIR OF ADHESIVE-BONDED METAL SANDWICH (ref. 16-2)

### 16.5.1 Repair Materials

#### 16.5.1.1 Aluminum Alloy Sheet

The stronger alloys of aluminum, such as 7075-T6, 2024-T3, or 2014-T6, are commonly used in the repair of facings for structural sandwich parts having aluminum facings.

Occasionally, magnesium alloy sheets and stainless steel sheets are used for facings on miscellaneous sandwich parts. For the present, when these materials are encountered in repair, the repair to magnesium facings can be accomplished with aluminum alloy sheets if necessary. If a major repair is involved, the part should be replaced.

16.5.1.2 Adhesives

Metal-faced sandwich parts are normally bonded with commercially available metal-to-metal adhesives that require high temperatures to complete the cure, and sometimes require in addition the application of rather high pressures. Neither of these requirements is easily met in field repair; therefore, adhesives that will cure at room temperature or slightly higher, with the application of a minimum of pressure, are the only ones that can be practically employed. At the present time only the adhesives based on the use of epoxy resins appear to satisfy these requirements. However, there undoubtedly are other combinations that will prove equally satisfactory.

Several companies are now manufacturing kits used for field mixing of the epoxy adhesives in repair work. The proper amount of catalyst is contained in an ampoule and can be forced into a large plastic bag containing the epoxy where it is mixed thoroughly before being used.

16.5.1.3 Core Materials

Aluminum-faced sandwich parts normally have cores of honeycomb or end-grain balsa. In repairing sandwiches of this type, it is advisable whenever possible to use the same material for the replacement of the core in the damaged area; however, since the core in a structural sandwich having aluminum facings is chosen primarily for strength requirements, any replacement material that satisfies these strength requirements will be acceptable in an emergency, provided it is equally durable. Plywood of the exterior type has been found to be suitable emergency material for replacing either aluminum honeycomb or end-grain balsa in small repairs.

## 16.5.2 Repair Techniques

### 16.5.2.1 Class 1 Repairs

Dents, scars, or fractures not exceeding 1/4 inch in largest dimension in aluminum facings may be repaired by the use of a suitable filler such as a viscous epoxy resin. The dent, after being cleaned with fine (300 grit) aluminum oxide paper and acetone is completely filled with a viscous room-temperature-setting epoxy resin. If the structure is to be exposed in a marine atmosphere the surface shall be treated with a chemical film, MIL-C-5541, prior to filling with resin. After the resin is cured at room temperature for several hours the excess is removed by means of a sharp chisel and aluminum oxide paper to the original metal surface. The insert of epoxy resin is then completely cured by means of a hot sandbag or an infrared bulb at a temperature of about 93° C (200° F ). If the damage has been accompanied by a small fracture of the aluminum facing so that there might be danger of the strength being impaired, the area around the filled hole is then recleaned and a surface patch applied by means of an epoxy resin and a similar curing cycle.

Filled repairs of this type to facings of clad 2024-T3 aluminum have been exposed to more than 75 cycles of 24 hours in an oven at 104° C (220° F ), followed by 24 hours under water at room temperature, with no apparent effect on the repair. This exposure, however, did produce some corrosion on the unpainted aluminum facings.

### 16.5.2.2 Class 2 Repairs

Fractures or punctures in one facing and partial damage to the core of a sandwich part may be repaired by several different methods depending on the size of the damage and on the strength, aerodynamic, and sonic fatigue resistance requirements of the area involved. Typical damage to one facing and the honeycomb core is shown in figure 16-5.

16.5.2.2.1 Removal of Damaged Facing and Core.--After location of the complete damaged area by tapping or other nondestructive test methods, the area should be outlined with marking pencil and the center coordinates determined. The damaged facing and that portion of the core which is damaged is then removed, usually in the form of a circular area. If the damage is in the shape of a long, narrow rupture, an area including the damage can be removed in which the ratio of length to width is approximately 2 to 1, and the corners preferably have a radius of at least 1 inch. The damaged area can be removed by the use of hole saw, router, or rotary file bits in an electric drill or pneumatic router as shown in figures 16-6 and 16-7. Templates with standard-size holes and shapes to guide these tools accurately can be fabricated of plywood, metal, or plastic laminates.

The option of routing of the core to the adhesive fillet line on the opposite face or to remove the core to only its damaged depth will depend on the type of repair to be fabricated.

After removal of the damaged area, the edges of the hole should be carefully deburred using a hand file. Any loose particles in the core cavity should then be blown out.

**WARNING**

Care should be taken by wearing safety glasses throughout this routing operation.

If there is a possibility that any oils or other contaminates might have entered the core cavity, it should be wiped out with a clean cloth saturated with trichloroethylene, and then force dried with a heat lamp.

**WARNING**

Trichloroethylene is not flammable, but caution should be taken to avoid inhaling the vapors as they have a cumulative toxic effect.

For some types of repair requiring aerodynamically smooth surfaces, step cutting (fig. 16-8), of the facing to one-half of its thickness is required. This step cutting can be done, taking great care, by the use of a router and end mill bit, stand, and template as shown in figure 16-7. Scarfing of the facings might also be done using similar routers and templates with a scarf-type face patch. The technique for preparing long scarfs in these thin facings will, however, need to be carefully developed.

Undercutting of the core surrounding the repair hole is used in certain repair procedures to obtain better bonding of plastic fill materials in replacing the damaged core in the sandwich panel. This undercutting of the core can be done with special undercutting router bits or by the use of a hand undercutting tool of the type shown in figure 16-9.

CAUTION

Throughout the machining operations required to remove the damaged skin and core, extreme care should be taken not to scratch or otherwise damage the surrounding surfaces. Paper and plastic films can be taped in place to protect these surfaces.

16.5.2.2.2 Replacement of Core.--The method of replacement of the damaged area of the honeycomb or other core material varies among the different repair methods shown in figure 16-10.

In some repair operations, cores of the same type as the original core are fabricated to shape, keeping the core ribbon direction the same as in the original core, and then bonded in place using epoxy adhesives of the type to give equivalent performance to that of the original adhesive. Balsa or glass-fabric honeycomb cores are normally considered easier to fabricate to shape on the job, and they are, therefore, sometimes used in the repair of aluminum honeycomb panels.

For the smaller core damages, epoxy resin fills are used to replace the cores. These epoxy resin fills may be modified, in addition to the required catalysts, with polysulfide or polyamide resins, or with microballoons or low-density insulating materials to lower the density, give greater flexibility, and to lower the stress concentration in the area of the repair.

When the core fill is also to be used in the same repair for a surface fill to replace the removed skin, milled glass fibers or flakes or aluminum dust are sometimes used in combination with the epoxy resin fills to impart additional strength and restrain shrinkage of the fill material.

These fill materials may be placed into the core cavity by the use of a caulking or sealant gun, a spatula, or poured into place using plastic molded "dams". Thorough working of the resin fill with spatula or rod should be done to remove all entrapped air. Small holes are sometimes punctured into the core surrounding the core cavity to permit some of the entrapped air to escape. The surface surrounding the core cavity should be protected with polyester or polyvinyl tape or film to prevent excess adhesive from adhering to it.

If the core fill is made flush with or slightly above the surface of the skin, it can be retained in place and the necessary pressure applied by taping over it with polyester or polyvinyl tape.

The epoxy resin fill can be cured at room temperatures, or by the use of heat lamps, hot sandbags, or by the use of thermostatically controlled heat blankets.

For those repairs of larger holes in which it is inconvenient to use a face patch because of aerodynamic smoothness requirements of the area, core and facing can be repaired using a combination of glass fabric and epoxy laminating resin. This repair is done using undercut core. Precut epoxy resin-saturated glass cloth disks are worked into place in the routed hole, rubbing out each ply smooth to remove air bubbles as shown in the figure. Special care should be taken that the final plies in the core cavity fit well against the overlapping skin. Final resin fabric plies to fill the skin hole are then inserted in the hole, rubbing out each individual ply in place. A wire screen is then placed over the repair, and any excess resin and air worked out.

This is followed by placing a polyvinyl sheet over the repair and the additional working out of excess resin. After a preliminary room temperature cure, the polyvinyl sheet is removed, and the laminate is given a final cure with heat lamps. The repair is surfaced smooth and then given a final surface coating.

Another method of replacing the core, and also at the same time bonding on a facing patch, is to use a patch made as shown in figure 16-10E from a section of sandwich panel having the same construction and curvature as that of the repair area. Epoxy resin adhesive is used for bonding this patch in place, following the general procedure for cleaning the surfaces and applying curing pressure and temperatures listed in sections 16.5.2.2.3 and 16.5.2.2.5. For standard constructions, these sandwich patches can be prefabricated in standard sizes, with the bonding surfaces treated and primed so that no chamical treatment of the surface is required at the time of use.

16.5.2.2.3 Cleaning of Bonding Surfaces.--All surfaces to be bonded must be cleaned free of all oil, grease, wax, paint, and adhesive, and then, if possible, given an acid etch.

A light abrasion with an abrasive cloth or metal wool can be used to remove old adhesive and paint coatings from the repair area.

CAUTION

The use of abrasive materials containing metal particles that differ from the metal being cleaned should be avoided to prevent establishing electrolytic corrosion conditions. Approved cleaning materials are recommended in NAV WEPS 07-1-503, NAV WEPS 01-1A-506, and Air Force T.O. 1-1-1. The stripping solutions should not be allowed to soak into the adhesive bond adjacent to the repair areas.

Chemical solvents such as methyl ethyl ketone, lacquer thinner, toluol, and aliphatic naphtha can be used to degrease the surfaces. The solvents are wiped on the surfaces with a soft, clean cloth, and carefully wiped off before the solvent dries. A clean cloth is used for the final application of solvent to each area.

WARNING

Rubber gloves should be worn to avoid contact of solvent with the skin. Aliphatic naphtha should not be used near sparks or an open flame. If the liquid is spilled on the skin, it should be washed off immediately with clean, clear water.

Some fabricators follow solvent degreasing by washing with a detergent-wetting agent water solution, rinsing, and wiping dry to further clean the surface. Etching can be accomplished by using a sulfuric sodium dichromate paste. Other fabricators treat the surfaces, after solvent degreasing, by brushing on a Deoxidine 624 solution to keep the surface wet for 20 minutes, followed by rinsing with a water-soaked cloth, and wiping dry. This treatment is followed by a brushing with Alodine 600 solution, left on the surface for 2 to 5 minutes, rinsed with a water-soaked cloth, and dried.

Great care must be taken that corrosive materials or water do not become entrapped within the repair areas. Water entering the honeycomb core will cause serious structural damage under freezing conditions.

**WARNING**

> Hazardous bonding and cleaning materials should not be used in enclosed area. Dirt and grease should be removed from all equipment before repair work is begun. Fuel tanks must be emptied and defumed, and wings shored to a level position, if the repair work employs a heat cycle in any way.

Several fabricators apply a dilute solution of a rubber-base phenolic adhesive primer to the bonding surface as a final step in the pretreatment. These primer treatments are said to improve peel and salt-water spray resistance.

The aluminum facing patches themselves, which are more convenient to handle than the areas on the sandwich panel, can be given a complete surface treatment with sulfuric acid-sodium dichromate solution. This etched surface is protected until use, in some repair kits, by a thin peelable aluminum foil attached to the surface, using a bondable adhesive primer.

16.5.2.2.4 Bonding of Facing Patch.--After replacement of the core as described in section 16.5.2.2.2, a facing patch must be separately bonded in place, except for those repairs made on small areas in which the epoxy resin fill is used to replace both core and facing, or for those repairs in which glass-fabric laminate or sandwich panel section (fig. 16-10E) has been used to replace both core and facing.

Five general types of facing patches are used, depending upon the service requirements for the sandwich part:

(1) A small, flush plug-type facing patch in which a metal facing plug is merely bonded in the facing hole after the core has been replaced. This type of patch gives aerodynamic smoothness, but does not replace any of the strength lost from the damage to the sandwich part. The plug-type patch can, after being cleaned, be bonded into place with epoxy resins using only minor pressure applied by tapes, and cured at room temperatures or by the use of heat lamps or hot sandbags.

(2) An overlap type of metal facing patch with the outer edge scarfed for strength and aerodynamic efficiency. With this type of facing repair and with good bonding techniques, practically full strength of the facing can be regained. The overlap patch is bonded in place over the facing and replaced core after first cleaning the skin surfaces and patch. Epoxy-resin adhesives are normally used for the bonding because of their lower pressure and cure temperature requirements. However, for optimum results, special pressure devices and curing methods as described in section 16.5.2.2.5 should be used. The length of the overlap to the thickness of the skin should be approximately 125 to 1, but shorter overlaps can be used in repairs in which the skins are not highly stressed.

(3) A step type of facing patch (fig. 16-11) having aerodynamic smoothness, but with which only 50 percent of the original tensile strength of the facing can be developed. The step-type patch is bonded in place, after the core has been replaced, by methods similar to the overlap skin patch. However, because it is normally used in areas having high aerodynamic smoothness requirements and aerodynamic heating, heat-resistant adhesives are frequently employed. For maximum efficiency, these adhesives require high cure temperatures and pressures such as can be attained by vacuum box assembly, as described in section 16.5.2.2.5.

(4) A scarf-type facing patch in which the metal facing and facing plug are both scarfed. This is a combination of the overlap and step types of skin repairs, in which better aerodynamic smoothness can be obtained than with the overlap patch, and higher strength efficiency than with the step patch. This type of repair, however, requires the use of tools and techniques capable of accurately machining long scarfs on extremely thin facings.

(5) An overlap type of resin-glass fabric facing patch (fig. 16-12), which has fair aerodynamic smoothness, is easy to fabricate in the field with a minimum of equipment and fits easily to transition curvatures in skin surfaces. An overlap type of glass-fabric skin patch is fabricated by impregnating glass cloth disks with epoxy laminating resin. These disks are then laid over the replaced core and on the clean skin surface as indicated in the figure. The skin area should be treated for adhesive bonding as described in section 16.5.2.2.3. Each individual resin-impregnated disk is worked into place using a squeegee blade, and the final ply is covered with resin and polyvinyl acetate film before final working out of the entrapped air. The repair can be cured without additional pressure at room temperatures, or at elevated temperatures by the use of a heat blanket, hot sandbags, or heat lamp.

16.5.2.2.5 Application of Curing Pressure and Temperature. --Several methods are employed for the application of curing pressure and temperature to the adhesive used in bonding repair patches:

(1) In the filling of the core cavity with epoxy-resin fill materials, bonding cores into place with epoxy-resin adhesives, or in the use of epoxy-resin glass-cloth repair patches, moderate pressures are often used. These methods consist of working out air bubbles using rod or spatula and then retaining the replacement with tape or film across the repair area, or the use of fitted metal blocks and lead or sand weights to apply pressure. These types of repairs are frequently cured at normal room conditions, but in some instances, additional heat is applied by the use of heat lamps, hot sandbags, or heat blankets.

(2) Pressure required for bonding patches to facings with epoxy adhesives can be obtained by mechanical means. On the trailing edge repair of sandwich parts, conventional hand clamps can be used in combination with the necessary wedges and soft cushion materials for even distribution of pressure. For some repairs, cherry blind rivets are used for application of adhesive bonding pressure. For less critical areas on trailing edge parts, through rivets are used in combination with micarta plastic doublers to withstand the riveting pressure.

A suggested method of repair using self-tapping screws, a plywood pressure plate, and a cushion material for applying pressure is shown in figure 16-13.

(3) A flexible thermostatically controlled electric heat blanket and vinyl vacuum bag is a convenient method if electric and vacuum sources are available for applying heat and pressure to cure a surface skin patch bonded with epoxy-resin adhesives. Figure 16-14 illustrates a method of bonding a surface patch using a vacuum gage and electric heating blanket.

**CAUTION**

When using the vacuum blanket repair technique with a flexible heating pad, extreme caution should be exercised to see that the blanket seal is tight and that the patch plate fits exactly to the contour of the sandwich. A leaky seal and a poorly fitted patch plate can result in no pressure on the bond.

Figure 16-15 shows the use of rigid heating blocks instead of the flexible heat blankets for applying the curing temperature in combination with a vacuum bag to apply pressure. By the use of rigid heat blocks larger than their contact surface with the metal skin patch, bonding pressures greater than normal vacuum pressure can be obtained. The same general principle has been used in the design (fig. 16-16) of a rigid vacuum box and heater block attached through a flexible gasket to the sandwich panel.

CAUTION

The design and use of these vacuum bag or box devices in combination with rigid head blocks should be carefully controlled by technical personnel so that the pressures obtained on the areas do not cause failure of the sandwich panel.

(4) In addition to the thermostatically controlled flexible heat blankets and rigid heat blocks, infrared heat lamps or hot sandbags can be used to complete the cure of the adhesive bond in certain types of bonded repairs.

The heat lamps should be rigidly stationed (fig. 16-17) at a reasonable distance from the repair area. A shielded thermocouple should be used to indicate the temperature, and the temperature should be closely monitored by moving the lamp nearer or away from the repair so that the temperature does not rise too rapidly, and so that a constant curing temperature is obtained.

Heated sandbags can also be used to apply both pressure and curing temperature to the adhesive bonds on horizontal surfaces. The heated sandbags will generally apply heat more uniformly over the entire repair area than can be obtained with heat lamps.

Excessive temperature concentration or too rapid temperature rise by any heating method can cause failure in the surrounding areas of certain types of bonded construction.

16.5.2.3 Class 3 Repairs

Damages that extend completely through the core and both facings of the sandwich panel may be repaired by the same general techniques as used for class 2 repairs but there must be access available to both facings of the panel, the panel must be removed, or special techniques must be used to apply pressure in bonding the inner facing patch in place.

16.5.2.3.1 Access Available to Both Facings.--When access is available to both facings of the sandwich panel, the damaged area can be removed and a repair made following the general techniques listed in section 16.5.2.2. The inner facing patch is first bonded in place, core replaced, and then the top facing patch bonded. In certain areas, such as trailing edges, it is possible to first replace the core, and then simultaneously bond both facing patches on using mechanical or vacuum pressure.

Sandwich panels with class 3 damage can also be repaired with a sandwich patch fabricated (fig. 16-10E) from a section of sandwich panel having the same construction and curvature as the original panel. Pressure need be applied only to the outer facing because, in a properly fit patch, this pressure will be distributed to the bonding surface of the inner facing. Heat required for the adhesive, however, should be applied to both surfaces. This patch can also be fabricated with the overlap facing on the inner facing of the sandwich panel, and the repair hole in the outer facing filled with a butt-type flush facing patch, after the sandwich patch has been bonded in place, to result in an aerodynamically smooth outer surface. Care must be taken, possibly by bonding a doubler to the inner face, to prevent peeling of the unsupported inner facing during the application of pressure to the sandwich patch.

16.5.2.3.2 Access Not Available to Both Facings.--When access is not available to the inner facing of a sandwich panel, the following procedure is suggested:

(1) Remove the damaged facings and core in the form of a rectangular area using the general methods described in section 16.5.2.2.1.

(2) Fabricate backing plate and drill necessary holes in plate and sandwich panel (fig. 16-18) for self-tapping screws to be used in applying pressure.

(3) Clean the surface of the backing plate and the area around the cutout on the back of the repair.

(4) Apply adhesive to the backing plate and position in place on the inner facing of the sandwich part.

(5) Fabricate replacement core patch and place in the core cavity over the backing plate.

(6) Apply cellophane sheet, plywood caul, and self-tapping screws as shown in step 1 of figure 16-18.

(7) After the adhesive has cured, the screws and caul can be removed and the screw holes filled with a viscous mixture of epoxy resin.

(8) The upper overlap facing is then bonded in place using screw pressure or by the use of pressure methods listed in section 16.5.2.2.5.

An alternate procedure is the use of a replacement sandwich patch with pressure being distributed to both facings simultaneously when pressure is applied to the face of the patch using methods outlined in section 16.5.2.2.5.

Heat for curing the adhesive can be applied to the outer bond line by the use of heat blankets, hot sandbags, or heat lamps, but it is difficult to obtain heat on the inner bond line and therefore adhesives should be used there that cure adequately at room conditions.

## 16.6 REPAIR OF BRAZED OR WELDED SANDWICH

Detailed repair procedures are not available in published specifications or standards. The following general procedures coupled with proper choice of materials can merely serve as a crude guide.

Repairs can be accomplished by filling superficial dents and light damage with compounds such as silicone rubber or injecting adhesives or potting compounds. Small holes can be repaired by brazing on patch plates. Severely damaged areas cannot be repaired for continued service of the part and attempts to make repairs should only be undertaken in emergency after which the damaged part should be replaced as soon as possible.

### 16.6.1 Adhesive Injection Repairs

Clean the surface to be drilled with MEK (methyl-ethyl-ketone) or acetone. Wipe area dry with a clean cheesecloth.

Outline the void area using a grease pencil or felt point pen.

CAUTION: Do not use carbon lead pencils to outline void areas or mark hole patterns.

Lay out an injection hole pattern within the outlined void area or dented area. The distance between adjacent holes in the pattern shall be from 1.0 to 1.5 inches. The hole pattern shall extend to within 0.50 inch of the void perimeter outline. For dents 1.0 inch or less in diameter, one hole shall be drilled in the approximate center of the dent. For dents over 1.0 inch to 1-1/2 inches in diameter the distance between adjacent holes in the pattern shall be approximately 1.0 inch. Refer to figure 16-19.

Using a 0.125-inch-diameter drill with a drill stop attached, drill hole pattern. For core to facing and vertical tie void areas drill holes to a depth of 0.10 inch. For core to facing void areas adjacent to an edge member vertical wall, drill holes in vertical wall to a depth of 1.0 inch.

CAUTION: Do not use a center punch to start drill. Do not apply excessive pressure to facing or edge member when drilling.

Tape a thermocouple close to the repair area and dry panel at 250° F for 30 minutes. Do not tape over injection holes.

Remove thermocouple and tape. Inject five to eight shots of adhesive into each hole using a lever gun as shown in figure 16-20.

CAUTION: Do not apply pressure to facing or edge member with lever gun.

Remove adhesive from area surrounding injection holes using clean cheesecloth moistened with MEK or acetone. Wipe area dry with a clean cheesecloth.

CAUTION: Do not allow flow of solvent into injected holes.

Apply one layer of polyester tape or equivalent over injected area.

CAUTION: Do not trim tape on panel.

Open each injection hole in layer of tape using a blunt punch.

Insert a thermocouple into an opened injection hole approximately 1/8 inch deep.

NOTE: When more than one injected area is on any one surface, a minimum of one thermocouple shall be used for each injected area.

Apply a second layer of polyester tape or equivalent over injected area and thermocouple lead.

CAUTION: Do not trim tape on panel.

Apply a film of release compound to tape and local area surrounding tape.

Cure injected adhesive with void or dented surface down. using an oven in which the temperature can be controlled to within ±10° F.

Allow assembly to cool to room temperature.

Remove thermocouple and tape from injected area.

Clean surfaces of any excess adhesive.

CAUTION: In removing excess adhesive do not damage the thin facings. A lightweight instrument having beveled edges with no sharp corners should be used in the cleaning operation. Wipe the injected area with acetone or MEK to remove surface film caused from polyester tape and release compound.

Redrill injection holes to a depth of 0.12 inch using a 0.125-inch-diameter drill with a drill stop attached. When an inspection plug hole has been used as an injection hole, redrill the hole to a depth of 0.12 inch using a 5/16-inch-diameter drill with a drill stop attached.

Seal injection holes and complete dent repair according to paragraph 16.6.2.

## 16.6.2 Potting Repairs

Wipe the discrepant area and the surrounding area with clean cheesecloth moistened with MEK.

Sand the discrepant area very lightly using aluminum oxide paper.

Flush the area thoroughly with clean trichloroethylene.

Blow the surface dry with clean dry air.

Wipe the discrepant area thoroughly with clean cheesecloth moistened with acetone.

Mask off around the cleaned area with polyester tape or equivalent and allow the area to air dry for 30 minutes.

Fill the discrepant area with potting compound and smooth to contour with straightedge or soft bristle brush moistened with solvent before the compound vulcanizes.

Cure at room temperature for 24 hours.

## 16.6.3 Brazed Patch Repair

This type repair shall be used on brazed honeycomb panel core to facing areas which have been damaged by dents or punctures. A puncture is defined as a hole or crack through one facing only.

### 16.6.3.1 Preparation of Damaged Area Prior to Brazing

(1) Clean very thoroughly at least 12- by 12-inch area of facing (damaged area in approximate center) with trichloroethylene. Wipe the surface with a clean cheesecloth (or equivalent) which has been moistened with the solvent and follow immediately with a clean dry cloth. All excess trichloroethylene shall be wrung from the cleaning cloth prior to wiping over the damaged facing.

CAUTION: Store trichloroethylene in a clean metal container. Do not dip cleaning cloth into solvent. Pour solvent onto cloth.

(2) Determine the size of the damaged area. The damaged area, by definition, will include the following:

(a) The dent, including the extent of any core-to-facing delamination, or

(b) The hole or cracks including the extent of the accompanying dented area around the puncture and, in addition, any core-to-facing delamination. The area adjacent to the dent or the puncture shall be checked for core-to-facing delamination by tapping the facing lightly with a light blunt instrument or metal disk such as a coin.

(3) Buff the area to be repaired lightly with No. 120g aluminum oxide paper until a uniform surface appearance is obtained.

(4) Cracks only: Stop-drill each end of the crack using a No. 30 (0.1285-inch-diameter) drill. Use appropriate methods to determine the extent of the crack prior to stop drilling.

CAUTION: Use drill stop to prevent drilling into opposite facing.

For repairs requiring facing removal accomplish the following (in addition to the steps outlined above):

(1) Outline the damaged area using a grease pencil or felt point pen.

CAUTION: Do not use carbon lead pencils.

(2) Measure the largest dimension of the damaged area. This dimension shall be the diameter of the circular cut-out in the damaged facing. Make a 6- by 6-inch template, 0.020 to 0.040 inch thick, with a circular cut-out the same diameter as the damaged facing section to be removed. Form template, if necessary, to same contour as area surrounding damage.

(3) Using the template as a guide cut completely through the damaged facing with a sharp-pointed instrument such as a scribe. Refer to figure 16-21.

(4) Pry up edge of damaged facing using a small screwdriver (or equivalent). Pliers may then be used to peel off facing cut-out.

CAUTION: Use extreme care when removing facing cut-out so as not to damage the core or panel further.

(5) Smooth edge of opening in facing to remove all nicks and burrs. File smooth and uniform as required.

(6) Straighten damaged and bent core cell walls to bring edges back to their original surface (inside surface of damaged facing). If the core cell walls are damaged extensively and cannot be restored to their original surface, or if facing being repaired exceeds 0.008 inch thick, accomplish the following:

(a) Nest inside original core cells foil ribbons or strips of proper alloy and thickness. Restore replacement core to original core cell size and configuration as near as possible. Refer to figure 16-22.

NOTE: Clean strips with trichloroethylene before putting in place.

(b) Tack-weld core replacement strips to remaining original core cells and to each other. Refer to figure 16-23.

CAUTION: Do not burn through foil ribbons.

NOTE: It is not necessary for core replacement strips to extend to opposite facing. It will be permissible to bring the surface of the replacement core cell wall edges up to the same contour as the outside of the damaged facing but not beyond. Use No. 120g emery cloth and sanding block to sand core down to contour.

(7) Drill a No. 30 (0.1285-inch-diameter) hole in the facing opposite the repair area. The hole shall be drilled in the center of the cell which is closest to the center of the facing cut-out.

16.6.3.2 Preparation of Auxiliary Equipment Prior to Brazing

(1) Fabricate a graphite heater block 0.5 to 1.0 inch thick, with a base diameter 0.12 inch larger than the external patch diameter. Contour the graphite block to the panel by rubbing the block on a sheet of No. 120g emery cloth laid on the panel adjacent to the repair area. When contouring block for nacelle panel repair aline centerline of block with centerline of area to be repaired and sand block parallel to direction of least contour (longitudinal). Mark top side of block so it can be properly oriented with repair area when placed on the cover sheet.

NOTE: Contouring of graphite block must be accomplished with extreme care to insure full contact of external patch with the facing and core in the area of the repair.

(2) Make two 6- by 6-inch chill plates from 0.064-inch-thick copper (Commercial grade, soft annealed). Form chill plates to contour of panel on facing area directly opposite repair area. Drill No. 30 hole in center of each plate.

(3) Make a square stop-off screen from stainless steel wire cloth (No. 100 square mesh, plain weave-wire size 0.003-inch-diameter material). The screen shall be 1.0 inch larger than the diameter of the external patch.

(4) Make an 8- by 8-inch cover sheet from 0.005-inch-thick stainless steel.

16.6.3.3 Preparation of Patch Plate and Repair Alloy

(1) Fabricate the patch from the facing alloy at the proper heat treatment and thickness. If the thickness of the external patch is 0.016 inch or greater, the edge of patch shall be chamfered at a 5:1 ratio. The edge of the patch shall be free from nicks and burrs. File smooth and uniform as required.

(2) Cut repair alloy disks the same diameter as the opening in the facing. Cut or slice the alloy disks in the manner illustrated by figure 16-24.

NOTE: This step not required for patch repair of dents and stop-drilled cracks.

(3) Cut one (1) repair alloy disk 0.12 (±0.03) inch larger in diameter than the diameter of the external patch. Cut or slice alloy disk in the manner illustrated by figure 16-24.

(4) For dents, cut several small slivers or strips of repair alloy approximately 1/16 inch wide to be used for filling depression in skin.

16.6.3.4 Cleaning Procedures for Repair Materials and Repair Alloy

(1) Buff patch with No. 320 emery cloth (or equivalent) until a uniform surface appearance is obtained.

(2) Clean the patch, repair alloy, wire cloth, and cover sheet very thoroughly with trichloroethylene.

NOTE: Use clean rubber gloves or clean white lintless cotton gloves to handle cleaned repair materials. Keep cleaned repair materials in clean wrapping paper or cheesecloth until ready to place in position over repair area.

(3) Clean the area to be repaired in the following manner:

(a) For dents scrub the patch overlap area and 6 inches beyond very thoroughly with clean cheesecloth which has been moistened with phosphoric acid cleaner.* Wipe the area cleaned with the acid several times with clean cheesecloth which has been moistened with distilled water.

CAUTION: Do not wipe past the perimeter of the acid cleaned area when removing acid with distilled water. Do not touch cleaned area with bare hands.

(b) For punctures (stop-drilled cracks and damage requiring facing removal) scrub the patch overlap area and six (6) inches beyond very thoroughly with clean cheesecloth which has been moistened with phosphoric acid cleaner.* All excess acid cleaner shall be wrung from the cleaning cloth prior to rubbing over the patch overlap area.

CAUTION: Use every precaution to prevent the phosphoric acid cleaner from entering the core area of the panel.

If any acid cleaner enters the core area, turn the panel over so that the repair area is down and flush the opening(s) in the panel several times with a distilled water spray. Allow excess water to drip out, then turn panel over. Place a thermocouple lead in the approximate center of the repair area and dry the panel at 250° F for 30 minutes with heat lamps.

If no acid cleaner enters the core area, wipe the cleaned area several times with clean cheesecloth which has been moistened with distilled water. All excess water shall be wrung from the cleaning cloth prior to wiping over the cleaned area.

CAUTION: Do not wipe past the perimeter of the acid-cleaned area when removing acid with distilled water. Do not touch the cleaned area with bare hands.

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*Cleaner composition, by weight: 12% phosphoric acid (85% N. F. or better); 16% citric acid (USP); 8% synthetic soap; 12% MEK; 52% distilled water.

16.6.3.5 Lay-Up and Brazing of Repair Area

(1) Draw coordinate lines on facing to locate the center of the area to be repaired using a grease pencil or felt point pen so that the lines will extend past the edges of the cover sheet.

CAUTION: Do not draw lines through the area cleaned with phosphoric acid. Do not use carbon lead pencils.

(2) Place small disks of repair alloy over core in facing opening.

NOTE: This step not required for patch repair to dents or stop-drilled cracks.

CAUTION: Do not touch cleaned area or repair materials with bare hands. Wear clean rubber gloves or white lintless cotton gloves.

(3) For dents fill depression in facing with small slivers or strips of repair alloy.

(4) Tack-weld large disk of repair alloy to patch. Allow even overlap of alloy around circumference of patch.

(5) Tack-weld (two places, spaced 180° apart approximately 1/16 inch in from edge of patch) the patch and repair alloy to the panel so that the center of the patch is over the center of the area to be repaired.

(6) Place thermocouple lead in position so that the fused end-wire bead is touching the edge of the alloy extending past edge of external patch. Aline thermocouple lead and tape in position. Use No. 30 gage chromel-alumel or iron-constantan depending upon type of temperature recorder available.

(7) Tack-weld (two places) stainless steel wire cloth to edge of patch so that wire cloth is centered over patch. Refer to figure 16-25.

(8) Place 0.005-inch-stainless steel cover sheet in position so that center of sheet is as close to the center of the repair area as possible. Hold cover sheet to contour of panel with hand pressure and tape cover sheet to panel on one side. Mark coordinate lines on cover sheet.

(9) Insert argon line (0.06-inch-minimum inside diameter cooper tube, commercial grade) under cover sheet 1/8 inch to 3/8 inch. Tape argon line in position and finish taping cover sheet to panel. Refer to figure 16-25.

(10) Insert argon line (0.06-inch-minimum inside diameter copper tube, commercial grade) through holes in chill plates and then through hole in facing opposite repair area. Tube shall extend past facing inside panel approximately 1/8 inch to 1/4 inch.

(11) Place chill plates and chill plate support rack in position next to facing opposite center of repair area. Apply vacuum (20 inches Hg minimum) to chill plate support rack vacuum cups using venturi and compressed air or by using vacuum pump.

(12) Attach argon lines to storage cylinder and start argon purge. For purge of repair area under cover sheet set flow rate at 20 (±1) cubic feet per hour. When required, flow rate for purging of panel interior shall be 5 (±1) cubic feet per hour. Purge for a minimum of 20 minutes.

NOTE: For each brazed patch repair, argon dew point temperature shall be -80° F or lower.

(13) Adjust oxygen (commercial grade, welding) and acetylene (commercial grade) flow valves on brazing torch to insure correct size and intensity of flame. After correct adjustments have been made, flame can be cut off.

(14) Center graphite block on patch. Use coordinate lines to aline graphite block. Use extreme care to insure that graphite block is in proper position. Place graphite block support cup in position on block and apply 30 (±5) psi to support cup through pressure rods. When a minimum of 20 minutes' time has elapsed since start of purging, reduce argon flow to repair area under cover sheet to 5(±1) cubic feet per hour. When panel interior purging is required, reduce flow rate to 2(±1) cubic feet per hour.

(15) Apply heat to repair area through graphite block at such a rate that a thermocouple temperature is reached for the proper time to braze the repair.

CAUTION: Use Fiberfrax blanket to cover top of cover sheet and to protect brazing tool.

(16) Record time-temperature cycle and other pertinent panel data on history sheet. Record temperature at 1-minute intervals.

(17) Allow repair area to cool properly. Maintain pressure on repair area. Do not force air cool repair area, but continue argon flow at 5(±1) cubic feet per hour.

(18) Inspect both sides of panel in repair area to determine conformance to contour requirements.

## REFERENCED DOCUMENTS

(16-1) U.S. DEPARTMENT OF DEFENSE
Current Instructions for Repair of Aircraft and Weapons Sandwich Structures. Part I--All Plastic Construction. Military Standard MIL-STD-768(ASG).

(16-2) U.S. DEPARTMENT OF DEFENSE
Current Instructions for Repair of Aircraft and Weapons Sandwich Structures. Part II--Metal Construction. Military Standard MIL-STD-768(ASG).

Additional detailed information is available in the following:

(1) T.O. 1F-4C-3-1 Technical manual, structural repair instructions, U.S.A.F., F-4C, F-4D, and RF-4C.
(2) T.O. 1F-102A-3-1 Technical manual, structural repairs, U.S.A.F. Series, F-102A and TF-102A.
(3) T.O. 1F-106A-3 Technical manual, structural repairs, U.S.A.F. Series, F-106A and F-106B.
(4) T.O. 1B-58A-3 Technical manual, structural repair instructions, aircraft and pods, U.S.A.F. Series, B 58A, NB 58A, TB 58A, and YB/RB-58A.
(5) (U.S.A.F.) T.O.-1F-111A-3
(Navy) NAVAIR 01-10FAA-3
Technical manual, structural repair instructions, U.S.A.F. Series, F-111A, Navy Series F-111B.
(6) T.O. 1C-141A-3 Technical manual, structural repair instructions, USAF Series, 141A, Aircraft.
(7) T.O. 1C-5A-3 Technical manual, structural repair instructions, USAF Series, 5A, Aircraft.

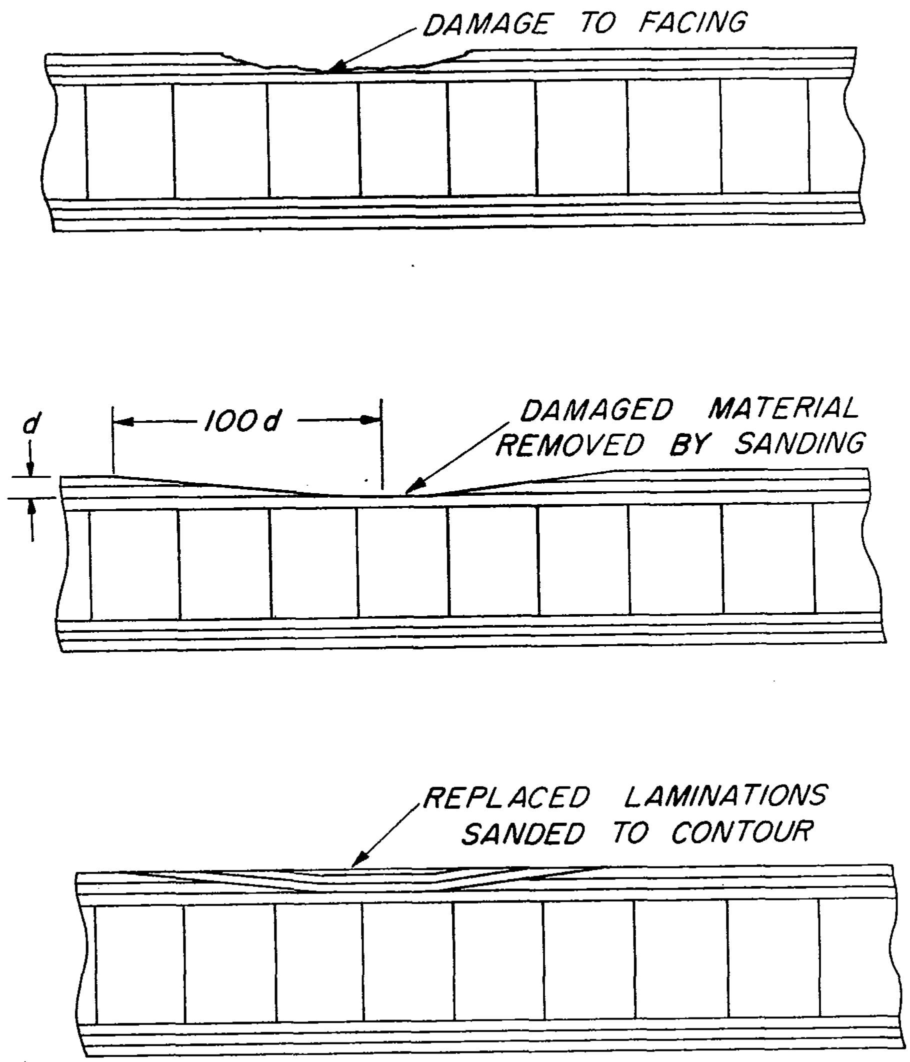


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Figure 16-1.--Steps in repair of class 1 damages to sandwich facings.

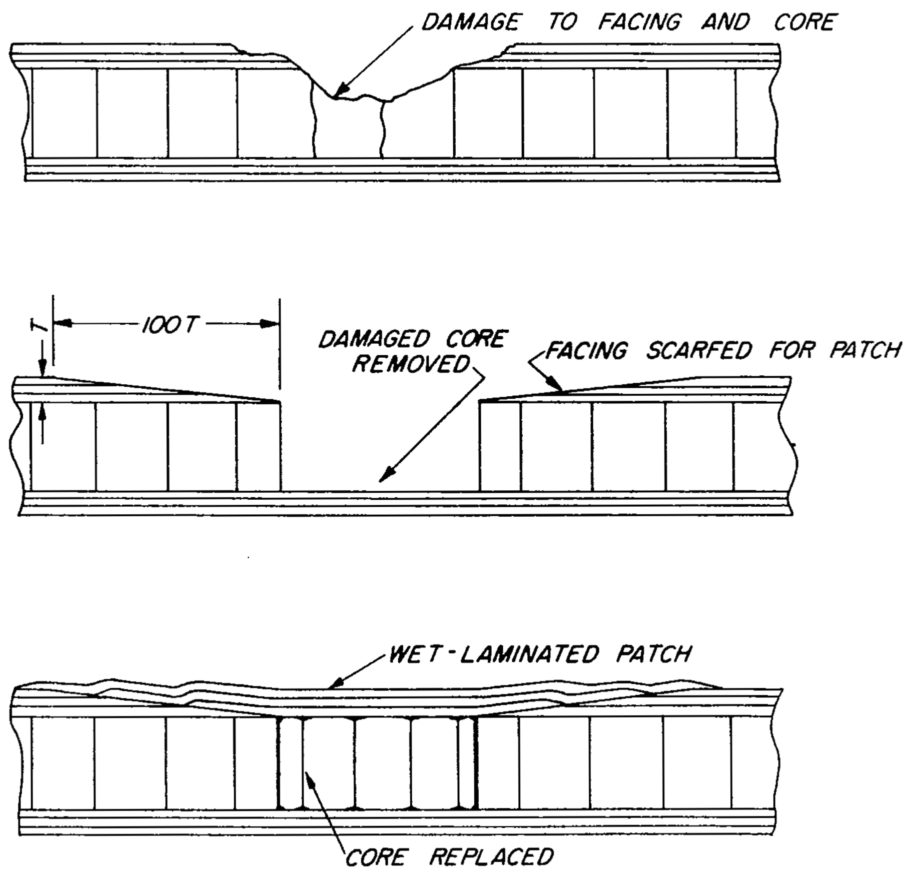


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Figure 16-2.--Steps in the repair of class 2 damages.

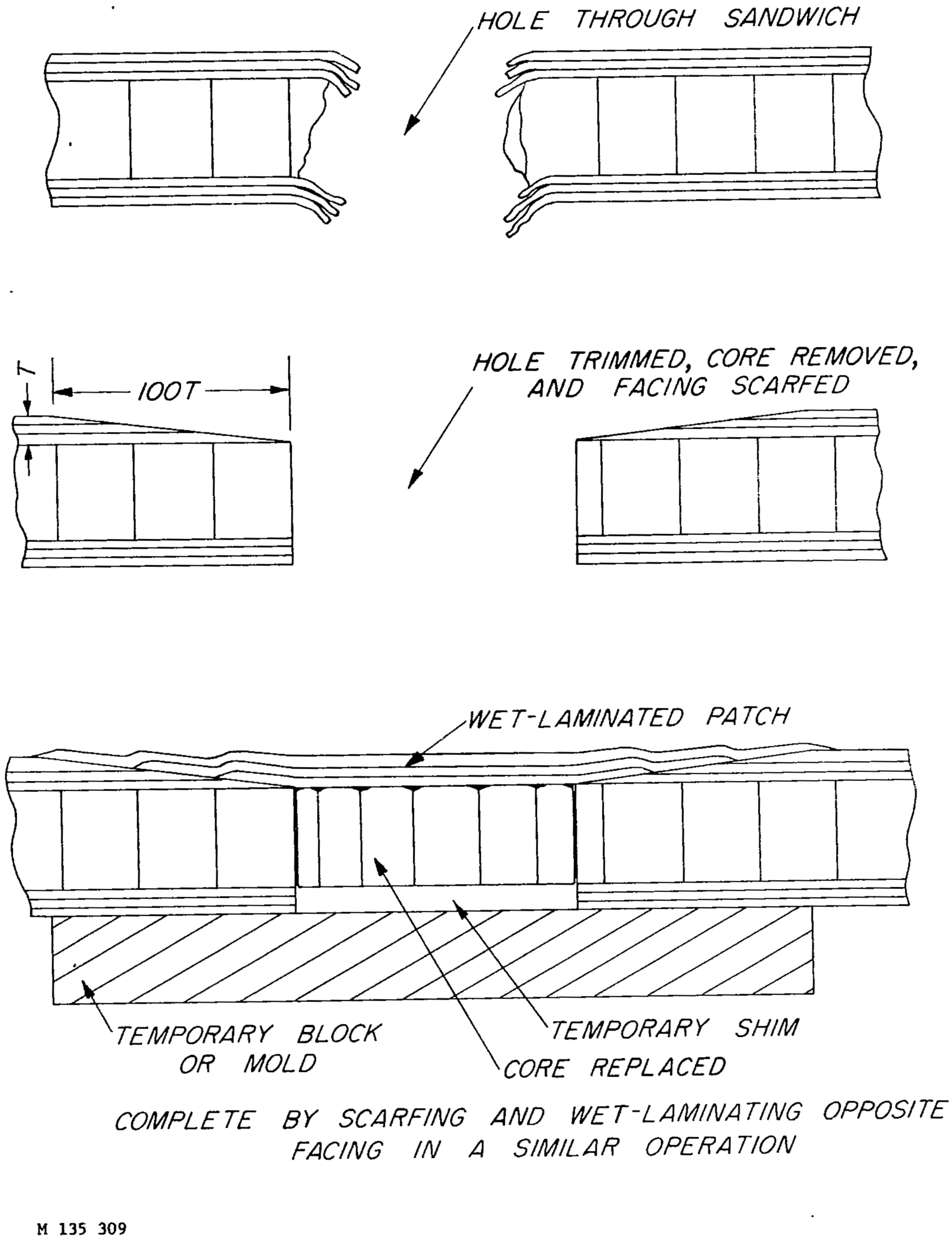


Figure 16-3.--Steps in the scarfed type of repair to class 3 damages.

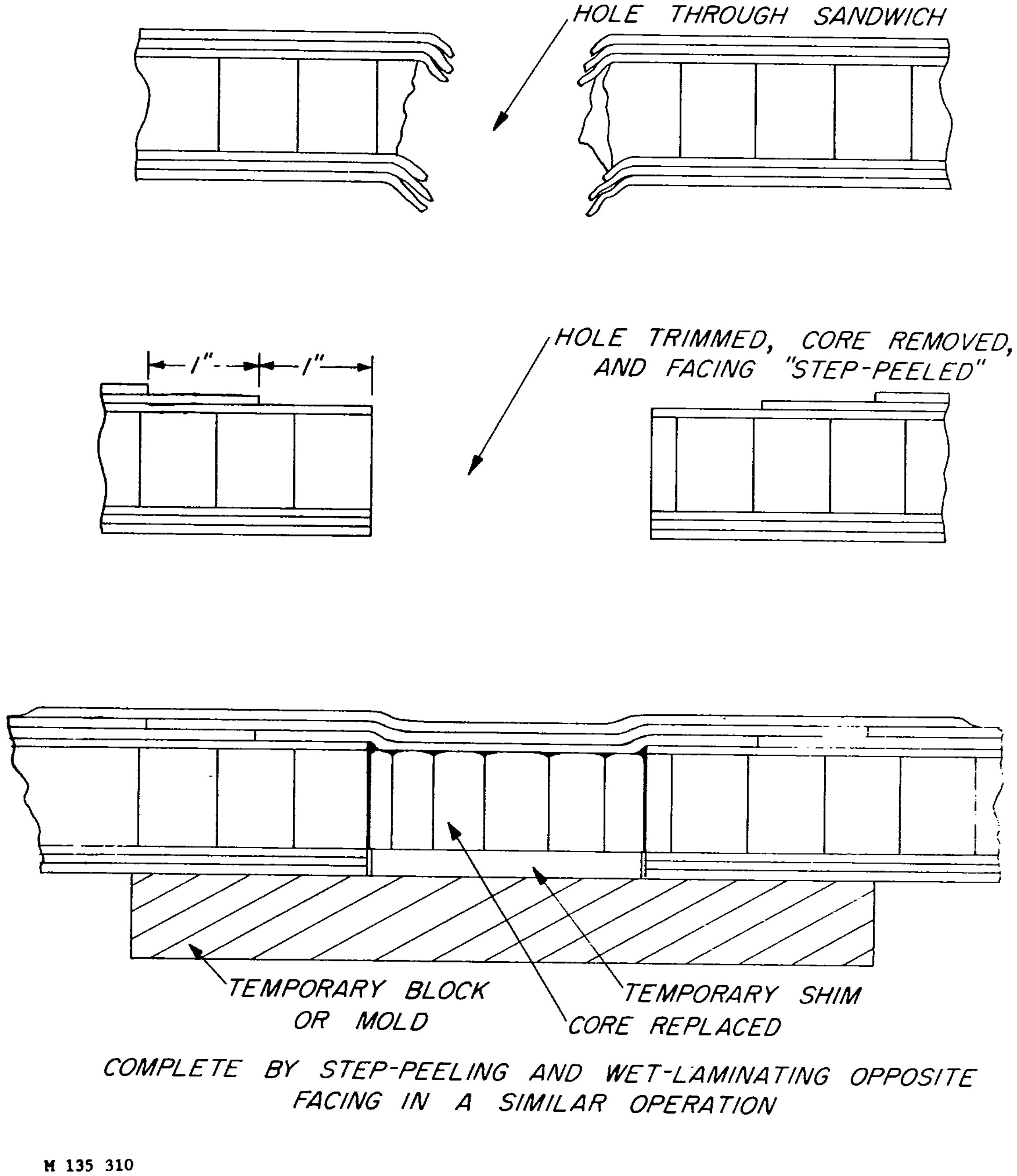


Figure 16-4.--Details of stepped-joint method of repair of class 3 damages.

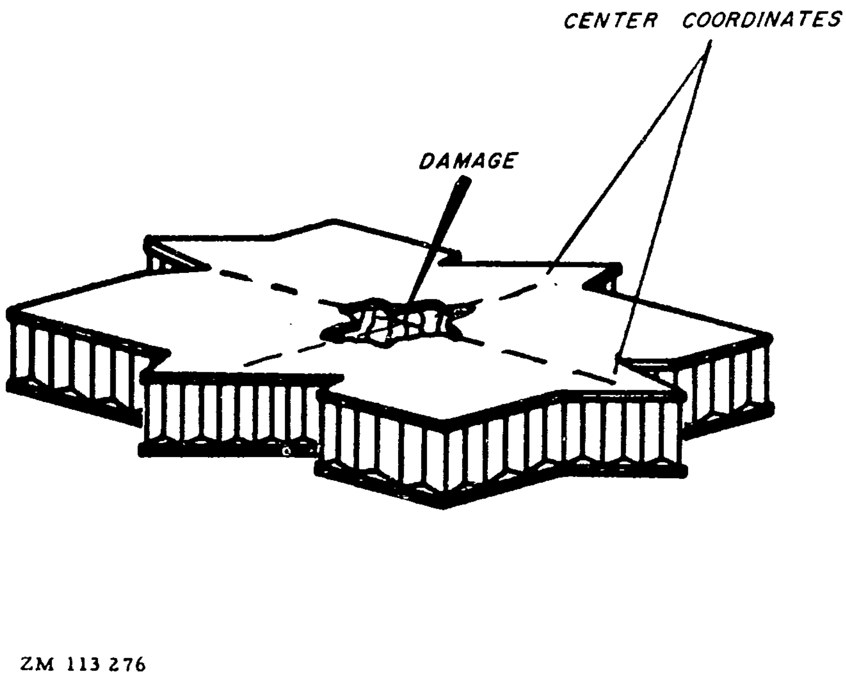


Figure 16-5.--Typical class 2 damage to one facing and core of sandwich panel.

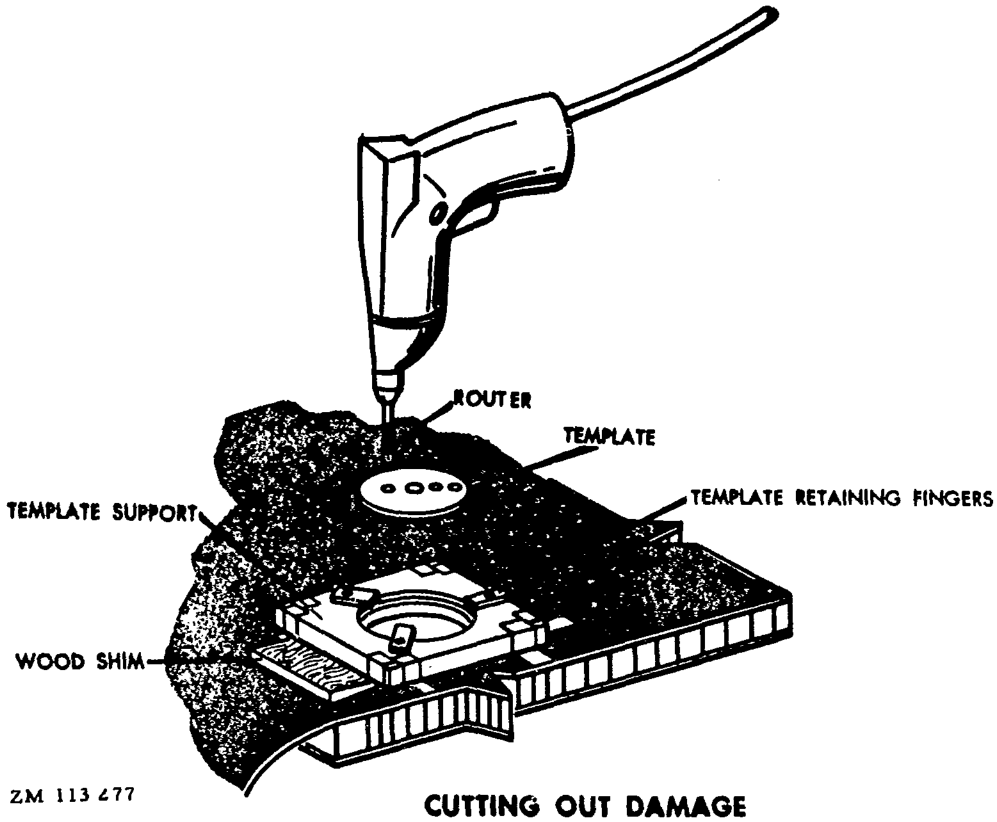


Figure 16-6.--Removal of damaged area from sandwich panel using electric drill, router bit, and template.

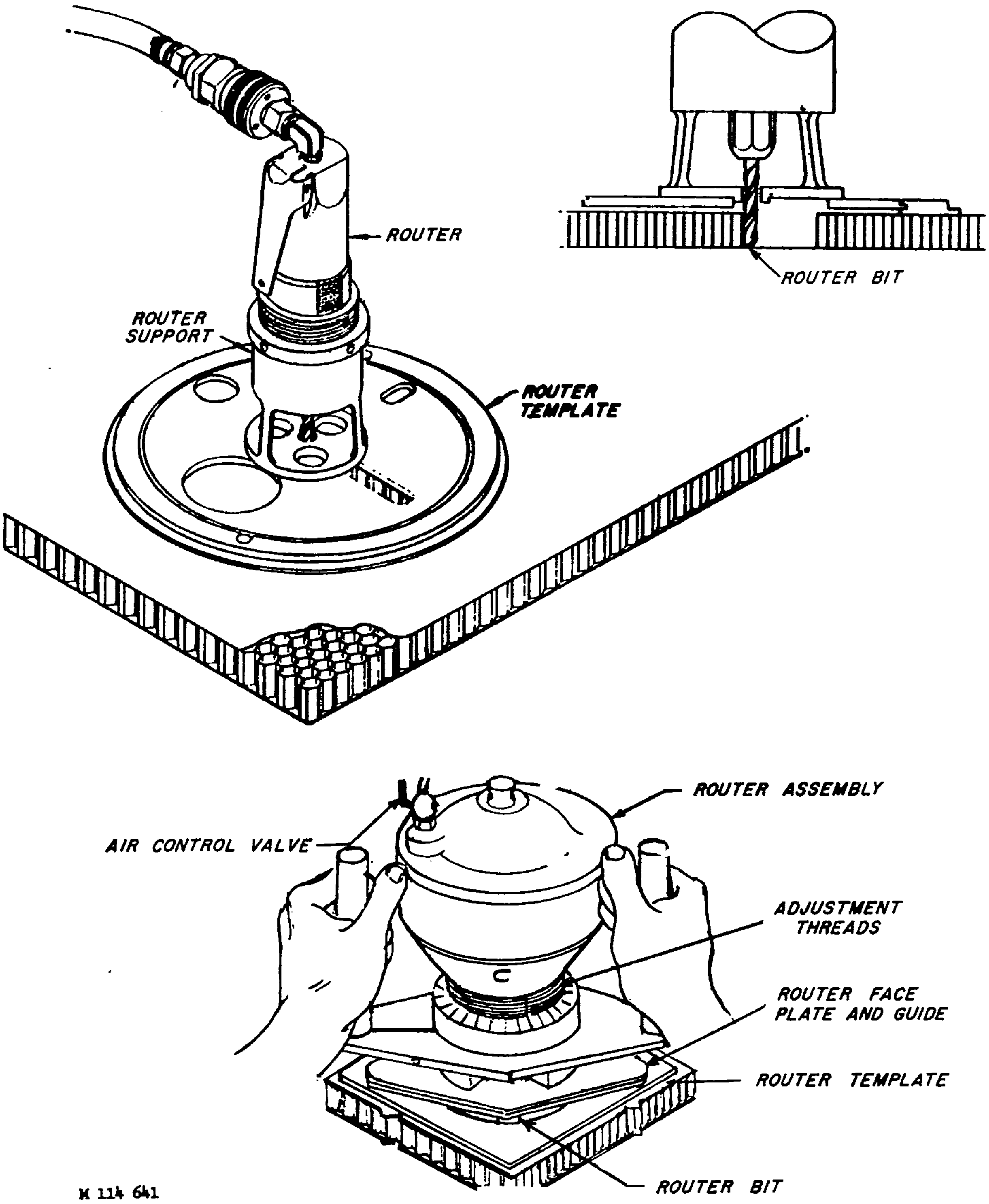


Figure 16-7.--Removal of damaged area from sandwich panel using pneumatic routers, router bit, and template.

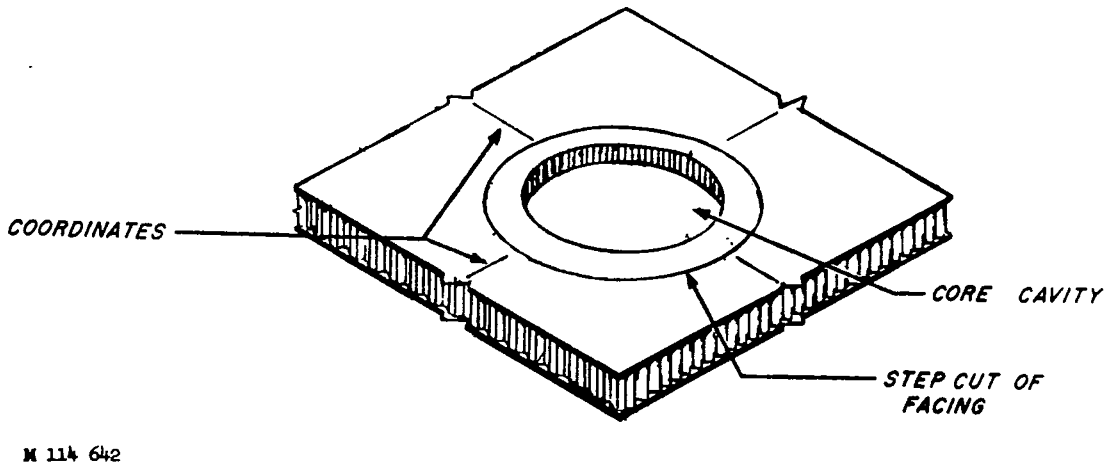


Figure 16-8.--Step cut of facing surrounding core cavity for use in fabricating flush repair.

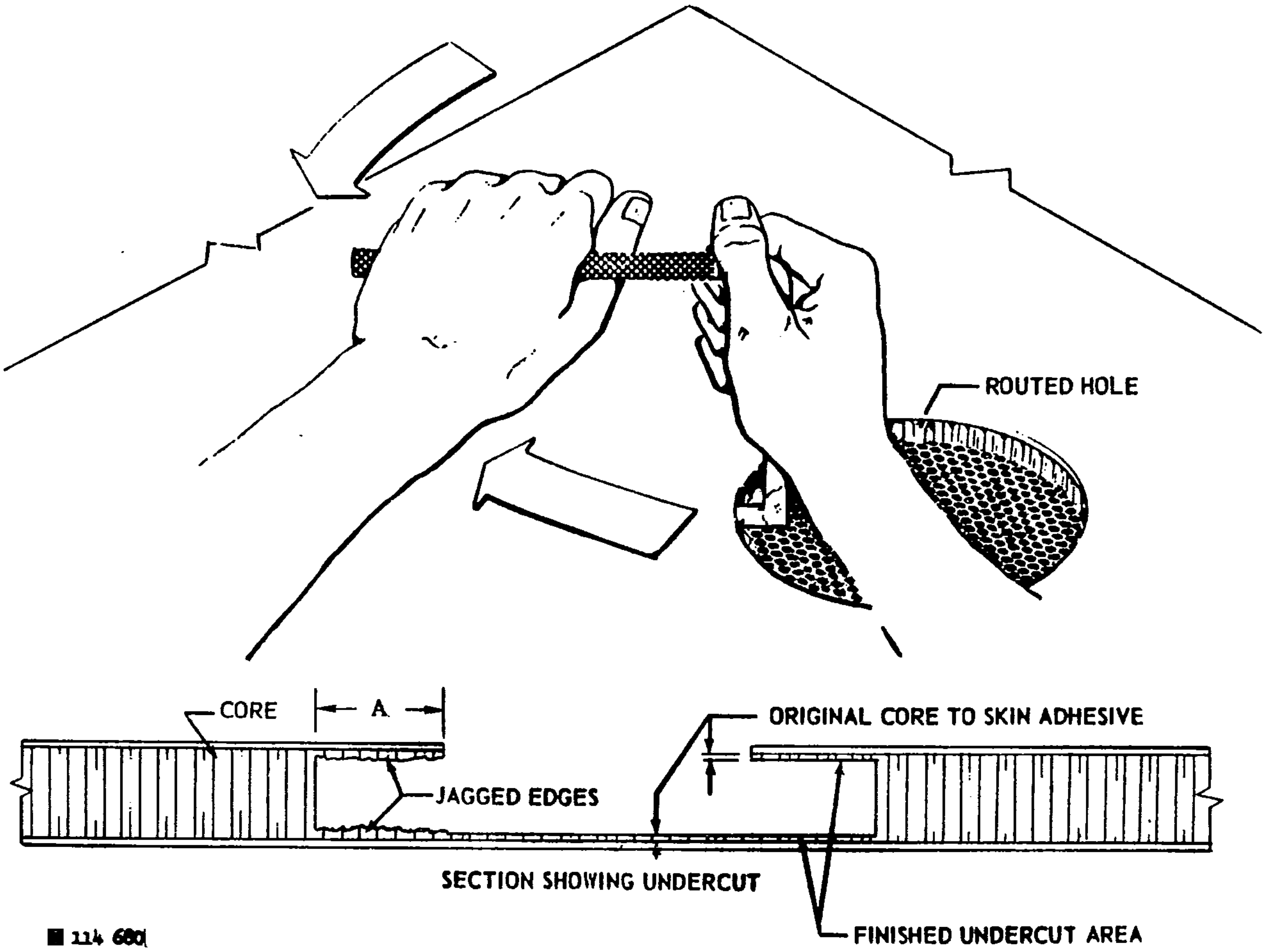


Figure 16-9.--Use of hand-operated cutting tool to undercut core material.

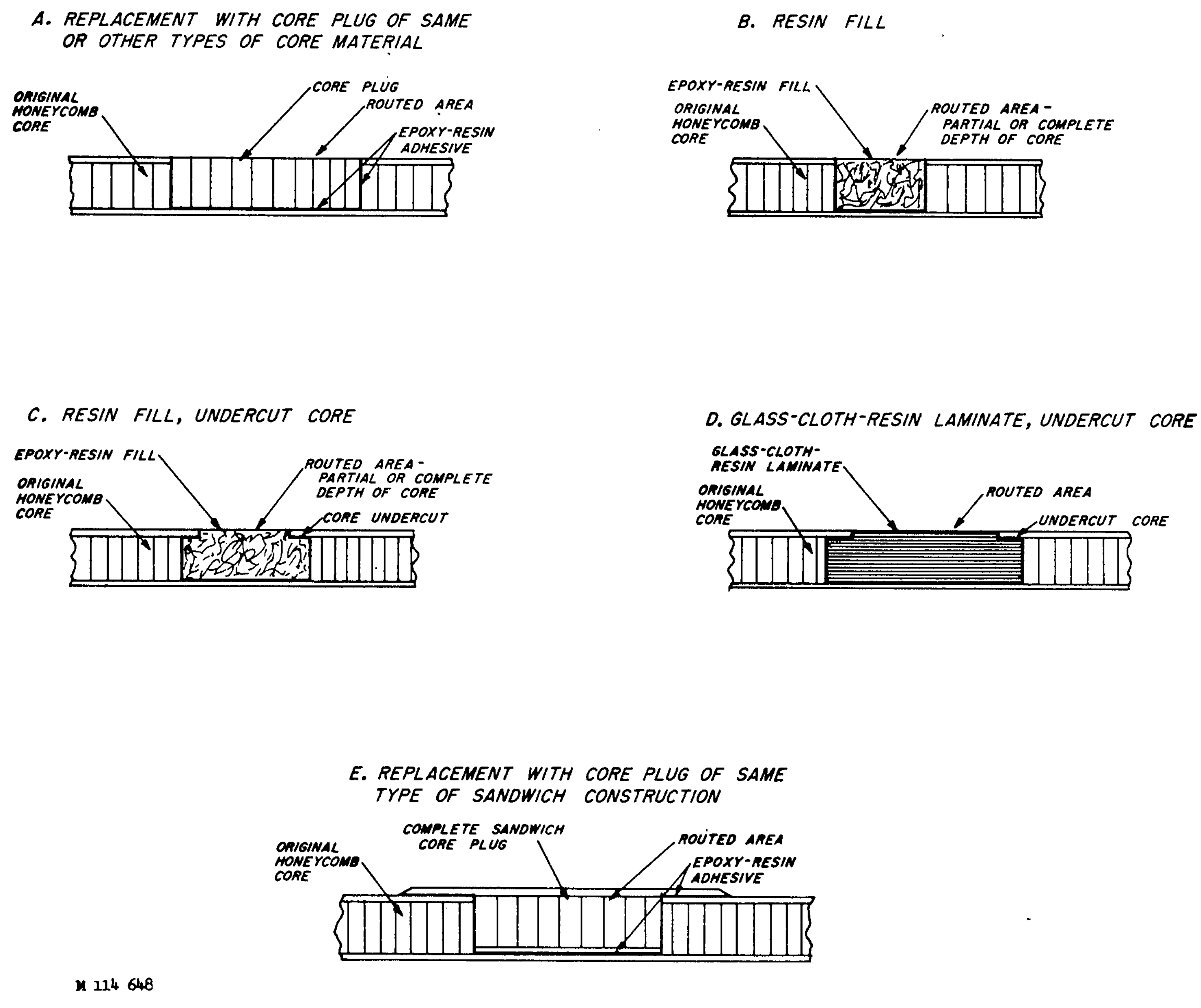


Figure 16-10.--Typical types of core replacements.

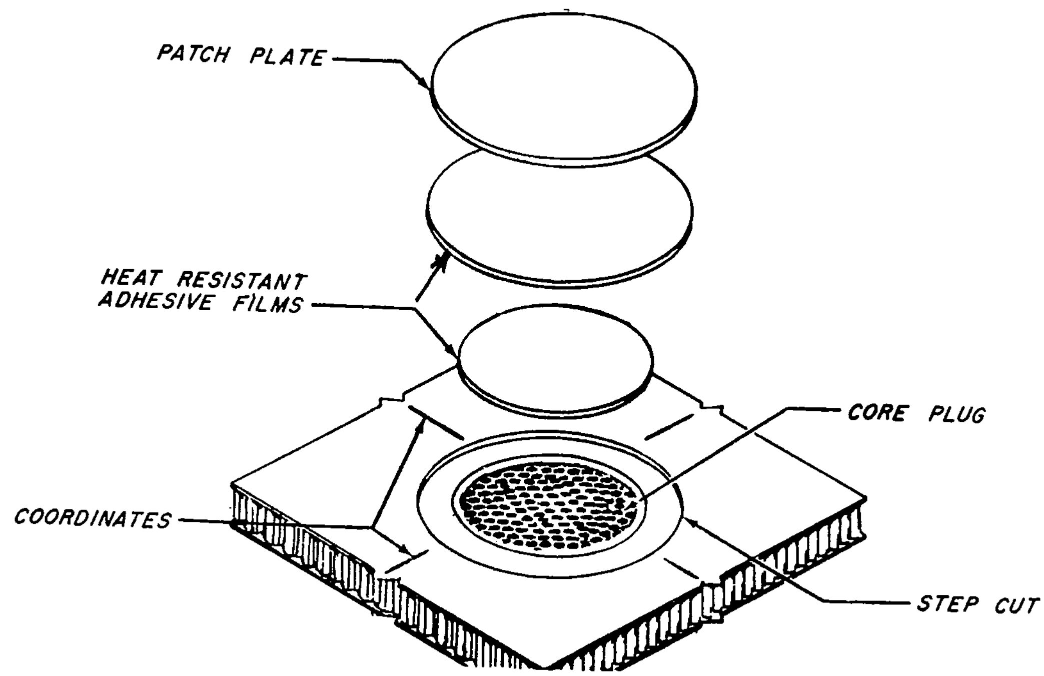


Figure 16-11.--Step-type skin patch for sandwich repair.

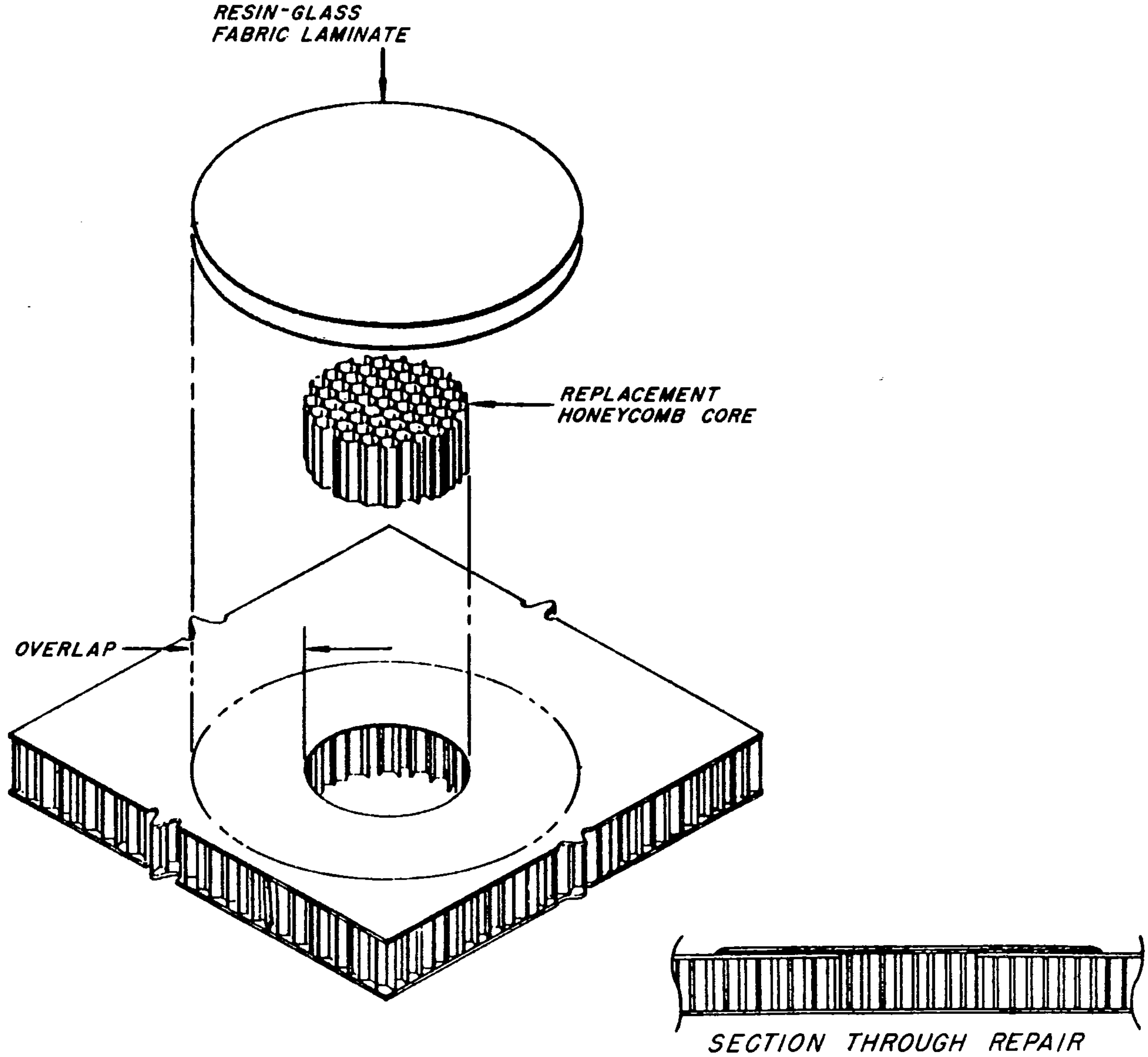


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Figure 16-12.--Overlap glass-fabric facing patch for sandwich repair.

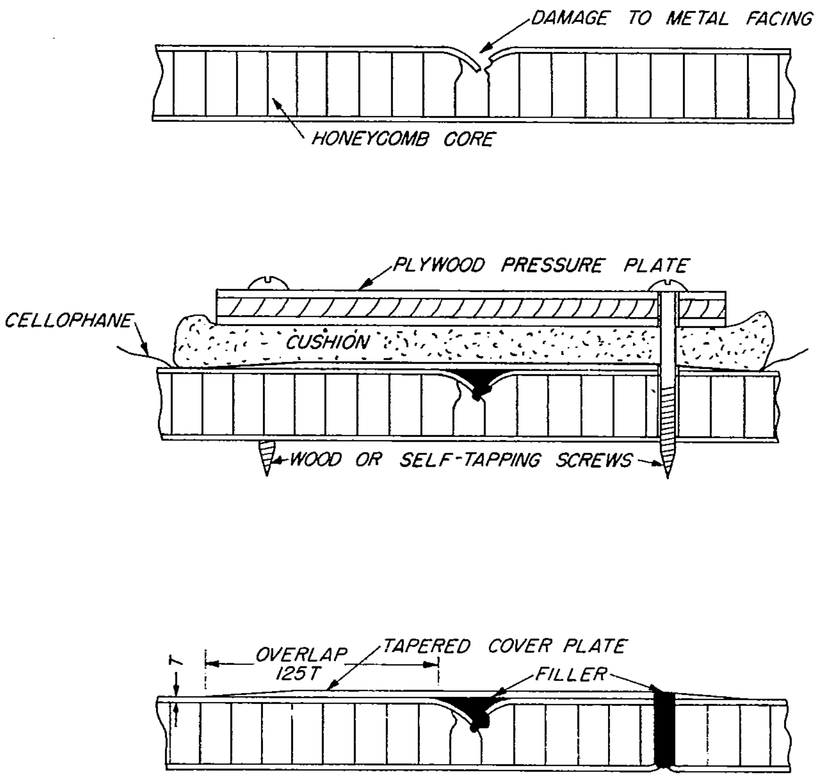


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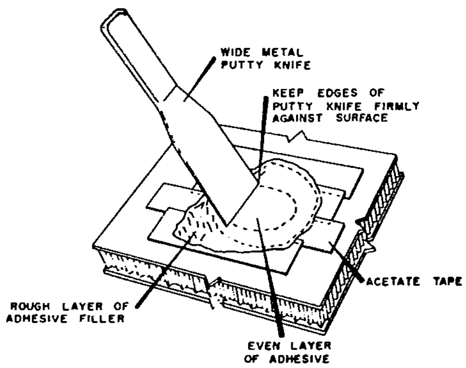
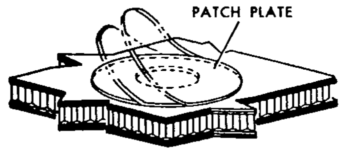
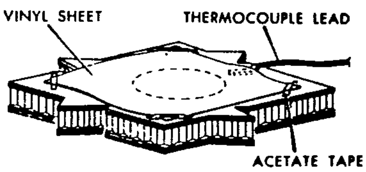
Figure 16-13.--Method of applying curing pressure to single facing patch (class 2 damage) using metal self-tapping screws and cushioned plywood plate.



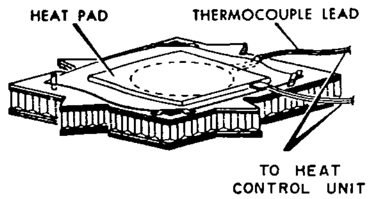

A Application of adhesive to surface of sandwich.



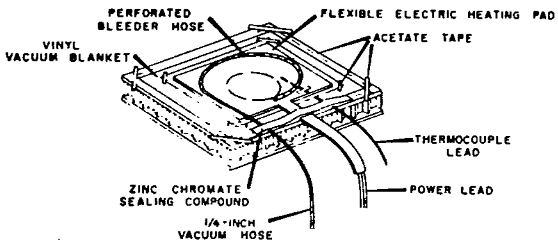

B Placing facing patch over repair area.




C Taping vinyl sheet and thermocouple in place over facing patch.




D Placing heat pad over repair area.




E Heat blanket is covered with glass fabric and vinyl vacuum blanket is fastened over vacuum hose.

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Figure 16-14.--Bonding facing patch on a sandwich panel, using heating blanket and vacuum bag.

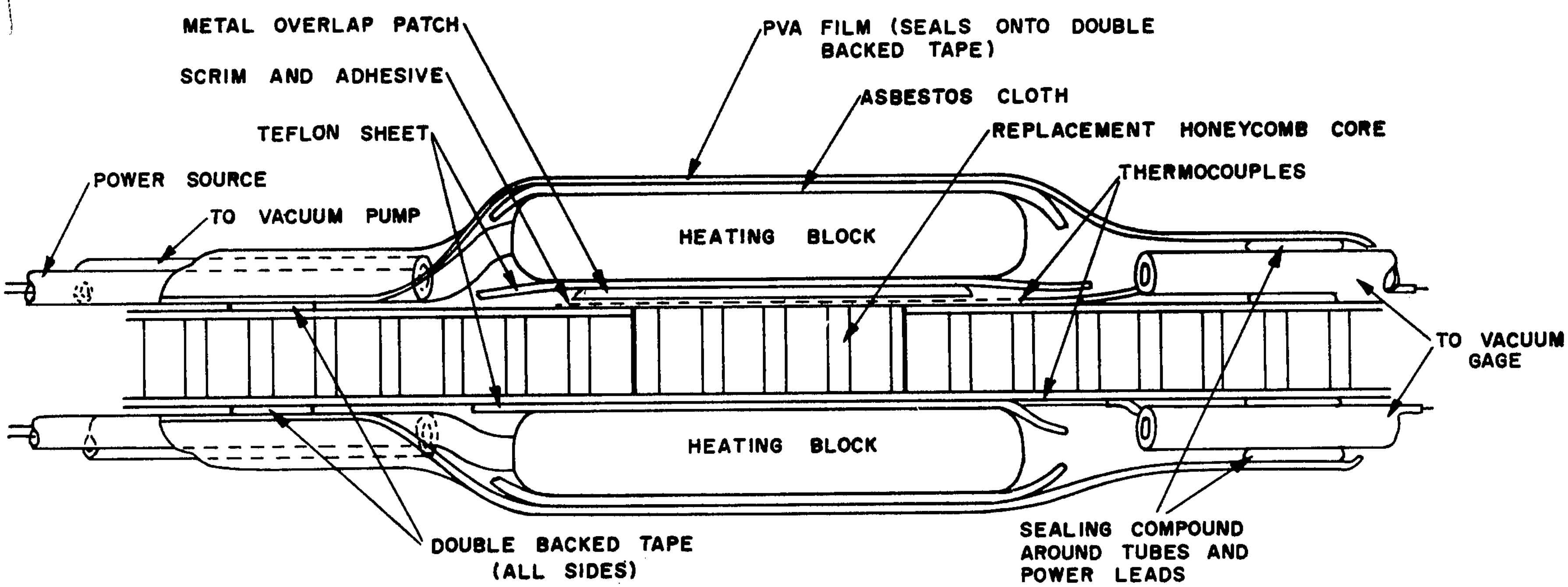


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Figure 16-15.--Cross section of vacuum bag and rigid heating blocks being employed to cure overlap type of skin patch.

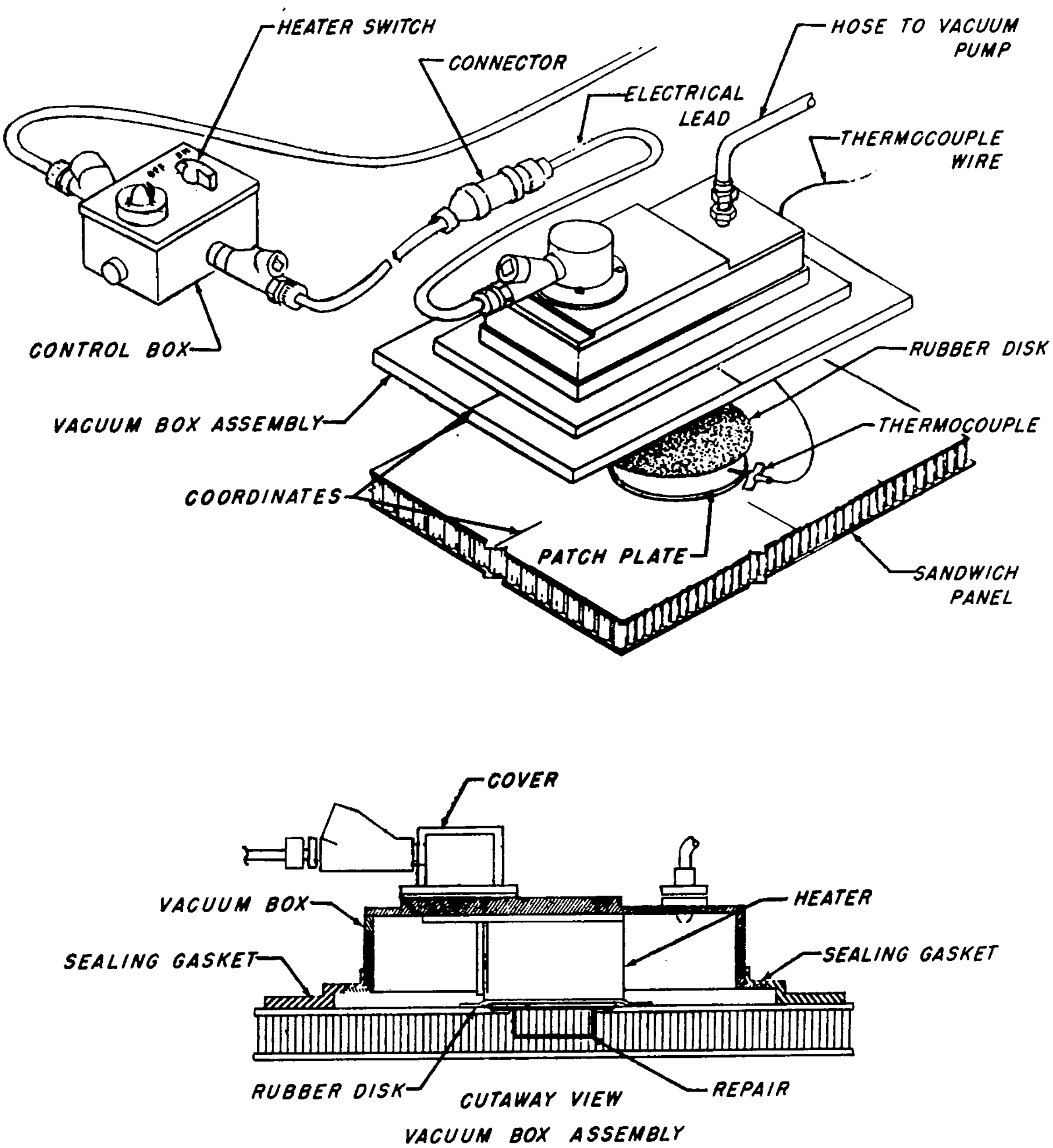


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Figure 16-16.--Vacuum box and rigid heater block used for maintaining temperature and pressure during cure of adhesive-bonded repair patch.

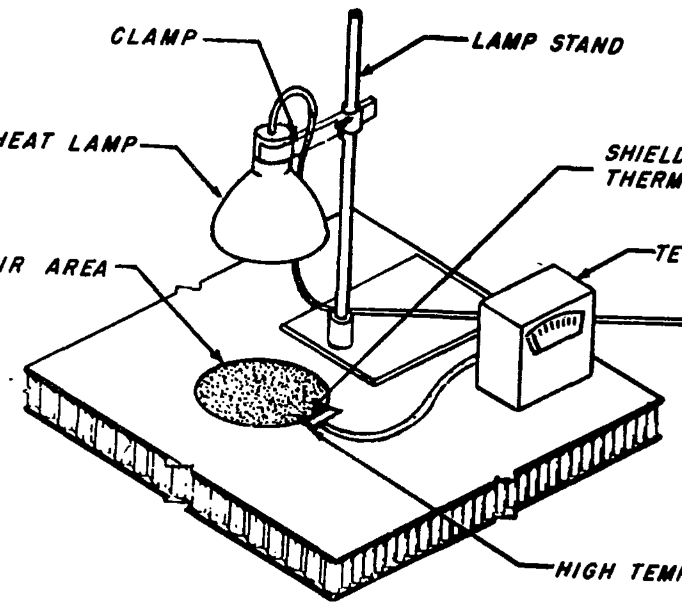


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Figure 16-17.--Use of heat lamp to complete cure of bonded repair.

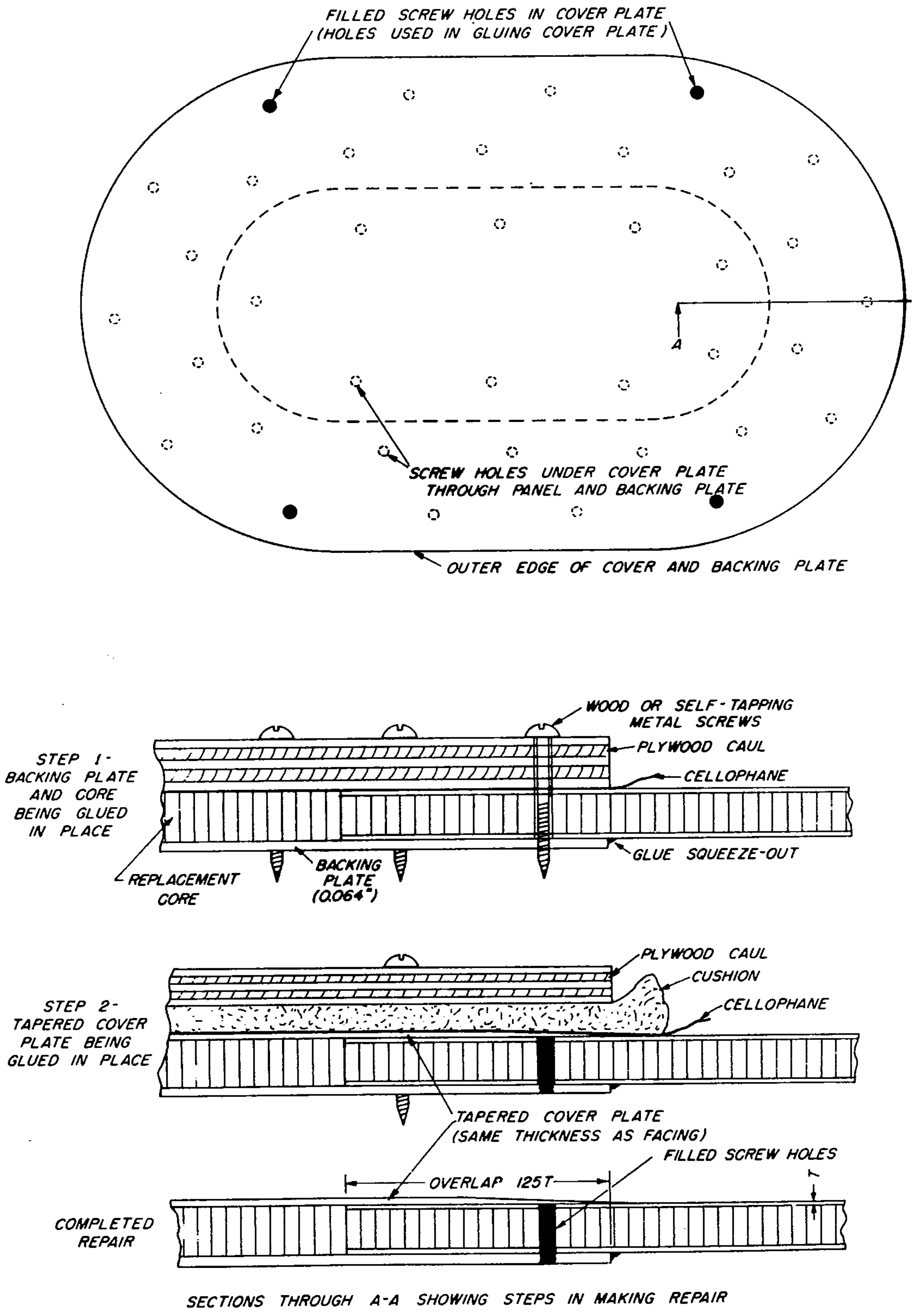


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Figure 16-18.--Method of repairing class 3 damage when panel is accessible from only one side.

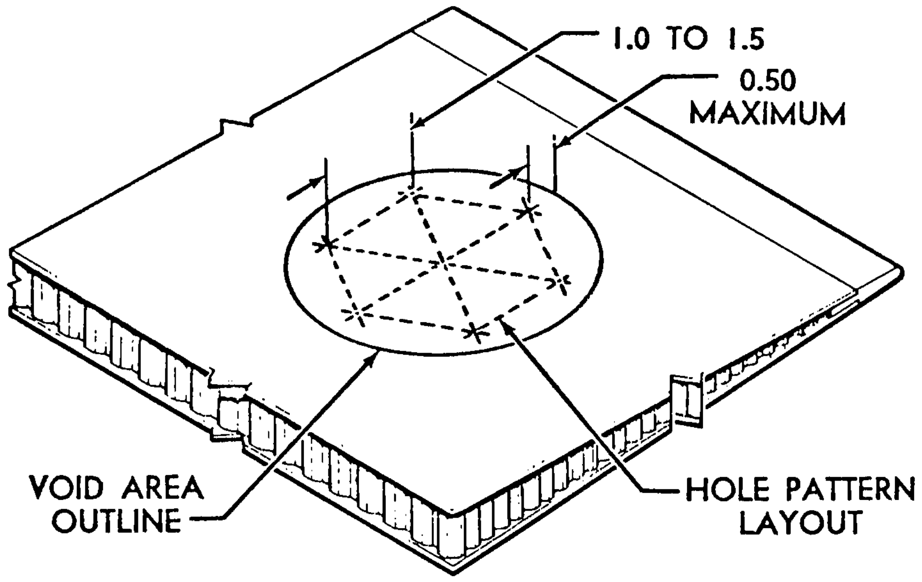


Figure 16-19.--Injection hole pattern.

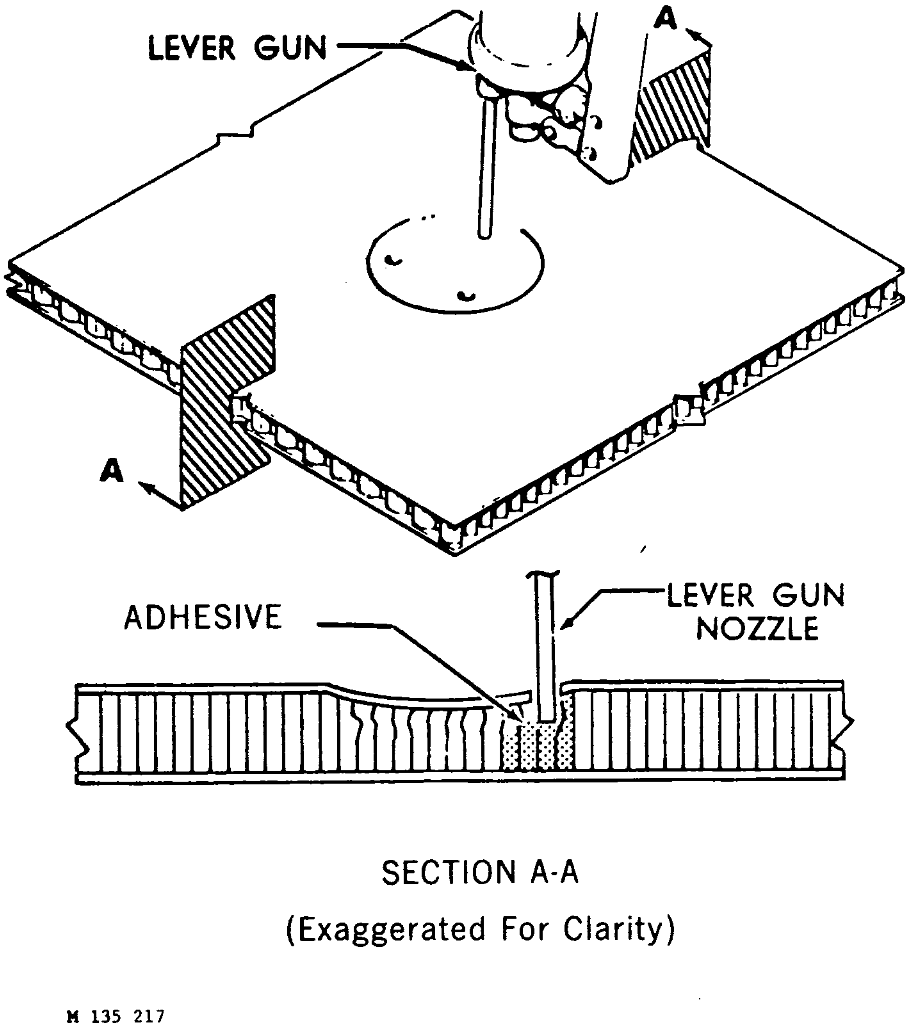


Figure 16-20.--Injection of adhesive with lever gun.

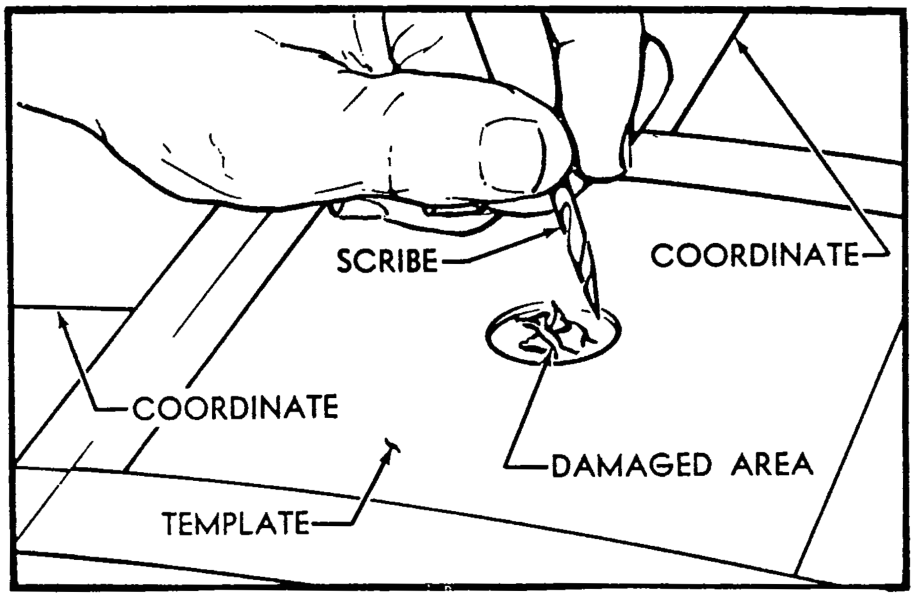


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Figure 16-21.--Preparation of sandwich facing for repair.

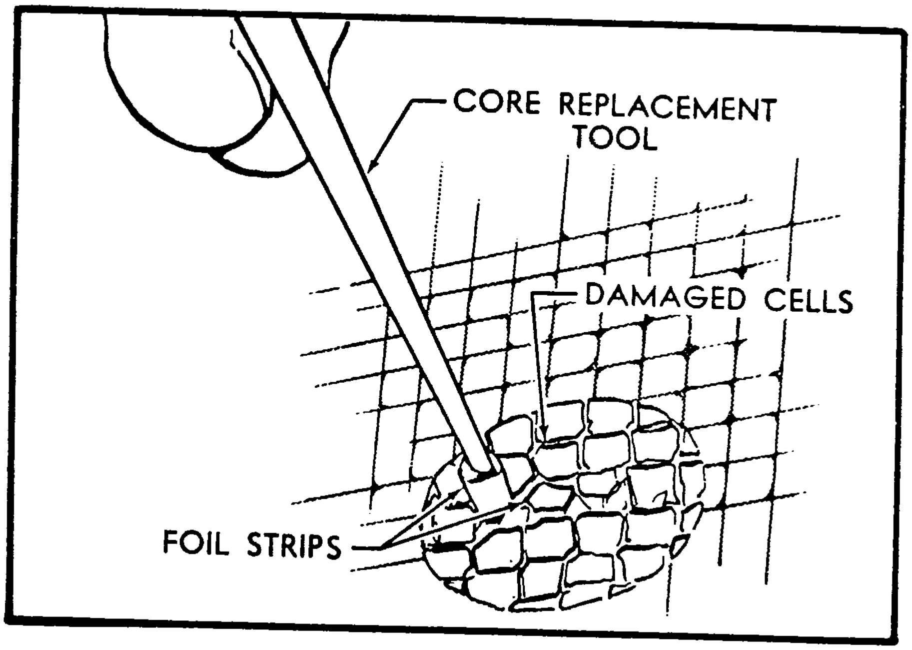


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Figure 16-22.--Repair of sandwich core.

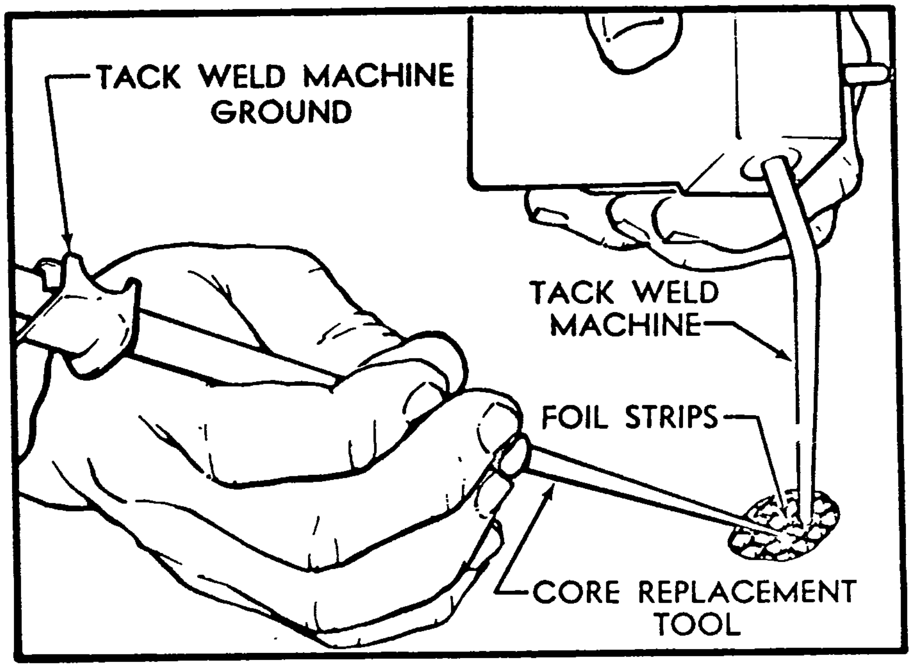


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Figure 16-23.--Tack-welding sandwich core.

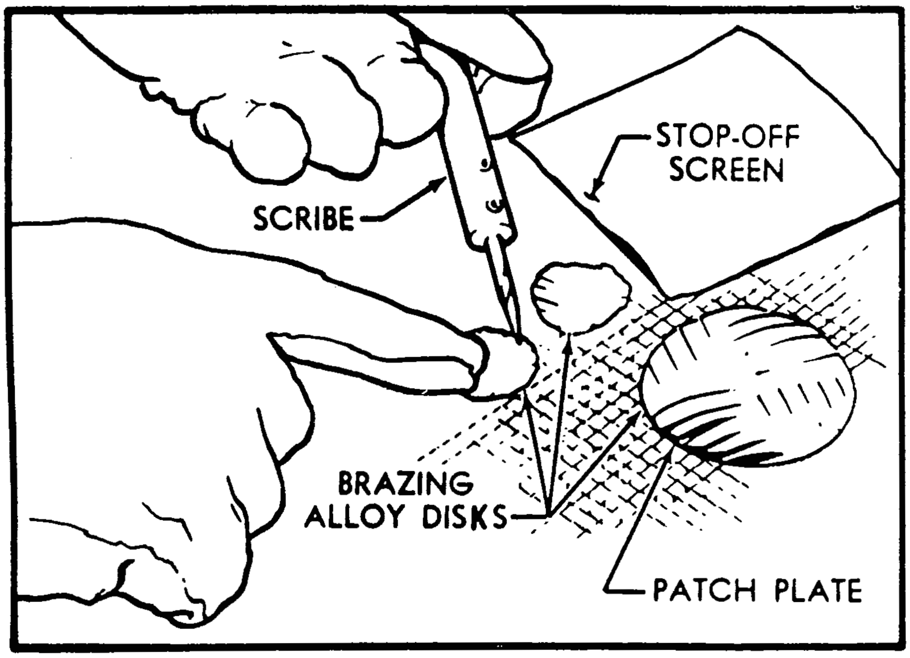


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Figure 16-24.--Preparation of braze alloy disks.

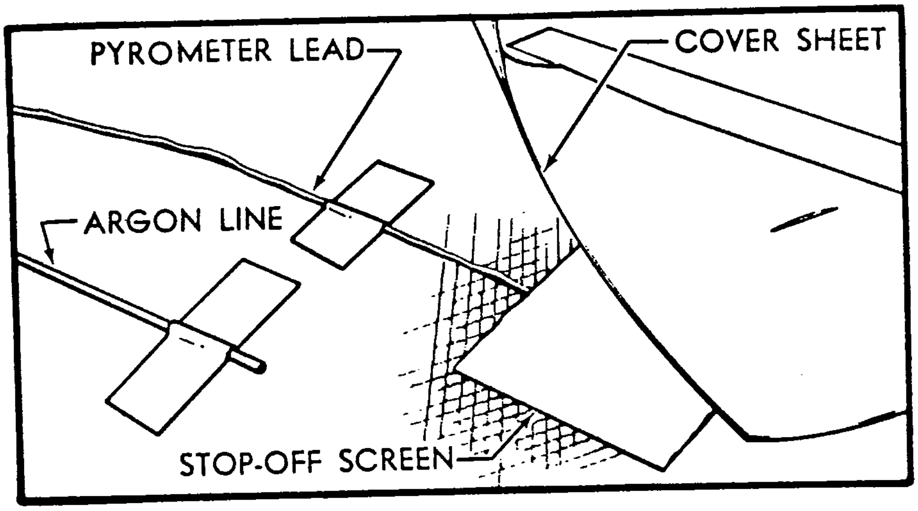


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Figure 16-25.--Arrangement of repair components.

# CHAPTER 17

# DURABILITY

## 17.1 GENERAL

An acceptable sandwich structure, in addition to possessing specified initial physical properties, must be relatively unaffected by continued exposure to conditions imposed by severe service. Obviously, with sandwich combinations involving new and untried materials, it is impossible to provide the assurance of adequate service tests, and reliance must therefore by placed on tests conducted after artificial aging under conditions thought to be typical of severe service. Artificial-aging tests are time-consuming and often do not include all the possible combinations of exposure conditions that might be encountered in actual service.

### 17.1.1 Environmental Exposure of Adhesive-Bonded Joints

Bonded lap-joint aluminum panels prepared with various adhesives have been weathered for periods up to 3 years in Fairbanks, Alaska; State College, N. Mex.; Madison, Wis.; and the Panama Canal Zone (refs. 17-1 and 17-2). The effects of these environments on the strength of adhesive-bonded aluminum lap joints are given in table 17-1. In general, warm humid atmospheres were much more detrimental than temperate or colder exposures.

The exposure of organic materials to space environment (ref. 17-6) has demonstrated that epoxy, phenolic, polyester, and silicone-type polymers would have no measurable equilibrium weight loss rate ($<10^{-11}$ g/cm$^2$-sec) in a high vacuum at temperatures less than 200° F. Exposure to high vacuum at elevated temperature caused serious decrease in the strength of polyester laminates but increased the strength of laminates of the other resins. The increase in strength while at high vacuum was not retained after subsequent return to normal atmospheric conditions.

## 17.1.2 Environmental Evaluation of Sandwich Constructions

Aluminum sandwich properly bonded with epoxy-phenolic or nitrile-elastomer-phenolic adhesives showed no significant reduction in strength after outdoor weathering exposure for 5 years (ref. 17-10). Laboratory aging and exposure to JP-4 fuel showed no deleterious effects on panel strength. Exposure of a similar construction to more severe conditions for a shorter time period produced no marked effects (ref. 17-11).

The service history of sandwich of reinforced-plastic materials combined with simulated weather aging has developed data showing wide scatter but analysis of the information showed that service life reduced strength more than did shelf life (ref. 17-5). After 3 years' exposure at several outdoor sites the salt-air exposure appeared to be the most severe and produced a somewhat eroded surface on laminates, with exposure of some glass fibers on the surface (ref. 17-12). A summary of U.S. Air Force service experience showed sandwich with reinforced plastic facings had no basic weakness except for rapid rain erosion (ref. 17-9).

Exposure of sandwich with paper honeycomb core to 3 years' rural atmosphere and 3 years of exposure to salt-water atmosphere produced rather inconclusive results but indicated good aging possibilities (ref. 17-13).

A variety of solvent materials can be successfully resisted by bonded sandwich for exposures of 30 days except exposure to paint removers, which degraded strength drastically (ref. 17-7).

The most serious and difficult service problem is that of water entry into the sandwich cores. Water accumulation can result in damage to the panel from freezing, or in supersonic, high-altitude aircraft by boiling, which can rupture the core or panel itself, and from corrosion at the bond interfaces that destroys the chemical bond (refs. 17-7 and 17-8). Fluid entry can also contribute to dynamic unbalance and weight gain in such parts as control surfaces and helicopter rotor blades. Fluids in radome structure affect its transmission and structural characteristics. In several instances, foam core materials have failed due to vibration and have accumulated moisture with resulting corrosion of the metal faces adjacent to the foam. Moisture penetration of balsa core panels through the edges or from seepage around fasteners has resulted in corrosion damage at the metal-adhesive interface with a resultant loss of the bond.

In service, water entry occurs primarily during descent since the lag in pressure and temperature changes in the panel means the internal pressure is less than the external pressure and a partial vacuum draws the moisture into the panel through any defect or omission of the sealant. In production or during fabrication and finishing operations, moisture may enter if panels are immersed or sprayed with water or other fluids. Also, panels with adhesive bonds with poor moisture resistance or bonds of a porous nature and skins or edges of laminated plastic or other porous materials allow fluids to enter by transmission directly through the material, though the quantity depends on the degree of porosity.

Difficulty may result even with a fully sealed panel because of one or more of the following conditions.

1. High levels of sonic vibration cause sealant breakdown.

2. Structural deflection.

3. Differential pressure.

4. Inadequate overlap in bonded joint.

5. External accidental damage to panel.

6. Inadequate design for sealing.

7. Thermal stresses due to steam cleaning cause sealing or bonded joints to fail.

8. Aging and deterioration of sealing materials.

9. Inadequate material properties.

The techniques and materials used to provide effective sealing must take the above conditions into consideration. The quality of the adhesive bond, i.e., degree of porosity and adhesion qualities, has a direct bearing on its sealing characteristics. Polysulfide and filled epoxy compounds are the most frequently used materials for sealing open core areas, joints between edge members, relief cutouts, and tool or vent holes. For laminated plastic skins of radomes or other plastic assemblies, the use of void-free laminating techniques and nylon or epoxy sealer coatings is recommended. Another procedure is to use nonperforated core to prevent the spread of fluids throughout the panel. This requires the use of adhesives which give off little or no volatiles during curing of the sandwich panel.

The effects of seashore exposure on brazed stainless steel sandwich has shown (ref. 17-3) that proper braze alloy can result in superior performance because of less corrosion.

## 17.2 RAIN EROSION OF PLASTIC LEADING EDGES

High-speed flight through rain causes erosion damage to the exterior plastic leading edges of flight vehicles. The severity of the rain-erosion damage has been extensive enough in some cases to cause a complete structural failure of the plastic part. Several studies have been undertaken to (1) determine the mechanism of rain-erosion damage, (2) evaluate available and promising new materials, (3) determine the variables that most seriously affect the amount of rain-erosion damage. The rain-erosion evaluation of materials and affecting variables has been conducted on a rotating-arm apparatus for subsonic evaluation and on both a recoverable ballistic test and on a rocket sled apparatus for supersonic evaluation. Correlation of the laboratory test data has been made with service test data at both subsonic and supersonic speeds. Extensive data have been obtained which indicate that the most critical variables involved are speed of flight, drop size and rainfall concentration, and angle of impact (ref. 17-4).

There have been no reinforced plastic laminates or composite material constructions developed to date that are satisfactory without protection for service use involving exposure at high flight speeds in rain for extensive time periods.

Neoprene coatings have been used as a means of protection to prevent rain-erosion damage to the plastic leading edges at subsonic speeds. A 10-mil thickness is utilized to obtain the best combination of rain-erosion protection and electrical transmission properties for end item usage where electrical requirements are involved, such as radomes. It has been determined that, for optimum performance of the coatings, it is essential that the coating be applied to structurally sound material. For nonelectrical applications, the use of thicker neoprene coatings will greatly increase the rain-erosion resistance of the plastic leading edge. Temperature limitations for the neoprenes are 300° F for extended use (100 hours) and 400° F for extremely short time periods (minutes).

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Table 17-1.--Performance of bonded 1/2-inch overlap joints of 0.065-inch aluminum after weathering exposure[1]

| Exposure[2] | Nitrile-elastomer-phenolic | Polyvinyl-phenolic | Epoxy | Epoxy-phenolic | Polyamide-elastomer-phenolic |
|---|---|---|---|---|---|
| | (Percent) | (Percent) | (Percent) | (Percent) | (Percent) |
| Madison, Wis. | | | | | |
| 3 months | | | | | |
| stressed | 90 - 110 | 85 - 105 | 0 - 90 | 105 | 85 |
| unstressed | 95 - 110 | 95 - 100 | 85 - 95 | 95 | 90 |
| 12 months | | | | | |
| stressed | 80 - 100 | 90 - 105 | 40 - 85 | 95 | 90 |
| unstressed | 105 - 115 | 100 - 105 | 65 - 95 | 100 | 95 |
| 36 months | | | | | |
| stressed | 70 - 90 | 85 - 95 | 30 | --- | 85 |
| unstressed | 105 - 130 | 95 - 100 | 80 | --- | 105 |
| Panama Canal Zone | | | | | |
| 3 months | | | | | |
| stressed | 85 - 95 | 95 | 0 - 90 | 95 | 55 |
| unstressed | 100 - 105 | 85 - 115 | 15 - 80 | 100 | 70 |
| 12 months | | | | | |
| stressed | 85 - 95 | 90 - 110 | 0 - 15 | 85 | 0 |
| unstressed | 95 - 105 | 95 - 100 | 0 - 80 | 90 | 30 |
| 36 months | | | | | |
| stressed | 80 - 90 | 45 - 85 | 0 | --- | 30 |
| unstressed | 80 - 115 | 75 - 95 | 0 - 40 | --- | 20 |
| Fairbanks, Alaska | | | | | |
| 3 months | | | | | |
| stressed | 95 - 110 | 95 - 105 | 35 - 90 | 100 | 100 |
| unstressed | 100 - 110 | 100 | 80 - 95 | 100 | 105 |
| 12 months | | | | | |
| stressed | 95 - 100 | 95 - 110 | 45 - 90 | 95 | 100 |
| unstressed | 105 - 110 | 95 - 100 | 85 | 95 | 90 |
| 36 months | | | | | |
| stressed | 85 - 90 | 95 | 0 - 80 | 95 | 70 |
| unstressed | 100 - 105 | 90 - 105 | 90 | 95 | 70 |

(Page 1 of 2)

Table 17-1.--Performance of bonded 1/2-inch overlap joints of 0.065-inch aluminum after weathering exposure[1] (cont.)

| Exposure[2] | Nitrile-elastomer-phenolic | Polyvinyl-phenolic | Epoxy | Epoxy-phenolic | Polyamide-elastomer-phenolic |
|---|---|---|---|---|---|
| | (Percent) | (Percent) | (Percent) | (Percent) | (Percent) |
| New Mexico | | | | | |
| 3 months unstressed | 100 - 105 | 90 - 105 | 90 - 100 | 105 | 90 |
| 12 months unstressed | 95 - 115 | 95 - 100 | 90 | 100 | 90 |
| 36 months unstressed | 105 - 135 | 95 - 100 | 85 - 95 | 95 | 100 |
| Florida | | | | | |
| 3 months unstressed | 95 - 105 | 100 - 115 | 70 - 85 | 95 | 90 |
| 12 months unstressed | 95 - 105 | 75 - 100 | 0 - 75 | 95 | 75 |
| 36 months unstressed | 5 - 55 | 0 - 100 | 15 | --- | 0 |

[1]Values tabulated are percentages of unexposed control strengths (ref. 17-1 and 17-2).

[2]Exposures designated "stressed" refer to panels in which the lap joints were subjected to bending stress during exposure.



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CHAPTER 18 -- "OPTIMUM" SANDWICH

# CHAPTER 18

## "OPTIMUM" SANDWICH

### 18.1 INTRODUCTION

The concept of sandwich construction combining thin, strong facings on lightweight, thick cores suggests possibilities of deriving constructions so proportioned that minimum-weight constructions, often called "optimum" constructions, for a given stiffness or loading capability are attained. It is important to realize that the minimum-weight construction derived may not be practical because "optimization" may require unusually thin facings which may not be available, or unusually lightweight cores of great thickness. Previous chapters for design of specific sandwich components will give correct sandwich proportions regarding stresses in facings and core, buckling, or deflections; but these sandwiches may not be minimum weight. Examples will be given to illustrate this point.

Direct optimization without examination of the resultant designs may lead to erroneous conclusions when comparing material requirements with constructions other than sandwich because the "optimized" sandwich may not be a realistic one.

Intuitive optimization such as requiring that all parts be fully stressed or that failure occur in all modes simultaneously does not necessarily produce minimum-weight structural components (ref. 18-6).

### 18.2 SANDWICH WEIGHT

The weight of a sandwich is given by the formula

$$W = w_1 t_1 + w_2 t_2 + w_c t_c + W_B \qquad (18{:}1)$$

$$W = 2wt + w_c t_c + W_B \text{ (for equal facings)} \qquad (18{:}1a)$$

where W is sandwich weight (per unit sandwich area); w is density; t is thickness; subscripts 1 and 2 denote facings 1 and 2; subscript c denotes core; and $W_B$ is total weight of bond (per unit sandwich area) between facing and core. This bond may be an adhesive or braze material. If it is assumed the bond weight is the same for all sandwich of the type considered, then weight comparisons can be made on the basis of $(W - W_B)$. It is also convenient to express $t_c$ as $\left(h - \frac{t_1 + t_2}{2}\right)$ where h is distance between facing centroids. Then formulas (18:1) and (18:1a) can be rewritten as

$$(W - W_B) = \phi_1 t_1 + \phi_2 t_2 + w_c h \qquad (18:2)$$

$$(W - W_B) = 2\phi t + w_c h \qquad (18:2a)$$

where

$$\phi_1 = w_1 - \frac{w_c}{2}, \qquad \phi_2 = w_2 - \frac{w_c}{2}, \qquad \phi = w - \frac{w_c}{2}$$

It is essential that the weight units be consistent in using the formulas. Thus if w is density in pounds per cubic inch, t and h must be in inches and then $(W - W_B)$ is weight in pounds per square inch of sandwich area.

Example: Compute $(W - W_B)$ for a sandwich with 0.032-in. aluminum façings on a 3/4-in. honeycomb core having a density of 6 pcf. Using formula (18:2a)

$$(W - W_B) = 2(0.1000 - 0.00174)(0.032) + 0.0035(0.782)$$

$$(W - W_B) = 0.00629 + 0.00274 = 0.00903 \text{ psi}$$

or

$$(W - W_B) = 144(0.00903) = 1.30 \text{ psf}$$

## 18.3 SANDWICH BENDING STIFFNESS

Since the primary purpose of structural sandwich is to provide stiffness, hence low deflection under transverse load and high resistance to buckling under edgewise (in-plane) load, a minimum-weight sandwich to provide a specified bending stiffness can be determined.

The bending stiffness of a sandwich, per unit width, is given by the formula

$$D = \frac{\frac{E_1 t_1}{\lambda_1} \frac{E_2 t_2}{\lambda_2}}{\frac{E_1 t_1}{\lambda_1} + \frac{E_2 t_2}{\lambda_2}} h^2 \qquad (18:3)$$

$$D = \frac{Et}{2\lambda} h^2 \qquad (18:3a)$$

where D is bending stiffness; subscripts 1 and 2 denote facings 1 and 2; E is facing elastic modulus; $\lambda$ is one minus the product of two Poisson's ratios; t is facing thickness; and h is distance between facing centroids.

Substitution of the stiffness expression (18:3) into the weight equation (18:2) and minimizing the weight by calculus (ref. 18-4) results in the following expressions for h and t to produce minimum-weight sandwich for a required stiffness D.

$$h^3 = \frac{2D}{w_c} \left[ \sqrt{\frac{\phi_1 \lambda_1}{E_1}} + \sqrt{\frac{\phi_2 \lambda_2}{E_2}} \right]^2 \qquad (18:4)$$

$$h^3 = \frac{8D\phi\lambda}{w_c E} \qquad (18:4a)$$

and

$$t_1 = \frac{h}{2}\frac{w_c}{\phi_1}\frac{\sqrt{\frac{\phi_1\lambda_1}{E_1}}}{\left(\sqrt{\frac{\phi_1\lambda_1}{E_1}} + \sqrt{\frac{\phi_2\lambda_2}{E_2}}\right)}$$

$$t_2 = \frac{h}{2}\frac{w_c}{\phi_2}\frac{\sqrt{\frac{\phi_2\lambda_2}{E_2}}}{\left(\sqrt{\frac{\phi_1\lambda_1}{E_1}} + \sqrt{\frac{\phi_2\lambda_2}{E_2}}\right)} \qquad (18:5)$$

$$t = \frac{h}{4}\frac{w_c}{\phi} \qquad (18:5a)$$

The resultant construction will be found to be proportioned so that approximately two-thirds of the sandwich weight will be in the core (refs. 18-1, 18-2, 18-3, 18-4, 18-5).

Example: Determine dimensions of sandwich components so that the resultant composite will have a bending stiffness $D = 3.0 \times 10^6$ lb-in.$^2$ per in. of width. The facing properties are $E_1/\lambda_1 = 10^7$ psi, $w_1 = 0.100$ pci, $E_2/\lambda_2 = 3 \times 10^6$ psi, $w_2 = 0.061$ pci, and the core weight $w_c = 0.0034$ pci.

Minimum weight design--

From formula (18:4)

$$h = \left\{ \frac{2(3.0)(10^6)}{0.0034} \left[ \sqrt{\frac{0.0983}{10^7}} + \sqrt{\frac{0.0593}{3(10^6)}} \right]^2 \right\}^{\frac{1}{3}} = 4.66 \text{ in.}$$

and from formulas (18:5)

$$t_1 = 2.33 \frac{0.0034 \sqrt{\frac{0.0983}{10^7}}}{0.0983 \left( \sqrt{\frac{0.0983}{10^7}} + \sqrt{\frac{0.0593}{3(10^6)}} \right)} = 0.033 \text{ in.}$$

$$t_2 = 2.33 \frac{0.0034 \sqrt{\frac{0.0983}{10^7}}}{0.0593 \left( \sqrt{\frac{0.0983}{10^7}} + \sqrt{\frac{0.0593}{3(10^6)}} \right)} = 0.078 \text{ in.}$$

With these dimensions the sandwich weight (minus bond weight) is 0.0237 psi of which 0.0156 psi is in the core, 0.0033 psi in facing 1, and 0.0048 psi in facing 2. About two-thirds of the sandwich weight is in the core.

Minimum weight design for sandwich with equal facings--

Sandwich with both facings of type 1--

From formula (18:4a)

$$h = \left\{\frac{8(3)(10^6)(0.0983)}{0.0034(10^7)}\right\}^{\frac{1}{3}} = 4.11 \text{ in.}$$

and from formula (18:5a)

$$t = \frac{4.10(0.0034)}{4(0.00983)} = 0.035 \text{ in.}$$

The sandwich weight (minus bond weight) is 0.0209 psi of which 0.0139 psi is in the core and 0.0070 psi is in the facings. The core weight is 66 percent of the sandwich weight.

Sandwich with both facings of type 2--

From formula (18:4a)

$$h = \left\{\frac{8(3)(10^6)(0.0593)}{0.0034(3)(10^6)}\right\}^{\frac{1}{3}} = 5.19 \text{ in.}$$

and from formula (18:5a)

$$t = \frac{5.19(0.0034)}{4(0.0593)} = 0.074 \text{ in.}$$

The sandwich weight (minus bond weight) is 0.0262 psi of which 0.0171 psi, or 65 percent, is core weight.

A summary of the dimensions is shown in table 18-1.

Table 18-1. --Summary table of component dimensions for minimum weight sandwich

| Facings | Thickness | | | Sandwich weight* |
|---|---|---|---|---|
| | h | $t_1$ | $t_2$ | |
| | In. | In. | In. | Psi |
| Types 1 and 2 | 4.66 | 0.033 | 0.078 | 0.0237 |
| Both facings type 1 | 4.11 | .035 | .035 | .0209 |
| Both facings type 2 | 5.19 | .074 | .074 | .0262 |

*Does not include bond weight.

The values in table 18-1 show that the lightest sandwich is that with both facings of type 1 material (facing with the lower value of $\phi\lambda/E$). The thinnest facing of type 2 material is obtained when both facings are of type 2 but this produces a sandwich about 10 percent heavier than one of minimum weight.

## 18.4 SANDWICH BENDING MOMENT CAPACITY

The bending moment resistance of a sandwich with thin, equal facings on a core of negligible bending stiffness is given by the formula

$$M = Fth \qquad (18{:}6)$$

where M is bending moment per unit width; F is facing stress; t is facing thickness; and h is distance between facing centroids. Solving formula (18:6) for t and substitution of this into the weight equation (18:2a) and minimizing with respect to h (ref. 18-4) results in

$$h^2 = \frac{2M\phi}{Fw_c} \qquad (18{:}7)$$

and finally

$$t = \frac{hw_c}{2\phi} \qquad (18{:}8)$$

Comparison of these expressions with those based on stiffness criteria show that facings could be about twice as thick for moment resistance criteria as for stiffness criteria and that h values are dependent on relative stiffness and bending moment requirements. The resultant construction will have about half its weight in the core.

Example: Determine dimensions of sandwich components so that the resultant composite will have a bending moment resistance of 7,000 in.-lb per in. of width. The facing properties are F = 45,000 psi yield stress and w = 0.100 pci and the core weight $w_c$ = 0.0034 pci.

From formula (18:7)

$$h = \left\{ \frac{2(7,000)(0.0983)}{45,000(0.0034)} \right\}^{\frac{1}{2}} = 3.00 \text{ in.}$$

and from formula (18:8)

$$t = \frac{3.00(0.0034)}{2(0.0983)} = 0.052 \text{ in.}$$

With these dimensions the sandwich weight (minus bond weight) is 0.0204 psi of which 0.0101 psi or about 50 percent is in the core.

Example: Determine dimensions of sandwich components so that the resultant composite will have a bending moment resistance of at least 7,000 in.-lb per in. of width and a bending stiffness of at least $D = 3 \times 10^6$ lb-in.$^2$ per in. of width. The facing properties are $E/\lambda = 10^7$ psi, w = 0.100 pci, and $w_c$ = 0.0034 pci.

From the example in 18.3 the minimum-weight sandwich for the required stiffness will have h = 4.11 in., t = 0.035 in., and weight, W = 0.0209 psi. From formula (18:6) the facing stress in this sandwich due to bending moment is

$$F = \frac{7,000}{0.035(4.11)} = 48,600 \text{ psi}$$

and an alloy stronger than this stress must be used in the facings.

If an alloy with a yield stress of only 20,000 psi must be used, the design must be changed as follows, based on bending moment criteria

$$h = \left\{\frac{2(7,000)(0.0983)}{20,000(0.0034)}\right\}^{\frac{1}{2}} = 4.50 \text{ in.}$$

$$t = \frac{4.50(0.0034)}{2(0.0983)} = 0.078 \text{ in.}$$

These dimensions are larger than those necessary for required stiffness, thus the stiffness will be much more than needed (nearly three times as stiff). The sandwich weight (minus bond weight) is 0.0306 psi which is about 46 percent heavier than needed for stiffness criteria only. Thus the use of a stronger facing alloy would be distinctly advantageous.

The facing stress, F, should not exceed wrinkling or dimpling stresses given by procedures in chapters 3 and 4.

## 18.5 SANDWICH PANEL BUCKLING

The load at which general buckling of sandwich panels occurs is given by the formula

$$N = K\frac{\pi^2}{b^2}D \qquad (18:9)$$

where N is buckling load per unit panel width; K is a coefficient dependent upon type of loading, type of edge support, panel aspect ratio, and a shear parameter, V; b is panel width; and D is sandwich bending stiffness per unit width. The parameter $V = \pi^2 D/b^2 U$ where U is the sandwich shear stiffness. V is usually quite small and the dependence of K upon V is of a secondary nature; thus the proportion of sandwich components to produce a minimum-weight construction having a given value of N will be very nearly the same as for a sandwich designed to have minimum weight and a specified stiffness (18.3). It is possible to minimize weight based on panel buckling criteria but most often so difficult that first approximations based on stiffness criteria suffice. An example is given to demonstrate procedure.

Example: Determine dimensions of sandwich components such that a simply supported panel 40 in. wide and 80 in. long will not buckle under a load (applied on the 40-in. side) of 40,000 lb. The facing properties are $E/\lambda = 10^7$ psi and w = 0.100 pci and the core properties $w_c = 0.0034$ pci and $G_c = 20{,}000$ psi.

For this panel the buckling coefficient is

$$K = \frac{4}{(1 + V)^2} \tag{18:10}$$

and combining this expression with (18:9) and the weight equation (18:1a) and minimizing the weight (ref. 18-4) results in:

$$h^3 = \frac{Nb^2(1 + V)^2}{2\pi^2 E/\lambda (1 - V)\frac{w_c}{4w}}$$

$$t = h(1 - V)\frac{w_c}{4w}$$

For this example, $w_c/4w = 0.0085$

then

$$h = \left\{\frac{40,000(40)(1 + V)^2}{2\pi^2(10^7)(0.0085)(1 - V)}\right\}^{\frac{1}{3}} = \left\{0.954\frac{(1 + V)^2}{(1 - V)}\right\}^{\frac{1}{3}}$$

$$t = 0.0085h(1 - V)$$

Assume values of V and compute h and t, then

| V | h | t |
|---|---|---|
| 0 | 0.984 | 0.0084 |
| 0.05 | 1.035 | 0.0084 |
| 0.10 | 1.086 | 0.0083 |
| 0.15 | 1.141 | 0.0082 |

This tabulation of values shows that variations in V have little influence on h and practically no influence on t.

Assume t = 0.0085 in., then the facing stress is

$$F = \frac{N}{2t} = \frac{1,000}{0.0170} = 59,000 \text{ psi}$$

Thus a strong facing material must be used; and if the core is a honeycomb, it must have a very small cell size to prevent face dimpling. Assuming these are possible, the actual value of V can be calculated. Assume h = 1 in. Then

$$V = \frac{\pi^2 thE/\lambda}{2b^2 G_c} = \frac{\pi^2(0.0085)(1)(10^7)}{2(1,600)(20,000)} = 0.0131$$

This value of V is so small that the effect of V is indeed negligible.

The weight of this panel is

$$W = 1(0.0034) + 0.017(0.100) = 0.0051 \text{ psi}$$

Choose a thicker facing to lower the stress--

$$\text{for } t = 0.020 \text{ in.,} \qquad F = \frac{1{,}000}{0.04} = 25{,}000 \text{ psi}$$

Then solving formulas (18:9) and (18:10) for D and finally h results in

$$h = 0.64 \text{ in. for } V = 0$$

$$h = 0.65 \text{ in. for } V = 0.0197 \text{ for } t = 0.020$$

The weight of this panel is

$$W = 0.65(0.0034) + 0.040(0.100) = 0.0062 \text{ psi}$$

which is a reasonable value; but is about 20 percent heavier than for sandwich with 0.0085-in. facings.

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# CHAPTER 19 -- DESIGN OF SANDWICH STRIPS UNDER TORSION LOAD

# CHAPTER 19

## DESIGN OF SANDWICH STRIPS UNDER TORSION LOAD

### 19.1 SCOPE

The design of sandwich strips under torsion load is based primarily upon limitations on the amount of twist rather than limitations upon torque-produced stresses in sandwich facings or core.

Design information is presented for sandwich strips of trapezoidal and triangular cross section. Strips of rectangular cross section are included as a limiting case of the trapezoidal cross section. The information presented applies to strips having thin, isotropic facings of equal thickness.

Design procedures for sandwich strips are arranged in a manner similar to the design of other sandwich components wherein facing and core thicknesses and properties can be determined for sandwich having a fixed width, length, and torsional rigidity. The shape of the cross section may be determined by nonstructural design features such as airfoil characteristics that require a specified angle between sandwich facings and a definite width of strip as for a control surface. Checking procedures are also presented.

A useful design hint for sandwich strips of any shape of cross section is that the torque is directly proportional to facing thickness for a given twist, facing stress, or core stress. The following procedures are restricted to linear elastic behavior.

### 19.2 DESIGN AND CHECKING PROCEDURES

Assuming that a design begins with chosen design stresses and a given load to transmit, a sandwich strip under torsion load shall be designed to comply with the four basic design principles summarized in 1.2 of the Introduction. These four conditions must be met.

Detailed procedures giving theoretical formulas and graphs for determining dimensions of facings and core, as well as necessary core properties, are given in following paragraphs. Facing modulus of rigidity values, G, and stress values, $F_s$, shall be values at the conditions of use; that is, if application is at elevated temperature, then facing properties at elevated temperature shall be used in design.

### 19.2.1 DETERMINING FACING THICKNESS, CORE THICKNESS AND CORE SHEAR MODULUS FOR SANDWICH STRIPS OF TRAPEZOIDAL AND RECTANGULAR CROSS SECTION

This section gives procedures for determining sandwich facing and core thicknesses and core shear modulus so that chosen design facing stresses and allowable sandwich twist will not be exceeded (ref. 19-1).

The angle of twist on one end of a trapezoidal sandwich strip of length L relative to the other end is given by the formula

$$\theta = \frac{k_1 TL}{2th^2 bG} \qquad (19:1)$$

where $\theta$ is angle of twist (radians), $k_1$ is a coefficient dependent upon a value of V and R, T is applied torque, b is width of sandwich strip, h is distance between centroids of sandwich facings, t is thickness of sandwich facing (see fig. 19-1 for notation), G is modulus of rigidity of sandwich facing, and V and R are given by the formulas

$$V = \frac{thG}{2b^2 G_c} \qquad (19:2)$$

$$R = \frac{b}{h} \tan \alpha \qquad (19:3)$$

where $G_c$ is core shear modulus, $\alpha$ is the angle shown in figure 19-1, and the remaining symbols are as defined previously.

The facing shear stress is maximum near the center of the strip width and is given by the formula

$$F_s = \frac{k_2 T}{2thb} \qquad (19:4)$$

where $F_s$ is facing shear stress, the $k_2$ is a coefficient dependent upon values of V and R.

The core shear stress is maximum at the thinner edge of the strip and is given by the formula

$$F_{sc} = \frac{k_3 T}{2hb} \sqrt{\frac{2G_c}{thG}} \qquad (19:5)$$

where $F_{sc}$ is core shear stress and $k_3$ is a coefficient dependent upon values of V and R.

Combining formulas (19:1) and (19:4) and solving for h results in

$$h = \frac{k_1 F_s L}{k_2 G \theta} \qquad (19:6)$$

Graphs of $k_1$ and $k_2$ are given in figures 19-2 to 19-5 wherein these coefficients are presented as functions of V and R.

### 19.2.1.1 DETERMINATION OF MINIMUM VALUES OF h AND t

Minimum values of h and t will be determined by assuming V = 0 for a first approximation. The values of h and t and minimum because V = 0 only if the core shear modules is infinite; for any actual core the shear modulus is not infinite, hence thicker cores and facings must be used. Values of $k_1$ and $k_2$ for V = 0 are obtained from the graphs of figures 19-2 and 19-4 and substituted into formula (19:6) to obtain a minimum value of h.

Substitution of this value of h into formula (19:4) and solving for t results also in a minimum value for t.

If the resultant value of t is too small for a reasonable facing thickness, it will be necessary to lower the value of the facing stress $F_s$ and begin the design again with formula (19:6).

### 19.2.1.2 DETERMINATION OF ACTUAL VALUES OF h AND t

Since actual core shear modulus values are not very large, values of h and t somewhat greater than that given by formulas (19:6) and (19:4) must be used. Actual values of h can be determined from formula (19:6) with values of $k_1$ and $k_2$ read from the graphs of figures 19-2 through 19-5 for $V \neq 0$. In using these graphs it is necessary to iterate because V is directly proportional to h and t and R is dependent upon h. As an aid to finally determining h and $G_c$, figure 19-6 presents a number of lines representing V for various values of $G_c$ with V ranging from 0.01 to 2 and $G_c$ ranging from 1,000 to 1,000,000 psi. The following procedure is suggested:

1. Determine R from formula (19:3) using the minimum value of h from 19.2.1.1.

2. Determine $k_1$ and $k_2$ from figures 19-2 and 19-4 using a value of 0.01 for V.

3. Compute h with formula (19:6) and with this value of h compute a new value of R using formula (19:3).

4. Repeat steps 2 and 3 until the value of h from (19:6) agrees with the value used in (19:3) to compute R.

5. Compute t with formula (19:4) solved for t

$$t = \frac{k_2 T}{2hbF_s}$$

6. Compute the constant relating V to $G_c$

$$\frac{thG}{2b^2} = VG_c$$

7. With this constant enter figure 19-6 and determine necessary $G_c$.

8. If the shear modulus is outside the range of values for materials available, slide up the appropriate line figure 19-6 and pick a new value for V, for a reasonable value of core shear modulus.

9. Reenter figures 2 and 3 with new value of V and repeat previous steps.

### 19.2.1.3 CHECKING PROCEDURE FOR SANDWICH STRIPS OF TRAPEZOIDAL AND RECTANGULAR CROSS SECTION

The design shall be checked by using the graphs of figures 19-2 to 19-8 to determine the k coefficients and formulas (19:1), (19:4), and (19:5) to determine theoretical performance.

If the rectangular cross section is enclosed the angle of twist can be estimated by elementary theory for torsion of rectangular cross sections. The coefficient $k_1$ for enclosed, thin-walled, rectangular cross sections is given in the graph of figure 19-9.

### 19.2.2 DETERMINING FACING THICKNESS AND CORE SHEAR MODULUS FOR SANDWICH STRIPS OF TRIANGULAR CROSS SECTION

This section gives procedures for determining sandwich facing thickness and core shear modulus so that chosen design facing stresses and allowable sandwich twist will not be exceeded (ref. 19-1).

The angle of twist of one end of a triangular sandwich strip of length L relative to the other end is given by the formula

$$\theta = \frac{k_{11} TL}{8tb^3 G} \qquad (19:7)$$

where $\theta$ is angle of twist (radius), $k_{11}$ is a coefficient dependent upon values of W and $\alpha$, T is applied torque, b is width of sandwich strip, t is thickness of sandwich facing, $\alpha$ is the angle shown in the sketch of notation in figure 19-10, G is modulus of rigidity of sandwich facing, and W is given by the formula

$$W = \frac{tG}{2bG_c} \qquad (19:8)$$

where $G_c$ is core shear modulus and the remaining symbols are as defined previously.

The facing shear stress is maximum near the center of the strip width and is given by the formula

$$F_s = \frac{k_{22}T}{4tb^2} \qquad (19:9)$$

where $F_s$ is facing shear stress, and $k_{22}$ is a coefficient dependent upon values of W and $\alpha$.

The core shear stress is maximum at the thicker edge of the strip and is given by the formula

$$F_{sc} = \frac{k_{33}T}{4b^3} \qquad (19:10)$$

where $F_{sc}$ is core shear stress and $k_{33}$ is a coefficient dependent upon values of W and $\alpha$ .

Solution of formulas (19:7) and (19:9) for facing thickness, t, results in for following two expressions

$$\theta = \frac{k_{11}TL}{8b^3G} \qquad (19:11)$$

and

$$t = \frac{k_{22}T}{4b^2F_s} \qquad (19:12)$$

and the larger value determined by (19:11) or (19:12) must be used to prevent excessive twist or stress.

### 19.2.2.1 DETERMINATION OF MINIMUM VALUES OF t

A minimum value of t will be determined by assuming W = 0 for a first approximation. The value of t is minimum because W = 0 only if the core shear modulus is infinite; for any actual core the shear modulus is not infinite, hence a thicker core must be used. Values of $k_{11}$ and $k_{22}$ for W = 0 are obtained from the graphs of figures 19-11 and 19-12 and substituted into formulas (19:11) and (19:12) to obtain minimum values of t. The larger value from formulas (19:11) and (19:12) will be the value of t for W = 0. If this value of t is too small for a reasonable facing thickness, it will be necessary to lower the values of twist, $\theta$, and facing stress, $F_s$, and begin the design again with formulas (19:11) and (19:12).

### 19.2.2.2 DETERMINATION OF ACTUAL VALUES OF t

Since actual core shear modulus values are not very large, a value of t somewhat greater than that given by formula (19:11) or (19:12) must be used. Actual values of t can be determined from formulas (19:11) or (19:12) with values of $k_{11}$ and $k_{22}$ read from the graphs of figures 19-11 and 19-12 for $W \neq 0$. In using these graphs it is necessary to iterate because W is directly proportional to t. As an aid to finally determining t and $G_c$ figure 19-6 presents a number of lines representing V or W for various values of $G_c$ with V or W ranging from 0.01 to 2 and $G_c$ ranging from 1,000 to 1,000,000 psi. The following procedure is suggested:

1. Determine $k_{11}$ and $k_{22}$ from figures 19-11 and 19-12 using a value of 1 for W.

2. Compute t as the larger of formulas (19:11) or (19:12).

3. Compute the constant relating W to $G_c$

$$\frac{tG}{2b} = WG_c$$

4. With this constant enter figure 19-6 and determine necessary $G_c$.

5. If the shear modulus is outside the range of values for materials available, slide up the appropriate line of figure 19-6 and pick a new value for W, for a reasonable value of core shear modulus.

6. Reenter figures 19-11 and 19-12 with the new value of W and repeat previous steps 1 through 5.

## 19.2.2.3 CHECKING PROCEDURE FOR SANDWICH STRIPS OF TRIANGULAR CROSS SECTION

The design shall be checked by using the graphs of figures 19-11 to 19-13 to determine the k coefficients and formulas (19:7), (19:9) and (19:10) to determine theoretical performance.

If the triangular cross section is enclosed the angle of twist can be determined by theory of Reference (19-2). The coefficient $k_{11}$ for enclosed, thin-walled, triangular cross sections is given in the graph of figure 19-14.

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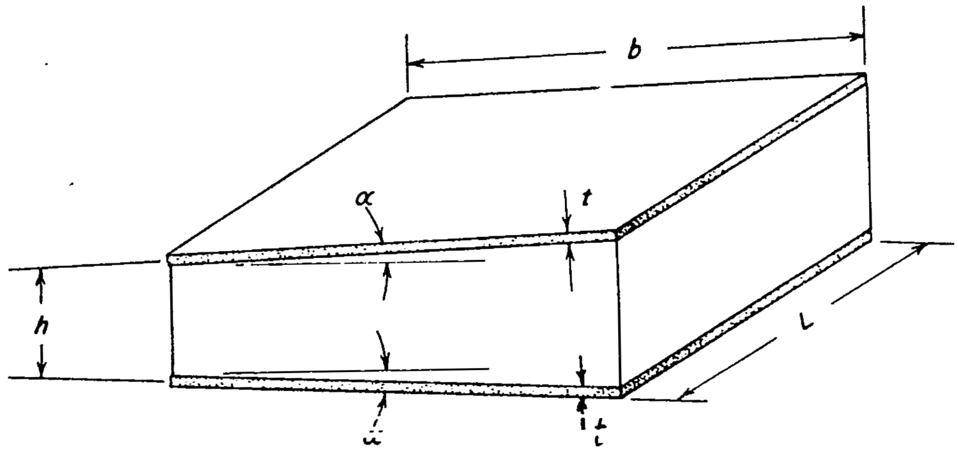


Figure 19-1.--Notation for sandwich of trapezoidal cross section in torsion.

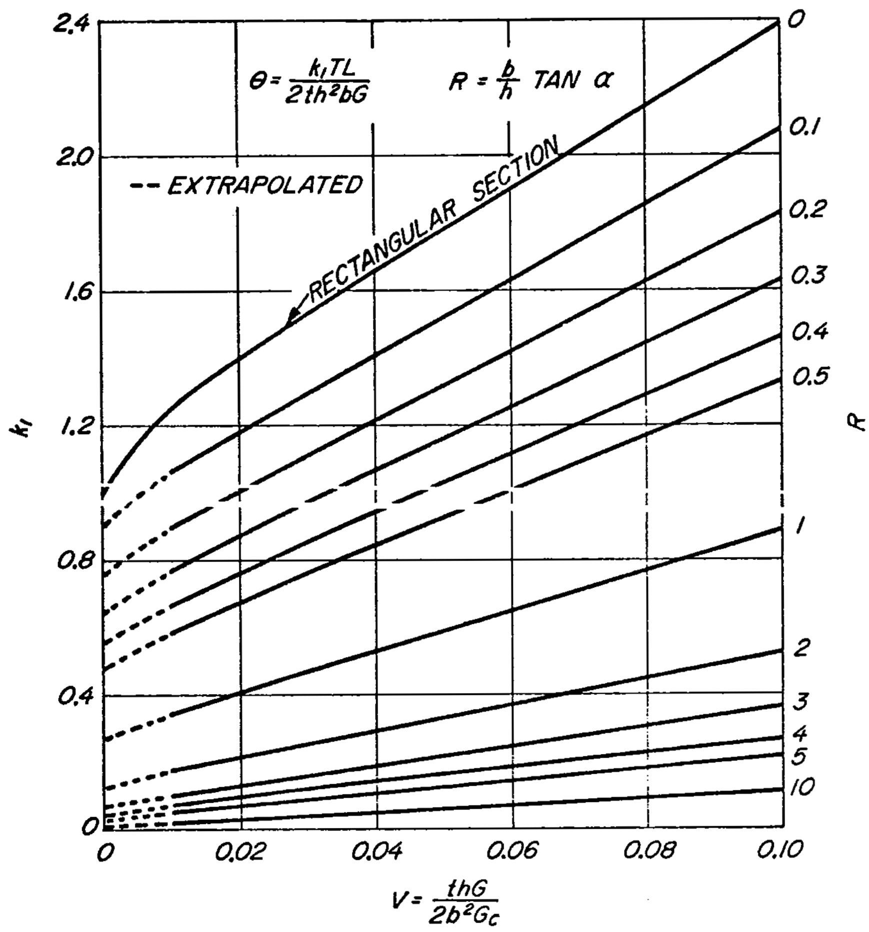


Figure 19-2.--Coefficient $k_1$ for designing sandwich of rectangular and trapezoidal cross section--stiff cores.

(M 141 398)

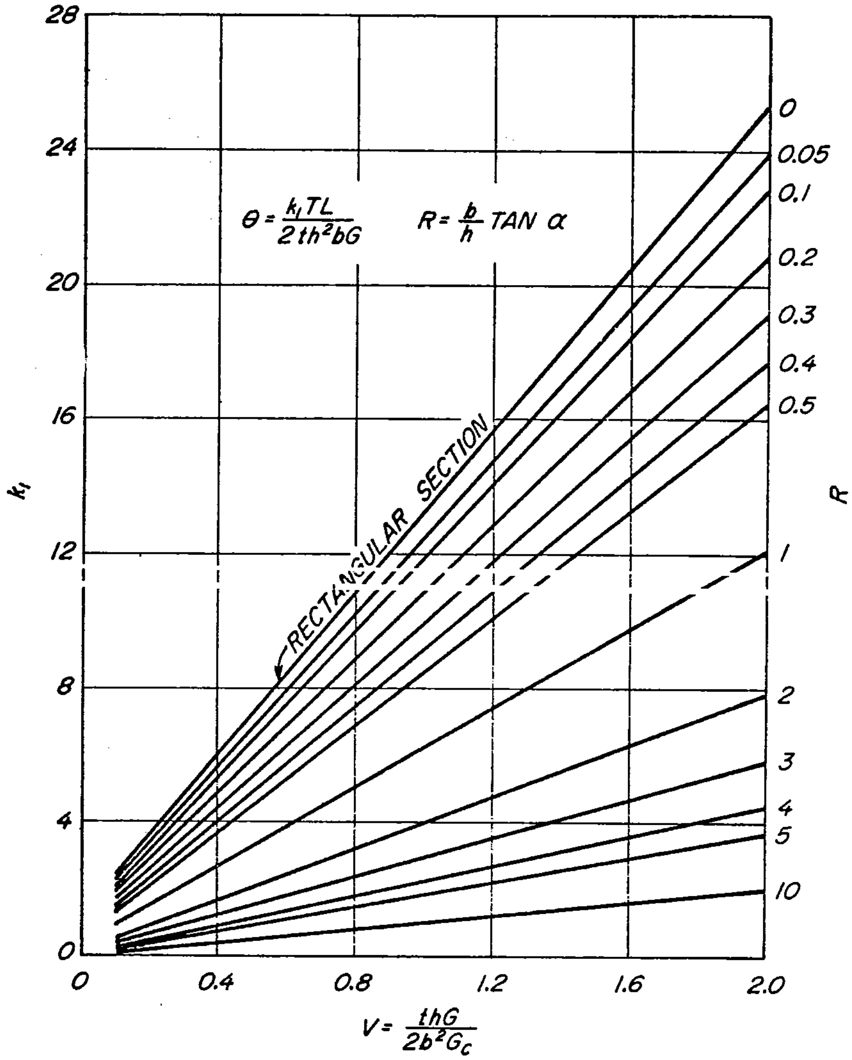


Figure 19-3.--Coefficient $k_1$ for designing sandwich of rectangular and trapezoidal cross section.

(M 141 399)

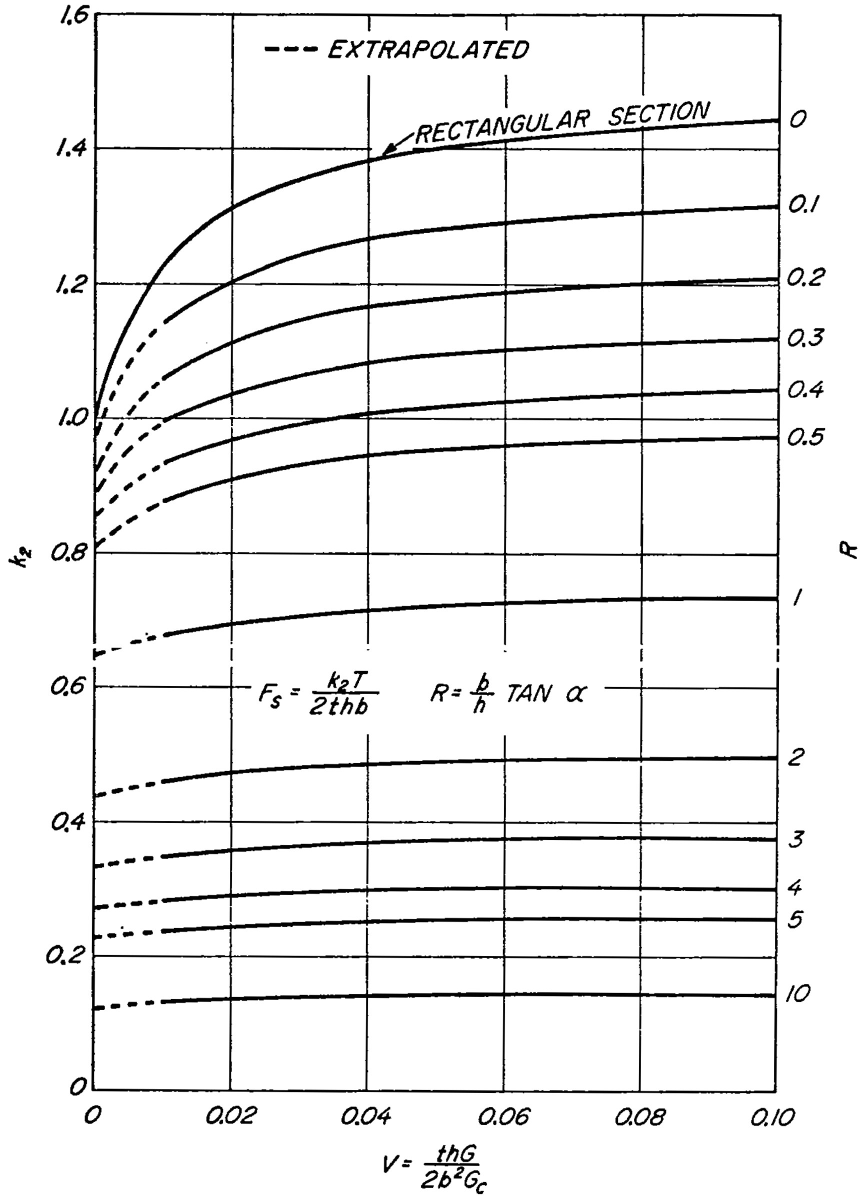


Figure 19-4.--Coefficient $k_2$ for designing sandwich of rectangular and trapezoidal cross section--stiff cores.

(M 141 400)

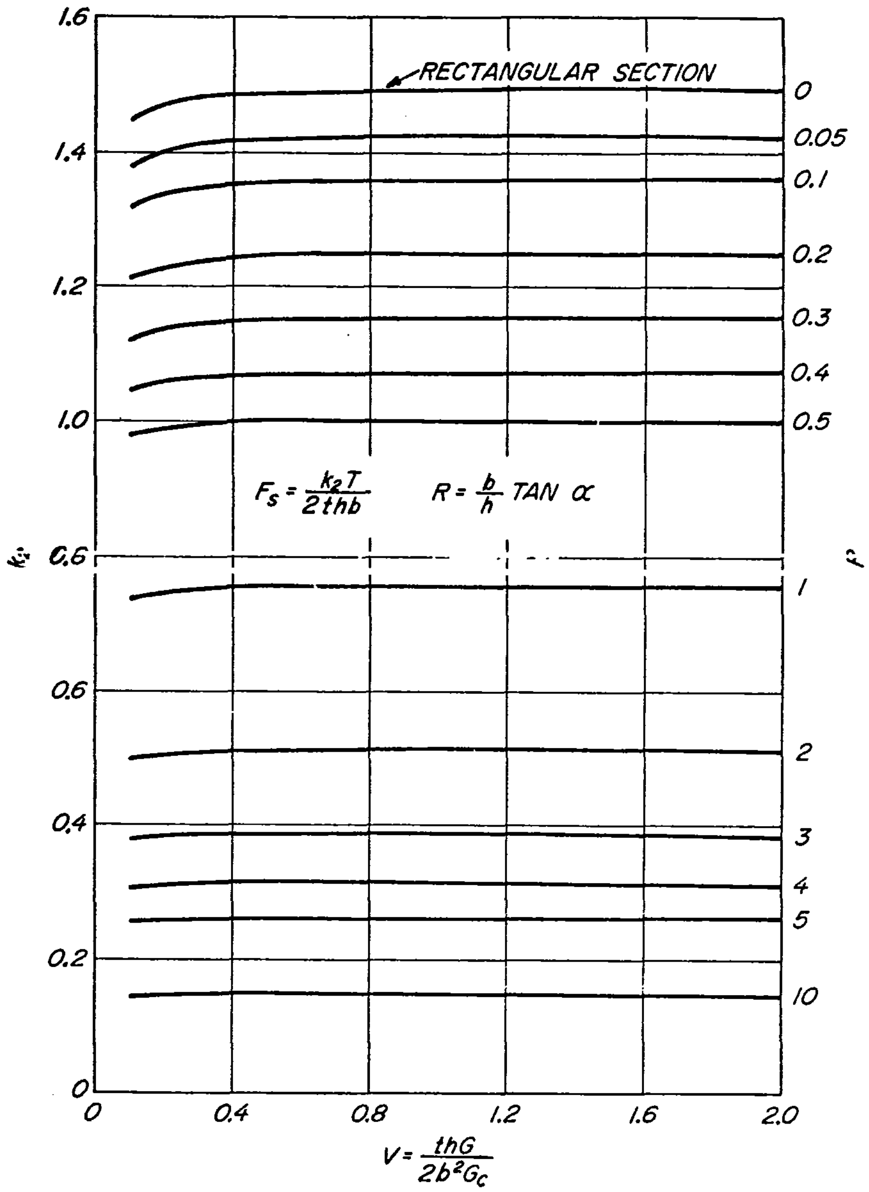


Figure 19-5.--Coefficient $k_2$ for designing sandwich of rectangular and trapezoidal cross section.

(M 141 401)

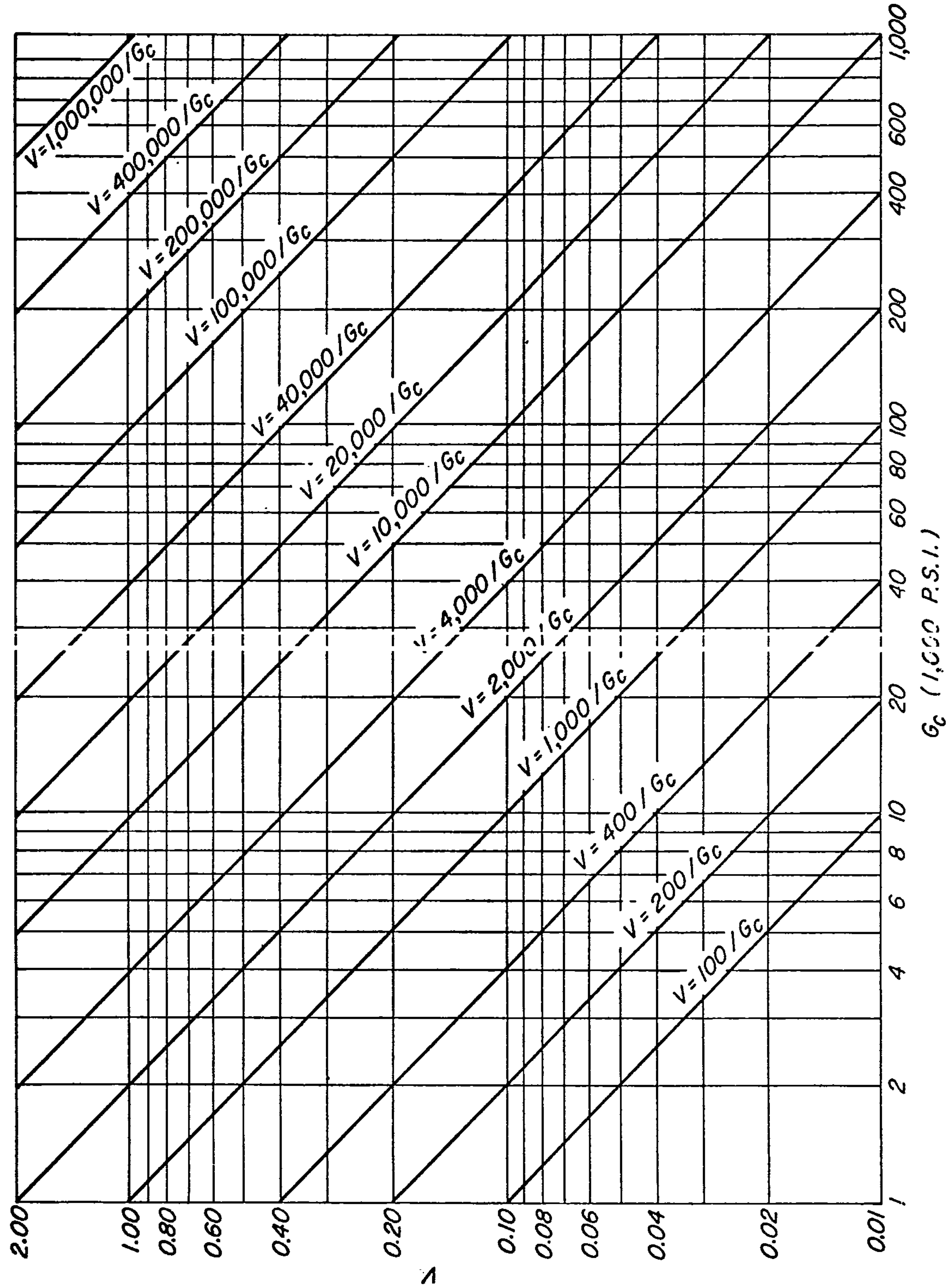


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Figure 19-6.--Chart for determining V or W and $G_c$ for sandwich strips in torsion.

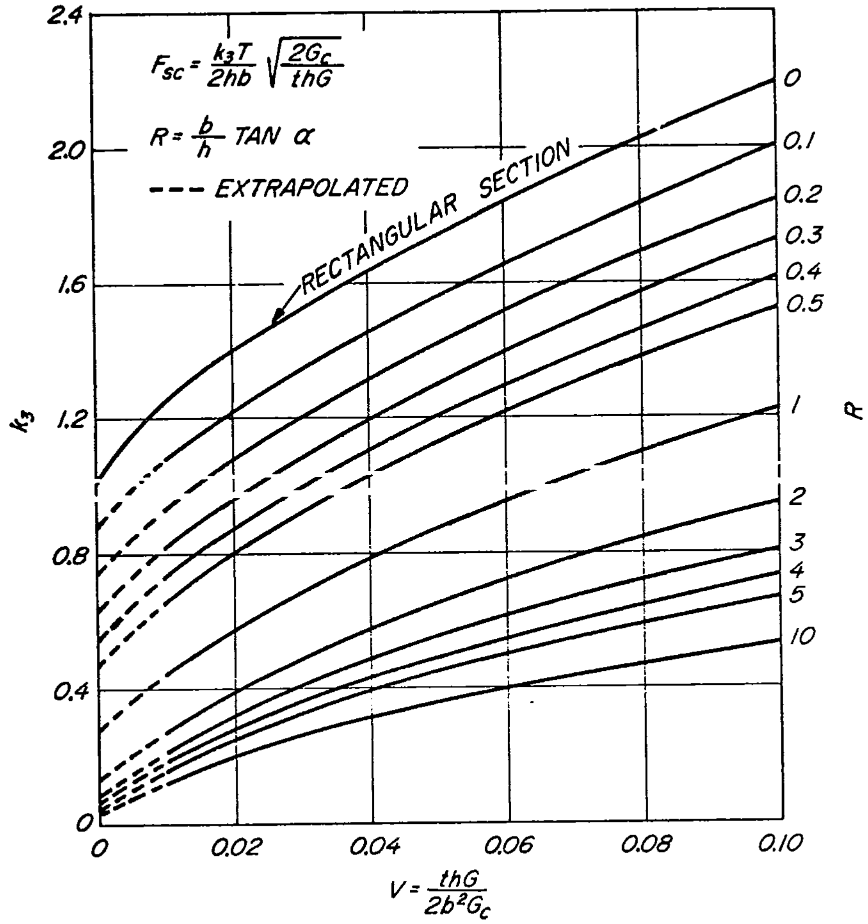


Figure 19-7.--Coefficient $k_3$ for designing sandwich of rectangular and trapezoidal cross section--stiff cores.

(M 141 407)

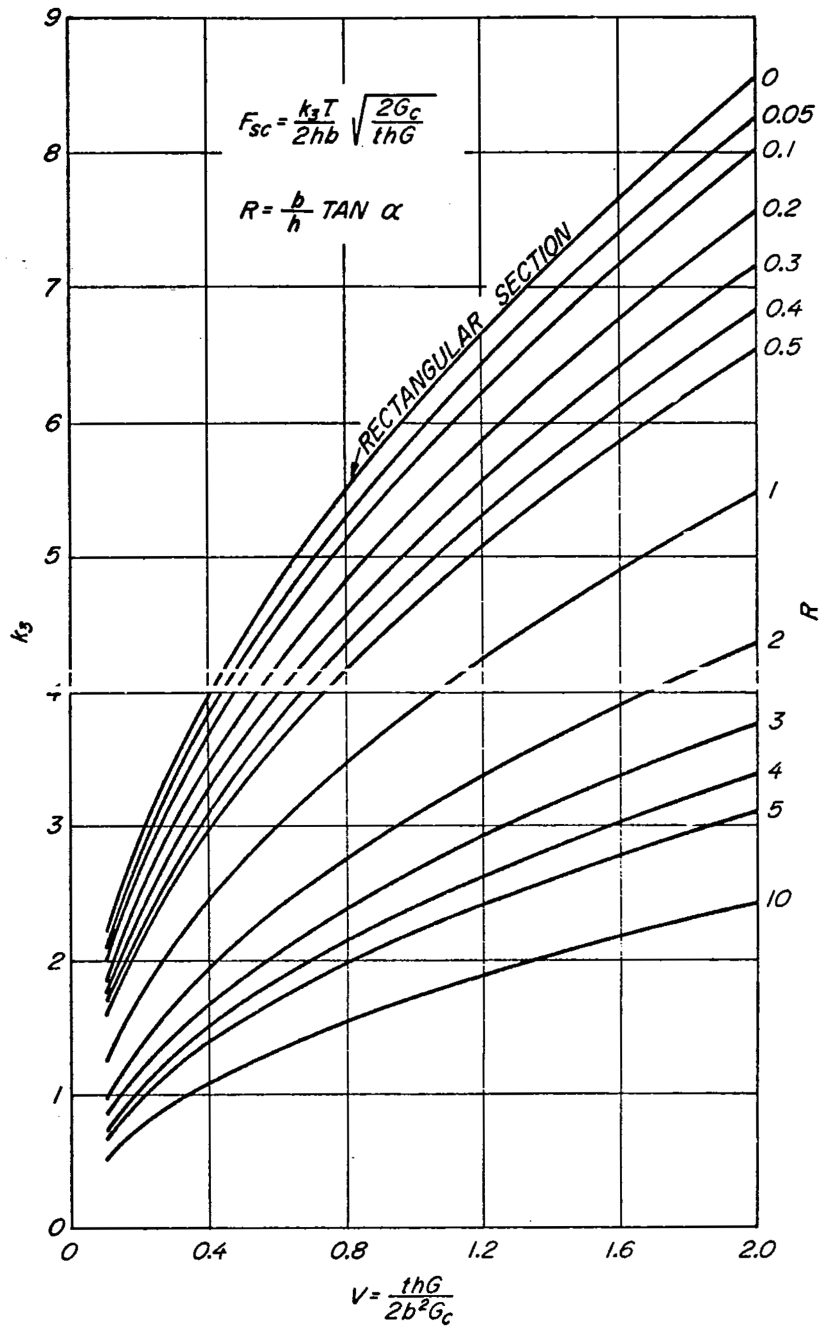


Figure 19-8.--Coefficient $k_3$ for designing sandwich of rectangular and trapezoidal cross section.



(M 141 402)

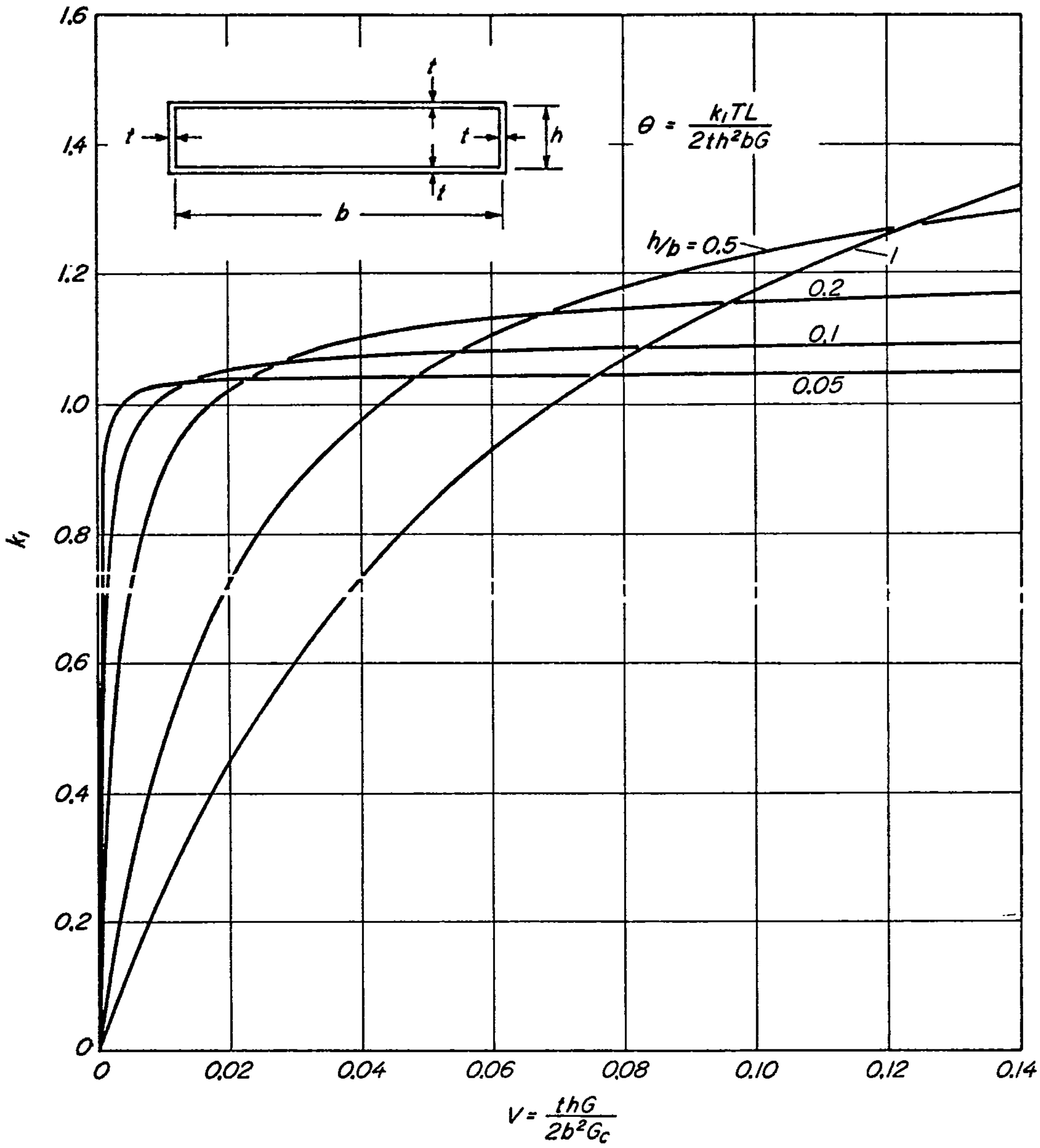


Figure 19-9.--Coefficient $k_1$ for designing sandwich strips of enclosed, thin-walled, rectangular cross section in torsion.

(M 141 403)

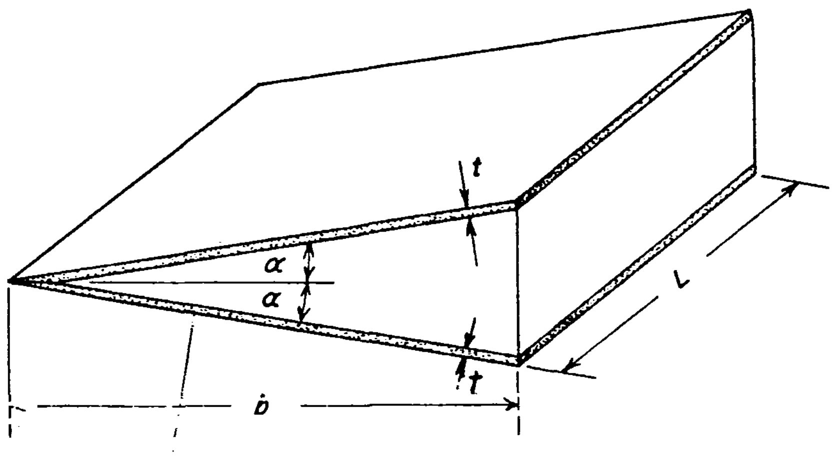


**Figure 19-10.**--Notation for sandwich of triangular cross section in torsion.

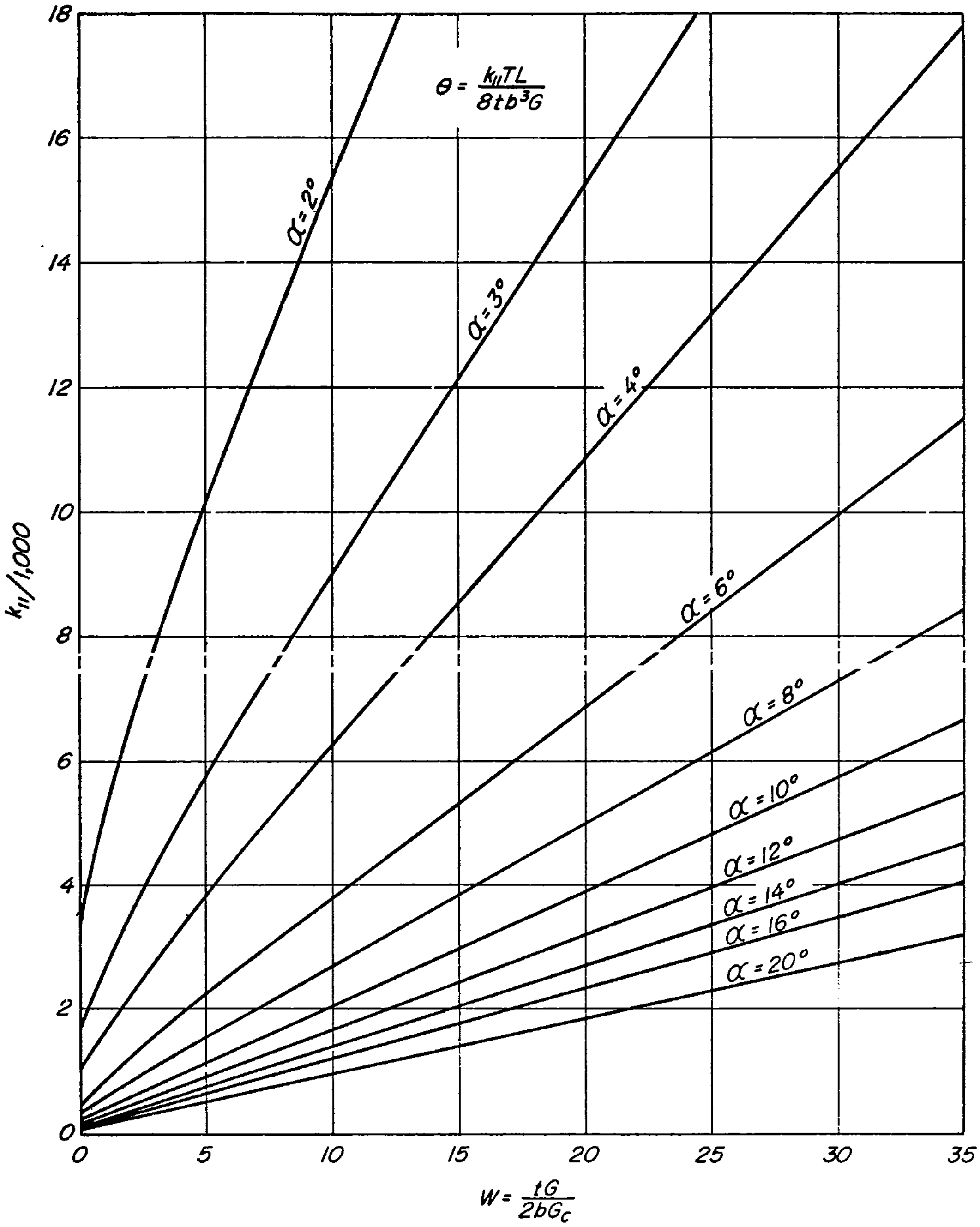


Figure 19-11.--Coefficient $k_{11}$ for designing sandwich strips of triangular cross section in torsion.



(M 141 404)

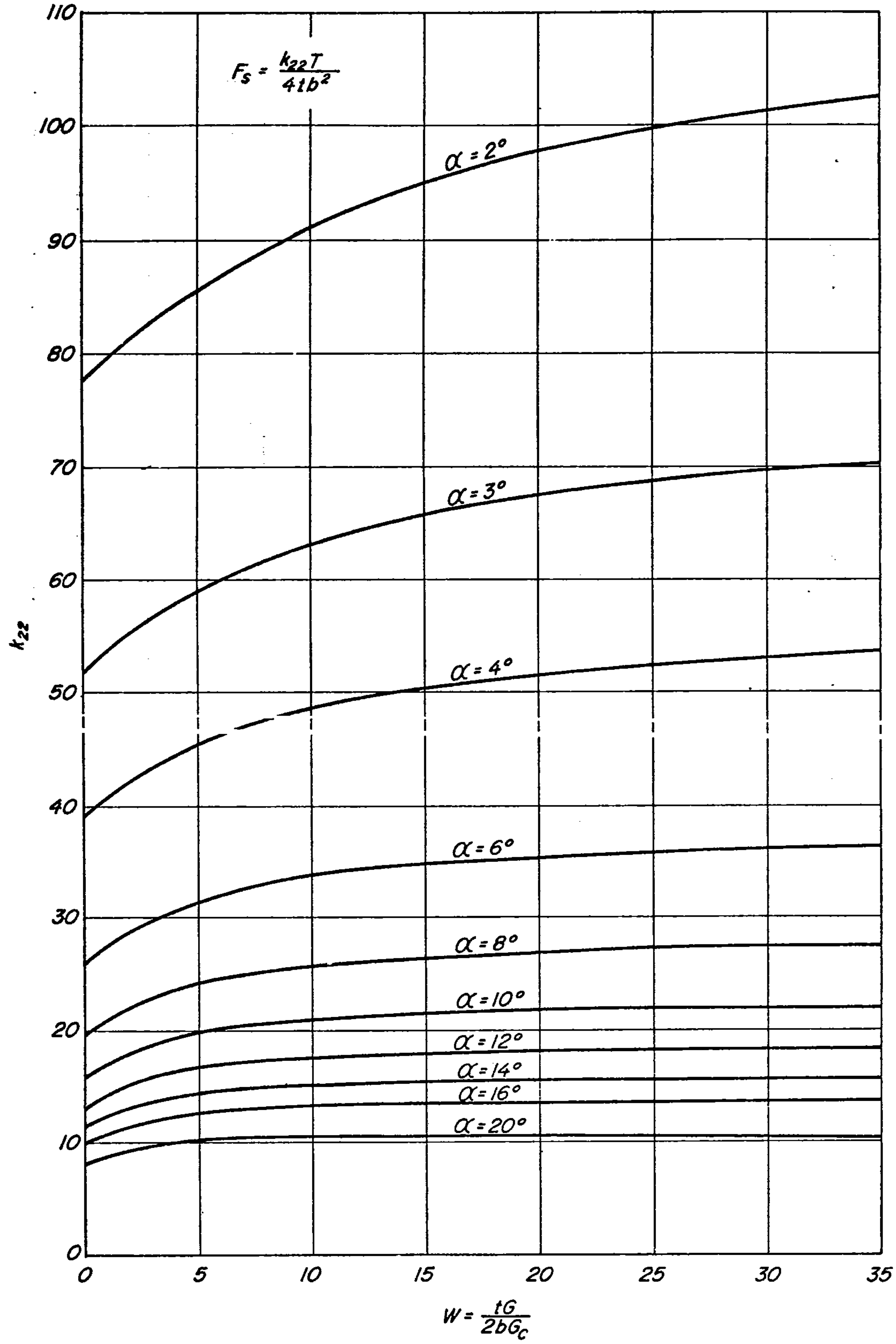


Figure 19-12.--Coefficient $k_{22}$ for designing sandwich strips of triangular cross section in torsion.

(M 141 307)

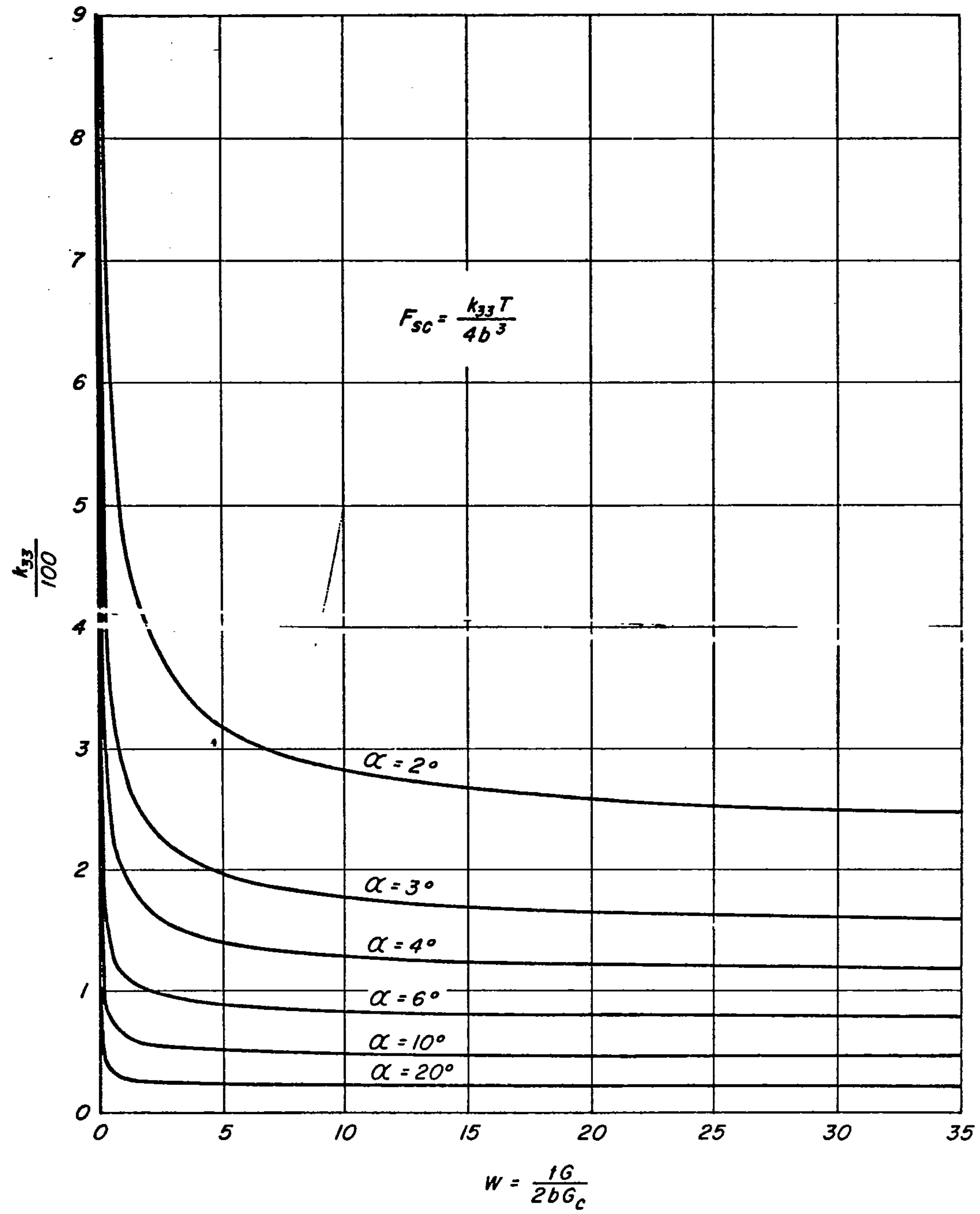


Figure 19-13.--Coefficient $k_{33}$ for designing sandwich strips of triangular cross section in torsion.

(M 141 405)

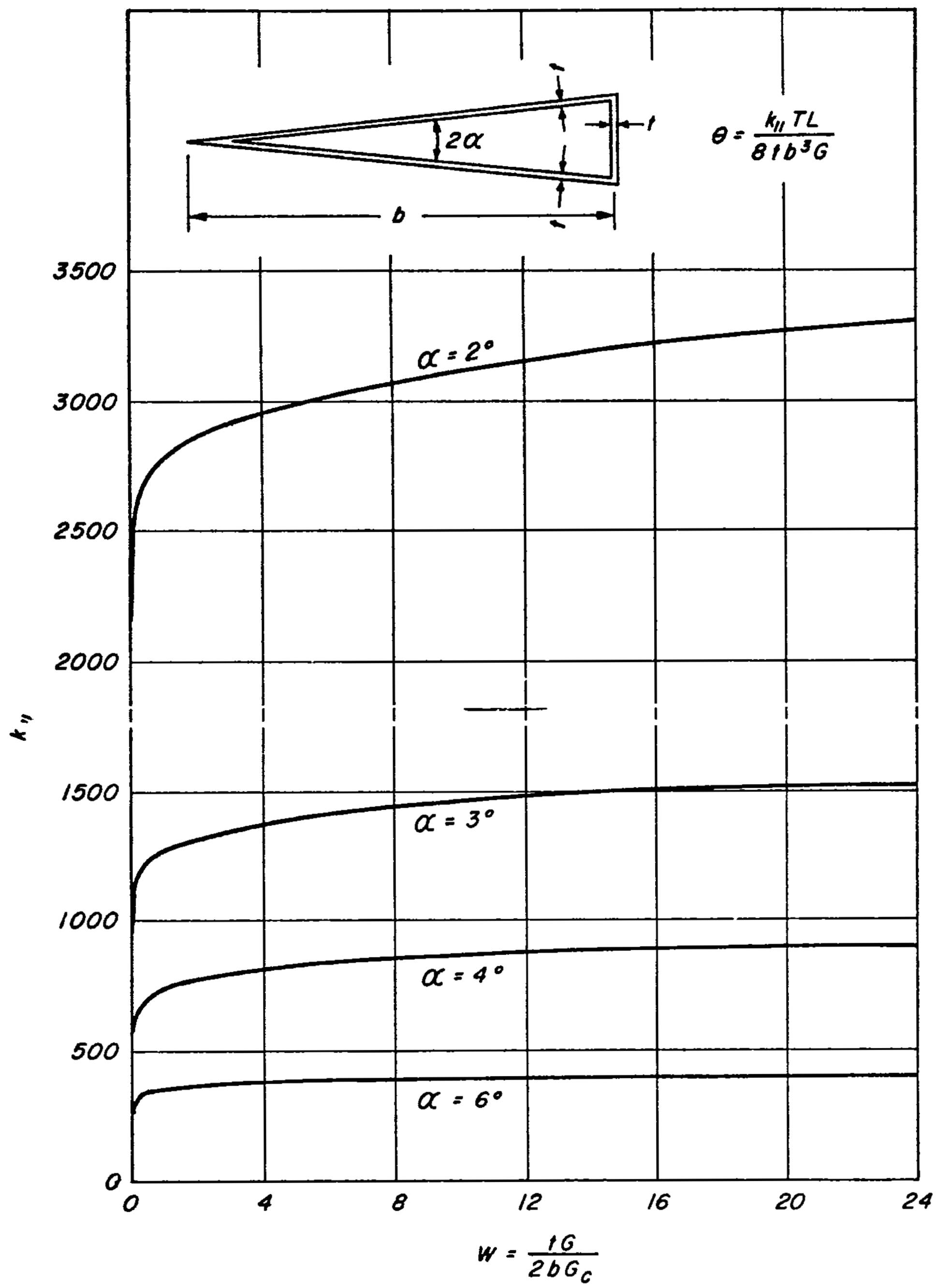


Figure 19-14.--Coefficient $k_{11}$ for designing sandwich strips of triangular cross section in torsion.



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# CHAPTER 20 -- DESIGN OF CIRCULAR SANDWICH PANELS LOADED AT AN INSERT

# CHAPTER 20

## DESIGN OF FLAT CIRCULAR SANDWICH PANELS LOADED AT AN INSERT

### 20.1 SCOPE

This chapter presents information for the design of a sandwich panel with a rigid insert. The insert is placed in the sandwich panel to allow the introduction of load from a point outside the plane of the panel. The basic formulas for deflections and stresses (ref. 20-1) were derived for a load normal to the panel. Experimental data (ref. 20-3), however, have shown that the formulas were also satisfactory for loads inclined at angles between 45° and 90° to the panel plane provided that the formulas were modified to utilize the normal component of the inclined load. Deflections at the insert and stresses in the neighborhood of the insert are the bases for design.

Although the design formulas were derived for circular panels, their application to panels of other shapes would not be expected to be in great error if the insert size was relatively small compared with the panel size.

### 20.2 BASIC PRINCIPLES

Usually the design of a sandwich panel with an insert will begin with a panel configuration based upon in-plane or normal distributed loading as covered by other chapters in this handbook, thus resulting in known facing and core thicknesses and core shear properties. An insert is then to be placed in the panel to allow introduction of load, and the size of the insert must be determined plus the stresses and deflections caused by the load applied at the insert. The procedure followed here will be to determine insert size based on core shear stress limitations and then check facing stresses and sandwich deflections.

Assuming that a design begins with chosen design stresses and a given load to transmit, a sandwich panel with a loaded insert shall be designed to comply with the four basic design principles summarized in 1.2 of Introduction. These four conditions must be met.

Detailed procedures giving theoretical formulas and graphs for determining insert size, facing stresses, and panel deflections are given in the following paragraphs. Where double formulas are given, one formula is for sandwich with facings of different materials and thicknesses and a second formula is for sandwich with each facing of the same material and thickness. Facing and core elastic properties and stresses shall be values at the condition of use; that is, if application is at elevated temperature then properties at elevated temperature shall be used in design. The following procedures are restricted to linear elastic behavior.

## 20.3 DETERMINING INSERT SIZE

This section gives the procedure for determining the insert diameter so that the shear stress in the sandwich core will not exceed allowable values. The core shear stress is given by the theoretical formula (ref. 20-1):

$$F_{sc} = \frac{k_r P}{2\pi hb} \qquad (20:1)$$

where P is the normal component of the load applied at the insert, h is distance between facing centroids, b is insert radius, and $k_r$ is a coefficient dependent upon b/a and $\phi a$ where

$$\phi a = \left(\frac{hG_c}{D_F}\right)^{1/2} a \qquad (20:2)$$

where a is radius of circular sandwich plate, $G_c$ is core shear modulus and

$$D_F = \frac{1}{12}\left(\frac{E_1 t_1^3}{\lambda_1} + \frac{E_2 t_2^3}{\lambda_2}\right) \text{(for unequal facings)} \qquad (20:3)$$

$$D_F = \frac{Et^3}{6\lambda} \text{ (for equal facings)} \qquad (20:3a)$$

where E is modulus of elasticity of facing; $\lambda = 1 - \mu^2$; $\mu$ is facing Poisson's ratio; t is facing thickness; and 1 and 2 are subscripts denoting facing 1 or 2.

The radial distribution of the core shear stress coefficient $k_r$ is shown in figure 20-1 for a panel in which b/a = 0.04. The maximum shear stress coefficient occurs near the insert for large values of ($\phi$a) and moves away from the insert and becomes smaller as values of ($\phi$a) decrease. Therefore, it is not wise to use a stiff core if shear stresses approach design allowables in fairly large panels.

The maximum core shear stress upon which the design must be based is given by the formula (ref. 20-1)

$$F_{scmax} = \frac{k_3 P}{2\pi hb} \qquad (20:4)$$

where $k_3$ is given in the graph of figure 20-2. Solving formula (20:4) for b results in

$$b = \frac{k_3 P}{2\pi h F_{scmax}} \qquad (20:5)$$

Solution of formula (20:5) cannot be performed directly because the coefficient $k_3$ is dependent upon values of b as given in the abscissa, b/a, of figure 20-2. A means of indirect solution of (20:5) can be devised as follows: Solving (20:5) for $k_3$ in terms of b/a results in

$$k_3 = C\left(\frac{b}{a}\right) \qquad (20:6)$$

where

$$C = \frac{2\pi h a F_{scmax}}{P} \qquad (20:7)$$

Formula (20:6) represents a family of straight lines having a slope, C, and extending from the origin of the graph of figure 20-2. The value of C is determined from formula (20:7) with known dimensions, stress, and load. A solution of (20:5) is obtained from the intersection of a straight line of slope C with the appropriate $\phi$a curve on the graph of figure 20-2. The value of the insert radius, b, is obtained by multiplying the abscissa of the intersection point by the panel radius, a. This can be checked by reading $k_3$ at the intersection point and substitution into formula (20:5). Examples illustrating procedure will follow facing stress and panel deflection determinations.

The maximum facing stress occurs at the insert in the radial direction and is given by the formula

$$F_{1,2} = \frac{k_4 P}{4\pi t_{1,2} h} \qquad (20:8)$$

where $F_{1,2}$ is stress in facing 1 or 2 of thicknesses $t_1$ or $t_2$ and $k_4$ is given by the graph of figure 20-3. Curves are given, in figure 20-3, for panels with outer rim simply supported or clamped.

The deflection at the insert is given in two parts, bending deflection, $\delta_B$, and shear deflection, $\delta_S$. The bending deflection is given by the formula

$$\delta_B = \frac{k_1 P a^2}{16\pi D} \qquad (20:9)$$

where $k_1$ is given by the graph of figure 20-4 for panels with outer rim simply supported or clamped; and D is sandwich bending stiffness given by

$$D = \frac{E_1 t_1 E_2 t_2 h^2}{\lambda(E_1 t_1 + E_2 t_2)} \qquad (20:10)$$

$$D = \frac{Eth^2}{2\lambda} \qquad (20:10a)$$

The shear deflection at the insert is given by the formula

$$\delta_s = \frac{k_2 P}{2\pi h G_c} \qquad (20:11)$$

where $k_2$ is given by the graph of figure 20-5.

Examples:

1. A sandwich has 0.080-inch facings on a core 1.12 inch thick. The facing modulus of elasticity is E = 10,000,000 p.s.i. and Poisson's ratio is $\mu = 0.3$. The core shear modulus is $G_c = 2,000$ p.s.i. and core shear design stress $F_{sc} = 60$ p.s.i. The plate has a radius a = 25 inches and an insert supporting a normal load component of 1,900 pounds. Determine the insert sized and finally stresses and deflections.

From formula (20:3a) $D_F = 940$ pounds in. $^2$/in. of width; from formula (20:2) $\phi$ a = 40; and from formula (20:7) C = 5.95. From figure 20-2 the intersection of the line C = 5.95 with the curve $\phi$ a = 40 occurs at b/a = 0.091 and $k_3 = 0.54$. From this b = 0.091(25) = 2.28 inch, thus giving an insert diameter of 4.56 inches. Checking by substituting $k_3 = 0.54$ into formula (20:5) also produces the same insert size.

From figure 20-3 it is determined that $k_4 = 5.26$ for the rim simply supported; substitution of this into forumla (20:8) results in a facing stress of 8,280 p.s.i.

From formula (20:10a) the sandwich bending stiffness is found to be D = 633,000 pounds in. $^2$/in. of width. From the graph of figure 20-4 it is determined that $k_1 = 2.16$ for the rim simply supported and substitution of this into formula (20:9) results in a bending deflection of 0.081 inch. From figure 20-5, $k_2 = 2.15$ and substitution into formula (20:11) results in a shear deflection of 0.271 inch. Thus the total insert deflection was 0.352 inch.

2. A sandwich the same size as the previous example with the same material in the facings but a core 10 times stiff--$G_c = 20,000$ p.s.i. and strength of $F_{sc} = 300$ p.s.i. For these data values of a = 126 and C = 29.8 and from figure 20-2 there is no solution. A conservative solution can be made by assuming $k_3 = 1$. Then from formula (20:5) b = 0.84 inch, thus giving an insert diameter of 1.68 inch. Proceeding as in the previous example we determine:

Facing stress F = 11,460 p.s.i
Bending deflection $\delta_B$ = 0.090 inch
Shear deflection $\delta_s$ = 0.044 inch
Total deflection = 0.134 inch

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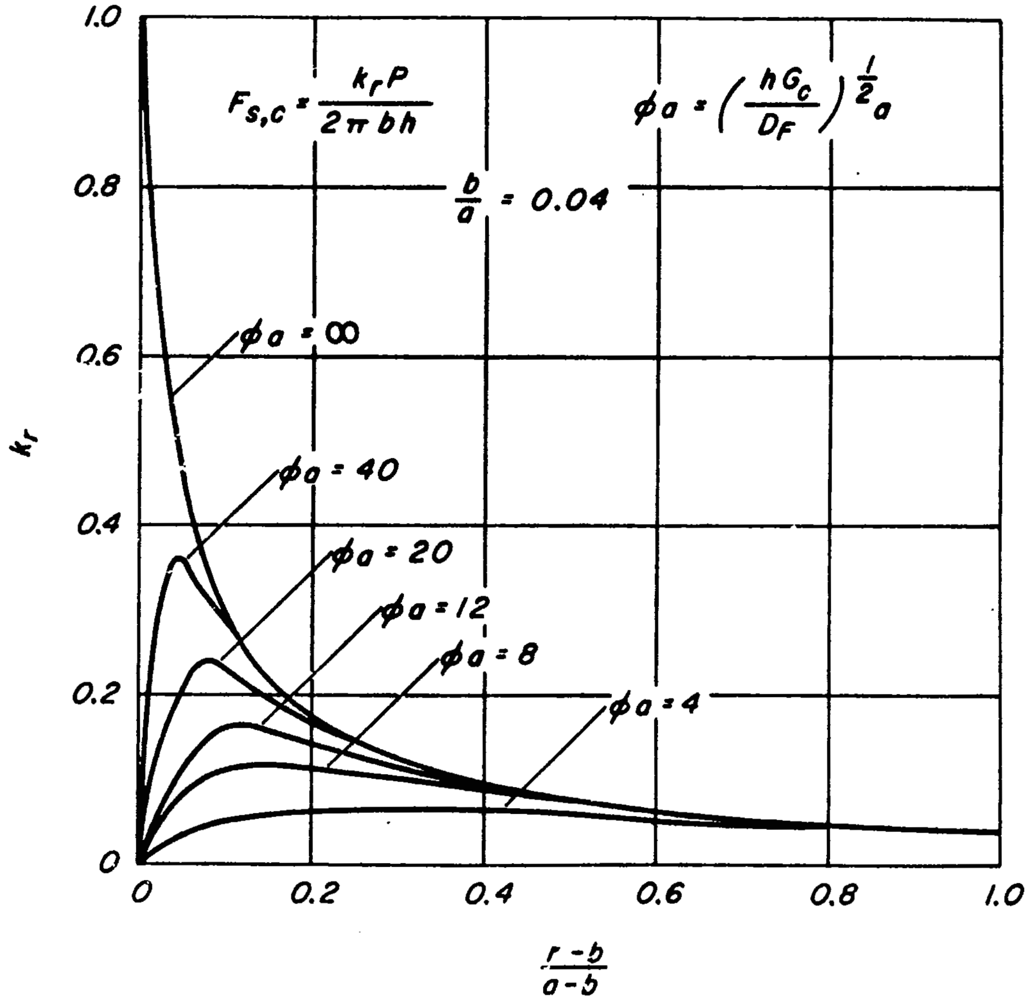


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Figure 20-1.--Radial distribution of core shear stress coefficient $k_r$. Rim of panel simply supported.

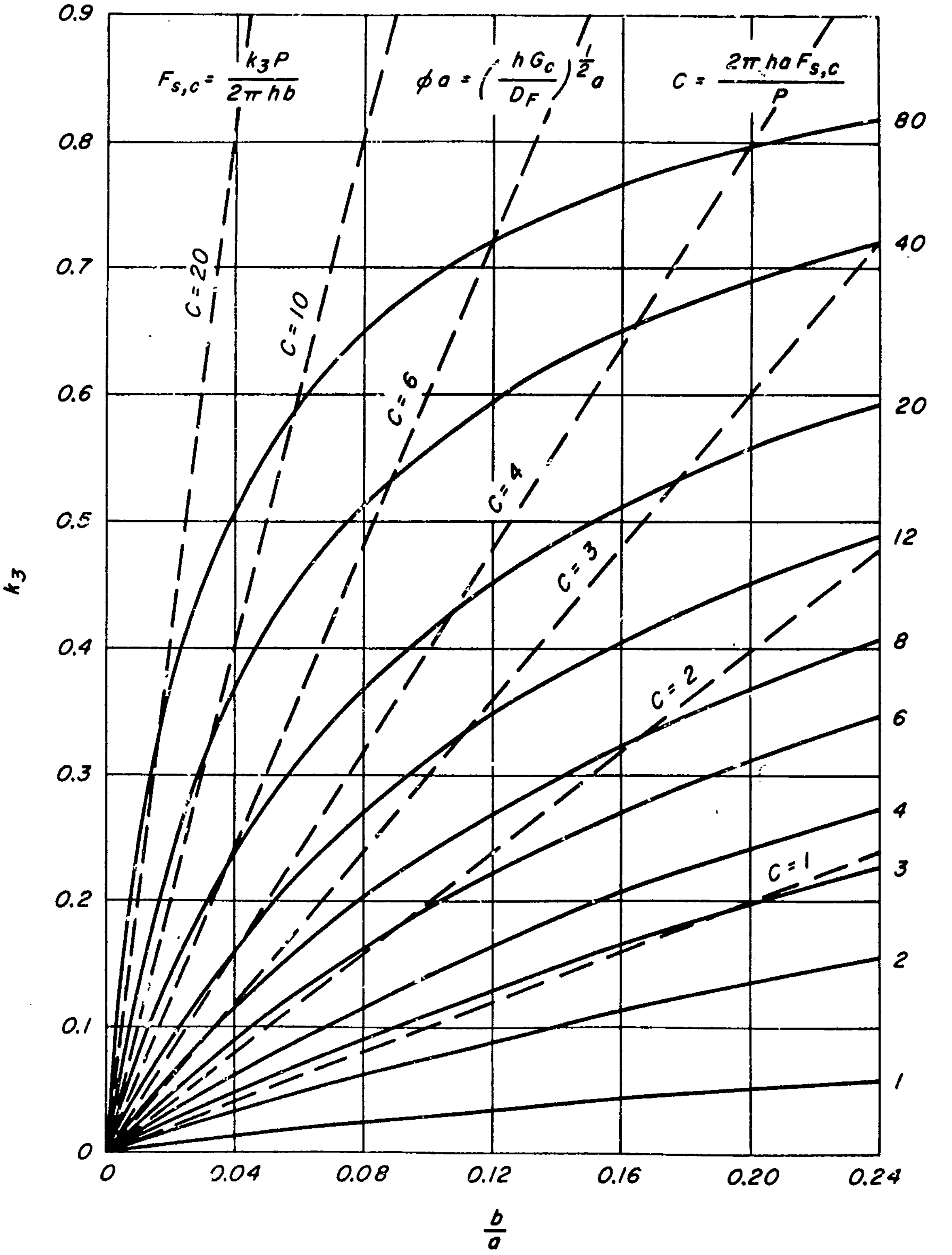


Figure 20-2.--Coefficient $k_3$ for determining maximum core shear stress; rim simply supported. (For a clamped rim $k_3$ values are conservative for $\phi a < 6$.)
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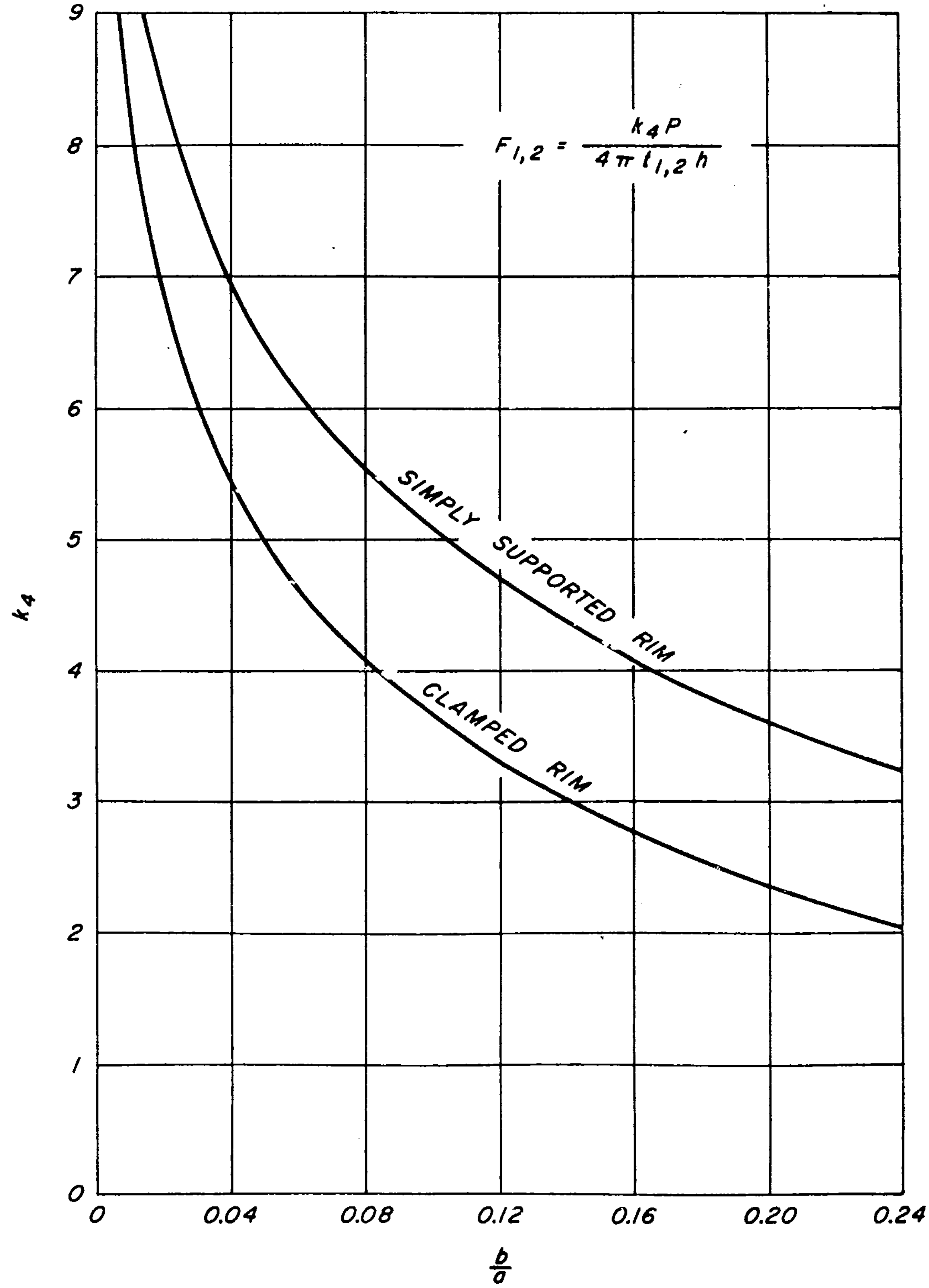


Figure 20-3.--Coefficient $k_4$ for determining maximum facing stress.

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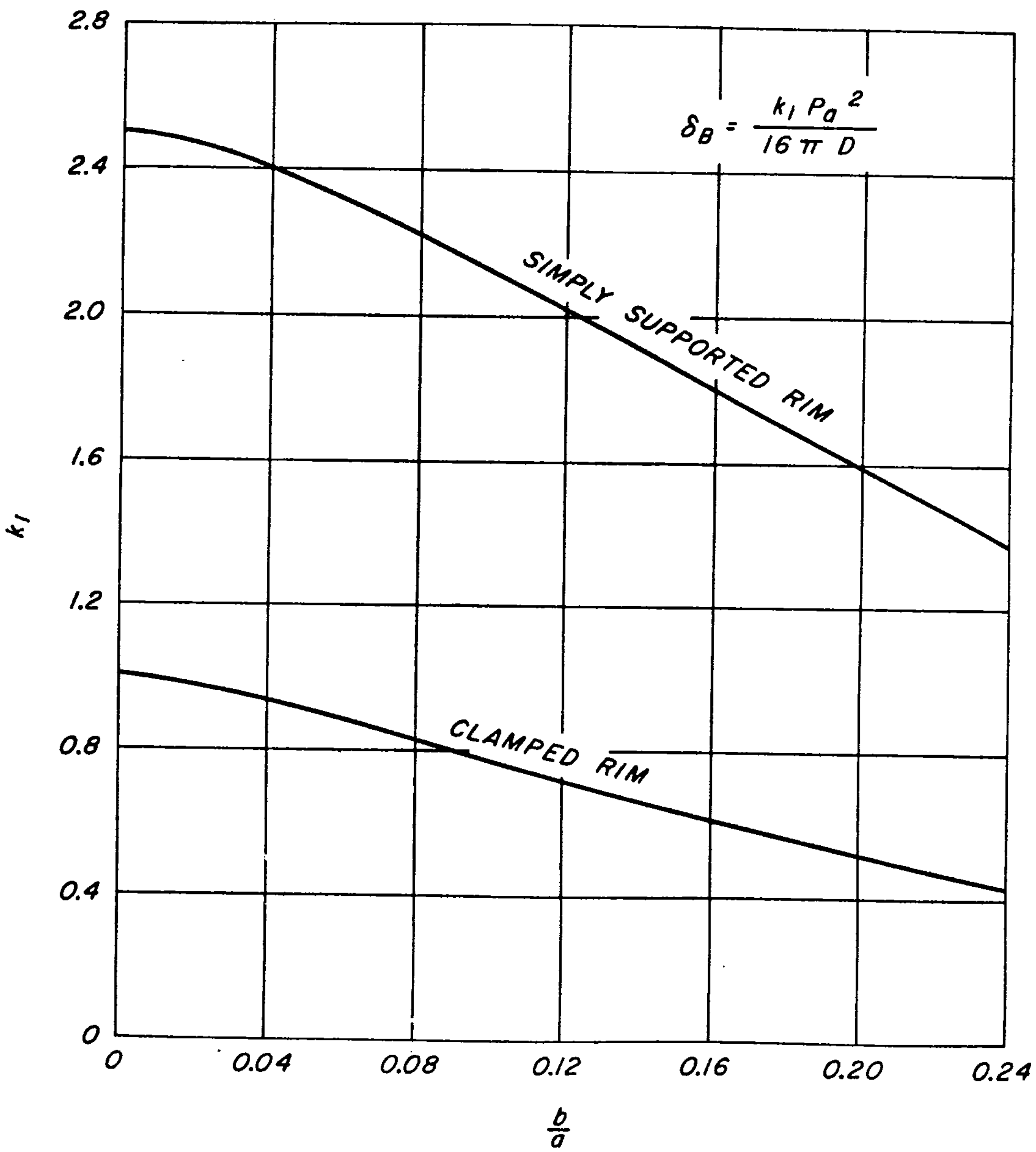


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Figure 20-4. -- Coefficient $k_1$ for determining bending deflection at insert.

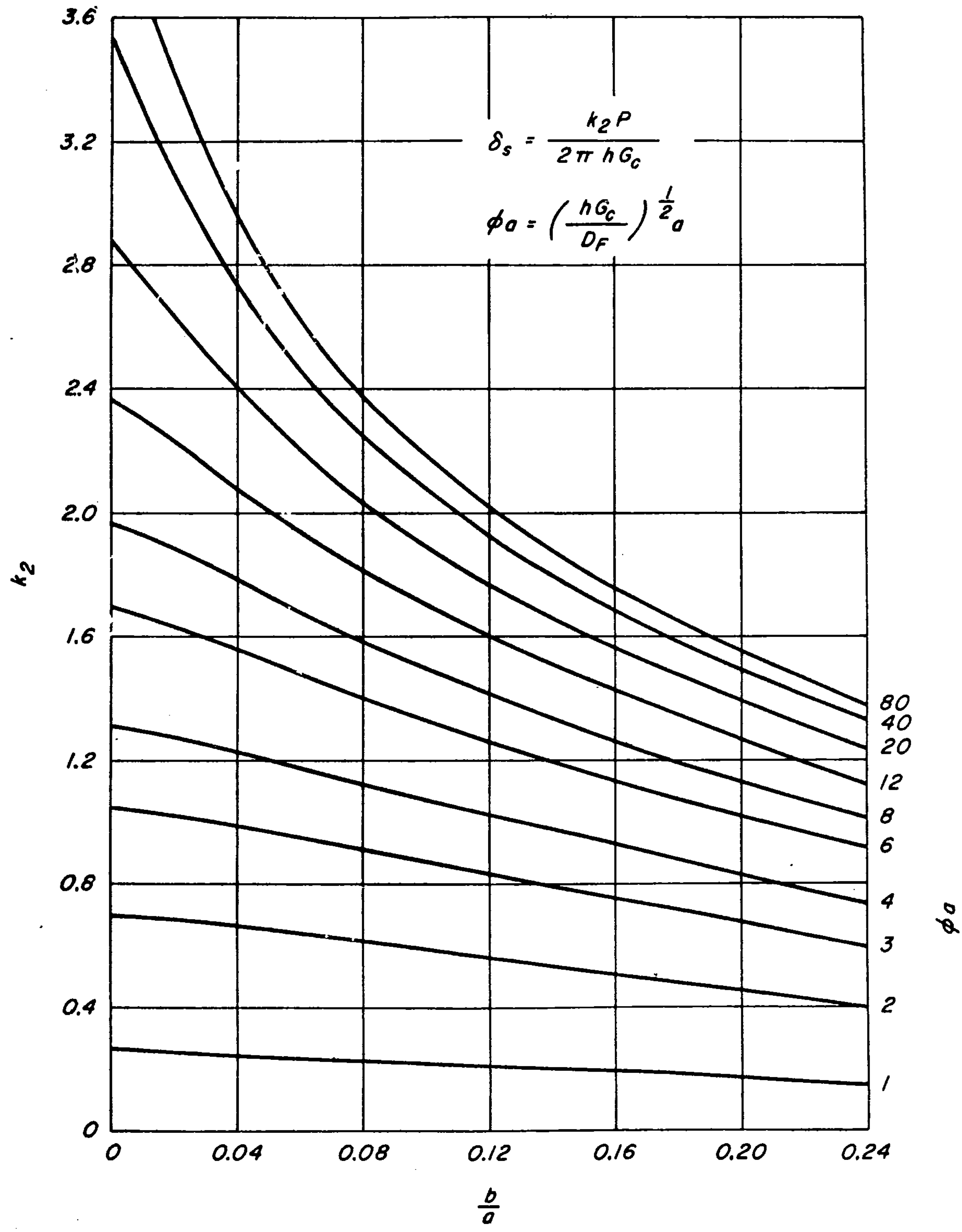


Figure 20-5.--Coefficient $k_2$ for determining shear deflection at insert, rim simply supported. (For a clamped rim $k_2$ values are conservative for $\phi a < 8$.) (M 141 658)