Composites Science and Technology 60 (2000) 2455–2463

COMPOSITES SCIENCE AND TECHNOLOGY

www.elsevier.com/locate/compscitech

Fabrication, testing and analysis of composite sandwich beams

Isaac M. Daniel *, Jandro L. Abot

Robert R. McCormick School of Engineering and Applied Science, Northwestern University, Evanston, IL 60208, USA

Received 12 February 1999; received in revised form 28 May 1999; accepted 26 January 2000

Abstract

The objective of this work was to determine experimentally the flexural behavior of composite sandwich beams and compare the results with predictions of theoretical models. Sandwich beams were fabricated by bonding unidirectional carbon/epoxy face sheets (laminates) to aluminum honeycomb cores with an adhesive film. All constituent materials (composite laminates, adhesive and core) were characterized independently. Special techniques were developed to prevent premature failures under the loading pins and to ensure failure in the test section. Sandwich beams were tested under four-point and three-point bending. Strains to failure in the face sheets were recorded with strain gages, and beam deflections, and strains in the honeycomb core were recorded by using moiré techniques. The beam face sheets exhibited a softening non-linearity on the compression side and a stiffening non-linearity on the tension side. Experimental results were in good agreement with predictions from simple models which assume the face sheets to behave like membranes, neglecting the contribution of the honeycomb core, and accounting for the non-linear behavior of the face sheets.

1. Introduction

Sandwich construction is of particular interest and widely used in many structures, because the concept is very suitable for lightweight structures with high in-plane and flexural stiffness. Sandwich panels typically consist of two thin face sheets or skins and a lightweight thicker core. Commonly used materials for face sheets are composite laminates and metals, while cores are made of metallic and non-metallic honeycombs, cellular foams, balsa wood or trusses. The face sheets are typically bonded to the core with an adhesive, and carry most of the bending and in-plane loads. The core provides the flexural stiffness and out-of-plane shear and compressive strength. The structural performance of sandwich panels depends not only on the properties of the skins, but also on those of the core, the adhesive bonding the core to the skins, and the geometrical dimensions of the components. Important issues in sandwich structures are the quality of the structure, the failure mechanisms that are developed under various loading conditions, effects of nonlinear material behavior and effects of geometric nonlinearities.

A great deal of work has been published on the behavior of sandwich structures in the last few decades. Many analytical and computational models are available to describe the behavior of sandwich beams, panels and shells under different loading conditions. The fundamentals of sandwich construction and reviews of analytical and computational methods are described in recent works by Zenkert [1], Noor et al. [2] and Reddy [3]. For the bending problem of sandwich beams, theoretical models are classified as three-dimensional, two-dimensional, detailed and simplified models. Depending on the span to depth ratio, beams are referred to as thin (ratio greater than 10), moderately thick (ratio between 4 and 10) and thick (ratio less than 4).

Many of the models proposed to date are approximations to the three-dimensional elasticity theory based on assumptions for the displacements, strains and/or stresses through the thickness. These assumptions allow the reduction of the three-dimensional problem to a two-dimensional one. The simplest approximation, applicable to slender beams, is the Bernoulli–Euler beam theory based on the assumptions of linear in-plane displacements and constant through the thickness transverse displacement. In the case of thicker beams, when the contribution of shear deformation is important, first-order shear theories are proposed where

* Corresponding author. Tel.: +1-847-491-5649; fax: +1-847-491-5227.

0266-3538/00/$ - see front matter
PII: S0266-3538(00)00039-7

in-plane displacements are assumed to vary linearly in the thickness direction, and the through the thickness transverse shear deformation is assumed to be constant. Higher order theories have also been proposed, where higher order polynomial approximations are assumed for the in-plane and out-of-plane displacements.

The validity of the various approximations depends on the geometry of the beam, properties of the component materials and loading conditions. Most theories assume linear elastic behavior for the component materials and small deflections. However, material and geometric non-linearities are important issues. It is known, for example, that carbon fiber composites exhibit stiffening non-linearity in longitudinal tension and softening non-linearity in longitudinal compression. In addition to modeling material behavior, the relative motions of the face sheets must be taken into account as in the so-called "multi-layer build-up" theory [4,5]. The high flexibility of the core relative to the face sheets imposes other limitations on linear analyses. When transverse deflections become of the order of the beam depth, non-linear analyses may be necessary [6]. Several papers have discussed the non-linear load deflection behavior of sandwich plates [7,8]. It has been discovered experimentally and by finite elements that, strains in the face sheets deviate from linearity prior to detection on the load/deflection curve and that these deviations are different for the two face sheets of the sandwich beam [9].

The limits of applicability of linear theories must be investigated as a function of geometric and material parameters of the sandwich beams. The combined effects of material and geometric non-linearities must be investigated experimentally to verify existing models and to assist in the development of new ones. The objective of this work is to experimentally determine the behavior of composite sandwich beams under bending and compare the results with predictions of theoretical models.

2. Experimental procedure

2.1. Component materials

The sandwich beam face sheets were unidirectional eight-ply carbon/epoxy laminates (AS4/3501-6). The composite sheets were fabricated by autoclave molding. Uniaxial tensile and compressive tests were conducted primarily in the longitudinal direction in order to obtain the relevant constitutive behavior of the facing material. The longitudinal tensile and compressive stress-strain behavior for the AS4-3501-6 carbon/epoxy is shown in Fig. 1. It can be seen that the material exhibits a characteristic stiffening nonlinearity in tension and softening nonlinearity in compression. The basic properties of the unidirectional material are tabulated in Table 1.

The core material used in this study was aluminum honeycomb PAMG 8.1-3/16-001-P-5052 (Plascore Co., 5052 aluminum alloy, 130 kg/m^3, 8.1 lb/ft^3 density, 4.76 mm, 3/16 in cell size, 0.025 mm, 0.001 in foil gauge). Specimens of 2.5 cm (1 in) thickness were obtained. The material is highly anisotropic. The in-plane stiffnesses E_1 and E_2 and the out-of-plane stiffness E_3 (along the cell axis) were obtained by means of flexural and pure compression tests. The out-of-plane shear modulus was obtained by means of a rail-shear test. Honeycomb core properties are tabulated in Table 2.

The adhesive used to bond the face sheets to the core was FM73 M film adhesive (Cytec-Fiberite). It is a 0.050 mm (0.002 in) thick toughened epoxy layer reinforced with non-woven polyester fabric. The shear properties of the adhesive were determined by using the Arcan fixture. Shear properties obtained from this test and other properties given by the manufacturer are tabulated in Table 3.

2.2. Fabrication of sandwich beams

A 2.54 cm (1 in) wide honeycomb core was machined from the 2.54 cm (1 in) thick sheet along the stiffer (E_1) direction. The 2.54 cm (1 in) wide composite face sheets were machined from the unidirectional panels. These face sheets were then bonded to the top and bottom of the honeycomb core with FM73 M film adhesive and the assembly was cured under pressure in an oven following the recommended curing cycle for the adhesive.

Beams for four-point flexural testing were 45.7 cm (18 in) long. Because of the low shear strength of the core, shear damage occurred in the core at low loads near the points of load application. In order to prevent premature failures and to insure failure in the pure bending section, the outer core sections subjected to shear were reinforced by filling the cells with epoxy. The best results were obtained when this cell reinforcement was tapered off gradually into the pure bending section as shown in Fig. 2.

Strains on the outer and inner surfaces of the face sheets and at the interface with the adhesive bond, were recorded with strain gages. Both longitudinal and transverse strains were recorded. The deflection of the beams was measured with a displacement transducer (LVDT) and also monitored with a coarse moiré grating (31 lines/cm, 80 lines/in). The displacement field in the core was recorded with a finer moiré grating of 118 lines/cm (300 lines/in). Before applying the moiré gratings, the lateral surface of the core was coated with a silicone rubber layer to make the surface smooth and reflective.

2.3. Testing procedure

Sandwich beams were loaded under four-point and three-point flexure in a servohydraulic machine, while

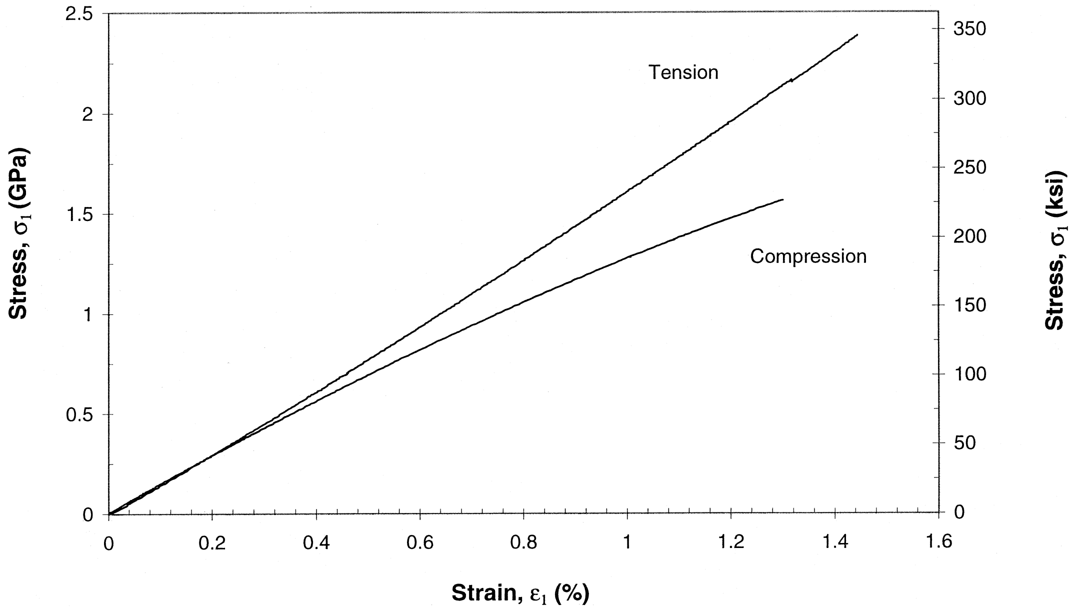

Fig. 1. Longitudinal tensile and compressive stress/strain behavior of AS4/3501-6 unidirectional carbon/epoxy.

recording load, strain gage, moiré and LVDT data. All specimens were loaded to failure. The four-point bending tests produced compressive face sheet failures at strains of over 1.5%. The three-point bending tests were carried out until core failure occurred. A large number of four-point bending tests (over 15) and three three-point bending tests was conducted.

3. Results

3.1. Beams under four-point bending

The applied bending moment was plotted versus the outer surface longitudinal strains for the beam under four-point bending in Fig. 3. The same type of stiffening and softening non-linearities observed before for the face sheet materials are seen here. Failure was governed by the compressive strength of the face sheet, which in this case reached a value of 1930 MPa (280 ksi), which was higher than the compression strength for this material measured under direct compression. The ultimate compressive strain recorded was 1.6%.

Before comparing the experimental results with available models, the variation of the longitudinal strain through the face sheet thickness was investigated. Results from another test in Figs. 4 and 5 show the variation with applied moment of longitudinal strains on the outer and inner surfaces of the face sheets. It is seen that these strains are not constant through the thickness. Analysis of the data indicates that the inner surface strains are between 3.5 and 4.2% lower (in absolute terms) than the corresponding outer surface strains. A linear strain variation through the entire beam section would imply strain differences of 4%.

The strain field in the core was investigated by the moiré technique discussed before. A moiré fringe pattern corresponding to longitudinal displacements in the core is shown in Fig. 6. A linear strain variation through

Table 1
Mechanical properties of unidirectional AS4/3501-6 carbon/epoxy

Property	Value
Fiber-volume ratio, V_f	0.65–0.70
Longitudinal Elastic Modulus, E_1 (GPa) (Msi)	146.6 (21.26)
Transverse elastic modulus, E_2 (GPa) (Msi)	10.35 (1.50)
In-plane shear modulus, G_{12} (GPa) (Msi)	7.6 (1.1)
Major Poisson's Ratio, ν_{12}	0.28
Minor Poisson's Ratio, ν_{21}	0.02
Longitudinal tensile strength, F_{1t} (MPa) (ksi)	2386 (346)
Longitudinal compressive strength, F_{1c} (MPa) (ksi)	1627 (235)
In-plane shear strength, F_{12} (MPa) (ksi)	71 (10.3)
Ultimate tensile strain, ε_{1t}^{u} (%)	1.45
Ultimate compressive strain, ε_{1c}^{u} (%)	1.36
Ultimate in-plane shear strain, γ_{12}^{u} (%)	1.50
Transverse tensile strength, F_{2t} (Mpa) (ksi)	64 (9.3)
Transverse compressive strength, F_{2c} (Mpa) (ksi)	228 (33)

Table 2
Mechanical properties of aluminum honeycomb (PAMG 8.1-3/16-001-P-5052)

Property	Value
Density, ρ (kg/m^3) (lb/ft^3)	129 (8.1)
Longitudinal modulus, E_1 (MPa) (ksi)	8.27 (1.2)
Transverse modulus, E_2 (MPa) (ksi)	1.31 (0.2)
Axial (out-of-plane) modulus, E_3 (MPa) (ksi)	2410 (350)
Out-of-plane shear modulus, G_{13} (MPa) (ksi)	580 (84)

the thickness in the pure bending zone would imply the following form for the strain and displacement

$$\varepsilon_1(z) = cz = \frac{\partial u}{\partial x} \quad (1)$$

Table 3
Mechanical properties of FM73 M film adhesive

Property	Value
Density, ρ (kg/m^3) (lb/ft^3)	1180 (74)
Longitudinal modulus, E_1 (MPa) (ksi)	1700 (247)
Out-of-plane shear modulus, G_{13} (MPa) (ksi)	110 (16)
Out-of-plane shear strength, F_{13} (MPa) (ksi)	33 (4.8)
Out-of-plane ultimate shear strain, γ_{13}^{u} (%)	0.63

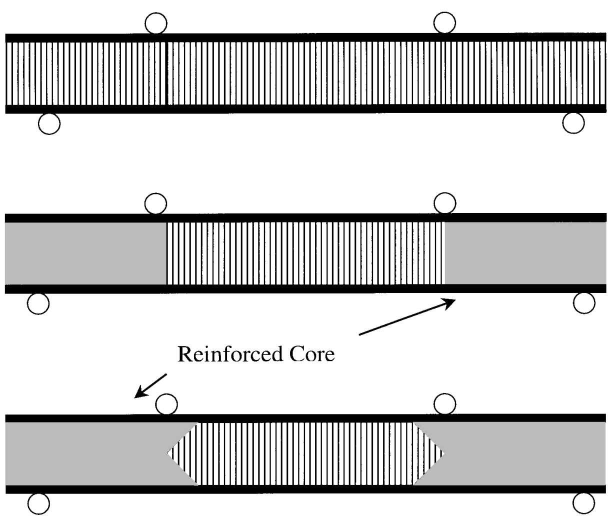

Fig. 2. Sandwich beam with reinforced and unreinforced honeycomb cores.

$$u(x, z) = cxz \quad (2)$$

since $u(0, z) = 0$ (along vertical axis of symmetry).

The moiré fringes, being loci of equal displacements, have the form of hyperbolas and are equidistant along any horizontal line. Furthermore, there is evidence that the neutral axis has shifted toward the tension side because of the different nonlinearities of the tension and compression face sheets.

The state of stress in the face sheets is not purely uniaxial because of the constraining effects of the core. Transverse strains were recorded in several tests. The transverse strain is plotted versus the longitudinal one in Fig. 7. The plot for the compression side is nearly linear, whereas it is very nonlinear for the tension side. In the linear region both curves have a common slope or strain ratio. A strain ratio (in absolute terms) of 0.38 was obtained, which is higher than the Poisson's ratio of the material, $\nu_{12} = 0.28$. From this information a transverse stress σ_2 is calculated for the face sheets as

$$\sigma_2 = -0.007\sigma_1$$

3.2. Beams under three-point bending

Under three-point bending and without any special core reinforcement, all beams failed prematurely due to shear crimping of the core. The failure load, being twice the shear force, remained nearly constant for varying span lengths. This implies that as the span length decreases, the applied maximum moment, and thereby the maximum face sheet strains at failure, decrease (Fig. 8).

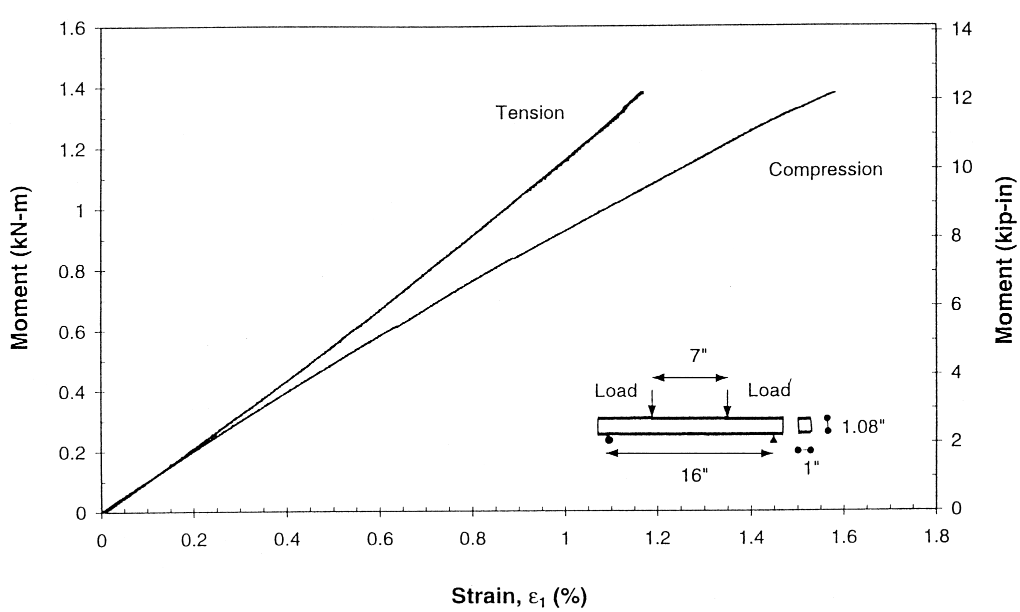

Fig. 3. Applied moment versus longitudinal strains for sandwich beam under four-point bending.

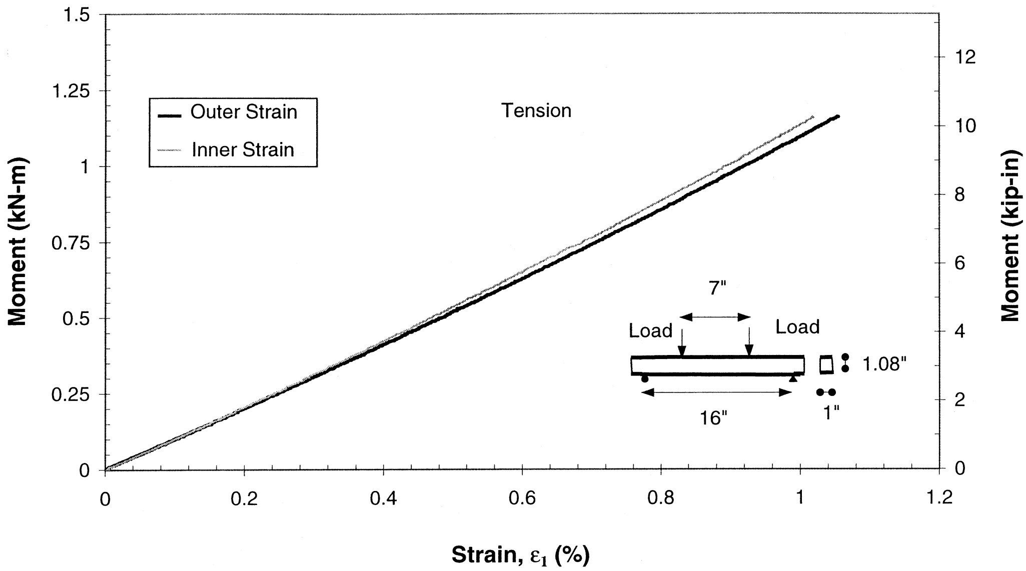

Fig. 4. Applied moment versus longitudinal strains on surface of tension facing of sandwich beam under four-point bending.

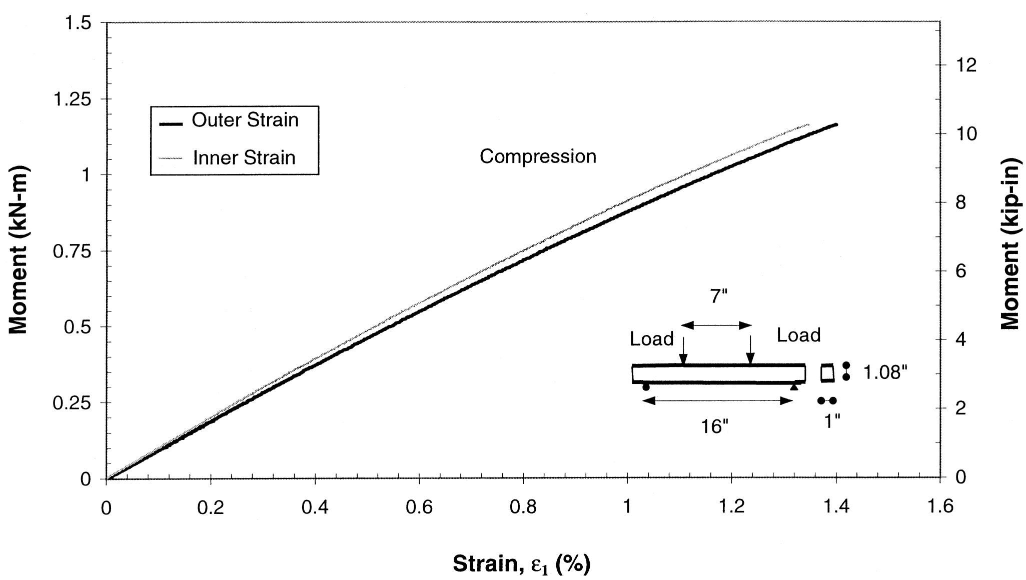

Fig. 5. Applied moment versus longitudinal strains on surfaces of compression facing of sanwich beam under four-point bending.

The results also indicate that even in cases of increased shear loading of the core, the bending moment is carried almost entirely by the face sheets.

3.3. Modeling

The objective of the modeling was to predict the relationship between applied loading (moment) and stresses or strains in the sandwich beams, based on the properties and dimensions of the components of the beam. Referring to the schematic of a sandwich beam in Fig. 9, the neutral axis is located at a distance.

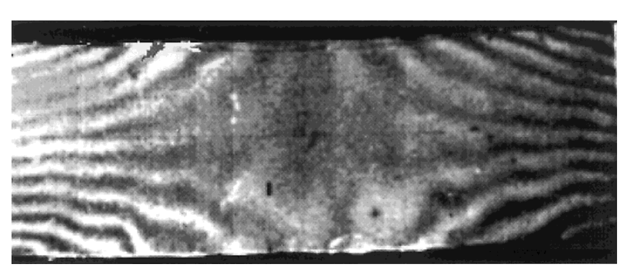

Fig. 6. Moiré fringe pattern in the core corresponding to longitudinal displacements (12 lines/mm; 300 lines/in).

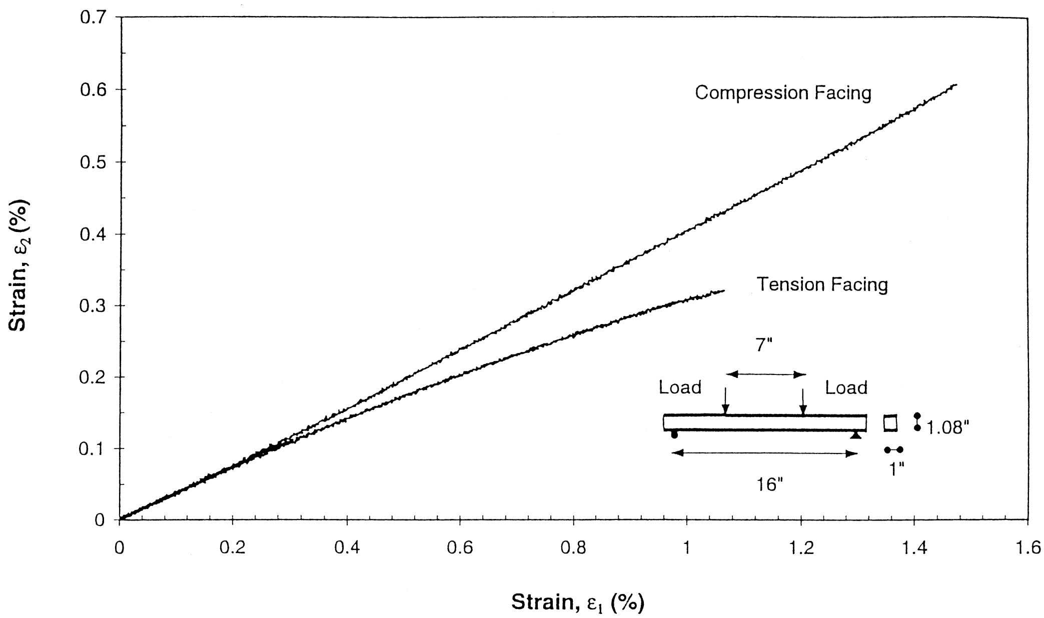

Fig. 7. Transverse versus longitudinal strain on facings of sandwich beam under four-point bending.

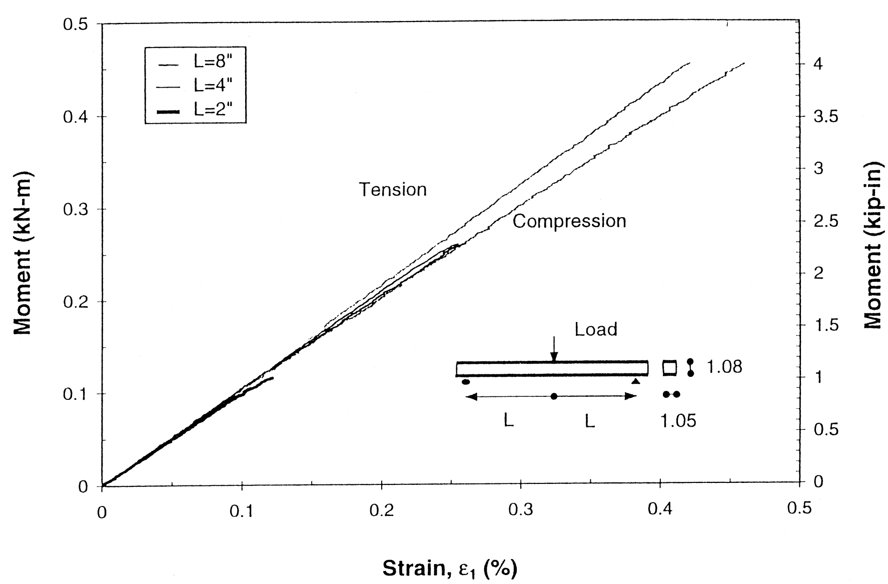

Fig. 8. Applied moment versus maximum facing strain for beams of different span length under three-point bending.

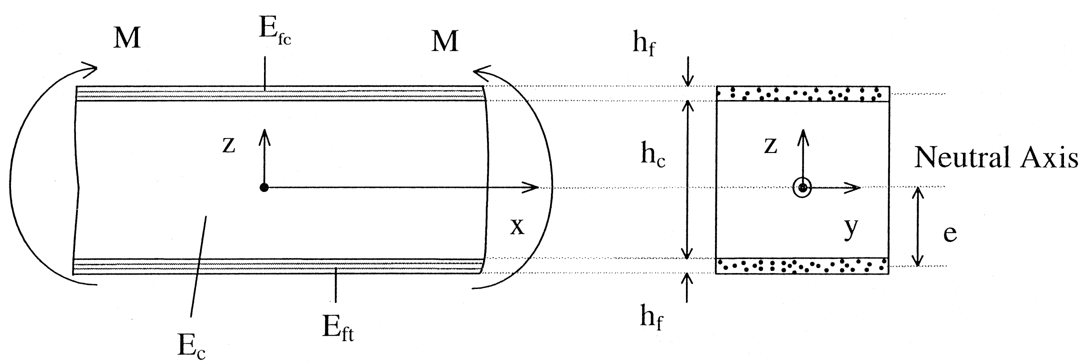

Fig. 9. Schematic of sandwich beam.

$$e = \frac{E_{fc} h_f d + E_c h_c (h_c + h_f)/2}{(E_{ft} + E_{fc}) h_f + E_c h_c} \tag{3}$$

and for a weak core, $E_c \ll E_{ft}, E_{fc}$,

$$e \cong \frac{E_{fc} d}{(E_{ft} + E_{fc}) h_f} \tag{4}$$

where

$$d = h_c + h_f$$

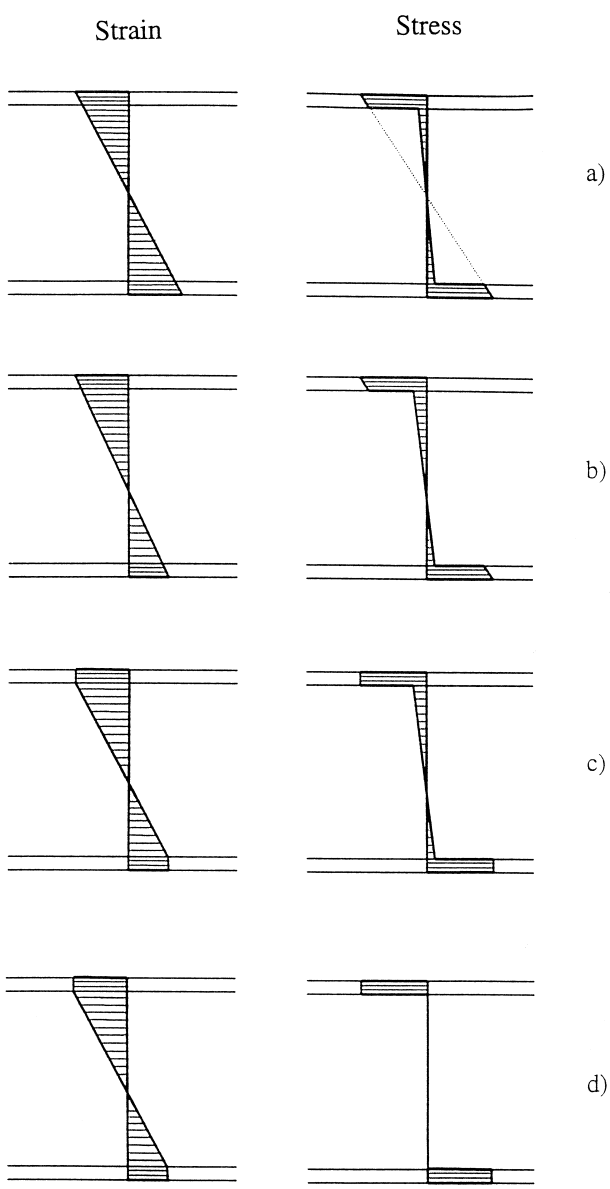

Fig. 10. Strain and stress distributions through the thickness of a sandwich beam for different cases/assumptions: (a) linear facing material with core contribution; (b) non-linear facing material with linear strain variation in facing and core contribution; (c) non-linear facing material with constant strain in the facing and core contribution; (d) non-linear facing material with constant strain in facing and without core contribution.

The bending stiffness for a weak core is

$$D = \frac{h_f^3}{12}(E_{ft} + E_{fc}) + \frac{E_{ft} E_{fc} h_f d^2}{E_{ft} + E_{fc}} \tag{5}$$

For thin facings, $h_f \ll h_c$ we have

$$D \cong \frac{E_{ft} E_{fc} h_f d^2}{E_{ft} + E_{fc}} \tag{6}$$

The normal stresses in the face sheets and core are

$$\sigma_{ft} = -\frac{Mz}{D} E_{ft}$$
$$\sigma_{fc} = -\frac{Mz}{D} E_{fc}$$
$$\sigma_c = -\frac{Mz}{D} E_c \tag{7}$$

For a weak core and thin face sheets

$$\sigma_{ft} = -\sigma_{fc} \cong \frac{M}{\mathrm{d} b h_f}$$

where b = width of beam.

The experimentally obtained stress/strain relationships of the face sheet material in tension and compression and that of the core were used to obtain moment/strain relations. Different cases/assumptions were considered in modeling the sandwich beams tested under pure bending as outlined in Fig. 10. In the first case, a linear variation of strain through the thickness is assumed with a neutral axis through the centroid of the cross section. This is only valid in the linear range of the face sheet material. At higher loads, the nonlinear response of the face sheets must be considered, although other simplifying assumptions can be made. For example, the core contribution could be neglected since its

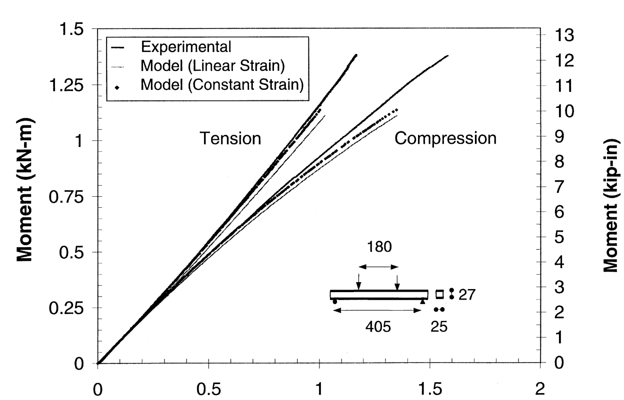

Fig. 11. Experimental and predicted moment/strain curves for two facings of a composite sandwich beam under four-point bending (dimension are in mm).

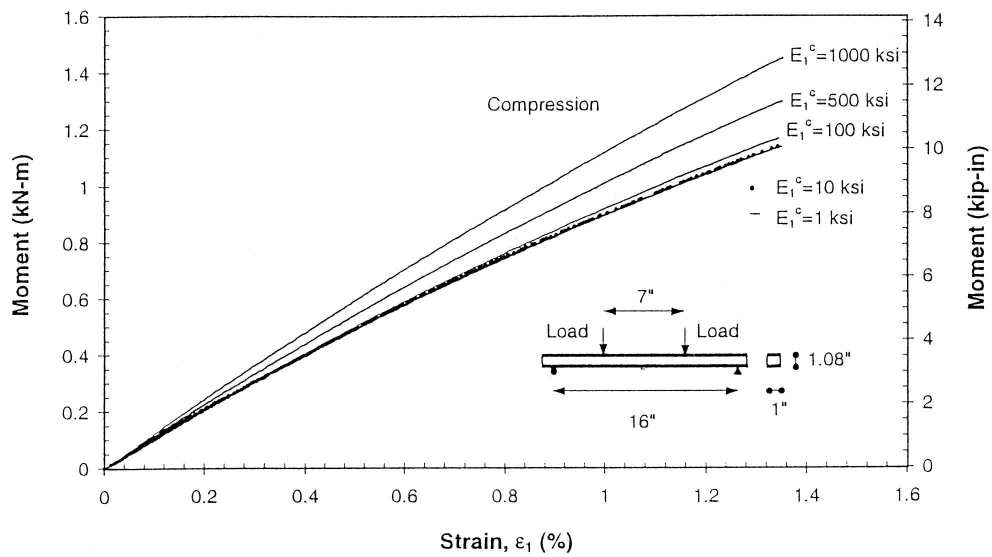

Fig. 12. Effect of core modulus on the moment/strain relationship for sandwich beam under four-point bending (compression facing).

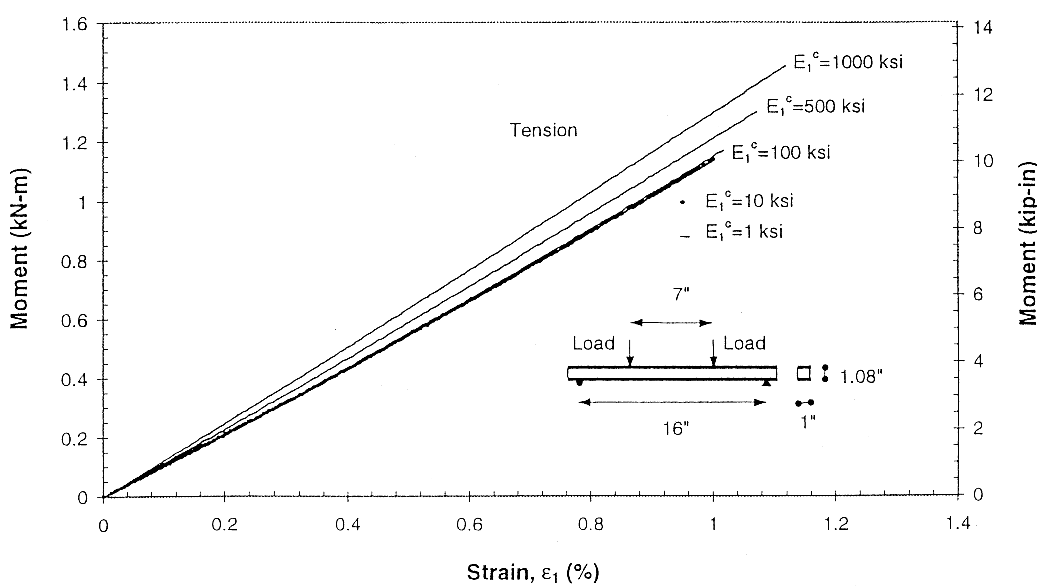

Fig. 13. Effect of core modulus on the moment/strain relationship for sandwich beam under four-point bending (tension facing).

modulus is much smaller than the facing modulus ($E_c \ll E_f$). The strain, and hence the stress, in the face sheets can be assumed to vary linearly or to be constant through the face sheet thickness. The latter assumption is valid when the face sheet thickness is much smaller than the core thickness ($h_f \ll h_c$).

In the present case two models were implemented, one by assuming linear variation of strain through the face sheet thickness and the other by assuming a constant strain through the face sheet thickness. In both models the core contribution was neglected. The nonlinear behavior of the face sheet material was considered in an incremental computational scheme. Results are plotted in Fig. 11 and compared with experimental moment/strain results. It appears that the assumption of constant strain gives better agreement with experimental results. The small discrepancies observed are not attributed to the model but rather to the difficulty in obtaining reliable stress/strain curves in direct longitudinal compression.

The contribution of the core to the moment/strain relations was found to be negligible. The effect of core modulus was investigated using a model with the assumption of constant strain through the face sheet thickness. Results are shown in Figs. 12 and 13 for the compression and tension face sheet, respectively. It appears that the influence of the core is negligible until its stiffness is one-hundred times that of the core used in this study, or equivalently 1/200 times the face sheet modulus.

4. Summary and conclusions

An experimental study was conducted on the behavior of composite sandwich beams under four-point and three-point bending. The sandwich beams were prepared with unidirectional carbon/epoxy face sheets and aluminum honeycomb core. Strains in the face sheets and the core were measured with strain gages and moiré gratings. The bending behavior of the beams, whether loaded under four-point or three-point bending, is governed by the face sheets. Therefore, the moment/strain relations for the face sheets display the same type of non-linear behavior as the composite material itself, i.e., a stiffening non-linearity in tension and a softening non-linearity in compression. A linear variation in strain through the thickness was determined in both core and skins. The contribution of the most widely used cores to the bending stiffness can be neglected. In the case of pure bending, failure takes place on the compressive facing of the beam where the ultimate compressive stress and strain can reach values higher than any recorded for the composite material under direct compression. When shear is present, failure of the sandwich beam was governed by the low shear strength of the honeycomb core, 2415 kPa (350 psi). Experimental results were in good agreement with predictions of simple models assuming the face sheets to behave like membranes and neglecting the contribution of the core, but accounting for the non-linear behavior of the face sheets.

Acknowledgements

The work described here was supported by the Office of Naval Research (ONR). The authors would like to thank Dr. Y.D.S. Rajapakse of ONR for his support and cooperation and Mrs. Yolande Mallian for typing the manuscript. We also wish to thank Mr. K.A. Wang for his contribution in the characterization of the core and adhesive materials.

References

[1] Zenkert D. An introduction to sandwich construction. London: Engineering Materials Advisory Services, 1995.
[2] Noor AK, Burton WS, Bert CW. Computational models for sandwich panels and shells. Applied Mechanics Reviews 1996;49:15–199.
[3] Reddy JN. Mechanics of laminated composite plates: theory and analysis. Boca Raton, FL: CRC Press, 1997.
[4] Sun CT. Microstructure theory for a composite beam. J of Appl Mech 1971;38(4):947–54.
[5] Kemmochi K, Uemura M. Measurement of stress distribution in sandwich beams under four-point bending. Exper Mech 1980;20:80–6.
[6] Reissner E. Finite deflections of sandwich plates. J Aeronaut Scie 1948;15:435–40.
[7] Meyer-Piening H-R. Remarks on higher order sandwich stress and deflection analysis. In: Olsson K-A, Reichard RP, editors. Proc. of the First Int. Conf. on Sandwich Constructions. West Midlands, UK: EMAS, 1989. p. 107–27.
[8] Reichard RP. The design of FRP sandwich panels for ship and boat hulls. In: Olsson K-A, Reichard RP, editors. Proc. of the First Int. Conf. on Sandwich Constructions. West Midlands, UK: EMAS, 1989. p. 349–61.
[9] Bau-Madsen NK, Svendsen K-H, Kildegaard A. Large deflections of sandwich plates — an experimental investigation. Composite Structures 1993;23:47–52.