PART IV-B – STRUCTURAL ANALYSIS AND PROPORTIONING OF MEMBERS – ULTIMATE STRENGTH DESIGN

CHAPTER 15 — GENERAL STRENGTH AND SERVICEABILITY REQUIREMENTS — ULTIMATE STRENGTH DESIGN

1500—Notation

A_s = area of tension reinforcement
A_s' = area of compression reinforcement
A_{sf} = area of reinforcement to develop compressive strength of overhanging flanges in I- and T-sections
a = depth of equivalent rectangular stress block = k_1c
b = width of compression face of flexural member
b' = width of web in I- and T-sections
c = distance from extreme compression fiber to neutral axis at ultimate strength
D = dead load
d = distance from extreme compression fiber to centroid of tension reinforcement
E = earthquake load
f_c' = compressive strength of concrete (see Section 301)
f_y = yield strength of reinforcement (see Section 301)
k_1 = a factor defined in Section 1503(g)
L = specified live load plus impact
p = A_s/bd
p' = A_s'/bd
p_f = $A_{sf}/b'd$
p_w = $A_s/b'd$
U = required ultimate load capacity of section
W = wind load
ϕ = capacity reduction factor (see Section 1504)

1501—Definition

Ultimate strength design is a method of proportioning reinforced concrete members based on calculations of their ultimate strength. To ensure serviceability, consideration is also given to control of deflection and cracking under service loads.

1502—General requirements

(a) All provisions of this code, except those of Part IV-A, shall apply to the design of members by ultimate strength method, unless otherwise specifically provided in this Part IV-B.

(b) Bending moments in an axially loaded member shall be taken into account in the calculation of the strength required of the member.

(c) Except as provided in (d), analysis of indeterminate structures, such as continuous beams, frames, and arches, shall be based on the assumption of elastic behavior. For buildings of usual type of construction, spans, and story heights, approximate methods as provided in Chapter 9 are acceptable for determination of moments and shears.

(d) Except where approximate values for bending moments are used, the negative moments calculated by elastic theory, for any assumed loading arrangement, at the supports of continuous flexural members may each be increased or decreased by not more than 10 percent, provided that these modified negative moments are also used for final calculations of the moments at other sections in the spans corresponding to the same loading condition. Such an adjustment shall only be made when the section at which the moment is reduced is so designed that p, $(p - p')$, or $(p_w - p_f)$, which ever is applicable, is equal to or less than 0.50 times the reinforcement ratio p_b, producing balanced conditions at ultimate strength as calculated by Eq. (16-2).

1503—Assumptions

(a) Ultimate strength design of members for bending and axial load shall be based on the assumptions given in this section, and on satisfaction of the applicable conditions of equilibrium and compatibility of strains. The simplified design equations given in Chapters 16 and 19 are satisfactory.

(b) Strain in the concrete shall be assumed directly proportional to the distance from the neutral axis. Except in anchorage regions, strain in reinforcing bars shall be assumed equal to the strain in the concrete at the same position.

(c) The maximum strain at the extreme compression fiber at ultimate strength shall be assumed equal to 0.003.

(d) Stress in reinforcing bars below the yield strength, f_y, for the grade of steel used shall be taken as 29,000,000 psi times the steel strain. For strain greater than that corresponding to the design yield strength, f_y, the reinforcement stress shall be considered independent of strain and equal to the design yield strength, f_y.

(e) Tensile strength of the concrete shall be neglected in flexural calculations.

(f) At ultimate strength, concrete stress is not proportional to strain. The diagram of compressive concrete stress distribution may be assumed to be a rectangle, trapezoid, parabola, or any other shape which results in predictions of ultimate strength in reasonable agreement with the results of comprehensive tests.

(g) The requirements of (f) may be considered satisfied by the equivalent rectangular concrete stress distribution which is defined as follows: At ultimate strength, a concrete stress intensity of 0.85 f_c' shall be assumed uniformly distributed over an equivalent compression zone bounded by the edges of the cross section and a straight line located parallel to the neutral axis at a distance $a = k_1c$ from the fiber of maximum compressive strain. The distance c from the fiber of maximum strain to the neutral axis is measured in a direction perpendicular to that axis. The fraction k_1 shall be taken as 0.85 for strengths, f_c', up to 4000 psi and shall be reduced continuously at a rate of 0.05 for each 1000 psi of strength in excess of 4000 psi.

1504—Safety provisions*

(a) Strengths shall be computed in accordance with the provisions of Part IV-B.

(b) The coefficient ϕ shall be 0.90 for flexure; 0.85 for diagonal tension, bond, and anchorage; 0.75 for spirally reinforced compression members; and 0.70 for tied compression members.

(c) The strength capacities of members so computed shall be at least equal to the total effects of the design loads required by Section 1506.

1505—Design strengths for reinforcement

(a) When reinforcement is used that has a yield strength, f_y, in excess of 60,000 psi, the yield strength to be used in design shall be reduced to 0.85 f_y or 60,000 psi, whichever is greater, unless it is shown by tension tests that at a proof stress equal to the specified yield strength, f_y, the strain does not exceed 0.003.

(b) Designs shall not be based on a yield strength, f_y, in excess of 75,000 psi. Design of tension reinforcement shall not be based on a yield strength, f_y, in excess of 60,000 psi unless tests are made in compliance with Section 1508(b).

1506—Design loads†

(a) The design loads shall be computed as follows:

1. For structures in such locations and of such proportions that the effects of wind and earthquake may be neglected the design capacity shall be

$$U = 1.5D + 1.8L \quad \ldots\ldots\ldots\ldots\ldots \quad (15\text{-}1)$$

The loads D, L, W, and E are the loads specified in the general code of which these requirements form a part.

*The coefficient ϕ provides for the possibility that small adverse variations in material strengths, workmanship, dimensions, control, and degree of supervision, while individually within required tolerances and the limits of good practice, occasionally may combine to result in undercapacity.

†The provisions of Section 1506 provide for such sources of possible excess load effects as load assumptions, assumptions in structural analysis, simplifications in calculations, and effects of construction sequence and methods.

2. For structures in the design of which wind loading must be included, the design capacity shall be

$$U = 1.25\,(D + L + W) \quad \ldots\ldots\ldots\ldots \quad (15\text{-}2)$$

or

$$U = 0.9D + 1.1W \quad \ldots\ldots\ldots\ldots\ldots \quad (15\text{-}3)$$

whichever is greater, provided that no member shall have a capacity less than required by Eq. (15-1).

3. For those structures in which earthquake loading must be considered, E shall be substituted for W in Eq. (15-2).

4. In considering the combination of dead, live, and wind loads, the maximum and minimum effects of live loads shall be taken into account.

5. In structures in which it is normal practice to take into account creep, elastic deformation, shrinkage, and temperature, the effects of such items shall be considered on the same basis as the effects of dead load.

1507—Control of deflections

(a) The computed deflection of members at the service load level of $D + L$ shall conform to the provisions of Section 909, and deflections shall always be checked whenever the required net reinforcement ratio p, $(p - p')$, or $(p_w - p_f)$ in any section of a flexural member exceeds $0.18f_c'/f_y$, or whenever the specified yield strength, f_y, exceeds 40,000 psi.

1508—Control of cracking

(a) Only deformed bars shall be used, except that plain bars may be used as temperature bars and column spirals and #2 plain bars may be used as stirrups and column ties. Tension reinforcement shall be well distributed in the zones of maximum concrete tension and in the flange of T-beams.

(b) The design yield strength, f_y, for tension reinforcement shall not exceed 60,000 psi, unless it is shown by full-scale tests of typical members that the average crack width at service load at the concrete surface of the extreme tension edge, does not exceed 0.015 in. for interior members and 0.010 in. for exterior members. These requirements shall not apply to compression reinforcement.