## c. Limits for Reinforcement

The ACI Code classifies prestressed concrete flexural members as tension-controlled or compression-controlled based on the net tensile strain $\epsilon_t$ in the same manner as done for ordinary reinforced concrete beams. Section 3.4d describes the strain distributions and the variation of strength-reduction factors associated with limitations on the net tensile strain. Recall that the net tensile strain excludes strains due to creep, shrinkage, temperature, and effective prestress. To maintain a strength-reduction factor $\phi$ of 0.90 and ensure that, if flexural failure were to occur, it would be a ductile failure, a net tensile strain of at least 0.005 is required. Due to the complexity of computing net tensile strain in prestressed members, it is easier to perform the check using the $c/d_t$ ratio. From Fig. 3.10a, this simplifies to

$$\frac{c}{d_t} \leq 0.375 \tag{19.16}$$

where $d_t$ is the distance from the extreme compressive fiber to the extreme tensile steel. In many cases, $d_t$ will be the same as $d_p$, the distance from the extreme compressive fiber to the centroid of the prestressed reinforcement. However, when supplemental nonprestressed steel is used or the prestressing strands are distributed through the depth of the section, $d_t$ will be greater than $d_p$. If the prestressed beam does not meet the requirements of Eq. (19.16), it may no longer be considered as tension-controlled, and the strength reduction factor $\phi$ must be determined as shown in Fig. 3.9. If $c/d_t \geq 0.60$, corresponding to $\epsilon_t \leq 0.002$, the section is considered to be *over-reinforced*, and alternative equations must be derived for computing the flexural strength (see Ref. 19.1).

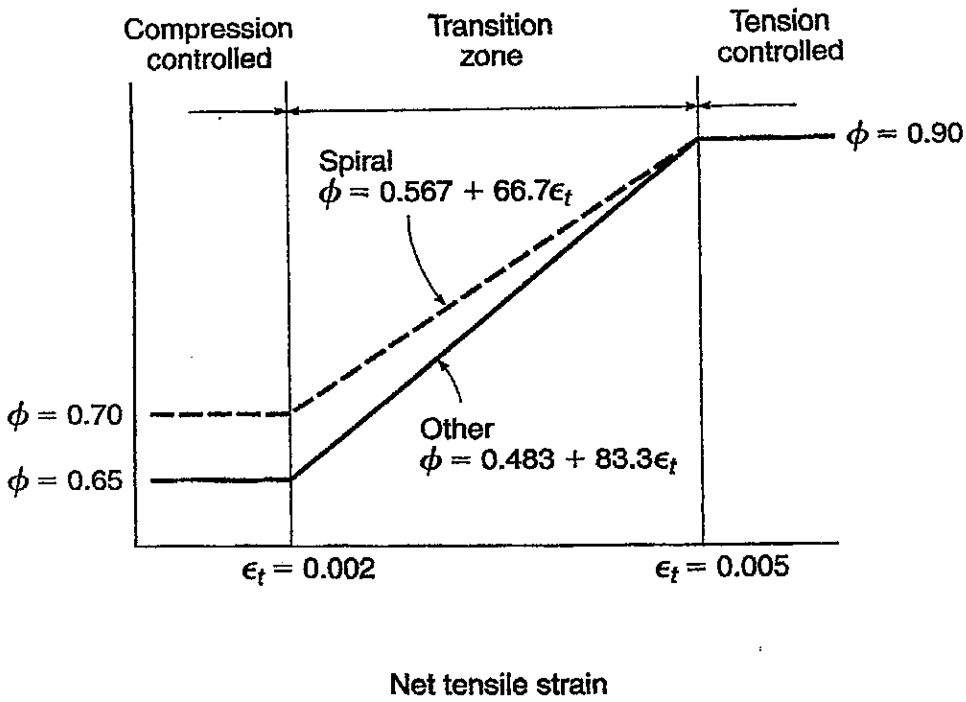
It will be recalled that a *minimum tensile reinforcement ratio* is required for ordinary reinforced concrete beams, so that the beams will be safe from sudden failure upon the formation of flexural cracks. For prestressed beams, because of the same concern, ACI Code 18.8.2 requires that the total tensile reinforcement must be adequate to support a factored load of at least 1.2 times the cracking load of the beam, calculated on the basis of a modulus of rupture of $7.5\sqrt{f_c'}$.

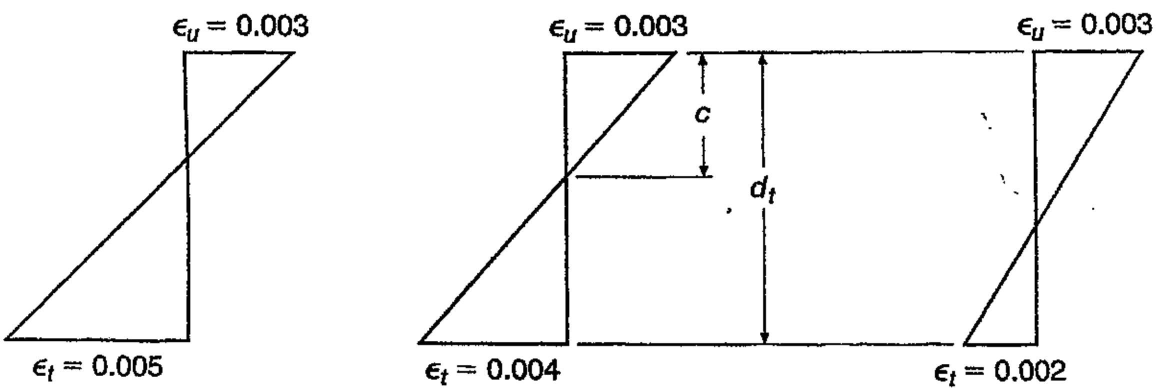
## d. Minimum Bonded Reinforcement

To control cracking in beams and one-way prestressed slabs with *unbonded tendons*, some bonded reinforcement must be added in the form of nonprestressed reinforcing bars, uniformly distributed over the tension zone as close as permissible to the extreme tension fiber. According to ACI Code 18.9.2, the minimum amount of such reinforcement is

$$A_s = 0.004A \tag{19.17}$$

where $A$ is the area of that part of the cross section between the flexural tension face and the centroid of the gross concrete cross section. Exceptions are provided for two-way slabs with very low tensile stresses.




$$\frac{c}{d_t} = \frac{0.003}{0.003 + 0.005} = 0.375$$

(*a*)
Tension-controlled member

$$\frac{c}{d_t} = \frac{0.003}{0.003 + 0.004} = 0.429$$

(*b*)
Minimum net tensile strain for flexural member

$$\frac{c}{d_t} = \frac{0.003}{0.003 + 0.002} = 0.600$$

(*c*)
Compression-controlled member

**TABLE 19.1**

## Maximum permissible stresses in prestressing steel

| | |
|---|---|
| 1. Due to tendon jacking force but not greater than the lesser of $0.80f_{pu}$ and the maximum value recommended by the manufacturer of the prestressing steel or anchorage devices | $0.94f_{py}$ |
| 2. Immediately after prestress transfer but not greater than $0.74f_{pu}$ | $0.82f_{py}$ |
| 3. Post-tensioning tendons, at anchorage devices and couplers, immediately after tendon anchorage | $0.70f_{pu}$ |

**TABLE 19.2**

## Permissible stresses in concrete in prestressed flexural members

| Condition† | Class U | Class T | Class C* |
|---|---|---|---|
| a. Extreme fiber stress in compression immediately after transfer | $0.60f'_{ci}$ | $0.60f'_{ci}$ | $0.60f'_{ci}$ |
| b. Extreme fiber stress in tension immediately after transfer (except as in c)† | $\sqrt{f'_{ci}}/4$ | $\sqrt{f'_{ci}}/4$ | $\sqrt{f'_{ci}}/4$ |
| c. Extreme fiber stress in tension immediately after transfer at the end of a simply supported member‡ | $\sqrt{f'_{ci}}/2$ | $\sqrt{f'_{ci}}/2$ | $\sqrt{f'_{ci}}/2$ |
| d. Extreme fiber stress in compression due to prestress plus sustained load | $0.45f'_c$ | $0.45f'_c$ | — |
| e. Extreme fiber stress in compression due to prestress plus total load | $0.60f'_c$ | $0.60f'_c$ | — |
| f. Extreme fiber stress in tension $f_t$ in precompressed tensile zone under service load | $\leq \sqrt{f'_c}$ 0.625 | $> \sqrt{f'_c}$ and $\leq \sqrt{f'_c}$ 0.625 | — |

* There are no service stress requirements for Class C.

† Permissible stresses may be exceeded if it is shown by test or analysis that performance will not be impaired.

‡ When computed tensile stresses exceed these values, bonded auxiliary prestressed or nonprestressed reinforcement shall be provided in the tensile zone to resist the total tensile force in the concrete computed with the assumption of an uncracked section.

## a. Stress in the Prestressed Steel at Flexural Failure

When a prestressed concrete beam fails in flexure, the prestressing steel is at a stress $f_{ps}$ that is higher than the effective prestress $f_{pe}$ but below the tensile strength $f_{pu}$. If the effective prestress $f_{pe} = P_e/A_{ps}$ is not less than $0.50f_{pu}$, ACI Code 18.7.2 permits use of certain approximate equations for $f_{ps}$. These equations appear quite complex as they are presented in the ACI Code, mainly because they are written in general form to account for differences in type of prestressing steel and to apply to beams in which nonprestressed bar reinforcement may be included in the flexural tension zone or the compression region or both. Separate equations are given for members with bonded tendons and unbonded tendons because, in the latter case, the increase in steel stress at the maximum moment section as the beam is overloaded is much less than if the steel were bonded throughout its length.

For the basic case, in which the prestressed steel provides all of the flexural reinforcement, the ACI Code equations can be stated in simplified form as follows:

1. For members with bonded tendons:

$$f_{ps} = f_{pu}\left(1 - \frac{\gamma_p}{\beta_1}\frac{\rho_p f_{pu}}{f'_c}\right) \tag{19.6}$$

where $\rho_p = A_{ps}/bd_p$, $d_p$ = effective depth to the prestressing steel centroid, $b$ = width of compression face, $\beta_1$ = the familiar relations between stress block depth and depth to the neutral axis [Eq. (3.26)], and $\gamma_p$ is a factor that depends on the type of prestressing steel used, as follows:

$$\gamma_p = \begin{cases} 0.55 \text{ for } f_{py}/f_{pu} \geq 0.80 \text{ (typical high-strength bars)} \\ 0.40 \text{ for } f_{py}/f_{pu} \geq 0.85 \text{ (typical ordinary strand)} \\ 0.28 \text{ for } f_{py}/f_{pu} \geq 0.90 \text{ (typical low-relaxation strand)} \end{cases}$$

2. For members with unbonded tendons and with a span-depth ratio of 35 or less (this includes most beams),

$$f_{ps} = f_{pe} + \overset{70}{\cancel{10{,}000}} + \frac{f'_c}{100\rho_p} \tag{19.7}$$

but not greater than $f_{py}$ and not greater than $f_{pe}$ + ~~60,000 psi.~~ 420 MPa

3. For members with unbonded tendons and with span-depth ratio greater than 35 (applying to many slabs),

$$f_{ps} = f_{pe} + \overset{70}{\cancel{10{,}000}} + \frac{f'_c}{300\rho_p} \tag{19.8}$$

but not greater than $f_{py}$ and not greater than $f_{pe}$ + ~~30,000 psi.~~ 210 MPa