CHAPTER 9 — SECTIONAL STRENGTH

9.1 — Scope

9.1.1 — This chapter provides minimum strength requirements for sections of members as required by other chapters of this Code. Sectional strength requirements of this chapter shall be satisfied unless the member or region of the member is designed in accordance with Chapter 18.

9.1.2 — Design strength at a section shall be taken as the nominal strength multiplied by the applicable strength reduction factor, \( \phi \), defined in Chapter Y.

9.1.3 — Nominal strength at a section of a member shall be calculated in accordance with:

(a) 9.3 for flexure
(b) 9.4 for combined flexure and axial force
(c) 9.5 for one-way shear
(d) 9.6 for two-way shear
(e) 9.7 for torsion

9.2 — Design assumptions for flexural moment and axial strength

9.2.1 — Equilibrium and strain compatibility

9.2.1.1 — Conditions of equilibrium shall be satisfied at each section.

9.2.1.2 — Strain in concrete and nonprestressed reinforcement shall be assumed proportional to the distance from neutral axis.

9.2.1.3 — Strain in prestressed concrete and in bonded and unbonded prestressed reinforcement shall include the strain due to effective prestress.

9.2.1.4 — Changes in strain for bonded prestressed reinforcement shall be assumed proportional to the distance from neutral axis.

9.2.2 — Design assumptions for concrete

9.2.2.1 — Maximum strain at the extreme concrete compression fiber shall be assumed equal to 0.003.

9.2.2.2 — Tensile strength of concrete shall be neglected in flexural and axial strength calculations.
9.2.2.3 — The relationship between concrete compressive stress and strain shall be represented by a rectangular, trapezoidal, parabolic, or other shape that results in prediction of strength in substantial agreement with results of comprehensive tests. <10.2.6>

9.2.2.4 — The equivalent rectangular concrete stress distribution defined in 9.2.2.4.1 through 9.2.2.4.3 satisfies 9.2.2.3. <10.2.7>

9.2.2.4.1 — Concrete stress of $0.85f'_c$ shall be assumed uniformly distributed over an equivalent compression zone bounded by edges of the cross section and a line parallel to the neutral axis located a distance $a$ from the fiber of maximum compressive strain:

$$a = \beta_1 c$$

(9.2.2.4.1)

9.2.2.4.2 — Distance from the fiber of maximum compressive strain to the neutral axis, $c$, shall be measured perpendicular to the neutral axis. <10.2.7.2>

9.2.2.4.3 — Values of $\beta_1$ shall be in accordance with Table 9.2.2.4.3 <10.2.7.3>

Table 9.2.2.4.3 — Values of $\beta_1$ for equivalent rectangular concrete stress distribution

<table>
<thead>
<tr>
<th>$f'_c$ , psi</th>
<th>$\beta_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2500 ≤ $f'_c$ ≤ 4000</td>
<td>0.85 (a)</td>
</tr>
<tr>
<td>4000 &lt; $f'_c$ &lt; 8000</td>
<td>$0.85 - \frac{0.05(f'_c - 4000)}{1000}$ (b)</td>
</tr>
<tr>
<td>$f'_c$ ≥ 8000</td>
<td>0.65 (c)</td>
</tr>
</tbody>
</table>

9.2.3 — Design assumptions for nonprestressed reinforcement

9.2.3.1 — Deformed reinforcement used to resist tensile or compressive forces shall conform to 6.2.1. <~>

9.2.3.2 — Stress-strain relationship and modulus of elasticity for deformed reinforcement shall be idealized in accordance with 6.2.2.1 and 6.2.2.2. <10.2.4>

9.2.4 — Design assumptions for prestressing reinforcement

9.2.4.1 — For members with bonded prestressing reinforcement conforming to 6.3.1, stress at nominal flexural strength, $f_{ps}$, shall be calculated in accordance with 6.3.2.3. <18.7.2>

9.2.4.2 — For members with unbonded prestressing reinforcement conforming to 6.3.1, $f_{ps}$ shall be calculated in accordance with 6.3.2.4. <18.7.2>

9.2.4.3 — If the embedded length of the prestressing strand is less than $\ell_d$, the design strand stress shall not exceed the value defined in 21.4.8.3, as modified by 21.4.8.1(b). <12.9.3>
9.3 — **Flexural Moment** strength

9.3.1 — **General**

9.3.1.1 — Nominal flexural moment strength $M_n$ shall be calculated in accordance with the assumptions of 9.2. <~>

9.3.2 — **Strength reduction factor**

9.3.2.1 — Strength reduction factor for flexural strength, $\phi$, in nonprestressed members and at sections in pretensioned members where strand embedment equals or exceeds the development length shall be calculated in accordance with 0. <9.3.1> <9.3.2.1> <10.3.2> <10.3.3> <10.3.4> <18.8.1>

9.3.2.2 — For sections in pretensioned members where strand is not fully developed, $\phi$ shall be calculated at each section based on the distance from the end of the member in accordance with Table 9.3.2.2, where $t_{db}$ is the longest debonded length at the end of the member and $t_{lr}$ is defined in Eq. (9). $f_{se}$ is the effective stress in the prestressed reinforcement after allowance of all losses, and $t_d$ is defined in 21.4.8.1. <9.3.2.7> <CE093>

$$t_{lr} = \left( \frac{f_{se}}{3000} \right)^{d_b}$$

(9.3.2.2)

<table>
<thead>
<tr>
<th>Condition near end of member</th>
<th>Stress in concrete under service load $^*$</th>
<th>Distance from end of member to section under consideration</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>All strands bonded</td>
<td>Not applicable</td>
<td>$t_{lr}$ to $t_d$</td>
<td>0.75 (a)</td>
</tr>
<tr>
<td>One or more strands debonded</td>
<td>No tension</td>
<td>$t_{db} + t_{lr}$ to $t_{db} + t_d$</td>
<td>0.75 (e)</td>
</tr>
<tr>
<td>Tension calculated</td>
<td></td>
<td>$t_{db} + t_{lr}$ to $t_{db} + 2t_d$</td>
<td>0.75 (e)</td>
</tr>
</tbody>
</table>

* Calculated stress in extreme concrete fiber of precompressed tensile zone under service loads, at any section along the length of the beam, after allowance for all prestress losses using gross cross-sectional properties.

† For sections within the regions defined in rows (b), (d), and (f), it shall be permitted to use a strength reduction factor of 0.75. <9.3.2.7>
9.3.2 — Prestressed concrete members

9.3.2.1 — Deformed reinforcement conforming to 6.2.1 used with prestressed reinforcement shall be permitted to be considered to contribute to the tensile force and be included in flexural strength calculations at a stress equal to \( f_y \). <18.7.3>

9.3.2.2 — Other nonprestressed reinforcement shall be permitted to be included in flexural strength calculations if a strain compatibility analysis is performed to determine stresses in such reinforcement. <18.7.3>

9.3.3 — Composite concrete members

9.3.3.1 — Provisions of 9.3.3 apply to concrete elements constructed in separate placements but connected so that all elements resist loads as a unit. <17.1.1>

9.3.3.2 — For calculation of \( M_n \) for composite concrete slabs and beams, use of the entire composite section shall be permitted. <17.2.1>

9.3.3.3 — For calculation of \( M_n \) for composite concrete slabs and beams, no distinction shall be made between shored and unshored members. <17.2.4>

9.3.3.4 — For calculation of \( M_n \) for composite concrete members where the specified concrete compressive strength of different elements vary, properties of the individual elements shall be used in design. Alternatively, it shall be permitted to use the value of \( f'_c \) for the element that results in the most critical value of \( M_n \).<17.2.3>

9.4 — Axial strength or combined flexural moment and axial strength

9.4.1 — General

9.4.1.1 — Nominal axial strength or combined flexural moment and axial strength shall be calculated in accordance with the assumptions of 9.2. <18.11.1>

9.4.2 — Strength reduction factor

9.4.2.1 — Strength reduction factor for combined flexural and axial strength, \( \phi \) shall be in accordance with Table 9.4.2.1. <9.3.1> <10.3.2> <10.3.3> <10.3.4> <18.8.1>
Table 9.4.2.1 — Strength reduction factor for flexural and axial strength

<table>
<thead>
<tr>
<th>Net tensile stain, $\varepsilon_t$</th>
<th>Classification</th>
<th>$\phi$</th>
<th>Transverse reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_t &lt; \varepsilon_{ty}$</td>
<td>Compression controlled</td>
<td>0.75</td>
<td>(a)</td>
</tr>
<tr>
<td>$\varepsilon_{ty} &lt; \varepsilon_t &lt; 0.005$</td>
<td>Transition</td>
<td>$0.75 + 0.15 \left( \frac{\varepsilon_t - \varepsilon_{ty}}{0.005 - \varepsilon_{ty}} \right)$</td>
<td>(c) $^*$</td>
</tr>
<tr>
<td>$\varepsilon_t \geq 0.005$</td>
<td>Tension controlled</td>
<td>0.90</td>
<td>(e)</td>
</tr>
</tbody>
</table>

$^*$ For sections classified as transition, it shall be permitted to use the strength reduction factor corresponding to compression-controlled conditions. <9.3.2.2>

9.4.2.2 — For deformed reinforcement, $\varepsilon_{ty}$ shall be taken as $f_y/E_y$. For Grade 60 deformed reinforcement, it shall be permitted to take $\varepsilon_{ty}$ equal to 0.002. <10.3.3>

9.4.2.3 — For all prestressed reinforcement, $\varepsilon_{ty}$ shall be taken as 0.002. <10.3.3>

9.4.2 — Maximum axial strength

9.4.2.1 — Nominal axial strength of compression member, $P_n$, shall not be taken greater than $P_{n,\text{max}}$, as defined in Table 9.4.2.1, where $P_o$ is defined in 9.4.2.2 for nonprestressed and composite members and in 9.4.2.3 for prestressed members. <10.3.6> <10.3.6.1> <10.3.6.2> <10.3.6.3>

Table 9.4.2.1 — Maximum axial strength

<table>
<thead>
<tr>
<th>Member</th>
<th>Transverse Reinforcement</th>
<th>$P_{n,\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonprestressed</td>
<td>Ties conforming to 9.4.2.4</td>
<td>0.80$P_o$</td>
</tr>
<tr>
<td></td>
<td>Spirals conforming to 9.4.2.5</td>
<td>0.85$P_o$</td>
</tr>
<tr>
<td>Prestressed</td>
<td>Ties</td>
<td>0.80$P_o$</td>
</tr>
<tr>
<td></td>
<td>Spirals</td>
<td>0.85$P_o$</td>
</tr>
<tr>
<td>Composite conforming to Chapter 14</td>
<td>All</td>
<td>0.85$P_o$</td>
</tr>
</tbody>
</table>

9.4.2.2 — For nonprestressed and composite members, $P_o$ shall be calculated as:

$$P_o = 0.85 f'_c \left( A_g - A_{st} \right) + f_y A_{st} \quad (9.4.2.2)$$

where $A_{st}$ is the total area of nonprestressed longitudinal reinforcement.
9.4.2.3 — For prestressed members, $P_o$ shall be calculated as:

$$P_o = 0.85 f'_c \left( A_g - A_{st} - A_{pd} \right) + f_y A_{st} - \left( f_{se} - 0.003 E_p \right) A_{pt}$$

(9.4.2.3)

where $A_{pt}$ is the total area of prestressing reinforcement, $A_{pd}$ is the total area occupied by duct, sheathing, and prestressing reinforcement, and the value of $f_{se}$ shall not be taken less than $\left( 0.003 E_p \right)$. For grouted, post-tensioned tendons, it shall be permitted to assume $A_{pd} = A_{pt}$. <~> <Balloted as CE091>>

9.4.2.4 — Tie reinforcement for compression members shall satisfy provisions for lateral support of longitudinal reinforcement in 14.7.6.2 and detailing provisions in 21.8.2. <7.10.5>

Reference to 14.7.6.2 per LB12-10.

9.4.2.5 — Spiral reinforcement for compression members shall satisfy provisions for lateral support of longitudinal reinforcement in 14.7.6.3 and detailing provisions in 21.8.3. <7.10.4>

Reference to 14.7.6.3 per LB12-10.

9.5 — One-way shear strength

9.5.1 — General

9.5.1.1 — Nominal one-way shear strength at a section, $V_n$, shall be calculated as: <11.1.1>

$$V_n = V_c + V_s$$

(9.5.1.1)

9.5.1.2 — Cross-sectional dimensions shall satisfy Eq. (9.5.1.2). <11.4.7.9>

$$V_u \leq \phi \left( V_c + 8 \sqrt{f'_c b_w d} \right)$$

(9.5.1.2)

9.5.1.3 — For nonprestressed members, $V_c$ shall be calculated in accordance with 9.5.5, 9.5.6, or 9.5.7. <~>

9.5.1.4 — For prestressed members, $V_c$, $V_{ci}$, and $V_{cw}$ shall be calculated in accordance with 9.5.8 or 9.5.9. <~>

9.5.1.5 — For calculation of $V_c$, $V_{ci}$, and $V_{cw}$, $\lambda$ shall be determined in accordance with 5.2.4. <~>

9.5.1.6 — $V_s$ shall be calculated in accordance with 9.5.10. <~>

9.5.1.7 — Effect of any openings in members shall be considered in calculating $V_n$. <11.1.1.1>
9.5.1.8 — Effects of axial tension due to creep and shrinkage in restrained members shall be considered in calculating $V_c$. <11.1.1.2>

9.5.1.9 — Effect of inclined flexural compression in variable depth members shall be permitted to be considered in calculating $V_c$. <11.1.1.2>

9.5.2 — Strength reduction factor

9.5.2.1 — Strength reduction factor for one-way shear, $\phi$, shall be 0.75. <9.3.2.3>

9.5.2.2 — Geometric assumptions

9.5.2.1 — For calculation of $V_c$ and $V_s$ in prestressed members, $d$ shall be taken as the distance from extreme compression fiber to centroid of prestressed and any nonprestressed longitudinal reinforcement but need not be taken less than $0.8h$. <11.3.1> <11.4.3>

9.5.2.2 — For calculation of $V_c$ and $V_s$ in solid, circular sections, $d$ shall be permitted to be taken as 0.8 times the diameter and $b_w$ shall be permitted to be taken as the diameter. <11.2.3> <11.4.7.3>

9.5.3 — Limiting material strengths

9.5.3.1 — The value of $\sqrt{f'}$ used to calculate $V_c$, $V_{ci}$, and $V_{cw}$ for one-way shear shall not exceed 100 psi, except as allowed in 9.5.3.2. <11.1.2>

9.5.3.2 — Values of $\sqrt{f'}$ greater than 100 psi shall be permitted in calculating $V_c$, $V_{ci}$, and $V_{cw}$ for reinforced or prestressed concrete beams and concrete joist construction having minimum web reinforcement in accordance with 13.6.3.3 or 13.6.4.2. <11.1.2.1>

9.5.3.3 — The values of $f_y$ and $f_{yt}$ used to calculate $V_s$ shall not exceed the limits in 6.2.2.4. <11.4.2>

9.5.4 — Composite concrete members

9.5.4.1 — Provisions of 9.5.4 apply to concrete elements constructed in separate placements but connected so that all elements resist loads as a unit. <17.1.1>

9.5.4.2 — For calculation of $V_n$ for composite concrete members, no distinction shall be made between shored and unshored members. <17.2.4>

9.5.4.3 — For calculation of $V_n$ for composite concrete members where the specified concrete compressive strength, unit weight, or other properties of different elements vary, properties of the individual elements shall be used in design. Alternatively, it shall be
permitted to use the properties for the element that results in the most critical value of $V_n$.

9.5.4.4 — If an entire composite concrete member is assumed to resist vertical shear, $V_c$ shall be permitted to be calculated assuming a monolithically cast member of the same cross-sectional shape. <17.2.1> <17.4.1>

9.5.4.5 — If an entire composite concrete member is assumed to resist vertical shear, $V_s$ shall be permitted to be calculated assuming a monolithically cast member of the same cross-sectional shape provided that shear reinforcement is fully anchored into the interconnected elements in accordance with 21.8. <17.4.1> <17.4.2>

9.5.5 — $V_c$ for nonprestressed members without axial force

9.5.5.1 — For nonprestressed members without axial force, $V_c$ shall be calculated in accordance with Eq. (9.5.5.1), unless a more detailed calculation is made in accordance with Table 9.5.5.1. <11.2.1> <11.2.1.1> <11.2.2.1>

\[
V_c = 2\lambda \sqrt{f'_c b_w d} \tag{9.5.5.1}
\]

Table 9.5.5.1 — Detailed method for calculating $V_c$

<table>
<thead>
<tr>
<th>$V_c$</th>
<th>Least of (a), (b), and (c):</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[ 1.9\lambda \sqrt{f'_c + 2500\rho_w \frac{V_u d}{M_u}} b_w d ] (a)*</td>
</tr>
<tr>
<td></td>
<td>[ 1.9\lambda \sqrt{f'_c + 2500\rho_w} b_w d ] (b)</td>
</tr>
<tr>
<td></td>
<td>3.5\lambda \sqrt{f'_c} b_w d</td>
</tr>
</tbody>
</table>

* $M_u$ occurs simultaneously with $V_u$ at the section considered

9.5.6 — $V_c$ for nonprestressed members with axial compression

9.5.6.1 — For nonprestressed members with axial compression, $V_c$ shall be calculated in accordance with Eq. 9.5.6.1, unless a more detailed calculation is made in accordance with Table 9.5.6.1, where $N_u$ is positive for compression. <11.2.1> <11.2.1.2> <11.2.2.2>

\[
V_c = 2 \left( 1 + \frac{N_u}{2000A_g} \right) \lambda \sqrt{f'_c b_w d} \tag{9.5.6.1}
\]
Table 9.5.6.1 — Detailed method for calculating $V_c$

<table>
<thead>
<tr>
<th>$V_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lesser of (a) and (b):</td>
</tr>
<tr>
<td>$1.9 \lambda \sqrt{f_c' + 2500 \rho_w} \frac{V_u d}{M_u - N_u \left(\frac{4h - d}{8}\right)} b_w d$ (a)*,†</td>
</tr>
<tr>
<td>$3.5 \lambda \sqrt{f_c' b_w d} \left(1 + \frac{N_u}{500 A_g}\right)$ (b)</td>
</tr>
</tbody>
</table>

* $M_u$ occurs simultaneously with $V_u$ at the section considered.

† (a) is not applicable if $M_u - N_u \left(\frac{4h - d}{8}\right) \leq 0$.

9.5.7 — $V_c$ for nonprestressed members with significant axial tension

9.5.7.1 — For nonprestressed members with significant axial tension, $V_c$ shall be taken as zero unless a more detailed calculation is made in accordance with Eq. 9.5.7.1, where $N_u$ is negative for tension, and $V_c$ shall not be taken less than zero. <11.2.1> <11.2.2.2>

$$V_c = 2 \left(1 + \frac{N_u}{500 A_g}\right) \lambda \sqrt{f_c' b_w d} \quad (9.5.7.1)$$

9.5.8 — $V_c$ for prestressed members

9.5.8.1 — The provisions of 9.5.8 shall govern the calculation of $V_c$ for post-tensioned members and for pretensioned members in regions where the effective force in the prestressed reinforcement is fully transferred to the concrete. For regions of pretensioned members where the effective force in the prestressed reinforcement is not fully transferred to the concrete, the provisions of 9.5.9 shall govern the calculation of $V_c$. <~>

9.5.8.2 — For prestressed flexural members with effective prestress force that is at least 40 percent of the tensile strength of the flexural reinforcement, $V_c$ shall be calculated in accordance with Table 9.5.8.2, but need not be taken less than the value obtained from Eq. (9.5.5.1). Alternatively, it shall be permitted to determine $V_c$ in accordance with 9.5.8.3. <11.3.2>
Table 9.5.8.2 — Approximate method for calculating $V_c$

<table>
<thead>
<tr>
<th>Least of (a), (b), and (c):</th>
<th>$V_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>(a)</em> $0.6\lambda\sqrt{f'_c} + 700\left\frac{V_u d_p}{M_u}\right b_w d$</td>
<td></td>
</tr>
<tr>
<td><em>(b)</em> $0.6\lambda\sqrt{f'_c} + 700 b_w d$</td>
<td></td>
</tr>
<tr>
<td><em>(c)</em> $5\lambda\sqrt{f'_c} b_w d$</td>
<td></td>
</tr>
</tbody>
</table>

* $M_u$ occurs simultaneously with $V_u$ at the section considered

9.5.8.3 — For prestressed members, $V_c$ shall be permitted to be taken as the lesser of $V_{ci}$ calculated in accordance with 9.5.8.3.1 and $V_{cw}$ calculated in accordance with 9.5.8.3.2 or 9.5.8.3.3. <11.3.3>

9.5.8.3.1 — The flexure-shear strength, $V_{ci}$, shall be taken as the greater of (a) and (b): <11.3.3.1>

(a) $0.6\lambda\sqrt{f'_c} b_w d_p + V_d + \frac{V_i M_{cre}}{M_{max}}$

(b) $1.7\lambda\sqrt{f'_c} b_w d$

where $d_p$ need not be taken less than 0.80$h$, the values of $M_{max}$ and $V_i$ shall be calculated from the load combinations causing maximum factored moment to occur at section considered, and $M_{cre}$ shall be calculated as:

$$M_{cre} = \left(\frac{I}{y_l}\right)(6\lambda\sqrt{f'_c} + f_{pe} - f_d)$$  \hspace{1cm} (9.5.8.3.1)

9.5.8.3.2 — The web-shear strength, $V_{cw}$, shall be calculated as: <11.3.3.2>

$$V_{cw} = \left(3.5\lambda\sqrt{f'_c} + 0.3 f_{pc}\right) b_w d_p + V_p$$  \hspace{1cm} (9.5.8.3.2)

where $d_p$ need not be taken less than 0.80$h$ and $V_p$ is the vertical component of the effective prestress.

9.5.8.3.3 — As an alternative to 9.5.8.3.2, $V_{cw}$ shall be permitted to be calculated as the shear force corresponding to dead load plus live load that results in a principal tensile stress of $4\lambda\sqrt{f'_c}$ at the location indicated in (a) or (b): <11.3.3.2>

(a) If the centroidal axis of the prestressed cross section is in the web, the principal tensile stress shall be calculated at the centroidal axis.
(b) If the centroidal axis of the prestressed cross section is in the flange, the principal tensile stress shall be calculated at the intersection of the flange and the web.

9.5.8.3.4 — In composite members, the principal tensile stress defined in 9.5.8.3.3 shall be calculated using the cross section that resists live load. <11.3.3.2>

9.5.9 — \( V_c \) for pretensioned members in regions of reduced prestress force

9.5.9.1 — When calculating \( V_c \), the transfer length of prestressed reinforcement, \( \ell_{tr} \), shall be assumed to be 50\( d_b \) for strand and 100\( d_b \) for wire. <11.3.4> <11.3.5>

9.5.9.2 — If bonding of strands extends to the end of the member, the effective prestress force shall be assumed to vary linearly from zero at the end of the prestressed reinforcement to a maximum at a distance \( \ell_{tr} \) from the end of the prestressed reinforcement. <11.3.4>

9.5.9.3 — At locations corresponding to a reduced effective prestress force according to 9.5.9.2, the value of \( V_c \) shall be calculated in accordance with (a), (b), and (c): <11.3.4>

- (a) The reduced effective prestress force shall be used to determine the applicability of 9.5.8.2.
- (b) The reduced effective prestress force shall be used to calculate \( V_{cw} \) in 9.5.8.3.
- (c) The value of \( V_c \) calculated using 9.5.8.2 shall not exceed the value of \( V_{cw} \) calculated using the reduced effective prestress force.

9.5.9.4 — If bonding of strands does not extend to the end of the member, the effective prestress force shall be assumed to vary linearly from zero at the point where bonding commences to a maximum at a distance \( \ell_{tr} \) from that point. <11.3.5>

9.5.9.5 — At locations corresponding to a reduced effective prestress force according to 9.5.9.4, the value of \( V_c \) shall be calculated in accordance with (a), (b), and (c): <11.3.5>

- (a) The reduced effective prestress force shall be used to determine the applicability of 9.5.8.2.
- (b) The reduced effective prestress force shall be used to calculate \( V_c \) in accordance with 9.5.8.3.
- (c) The value of \( V_c \) calculated using 9.5.8.2 shall not exceed the value of \( V_{cw} \) calculated using the reduced effective prestress force.

9.5.10 — One-way shear reinforcement

9.5.10.1 — At each section where \( V_u > \phi V_c \), transverse reinforcement shall be provided such that Eq. (9.5.10.1) is satisfied. <11.4.7.1>
\[ V_s \geq \frac{V_u}{\phi} - V_c \]  
(9.5.10.1)

9.5.10.2 — For one-way members reinforced with stirrups, ties, hoops, crossties, or spirals, \( V_s \) shall be calculated in accordance with 9.5.10.5. <~>

9.5.10.3 — For one-way members reinforced with bent-up longitudinal bars, \( V_s \) shall be calculated in accordance with 9.5.10.6. <~>

9.5.10.4 — If more than one type of shear reinforcement is provided to reinforce the same portion of a member, \( V_s \) shall be calculated as the sum of the \( V_s \) values calculated for the various types of shear reinforcement. <11.4.7.8>

9.5.10.5 — One-way shear strength provided by stirrups, ties, hoops, crossties, and spirals

9.5.10.5.1 — Shear reinforcement satisfying (a), (b), or (c) shall be permitted in nonprestressed and prestressed members: <11.4.1.1>

(a) Stirrups, ties, or hoops perpendicular to longitudinal axis of member
(b) Welded wire reinforcement with wires located perpendicular to longitudinal axis of member
(c) Spiral reinforcement

9.5.10.5.2 — Inclined stirrups making an angle of at least 45 degrees with the longitudinal axis of the member and crossing the plane of the potential shear crack shall be permitted to be used as shear reinforcement in nonprestressed members. <11.4.1.2>

9.5.10.5.3 — \( V_s \) for shear reinforcement complying with 9.5.10.5.1 shall be calculated as: <11.4.7.2>

\[ V_s = \frac{A_v f_{yd} d}{s} \]  
(9.5.10.5.3)

where \( s \) is the spiral pitch or the longitudinal spacing of the shear reinforcement and \( A_v \) is defined in 9.5.10.5.5 or 9.5.10.5.6.

9.5.10.5.4 — \( V_s \) for shear reinforcement complying with 9.5.10.5.2 shall be calculated as: <11.4.7.4>

\[ V_s = \frac{A_v f_{yd} (\sin \alpha + \cos \alpha) d}{s} \]  
(9.5.10.5.4)

where \( \alpha \) is the angle between the inclined stirrups and the longitudinal axis of the member, \( s \) is measured parallel to the longitudinal reinforcement, and \( A_v \) is defined in 9.5.10.5.5.

9.5.10.5.5 — For each rectangular tie, stirrup, hoop, or crosstie, \( A_v \) shall be taken as the effective area of all bar legs or wires within spacing \( s \). <~>
9.5.10.5.6 — For each circular tie or spiral, $A_v$ shall be taken as two times the area of the bar or wire within spacing $s$. <11.4.7.3>
9.5.10.6 — One-way shear strength provided by bent-up longitudinal bars

9.5.10.6.1 — The center three-fourths of the inclined portion of bent-up longitudinal bars shall be permitted to be used as shear reinforcement in nonprestressed members if the angle $\alpha$ between the bent-up bars and the longitudinal axis of the member is at least 30 degrees. <11.4.7.7>

9.5.10.6.2 — If shear reinforcement consists of a single bar or a single group of parallel bars having an area $A_v$, all bent the same distance from the support, $V_s$ shall be taken as the lesser of (a) and (b): <11.4.7.5>

(a) $A_v f_y \sin \alpha$

(b) $3 \sqrt{f_y b_n d}$

where $\alpha$ is the angle between bent-up reinforcement and longitudinal axis of the member.

9.5.10.6.3 — If shear reinforcement consists of a series of parallel bent-up bars or groups of parallel bent-up bars at different distances from the support, $V_s$ shall be calculated in accordance with Eq. (9.5.10.5.4). <11.4.7.6>

9.6 — Two-way shear strength

9.6.1 — General

9.6.1.1 — Provisions 9.6.1 through 9.6.8 define the nominal shear strength of two-way members with and without shear reinforcement. Where structural steel I- or channel-shaped sections are used as shearheads, two-way members shall be designed for shear in accordance with 9.6.9. <~> <11.11.4>

9.6.1.2 — Nominal shear strength for two-way members without shear reinforcement shall be calculated in accordance with Eq. 9.6.1.2. <~> <11.11.1> <11.11.7.2>

$$v_n = v_c$$  \hspace{1cm} (9.6.1.2)

9.6.1.3 — Nominal shear strength for two-way members with shear reinforcement other than shearheads shall be calculated in accordance with Eq. 9.6.1.3. <11.1.1> <11.11.7.2>

$$v_n = v_c + v_s$$  \hspace{1cm} (9.6.1.3)

9.6.1.4 — Two-way shear shall be resisted by a section with a depth $d$ and an assumed critical perimeter $b_o$ that extends completely or partially around the column, concentrated load, or reaction area. <~>

9.6.1.5 — $v_c$ for two-way shear shall be calculated in accordance with 9.6.5. For two-way members with shear reinforcement, $v_c$ shall not exceed the limits in 9.6.6.1. <~> <11.11.3.1>

9.6.1.6 — For calculation of $v_c$, $\lambda$ shall be determined in accordance with 5.2.4. <~>
9.6.1.7 — For two-way members reinforced with single- or multi-leg stirrups, \( v_s \) shall be calculated in accordance with 9.6.7. <~> <11.11.3.1>

9.6.1.8 — For two-way members reinforced with headed shear stud reinforcement, \( v_s \) shall be calculated in accordance with 9.6.8. <~> <11.11.5.1>

9.6.2 — Strength reduction factor

9.6.2.1 — Strength reduction factor for two-way shear, \( \phi \), shall be 0.75. <9.3.2.3>

9.6.2 — Effective depth

9.6.2.1 — For calculation of \( v_e \) and \( v_s \) for two-way shear, \( d \) shall be taken as the average of the effective depths in the two orthogonal directions. <~>

9.6.2.2 — For prestressed, two-way members, \( d \) need not be taken less than 0.8\( h \). <11.3.1> <11.4.3>

9.6.3 — Limiting material strengths

9.6.3.1 — The value of \( \sqrt{f_m} \) used to calculate \( v_e \) for two-way shear shall not exceed 100 psi. <11.1.2> <11.1.2.1>

9.6.3.2 — The value of \( f_{yt} \) used to calculate \( v_s \) shall not exceed the limits in 6.2.2.4. <11.4.2>

9.6.4 — Critical sections for two-way members

9.6.4.1 — For two-way shear, critical sections shall be located so that the perimeter \( b_o \) is a minimum but need not be closer than \( d/2 \) to: <11.11.1.2> <15.5.2>

(a) Edges or corners of columns, concentrated loads, or reaction areas

(b) Changes in slab or footing thickness, such as edges of capitals, drop panels, or shear caps

9.6.4.2 — For two-way members reinforced with single- or multi-leg stirrups, a critical section with perimeter \( b_o \) located \( d/2 \) beyond the outermost line of stirrup legs that surround the column shall also be considered. <11.11.7.2>

9.6.4.3 — For two-way members reinforced with headed shear stud reinforcement, a critical section with perimeter \( b_o \) located \( d/2 \) beyond the outermost peripheral line of shear reinforcement shall also be considered. <11.11.5.4>

9.6.4.4 — For square or rectangular columns, concentrated loads, or reaction areas, critical sections for two-way shear shall be permitted to be calculated assuming straight sides. <11.11.1.3>
9.6.4.5 — For a circular or regular polygon-shaped column, critical sections for two-way shear shall be permitted to be calculated assuming a square column of equivalent area. <15.3>

9.6.4.6 — If an opening is located within a column strip or closer than 10h from a concentrated load or reaction area, a portion of \( b_o \) enclosed by straight lines projecting from the centroid of the column, concentrated load or reaction area and tangent to the boundaries of the opening shall be considered ineffective. <11.11.6>

9.6.5 — Two-way shear strength provided by concrete

9.6.5.1 — For nonprestressed, two-way members, \( v_e \) shall be calculated in accordance with Table 9.6.5.1, where \( \beta \) is the ratio of long side to short side of the column, concentrated load, or reaction area and \( \alpha_s \) is defined in 9.6.5.2. <11.11.2.1>

Table 9.6.5.1 — Calculation of \( v_e \) for two-way shear

<table>
<thead>
<tr>
<th>( v_e )</th>
<th>( \beta )</th>
<th>( \alpha_s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Least of (a), (b), and (c):</td>
<td> </td>
<td> </td>
</tr>
<tr>
<td>( 4\lambda\sqrt{f'_c} )</td>
<td>(a)</td>
<td> </td>
</tr>
<tr>
<td>( \left( 2 + \frac{4}{\beta} \right) \lambda\sqrt{f'_c} )</td>
<td>(b)</td>
<td> </td>
</tr>
<tr>
<td>( 2 + \frac{\alpha_s d}{b_o} ) ( \lambda\sqrt{f'_c} )</td>
<td>(c)</td>
<td> </td>
</tr>
</tbody>
</table>

9.6.5.2 — The value of \( \alpha_s \) is 40 for interior columns, 30 for edge columns, and 20 for corner columns. <11.11.2.1>

9.6.5.3 — For prestressed, two-way members, it shall be permitted to calculate \( v_e \) using 9.6.5.4 provided that (a), (b), and (c) are satisfied. <11.11.2.2>

(a) Bonded reinforcement is provided in accordance with 12.6.2.3 and 12.7.5.5

(b) No portion of the column cross section is closer to a discontinuous edge than four times the slab thickness \( h \)

(c) Effective prestress, \( f_{pe} \), in each direction is not less than 125 psi

9.6.5.4 — For prestressed, two-way members conforming to 9.6.5.3, \( v_e \) shall be permitted to be calculated as the lesser of (a) and (b): <11.11.2.2>

(a) \( \left( 3.5\lambda\sqrt{f'_c} + 0.3f_{pe} \right) + \frac{V_p}{b_od} \)

(b) \( \left( 1.5 + \frac{\alpha_s d}{b_o} \right) \lambda\sqrt{f'_c} + 0.3f_{pe} + \frac{V_p}{b_od} \)
where \( \alpha_s \) is defined in 9.6.5.2, the value of \( f_{pc} \) is the average of \( f_{pc} \) in the two directions and shall not be taken greater than 500 psi, \( V_p \) is the vertical component of all effective prestress forces crossing the critical section, and the value of \( \sqrt{f_c} \) shall not exceed 70 psi.

**9.6.6 — Maximum shear for two-way members with shear reinforcement**

**9.6.6.1** — For two-way members with shear reinforcement, value of \( v_c \) calculated at the critical sections defined in 9.6.4 shall not exceed the values in Table 9.6.6.1.

**Table 9.6.6.1 — Maximum \( v_c \) for two-way members with shear reinforcement**

<table>
<thead>
<tr>
<th>Type of shear reinforcement</th>
<th>Maximum ( v_c ) at critical sections defined in 9.6.4.1</th>
<th>Maximum ( v_c ) at critical section defined in 9.6.4.2 and 9.6.4.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stirrups</td>
<td>( 2\lambda\sqrt{f_c'} ) (a)</td>
<td>( 2\lambda\sqrt{f_c'} ) (b)</td>
</tr>
<tr>
<td>Headed shear stud reinforcement</td>
<td>( 3\lambda\sqrt{f_c'} ) (c)</td>
<td>( 2\lambda\sqrt{f_c'} ) (d)</td>
</tr>
</tbody>
</table>

**9.6.6.2** — For two-way members with shear reinforcement, effective depth shall be selected such that \( v_u \) calculated at the critical sections defined in 9.6.4.1 does not exceed the values in Table 9.6.6.2.

**Table 9.6.6.2 — Maximum \( v_u \) for two-way members with shear reinforcement**

<table>
<thead>
<tr>
<th>Type of shear reinforcement</th>
<th>Maximum ( v_u ) at critical sections defined in 9.6.4.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stirrups</td>
<td>( \phi 6\sqrt{f_c'} ) (a)</td>
</tr>
<tr>
<td>Headed shear stud reinforcement</td>
<td>( \phi 8\sqrt{f_c'} ) (b)</td>
</tr>
</tbody>
</table>

**9.6.7 — Two-way shear strength provided by single- or multiple-leg stirrups**

**9.6.7.1** — Single- or multiple-leg stirrups fabricated from bars or wires shall be permitted to be used as shear reinforcement in slabs and footings conforming to (a) and (b):

- (a) \( d \) is at least 6 in.
- (b) \( d \) is at least 16\( dB \), where \( dB \) is the diameter of the stirrups

**9.6.7.2** — For two-way members with stirrups, \( v_s \) shall be calculated as:

\[
v_s = \frac{A_v f_{vl}}{b_0 s}
\]  

(9.6.7.2)
where $A_v$ is the sum of the area of all legs of reinforcement on one peripheral line that is geometrically similar to the perimeter of the column section, and $s$ is the spacing of the peripheral lines of shear reinforcement in the direction perpendicular to the column face.

### 9.6.8 — Two-way shear strength provided by headed shear stud reinforcement

#### 9.6.8.1 — Headed shear stud reinforcement shall be permitted to be used as shear reinforcement in slabs and footings if the placement and geometry of the headed shear stud reinforcement satisfies 12.7.7. <11.11.5>

#### 9.6.8.2 — For two-way members with headed shear stud reinforcement, $v_s$ shall be calculated as: <11.4.7.2> <11.11.5.1>

$$v_s = \frac{A_v f_{yt}}{b_o s}$$  \hspace{1cm} (9.6.8.2)

where $A_v$ is the sum of the area of all shear studs on one peripheral line that is geometrically similar to the perimeter of the column section, and $s$ is the spacing of the peripheral lines of headed shear stud reinforcement in the direction perpendicular to the column face.

#### 9.6.8.3 — If headed shear stud reinforcement is provided, $\frac{A_v}{s}$ shall satisfy Eq. (9.6.8.3).

<11.11.5.1>

$$\frac{A_v}{s} \geq 2 \sqrt{f_c} \frac{b_o}{f_{yt}}$$  \hspace{1cm} (9.6.8.3)

### 9.6.9 — Design provisions for two-way members with shearheads

#### 9.6.9.1 — Each shearhead shall consist of steel shapes fabricated with a full penetration weld into identical arms at right angles. Shearhead arms shall not be interrupted within the column section. <11.11.4.1>

#### 9.6.9.2 — A shearhead shall not be deeper than 70 times the web thickness of the steel shape. <11.11.4.2>

#### 9.6.9.3 — The ends of each shearhead arm shall be permitted to be cut at angles of at least 30 degrees with the horizontal if the plastic moment strength, $M_p$, of the remaining tapered section is adequate to resist the shear force attributed to that arm of the shearhead. <11.11.4.3>

#### 9.6.9.4 — Compression flanges of steel shapes shall be within $0.3d$ of the compression surface of the slab. <11.11.4.4>
9.6.9.5 — The ratio \( \alpha_v \) between the flexural stiffness of each shearhead arm and that of the surrounding composite cracked slab section of width \((c_2 + d)\) shall be at least 0.15.

9.6.9.6 — For each arm of the shearhead, \( M_p \) shall satisfy Eq. (9.6.9.6).

\[
M_p \geq \frac{V_u}{2\phi n} \left( V_c \alpha_v \left( \ell_v \frac{c_1}{2} \right) \right) \tag{9.6.9.6}
\]

where \( \phi \) corresponds to tension-controlled members in 9.4.2.4, \( n \) is the number of shearhead arms, and \( \ell_v \) is the minimum length of each shearhead arm required to comply with 9.6.9.8 and 9.6.9.10.

9.6.9.7 — Nominal flexural strength contributed to each slab column strip by a shearhead, \( M_v \), shall satisfy Eq. (9.6.9.7).

\[
M_v \leq \frac{\phi \alpha \frac{V_u}{2n}}{2} \left( \ell_v \frac{c_1}{2} \right) \tag{9.6.9.7}
\]

where \( \phi \) corresponds to tension-controlled members in 9.4.2.4. However, \( M_v \) shall not be taken greater than the least of (a), (b), and (c).

(a) 30 percent of \( M_u \) in each slab column strip
(b) Change in \( M_u \) in column strip over the length \( \ell_v \)
(c) \( M_p \) as defined in 9.6.9.6

9.6.9.8 — The critical section for shear shall be perpendicular to the plane of the slab and shall cross each shearhead arm at a distance \((3/4)\left[ \ell_v \frac{c_1}{2} \right] \) from the column face. This critical section shall be located so \( b_o \) is a minimum, but need not be closer than \( d/2 \) to the edges of the supporting column.

9.6.9.9 — If an opening is located within a column strip or closer than \( 10h \) from a column in slabs with shearheads, the ineffective portion of \( b_o \) shall be one-half of that defined in

9.6.4.6.

9.6.9.10 — Factored shear stress due to vertical loads shall not be greater than \( \phi 4 \sqrt{f_c} \) on the critical section defined in 9.6.9.8 and shall not be greater than \( \phi 7 \sqrt{f_c} \) on the critical section closest to the column defined in 9.6.4.1(a).

9.6.9.11 — Where transfer of moment is considered, the shearhead must have adequate anchorage to transmit \( M_p \) to the column.

9.6.9.12 — Where transfer of moment is considered, the sum of factored shear stresses due to vertical load acting on the critical section defined by 9.6.9.8 and the shear stresses resulting
from factored moment transferred by eccentricity of shear about the centroid of the critical section closest to the column defined in 9.6.4.1(a) shall not exceed $4\phi\lambda\sqrt{f'_c}$.
9.7 — Torsion

9.7.1 — General

9.7.1.1 — Provisions of 9.7 apply to members if \( T_u \geq \phi T_{th} \), where \( \phi \) is defined in 9.7.4. If \( T_u < \phi T_{th} \), it shall be permitted to neglect torsional effects. \(<11.5.1>\)

9.7.1.2 — Nominal torsional strength shall be calculated in accordance with 9.7.6. \(<~>\)

9.7.1.3 — For calculation of \( T_{th} \) and \( T_{cr} \), \( \lambda \) shall be determined in accordance with 5.2.4. \(<~>\)

9.7.2 — Strength reduction factor

9.7.2.1 — Strength reduction factor for torsion, \( \phi \), shall be 0.75. \(<9.3.2.3>\)

9.7.2 — Limiting material strengths

9.7.2.1 — The value of \( \sqrt{f_y} \) used to calculate \( T_{th} \) and \( T_{cr} \) shall not exceed 100 psi. \(<11.1.2>\)

9.7.2.2 — The values of \( f_y \) and \( f_{yf} \) for longitudinal and transverse torsion reinforcement shall not exceed the limits in 6.2.2.4. \(<11.4.2>\)

9.7.3 — Factored design torsion

9.7.3.1 — If \( T_u \geq \phi T_{th} \) and \( T_u \) is required to maintain equilibrium, the member shall be designed to resist \( T_u \). \(<11.5.2.1>\)

9.7.3.2 — In a statically indeterminate structure where \( T_u \geq \phi T_{th} \) and reduction of \( T_u \) in a member can occur due to redistribution of internal forces after torsional cracking, \( T_u \) shall be permitted to be reduced to \( \phi T_{cr} \), where the cracking torsion, \( T_{cr} \), is defined in 9.7.5. \(<11.5.2.2>\)

9.7.3.3 — If \( T_u \) is redistributed in accordance with 9.7.3.2, the factored moments and shears used for design of the adjoining members shall be in equilibrium with the reduced torsion. \(<11.5.2.2>\)

9.7.4 — Threshold torsion
9.7.4.1 — Threshold torsion, $T_{th}$, shall be calculated in accordance with Table 9.7.4.1(a) for solid cross sections and Table 9.7.4.1(b) for hollow cross sections, where $N_u$ is positive for compression and negative for tension. <11.5.1>
### Table 9.7.4.1(a) — Threshold torsion for solid cross sections

<table>
<thead>
<tr>
<th>Type of member</th>
<th>( T_{th} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonprestressed member</td>
<td>( \lambda \sqrt{f'<em>c} \left( \frac{A</em>{cp}^2}{p_{cp}} \right) )</td>
</tr>
<tr>
<td>Prestressed member</td>
<td>( \lambda \sqrt{f'<em>c} \left( \frac{A</em>{cp}^2}{p_{cp}} \right) \sqrt{1 + \frac{f_{pc}}{4\lambda \sqrt{f'_c}}} )</td>
</tr>
<tr>
<td>Nonprestressed member subjected to axial force</td>
<td>( \lambda \sqrt{f'<em>c} \left( \frac{A</em>{cp}^2}{p_{cp}} \right) \sqrt{1 + \frac{N_u}{4A_{g} \lambda \sqrt{f'_c}}} )</td>
</tr>
</tbody>
</table>

### Table 9.7.4.1(b) — Threshold torsion for hollow cross sections

<table>
<thead>
<tr>
<th>Type of member</th>
<th>( T_{th} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonprestressed member</td>
<td>( \lambda \sqrt{f'<em>c} \left( \frac{A</em>{g}^2}{p_{cp}} \right) )</td>
</tr>
<tr>
<td>Prestressed member</td>
<td>( \lambda \sqrt{f'<em>c} \left( \frac{A</em>{g}^2}{p_{cp}} \right) \sqrt{1 + \frac{f_{pc}}{4\lambda \sqrt{f'_c}}} )</td>
</tr>
<tr>
<td>Nonprestressed member subjected to axial force</td>
<td>( \lambda \sqrt{f'<em>c} \left( \frac{A</em>{g}^2}{p_{cp}} \right) \sqrt{1 + \frac{N_u}{4A_{g} \lambda \sqrt{f'_c}}} )</td>
</tr>
</tbody>
</table>

### 9.7.5 — Cracking torsion

#### 9.7.5.1 — Cracking torsion, \( T_{cr} \), shall be calculated in accordance with Table 9.7.5.1 for solid and hollow cross sections, where \( N_u \) is positive for compression and negative for tension. <11.5.2>
Table 9.7.5.1 — Cracking torsion

<table>
<thead>
<tr>
<th>Type of member</th>
<th>( T_{cr} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonprestressed member</td>
<td>( 4\lambda \sqrt{f_c} \left( \frac{A_{cp}^2}{p_{cp}} \right) ) (a)</td>
</tr>
<tr>
<td>Prestressed member</td>
<td>( 4\lambda \sqrt{f_c'} \left( \frac{A_{cp}^2}{p_{cp}} \right) \left[ 1 + \frac{f_{pc}}{4\lambda \sqrt{f_c'}} \right] ) (b)</td>
</tr>
<tr>
<td>Nonprestressed member subjected to axial force</td>
<td>( 4\lambda \sqrt{f_c'} \left( \frac{A_{cp}^2}{p_{cp}} \right) \left[ 1 + \frac{N_u}{4A_c \lambda \sqrt{f_c'}} \right] ) (c)</td>
</tr>
</tbody>
</table>

9.7.6 — Torsional strength

9.7.6.1 — For prestressed and nonprestressed members, \( T_n \) shall be calculated as the lesser of (a) and (b):

\[
T_n = \frac{2A_o A_t f_{yt}}{s} \cot \theta \quad (9.7.6.1a)
\]

\[
T_n = \frac{2A_o A_t f_y}{p_h} \tan \theta \quad (9.7.6.1b)
\]

where \( A_o \) shall be determined by analysis, \( \theta \) shall not be taken less than 30 degrees nor greater than 60 degrees, \( A_t \) is the area of one leg of a closed stirrup resisting torsion, \( A_t \) is the area of longitudinal torsion reinforcement, and \( p_h \) is the perimeter of the centerline of the outermost closed stirrup. <11.5.3.6> <11.5.3.7>

9.7.6.1.1 — In Eq. (9.7.6.1a) and (9.7.6.1b), it shall be permitted to take \( A_o \) equal to 0.85 \( A_{oh} \). <11.5.3.6>

9.7.6.1.2 — In Eq. (9.7.6.1a) and (9.7.6.1b), it shall be permitted to take \( \theta \) equal to (a) or (b): <11.5.3.6>

(a) 45 degrees for nonprestressed members or members with effective prestress force less than 40 percent of the tensile strength of the longitudinal reinforcement

(b) 37.5 degrees for prestressed members with an effective prestress force of at least 40 percent of the tensile strength of the longitudinal reinforcement
9.7.7 — Cross-sectional limits

9.7.7.1 — Cross-sectional dimensions shall be such that (a) or (b) is satisfied. <11.5.3.1>

(a) For solid sections

\[
\sqrt{\left(\frac{V_u}{b_wd}\right)^2 + \left(\frac{T_u p_h}{1.7 A_{oh}^2}\right)^2} \leq \phi \left(\frac{V_c}{b_w d} + 8\sqrt{f'_c}\right)
\]  

(9.7.7.1a)

(b) For hollow sections

\[
\left(\frac{V_u}{b_w d}\right) + \left(\frac{T_u p_h}{1.7 A_{oh}^2}\right) \leq \phi \left(\frac{V_c}{b_w d} + 8\sqrt{f'_c}\right)
\]  

(9.7.7.1b)

9.7.7.1.1 — For prestressed members, the value of \(d\) used in 9.7.7.1 need not be taken less than 0.8\(h\). <11.5.3.1> <11.4.3>

9.7.7.1.2 — For hollow sections where the wall thickness varies around the perimeter, Eq. (9.7.7.1b) shall be evaluated at the location where the term \(V_u/b_w d + T_u p_h/1.7 A_{oh}^2\) is a maximum. <11.5.3.2>

9.7.7.2 — For hollow sections where the wall thickness is less than \(A_{oh}/p_h\), the term \(T_u p_h/1.7 A_{oh}^2\) in Eq. (9.7.7.1b) shall be taken as \(T_u/1.7 A_{oh} t\), where \(t\) is the thickness of the wall of the hollow section at the location where the stresses are being checked. <11.5.3.3>
Approved changes to Chapter 2 during balloting of Chapter 9

NOTATION:

\( A_{pd} \) = total area occupied by duct, sheathing, and prestressing reinforcement, in.\(^2\)

\( A_{pt} \) = total area of prestressing reinforcement, in.\(^2\)

\( \ell_{tr} \) = transfer length of prestressed reinforcement, in.

\( \ell_{db} \) = debonded length of prestressed reinforcement at end of member, in.

\( T_{th} \) = threshold torsional moment, in.-lb

\( T_{cr} \) = cracking torsional moment, in.-lb

\( \varepsilon_{ty} \) = value of net tensile strain in the extreme layer of longitudinal tension reinforcement used to define a compression-controlled section, see 9.4.2.2.

\( \sigma_c \) = stress corresponding to nominal two-way shear strength provided by concrete, psi

\( \sigma_s \) = equivalent concrete stress corresponding to nominal two-way shear strength provided by reinforcement, psi

\( \sigma_n \) = nominal shear stress equivalent concrete stress corresponding to nominal two-way shear strength of slab or footing, psi

\( \sigma_u \) = maximum factored two-way shear stress calculated around the perimeter of a given critical section, psi

DEFINITIONS:

Compression-controlled section – A cross section in which the net tensile strain in the extreme layer of longitudinal tension reinforcement at nominal strength does not exceed \( \varepsilon_{ty} \).

Compression-controlled strain limit—the net tensile strain at balanced strain conditions. See 10.3.2.3.