Torsion Design of Structural Concrete Based on ACI 318-05

By Mahmoud E. Kamara, Ph.D., and Basile G. Rabbat, Ph.D., S.E.

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Torsional moment develops in structural concrete members as a result of asymmetrical loading or member geometry, or as a result of structural framing. For example, spandrel beams built integrally with the floor slab are subject to torsional moment resulting from the restraining negative bending moment at the exterior end of the slab. The restraining moment is proportional to the torsional stiffness of the spandrel beam. In complex structures such as helical stairways, curved beams, and eccentrically loaded box beams, torsional effects dominate the structural behavior. Torsional moment tends to twist the structural member around its longitudinal axis, inducing shear stresses. However, structural members are rarely subjected to pure torsional moment. In most cases, torsional moments act concurrently with bending moment and shear forces.

During the first half of the twentieth century, structural codes were silent regarding torsion design. Torsion was looked at as a secondary effect that was covered in the factor of safety considered in the design. Demand for more complex structures, improved methods of analysis, new design approaches, and the need for more economical design required a better understanding of the behavior of reinforced concrete members subjected to torsion. In the second half of the twentieth century, research activities helped engineers understand many aspects of behavior of concrete members under torsion.

This article focuses on torsion in solid and hollow closed sections. Thin, open C- and U-shaped sections subject to torsion suffer distortions (referred to as Vlasov torsion), and are not covered in this article. The procedure presented herein reflects the provisions of the American Concrete Institute's Building Code Requirements for Structural Concrete (ACI 318-05) (Reference 1) and those of the soon-to-be-published ACI 318-08. All section numbers within this article refer to ACI 318-05. Note that the fourth edition of the American Association of State Highway and Transportation Officials' Load and Resistance Factor Design (AASHTO LRFD) Bridge Design Specifications prescribes torsion design approaches for structural concrete members slightly different from those of ACI 318.

Equilibrium versus compatibility torsion

It is important for designers to distinguish between two types of torsions: equilibrium torsion and compatibility torsion (References 2 and 3). Equilibrium torsion occurs when the torsional resistance is required to maintain static equilibrium. For this case, if sufficient torsional resistance is not provided, the structure will become unstable and collapse. External loads have no alternative load path and must be resisted by torsion.

Compatibility torsion develops where redistribution of torsional moments to adjacent members can occur. The term compatibility refers to the compatibility of deformation between

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Learning Objectives

This article discusses torsion in concrete structures. Upon reading the article and completing the quiz, the reader should be able to understand the behavior and design of structural concrete members subjected to torsion. The article presents the American Concrete Institute's Building Code (ACI 318-05) design provisions and detailing requirements for torsion design. All referenced items are from ACI 318-05, unless noted otherwise. Also, all notations and definitions in the article are in accordance with Chapter 2 of ACI 318-05.

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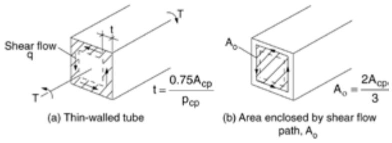

Figure 1: Thin-wall tube analogy

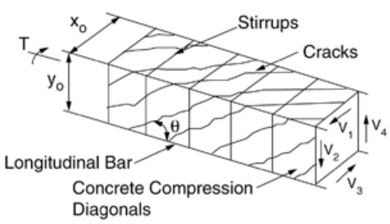

Figure 2: Space truss analogy

adjacent parts of a structure. As an example, consider a spandrel beam supporting an exterior slab. As load on the slab increases, so does the negative slab end moment, which induces torsion in the spandrel beam. The negative slab end moment will be proportional to the torsional stiffness of the spandrel beam. When the magnitude of the torsional moment exceeds the cracking torque, torsional cracks spiral around the member, and the cracked torsional stiffness of the spandrel beam is significantly reduced (Reference 4). As a result, some of the slab negative end moment is redistributed to the slab midspan.

In cases where equilibrium torsion exists or torsional behavior dominates the structural actions, the designer must design for the maximum torsional moments.

Behavior of beams in torsion

Prior to cracking, a torsional moment applied to a concrete member is resisted by internal shear stresses. The largest shear stresses occur in the middle of the outside faces or perimeter of the cross section. Shear stresses lead to diagonal principal tensile and compressive stresses. When the diagonal tension exceeds the tensile strength of the concrete, diagonal cracking occurs. It has been observed in experiments on beams subject to torsion that once the crack initiates, it spirals around the perimeter of the member. Simultaneously, the beam torsional stiffness drops significantly. It takes significant twisting before recovering the cracking torque. Upon further torsional loading, excessive twisting deformations lead to spalling of the concrete cover over the transverse reinforcement. Hence, transverse reinforcement must be properly anchored with 135-degree hooks.

It has further been observed experimentally that solid and hollow beams of similar external cross section and with similar longitudinal and transverse reinforcement achieve comparable torsional strengths (References 5 and 6). Thus, in a solid beam, part of the concrete core separates from the outer shell (inside the transverse reinforcement) and becomes inefficient. Therefore, when the torsional strength of a beam is reached, a solid section can be represented by a hollow section of the same external dimensions.

Evolution of torsion design provisions

The first design provision for torsion appeared in ACI 318-63. It consisted of one sentence, which prescribed the use of closed stirrups in edge and spandrel beams and one longitudinal bar in each corner of those closed stirrups. Comprehensive design provisions for torsion were introduced in the 1971 code. These design requirements remained essentially unchanged through the 1992 code. These first-generation provisions were semi-empirical and applied only to reinforced, non-prestressed concrete members. The design procedure for torsion was analogous to that for shear. Torsional strength consisted of a contribution from concrete, T_C, and a contribution from stirrups and longitudinal reinforcement, T_S, based on a skew bending model.

The design provisions for torsion were completely revised in the 1995 code and remain essentially unchanged since then. The design procedure for solid and hollow members is based on a thin-walled tube, space truss analogy. This unified approach applies equally to non-prestressed and prestressed concrete members.

Background of torsion design

For design purposes, the center portion of a solid beam can conservatively be neglected. This assumption is supported by test results reported in References 5 and 6. Therefore, the beam is idealized as a tube. Torsion is resisted through constant shear flow, $q = \frac{T}{2A_o}$, acting around the centerline of the tube as shown in Figure 1. By definition, shear flow is a force per unit length of wall centerline, where A_O is the area enclosed within the wall centerline.

When a concrete beam is subjected to a torsional moment, shear stresses lead to diagonal tensile stresses. When the diagonal tension exceeds $4\sqrt{f'_c}$, where f'_C = the specified compressive strength of concrete in pounds per square inch (psi), diagonal cracks spiral around the beam. After cracking, the tube is idealized as a space truss as shown in Figure 2. In this truss, diagonal members are inclined at an angle θ. For members with longitudinal and transverse reinforcement, inclination of the diagonals is assumed to be the same in all tube walls. Note that this angle is not necessarily 45 degrees. The resultant of the shear flow in each tube wall induces forces in the truss members. A basic premise for structural concrete design is that concrete is strong in compression, while steel is strong in tension. Therefore, in the truss analogy, truss members that are in tension consist of steel reinforcement or "tension ties." Truss diagonals and other members that are in compression consist of concrete "compression struts." Forces in the truss members can be determined from equilibrium conditions. These forces are used to proportion and detail the reinforcement.

Figure 3 depicts a free body extracted from the front vertical wall of the truss of Figure 2. Shear force, V_2, is equal to the shear flow, q, times the height of the wall, y_O. To achieve ductility in structural concrete members, reinforcement is designed to yield before the concrete crushes. Stirrups are designed to yield when the maximum torque is reached. The number of stirrups intersected is a function of the stirrup spacing, s, and the horizontal projection, $y_O \cot\theta$ of the inclined surface.

A free body diagram for horizontal equilibrium is shown in Figure 4 (page PDH5). The vertical shear force, V_i, in wall

"i" is equal to the product of the shear flow, q, times the length of the wall, y_i. Vector V_i can be replaced by two vectors: a diagonal component, D_i, with an inclination θ equal to the angle of the truss diagonals; and a horizontal component, N_i, centered at the mid height of the wall as shown in the figure.

Torsion can be neglected if the factored torque, T_u, is less than $\phi T_{cr}/4$, where

$$T_{cr} = 4\sqrt{f_c'}\left(\frac{A_{cp}^2}{p_{cp}}\right)$$

is the cracking torque (Section 11.6.1); ϕ = strength reduction factor for torsion; A_{cp} = area enclosed by outside perimeter of concrete cross section, including the void of hollow cross-sections; and p_{cp} = outside perimeter of concrete cross-section. The cracking torque corresponds to a principal tensile stress of $4\sqrt{f_c'}$.

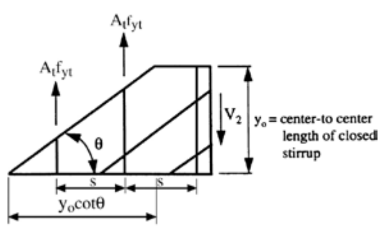

Figure 3: Free body diagram for vertical equilibrium

Whether a reinforced concrete member is subject to torsion only, or to flexure combined with shear, the stiffness of that member will decrease after cracking. The reduction in torsional stiffness after cracking of a member subject to torsion only is much larger than the reduction in flexural stiffness after cracking of a member subject to bending only. If the torsional moment, T_u, in a member cannot be reduced by redistribution of internal forces in the structure (equilibrium torsion), that member must be designed for the full torsional moment, T_u (Section 11.6.2.1). If redistribution of internal forces can occur, as in indeterminate structures (compatibility torsion), the design torque can be reduced. Members subject to compatibility torsion need not be designed for a torque larger than the product of the cracking torque times the strength reduction factor ϕ (which is 0.75 for torsion,). For cases of compatibility torsion where $T_u > \phi T_{cr}$, the member can be designed for ϕT_{cr} only, provided redistribution of internal forces is accounted for in the design of the other members of the structure (Section 11.6.2.2).

Critical section

In non-prestressed members, the critical section for torsion design is at distance d (effective depth) from the face of support. Sections located at a distance less than d from the face of support must be designed for the torque at distance d from the support. Where a cross beam frames into a girder at a distance less than d from the support, a concentrated torque occurs in the girder within distance d. In such cases, the design torque must be taken at the face of support. The same rule applies to prestressed members, except that $h/2$ replaces d, where h is the overall height of composite section.

Torsional moment strength

The design torsional strength should be equal to or greater than the required torsional strength: $\varphi T_n \geq T_u$. The nominal torsional moment strength in terms of stirrup yield strength is:

$$T_n = \frac{2A_o A_t f_{yt}}{s}\cot\theta$$

where $A_o = 0.85A_{oh}$ and A_{oh} = area enclosed by centerline of the outermost closed transverse torsional reinforcement having a yield strength f_{yt}, as illustrated in Figure 5; and θ = angle of compression diagonal, ranges between 30 and 60 degrees. It is suggested in Section 11.6.3.6 to use θ = 45 degrees for non-prestressed members and θ = 37.5 degrees for prestressed members with prestress force greater than 40 percent of tensile strength of the longitudinal reinforcement. To resist torsion, transverse as well as longitudinal reinforcement is required. The total area of longitudinal reinforcement A_ℓ distributed around the perimeter is computed from:

$$A_\ell = \left(\frac{A_t}{s}\right) p_h \left(\frac{f_{yt}}{f_y}\right)\cot^2\theta$$

where A_t = area of transverse torsional reinforcement at spacing s; p_h = perimeter of outermost transverse reinforcement; and f_y = yield strength of longitudinal reinforcement.

Maximum torsional capacity

To reduce unsightly cracking and prevent crushing of the concrete compression struts before yielding of the reinforcement, Section 11.6.3.1 prescribes an upper limit for the maximum nominal shear stress due to shear and torsion, analogous to that due to shear only. In solid sections, stresses due to shear act over the full width of the section, while stresses due to torsion are assumed resisted by a thin-walled tube. Thus, Section 11.6.3.1 specifies an elliptical interaction between stresses due to shear and those due to torsion for solid sections as follows:

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

For hollow sections, the interaction is linear and expressed as:

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

where V_c is the contribution of concrete to shear strength of non-prestressed and prestressed concrete members.

Details of torsional reinforcement

Longitudinal and transverse reinforcement are required to resist torsion. Longitudinal reinforcement may consist of non-prestressed or prestressed reinforcement. Transverse reinforcement may consist of stirrups, welded wire reinforcement, or spiral reinforcement. To control widths of diagonal cracks, the design yield strength of longitudinal and transverse torsional reinforcement must not exceed 60,000 psi (Section 11.6.3.4).

In the truss analogy illustrated in Figure 2, the diagonal compression strut forces bear against the longitudinal corner

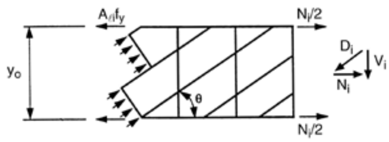

Figure 4: Free body diagram for horizontal equilibrium

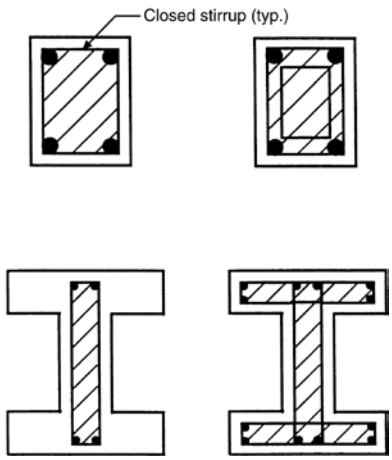

Figure 5: Definition of A_{oh}

reinforcement. In each wall, the component of the diagonal struts, perpendicular to the longitudinal reinforcement is transferred from the longitudinal reinforcement to the transverse reinforcement. It has been observed in torsional tests of beams loaded to destruction that as the maximum torque is reached, the concrete cover spalls. The forces in the compression struts outside of the stirrups, for example within the concrete cover, push out the concrete shell. Based on this observation, Section 11.6.4.2 specifies that the stirrups should be closed, with 135-degree hooks or seismic hooks as defined in Section 21.1. Stirrups with 90-degree hooks become ineffective when the concrete cover spalls. Similarly, lapped U-shaped stirrups have been found to be inadequate for resisting torsion due to lack of bond when the concrete cover spalls. Additionally, for hollow sections, the distance from the centerline of the transverse torsional reinforcement to the inside face of the wall of the hollow section must not be less than $0.5A_{oh}/p_h$ (Section 11.6.4.4).

Minimum torsion reinforcement

To ensure ductility of non-prestressed and prestressed concrete members, minimum reinforcement is specified for flexure (Section 10.5) and for shear (Section 11.5.6). Similarly, minimum transverse and longitudinal reinforcement is specified in Section 11.6.5 whenever $T_u > \phi T_{cr}/4$. Usually, a member subject to torsion will also be simultaneously subjected to shear. The minimum area of stirrups for shear and torsion is computed from:

$$(A_v + 2A_t) = 0.75\sqrt{f'_c}\,\frac{b_w s}{f_{yt}} \geq \frac{50 b_w s}{f_{yt}}$$

The minimum area of longitudinal reinforcement is computed from:

$$A_{\ell,min} = \frac{5\sqrt{f'_c}A_{cp}}{f_y} - \left(\frac{A_t}{s}\right)p_h\frac{f_{yt}}{f_y}$$

where A_t/s (due to torsion only) must not be taken less than $25b_w/f_{yt}$.

Spacing of torsion reinforcement

Spacing of stirrups must not exceed the smaller of $p_h/8$ and 12 inches. For a square beam subject to torsion, this maximum spacing is analogous to a spacing of about $d/2$ in a beam subject to shear.

The longitudinal reinforcement required for torsion must be distributed around the perimeter of the closed stirrups, at a maximum spacing of 12 inches. In the truss analogy, the compression struts push against the longitudinal reinforcement, which transfers the transverse forces to the stirrups. Thus, the longitudinal bars should be inside the stirrups. There should be at least one longitudinal bar or tendon in each corner of the stirrups to help transmit the forces from the compression struts to the transverse reinforcement. To avoid buckling of the longitudinal reinforcement due to the transverse component of the compression struts, the longitudinal reinforcement must have a diameter not less than 1/24 of the stirrup spacing, but not less than 3/8 of an inch.

Summary of ACI 318-05 Code Design Approach

The following steps summarize the design provisions outlined in Chapter 11 of ACI 318-05 for members subjected to the combined effects of flexure, shear, and torsion. The same provisions appear in ACI 318-08 except that the sections have been renumbered.

Step 1 — Determine the maximum factored torsional moment, T_u, at the critical section of the member from structural analysis of the framing system, based on the applicable factored load combination(s).

Step 2 — Determine whether torsional effects need to be considered by comparing the factored torsional moment T_u to $\phi T_{cr}/4$, where T_{cr} is calculated as follows for non-prestressed members:

$$T_{cr} = \phi 4\sqrt{f'_c}\left(\frac{A_{cp}^2}{P_{cp}}\right) \text{ inch-pounds (in.-lb); and}$$

for prestressed members:

$$T_{cr} = \phi 4\sqrt{f'_c}\left(\frac{A_{cp}^2}{P_{cp}}\right)\sqrt{1 + \frac{f_{pc}}{4\sqrt{f'_c}}} \text{ in.-lb.}$$

If $T_u < T_{cr}/4$, then torsional effects need not be considered, and the member must be designed for the effects of flexure and shear only (Section 11.6.1). However, if $T_u \geq T_{cr}/4$, the section must be designed for the effects of flexure, shear, and torsion. The following steps apply when torsional effects must be considered.

Step 3 — Ascertain whether the torsional moment T_u determined in Step 1 can be reduced by redistribution of internal forces after torsional cracking. For members in a statically indeterminate structure where redistribution of forces can occur, the maximum factored torsional moment at the critical section can be reduced to ϕT_{cr} where T_{cr} is as computed in Step 2.

It is important to note that the redistribution of internal forces must be considered in the design of the adjoining members (Section 11.6.2.2); the reactions from the adjoining members after redistribution must be transferred to the member that is subjected to the torsional moments.

When $\phi T_{cr}/4 < T_u < \phi T_{cr}$, the section should be designed to resist T_u. For members in which redistribution of the forces is not possible, the maximum factored torsional moment, T_u, at the critical section determined in Step 1 cannot be reduced (Section 11.6.2.1).

Step 4 — Check adequacy of cross-sectional dimensions (Section 11.6.3) as follows for solid sections:

$$\sqrt{\left(\frac{V_u}{b_w d}\right)^2+\left(\frac{T_u p_h}{1.7A_{oh}^2}\right)^2}\le\phi\left(\frac{V_c}{b_w d}+8\sqrt{f'_c}\right)\quad \text{in.-lb; and}$$

for hollow sections:

$$\left(\frac{V_u}{b_w d}\right)+\left(\frac{T_u p_h}{1.7A_{oh}^2}\right)\le\phi\left(\frac{V_c}{b_w d}+8\sqrt{f'_c}\right)\quad \text{in.-lb.}$$

The nominal shear strength provided by the concrete, V_c, can be determined from ACI 318-05 Equation 11-3 for non-prestressed members and Equation 11-9 for prestressed members with an effective prestress force not less than 40 percent of the tensile strength of the flexural reinforcement. The cross-sectional dimensions must be adjusted when the above applicable equation is not satisfied.

Step 5 — Determine transverse reinforcement required for torsion (Section 11.6.3.6):

$$\frac{A_t}{s}=\frac{T_u}{\phi 2A_o f_{yt}\cot\theta}$$

where $A_o = 0.85A_{oh}$ and $\theta = 45$ degrees for non-prestressed members, 37.5 degrees for prestressed members with an effective prestress force not less than 40 percent of the tensile strength of the longitudinal reinforcement. Note that f_{yt} must not exceed 60,000 psi (Section 11.6.3.4). Values of A_t/s can be determined at various locations along the span, depending on the variation of T_u.

Step 6 — Determine transverse reinforcement required for shear (Section 11.5.6):

$$\frac{A_v}{2s}=\frac{V_u-\phi V_c}{2\phi f_{yt} d}$$

Values of $A_v/2s$ can be determined at various locations along the span, depending on the variation of V_u, and, for prestressed members, also depending on the variation of V_c (see Equation 11-9).

Step 7 — Determine the total required transverse reinforcement per leg and the maximum allowable spacing, considering the most restrictive requirements for shear and torsion (Sections 11.6.3.8, 11.6.5.2, and 11.6.6.1):

$$\frac{A_t}{s}+\frac{A_v}{2s}\ge\frac{25b_w}{f_{yt}}\quad \text{in.-lb;}$$

where the maximum closed stirrup spacing, s, is the smaller of $p_h/8$; 12 inches; and $d/2$ for non-prestressed members, or $3h/4$ for prestressed members.

Step 8 — Determine longitudinal reinforcement required for torsion (Sections 11.6.3.7, 11.6.5.3):

$$A_\ell=\left(\frac{A_t}{s}\right)p_h\left(\frac{f_{yt}}{f_y}\right)\cot^2\theta\ge A_{\ell,min}$$

where

$$A_{\ell,min}=\frac{5\sqrt{f'_c}A_{cp}}{f_y}-\left(\frac{A_t}{s}\right)p_h\frac{f_{yt}}{f_y}\quad \text{in.-lb.}$$

Step 9 — Combine the longitudinal reinforcement required for torsion with that which is required for flexure (Section 11.6.3.8). To achieve a uniform distribution of reinforcement around the perimeter of the section, assign approximately one-quarter of A_ℓ to each face. For non-prestressed members, provide an area of steel equal to at least $A_\ell/4$ on each side face of the section, and add $A_\ell/4$ to the negative and positive flexural reinforcement at the top and bottom of the section, respectively. For prestressed members, provide additional reinforcing bars with a tensile capacity of $A_\ell f_y$, or use any overcapacity of the tendons to resist some of the axial force $A_\ell f_y$. ▼

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Quiz Instructions

On the Professional Development Series Reporting Form below, circle the correct answer for each of the following questions.

1. Prior to cracking, a torsional moment applied to a concrete member is resisted by internal shear stresses. The largest shear stresses occur at:

a) the middle of the outside faces of the section
b) the corners of the section
c) the center of the section
d) none of the above

2. Reinforcement required to resist torsion consists of:

a) transverse reinforcement
b) longitudinal reinforcement
c) transverse reinforcement and longitudinal reinforcement
d) none of the above

3. The current ACI 318 design provisions for torsion are based on:

a) moment distribution
b) thin-walled tube, space truss analogy
c) finite element
d) virtual work

4. Transverse reinforcement required for torsion must be anchored:

a) with 90-degree hook
b) with 135-degree hook
c) to the longitudinal reinforcement
d) in the compression zone

5. In beams subjected to torsional moment, diagonal cracks form when diagonal tension exceeds (in psi units):

a) $7.5\sqrt{f'_c}$ b) $6.7\sqrt{f'_c}$ c) $4\sqrt{f'_c}$ d) $2\sqrt{f'_c}$

6. For members in a statically indeterminate structure where redistribution of forces can occur, the maximum factored torsional moment at the critical section can be reduced to:

a) ϕT_{cr} b) T_{cr} c) $T_{cr}/4$ d) $T_u/4$

7. In non-prestressed members, the critical section for torsion design is at distance:

a) $d/2$ b) $h/2$ c) h d) d

8. Spacing of stirrups required for torsion must not exceed:

a) $d/2$
b) the smaller of $p_h/8$ and 12 inches
c) the smaller of $p_h/8$ and 8 inches
d) 18 inches

9. The longitudinal reinforcement required for torsion must be distributed around the perimeter of the closed stirrups, at a maximum spacing not to exceed:

a) d b) 6 inches c) 12 inches d) 18 inches

10. A rectangular cross section in a statically indeterminate member, where redistribution of forces is possible, is subjected to a factored torsional moment T_u = 80 foot-kips. Assuming that the section's cracking moment multiplied by strength reduction factor ϕT_{cr} = 100 foot-kips, which of the following statements is correct:

a) torsional effects need not be considered
b) the section must be designed for torsional moment = 80 foot-kips
c) the section must be designed for torsional moment = 100 foot-kips
d) the section must be designed for torsional moment = 25 foot-kips

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