Proposed Criteria for the Design of Masonry Beams Subjected to Torsion

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Presenting for:
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THE MASONRY SOCIETY

Outline

- Background
  - Holdover public comment from TMS 402-22 cycle
  - Masonry beams subjected to torsion
  - Torsion in Concrete beams (Research and ACI 318)
  - Previous Masonry Research on Beams Subjected to Torsion
- Proposed Immediate Solution (Ballot)
- Preliminary numerical work
- Concluding Remarks

Background

TMS 402/SM subcommittee received the following public comment in the 2022 cycle

PC-16:

The standard discusses lateral-torsional buckling of beams. However, there is **nothing** that provides **guidance to designers as to the design of masonry beams for torsional effects**.

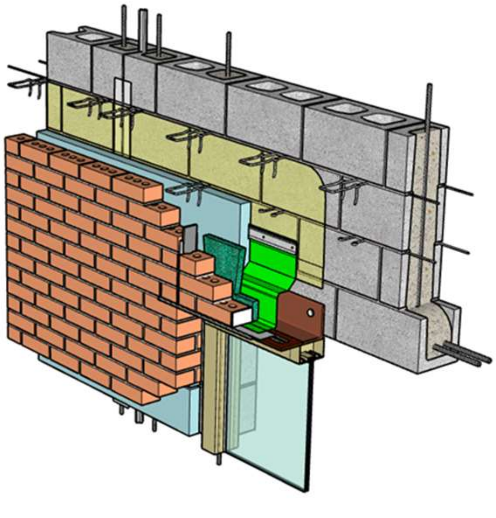
For example, masonry lintels/beams might have a shelf angle bolted to them for support of an anchored veneer. This induces torsion into the beam and its supporting wall jambs. ACI 318 has criteria for concrete beams, but TMS 402 is silent on torsion.

Masonry code criteria should be provided for torsion. Until that code criterion is provided, users should be warned of the torsional concerns through commentary.

Background

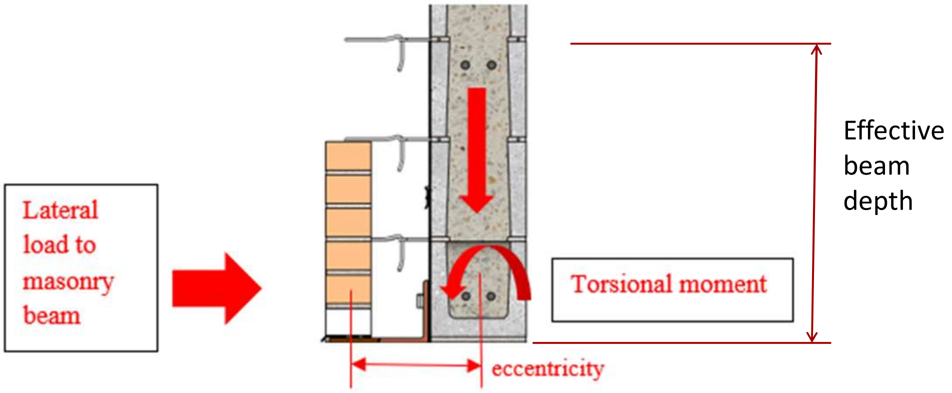
Masonry lintels and beams often have loadings that induce torsion.

Building codes in the USA, require engineers to account for torsional effects but give no guidance for torsion in masonry beams or lintels.



Courtesy of the International Masonry Institute

Background



Lateral load to masonry beam

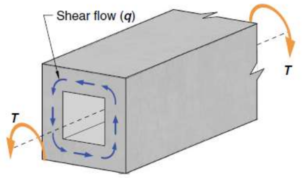
Torsional moment

Effective beam depth

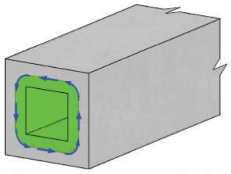
eccentricity

Concrete Beams- Torsion

- Concrete research led to designing beams using an idealized tube cross-section in ACI 318:
  - Hsu (1968)
  - MacGregor and Ghoneim (1995)
  - Hsu (1997)
  - Collins and Lampert (1973)
  - Hsu and Burton (1974)
- Thin-walled tube space truss analogy
- Once beam is cracked in torsion, torsional strength is provided primarily by closed stirrups and longitudinal bars located near the surface of the member



(a) Thin-walled tube



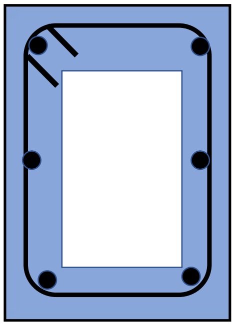
(b) Area enclosed by shear flow path

Fig. R22.7—(a) Thin-walled tube; and (b) area enclosed by shear flow path.

Concrete Beams- Torsion

Criteria

- Below 25% of cracking torsion (T_{cr}), ignore torsion (=T_{th}).
- Until cracking, torsional reinforcement is not effective.
- Post cracking, reinforcement takes 100% of torsion, concrete strength is ignored.



Closed stirrups for torsion

Torsional reinforcement is not required if :

$T_u \le \varphi T_{th}$ or $T_u \le \varphi\ (0.25)T_{cr}$

$\varphi = 0.75$

T_u = Factored torsional moment

T_{th} = Threshold torsional moment = ¼ cracking torsional moment (T_{cr})

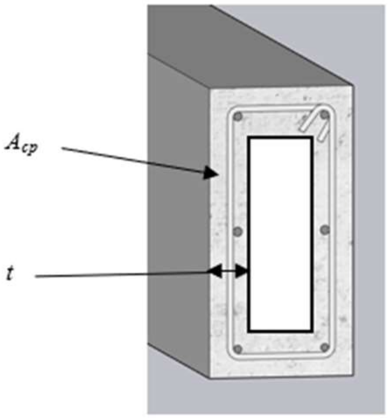
Concrete Beams- Torsion

Cracking torsion for solid cross sections for non-prestressed members

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

Threshold torsion for solid and hollow cross sections for non-prestressed members

$$T_{th} = \lambda\sqrt{f'_c}\left({A_{cp}}^2/p_{cp}\right)$$

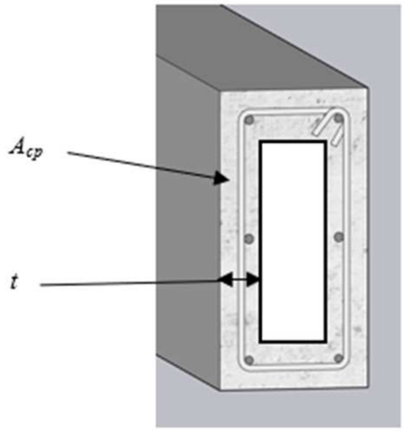


λ varies between 0.75 and 1.0 dependent on the aggregate type

Concrete Beams- Torsion

$$T_{th} = \lambda\sqrt{f'_c}\left({A_{cp}}^2/p_{cp}\right)$$

- A_{cp} = overall cross-sectional area
- p_{cp} = outside perimeter
- $t = 0.75\ A_{cp}/p_{cp}$
- A_0= The tube area is $2\ A_{cp}/3$



Limited Masonry Research

- TORSIONAL BEHAVIOR OF REINFORCED BRICK BEAMS Sriboonlue and Matthys (1990)
- Series 1 and 2 Beams

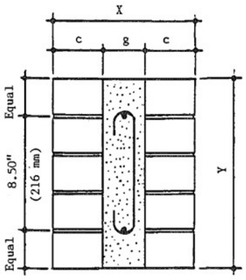


FIG. 1. Typical Cross Section of Beams in Series I

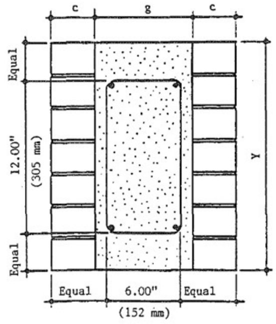


FIG. 2. Typical Cross Section of Beams in Series II

Limited Masonry Research

- Series 3 and 4 Beams

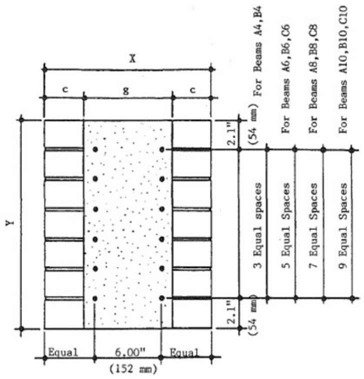


FIG. 3. Typical Cross Section of Beams in Series III

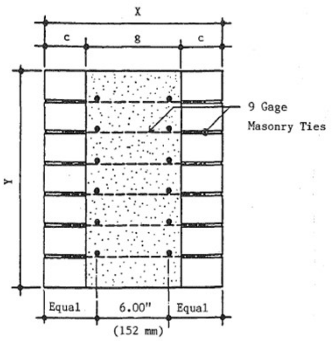


FIG. 4. Typical Cross Section of Beams in Series IV

Limited Masonry Research

- Tested under pure torsion.
- Compared to classical torsion theory.

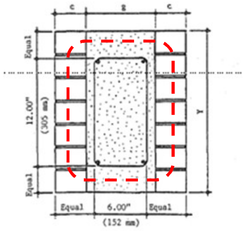
$$T_u = \frac{Y}{X}\left[\frac{2c^3}{3} + 2c(g + c)^2 + \frac{ng^3}{3}\right]f_{rm}$$

X = beam width
Y = beam depth
c = brick width; g = grout width
f_{rm}= modulus of rupture was taken as 0.062 f'_m
f'_m = masonry compressive strength

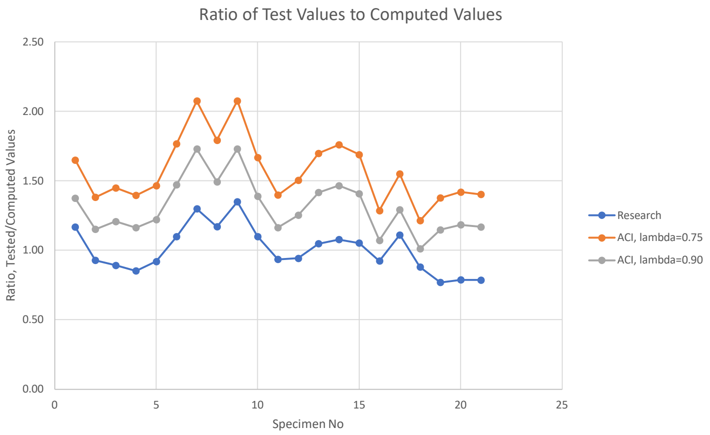
Limited Masonry Research

Their findings/conclusions:

- The torsional behavior of tested masonry beams is similar to a reinforced concrete beam before cracking.
- After cracking, the behavior is significantly different from a reinforced concrete beam.
- Reinforcement could not be placed close enough to the exterior
- In this case, the ultimate torsional strength depends on the compressive strengths of the brick masonry and grout.
- A reinforced **brick** masonry beam subjected to torsion should be designed with **cracking torque as the design criterion.**



ACI 318 method check of Sriboonlue and Matthys (1990) testing



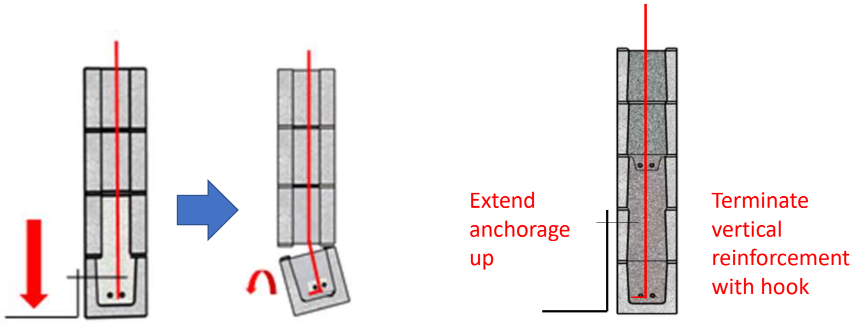
Recommendations for TMS 402

- Limit torsion on masonry beams
  - Use the concrete criteria for capacity based on limiting the **torsional moment to a threshold torque (T_{th}) that is 25% of the cracking moment** with the following modifications:
  - Substitute *f'm* for *f'c*
  - Use $\lambda = 0.90$ (based on check on prior experimental work).
  - $\varphi = 0.75$

$$T_u \le \varphi T_{th} \le \varphi\, \lambda \sqrt{f'_m}\left(A_{cp}^{\,2} / p_{cp}\right)$$

Recommendations for TMS 402

- Unlike concrete beams, masonry beams have a localized effect that should also be evaluated (future work).



Possible anchorage

Preliminary Numerical work
(time permitting)

- Software: ABAQUS
- Modeling accurately is key
- Test data on unreinforced & reinforced concrete beams (Hsu research)
  - Successful in simulating the thin-walled tube behavior
- Future work:
  - Model the brick beams in the referenced research and
  - Model modern CMU and brick beam designs
    - Flexural CMU beam test data coming up soon with NCMA foundation research

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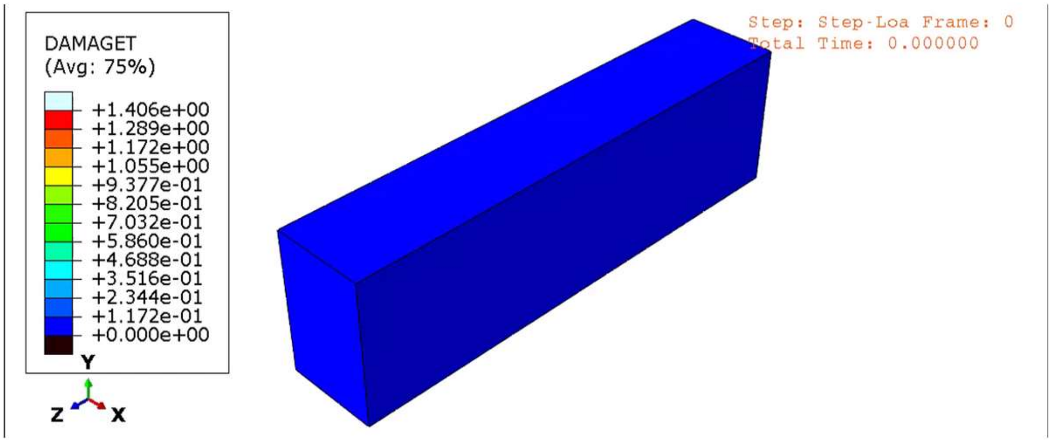
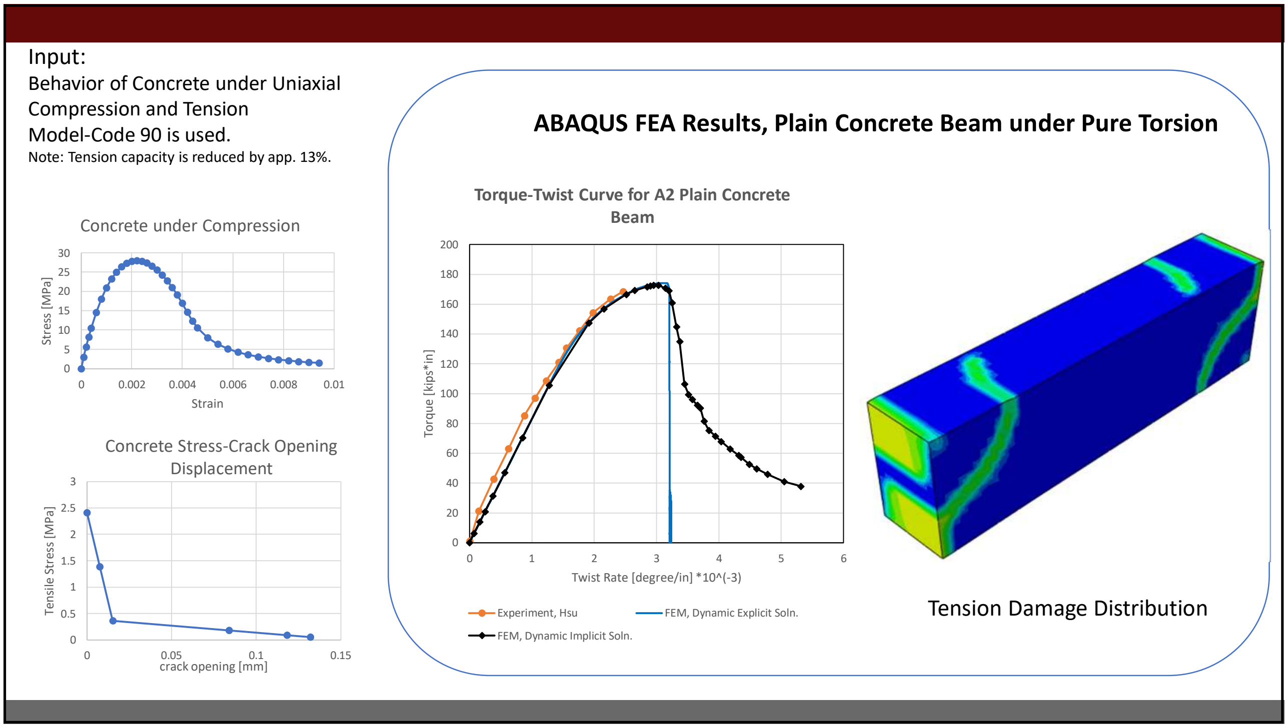
Plain Concrete Beam under Pure Torsion

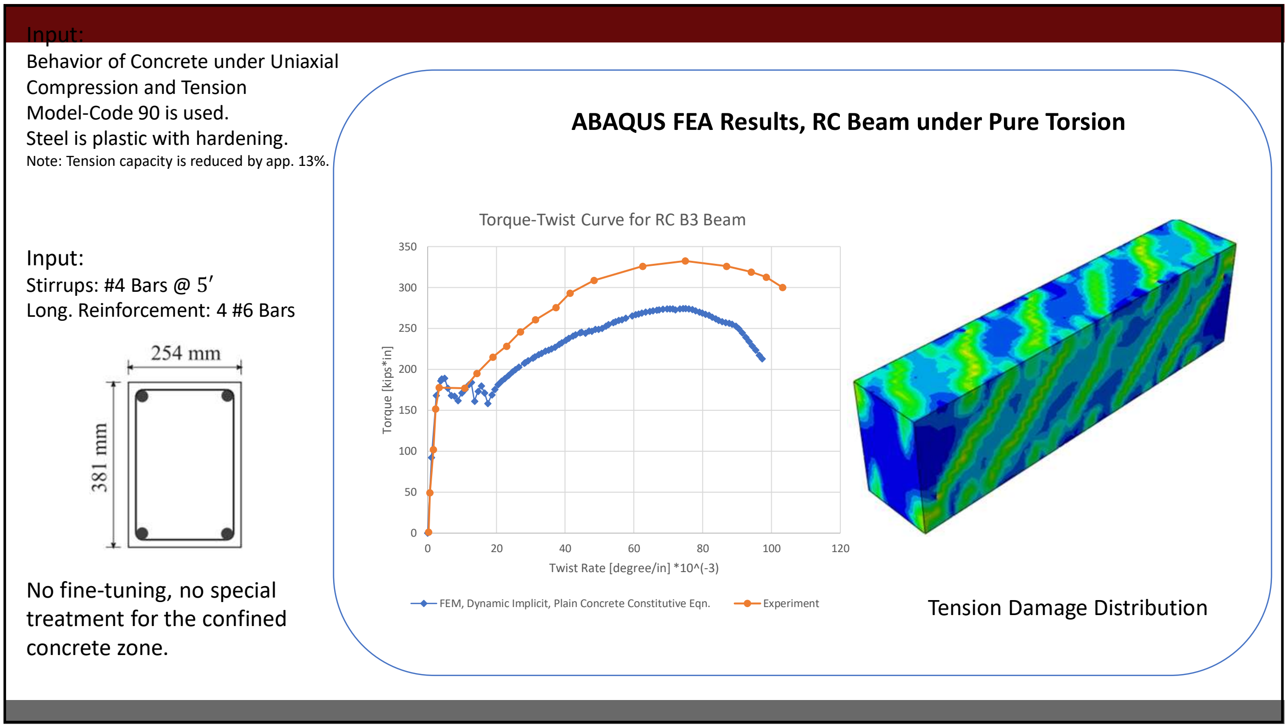




Input:
Behavior of Concrete under Uniaxial Compression and Tension
Model-Code 90 is used.
Note: Tension capacity is reduced by app. 13%.

ABAQUS FEA Results, Plain Concrete Beam under Pure Torsion

Tension Damage Distribution



Input:
Behavior of Concrete under Uniaxial Compression and Tension
Model-Code 90 is used.
Steel is plastic with hardening.
Note: Tension capacity is reduced by app. 13%.

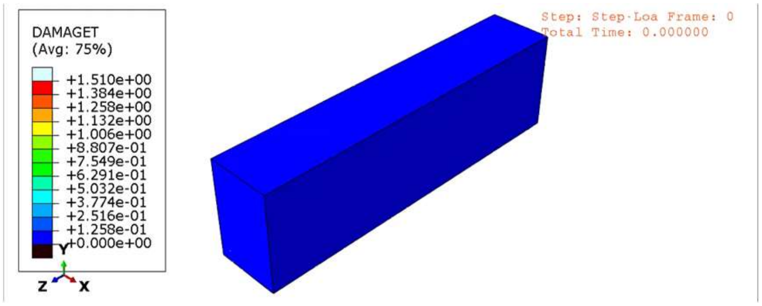
Input:
Stirrups: #4 Bars @ 5′
Long. Reinforcement: 4 #6 Bars

No fine-tuning, no special treatment for the confined concrete zone.

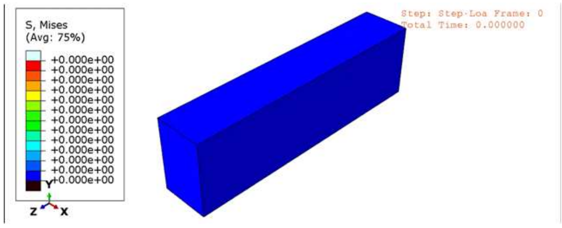
ABAQUS FEA Results, RC Beam under Pure Torsion

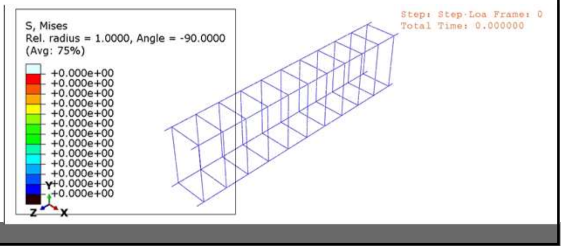
Tension Damage Distribution

RC Beam under Pure Torsion



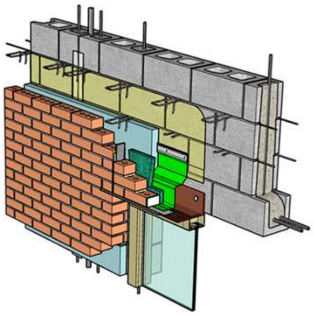
- 45 degree cracks occur, starting from the wide face of the beam
- Concrete cover spalling
- Up to this point, concrete carries the load
- After spalling, reinforcement start carrying load
- Steel reinforcement yields





Concluding Remarks

- For now
  - Acknowledge torsion acting on beams in Chapters 5, 8, 9
  - Limit torsion in beams to 25% of cracking moment (=threshold torque)
- Future Work
  - More research is needed for torsion with and without flexure and shear, as well as the influence of walls areas above.
  - Test data on modern beams including CMU and clay beams needed
  - Localized effects should also be considered



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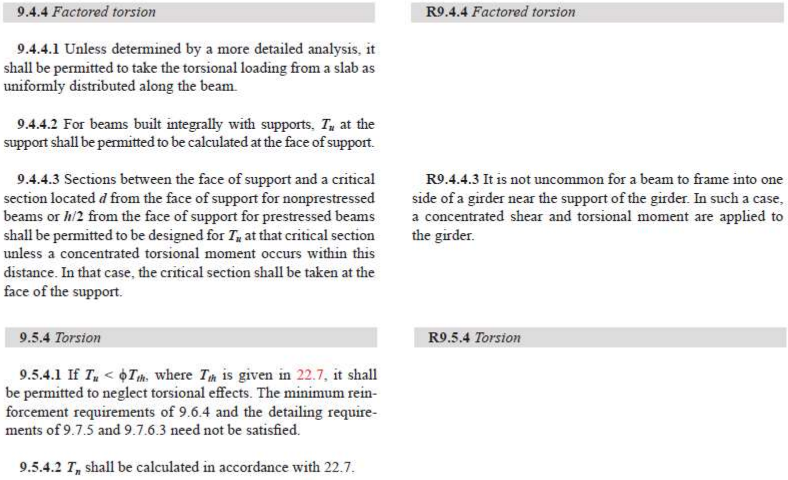
Appendix

Slides to refer to at code committee discussions or for Q&A

ACI 318-19 Torsion in Beams



9.4.4 *Factored torsion*

9.4.4.1 Unless determined by a more detailed analysis, it shall be permitted to take the torsional loading from a slab as uniformly distributed along the beam.

9.4.4.2 For beams built integrally with supports, T_u at the support shall be permitted to be calculated at the face of support.

9.4.4.3 Sections between the face of support and a critical section located d from the face of support for nonprestressed beams or $h/2$ from the face of support for prestressed beams shall be permitted to be designed for T_u at that critical section unless a concentrated torsional moment occurs within this distance. In that case, the critical section shall be taken at the face of the support.

R9.4.4 *Factored torsion*

R9.4.4.3 It is not uncommon for a beam to frame into one side of a girder near the support of the girder. In such a case, a concentrated shear and torsional moment are applied to the girder.

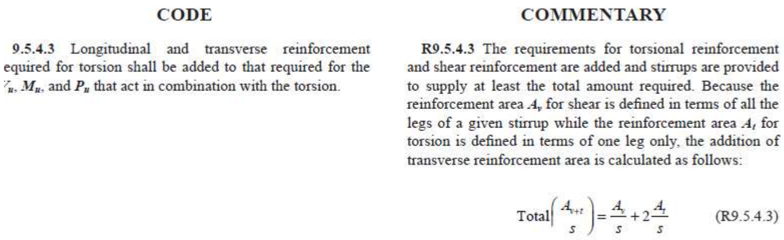
9.5.4 *Torsion*

9.5.4.1 If $T_u < \phi T_{th}$, where T_{th} is given in 22.7, it shall be permitted to neglect torsional effects. The minimum reinforcement requirements of 9.6.4 and the detailing requirements of 9.7.5 and 9.7.6.3 need not be satisfied.

9.5.4.2 T_n shall be calculated in accordance with 22.7.

R9.5.4 *Torsion*

ACI 318-19 Torsion in Beams



CODE

9.5.4.3 Longitudinal and transverse reinforcement equired for torsion shall be added to that required for the V_u, M_u, and P_u that act in combination with the torsion.

COMMENTARY

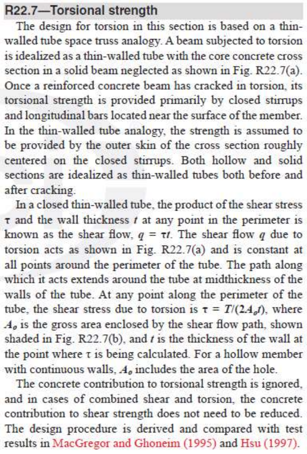
R9.5.4.3 The requirements for torsional reinforcement and shear reinforcement are added and stirrups are provided to supply at least the total amount required. Because the reinforcement area A_v for shear is defined in terms of all the legs of a given stirrup while the reinforcement area A_t for torsion is defined in terms of one leg only, the addition of transverse reinforcement area is calculated as follows:

$$\text{Total}\left(\frac{A_{v+t}}{s}\right) = \frac{A_v}{s} + 2\frac{A_t}{s} \qquad \text{(R9.5.4.3)}$$

Concrete Beams- Torsion

Thin-walled tube space truss analogy
Once beam is cracked in torsion, torsional strength is provided primarily by closed stirrups and longitudinal bars located near the surface of the member
Outer skin (concrete) roughly centered on the closed stirrups
q (shear flow)= t.tau
t= wall thickness
tau= shear stress

Concrete contribution to torsional strength is ignored
Combined shear and torsion: concrete contribution to shear strength need not be reduced



R22.7—Torsional strength

The design for torsion in this section is based on a thin-walled tube space truss analogy. A beam subjected to torsion is idealized as a thin-walled tube with the core concrete cross section in a solid beam neglected as shown in Fig. R22.7(a). Once a reinforced concrete beam has cracked in torsion, its torsional strength is provided primarily by closed stirrups and longitudinal bars located near the surface of the member. In the thin-walled tube analogy, the strength is assumed to be provided by the outer skin of the cross section roughly centered on the closed stirrups. Both hollow and solid sections are idealized as thin-walled tubes both before and after cracking.

In a closed thin-walled tube, the product of the shear stress τ and the wall thickness t at any point in the perimeter is known as the shear flow, $q = \tau t$. The shear flow q due to torsion acts as shown in Fig. R22.7(a) and is constant at all points around the perimeter of the tube. The path along which it acts extends around the tube at midthickness of the walls of the tube. At any point along the perimeter of the tube, the shear stress due to torsion is $\tau = T/(2A_o t)$, where A_o is the gross area enclosed by the shear flow path, shown shaded in Fig. R22.7(b), and t is the thickness of the wall at the point where τ is being calculated. For a hollow member with continuous walls, A_o includes the area of the hole.

The concrete contribution to torsional strength is ignored, and in cases of combined shear and torsion, the concrete contribution to shear strength does not need to be reduced. The design procedure is derived and compared with test results in MacGregor and Ghoneim (1995) and Hsu (1997).

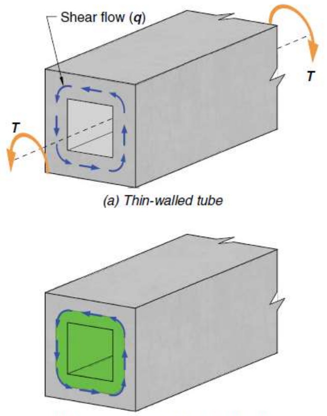


Fig. R22.7—(a) Thin-walled tube; and (b) area enclosed by shear flow path.