ELEMENTS OF ARCHITECTURAL STRUCTURES:
FORM, BEHAVIOR, AND DESIGN
ARCH 614
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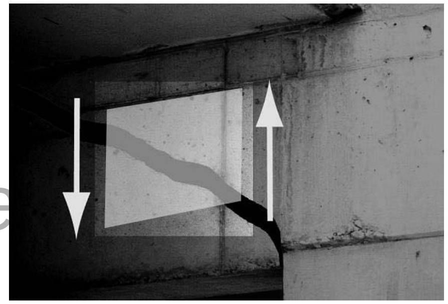
SPRING 2014

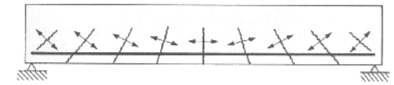
lecture
twenty three



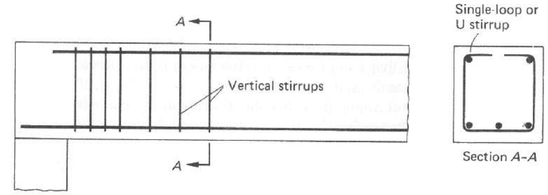
concrete construction:
shear & deflection

Shear in Concrete Beams

- *flexure combines with shear to form diagonal cracks*



- *horizontal reinforcement doesn't help*
- *stirrups = vertical reinforcement*



ACI Shear Values

- V_u *is at distance d from face of support*
- *shear capacity:* $V_c = \upsilon_c \times b_w d$
  - *where b_w means thickness of <u>web</u> at n.a.*

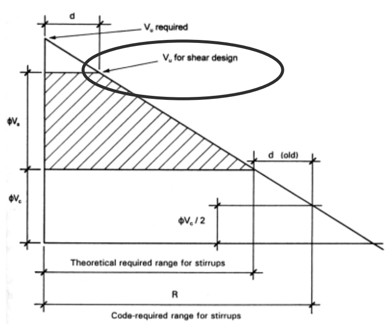


Figure 13.16 Layout for shear stress analysis: ACI Code requirements.

ACI Shear Values

- *shear stress (beams)*
  - $\upsilon_c = 2\sqrt{f'_c}$

    $\phi V_c = \phi 2\sqrt{f'_c}\, b_w d$

ϕ *= 0.75 for shear*

f'_c is in <u>psi</u>

- *shear strength:*

  $V_u \le \phi V_c + \phi V_s$

  - *V_s is strength from stirrup reinforcement*

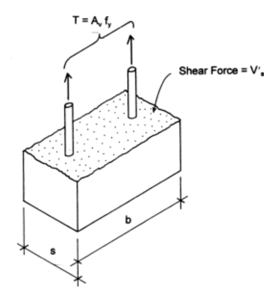


Figure 13.17 Consideration for spacing of a single stirrup.

Stirrup Reinforcement

- *shear capacity:*

$$V_s = \frac{A_v f_y d}{s}$$

  - A_v = *area in all legs of stirrups*
  - *s = spacing of stirrup*

- *may need stirrups when concrete has enough strength!*

Required Stirrup Reinforcement

- *spacing limits*

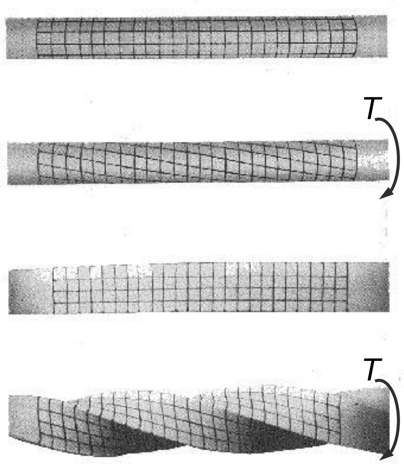
Table 3-8 ACI Provisions for Shear Design*

		$V_u \le \frac{\phi V_c}{2}$	$\phi V_c \ge V_u > \frac{\phi V_c}{2}$	$V_u > \phi V_c$
Required area of stirrups, A_v**		none	$\frac{50 b_w s}{f_y}$	$\frac{(V_u - \phi V_c)s}{\phi f_y d}$
Stirrup spacing, s	Required	—	$\frac{A_v f_y}{50 b_w}$	$\frac{\phi A_v f_y d}{V_u - \phi V_c}$
	Recommended Minimum†	—	—	4 in.
	Maximum†† (ACI 11.5.4)	—	$\frac{d}{2}$ or 24 in.	$\frac{d}{2}$ or 24 in. for $(V_u - \phi V_c) \le \phi 4\sqrt{f'_c}\, b_w d$
				$\frac{d}{4}$ or 12 in. for $(V_u - \phi V_c) > \phi 4\sqrt{f'_c}\, b_w d$

*Members subjected to shear and flexure only; $\phi V_c = \phi 2\sqrt{f'_c}\, b_w d$, ϕ = ~~0.85~~ 0.75 (ACI 11.3.1.1)
**$A_v = 2 \times A_b$ for U stirrups; $f_y \le 60$ ksi (ACI 11.5.2)
†A practical limit for minimum spacing is d/4
††Maximum spacing based on minimum shear reinforcement (= $A_v f_y / 50 b_w$) must also be considered (ACI 11.5.5.3).

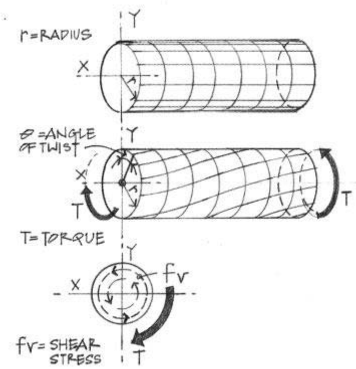
Torsional Stress & Strain

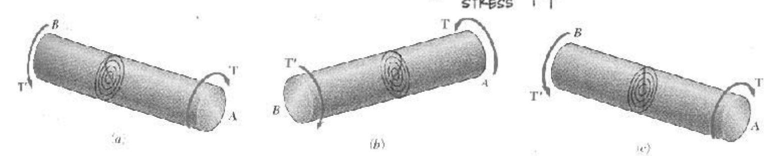
- *can see torsional stresses & twisting of axi-symmetrical cross sections*
  - *torque*
  - *remain plane*
  - *undistorted*
  - *rotates*
- *not true for square sections....*



Shear Stress Distribution

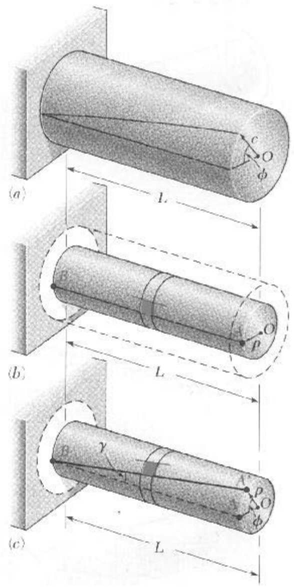
- *depend on the deformation*
- ϕ *= angle of twist*
  - *measure*
- *can prove planar section doesn't distort*





Shearing Strain

- *related to* ϕ $$\gamma = \frac{\rho\phi}{L}$$
- ρ *is the radial distance from the centroid to the point under strain*
- *shear strain varies linearly along the radius:* γ_{max} *is at outer diameter*

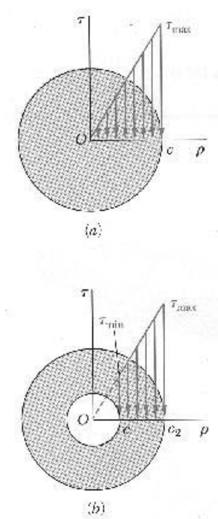


Torsional Stress - Strain

- *know* $f_v = \tau = G \cdot \gamma$ *and* $\gamma = \frac{\rho\phi}{L}$
- *so* $$\tau = G \cdot \frac{\rho\phi}{L}$$
- *where G is the Shear Modulus*

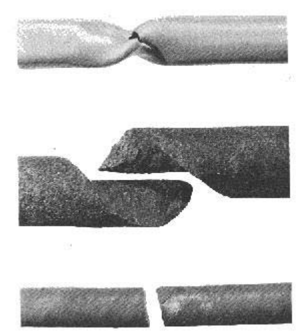
Torsional Stress - Strain

- *from* $$T = \Sigma\tau(\rho)\Delta A$$
- *can derive* $$T = \frac{\tau J}{\rho}$$
  - *where J is the polar moment of inertia*
  - *elastic range* $$\tau = \frac{T\rho}{J}$$



Shear Stress

- τ_{max} *happens at outer diameter*
- *combined shear and axial stresses*
  - *maximum shear stress at 45° "twisted" plane*



Shear Strain

- knowing $\tau = G \cdot \frac{\rho\phi}{L}$ and $\tau = \frac{T\rho}{J}$
- solve: $\phi = \frac{TL}{JG}$
- composite shafts: $\phi = \sum_i \frac{T_i L_i}{J_i G_i}$

Noncircular Shapes

- torsion depends on J
- plane sections don't remain plane
- τ_{max} is still at outer diameter

$$\tau_{max} = \frac{T}{c_1 ab^2} \qquad \phi = \frac{TL}{c_2 ab^3 G}$$

– where a is longer side (> b)

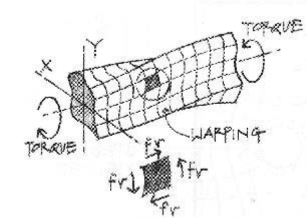
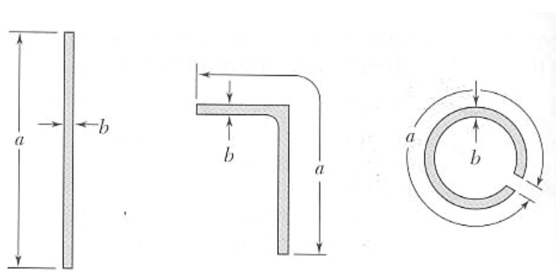


TABLE 3.1. Coefficients for Rectangular Bars in Torsion

a/b	c_1	c_2
1.0	0.208	0.1406
1.2	0.219	0.1661
1.5	0.231	0.1958
2.0	0.246	0.229
2.5	0.258	0.249
3.0	0.267	0.263
4.0	0.282	0.281
5.0	0.291	0.291
10.0	0.312	0.312
∞	0.333	0.333

Open Thin-Walled Sections

- with very large a/b ratios:



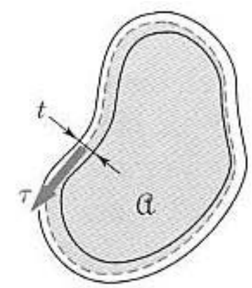
$$\tau_{max} = \frac{T}{\frac{1}{3} ab^2} \qquad \phi = \frac{TL}{\frac{1}{3} ab^3 G}$$

Shear Flow in Closed Sections

- q is the internal shear force/unit length

$$\tau = \frac{T}{2t\mathcal{a}}$$

$$\phi = \frac{TL}{4t\mathcal{a}^2} \sum_i \frac{s_i}{t_i}$$

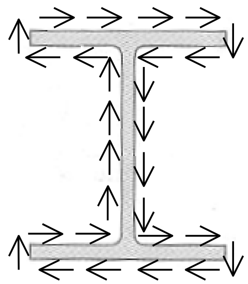


- $\mathcal{a}$ is the area bounded by the centerline
- s_i is the length segment, t_i is the thickness

Shear Flow in Open Sections

- each segment has proportion of T with respect to torsional rigidity,

$$\tau_{max} = \frac{Tt_{max}}{\frac{1}{3}\Sigma b_i t_i^3}$$



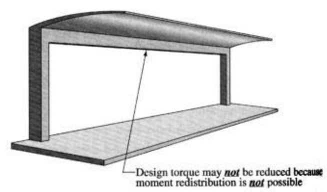
- total angle of twist:

$$\phi = \frac{TL}{\frac{1}{3}G\Sigma b_i t_i^3}$$

- I beams - web is thicker, so τ_{max} is in <u>web</u>

Torsional Shear Stress

- twisting moment
- <u>and</u> beam shear



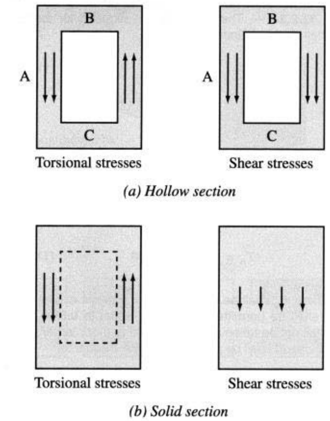


Fig. R11.6.3.1—Addition of torsional and shear stresses

Torsional Shear Reinforcement

- closed stirrups
- more longitudinal reinforcement

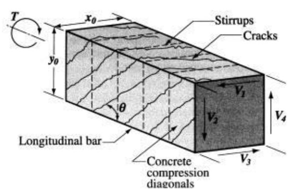
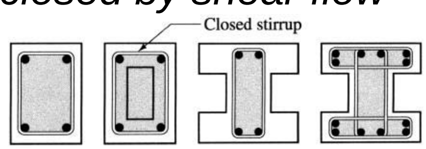


Fig. R11.6.3.6(a)—Space truss analogy

- area enclosed by shear flow

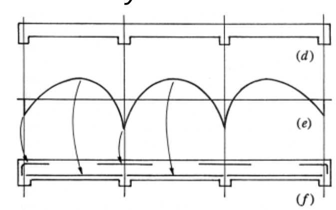


A_{oh} = shaded area

Fig. R11.6.3.6(b)—Definition of A_{oh}

Development Lengths

- required to allow steel to yield (f_y)
- standard hooks
  - moment at beam end



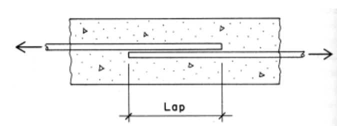
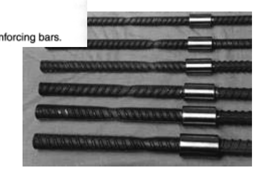
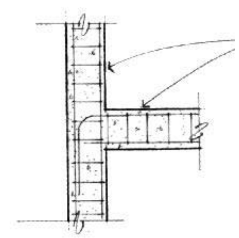


Figure 13.24 The lapped splice for steel reinforcing bars.





- splices
  - lapped
  - mechanical connectors

Development Lengths

- l_d , embedment required <u>both</u> sides
- proper cover, spacing:
  - No. 6 or smaller

$$l_d = \frac{d_b F_y}{25\sqrt{f'_c}} \quad \text{or 12 in. minimum}$$

  - No. 7 or larger

$$l_d = \frac{d_b F_y}{20\sqrt{f'_c}} \quad \text{or 12 in. minimum}$$

Development Lengths

- hooks
  - bend and extension

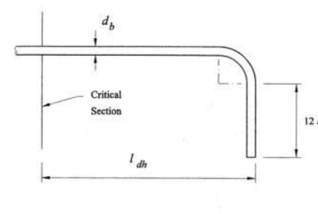


Figure 9-17: Minimum requirements for 90°bar hooks.

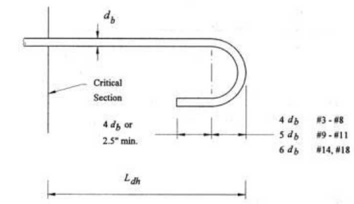


Figure 9-18: Minimum requirements for 180° bar hooks.

- minimum

$$l_{dh} = \frac{1200\, d_b}{\sqrt{f'_c}}$$

Development Lengths

- bars in compression

$$l_d = \frac{0.02\, d_b F_y}{\sqrt{f'_c}} \le 0.0003\, d_b F_y$$

- splices
  - tension minimum is function of l_d and splice classification
  - compression minimum
  - is function of d_b and F_y

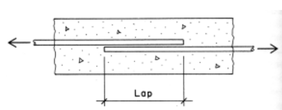


Figure 13.24 The lapped splice for steel reinforcing bars.

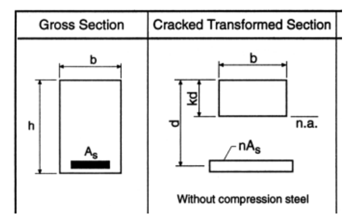
Concrete Deflections

- elastic range
  - I transformed
  - E_c (with f'_c in <u>psi</u>)
    - normal weight concrete (~ 145 lb/ft^3)

$$E_c = 57{,}000\sqrt{f'_c}$$

    - concrete between 90 and 160 lb/ft^3

$$E_c = w_c^{1.5}\, 33\sqrt{f'_c}$$



- cracked
  - I cracked
  - E adjusted

Deflection Limits

- *relate to whether or not beam supports or is attached to a damageable non-structural element*
- *need to check service live load and long term deflection against these*

L/180	*roof systems (typical) – live*
L/240	*floor systems (typical) – live + long term*
L/360	*supporting plaster – live*
L/480	*supporting masonry – live + long term*