ARCHITECTURAL STRUCTURES:

FORM, BEHAVIOR, AND DESIGN

ARCH 331

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FALL 2013

lecture
twenty two

concrete construction:

materials & beams

Concrete Beam Design

- *composite of concrete and steel*

- *American Concrete Institute (ACI)*
  - *design for maximum stresses*
  - *limit state design*
    - *service loads x load factors*
    - *concrete holds no tension*
    - *failure criteria is yield of reinforcement*
    - *failure capacity x reduction factor*
    - *factored loads < reduced capacity*
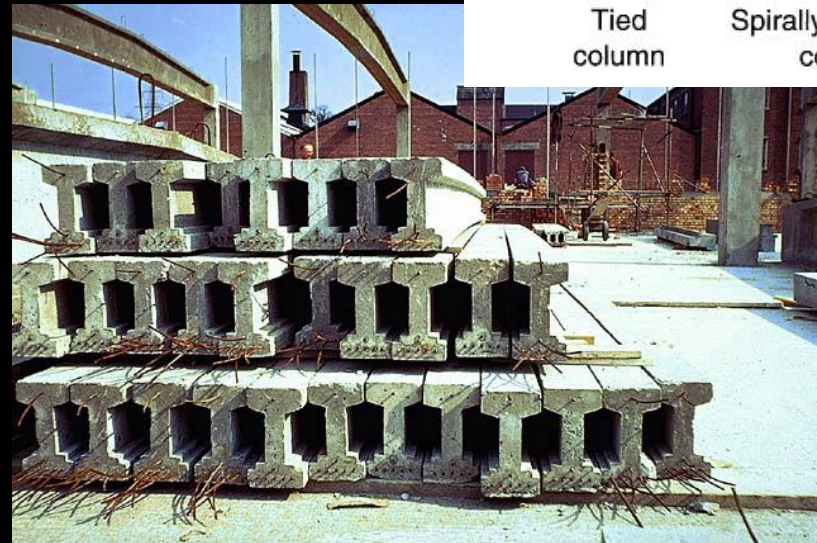 - *concrete strength = f'_c*

Concrete Construction

- *cast-in-place*

- *tilt-up*

- *prestressing*

- *post-tensioning*
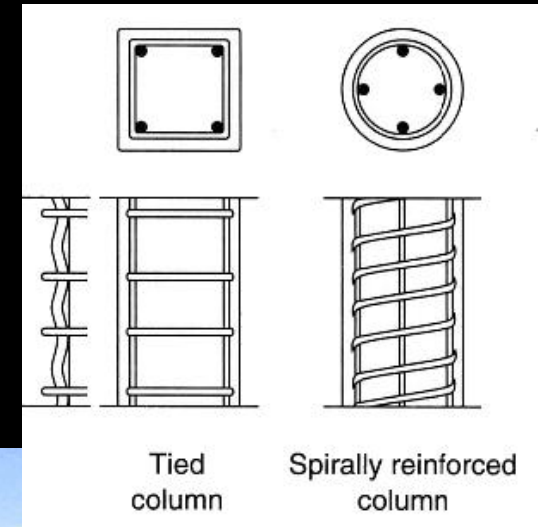
Tied column

Spirally reinforced column

arch.mcgill.ca

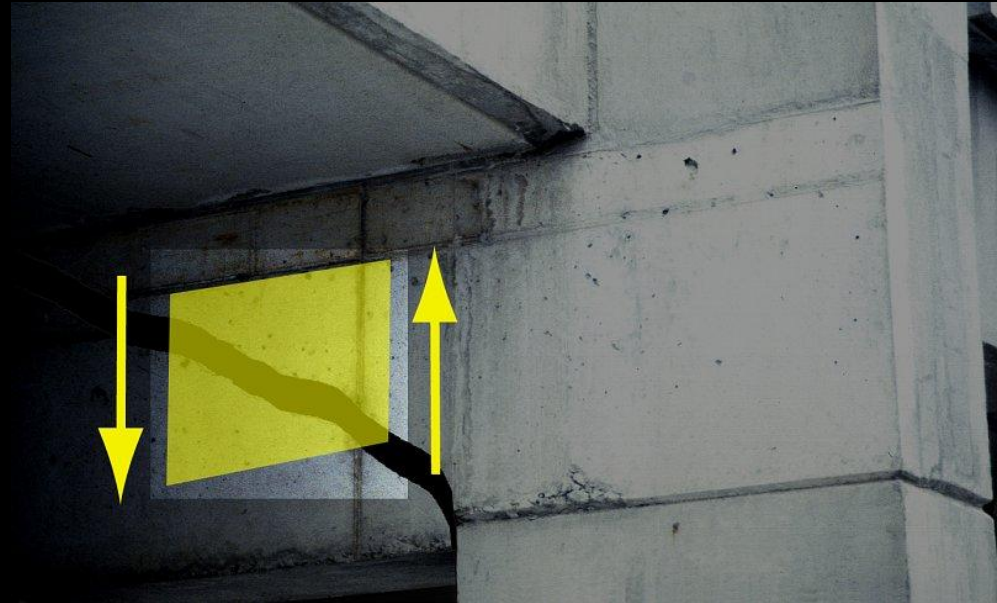

http:// nisee.berkeley.edu/godden

Concrete Beams

- *types*
  - *reinforced*
  - *precast*
  - *prestressed*

- *shapes*
  - *rectangular, I*
  - *T, double T's, bulb T's*
  - *box*
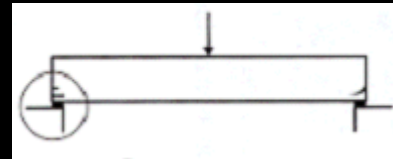 - *spandrel*
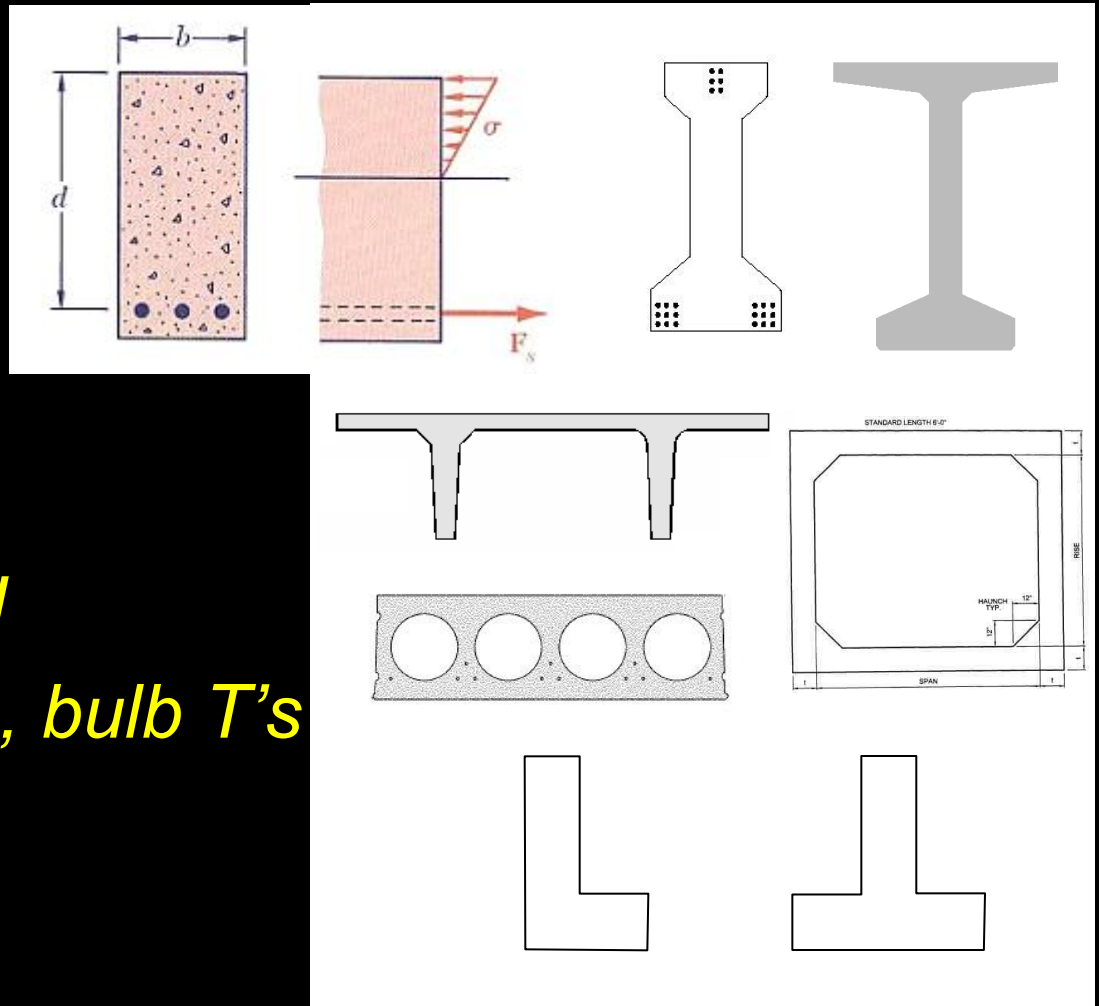
Concrete Beams

- *shear*
  - *vertical*
  - *horizontal*
  - *combination:*
    - *tensile stresses at 45°*

- *bearing*
  - *crushing*

http://urban.arch.virginia.edu
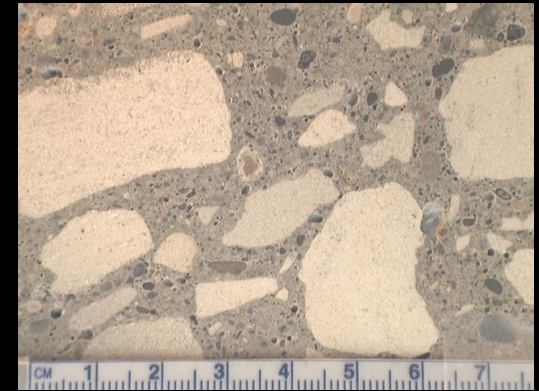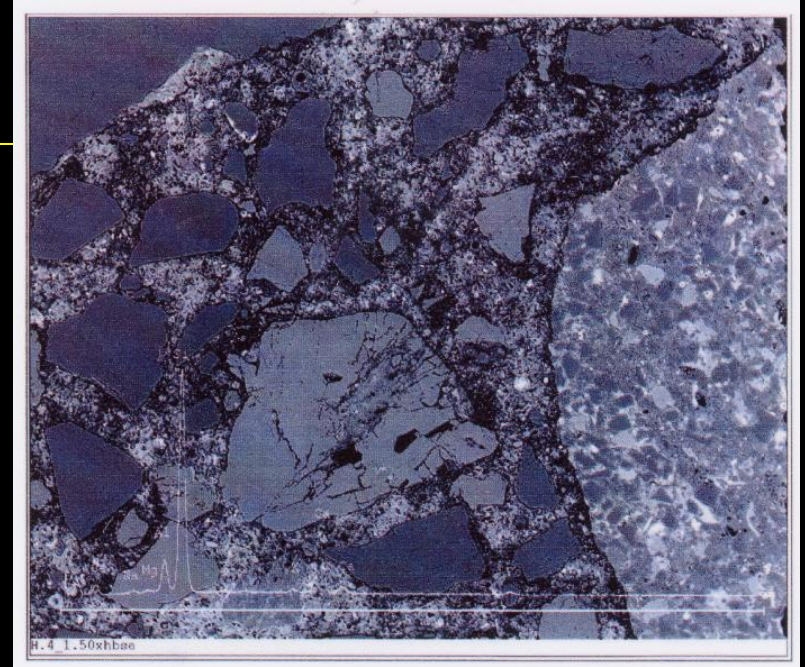
Concrete

- *low strength to weight ratio*

- *relatively inexpensive*
  - *Portland cement*
    - *types I - V*
  - *aggregate*
    - *course & fine*
  - *water*
  - *admixtures*
    - *air entraining*
    - *superplasticizers*

Concrete

- *hydration*
  - *chemical reaction*
  - *workability*
  - *water to cement ratio*
  - *mix design*
- *fire resistant*
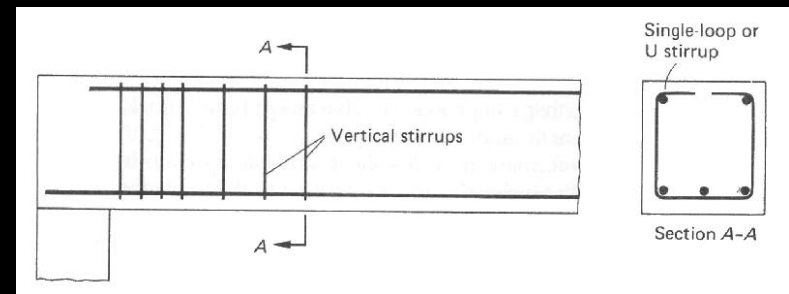- *cover for steel*
- *creep & shrinkage*

jci-web.jp

Concrete

- *placement (not pouring!)*
- *vibrating*
- *screeding*
- *floating*
- *troweling*
- *curing*
- *finishing*

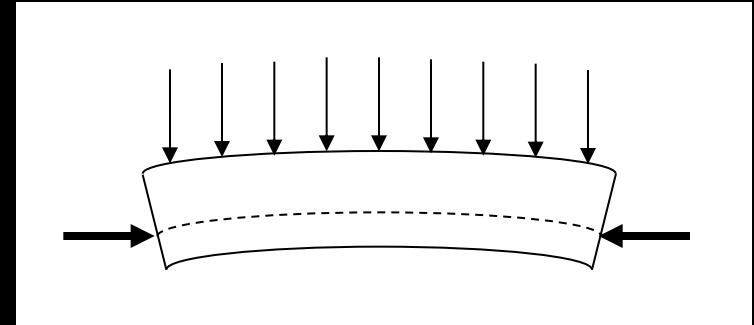# Reinforcement

- *deformed steel bars (rebar)*
  - *Grade 40, F_y = 40 ksi*
  - *Grade 60, F_y = 60 ksi - most common*
  - *Grade 75, F_y = 75 ksi*
  - *US customary in # of 1/8" ϕ*
  (nominal)

- *longitudinally placed*
  - *bottom*
  - *top for compression reinforcement*
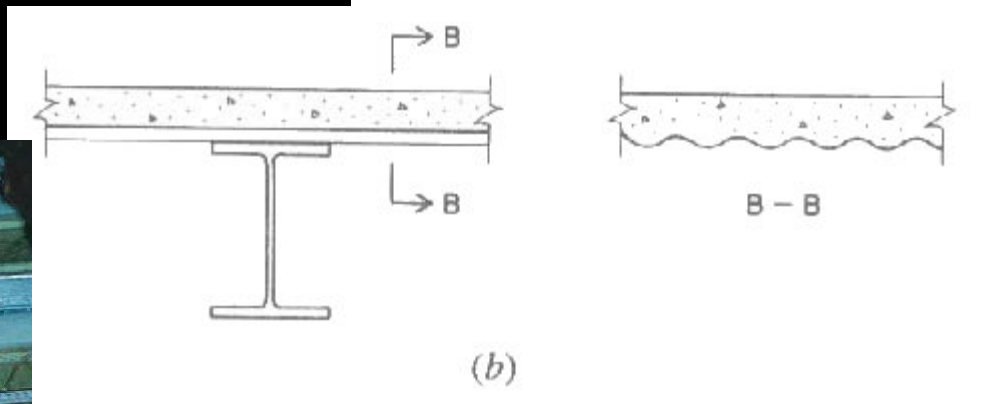
Reinforcement

- *prestressing strand*

- *post-tensioning*

- *stirrups*

- *detailing*

  – *development length*

  – *anchorage*

  – *splices*

http:// nisee.berkeley.edu/godden

Composite Beams

- *concrete*
  - *in compression*
- *steel*
  - *in tension*
- *shear studs*
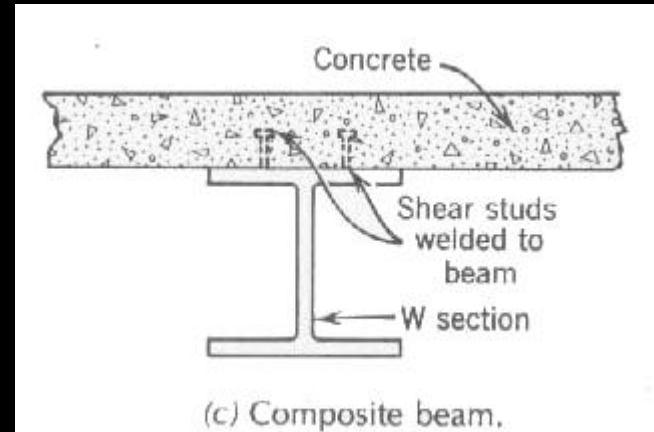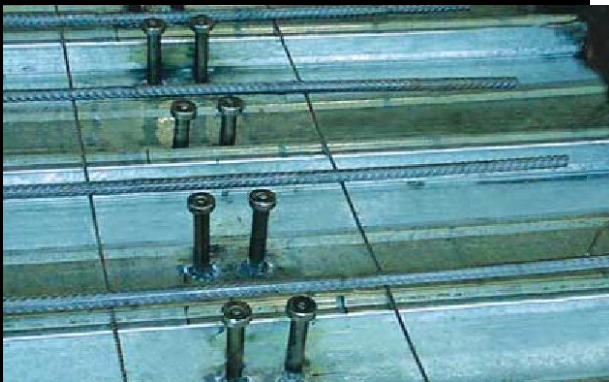
Behavior of Composite Members

- *plane sections remain plane*

- *stress distribution changes*
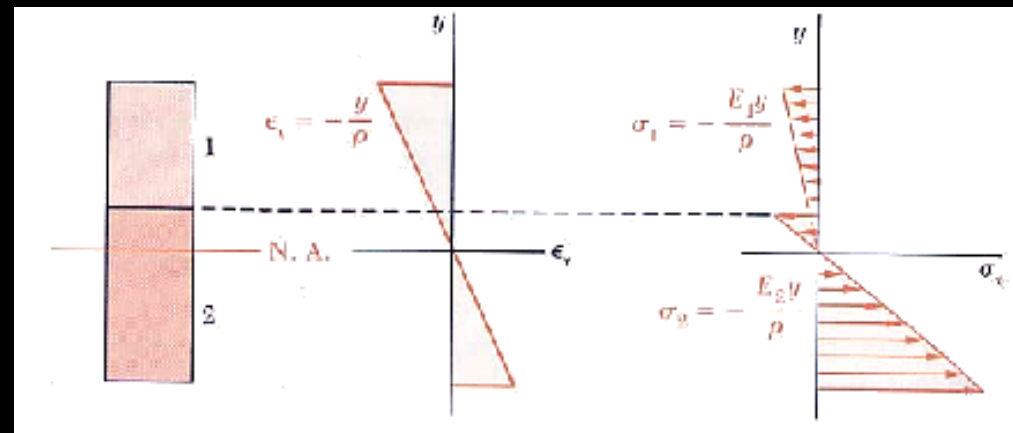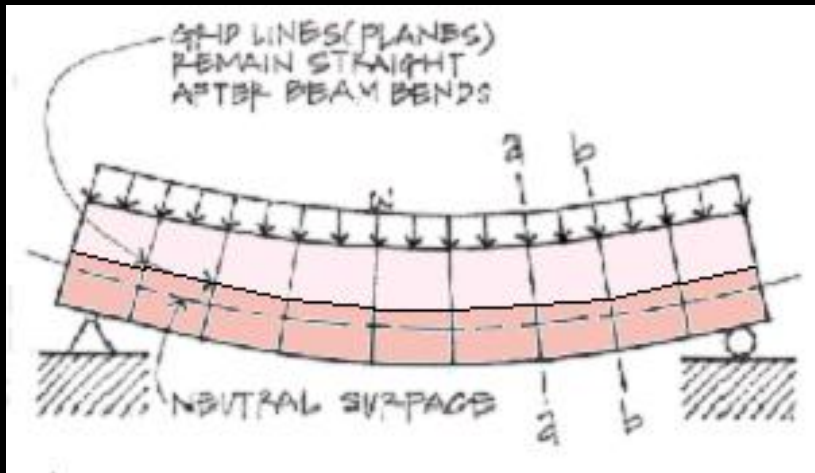
$$f_1 = E_1 \varepsilon = -\frac{E_1 y}{\rho}$$

$$f_2 = E_2 \varepsilon = -\frac{E_2 y}{\rho}$$

Transformation of Material

- *n is the ratio of E's*

$$n = \frac{E_2}{E_1}$$

- *effectively widens a material to get same stress distribution*
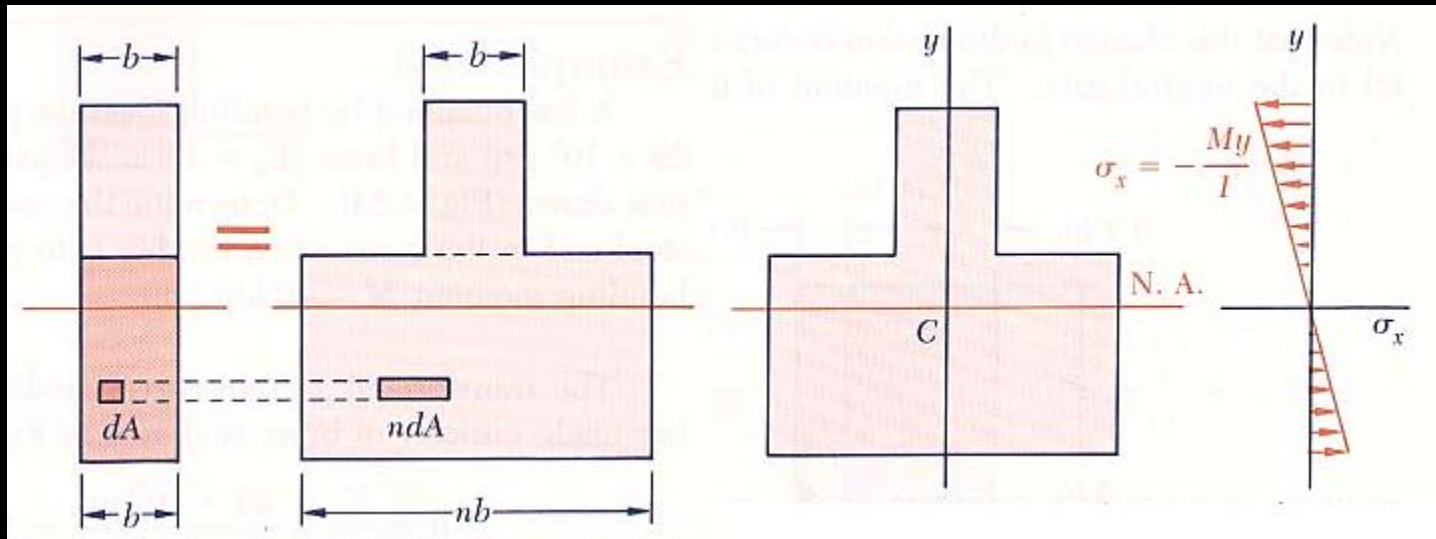
Stresses in Composite Section

- *with a section transformed to one material, new I*
  - *stresses in that material are determined as usual*
  - *stresses in the other material need to be adjusted by n*

$$n = \frac{E_2}{E_1} = \frac{E_{steel}}{E_{concrete}}$$

$$f_c = -\frac{My}{I_{transformed}}$$

$$f_s = -\frac{Myn}{I_{transformed}}$$

Reinforced Concrete - stress/strain

Strain distribution
Stress distribution
Resisting couple

Steel

Stresses in the concrete above the neutral axis are compressive and nonlinearly distributed. In the tension zone below the neutral axis, the concrete is assumed to be cracked and the tensile force present to be taken up by reinforcing steel.
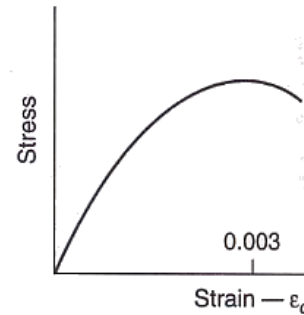
Typical stress-strain curve for concrete.
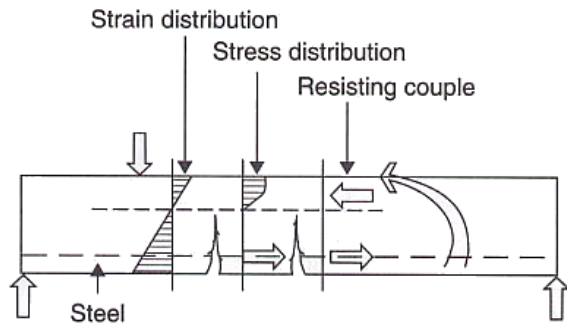
Stress

0.003

Strain — ε_c

f_{c_1}
T
T
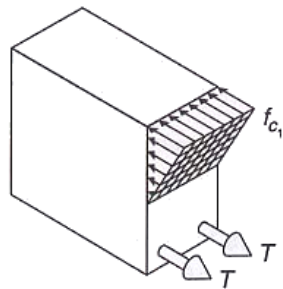
Working stress analysis. (Concrete stress distribution is assumed to be linear. Service loads are used in calculations.)

f_c
T
T
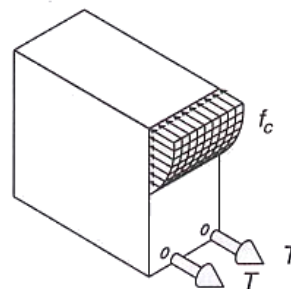
Actual stress distribution near ultimate strength (nonlinear).

f_{c_2}
T
T
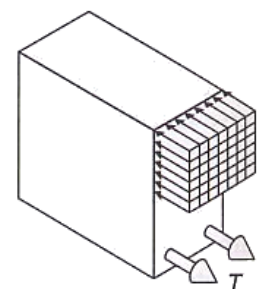
Ultimate strength analysis. (A rectangular stress block is used to idealize the actual stress distribution. Calculations are based on ultimate loads and failure stresses.)

FIGURE 6–37 Reinforced concrete beams.

Reinforced Concrete Analysis

- *for stress calculations*
  - *steel is transformed to concrete*
  - *concrete is in compression above n.a. and represented by an equivalent <u>stress block</u>*
  - *concrete takes <u>no tension</u>*
  - *steel takes tension*
  - *force <u>ductile</u> failure*
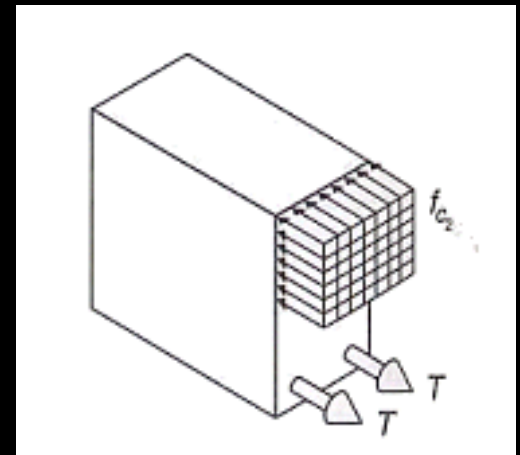
Location of n.a.

- *ignore concrete below n.a.*

- *transform steel*

- *same area moments, solve for x*
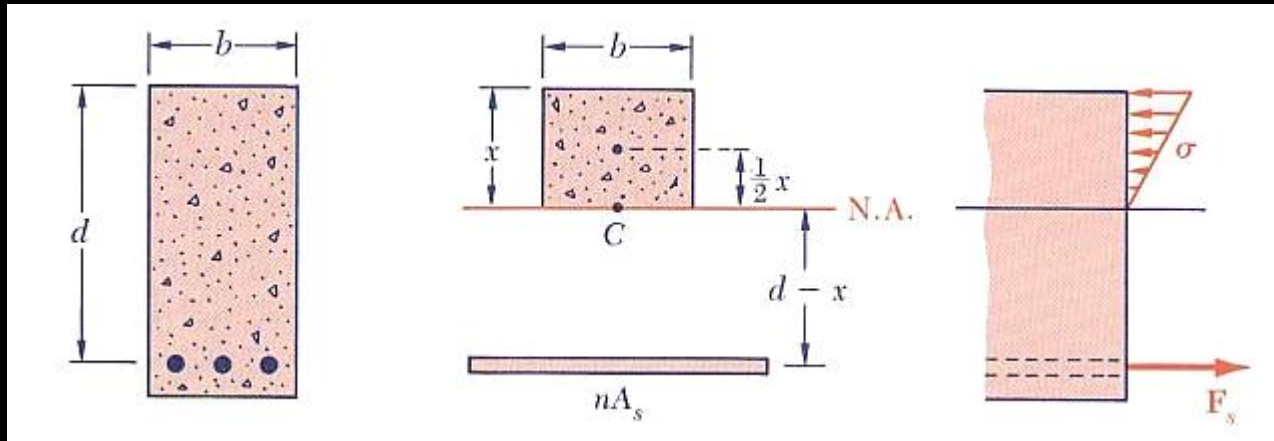
$$bx \cdot \frac{x}{2} - nA_s(d - x) = 0$$

T sections

- *n.a. equation is different if n.a. below flange*
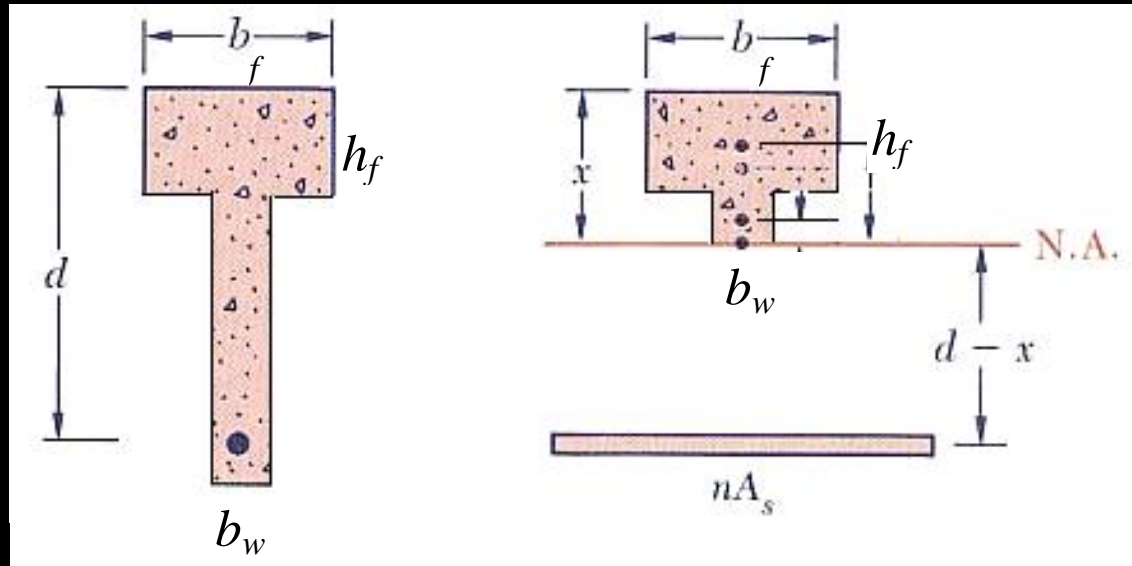
$$b_f h_f \left(x - \frac{h_f}{2} \right) + (x - h_f) b_w \frac{(x - h_f)}{2} - nA_s(d - x) = 0$$

ACI Load Combinations*

- 1.4D
- 1.2D + 1.6L + 0.5(L_r or S or R)
- 1.2D + 1.6(L_r or S or R) + (1.0L or 0.5W)
- 1.2D + 1.0W + 1.0L + 0.5(L_r or S or R)
- 1.2D + 1.0E + 1.0L + 0.2S
- 0.9D + 1.0W
- 0.9D + 1.0E

*can also use old ACI factors

Reinforced Concrete Design

- *stress distribution in bending*

actual stress

Whitney stress block
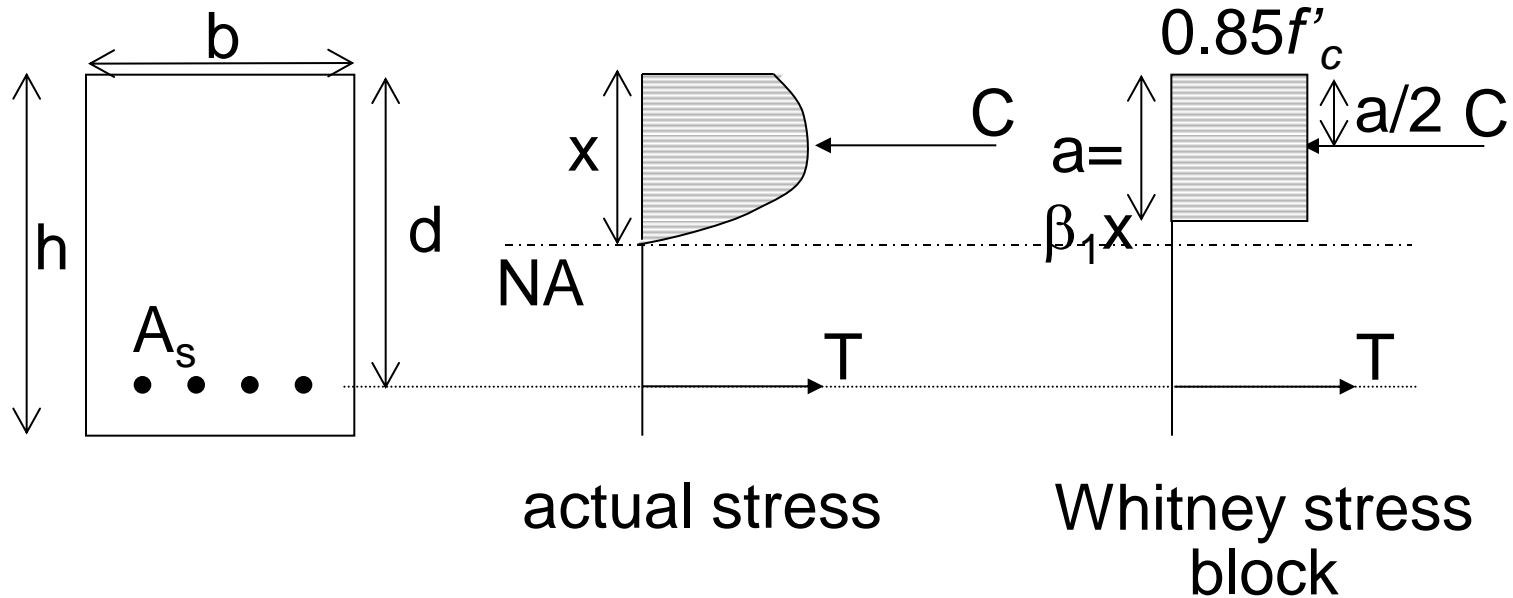
Wang & Salmon, Chapter 3

Force Equations

- $C = 0.85\,f'_c ba$

- $T = A_s f_y$

- where

  - f'_c = concrete compressive strength

  - a = height of stress block

  - β_1 = factor based on f'_c

  - x = location to the n.a.

  - b = width of stress block

  - f_y = steel yield strength

  - A_s = area of steel reinforcement
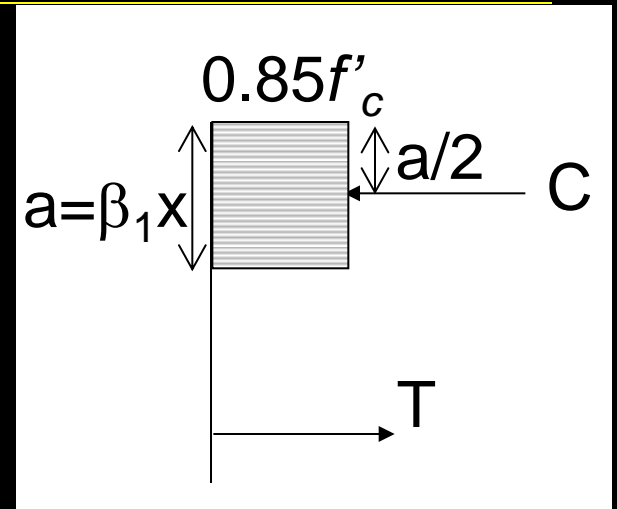
Equilibrium

- *$T = C$*

- *$M_n = T(d-a/2)$*
  - *d = depth to the steel n.a.*

- *with A_s*

  - *$a = \dfrac{A_s f_y}{0.85 f_c' b}$*

  - *$M_u \leq \phi M_n$ $\phi = 0.9$ for flexure**
  - *$\phi M_n = \phi\, T(d-a/2) = \phi\, A_s f_y\,(d-a/2)$*

Over and Under-reinforcement

- *over-reinforced*
  - *steel won't yield*

- *under-reinforced*
  - *steel will yield*

- *reinforcement ratio*

http://people.bath.ac.uk/abstji/concrete_video/virtual_lab.htm

$$\rho = \frac{A_s}{bd}$$

  - *use as a design estimate to find A_s,b,d*

  - *max ρ is found with $\varepsilon_{steel} \geq 0.004$ (not ρ_{bal})*

  - **with $\varepsilon_{steel} \geq 0.005$, $\phi = 0.9$*
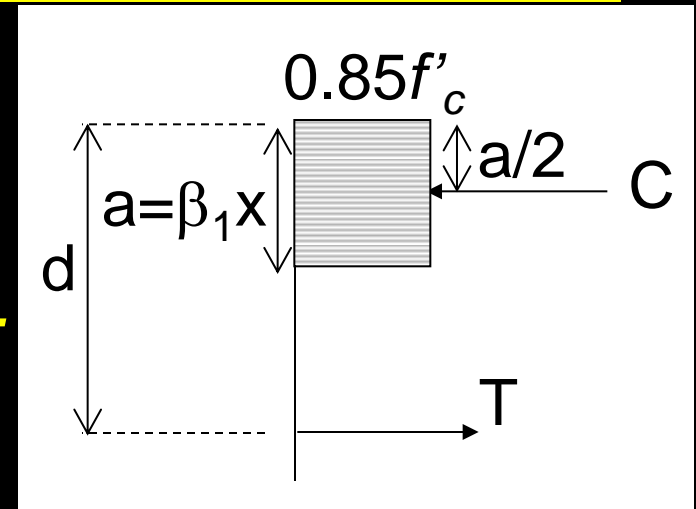
A_s for a Given Section

- ## several methods

  - ### guess a and iterate

    1. guess a (less than n.a.)

    2. $$A_s = \frac{0.85 f_c' b a}{f_y}$$

    3. solve for a from $M_u = \phi\, A_s f_y\, (d\text{-}a/2)$

    $$a = 2\left(d - \frac{M_u}{\phi A_s f_y} \right)$$

    4. repeat from 2. until a from 3. matches a in 2.

A_s *for a Given Section (cont)*

- *chart method*
  - *Wang & Salmon Fig. 3.8.1 R_n vs. ρ*

  1. *calculate* $R_n = \dfrac{M_n}{bd^2}$

  2. *find curve for f'_c and f_y to get ρ*
  3. *calculate A_s and a*

- *simplify by setting $h = 1.1d$*

Reinforcement

- *min for crack control*

- *required* $$A_s = \frac{3\sqrt{f_c'}}{f_y}(bd)$$

- *not less than* $$A_s = \frac{200}{f_y}(bd)$$

- *$A_{s\text{-}max}$:* $a = \beta_1(0.375d)$

- *typical cover*
  - *1.5 in, 3 in with soil*

- *bar spacing*
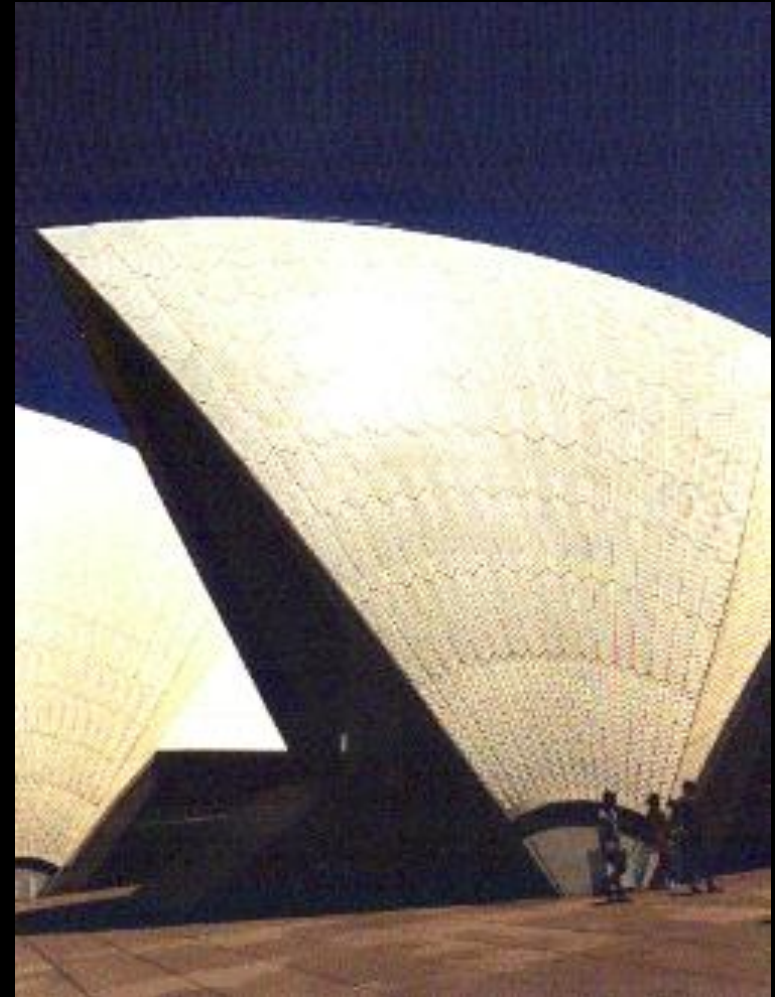
cover

spacing

Shells

Annunciation Greek Orthodox Church

- *Wright, 1956*

Concrete Beams 28
Lecture 22

Architectural Structures
ARCH 331

http://www.bluffton.edu/~sullivanm/

F2013abn

Annunciation Greek Orthodox Church

- *Wright, 1956*
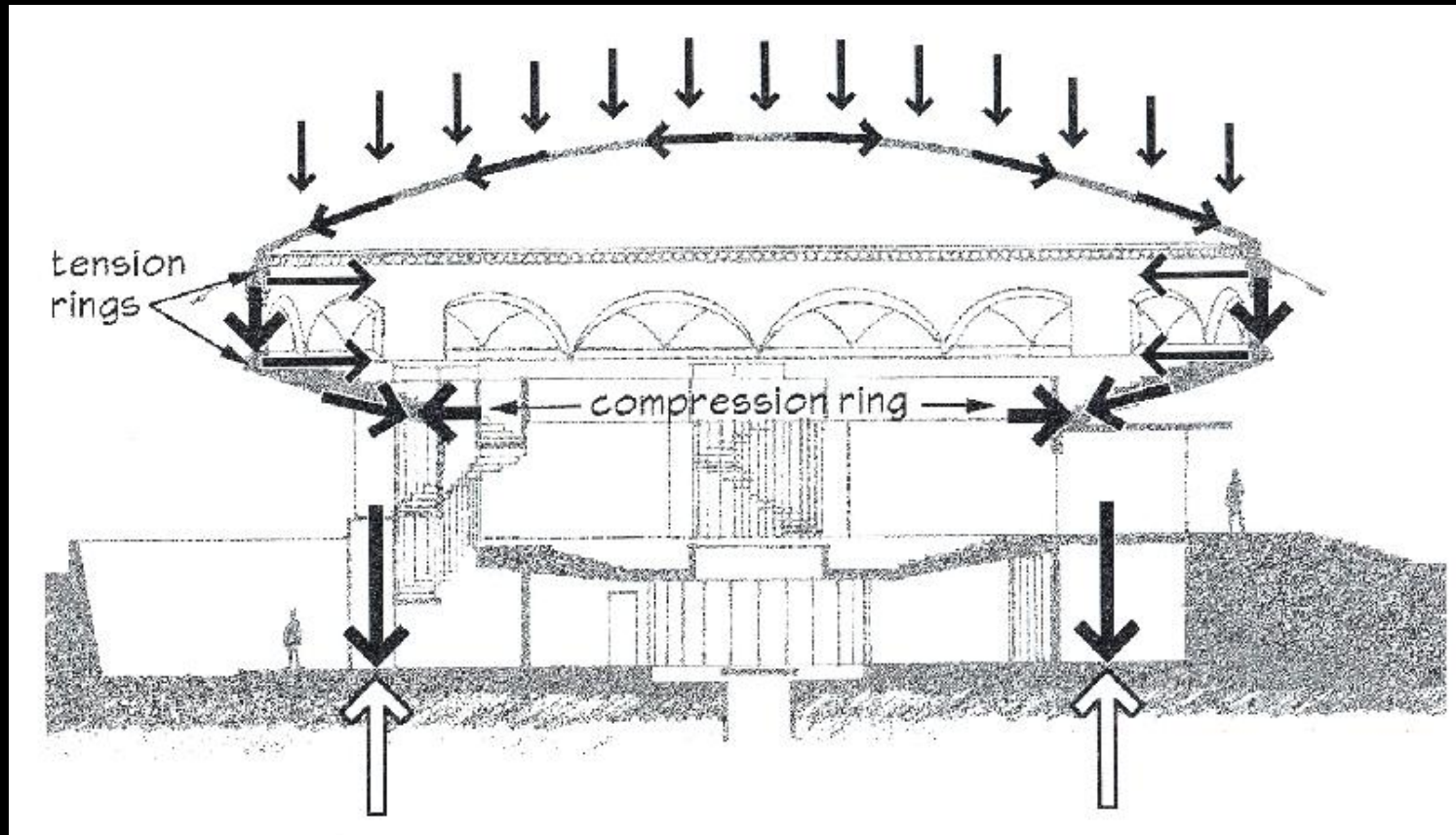
Cylindrical Shells

- *can resist tension*

- *shape adds "depth"*

CONTINUOUS

DISCONTINUOUS
(to admit daylight)

TRANSVERSE FOLDING

FREE FORM

compression
------ tension
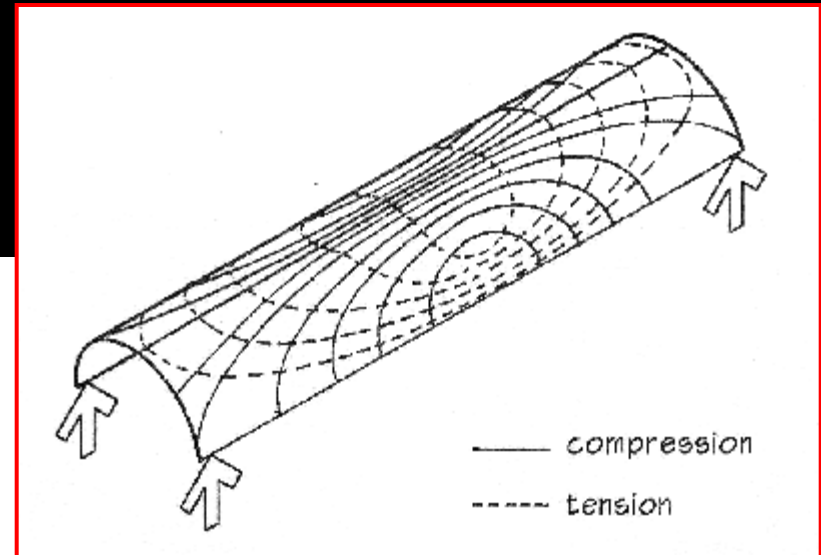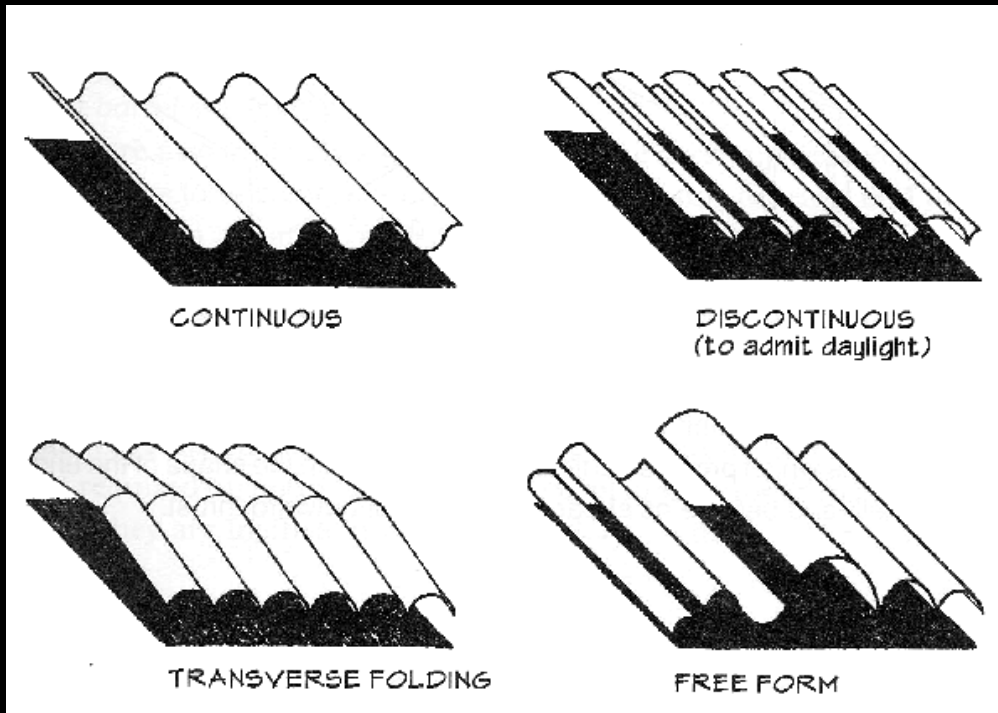
- *not vaults*
- *barrel shells*

Kimball Museum, Kahn 1972

Kimball Museum, Kahn 1972

- *outer shell edges*

Kimball Museum, Kahn 1972

- *skylights at peak*

top part of shell is in compression

bottom part of shell is in tension

www.GreatBuildings.com

Approximate Depths

Span

Feet 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180

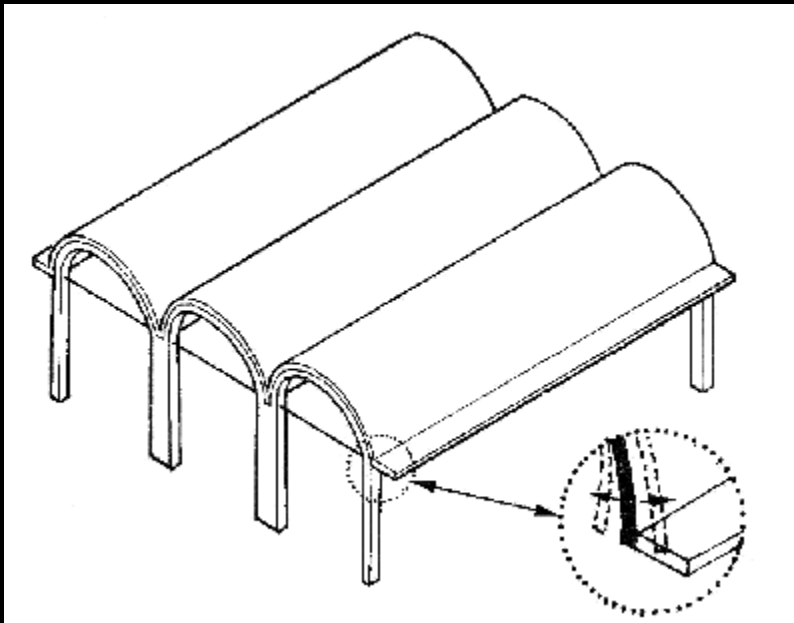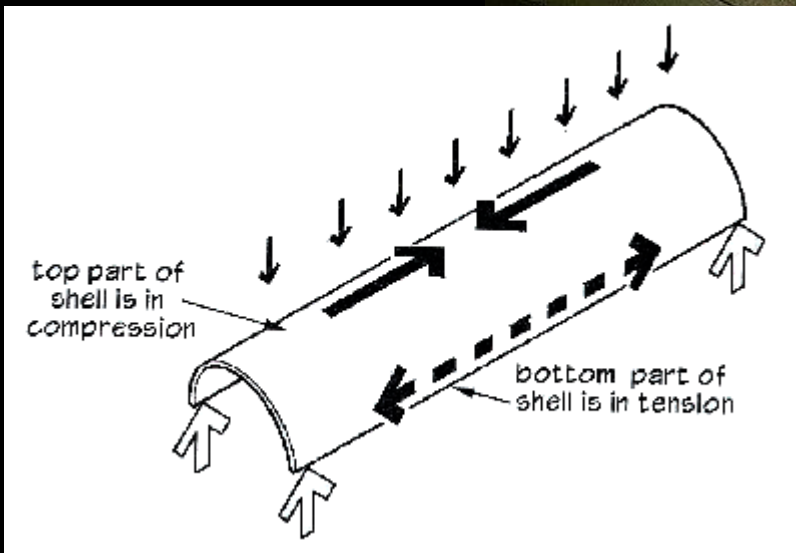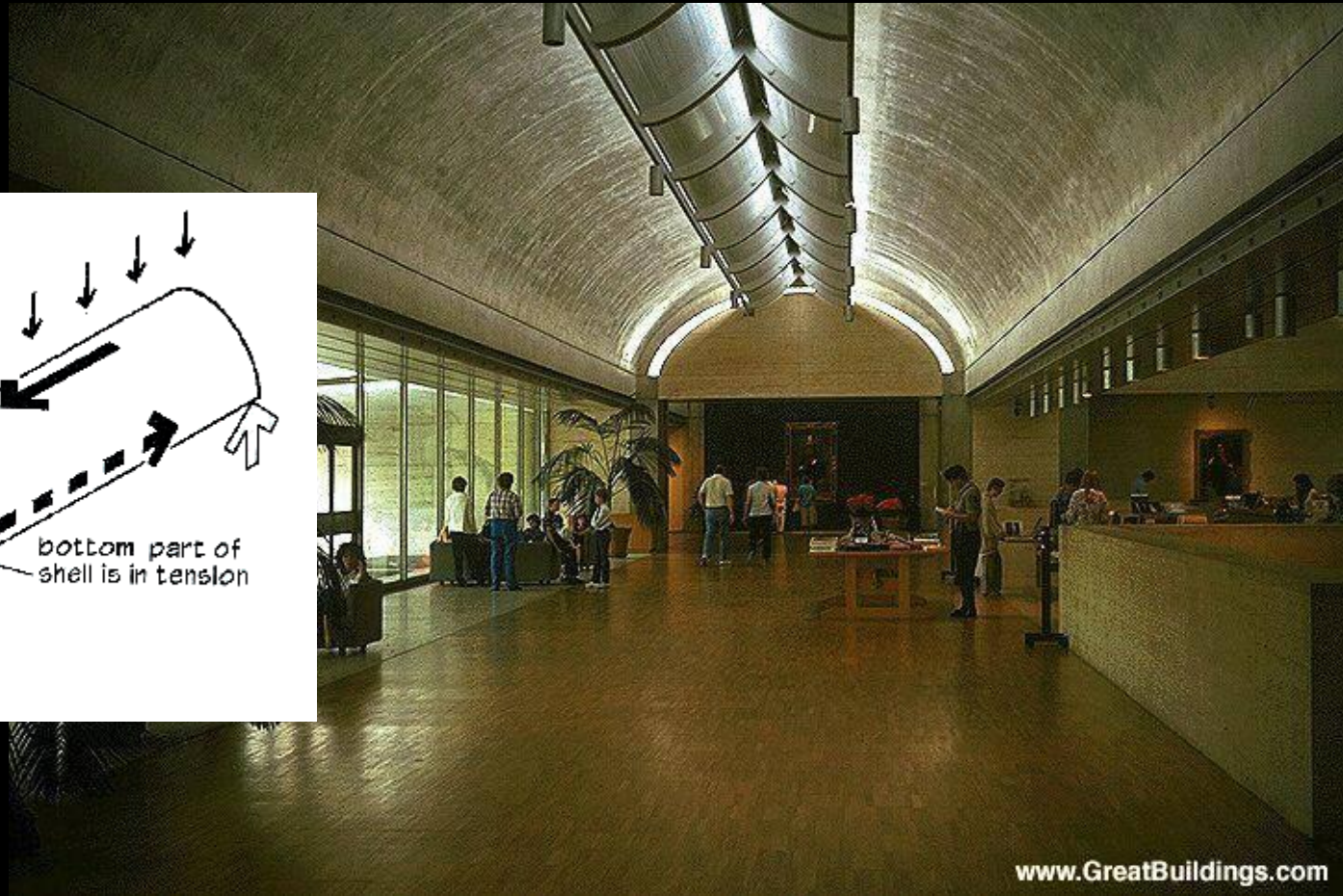|			
Slabs (poured in place)		Simply supported	L/25
		One end continuous	L/30
		Both ends continuous	L/35
		Cantilever	L/12
Beams (poured in place)		Simply supported	L/20
		One end continuous	L/23
		Both ends continuous	L/26
		Cantilever	L/10
Pan joist system (poured in place)		L/20–L/25	
Folded plate (poured in place)		L/8–L/15	
Barrel shell (poured in place)		L/8–L/15	
Planks (precast)		L/25–L/40	
Channels (precast)		L/20–L/28	
Tees (precast)		L/20–L/28	
Flat plate (poured in place)		L/30–L/40	
Flat slab (poured in place)		L/30–L/40	
Two-way beam and slab (poured in place)		L/30–L/40	
Waffle slab (poured in place)		L/23–L/35	
Dome (poured in place)		L/4–L/8	

Key: Minimum span   Possible span range   Maximum span

Typical span for member

Typical member length

(Meters) 0 5 10 15 20 25 30 35 40 45 50