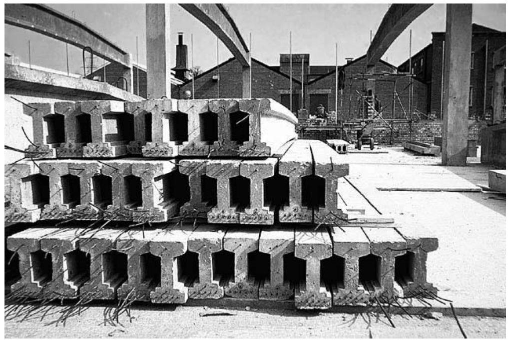
ARCHITECTURAL STRUCTURES:
FORM, BEHAVIOR, AND DESIGN
ARCH 331
DR. ANNE NICHOLS
FALL 2013

lecture
twenty two



http:// nisee.berkeley.edu/godden

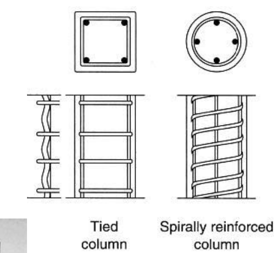
concrete construction: materials & beams

Concrete Beam Design

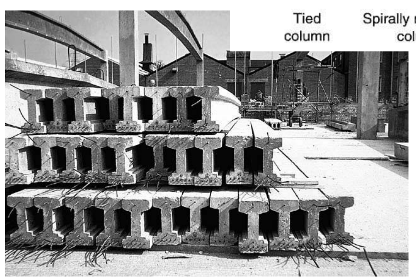
- composite of concrete and steel
- American Concrete Institute (ACI)
  - design for maximum stresses
  - limit state design
    - service loads x load factors
    - concrete holds no tension
    - failure criteria is yield of reinforcement
    - failure capacity x reduction factor
    - factored loads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

Concrete Construction

- cast-in-place
- tilt-up
- prestressing
- post-tensioning



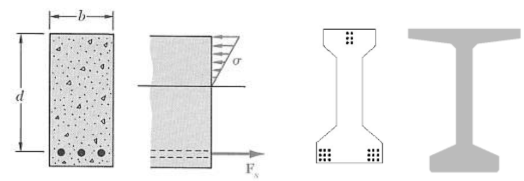
arch.mcgill.ca

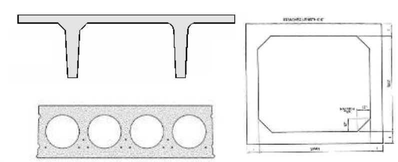


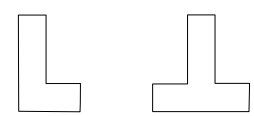
http:// nisee.berkeley.edu/godden

Concrete Beams

- types
  - reinforced
  - precast
  - prestressed
- shapes
  - rectangular, I
  - T, double T's, bulb T's
  - box
  - spandrel

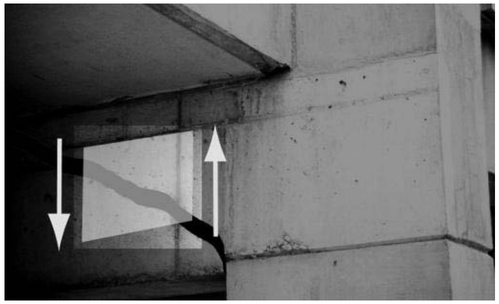




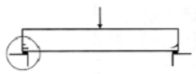


Concrete Beams

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

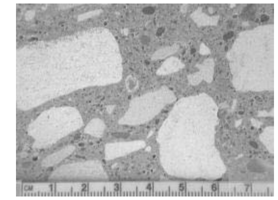


http://urban.arch.virginia.edu



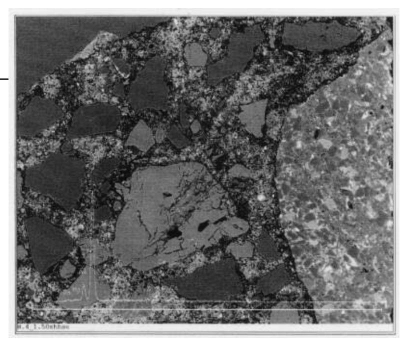
Concrete

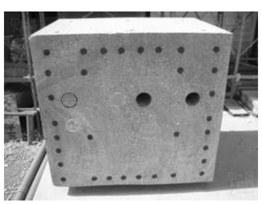
- *low strength to weight ratio*
- *relatively inexpensive*
  - *Portland cement*
    - *types I - V*
  - *aggregate*
    - *course & fine*
  - *water*
  - *admixtures*
    - *air entraining*
    - *superplasticizers*



Concrete

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





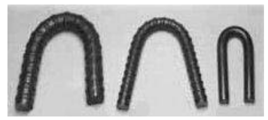
jci-web.jp

Concrete

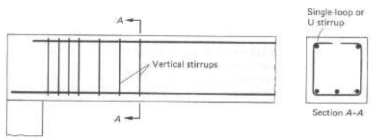
- *placement (not pouring!)*
- *vibrating*
- *screeding*
- *floating*
- *troweling*
- *curing*
- *finishing*

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)*

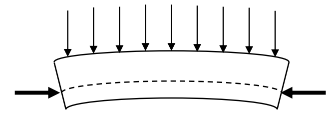


- *longitudinally placed*
  - *bottom*
  - *top for compression reinforcement*



Reinforcement

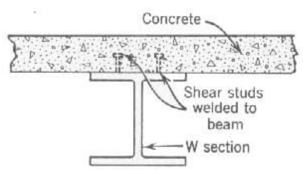
- *prestressing strand*
- *post-tensioning*
- *stirrups*
- *detailing*
  - *development length*
  - *anchorage*
  - *splices*



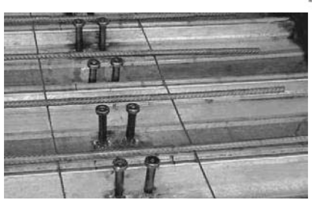
http:// nisee.berkeley.edu/godden

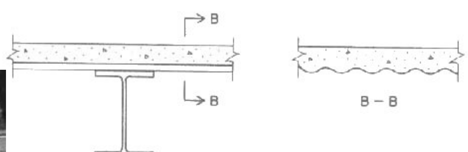
Composite Beams

- *concrete*
  - *in compression*
- *steel*
  - *in tension*
- *shear studs*



(c) Composite beam.

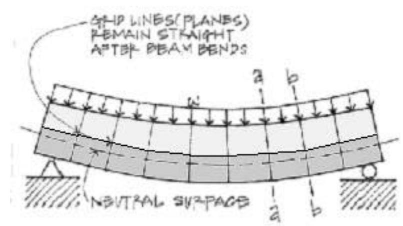


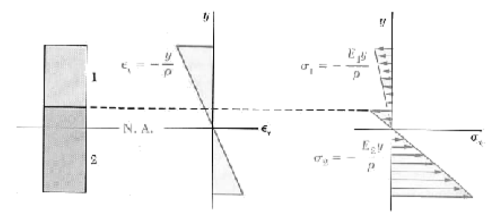


(b)

Behavior of Composite Members

- *plane sections remain plane*
- *stress distribution changes*

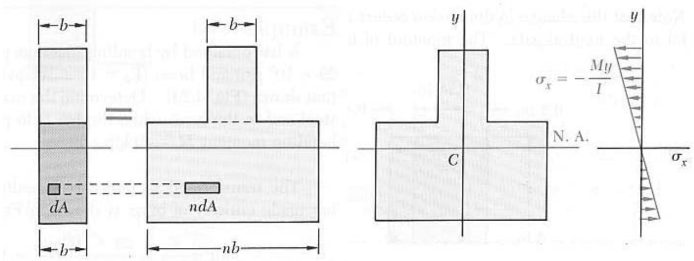




$$f_1 = E_1\varepsilon = -\frac{E_1 y}{\rho} \qquad f_2 = E_2\varepsilon = -\frac{E_2 y}{\rho}$$

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

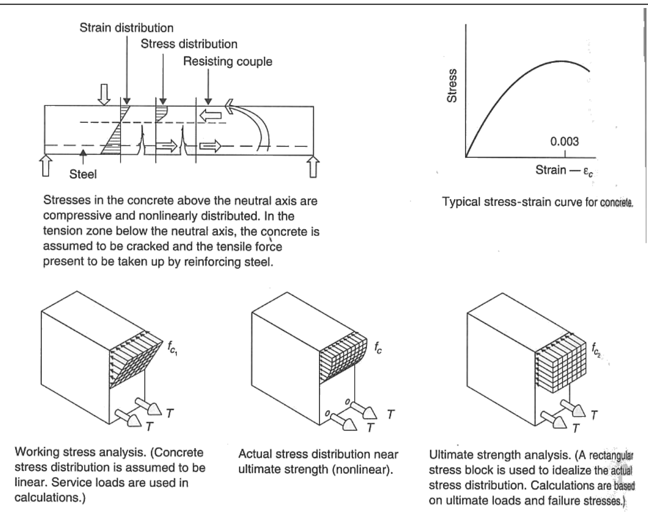
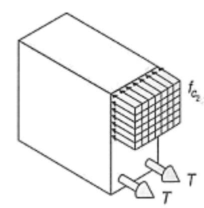


FIGURE 6–37 Reinforced concrete beams.

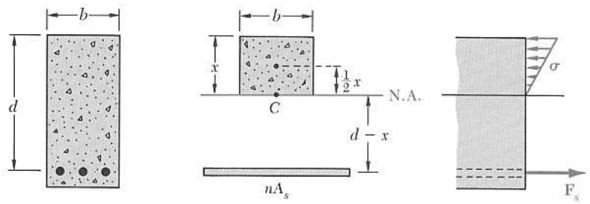
Reinforced Concrete Analysis

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



Location of n.a.

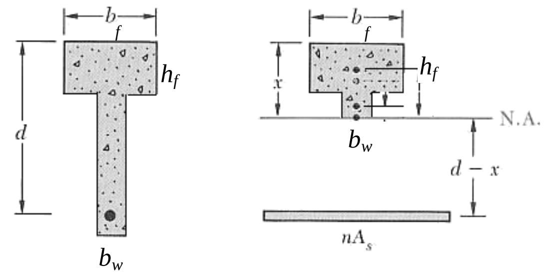
- ignore concrete below n.a.
- transform steel
- same area moments, solve for x



$$bx \cdot \frac{x}{2} - nA_s(d - x) = 0$$

T sections

- n.a. equation is different if n.a. below flange



$$b_f h_f\left(x - \frac{h_f}{2}\right) + (x - h_f)b_w \frac{(x - h_f)}{2} - nA_s(d - x) = 0$$

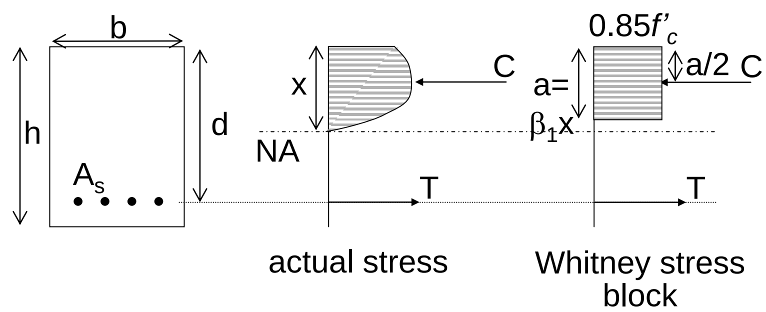
ACI Load Combinations*

- 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

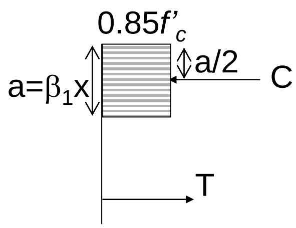
- stress distribution in bending



Wang & Salmon, Chapter 3

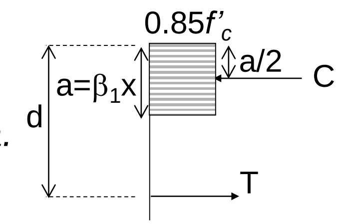
Force Equations

- $C = 0.85\ f'_c ba$
- $T = A_s f_y$
- 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



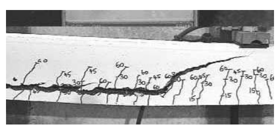
Equilibrium

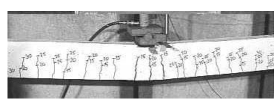
- $T = C$
- $M_n = T(d\text{-}a/2)$
  - d = depth to the steel n.a.
- with A_s
  - $a = \dfrac{A_s f_y}{0.85 f'_c b}$
  - $M_u \le \phi M_n \quad \phi = 0.9$ for flexure*
  - $\phi M_n = \phi\ T(d\text{-}a/2) = \phi\ A_s f_y\,(d\text{-}a/2)$



Over and Under-reinforcement

- over-reinforced
  - steel won't yield
- under-reinforced
  - steel will yield
- reinforcement ratio
  - $\rho = \dfrac{A_s}{bd}$
  - use as a design estimate to find A_s,b,d
  - max ρ is found with $\varepsilon_{steel} \ge 0.004$ (not ρ_{bal})
  - *with $\varepsilon_{steel} \ge 0.005$, $\phi = 0.9$





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

A_s for a Given Section

- several methods
  - guess a and iterate
    1. guess a (less than n.a.)
    2. $A_s = \dfrac{0.85 f'_c ba}{f_y}$
    3. solve for a from $M_u = \phi\ A_s f_y\,(d\text{-}a/2)$

       $a = 2\left(d - \dfrac{M_u}{\phi A_s f_y} \right)$
    4. repeat from 2. until a from 3. matches a in 2.

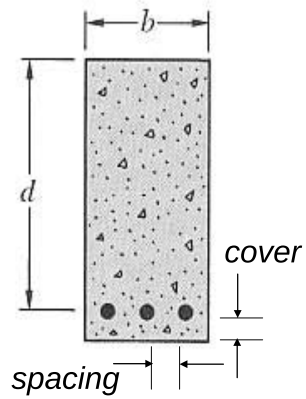
A_s for a Given Section (cont)

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

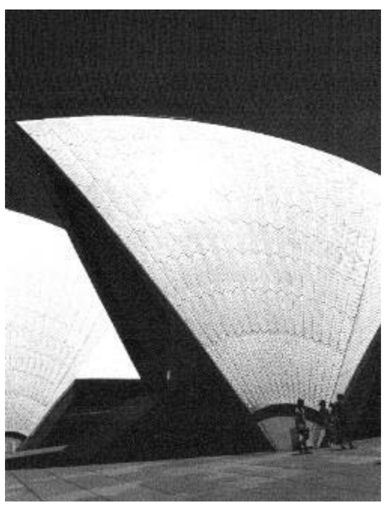
    1. calculate $R_n = \dfrac{M_n}{bd^2}$
    2. find curve for f'_c and f_y to get ρ
    3. calculate A_s and a
- simplify by setting h = 1.1d

Reinforcement

- min for crack control
- required $A_s = \dfrac{3\sqrt{f'_c}}{f_y}(bd)$
- not less than $A_s = \dfrac{200}{f_y}(bd)$
- $A_{s\text{-}max}$: $a = \beta_1(0.375d)$
- typical cover
  - 1.5 in, 3 in with soil
- bar spacing



Shells



http:// nisee.berkeley.edu/godden

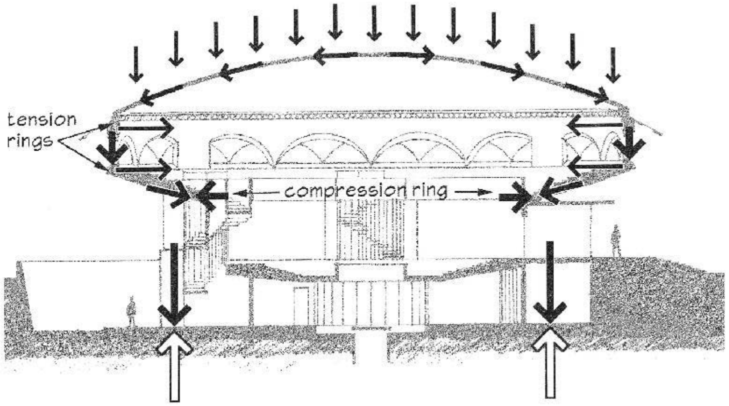
Annunciation Greek Orthodox Church

- Wright, 1956

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

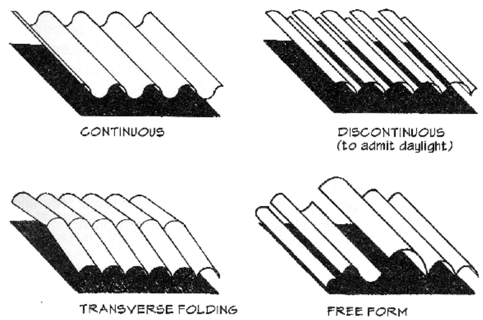
Annunciation Greek Orthodox Church

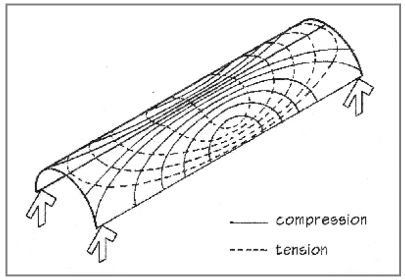
- Wright, 1956



Cylindrical Shells

- can resist tension
- shape adds "depth"



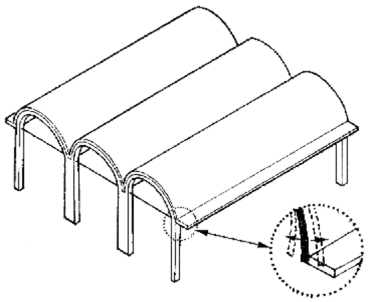


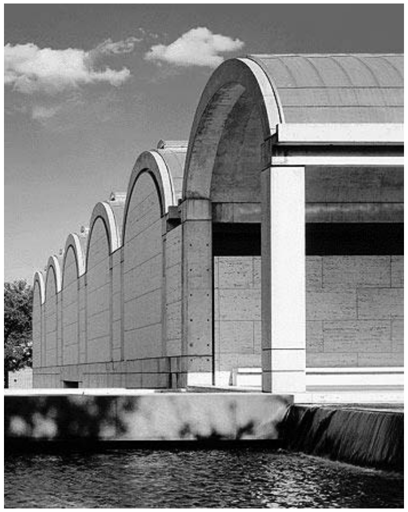
- not vaults
- barrel shells

Kimball Museum, Kahn 1972

Kimball Museum, Kahn 1972

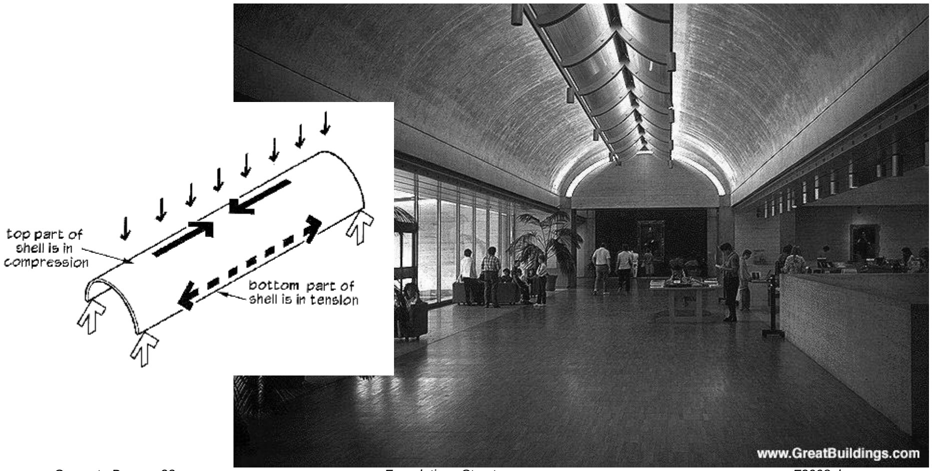
- outer shell edges





Kimball Museum, Kahn 1972

- *skylights at peak*



Approximate Depths