Architectural Structures: Form, Behavior, and Design

Arch 331 Dr. Anne Nichols Summer 2013

lecture NINEteen



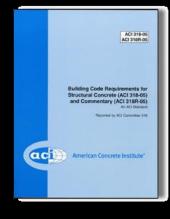
# **concrete construction**<sup>http://nisee.berkeley.edu/godden</sup> **materials & beams**

Concrete Beams 1 Lecture 19 Architectural Structures ARCH 331

# 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</li>

- concrete strength =  $f'_c$ 



# **Concrete Construction**

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

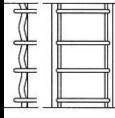


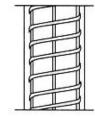
arch.mcgill.ca











Spirally reinforced column

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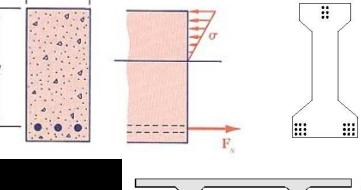
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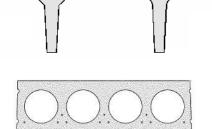
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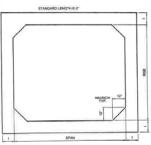
# Concrete Beams

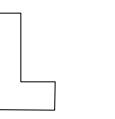
- types
  reinforced

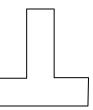
  - precast
  - prestressed
- shapes
  - rectangular, l
  - T, double T's, bulb T's
  - box
  - spandrel







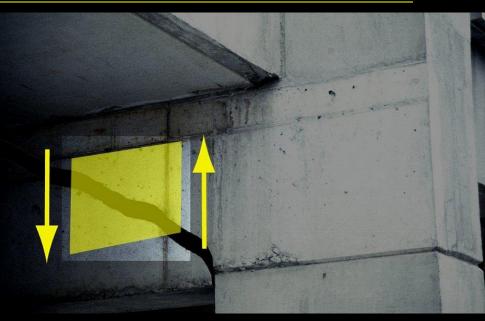




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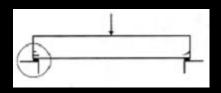
#### **Concrete Beams**

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



http://urban.arch.virginia.edu

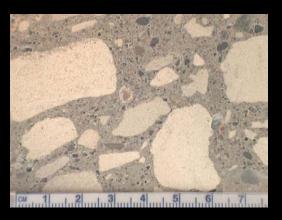
• bearing - crushing



# Concrete

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

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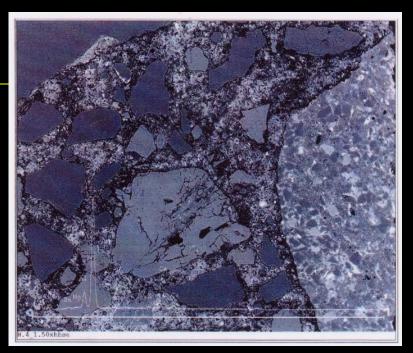
# Concrete

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



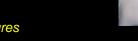


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# Concrete

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









#### Concrete Beams 8 Lecture 19

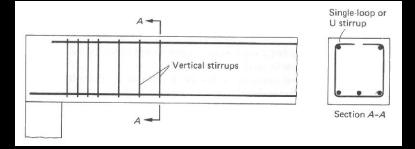
#### Reinforcement

- deformed steel bars (rebar)
  - Grade 40,  $F_{y} = 40$  ksi
  - Grade 60,  $F_v = 60$  ksi most common

(nominal)

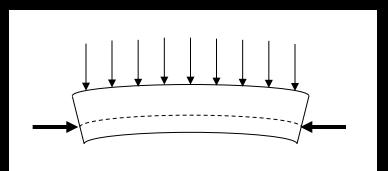
- Grade 75,  $F_{v} = 75$  ksi
- US customary in # of 1/8"  $\phi$
- Iongitudinally placed
  - bottom
  - top for compression reinforcement





# Reinforcement

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

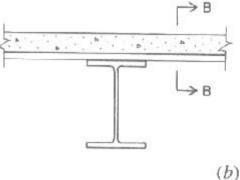


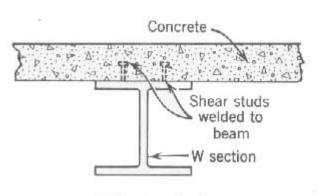


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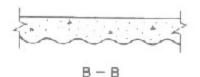
# **Composite Beams**

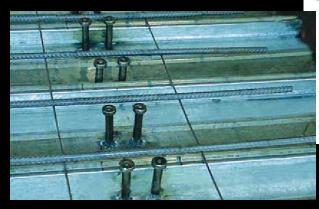
- concrete
  - in compression
- steel
  - in tension
- shear studs

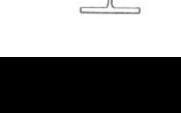




(c) Composite beam.



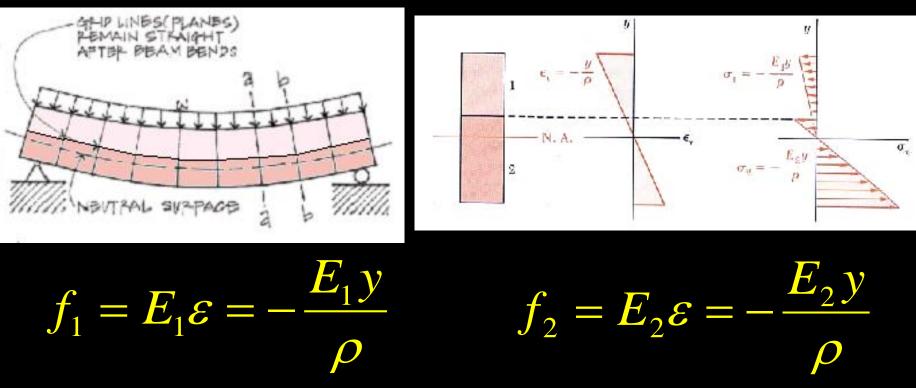






#### **Behavior of Composite Members**

- plane sections remain plane
- stress distribution changes

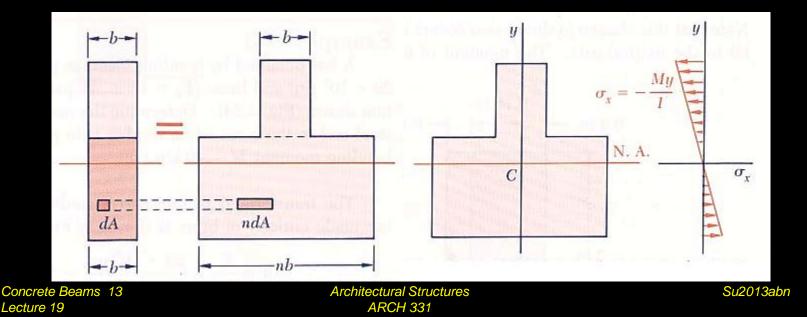


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#### **Transformation of Material**

n is the ratio of E's

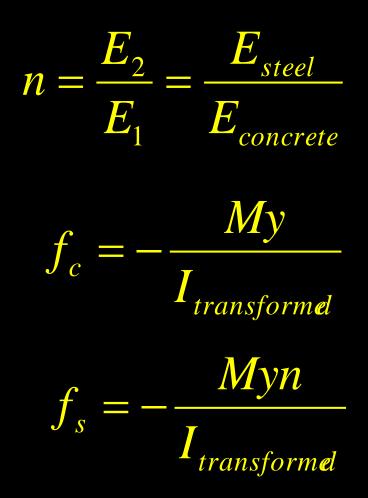
 effectively widens a material to get same stress distribution



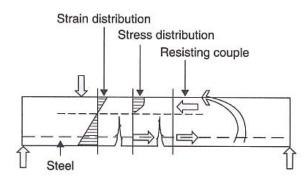
 $=\frac{E_2}{E_1}$ 

#### Stresses in Composite Section

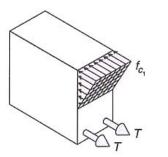
with a section  $\bigcirc$ transformed to one material, new l - stresses in that material are determined as usual - stresses in the other material need to be adjusted by n



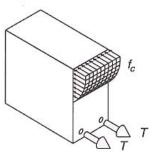
#### Reinforced Concrete - stress/strain



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.

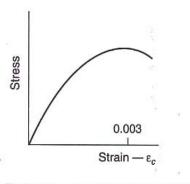


Working stress analysis. (Concrete stress distribution is assumed to be linear. Service loads are used in calculations.)

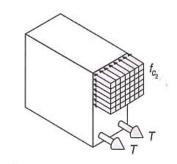


Actual stress distribution near ultimate strength (nonlinear).

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Typical stress-strain curve for concrete,



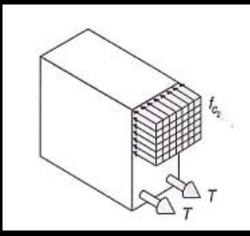
Ultimate strength analysis. (A rectangular stress block is used to idealize the actual stress distribution. Calculations are based on ultimate loads and failure stresses.)

FIGURE 6-37 Reinforced concrete beams.



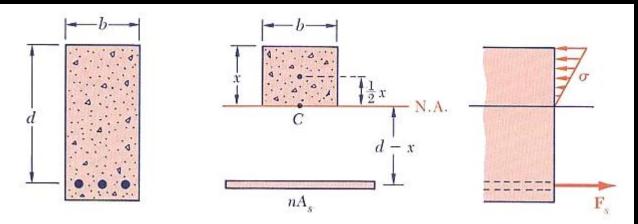
#### **Reinforced Concrete Analysis**

- 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 no tension
  - 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

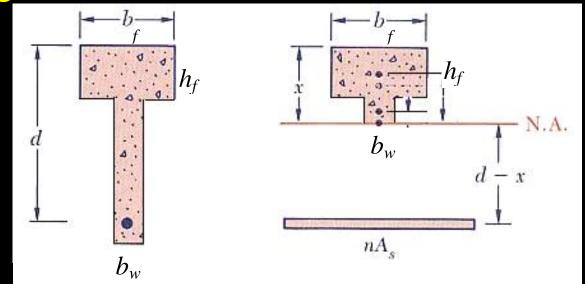


 $-nA_{c}(d-x)=0$ bx

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#### T sections

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



$$b_{f}h_{f}(x-\frac{h_{f}}{2})+(x-h_{f})b_{w}\frac{(x-h_{f})}{2}-nA_{s}(d-x)=0$$

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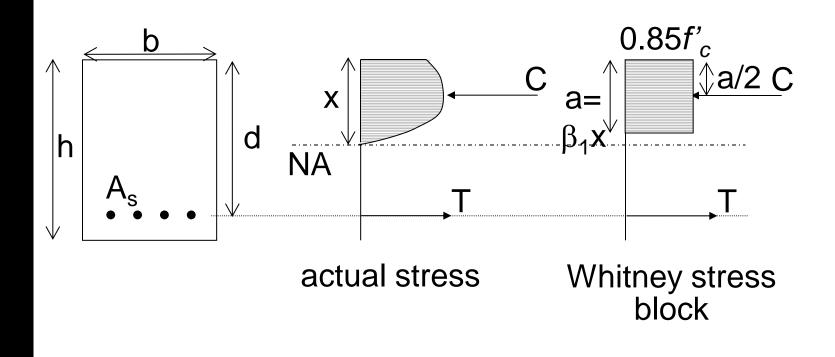
# **ACI Load Combinations\***

- 1.4D
- $1.2D + 1.6L + 0.5(L_r \text{ or } S \text{ or } R)$
- $1.2D + 1.6(L_r \text{ or } S \text{ or } R) + (1.0L \text{ or } 0.5W)$
- $1.2D + 1.0W + 1.0L + 0.5(L_r \text{ or } S \text{ or } R)$
- 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



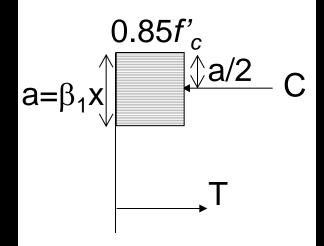
Wang & Salmon, Chapter 3

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# Force Equations

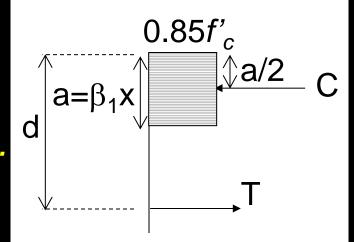
- $C = 0.85 f'_{c} ba$
- $T = A_s f_y$
- where
  - f'<sub>c</sub> = concrete compressive strength
  - a = height of stress block
  - $-\beta_1 =$  factor based on f'<sub>c</sub>
  - -x = location to the n.a.
  - b = width of stress block
  - $f_y = steel yield strength$
  - $-A_s = area of steel reinforcement$

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# Equilibrium

- T = C
- $M_n = T(d-a/2)$ - d = depth to the steel n.a.
- with  $A_s$  $-a = \frac{A_s f_y}{0.85 f'_c b}$



 $-M_{u} \leq \phi M_{n} \quad \phi = 0.9 \text{ for flexure}^{*}$  $-\phi M_{n} = \phi T(d-a/2) = \phi A_{s}f_{y}(d-a/2)$ 

#### **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

- use as a design estimate to find A<sub>s</sub>,b,d - max  $\rho$  is found with  $\varepsilon_{\text{steel}} \ge 0.004$  (not  $\rho_{\text{bal}}$ ) - \*with  $\varepsilon_{\text{steel}} \geq 0.005, \phi =$ 

Lecture 19

# A<sub>s</sub> for a Given Section

- several methods
  - guess a and iterate 1. guess a (less than n.a.) 2.  $A_{c} = \frac{0.85 f'_{c} ba}{1000}$ 3. solve for a from  $M_{\mu} = \phi A_s f_{\nu} (d-a/2)$ a = 2 d - $\phi A_s f_y$ 4. repeat from 2. until a from 3. matches a in 2.

# A<sub>s</sub> for a Given Section (cont)

- chart method
  - Wang & Salmon Fig. 3.8.1  $R_n$  vs.  $\rho$

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

2. find curve for  $f'_c$  and  $f_y$  to get  $\rho$ 3. calculate  $A_s$  and a

• simplify by setting h = 1.1d

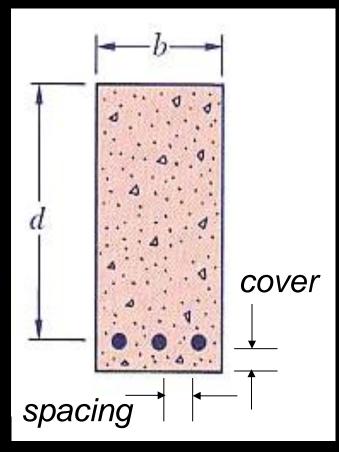
# Reinforcement

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

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(bd)

bd

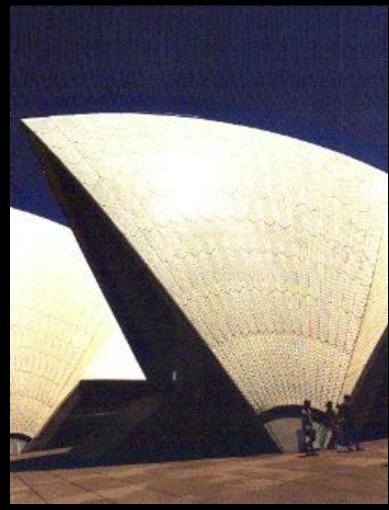




# Shells







http:// nisee.berkeley.edu/godden Architectural Structures Concrete Beams 27 ARCH 331 Lecture 19

# Annunciation Greek Orthodox Church

#### • Wright, 1956

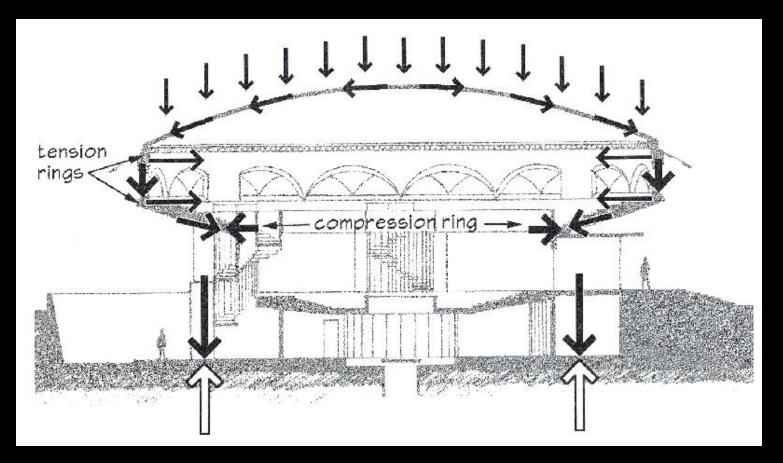


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res http://www.bluffton.edu/~sullivanm/

# Annunciation Greek Orthodox Church

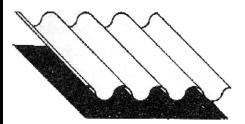
• Wright, 1956



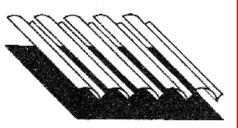
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# **Cylindrical Shells**

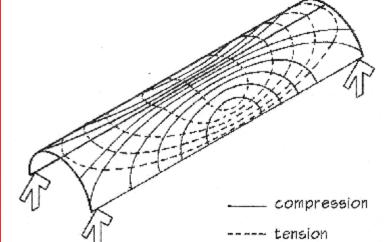
- can resist tension
- shape adds "depth"



CONTINUOUS



DISCONTINUOUS (to admit daylight)



not vaults  $\bigcirc$ 



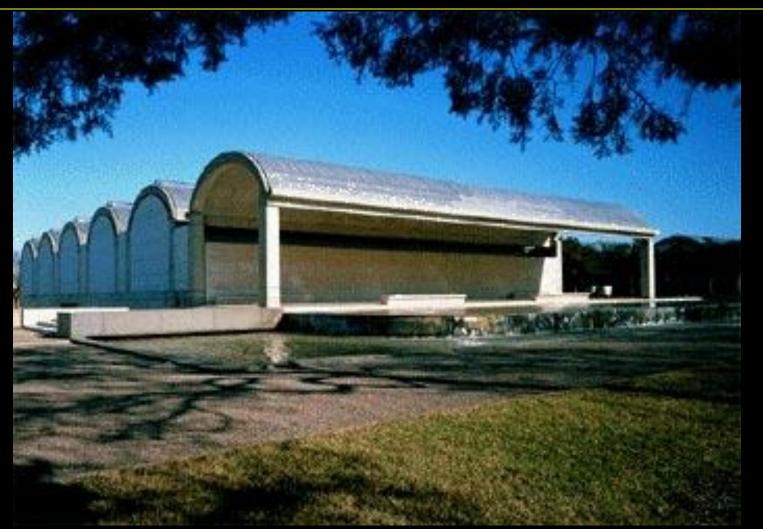
barrel shells

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TRANSVERSE FOLDING

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#### Kimball Museum, Kahn 1972

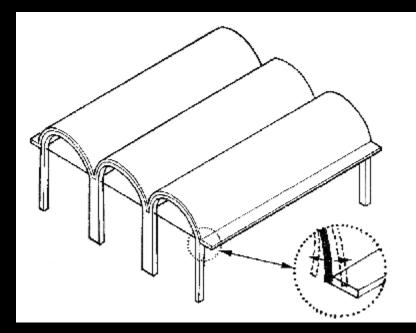


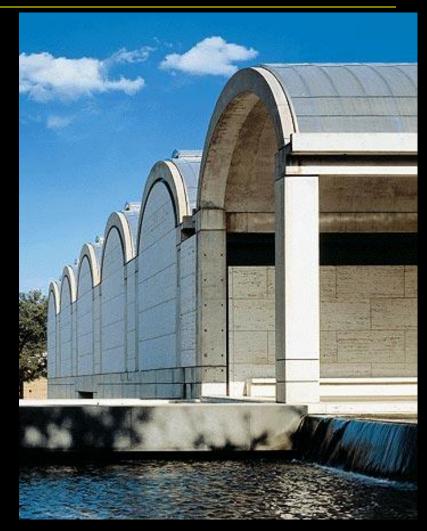
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# Kimball Museum, Kahn 1972

• outer shell edges

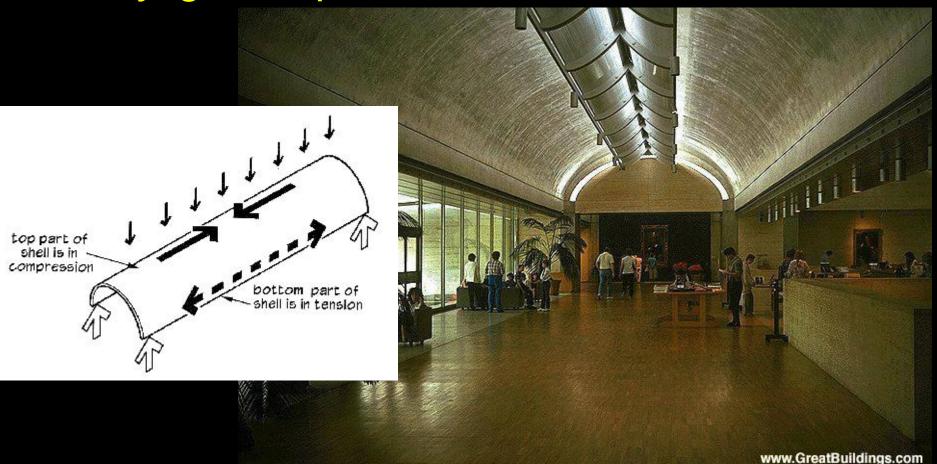




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# Kimball Museum, Kahn 1972

skylights at peak



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# Approximate Depths

Concre Lectur

|  |            |  | Span           |          |         |          |           |           |         |        |                      |   |                 |         |
|--|------------|--|----------------|----------|---------|----------|-----------|-----------|---------|--------|----------------------|---|-----------------|---------|
|  |            |  | 0 10 20 30     | 40 50 60 | 0 70 80 | 90 100 1 | 10 120 13 | 0 140 150 | 160 170 | 180    |                      |   |                 |         |
| Slabs<br>(poured in place)                   |            | Simply<br>supported L/25<br>One end L/30<br>Both ends L/35<br>continuous |                |          |         |          |           |           | ŀ       | Key: M | Minimum              | * | Possible span   | Maximum |
|  |            | Cantilever L/12  |                |          |         |          |           |           |         |        | span -               |   | lange           | span    |
| Beams<br>(poured in place)                   | • • •      | Simply<br>supported<br>One end<br>continuous<br>Both ends<br>continuous  |                |          |         |          |           |           |         |        | cal span<br>nember — |   |                 |         |
|  |            | Cantilever L/10  | ξ <del>μ</del> |          |         |          |           |           |         |        |                      |   | Typical Typical |         |
| Pan joist system (poured in place)           |            | L/20-L/25  |                | +        |         |          |           |           |         |        |                      |   | memberlengur    |         |
| Folded plate<br>(poured in place)            |            | <i>L</i> /8– <i>L</i> /15  |                |          |         |          |           |           |         |        |                      |   |                 |         |
| Barrel shell<br>(poured in place)            |            | <i>L</i> /8– <i>L</i> /15  |                |          |         |          |           |           |         |        |                      |   |                 |         |
| Planks<br>(precast)                          | 200003     | L/25-L/40  |                |          |         |          |           |           |         |        |                      |   |                 |         |
| Channels<br>(precast)                        | $\sqrt{-}$ | L/20–L/28  |                |          |         |          |           |           |         |        |                      |   |                 |         |
| Tees<br>(precast)                            |            | L/20-L/28  |                |          |         |          |           |           |         |        |                      |   |                 |         |
| Flat plate<br>(poured in place)              |            | L/30–L/40  | U I I          |          |         |          |           |           |         |        |                      |   |                 |         |
| Flat slab<br>(poured in place)               |            | L/30–L/40  |                | A<br>I   |         |          |           |           |         |        |                      |   |                 |         |
| Two-way beam<br>and slab<br>(poured in place |            | <i>L</i> /30– <i>L</i> /40   |                |          |         |          |           |           |         |        |                      |   |                 |         |
| Waffle slab<br>(poured in place)             |            | L/23–L/35  |                | hand C   |         |          |           |           |         |        |                      |   |                 |         |
| Dome<br>(poured in place)                    |            | L/4-L/8  |                |          |         |          |           |           |         |        |                      |   | Su2013abn       |         |
|  |            | (Meters)   |                |          | 1       |          | 1         |           |         |        |                      |   |                 |         |