ARCHITECTURAL STRUCTURES: FORM, BEHAVIOR, AND DESIGN
ARCH 331
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FALL 2015

lecture thirteen

design loads & methods, structural codes
Design

• factors out of the designer’s control
  – loads
  – occurrence

• factors within the designer’s control
  – choice of material
  – “cost” of failure (F.S., probability, location)
  – economic design method
  – analysis method
Design Methods

• different approaches to meeting strength/safety requirements
  – allowable stress design (elastic)
  – ultimate strength design
  – limit state design
  – plastic design
  – load and resistance factor design

• assume a behavior at failure or other threshold and include a margin of safety
Load Types

- $D = \text{dead load}$
- $L = \text{live load}$
- $L_r = \text{live roof load}$
- $W = \text{wind load}$
- $S = \text{snow load}$
- $E = \text{earthquake load}$
- $R = \text{rainwater load or ice water load}$
- $T = \text{effect of material & temperature}$
- $H = \text{hydraulic loads from soil (F from fluids)}$
Dead Loads

- fixed elements
  - structure itself
  - internal partitions
  - hung ceilings
  - all internal and external finishes
  - HVAC ductwork and equipment
  - permanently mounted equipment

- $F = mg$ (GRAVITY)
Weight of Materials

• for a volume
  - \( W = \gamma V \) where \( \gamma \) is weight/volume
  - \( W = \gamma tA \) for an extruded area with height of \( t \)

Table 5.1 Selected building material weights.

<table>
<thead>
<tr>
<th>Assembly</th>
<th>lb./ft.²</th>
<th>kN/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roofs:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-ply and gravel</td>
<td>5.5</td>
<td>0.26</td>
</tr>
<tr>
<td>5-ply and gravel</td>
<td>6.5</td>
<td>0.31</td>
</tr>
<tr>
<td>Wood shingles</td>
<td>2</td>
<td>0.10</td>
</tr>
<tr>
<td>Asphalt shingles</td>
<td>2</td>
<td>0.10</td>
</tr>
<tr>
<td>Corrugated metal</td>
<td>1–2.5</td>
<td>0.05–0.12</td>
</tr>
<tr>
<td>Plywood</td>
<td>3/inch</td>
<td>0.0057/mm</td>
</tr>
<tr>
<td>Insulation —fiberglass batt</td>
<td>0.5</td>
<td>0.0025</td>
</tr>
<tr>
<td>Insulation —rigid</td>
<td>1.5</td>
<td>0.075</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Assembly</th>
<th>lb./ft.²</th>
<th>kN/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floors:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete plank</td>
<td>6.5</td>
<td>0.31</td>
</tr>
<tr>
<td>Concrete slab</td>
<td>12.5/in.</td>
<td>0.59/mm</td>
</tr>
<tr>
<td>Steel decking</td>
<td></td>
<td></td>
</tr>
<tr>
<td>w/concrete</td>
<td>35–45</td>
<td>1.68–2.16</td>
</tr>
<tr>
<td>Wood joists</td>
<td>2–3.5</td>
<td>0.10–0.17</td>
</tr>
<tr>
<td>Hardwood floors</td>
<td>4/in.</td>
<td>0.19/mm</td>
</tr>
<tr>
<td>Ceramic tile</td>
<td></td>
<td></td>
</tr>
<tr>
<td>w/thin set</td>
<td>15</td>
<td>0.71</td>
</tr>
<tr>
<td>Lightweight concrete</td>
<td>8/in.</td>
<td>0.38/mm</td>
</tr>
<tr>
<td>Timber decking</td>
<td>2.5/in.</td>
<td>0.08/mm</td>
</tr>
</tbody>
</table>
Concentrated Loads
Distributed Loads

- for an area:
  \[ w = \gamma A \]
Dynamic Loads

- time, velocity, acceleration
- kinetics
  - forces causing motion
    \[ W = m \cdot g \]
  - work
  - conservation of energy
Load Locations

- centric
- eccentric
- bending or flexural load
- torsional load
- combined loading
Load Paths

- tributary areas
- transfer
Live Loads

- occupancy
- movable furniture and equipment
- construction / roof traffic – $L_r$
- minimum values
- reduction allowed as area increases
Wind Load

- wind speed
- gusting
- terrain
- windward, leeward, up and down!
- drag
- rocking
- harmonic
- torsion
Snow Load

- latitude
- solar exposure
- wind speed
- roof slope

Moscow 2006 (BBC News)
Seismic Load

- earthquake acceleration
  - \( F = ma \)
  - movement of ground (3D)
  - building mass responds
  - static models often used, \( V \) is static shear
  - building period, \( T \approx 0.1N \), determines \( C \)
  - building resistance – \( R_W \)
  - \( Z \) (zone), \( I \) (importance factor)

\[
V = \frac{ZICW}{R_W}
\]
Dynamic Response

Lateral ground motions associated with earthquakes cause inertial forces to develop that are dependent on the weight of the structure. Sliding failures can occur.

The lateral ground motions can also cause a sculpture to overturn. The magnitude of the overturning effect depends on the weight of the sculpture and its height above the ground.

Back and forth ground motions can cause different parts of the sculpture to move in different directions. Overturning or cracking of elements can consequently occur.
Dynamic Response

- period of vibration or frequency
  - wave
  - sway/time period
- damping
  - reduction in sway
- resonance
  - amplification of sway
Frequency and Period

• natural period of vibration
  – avoid resonance
  – hard to predict seismic period
  – affected by soil
  – short period
    • high stiffness
  – long period
    • low stiffness

“To ring the bell, the sexton must pull on the downswing of the bell in time with the natural frequency of the bell.”
Water Load

- rainwater – clogged drains
- ponding
- ice formation
Thermal Load

- stress due to strain
- restrained expansion or contraction
- temperature gradients
- composite construction
Hydraulic Loads

- **pressure by water in soil, \( H \)**
- **fluid pressure, \( F \)**
  - normal to surface
- **flood**
Building Codes

• documentation
  – laws that deal with planning, design, construction, and use of buildings
  – regulate building construction for
    • fire, structural and health safety
  – cover all aspect of building design
  – references standards
    • acceptable minimum criteria
    • material & structural codes
Building Codes

- **occupancy**
- **construction types**
- **structural chapters**
  - loads, tests, foundations
- **structural materials, assemblies**
  - roofs
  - concrete
  - masonry
  - steel

<table>
<thead>
<tr>
<th>OCCUPANCY OR USE</th>
<th>UNIFORM (psf)</th>
<th>CONCENTRATED (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Apartments (see residential)</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>2. Access floor systems</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Office use</td>
<td>50</td>
<td>2,000</td>
</tr>
<tr>
<td>Computer use</td>
<td>100</td>
<td>2,000</td>
</tr>
<tr>
<td>3. Armories and drill rooms</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>—</td>
</tr>
<tr>
<td>4. Assembly areas and theaters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fixed seats (fastened to floor)</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Lobbies</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Movable seats</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Stages and platforms</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>Follow spot, projections and control rooms</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Cawalks</td>
<td>40</td>
<td></td>
</tr>
</tbody>
</table>
Prescribed Loads

• **ASCE-7**
  – *live load reductions allowed*

• **International Building Code**
  – *occupancy*
  – *wind: pressure to static load*
  – *seismic: shear load function of mass and response to acceleration*
  – *fire resistance*
Structural Codes

• prescribe loads and combinations
• prescribe design method
• prescribe stress and deflection limits
• backed by the profession
• may require design to meet performance standards
• related to material or function
Structural Codes

• **Design Codes**
  – **Wood**
    - NDS
  – **Steel**
    - AISC
  – **Concrete**
    - ACI
    - AASHTO
  – **Masonry**
    - MSJC
Design Methods

- probability of loads and resistance
- material variability
- overload, fracture, fatigue, failure
- allowable stress design

\[ f_{\text{actual}} = \frac{P}{A} \leq f_{\text{allowed}} = \frac{f_{\text{capacity}}}{F.S.} \]

- limit state design
  - design loads & capacities
Allowable Stress Design

- historical method
- a.k.a. working stress, strength design
- stresses stay in ELASTIC range
ASD Load Combinations

- $D$
- $D + L$
- $D + 0.75(L_r \text{ or } S \text{ or } R)$
- $D + 0.75L + 0.75(L_r \text{ or } S \text{ or } R)$
- $D + (0.6W \text{ or } 0.7E)$
  - $D + 0.75L + 0.75(0.6W) + 0.75(L_r \text{ or } S \text{ or } R)$
  - $D + 0.75L + 0.75(0.7E) + 0.75S$
- $0.6D + 0.6W$
- $0.6D + 0.7E$

ASCE-7 (2010)
Limit State Design

• a.k.a. strength design
• stresses go to limit (strain outside elastic range)
• loads may be factored
• resistance or capacity reduced by a factor
• based on material behavior
• “state of the art”
Limit State Design

- **load and resistance factor design (LRFD)**
  - **loads:**
    - not constant,
    - possibly more influential on failure
    - happen more or less often
  - **UNCERTAINTY**
    \[
    \gamma_D R_D + \gamma_L R_L \leq \phi R_n
    \]
    - \(\phi\) - Resistance factor
    - \(\gamma\) - Load factor for (D)ead & (L)ive load
LRFD 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) + (L or 0.5W)**
- **1.2D + 1.0W + L + 0.5(L_r or S or R)**
- **1.2D + 1.0E + L + 0.2S**
- **0.9D + 1.0W**
- **0.9D + 1.0E**
  - F has same factor as D in 1-5 and 7
  - H adds with 1.6 and resists with 0.9 (permanent)

ASCE-7 (2010)
Deflection Limits

- based on service condition, severity

<table>
<thead>
<tr>
<th>Use</th>
<th>LL only</th>
<th>DL+LL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof beams:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industrial</td>
<td>L/180</td>
<td>L/120</td>
</tr>
<tr>
<td>Commercial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>plaster ceiling</td>
<td>L/240</td>
<td>L/180</td>
</tr>
<tr>
<td>no plaster</td>
<td>L/360</td>
<td>L/240</td>
</tr>
<tr>
<td>Floor beams:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ordinary Usage</td>
<td>L/360</td>
<td>L/240</td>
</tr>
<tr>
<td>Roof or floor (damageable elements)</td>
<td>L/480</td>
<td></td>
</tr>
</tbody>
</table>
Load Conditions

- loads, patterns & combinations
  - usually uniformly distributed gravity loads
  - worst case for largest moments...
  - wind direction can increase moments