Design loads, methods, structural codes & tracing
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

- $D =$ dead load
- $L =$ live load
- $L_r =$ live roof load
- $W =$ wind load
- $S =$ snow load
- $E =$ earthquake load
- $R =$ rainwater load or ice water load
- $T =$ effect of material & temperature
- $H =$ 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/in.</td>
<td>0.0057/mm</td>
</tr>
<tr>
<td>Insulation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>—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>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<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

![Properties of a sine wave:](image)

\[ y = A \sin 2\pi ft \]

- Frequency, \( f = \frac{1}{T} \)
- Wavelength, \( \lambda \) (or Period, \( T \))
- Amplitude, \( A \)
- Distance, \( x \) (or Time, \( t \))
- Peak
- Trough
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>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>Offices, projections and control rooms</td>
<td>50</td>
<td>—</td>
</tr>
<tr>
<td>Carts</td>
<td>40</td>
<td>—</td>
</tr>
</tbody>
</table>
Prescribed Loads

- **ASCE-7**
  - *live load (not roof) 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

Figure 5.20  Stress-strain diagram for various materials.
ASD Load Combinations

- $D$
- $D + L$
- $D + 0.75(L_r \text{ or } S \text{ or } R)$
- $D + 0.75L + 0.75(L_r \text{ or } S \text{ or } R)$
- $D + (0.6W \text{ or } 0.7E)$
  - $D + 0.75L + 0.75(0.6W) + 0.75(L_r \text{ or } S \text{ or } R)$
  - $D + 0.75L + 0.75(0.7E) + 0.75S$
- $0.6D + 0.6W$
- $0.6D + 0.7E$
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)
### 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><strong>Roof beams:</strong></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><strong>Floor beams:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ordinary Usage</td>
<td>L/360</td>
<td>L/240</td>
</tr>
<tr>
<td><strong>Roof or floor (damageable elements)</strong></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
**Structural Loads**

- gravity acts on mass \((F=m\times g)\)
- force of mass
  - acts at a point
    - ie. joist on beam
  - acts along a “line”
    - ie. floor on a beam
  - acts over an area
    - ie. people, books, snow on roof or floor
Equivalent Force Systems

- replace forces by resultant
- place resultant where $M = 0$
- using calculus and area centroids

\[ W = \int_0^L w \, dx = \int dA \quad = A_{\text{loading}} \]
### Area Centroids

- **Table 6.1 – pg. 304**

<table>
<thead>
<tr>
<th>Shape</th>
<th>( \bar{x} )</th>
<th>( \bar{y} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triangular area</td>
<td>( \frac{b}{3} )</td>
<td>( \frac{h}{3} ) right triangle only</td>
</tr>
<tr>
<td>Quarter-circular area</td>
<td>( \frac{4r}{3\pi} )</td>
<td>( \frac{4r}{3\pi} )</td>
</tr>
<tr>
<td>Semicircular area</td>
<td>0</td>
<td>( \frac{4r}{3\pi} )</td>
</tr>
<tr>
<td>Semiparabolic area</td>
<td>( \frac{3a}{8} )</td>
<td>( \frac{3h}{5} )</td>
</tr>
<tr>
<td>Parabolic area</td>
<td>0</td>
<td>( \frac{3h}{5} )</td>
</tr>
</tbody>
</table>
Equivalent Load Areas

- area is width x “height” of load
- \( w \) is load per unit length
- \( W \) is total load

\[
w \cdot x = W
\]

\[
\frac{w \cdot x}{2} = \frac{W}{2}
\]

\[
w \cdot \frac{x}{2} = \frac{W}{2}
\]

\[
w \cdot \frac{2x}{3} = \frac{W}{2}
\]

\[
w \cdot \frac{x}{6} = \frac{W}{2}
\]
Distributed Area Loads

- $w$ is also load per unit area

Figure 2.7 Area-distributed load (pressure) on floor decking.
Load Tracing

• how loads are transferred
  – usually starts at top
  – distributed by supports as actions
  – distributed by tributary areas
Load Tracing

• areas see distributed area load
• beams or trusses see distributed line loads
• “collectors” see forces
  – columns
  – supports

Figs. 1.1a, 1.1b  Structural loading diagram of an architectural condition
Load Tracing

Horizontal spanning system

Decking carries roof loads by bending.

Decking reactions become forces on beams (which carry loads by bending).

Beam reactions become forces on trusses.

Truss reactions cause compressive forces to develop in columns.

Columns are in compression.

Column reactions become forces on foundations (which distribute the forces into the earth).

tributary area
Load Tracing

- tributary load
  - think of water flow
  - “concentrates” load of area into center

\[
w = \left( \frac{\text{load}}{\text{area}} \right) \times \text{(tributary width)}
\]
Load Tracing

Patcenter
Rogers 1986

Figure 3.5: Patcenter, load path diagram.
Load Tracing

Alamillo Bridge
Calatrava 1992

Figure 3.12: Alamillo bridge, load path diagram.

http://en.structurae.de
Load Paths

- floors and framing

(a) FBD—decking.

(b) FBD—joists.

(c) FBD—beams.

(d) FBD—girder.
Load Paths

• wall systems
Load Paths

• openings & pilasters

Figure 4.15  Arching over wall openings.
Figure 4.16  Stud wall with a window opening.
Figure 4.17  Pilasters supporting concentrated beam loads.
Load Paths

- foundations

Figure 4.24 Spread footing.
Figure 4.25 Wall footing.
Figure 4.26 Mat or raft foundation.
Load Paths

- deep foundations
Spans

- **direction**
- **depth**

(a) Long, lightly loaded joists bearing on shorter beams create a more uniform structural depth. Space can be conserved if the joists and beams are flush framed.

(b) Short joists loading relatively long beams yield shallow joists and deep beams. The individual structural bays are more clearly expressed.

(c) Loads can be reduced on selected beams by introducing intermediate beams.

(d) The span capability of the decking material controls the spacing of the joists, while beam spacing is controlled by the allowable joist span.
Levels

- determine span at top level
- find half way to next element
- *include self weight
- look for “collectors”
- repeat

one:
Levels

- **two:**

- **three:**

Framing plan.
Irregular Configurations

- tracing still $\frac{1}{2}$ each side
Slabs

- edge support

Figure 2-16: Supporting beams' contributing areas for reinforced concrete floor system.

- linear and uniform distribution

Figure 2-17: Trapezoidal distributed load for Beam AB of Fig. 2-16.
Girders and Transfer

- openings
  - no load & no **half way**

- girder actions at beam supports

---

![Diagram](image-url)  
*Figure 5.54 (a) Isometric view of partial steel framing arrangement. (b) Partial floor framing—office structure.*
Sloped Beams

- stairs & roofs
- projected live load
- dead load over length

- perpendicular load to beam:
  \[ w_{\perp} = w \cdot \cos \alpha \]

- equivalent distributed load:
  \[ W_{\text{adj.}} = \frac{w}{\cos \alpha} \]
Framing Diagrams

- beam lines and "dots"
- breaks & ends
Retaining Walls

- **purpose**
  - retain soil or other material

- **basic parts**
  - wall & base
  - additional parts
    - counterfort
    - buttress
    - key
Retaining Wall Types

• “gravity” wall
  – usually unreinforced
  – economical & simple

• cantilever retaining wall
  – common

(a) Gravity wall

(b) Cantilever retaining wall
Retaining Wall Loads

- **gravity**
  \[ W = \gamma \times V \]

- **fluid pressure**
  \[ p = \omega' \times h \]
  \[ P = \frac{1}{2} p \times h \text{ at } h/3 \]

- **friction**
  \[ F = \mu \times N \]

- **soil bearing pressure, } q \]}
Retaining Wall Equilibrium

- **sliding** - overcome friction?
- **overturning at toe (o)** - overcome mass?

\[
SF = \frac{M_{\text{resist}}}{M_{\text{overturning}}} \geq 1.5 - 2
\]

\[
SF = \frac{F_{\text{horizontal-resist}}}{F_{\text{sliding}}} \geq 1.25 - 2
\]
Pressure Distribution

- want resultant of load from pressure inside the middle third of base (kern)
- triangular stress block with \( p_{\text{max}} \)
- \( x = \frac{1}{3} \times \text{width of stress} \)
- equivalent force location:

\[
W \cdot x = \frac{p_{\text{max}} \cdot 3x}{2} \cdot \frac{x}{3}
\]

\[
p_{\text{max}} = \frac{2W}{3x} = \frac{2W}{a} \quad \text{when } a \text{ is fully stressed}
\]

Figure 3.88  Tension possible at the heel.
Wind Pressure

• distributed load
• “collected” into V
• lateral loads must be resisted

Figure 4.48 Exploded view of a light-framed wood building showing the various lateral resisting components.
Bracing Configurations

Figure 4.54 Various shearwall arrangements—some stable, others unstable.