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
• for an extruded area with height of $t$

<table>
<thead>
<tr>
<th>Assembly</th>
<th>$w_{vol}$</th>
<th>$w_{area}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>6.5</td>
<td>0.31</td>
</tr>
<tr>
<td>Steel</td>
<td>12.5</td>
<td>0.59</td>
</tr>
<tr>
<td>Wood</td>
<td>1.8</td>
<td>0.10</td>
</tr>
<tr>
<td>Lighweight concrete</td>
<td>1.36</td>
<td>0.08</td>
</tr>
<tr>
<td>Timber</td>
<td>0.13</td>
<td>0.06</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 of 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

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)

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.

Moscow 2006 (BBC News)
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

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

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

Design Codes

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

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”

**LRFD Load Combinations**

- $1.4D$
- $1.2D + 1.6L + 0.5(L_r \text{ or } S \text{ or } R)$
- $1.2D + 1.6(L_r \text{ or } S \text{ or } R) + (L \text{ or } 0.5W)$
- $1.2D + 1.0W + L + 0.5(L_r \text{ or } S \text{ or } R)$
- $1.2D + 1.0E + L + 0.2S$
- $0.9D + 1.0W$
- $0.9D + 1.0E$
  - $F$ 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>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></td>
<td>L/480</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 \( F = m \cdot g \)
- 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
  \[
  \text{W} = \int_{0}^{L} w(x) \, dx = \int dA_{\text{loading}} = A_{\text{loading}}
  \]
Area Centroids

- **Table 7.1 – pg. 242**

<table>
<thead>
<tr>
<th>Shape</th>
<th>( x )</th>
<th>( y )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triangular area</td>
<td>( \frac{b}{3} )</td>
<td>( \frac{h}{3} )</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>Semicircular area</td>
<td>( \frac{4r}{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

\[
\begin{align*}
\text{w} \times x &= W \\
\text{w} \times \frac{x}{2} &= \frac{W}{2} \\
\text{w} \times \frac{x}{3} &= \frac{W}{3}
\end{align*}
\]

Distributed Area Loads

- \( w \) is also load per unit area

\[
\begin{align*}
\text{W} \text{ on plywood} & \quad \text{0.75-in.-thick plywood sheet} \\
2 \times 10 joist (1.5” thick \times 9.25” deep) & \quad \text{3.5-in.-thick bearing wall} \\
24 \text{ in.} & \quad \text{Figure 2.7: Area-distributed load (pressure) on floor decking.}
\end{align*}
\]

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

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

Alamillo Bridge
Calatrava 1992

Figure 3.12: Alamillo bridge, load path diagram.

Load Paths

• floors and framing

(a) FBD—decking.
(b) FBD—joists.
(c) FBD—beams.
(d) FBD—girder.

Load Paths

• wall systems

Figure 4.12 Uniform wall load from a slab.
Figure 4.13 Uniform wall load from floor and joists.
Figure 4.14 Concentrated loads from gravity and beam.

Load Paths

• openings & pilasters

Figure 4.15 Arching over wall opening.
Figure 4.16 Slab wall with a window opening.
Figure 4.17 Pilasters supporting concentrated load.
Load Paths

- foundations

![Spread footing](image1)

![Wall footing](image2)

![Mat or off foundation](image3)

Load Paths

- deep foundations

![Pile foundations](image4)

![Pile cap on one pile group](image5)

![Grade beams supporting a bearing wall](image6)

Spans

- direction
- depth

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

2. Short joints loading relatively long beams yield shallower joints and deep beams. The individual structural bays are more clearly expressed.

3. Loads can be reduced on selected beams by introducing intermediate beams.

4. The span capability of the decking material controls the spacing of the joints, while beam spacing is controlled by the allowable joint spacing.

Levels

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

- one:

![Framing plans](image7)
**Levels**

- two:

- three:

**Irregular Configurations**

- tracing still ½ each side

**Slabs**

- edge support

- linear and uniform distribution

**Girders and Transfer**

- openings
  - no load & no half way
- girder actions at beam supports
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
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:
  \[ W \times x = \frac{p_{\text{max}}}{2} \times \frac{3x}{3} \times \frac{x}{3} \]
  \[ p_{\text{max}} = \frac{2W}{3x} = \frac{2W}{a} \text{ when } a \text{ is fully stressed} \]

---

Wind Pressure

• distributed load

• “collected” into \( V \)

• lateral loads must be resisted

---

Figure 3.80: FEQ of a gravity retaining wall.

Figure 3.81: Bearing pressure under the wall footing.

Figure 3.82: Tension possible at the heel.

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

Figure 4.54 Various brace wall arrangements—some stable, others unstable.