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
- \( W = \gamma A t \) for an extruded area with height of \( t \)

<table>
<thead>
<tr>
<th>Assembly</th>
<th>( \gamma_{\text{al}} )</th>
<th>( \gamma_{\text{w}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floors</td>
<td>6.5</td>
<td>0.31</td>
</tr>
<tr>
<td>Concrete block</td>
<td>20.0</td>
<td>0.30</td>
</tr>
<tr>
<td>Steel deck</td>
<td>45.0</td>
<td>0.30</td>
</tr>
<tr>
<td>Wood</td>
<td>15.0</td>
<td>0.30</td>
</tr>
<tr>
<td>Wood</td>
<td>15.0</td>
<td>0.30</td>
</tr>
<tr>
<td>Ceramic tile</td>
<td>4.0</td>
<td>0.30</td>
</tr>
<tr>
<td>Fireresistant</td>
<td>5.0</td>
<td>0.30</td>
</tr>
<tr>
<td>Timber decking</td>
<td>8.0</td>
<td>0.30</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)

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

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.
- Overturning failures
- 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

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

Figure 5.20 Stress-strain diagram for various materials.

Design Codes

- Wood
  - NDS
- Steel
  - AISC
- Concrete
  - ACI
  - AASHTO
- Masonry
  - MSJC
### 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
  \[
  W = \int_0^L w(x) \, dx = \int dA_{\text{loading}} = A_{\text{loading}}
  \]
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>Semi-parabolic area</td>
<td>$\frac{3a}{8}$</td>
<td>$\frac{3h}{8}$</td>
</tr>
<tr>
<td>Parabolic area</td>
<td>0</td>
<td>$\frac{3h}{8}$</td>
</tr>
</tbody>
</table>

Equivalent Load Areas

• area is width x “height” of load
• $w$ is load per unit length
• $W$ is total load

\[ w \cdot x = W \]

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

Distributed Area Loads

• $w$ is also load per unit area

Load Tracing

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

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

http://en.structurae.de

Load Path Diagram

Figure 3.12: Alamillo bridge, load path diagram.

Load Tracing 15
Lecture 14
Foundations Structures
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F2008abn

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 4.23 Uniform wall load from offsets and joists.

Figure 4.14 Concentrated loads from trusses spread beams.

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Foundations Structures
ARCH 331
F2008abn

Load Paths

• openings & pilasters

Figure 4.15 Arching over wall openings.

Figure 4.36 Stair wall with a window opening.

Figure 4.17 Pilasters supporting concentrated load.

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Load Paths

- foundations

Load Paths

- deep foundations

Spans

- direction
- depth

Levels

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

![Spread footing](image1)
![Wall footing](image2)
![Mat or raft foundation](image3)

![Pile foundations](image4)
![Pile cap on one pile group](image5)
![Grade beam supporting a bearing wall](image6)
**Levels**

- two:

- three:

---

**Irregular Configurations**

- tracing still \( \frac{1}{2} \) 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:
  \[ w_{adj} = \frac{w}{\cos \alpha} \]

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, }**

### 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 }max
- \[ x = 1/3 \times \text{width of stress} \]
- equivalent force location:

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

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

### Wind Pressure

- **distributed load**
- “collected” into }V
- **lateral loads must be resisted**
**Bracing Configurations**

![Bracing Configurations Diagram]

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