structural behavior, systems, and design
Course Description

• statics
  – physics of forces and reactions on bodies and systems
  – equilibrium (bodies at rest)

• structures
  – something made up of interdependent parts in a definite pattern of organization

• design
  – assessing and meeting structural requirements of parts and the whole
Course Description

• mechanics of materials
  – external loads and effect on deformable bodies
  – use it to answer question if structure meets requirements of
    • stability and equilibrium
    • strength and stiffness
  – other principle building requirements
    • economy, functionality and aesthetics
Structure Requirements

• stability & equilibrium – STATICS

Figure 1.16 Equilibrium and Stability?—sculpture by Richard Byer. Photo by author.
Structure Requirements (cont)

- strength & stiffness
  - concerned with stability of components

Figure 1.15 Stability and the strength of a structure—the collapse of a portion of the UW Husky stadium during construction (1987) due to a lack of adequate bracing to ensure stability. Photo by author.
Structural System Selection

- kind & size of loads
- building function
- soil & topology of site
- systems integration
- fire rating
- construction ($$, schedule)
- architectural form
Knowledge Required

- external forces
- internal forces
- material properties
- member cross sections
- ability of a material to resist breaking
- structural elements that resist excessive
  - deflection
  - deformation

Figure 2.34 An example of torsion on a cantilever beam.
Problem Solving

1. STATICS:
   - equilibrium of external forces, internal forces, stresses

2. GEOMETRY:
   - cross section properties, deformations and conditions of geometric fit, strains

3. MATERIAL PROPERTIES:
   - stress-strain relationship for each material obtained from testing
Relation to Architecture

“The geometry and arrangement of the load-bearing members, the use of materials, and the crafting of joints all represent opportunities for buildings to express themselves. The best buildings are not designed by architects who after resolving the formal and spatial issues, simply ask the structural engineer to make sure it doesn’t fall down.” - Onouye & Kane

Statics and Strength of Materials for Architecture and Building Construction
Architectural Space and Form

- evolution traced to developments in structural engineering and material technology
  - stone & masonry
  - timber
  - concrete
  - cast iron, steel
  - tensile fabrics, pneumatic structures......
Architectural Space and Form

- structure is a device for channeling loads that result from the use and/or presence of the building to the ground
  - span a roof
  - hold up a floor
  - cross a river
  - suspend a canopy

www.pbs.org/wgbh/buildingbig/
Structural Action

- axial tension
- axial compression
- bending

Figure 1.2 (a) Axial tension, (b) axial compression, and (c) bending.
Structural Action

• member breadth & depth

Figure 1.4 (a) A very shallow beam and (b) a deep beam.

Figure 1.5 A sheet of material (a) set on edge and (b) configured as an I-beam.
Structural Action

- stabilization

**Figure 1.8** (a) A thin wall (b) subjected to lateral force.

**Figure 1.9** (a, b) Walls stabilizing each other at the ends.
**Structural Action**

- *shear & bracing*

*Figure 1.29* (a, b) Structural frame stabilized by adding shear panels.

*Figure 1.30* Bracing with (a) triangulation and (b) a rigid frame.
Structural Action

- lateral resistance

Figure 1.32 (a) A thin-shelled barrel vault and (b) a thin-shelled cross vault.

Figure 1.33 (a, b) A dome subjected to lateral load.
Structural Action

- twisting
Structural Design

- planning
- preliminary structural configuration
- determination of loads
- preliminary member selection
- analysis
- evaluation
- design revision
- final design
Structural Loads

- STATIC and DYNAMIC
- dead load
  - static, fixed, includes building weight, fixed equipment
- live load
  - transient and moving loads (including occupants), snowfall
Structural Loads

- wind loads
  - dynamic, wind pressures treated as lateral static loads on walls, up or down loads on roofs
**Structural Loads**

- **earthquake loads**
  - **seismic, movement of ground**

*Figure 1.14  Earthquake loads on a structure.*
Structural Loads

- **impact loads**
  - rapid, energy loads
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
Structural Math

- quantify environmental loads
  - how big is it?
- evaluate geometry and angles
  - where is it?
  - what is the scale?
  - what is the size in a particular direction?
- quantify what happens in the structure
  - how big are the internal forces?
  - how big should the beam be?
Structural Math

• physics takes observable phenomena and relates the measurement with rules: mathematical relationships

• need

  – reference frame
  – measure of length, mass, time, direction, velocity, acceleration, work, heat, electricity, light
  – calculations & geometry
Structural Organization

- classifications
  - geometry
    - line-forming
    - surface-forming
  - stiffness
    - rigid
    - flexible
  - one-way or two-way
    - spatial organization and load transfer
- materials
Structural Components

- bearing walls
- columns
- beams
- flat plates
- trusses
- arches
- shells
- cables
Bearing Walls

(a)

(b)
Bearing Walls

• behavior as “deep beams”
Columns & Walls

Introduction 31
Lecture 1

Architectural Structures
ARCH 331

Su2013abn
Beams & Plates

(a) shorter longer

(b) shorter longer
Beams & Plates
Trusses and Shells

(c) Pitched Pratt truss  (d) Pitched Howe truss

(a) Column (Point) Support
(b) Inverted Pyramid
(c) Crosshead Beams

SYNCLASTIC
DEVELOPABLE
Arches and Cables

(a) Uniform loads (vertically) — parabola.
(b) Uniform loads (vertically) — catenary.
(c) Uniform loads (horizontally) — parabola.
(d) Uniform loads (along the cable length) — catenary.
Building Framing

- Components or Assemblages

(a) Common types of horizontal spanning systems (one, two, and three level systems) used in relation to different types of load-bearing wall and columnar vertical support systems.
Building Framing

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).
System Selection

• evaluation of alternatives
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<td>Exposed, fire-resilient construction</td>
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<td>Inherently fire-resilient construction</td>
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<td>Irregular building form</td>
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<td>Simple, site-fabricated systems</td>
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<td>Irregular column placement</td>
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<td>Systems without beams in roof or floors</td>
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<td>Minimize floor thickness</td>
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<td>Precast-concrete systems without ribs</td>
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<td>Allow for future renovations</td>
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<td>Short-span, one-way, easily modified</td>
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<td>Permit construction in poor weather</td>
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<td>Quickly erected; avoid site-cast concrete</td>
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<td>Minimize off-site fabrication time</td>
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<td>Easily erected or built on site</td>
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<td>Minimize on-site erection time</td>
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<td>Highly prefabricated; modular components</td>
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<td>Minimize low-rise construction time</td>
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<td>Lightweight, easily formed or prefabricated</td>
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<td>Minimize medium-rise construction time</td>
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<td>Precast, site-cast concrete; steel frames</td>
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<td>Minimize high-rise construction time</td>
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<td>Strong; prefabricated; lightweight</td>
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<td>Minimize shear walls or diagonal bracing</td>
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<td>Capable of forming rigid joints</td>
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<td>Minimize dead load on foundations</td>
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<td>Lightweight, short-span systems</td>
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<td>Minimize damage due to foundation settlement</td>
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<td>Systems without rigid joints</td>
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<td>Minimize the number of separate trades on job</td>
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<td>Multipurpose components</td>
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<td>Provide concealed space for mech. services</td>
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<td>Systems that inherently provide voids</td>
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<td>Minimize the number of supports</td>
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<td>Two-way, long-span systems</td>
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<td>Long spans</td>
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<td>Long-span systems</td>
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</tbody>
</table>
**Structural Design Criteria**

- components stay together
- structure acts as whole to be stable
  - resist sliding
  - resist overturning
  - resist twisting and distortion
- internal stability
  - interconnectedness
- strength & stiffness
Structural Design Sequences

- **first-order design**
  - structural type and organization
  - design intent
  - contextual or programmatic

- **second-order**
  - structural strategies
  - material choice
  - structural systems

- **third-order**
  - member shaping & sizing
Systems by Materials

- Wood
- Steel
- Concrete
- Masonry
- Composite
Wood

- columns
- beams
- trusses
Timber Construction

- all-wood framing systems
  - studs, beams, floor diaphragms, shearwalls
  - glulam arches & frames
  - post & beams
  - trusses

- composite construction
  - masonry shear walls
  - concrete
  - steel
Timber Construction

• studs, beams
• floor diaphragms & shear walls
Timber Construction

- **glulam arches & frames**
  - manufactured or custom shapes
  - glue laminated
  - bigger members
Timber Construction

- post & beam

- trusses
Timber Construction

- composite construction
Steel

- cast iron – wrought iron - steel
- cables
- columns
- beams
- trusses
- frames

http://nisee.berkeley.edu/godden
Steel Construction

- standard rolled shapes
- open web joists
- plate girders
- decking
Steel Construction

- welding
- bolts
Steel Construction

- **fire proofing**
  - cementicious spray
  - encasement in gypsum
  - intumescent – expands with heat
  - sprinkler system
Concrete

- columns
- beams
- slabs
- domes
- footings
Concrete Construction

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

Tied column
Spirally reinforced column
Concrete Floor Systems

- types & spanning direction

ONE-WAY SLAB (with beams)

TWO-WAY SLAB (with beams)

TWO-WAY SLAB (with dropped panels)

heavily reinforced to resist shear around columns

FLAT PLATE
Concrete Floor Systems

(a) One-Way Concrete Joists

(b) Precast Double-Tees

(c) Wood Joists

(d) Waffle Slab (two-way joists)
Masonry (& Stone)

- columns
- walls
- lintels
- beams
- arches
- footings
Grids and Patterns

• often adopted early in design
  – give order
  – cellular, ex.

• vertical and horizontal

• square and rectangular
  – single-cell
  – aggregated bays
Grids and Patterns

(a) Square column grid.
Systems

- total of components
- behavior of whole
- classifications
  - one-way
  - two-way
  - tubes
  - braced
  - unbraced
One-Way Systems

- horizontal vs. vertical
Two-Way Systems

- spanning system less obvious
- horizontal
  - plates
  - slabs
  - space frames
- vertical
  - columns
  - walls

(i) Space-frame system on walls with cantilevers.
Two-Way Systems

(a) Flat-plate system.

(b) Flat-slab system.

(c) Two-way beam-and-slab system.

(d) Two-way ribbed system (waffle slab).

(e) Two-way ribbed system with surrounding beams.

(f) Two-way long-span beam-and-slab system.
Roof Shapes

- coincide
- within
Tubes & Cores

- stiffness

(c) Suspended structure, reinforced concrete core.

(c) Tube structure. The exterior columns are closely spaced. Horizontal spandrel beams are rigidly connected to columns to form an exterior tube, which carries all lateral forces and some gravity forces. Interior columns carry only vertical forces.
Span Lengths

• crucial in selection of system
• maximum spans on charts aren’t absolute limits, but usual maximums
• increase $L$, increase $depth^2$ required (ex. cantilever)
• deflections depend on $L$
# Approximate Depths

<table>
<thead>
<tr>
<th>Slabs (poured in place)</th>
<th>Simply supported</th>
<th>One end continuous</th>
<th>Both ends continuous</th>
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<tbody>
<tr>
<td>Cantilever L/12</td>
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<thead>
<tr>
<th>Beams (poured in place)</th>
<th>Simply supported</th>
<th>One end continuous</th>
<th>Both ends continuous</th>
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<tr>
<td>Cantilever L/10</td>
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<tr>
<th>Pan joist system (poured in place)</th>
<th>L/20–L/25</th>
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<tr>
<td>Folded plate (poured in place)</td>
<td>L/8–L/15</td>
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<td>Barrel shell (poured in place)</td>
<td>L/8–L/15</td>
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<tr>
<td>Planks (precast)</td>
<td>L/25–L/40</td>
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<tr>
<td>Channels (precast)</td>
<td>L/20–L/28</td>
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<td>Tees (precast)</td>
<td>L/20–L/28</td>
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<tr>
<td>Flat plate (poured in place)</td>
<td>L/30–L/40</td>
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<tr>
<td>Flat slab (poured in place)</td>
<td>L/30–L/40</td>
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<tr>
<td>Two-way beam and slab (poured in place)</td>
<td>L/30–L/40</td>
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<tr>
<td>Waffle slab (poured in place)</td>
<td>L/23–L/35</td>
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<tr>
<td>Dome (poured in place)</td>
<td>L/4–L/8</td>
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Loading Type and Structure Type

• light uniform loads
  – surface forming elements
  – those that pick up first load dictate spacing of other elements

• heavy concentrated loads
  – member design unique

• distributed vs. concentrated structural strategies
  – large beam vs. many smaller ones
Design Issues

• lateral stability – all directions
Design Issues

- configuration

Stabilizing elements may be placed within the interior or at the perimeter of a building.

Stabilizing elements should be arranged in a balanced fashion.

Rigid frame structures require no additional bracing or shear walls, as shown in this elevation and plan.

The locations of braced frames or shear walls must be considered in relation to the elevation and plan of the building.
Design Issues

• vertical load resistance

walls

columns
Design Issues

- lateral load resistance

Shear walls may be arranged in a box form to resist lateral forces from all directions.

When combined with other stabilizing mechanisms, shear walls may be arranged so as to resist forces in only one direction of a building.
Design Issues

- lateral load resistance

Shear walls are commonly used with column and slab systems. In this elevation and plan, the shear walls are shown incorporated into a pair of vertical cores. Rigid frame structures require no additional bracing or shear walls, as shown in this elevation and plan. The locations of braced frames or shear walls must be considered in relation to the elevation and plan of the building.
Design Issues

- multi-story
  - cores, tubes, braced frames
Design Issues

- multi-story
  - avoid discontinuities
    - vertically
    - horizontally

Transfer beams or trusses may be used to interrupt vertical loadbearing elements where necessary.

Discrete building masses should be structurally independent. Inherently unstable building masses should be avoided.

Discontinuities in the stiffness of structures at different levels should be avoided, or additional stabilizing elements may be required.
Foundation Influence

- type may dictate fit
  - piles vs. mats vs. spread
  - capacity of soil to sustain loads
    - high capacity – smaller area of bearing needing and can spread out
    - low capacity – multiple contacts and big distribution areas
Grid Dependency on Floor Height

- **wide grid = deep beams**
  - increased building height
  - heavier
  - foundation design
- **codes and zoning may limit**
- **utilize depth for mechanical**
Large Spaces

• ex. auditoriums, gyms, ballrooms

• choices
  – separate two systems completely and connect along edges
  – embed in finer grid
  – staggered truss
Meeting of Grids

• common to use more than one grid
• intersection important structurally
• can use different structural materials
  – need to understand their properties
    • mechanical
    • thermal
Meeting of Grids

• horizontal choices

(a) Random intersection.
(b) Alignment of patterns.
(c) Alignment of patterns.
(d) Mediating space.
Meeting of Grids

- **vertical choices**

(a) Alignment of grids.

(b) Bypassing of grids.
Other Conditions

• circulation

• building service systems
  – one-way systems have space for parallel runs
  – trusses allow for transverse penetration
  – pass beneath or interstitial floors
  • for complex or extensive services or flexibility
Other Conditions

- poking holes for member services
  - horizontal
    - need to consider area removed, where removed, and importance to shear or bending
  - vertical
    - requires framing at edges
    - can cluster openings to eliminate a bay
  - double systems
Fire Safety & Structures

- Fire safety requirements can impact structural selection
- Construction types
  - Light
    - Residential
    - Wood-frame or unprotected metal
  - Medium
    - Masonry
  - Heavy
    - Protected steel or reinforced concrete
Fire Safety & Structures

- degree of occupancy hazards
- building heights
- maximum floor areas between fire wall divisions
  - can impact load bearing wall location
Fire Safety & Structures

• *resistance ratings by failure type*
  – *transmission failure*
    • fire or gasses move
  – *structural failure*
    • high temperatures reduce strength
  – *failure when subjected to water spray*
    • necessary strength

• *ratings do not pertain to usefulness of structure after a fire*
Project