ENCE 353: An Overview of Structural Analysis and Design

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Spring Semester 2025

Outline

- Objectives of Structural Engineering
- A little history
- Structural Engineering Process
- Types of loads
- Types of structures
- Civil Engineering Materials
- Load paths in structures
- How can structures fail?
- Summary

Objectives of Structural Engineering

Structural engineering is …

… the field of engineering particularly concerned with the design of economical and efficient load-bearing structures.

Within civil engineering, it is largely …

… the implementation of mechanics to the design of the large structures that are fundamental to basic living, such as buildings, bridges, walls, dams, and tunnels.

Structural design is …:

… the process of determining location, material, and size of structural elements to resist forces acting in a structure

Objectives of Structural Engineering

- Structural engineers need to design structures that ...
- ... do not collapse or behave in undesirable ways while serving their useful functions.
- The efficient use of funds and materials to achieve these structural goals is also a major concern.
- Structural engineers work closely with geotechnical engineers, architects, construction managers, and transportation engineers, ME/EE, to name only a few.

How do I become a Structural Engineer?

Apprentice structural engineers may design …

… simple beams, columns, and floors of a new building, including calculating the loads on each member and the load capacity of various building materials (steel, timber, masonry, and concrete).

An experienced engineer would tend to design more complex structures, such as multistory buildings or bridges.

It is in the design of these more complex systems that a structural engineer must draw upon creativity -- this will be part design and part art -- in the application of mechanics principles.

A Little History

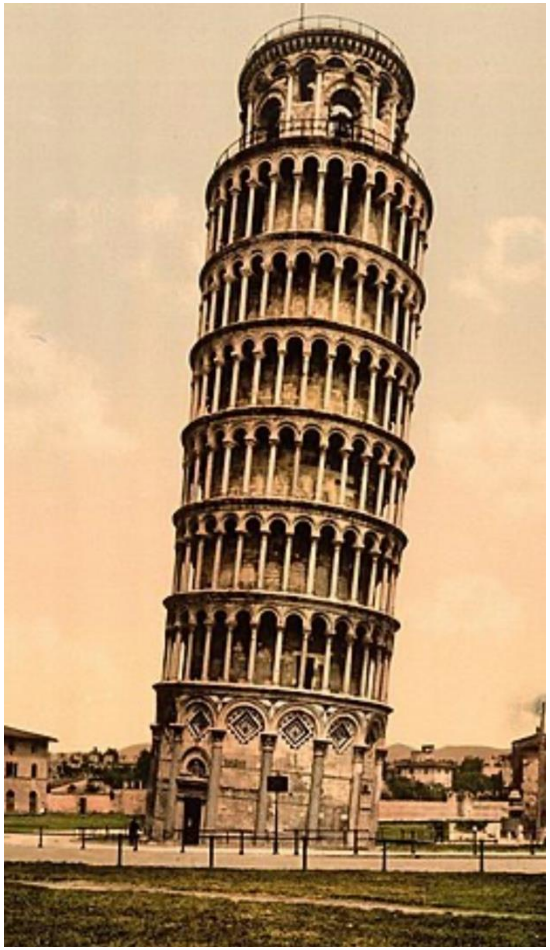
Exemplars of Early Work

- Great Pyramid of Giza, Egypt (20 year construction; finished 2556 BC).
- The Parthenon in Ancient Greece (447-438 BC).
- Construction of the Great Wall of China (220 BC).
- The Romans developed civil structures throughout their empire, including especially aqueducts, insulae, harbours, bridges, dams and roads.

A Little History

Leaning Tower of Pisa (12th Century)

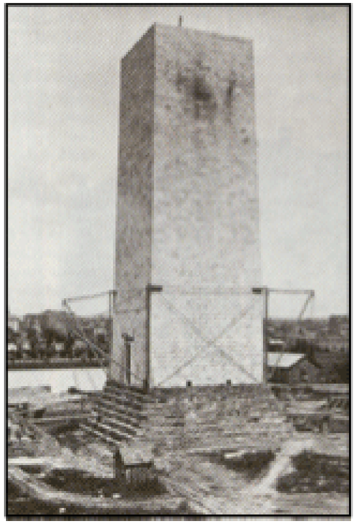


- Designed to be the tallest bell tower in Europe.
- Construction: Three stages over 199 years (1173-1372).
- Constructed from white marble.
- Tower leans because of weak unstable subsoil.
- It once leaned at 5.5 degrees.
- Currently leans at 3.99 degrees.
- Has survived 4 earthquakes –ironically, weak subsoil conditions work to protect Pisa from ground accelerations.

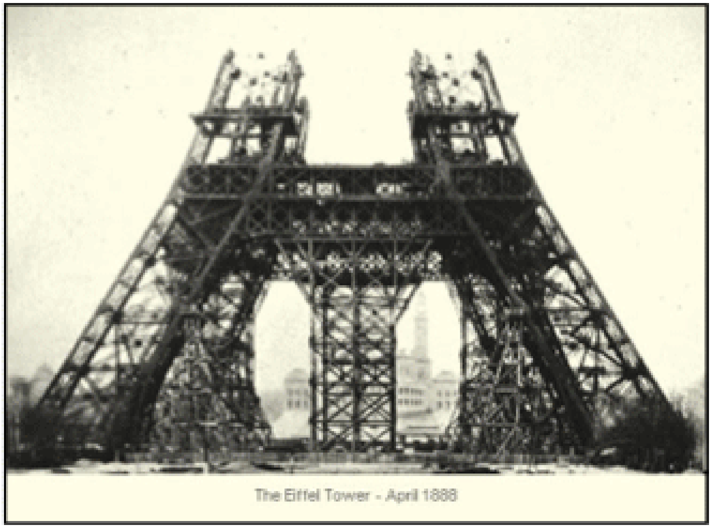
A Little History

Year	Milestone
1854	Bessemer invents steel converter.
1849	Monier develops reinforced concrete.
1863	Siemens-Martin open hearth process makes steel available in bulk.

1848 (approx).



1888



A Little History

Early Skyscrapers

Skyscrapers (1890s) create habitable spaces in tall buildings for office workers.

Enablers	Example: Empire State Building
• New materials → design of tall structures having large open interior spaces. • Elevators (1857) → vertical transportation building occupants. • Mechanical systems → delivery of water, heating and cooling. • Collections of skyscrapers → high-density CBDs/commuter society.	

A Little History

Urban Development in NYC

Urban Development in Shanghai

Challenges (2020-2060)

Crisis in Infrastructure Investment

Exemplars of Work from the 1800s and 1900s

From the 1800s	From the 1900s
Erie Canal (1825)	New York City Subway (1904)
Transcontinental Railroad (1869)	The Panama Canal (1914)
Brooklyn Bridge (1883)	Holland Tunnel (1927)
Washington Monument (1884)	Empire State Building (1931).
	Hoover Dam (1936).
	Golden Gate Bridge (1937)
	Interstate Highway System (1956)

Source: Celebrating the Greatest Profession, Magazine of the American Society of Civil Engineers, Vol. 72, No. 11, 2002.

Crisis in Infrastructure Investment

Universal Observations:

- Aging infrastructure becomes expensive to maintain.
- New (replacement) infrastructure is very expensive.
- Politicians are eager to talk up Infrastructure Investment , but slow to deliver ….

Bottom line:

- Critical infrastructure is taken for granted and not a national priority (ASCE, IEEE).

Delay, delay, delay ….

Bangkok, Thailand

Poster Child: Collapse of the Minneapolis bridge over 135W.

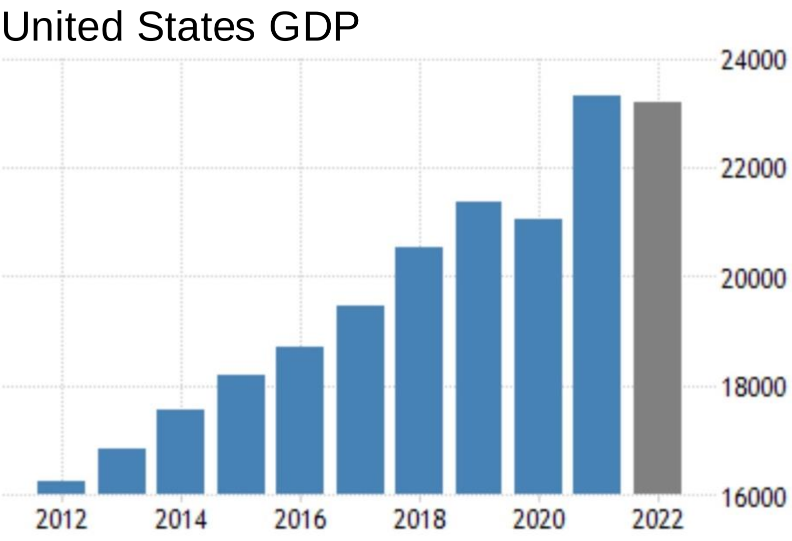
The 40-year old steel deck truss crossing had been considered structurally deficient since 1990, but engineers with the Minnesota Department of Transportation had not believed the bridge to be in danger of imminent collapse.

Thirteen commuters were killed and more than 100 were injured on August 1, 2007.

Crisis in Infrastructure Investment

Statistics:

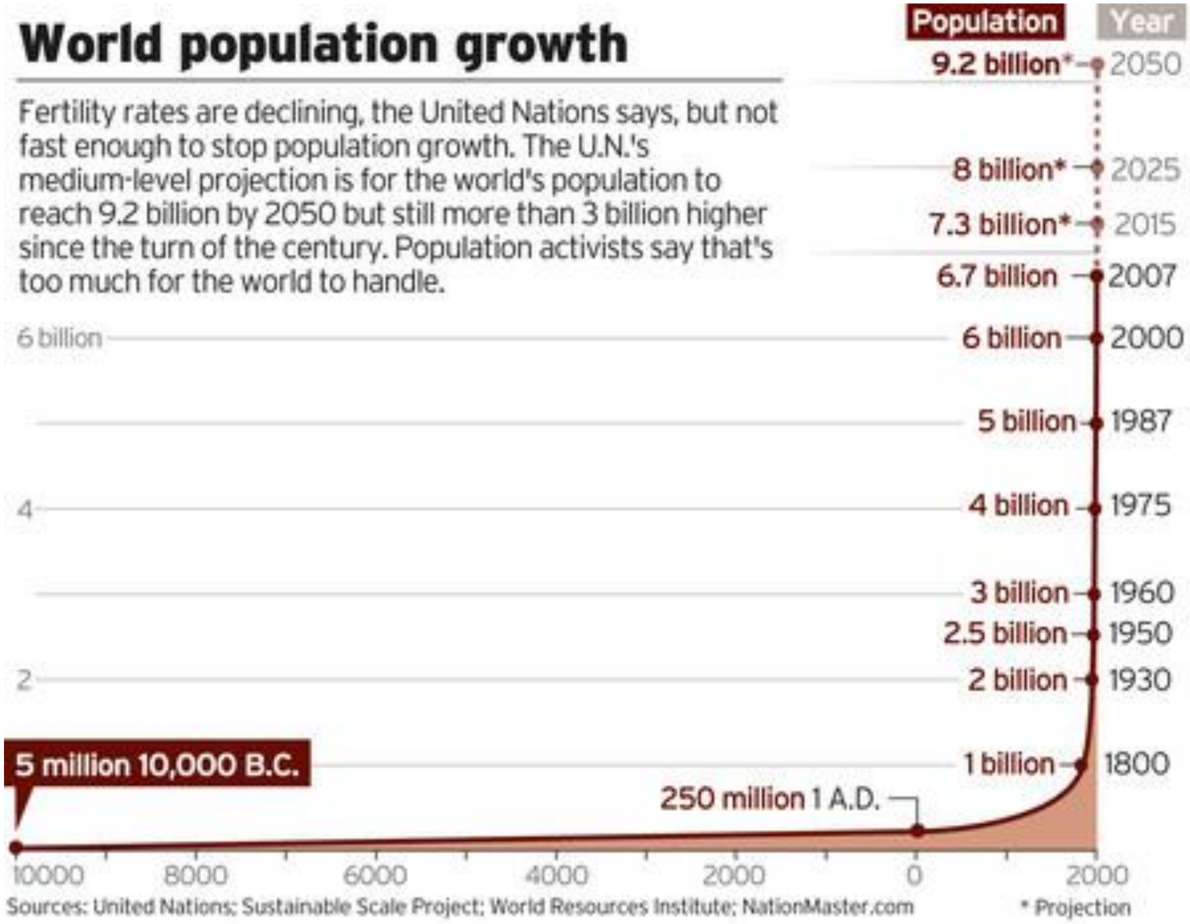
- US: Post World-War II (1950-1970): 3% of Gross Domestic Product (GDP)
- US: 1980-present: 2% of GDP.
- China: 5% GDP.
- India: 9% GDP.



Infrastructure Investment and Jobs Act (2021).

- Invest $1.2T over 10 years.
- Sounds like a lot – but is it too low, too high?
- Increases investment by 0.5% of GDP.

Looking Ahead



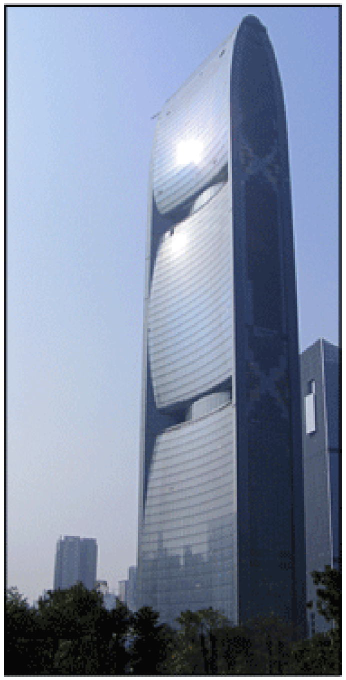
Increasing Population → Increased Demand on Limited Resources → Increasing need for Improvements to System Efficiency.

Looking Ahead

Example. Engineering Modern Skyscrapers

<table>
<tr><th>Enablers</th><th>Example: Pearl River Tower</th></tr>
<tr><td>

- High performance structure designed to produce as much energy as it consumes.
- Guides wind to a pair of openings at its mechanical floors.
- Winds drive turbines that generate energy for the heating, ventilation and air conditioning systems.
- Openings provide structural relief, by allowing wind to pass through the building.

</td><td></td></tr>
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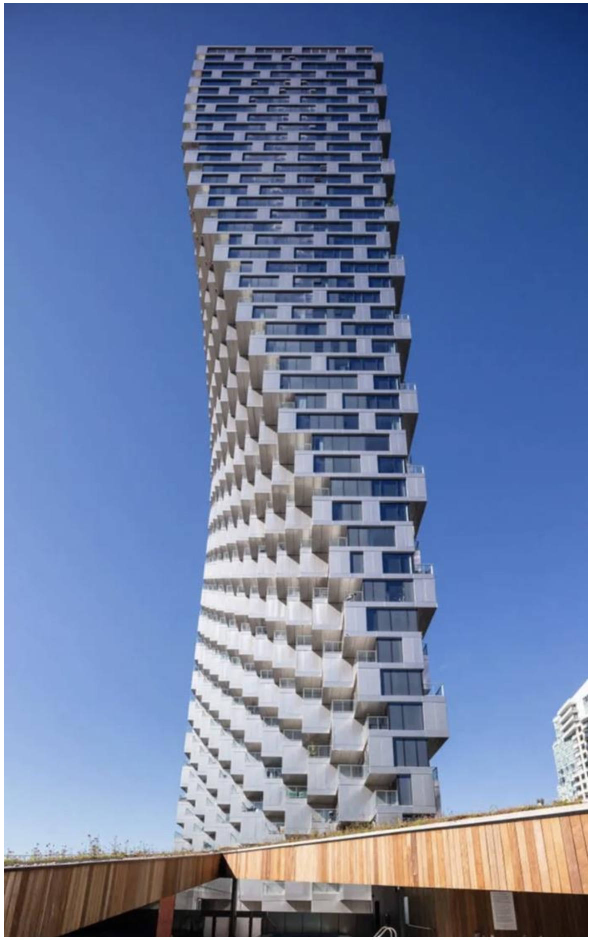
Looking Ahead

Emergence of New Architectural Forms



Looking Ahead

Parametric Architectural Design

Structural Design Process

Structural Design Process

- Determine types magnitudes of loads and forces acting on the structure
- Determine structural context
  - geometric and geological information
  - cost / schedule / height/ etc. limitations
- Generate alternative structural systems (e.g., moment resistant frame, materials selection),
- Analyze one or more alternatives
- Select and perform detailed design
- Implement (usually done by contractor)

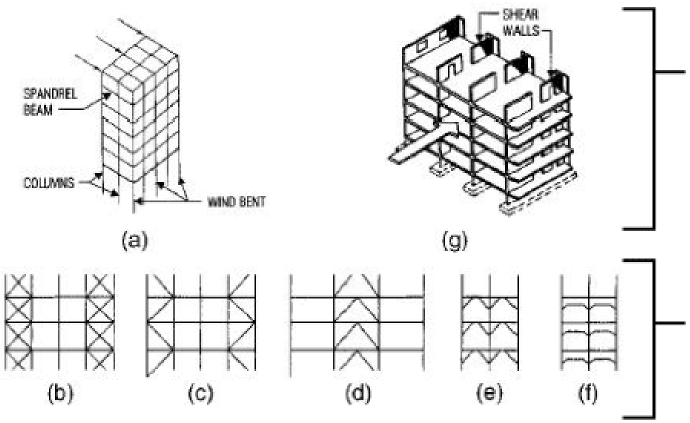
Note: New structural systems may also require an experimental testing phase to verify behavior and system performance.

Formal Approach to Structural Design

Formal Approaches to Behavior Modeling and Decision Making

Appropriate formalisms depend on the design domain of interest.

- Physical aspects of behavior are often characterized by differential equations.
- Logical aspects of system design can be captured by binary and multi-valued logic variables and boolean equations.



Structural behavior corresponds to solution of differential equations.

Selection of the structural system can be written mathematically as a problem in multi–valued logic.

Formal Approach to Structural Design

Structural Behavior

Time-dependent behavior corresponds to solutions of:

$$[M]\,\frac{d^2x}{d^2t} + [C]\,\frac{dx}{dt} + [K]\,x = P(t). \tag{1}$$

Here,

- M, C, and K are $(n \times n)$ matrices,
- x is a $(n \times 1)$ vector of displacements,
- P(t) is a vector of external loads applied to the structural degrees of freedom.

Design Parameters

- Selection of the best structural system (e.g., braced system) from a list of options.
- Size of the beams, columns, and bracing (if required).

Loads

Types of loads

- Dead loads
- Live loads
- Dynamic loads (e.g., trains, equipment)
- Wind loads
- Earthquake loads
- Thermal loads
- Settlement loads

Dead Loads

- weight of the structure itself
  - floors, beams, roofs, decks, beams/stringers, superstructure
- loads that are "always there"

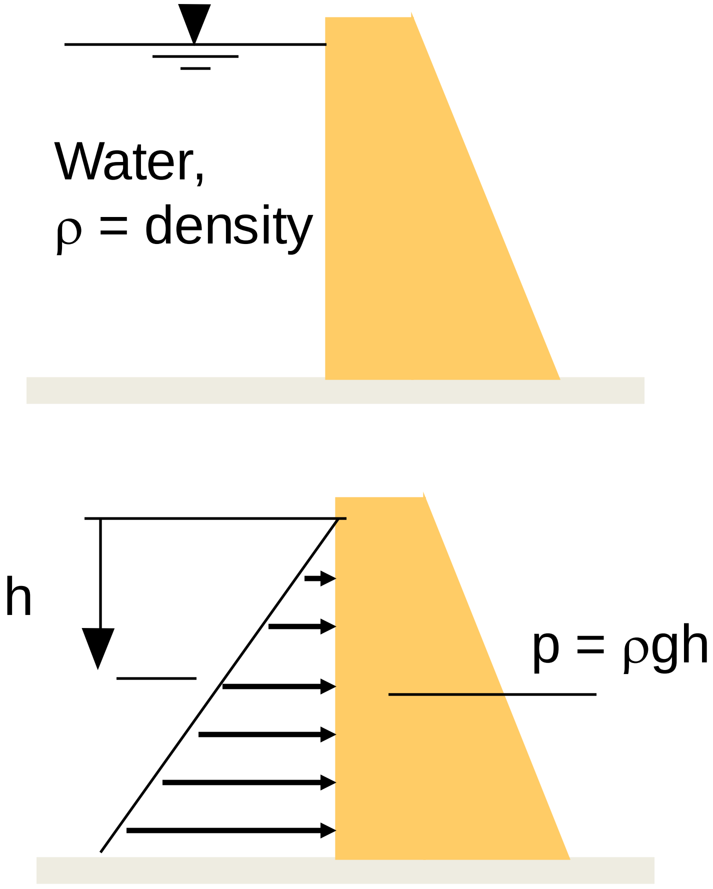
Live Loads

- People, furniture, equipment
- Loads that may move or change mass or weight
- Minimum design loadings are usually specified in the building code

Dynamic Loads

- Moving loads (e.g., traffic)
- Impact loads
- Gusts of wind
- Loads due to cycling machinery

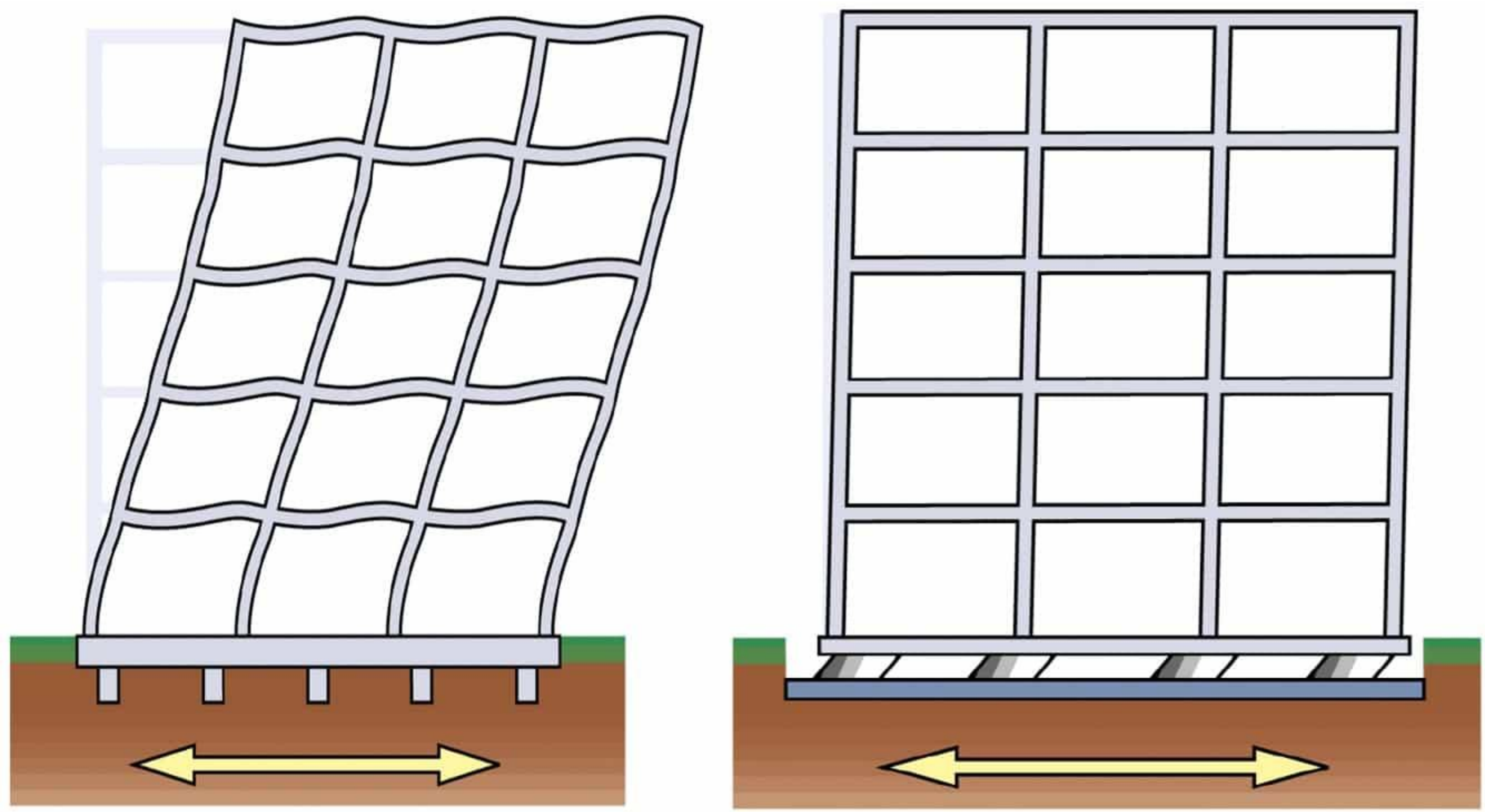
Load Example: Water in a dam

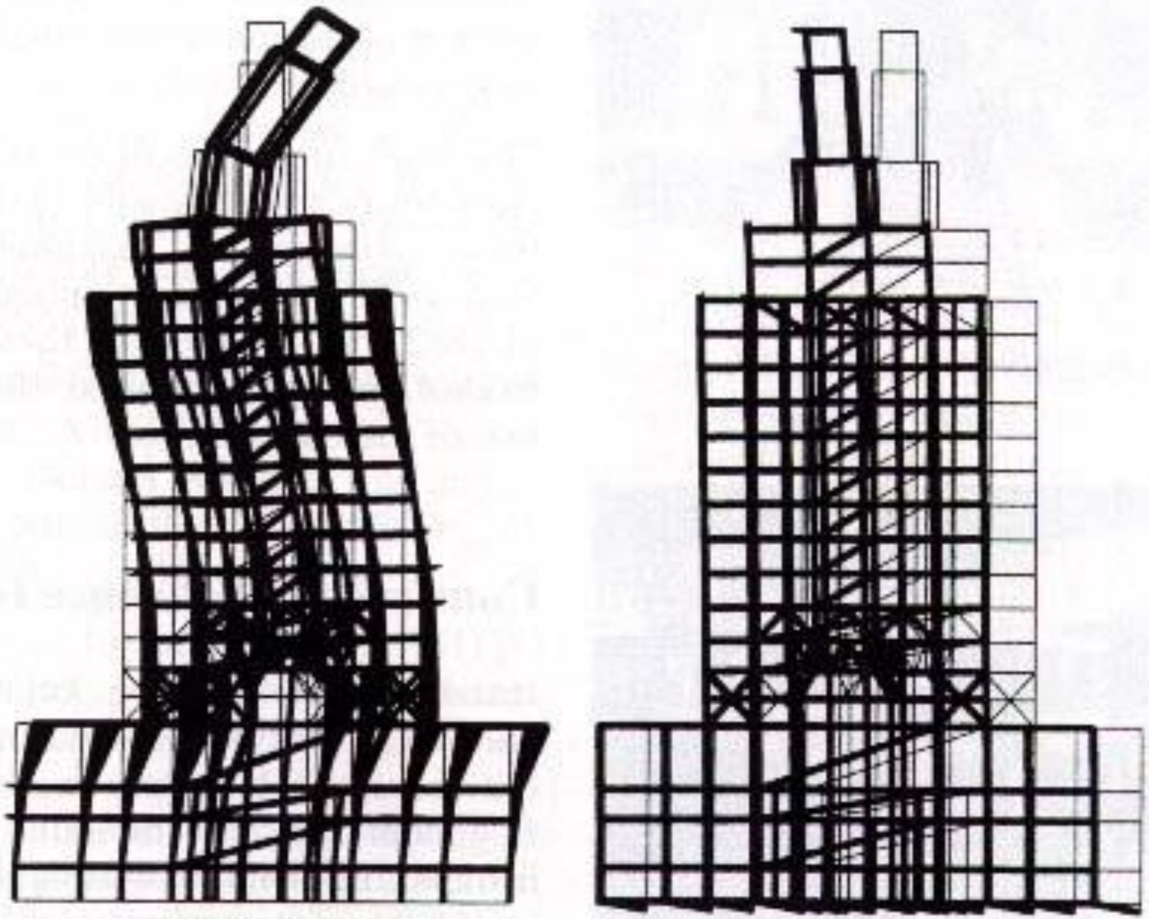


Earthquake Loads

- Structure loaded when base is shaken
- Response of structure is dependent on the frequency content and magnitude of ground motion.
- When frequencies of ground motion match with natural frequency of structure – resonance leads to amplified displacements.

Fixed-Base versus Base-Isolated Response



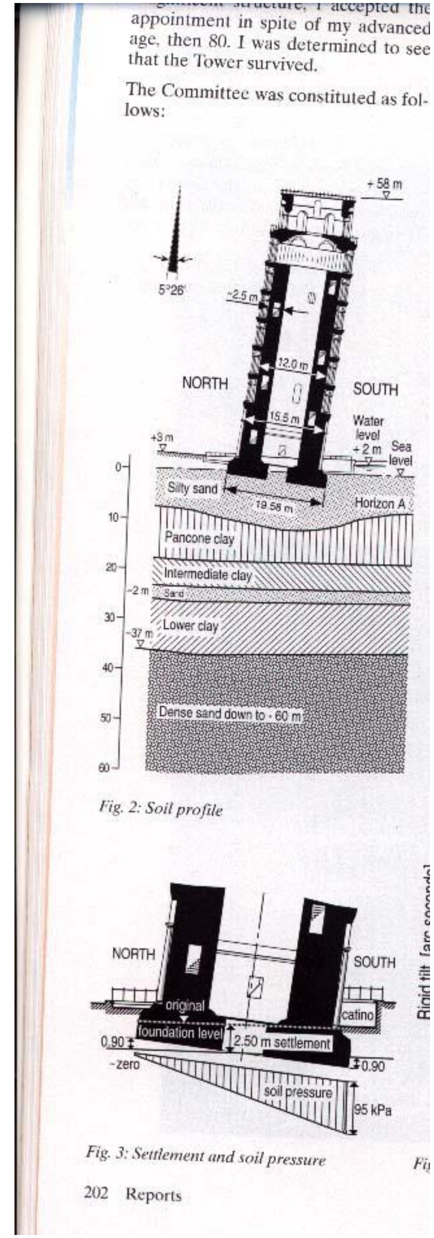


Fixed Base   Isolated

4: Seismic response of the building

Two Applications of Base Isolation

Settlement



...significant structure, I accepted the appointment in spite of my advanced age, then 80. I was determined to see that the Tower survived.

The Committee was constituted as follows:

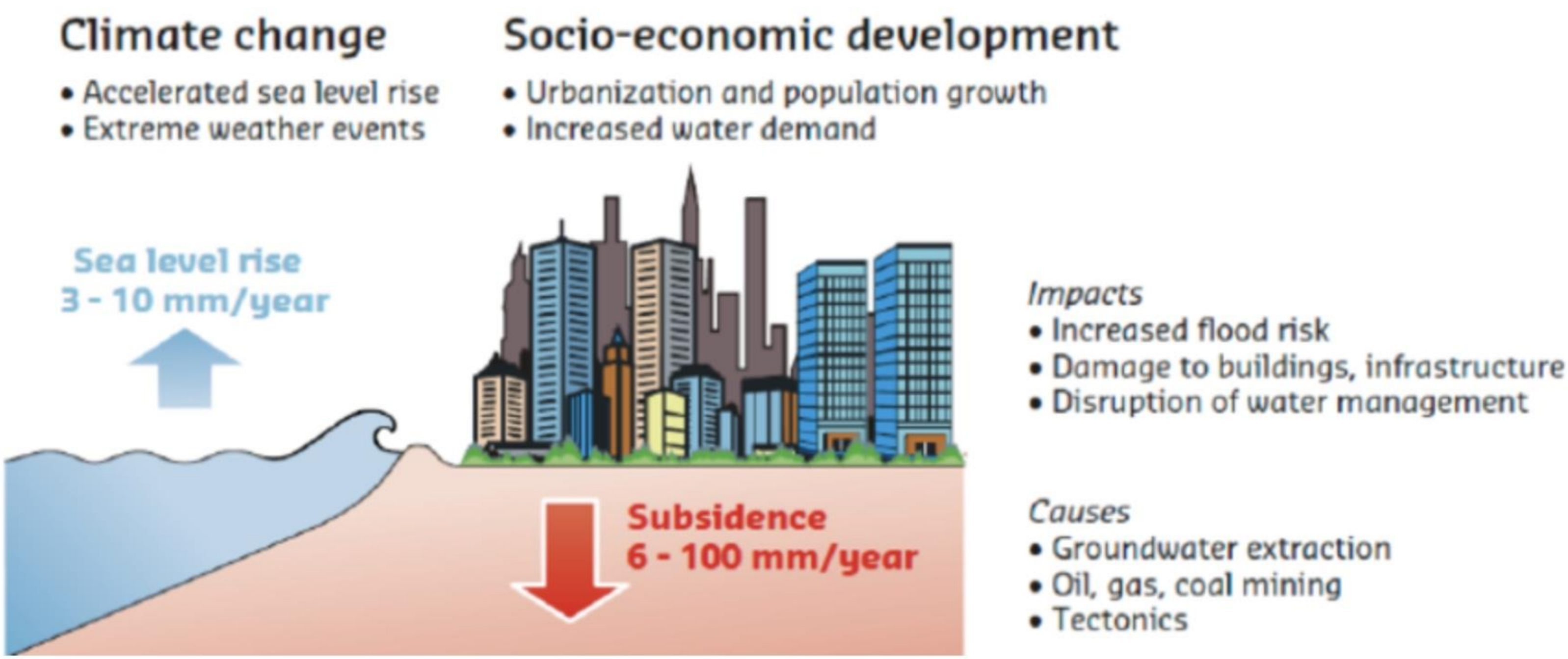
Fig. 2: Soil profile

Fig. 3: Settlement and soil pressure

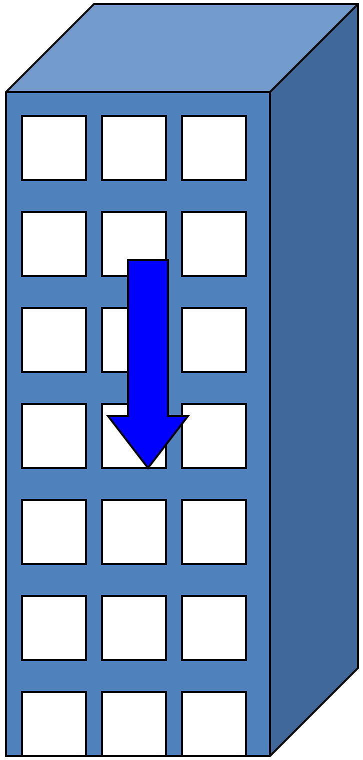
Note: See link on class web page to article on Settlement of Millennium Tower in San Francisco.

Sinking of Coastal Cities

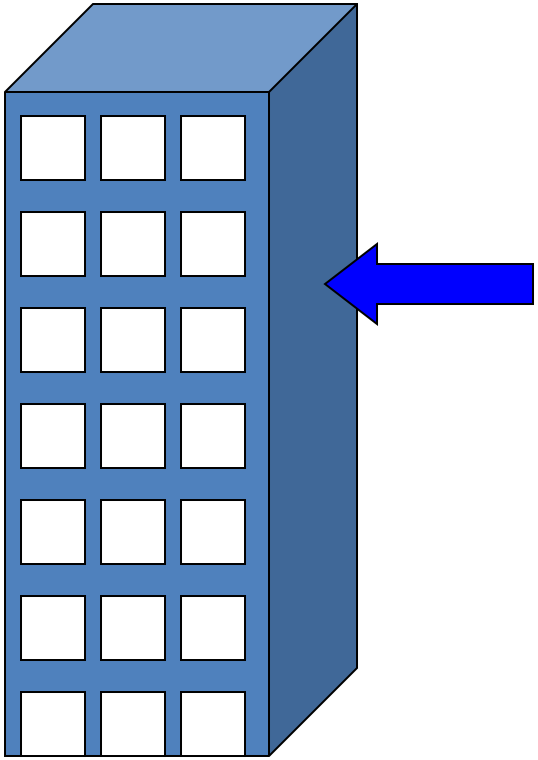
Emerging problem that will cause damage to buildings and urban infrastructure, increase the risk of flooding, and disrupt water supply systems.



Forces Acting in Structures

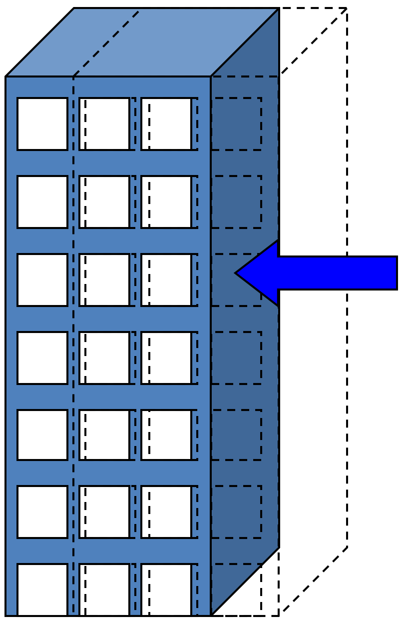


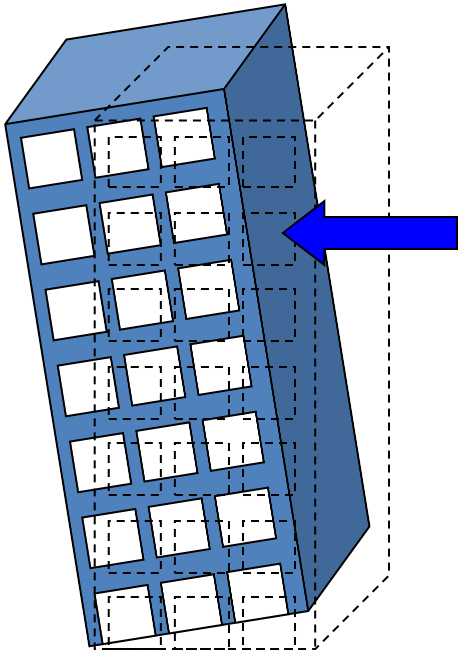
Vertical: Gravity



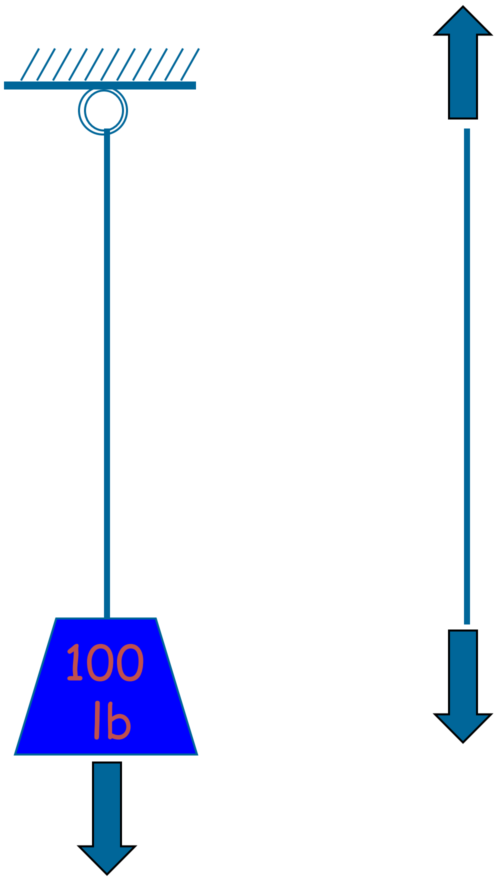
Lateral: Wind, Earthquake

Global Stability

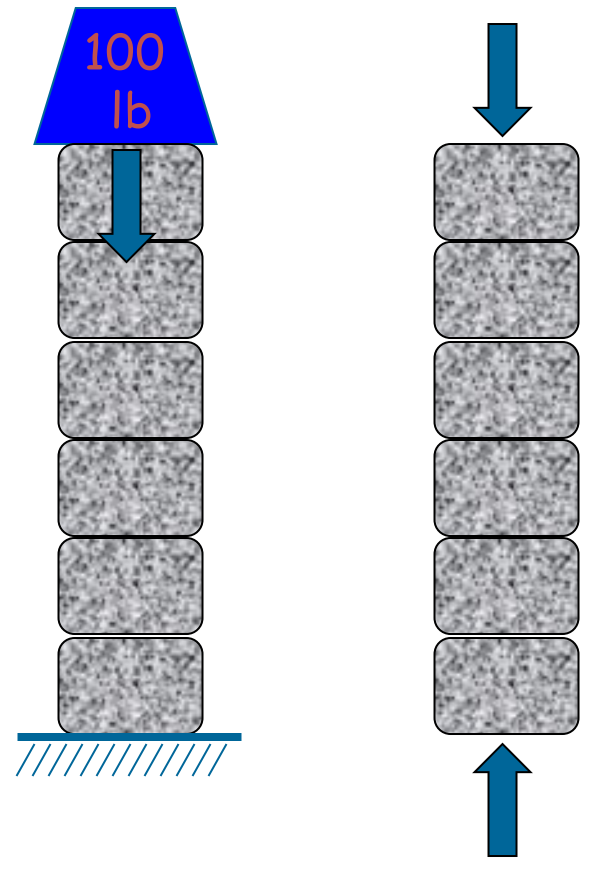

Sliding


Overturning

Forces in Structural Elements

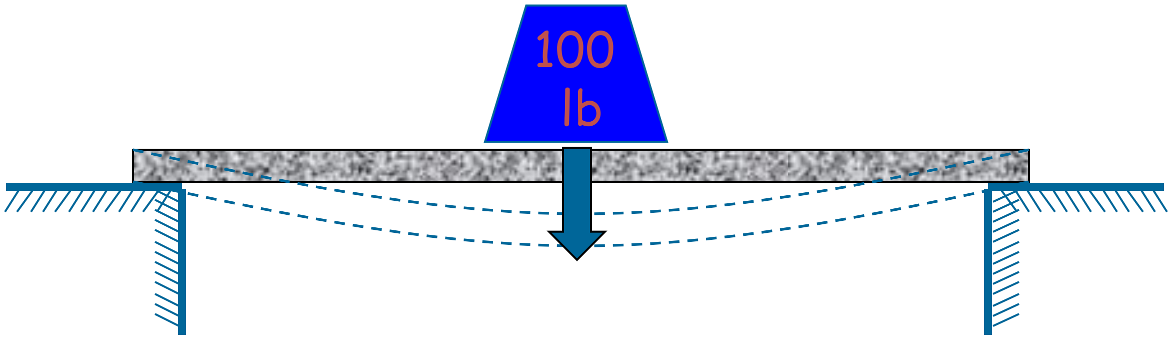


Tension

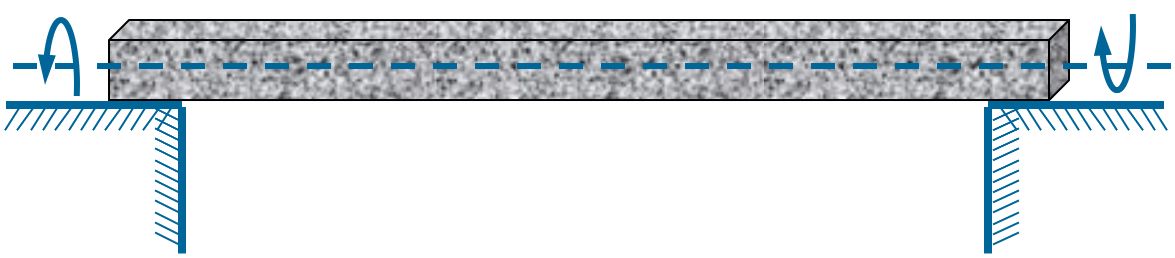


Compression

Forces in Structural Elements (cont.)



Bending



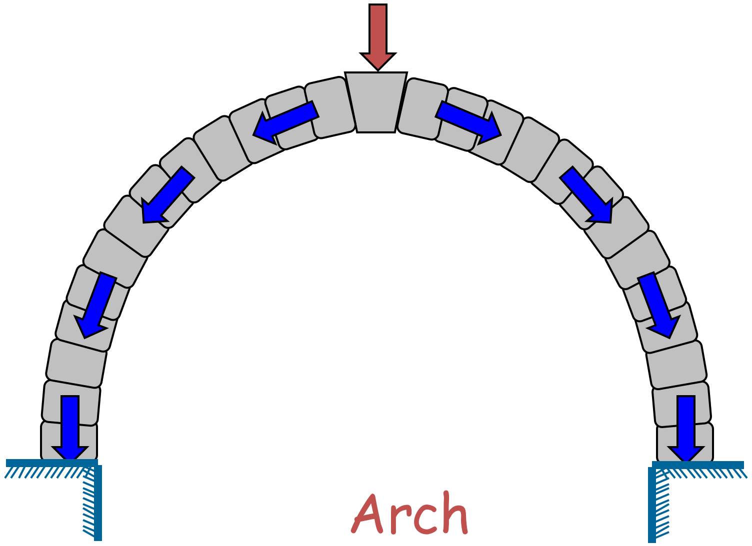
Torsion

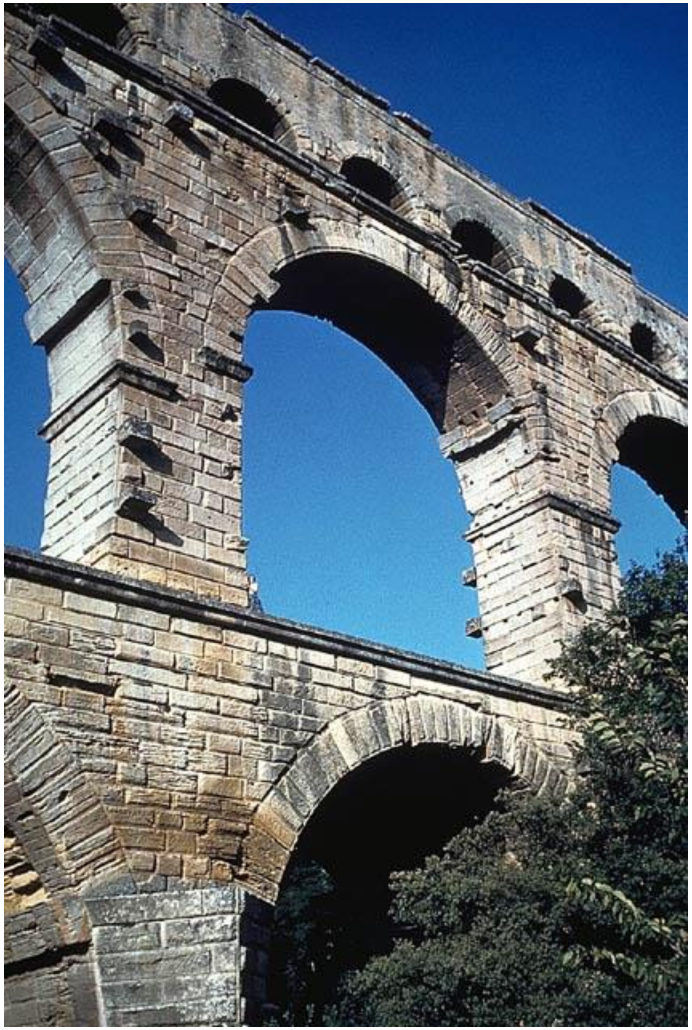
Types of Structural System

Some Types of Structures

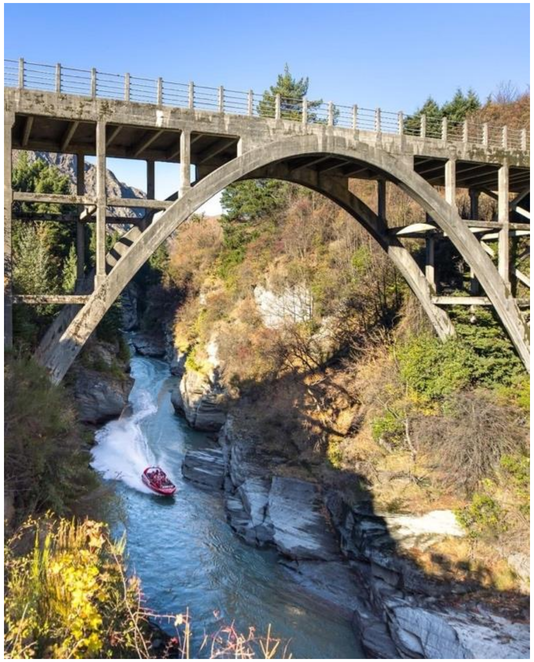
- Arch
- Planar Truss
- Beam/Girder
- Flat plate
- Braced and Rigid Frames
- Folded Plate and Shell Structures
- Cable Suspended Structure

Arch





Design objective: Structure needs to work and be aesthetically pleasing!!
Analysis objective: What shape should the arch be so that forces can be transferred to the foundation through compression mechanisms alone?




Key Bridge (Georgetown-Reston): 1923

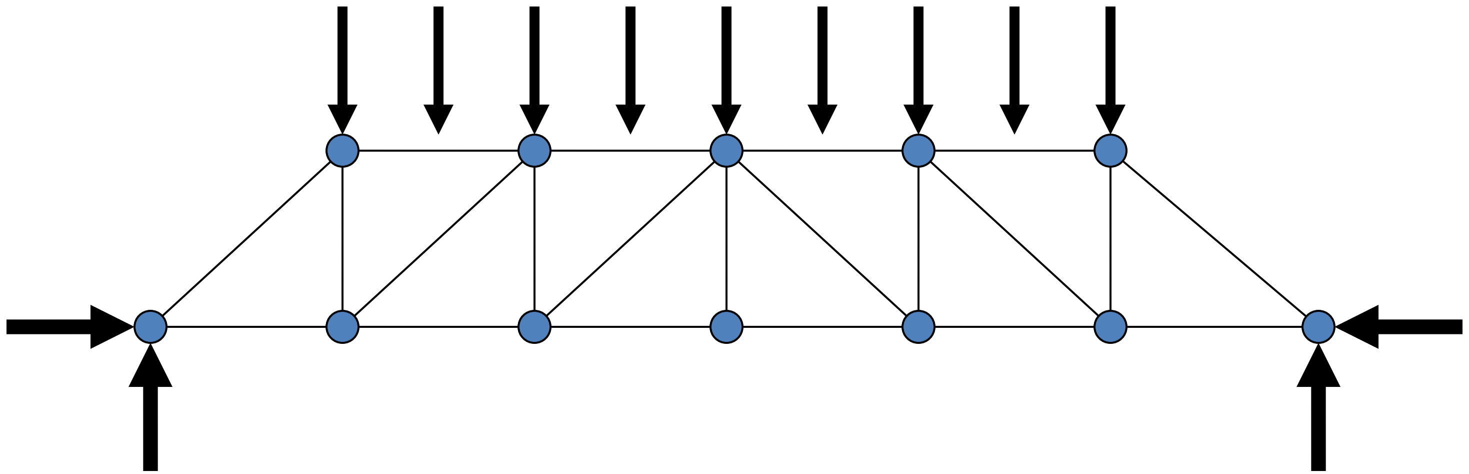
Arch Bridges are currently In Vogue

Frederick Douglass Memorial Bridge, Washington DC (2017-2022)

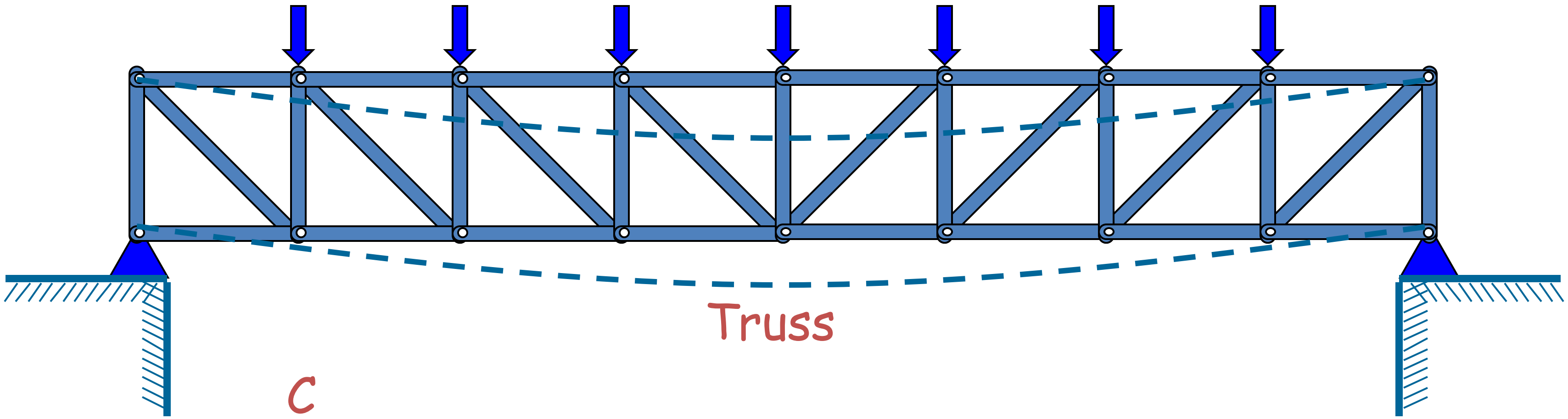
Science World,
Vancouver, Canada.

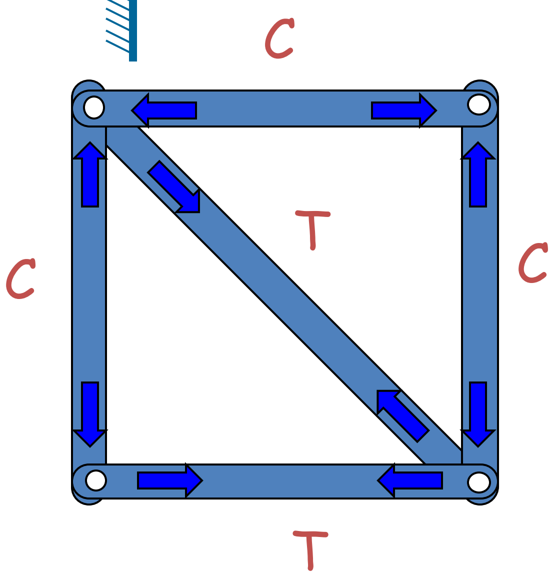
Truss

- Combination of square and triangle
  - Both vertical and lateral support



Planar Truss



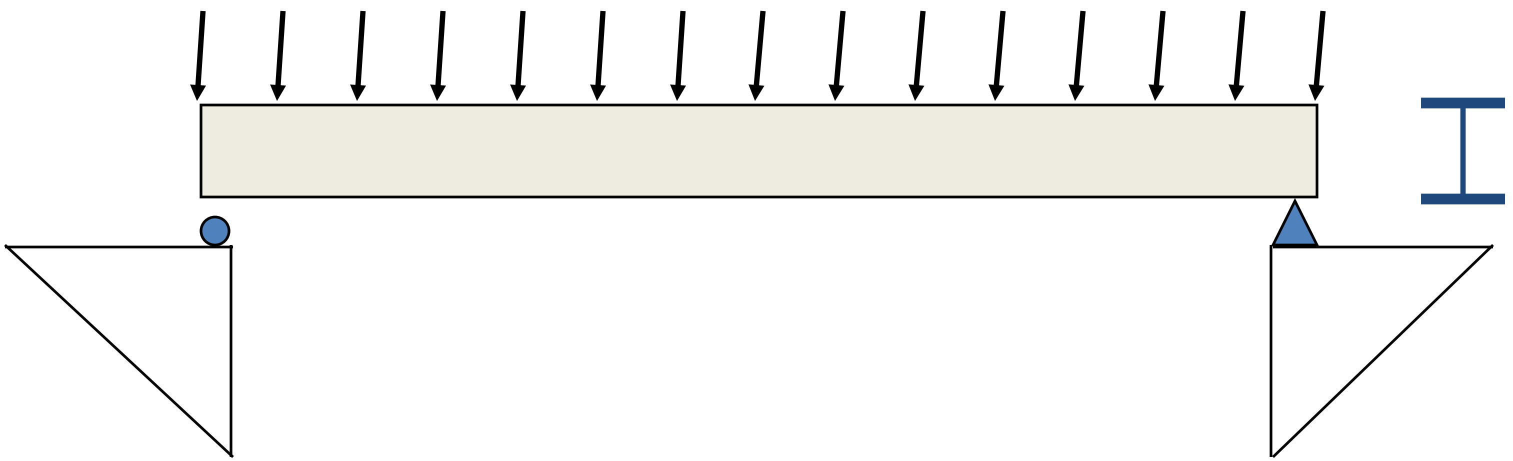


Forces in Truss Members




Three-Dimensional Truss Structure at BWI

Beam/Girder



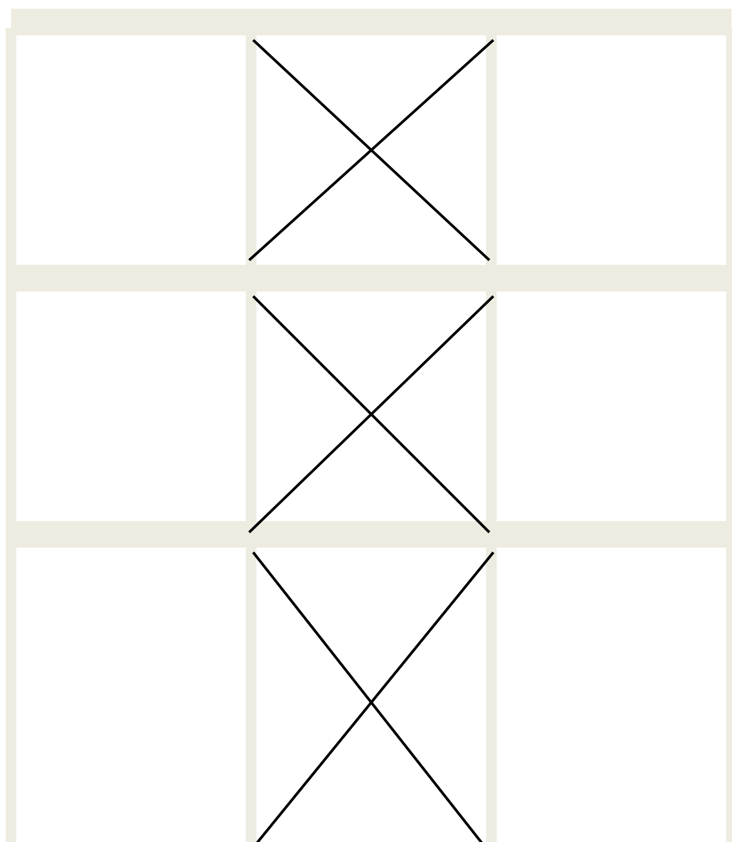

CB


New Computer Science Building at UMD (2017)

Construction of I-95, near Philadelphia, circa 1970.

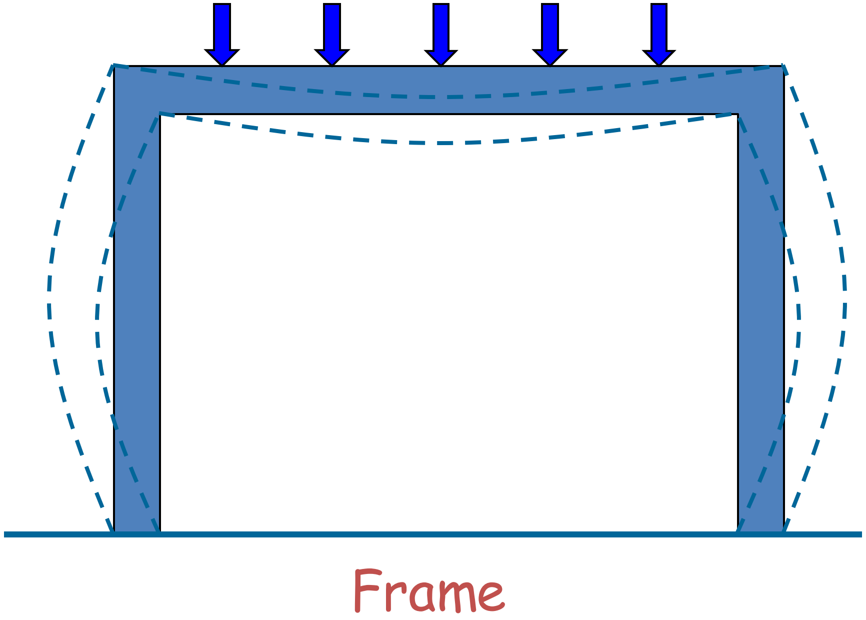
Frames

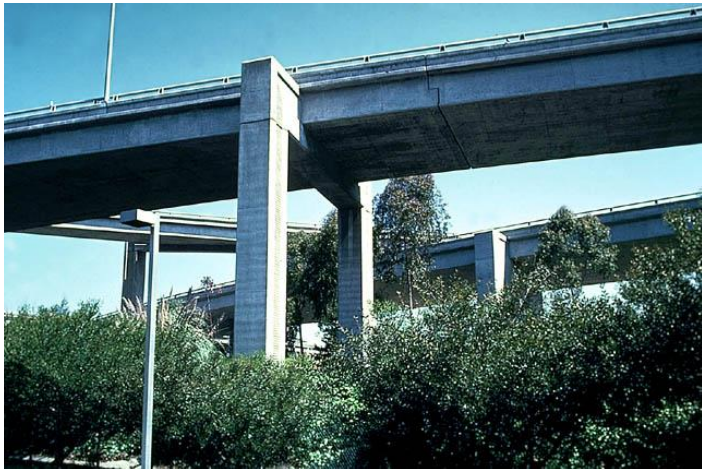
Braced



Rigid

Frames





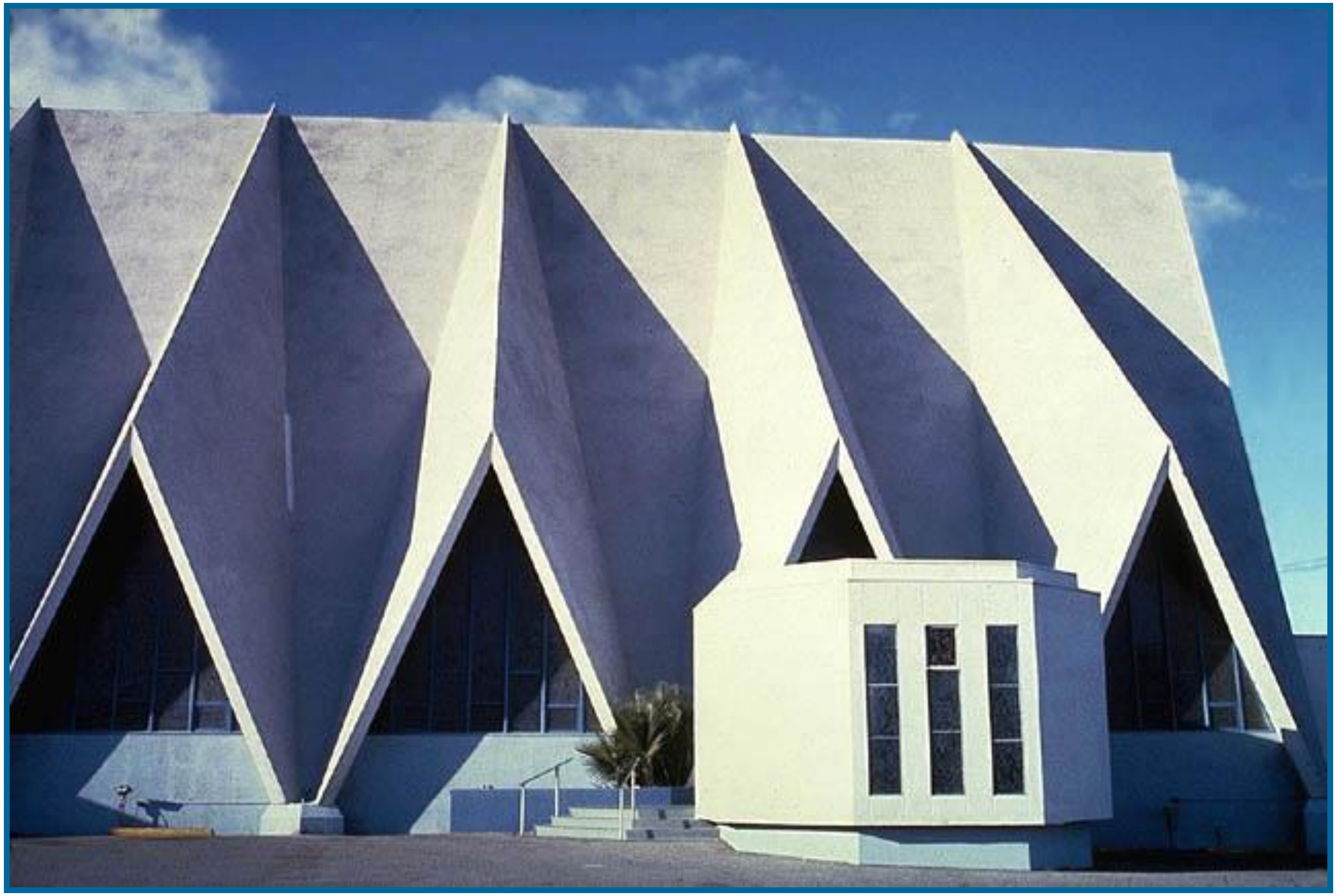
Analysis objective: We want to compute the distribution of forces – axial, bending moment, shear forces – throughout the structure.
What are the displacements?
Will the frame structure be stable?



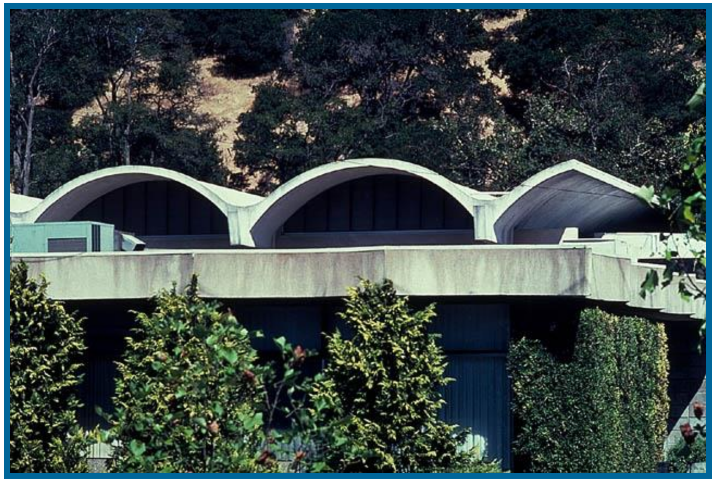
Flat Plate

Flat Slab construction at UMD (2024)

Folded Plate



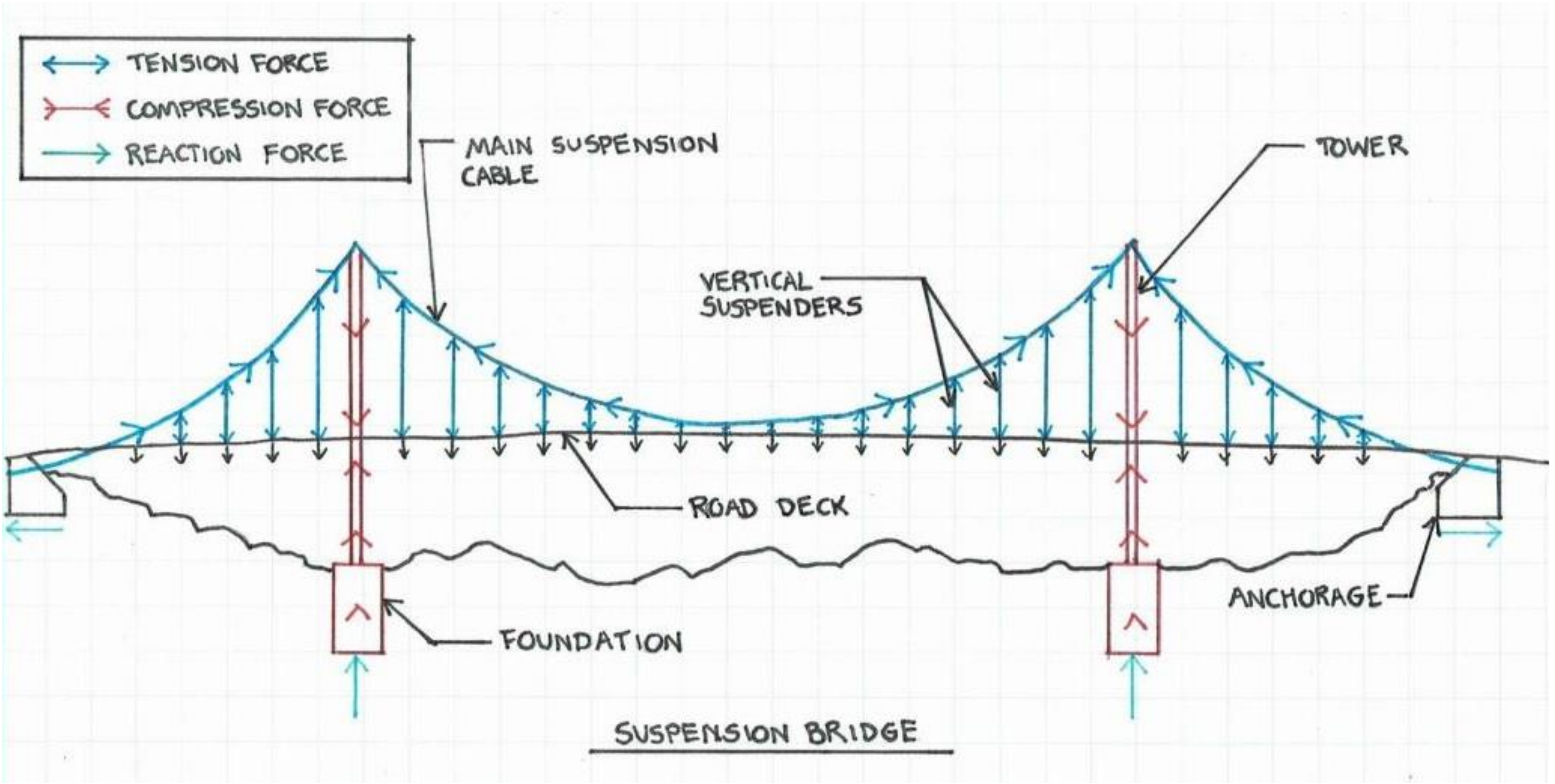
Shells



Circular Shell Structure

Lattice Shell Structure

Cable Suspended Structure

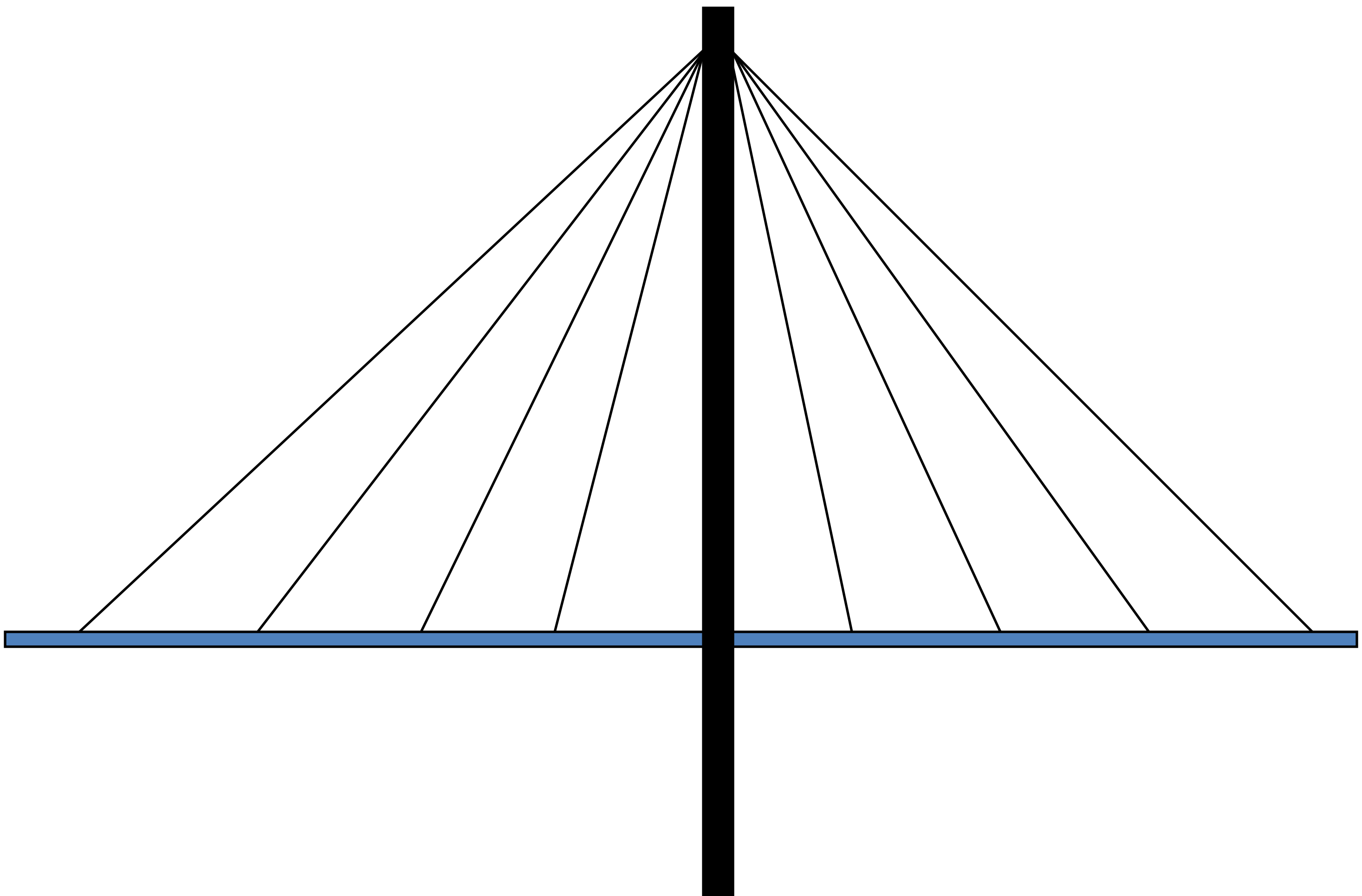


Analysis objectives What are the forces in the cable structure? How will the cable profile shape change with different distributions of live load? What are the bending moments in the bridge deck?


GOLDEN GATE BRIDGE
MAIN SPAN
4200 FEET
LENGTH OF ON CABLE .... 7650 FT. (2331.7m)
DIAMETER OF ONE CABLE .. 36 3/8 IN. (92 4cm)
WIRES IN EACH CABLE 27,572
TOTAL WIRE USED ... 80,000 MILES (128,748 km)
WEIGHT OF CABLE (SUSPENDERS & ACCESSORIES) 24,500 TONS (22,226 m.tons)
Cable Contractor : John A. Roebling's Sons Co.
Trenton & Roebling, New Jersey

Power Transmission Lines

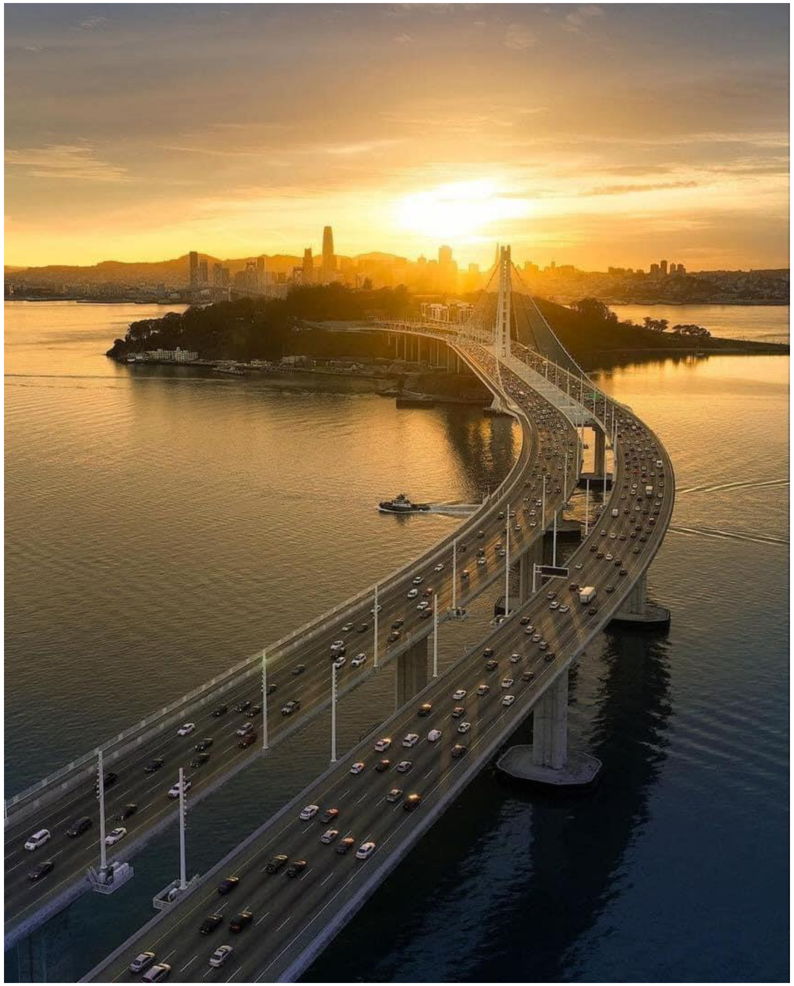
Cable Stayed Bridge



Port Mann Bridge (Vancouver, Canada): Opened 2012

Construction: Kiewit Corporation, 2009-2015.

Bay Bridge East Span (San Francisco-Oakland): Opened 2013

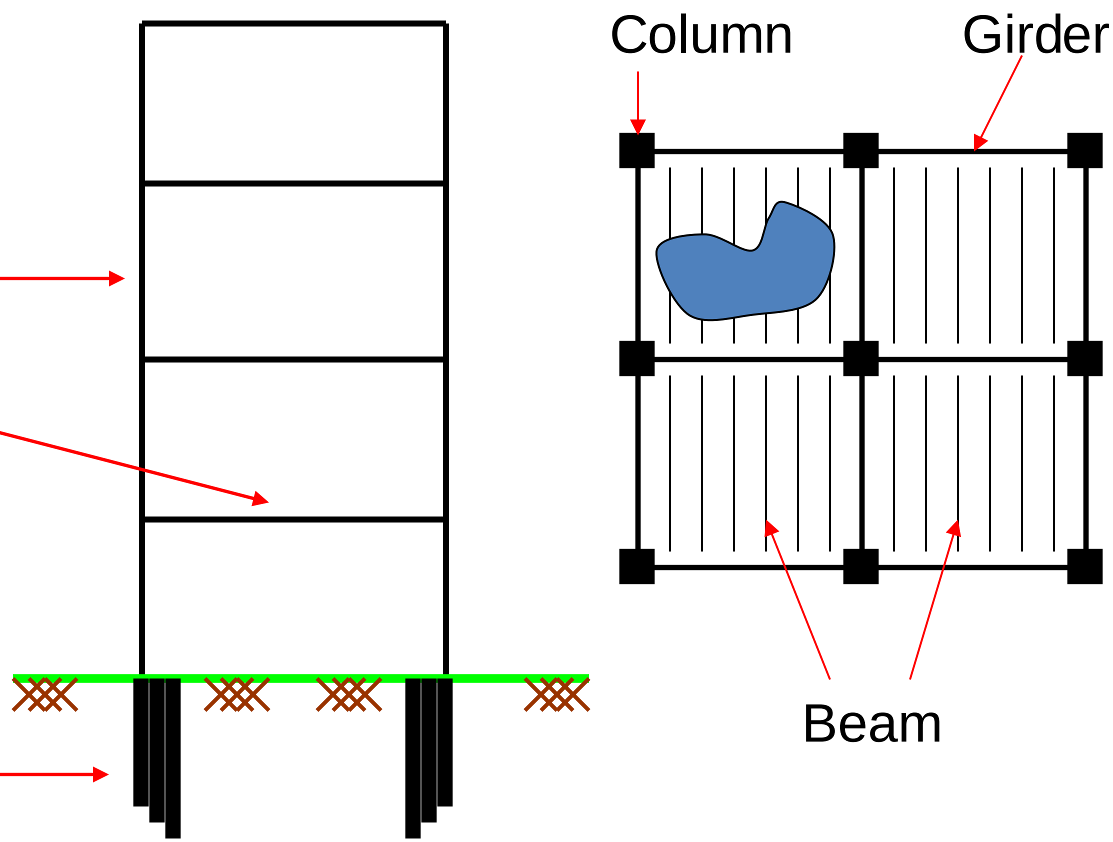


Construction: Kiewit Corporation.
Original budget: $250M; Final budget: $6.5B.

Structural Components and Load Paths

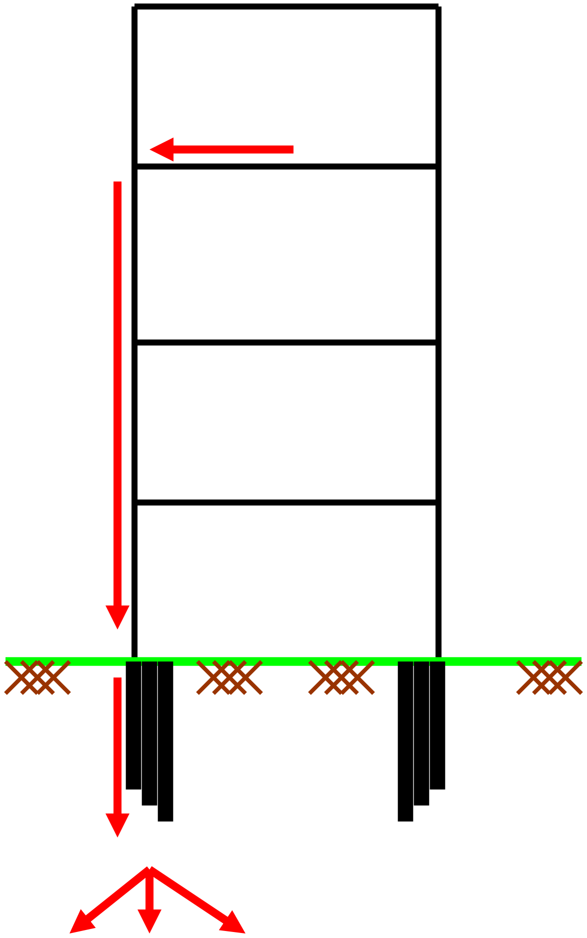
Structural Components

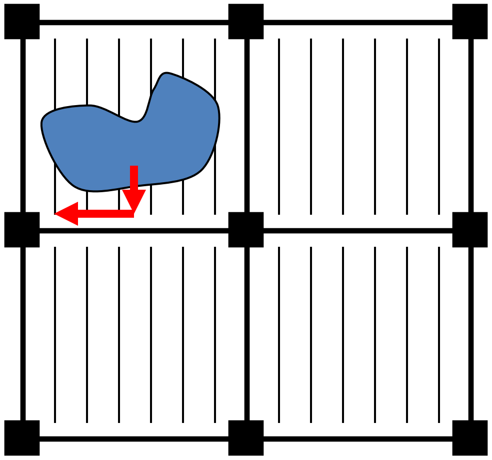
- Beams
- Girders
- Columns
- Floors
- Foundations



Load Path

- Floor
- Beams
- Girders
- Columns
- Foundation
- Soil/Bedrock





Overview of Structural Behavior

Depends on:

- Material properties (e.g., steel, concrete).
- Structural stiffness (e.g. axial stiffness, bending stiffness)
- Structural strength (e.g., ultimate member strength).

Design challenges (many tradeoffs to consider):

- If the structural stiffness is too low, then the displacements will be too large,
- In dynamics applications a high structural stiffness may attract high inertia forces.
- If the structural strength is too low, then the structural system may fail prematurely.

Engineering Properties of Materials

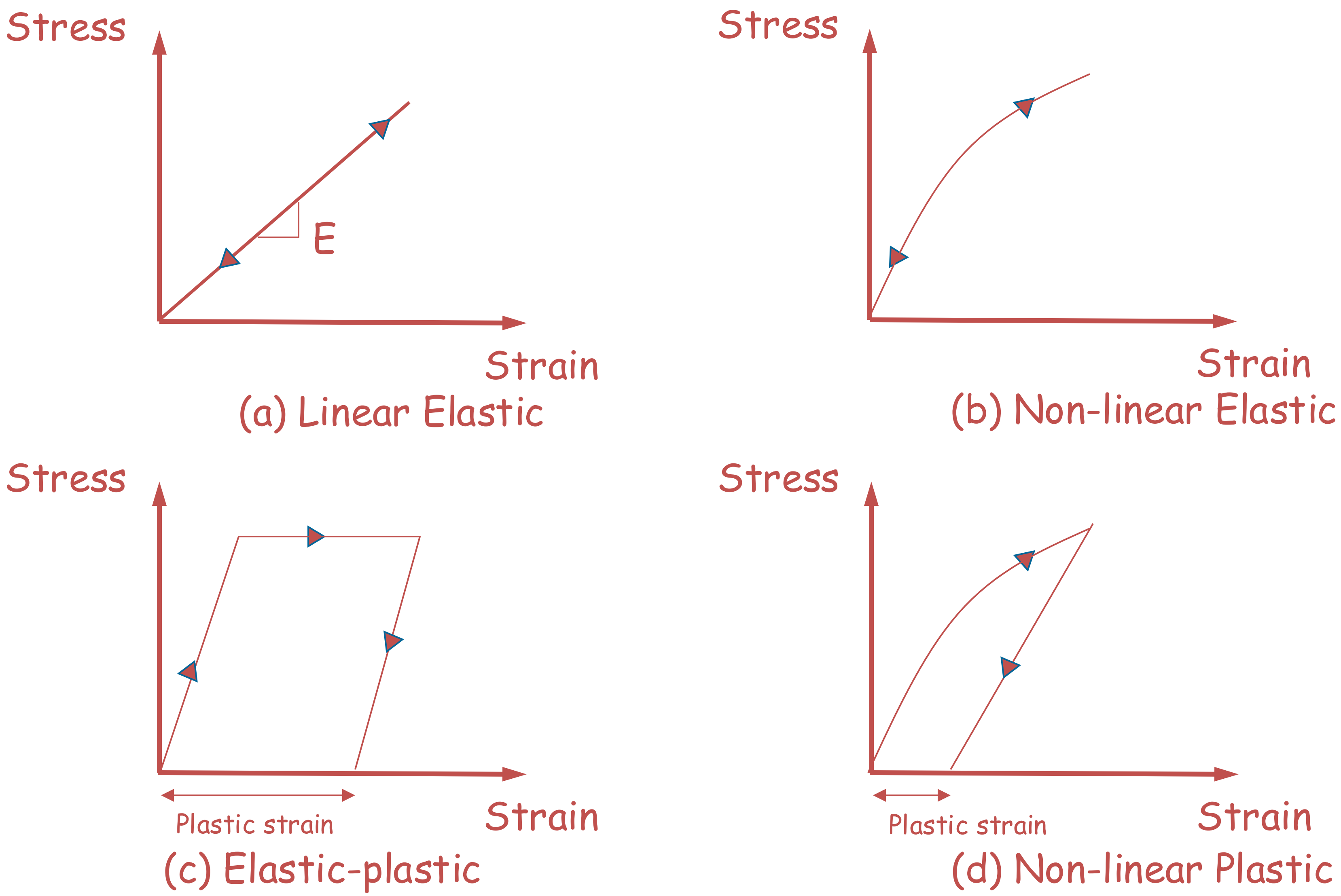
- Steel
  - Maximum stress: 40,000 – 120,000 lb/in^2
  - Maximum strain: 0.2 – 0.4
  - Modulus of elasticity: 29,000,000 lb/in^2

- Concrete
  - Maximum stress: 4,000 – 12,000 lb/in^2
  - Maximum strain: 0.004
  - Modulus of elasticity: 3,600,000 – 6,200,000 lb/in^2

- Wood

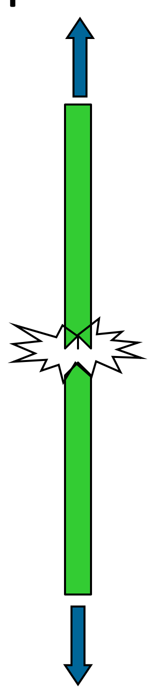
  Values depend on wood grade. Below are some samples
  - Tension stress: 1300 lb/in^2
  - Compression stress: 1500 lb/in^2
  - Modulus of elasticity: 1,600,000 lb/in^2

Types of Stress-Strain Behavior

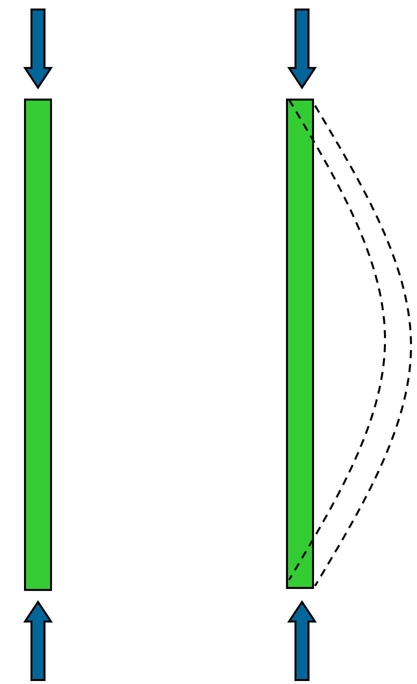


Engineering Properties of Structural Elements

- Strength
  - Ability to withstand a given stress without failure
    - Depends on type of material and type of force (tension or compression)

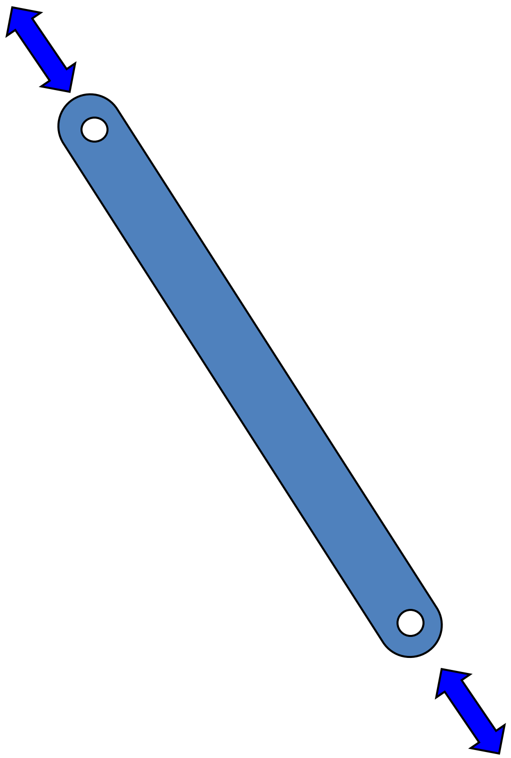


Tensile Failure

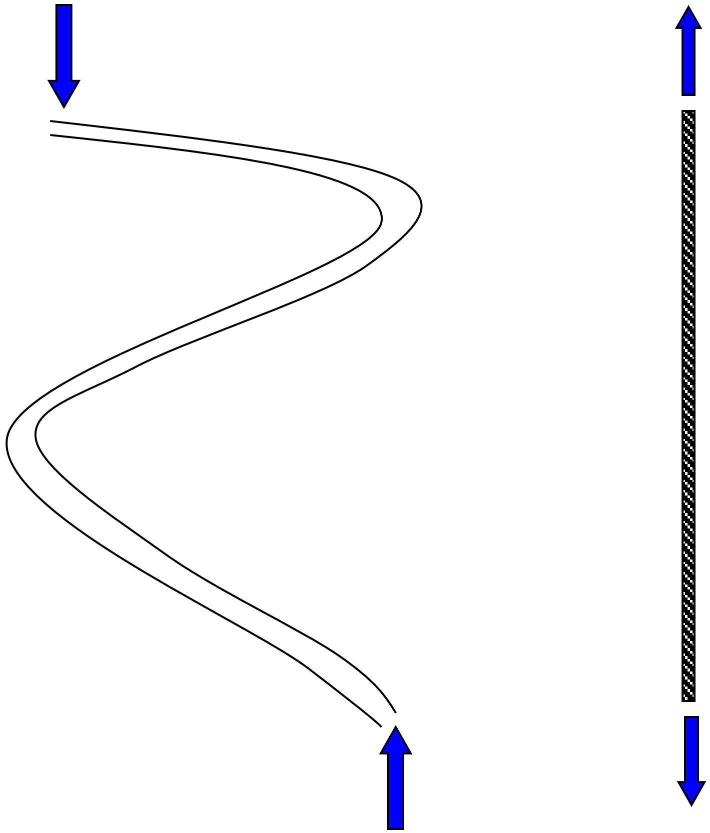


Compressive Failure

Types of Structural Elements – Bars and Cables

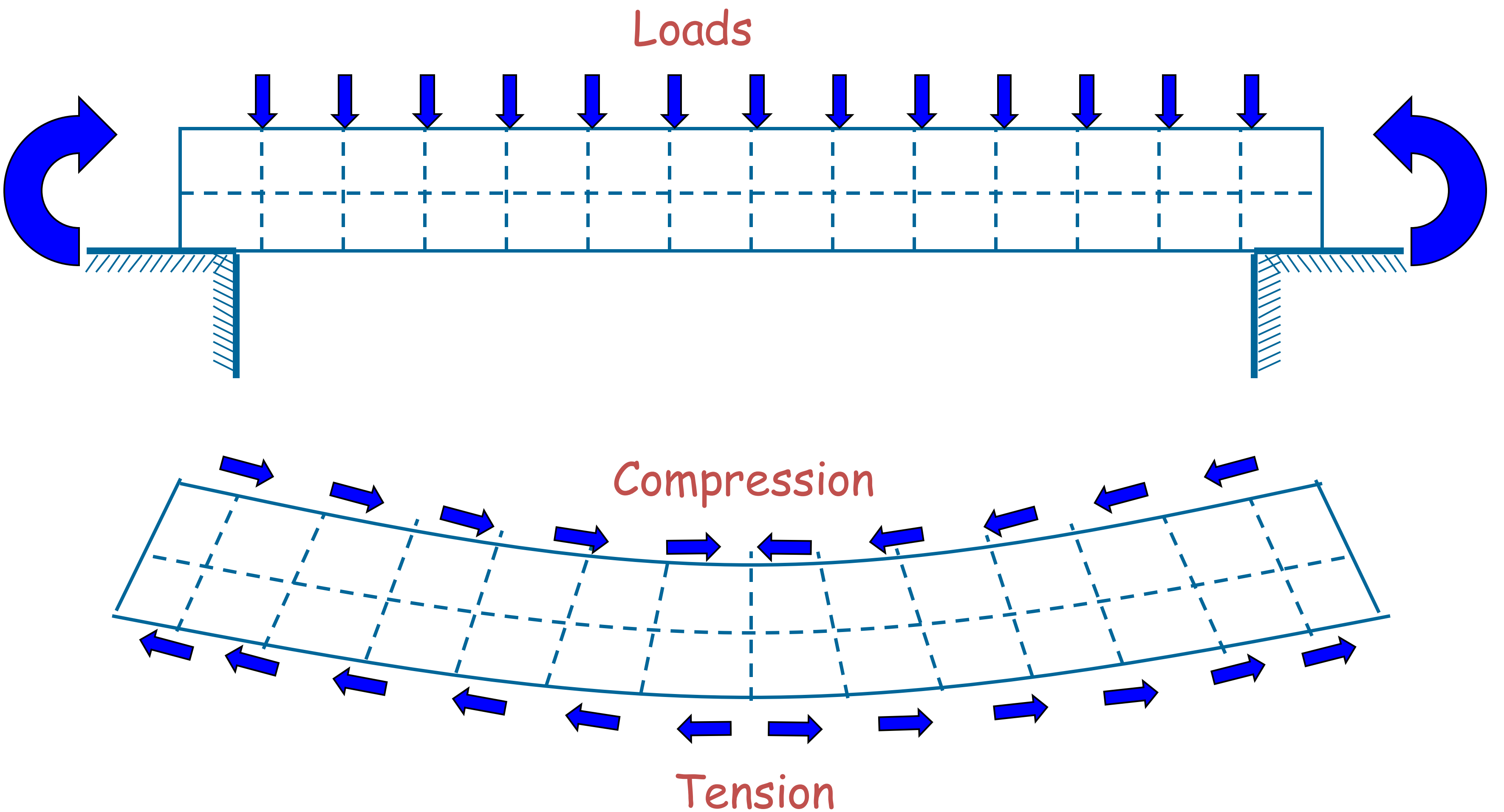


Bars can carry either tension or compression

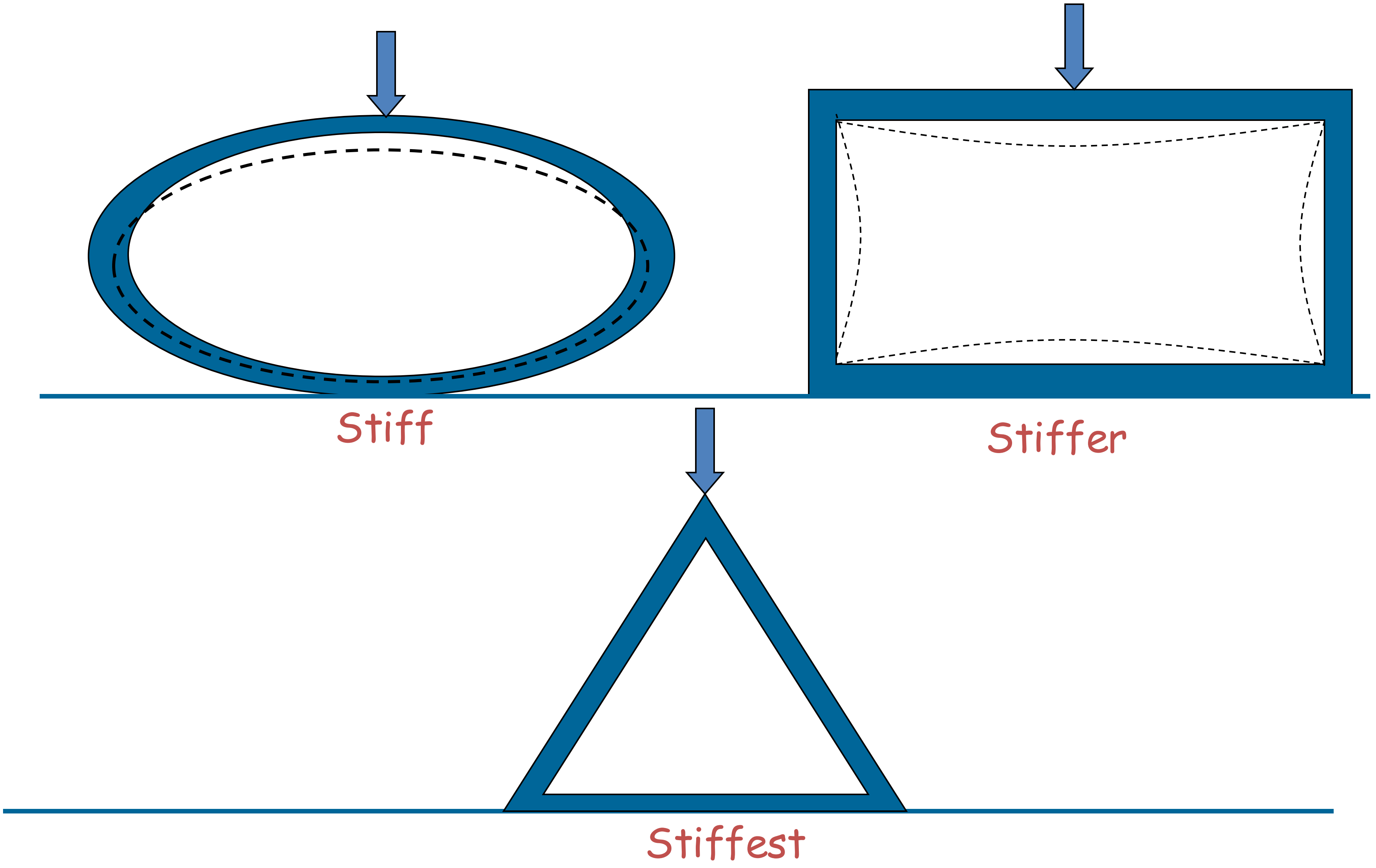


Cables can only carry tension

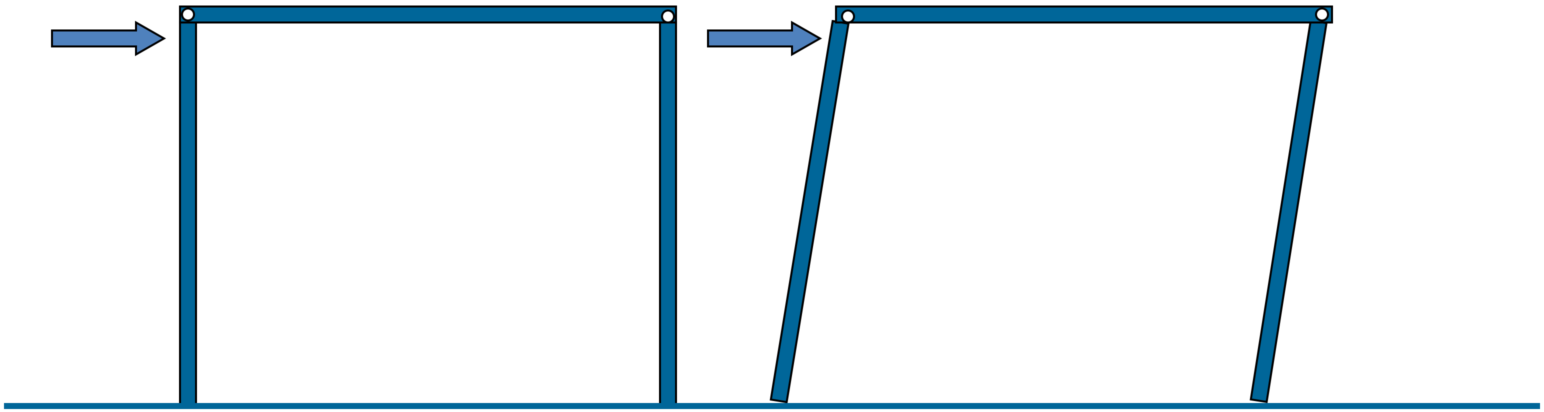
Types of Structural Elements – Beams



Stiffness of Different Structural Shapes



Providing Stability for Lateral Loads



Racking Failure of Pinned Frame

Braced Frame

Infilled Frame

Rigid Joints

Failure Mechanisms

Structural failure refers to loss in the load-carrying capacity of a component or member within a structure.

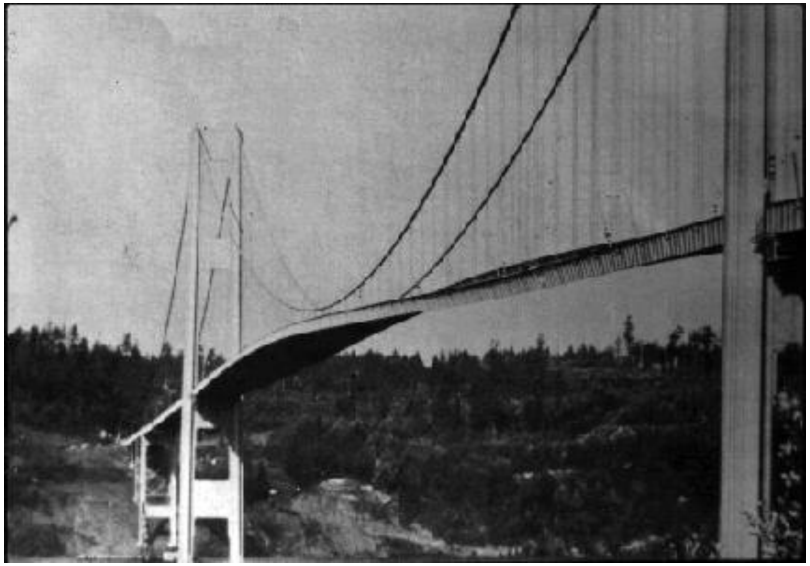
Failure is initiated when the material is stressed to the strength limit, thus causing fracture or excessive deformations.

Ultimate failure is usually associated with extreme events.

The structural engineer needs to prevent loss of life by prohibiting total collapse of the structural system.

Failure due to Dynamic Instability

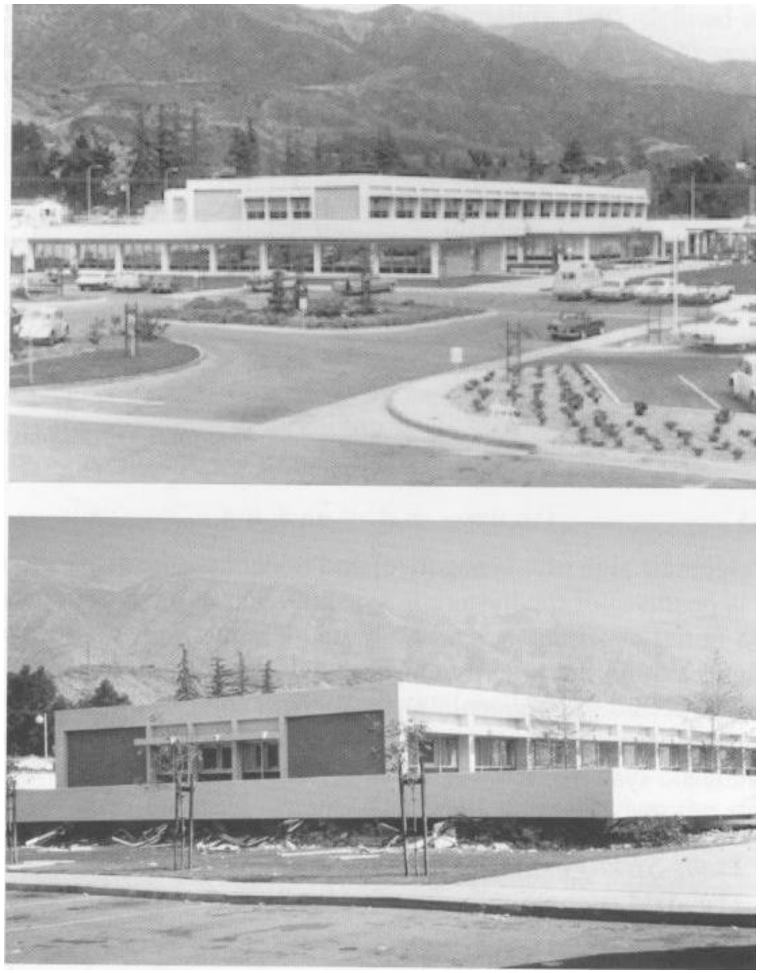
Failure to understand aeroelastic flutter can be catastrophic.



The Tacoma Narrows bridge opened in July 1940 and collapsed a few months later (November 1940) in a 40 mph wind.

Failure completely changed the way in which suspension bridges are analyzed and designed.

Failure due to lack of Ductility in Concrete Columns



Olive View Hospital
M 6.7 1971 San Fernando Earthquake

Frame buildings can have also be built with concrete columns and beams (as opposed to steel)

1971 San Fernando earthquake showed that many concrete frames were brittle

Potential for collapse at drifts of about 0.01 (lower than for steel buildings)

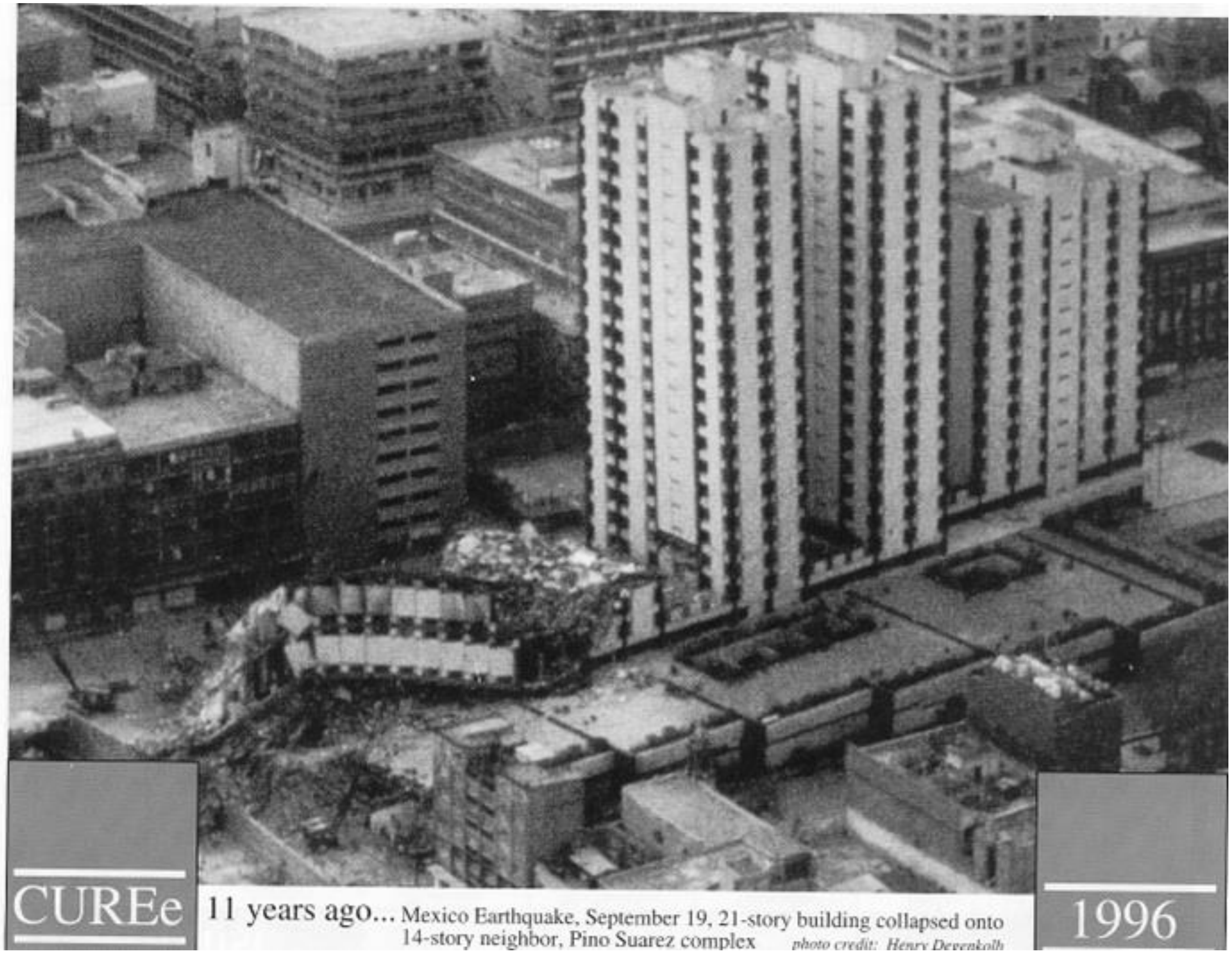
There are thousands of these buildings in California and occupants have not been notified

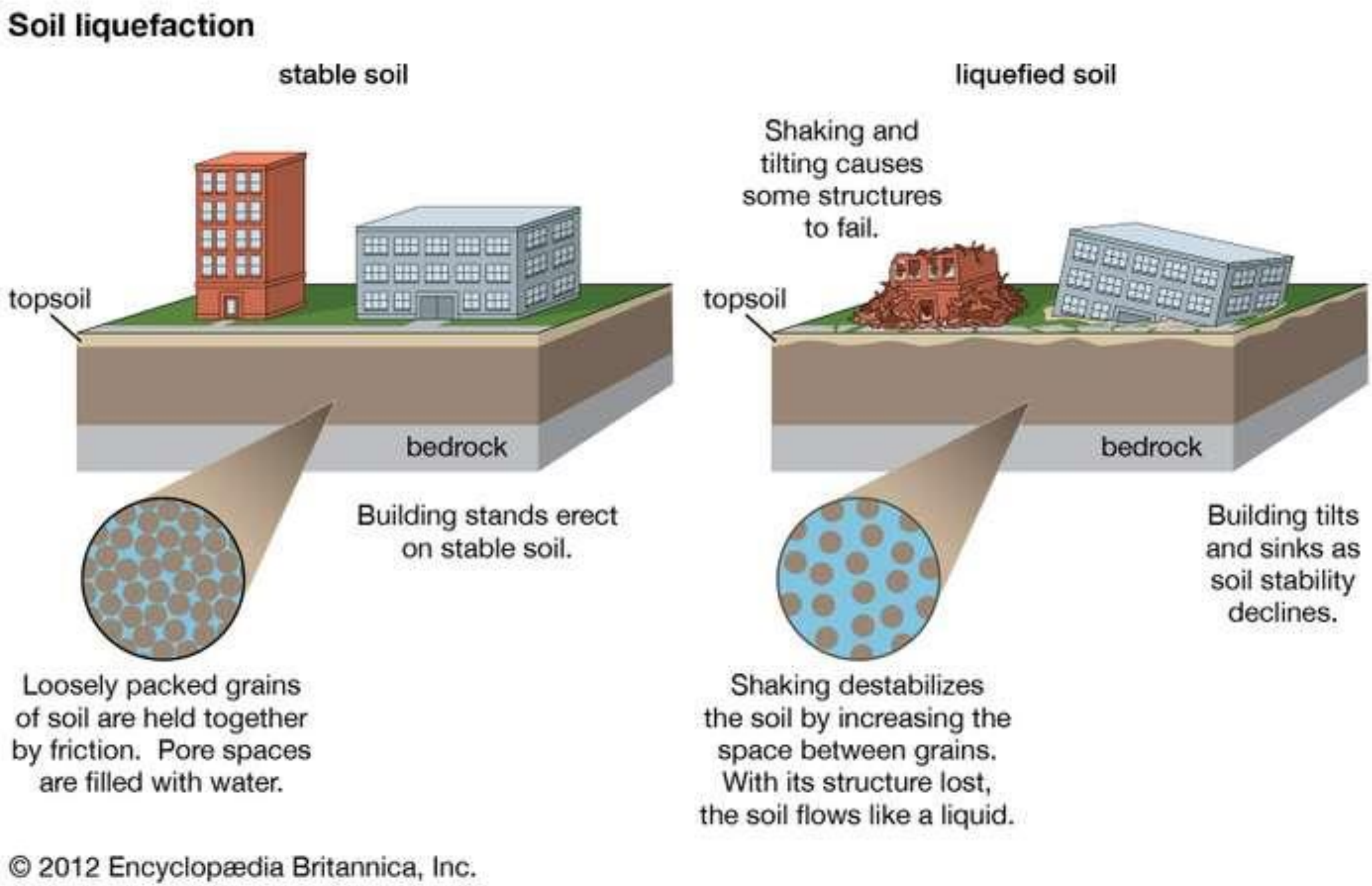
Northridge 118 FWY

Example of failure of a brittle concrete column (pre-1975 code)

Example of “ductile” behavior of concrete columns. Although the parking structure performed poorly, the exterior columns did not fail.

Mexico City Earthquake, 1996





YouTube Search: liquefaction

San Francisco Earthquake, 1906

Failure due to liquefaction in Japan

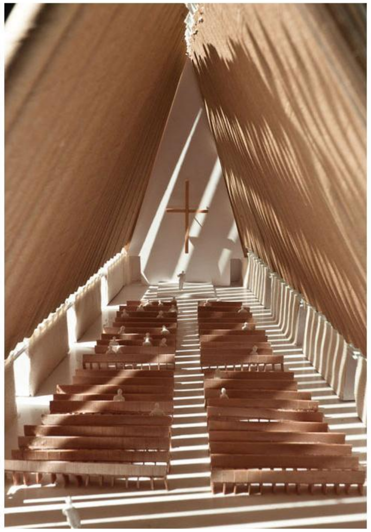
Sometimes you are simply in the wrong place at the wrong time ...

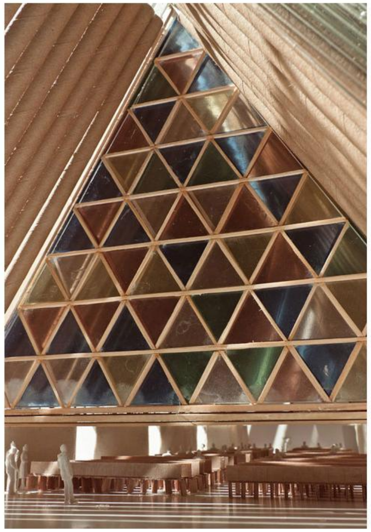
Christchurch, New Zealand, 2011.

Richter Magnitude = 6.3

Failure of the Christchurch Cathedral…

Sometimes extreme events spur real innovation!





Summary

- Structural Engineering:
  - Identifies loads to be resisted
  - Identifies alternatives for providing load paths (arch, truss, frame, ...)
  - Designs structure to provide safe and economical load paths (material, size, connections)
  - To be economical and safe, we must be able to predict what forces are in structure.

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