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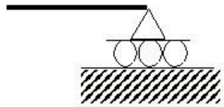
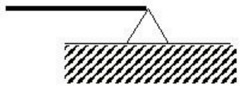
# Designing Connections

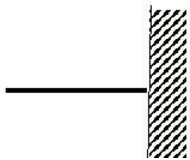
**Roller**



**Pin (hinge)**



**Rigid connection**



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# Connection Design

**Be clear in the function of the connection**

What loads does it have to resist.

**How could it fail.**

**Will it be easy to maintain in the future.**

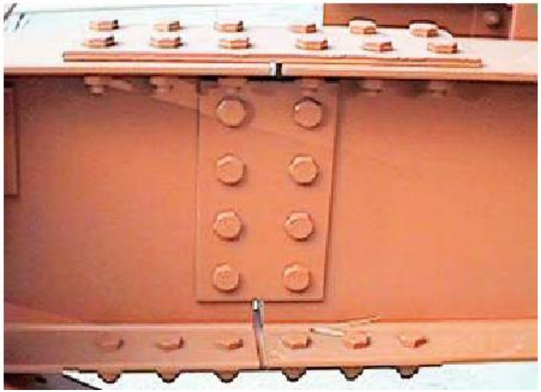
# Connection Design for Strength

**Must Resist:**

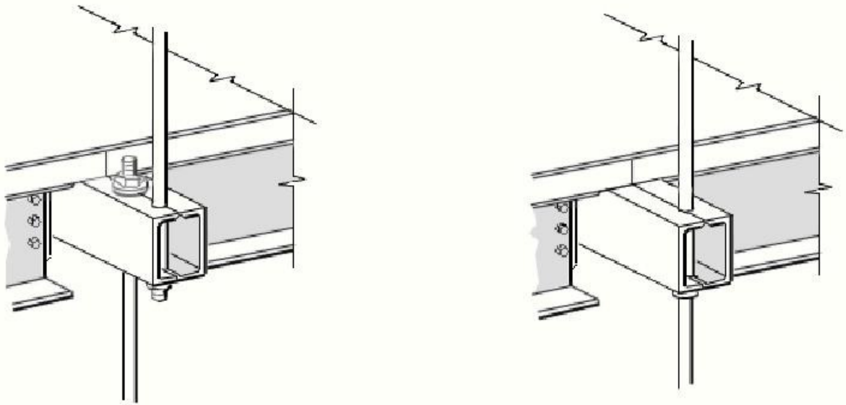
**Axial forces**

**Moment forces**

**Shear forces**



# Suspended Walkway of the Kansas City Hyatt Regency, 1981

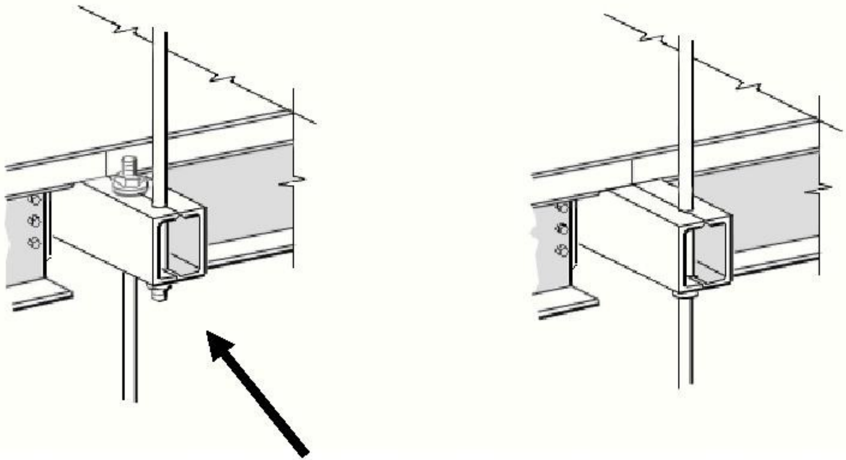


*Is there a difference between these two connections?*

*-Technically?*

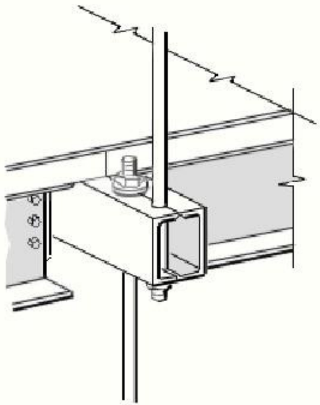
*-Aesthetically?*

## Suspended Walkway of the Kansas City Hyatt Regency, 1981

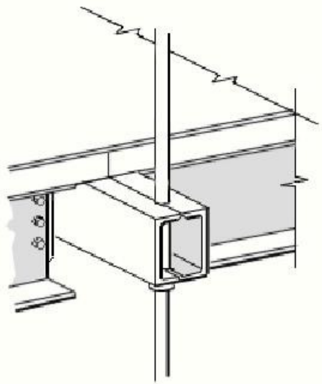


**What is the force on this bolt.**

Suspended Walkway of the Kansas City Hyatt Regency, 1981



As-built connection



Initial connection design

**Everyone agreed to the design change without thinking of the**

**implication**

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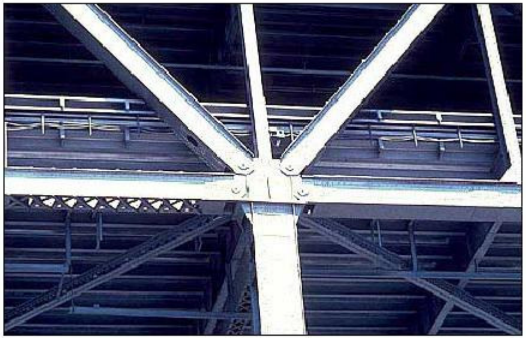
# Lessons from the Kansas City Collapse, 1981

**Imagine that you are the structural element or the connection: how could the forces be transferred from one member to the other.**

**For axial force members, align each member so the connection reduces to a**

**reduces to a single point**

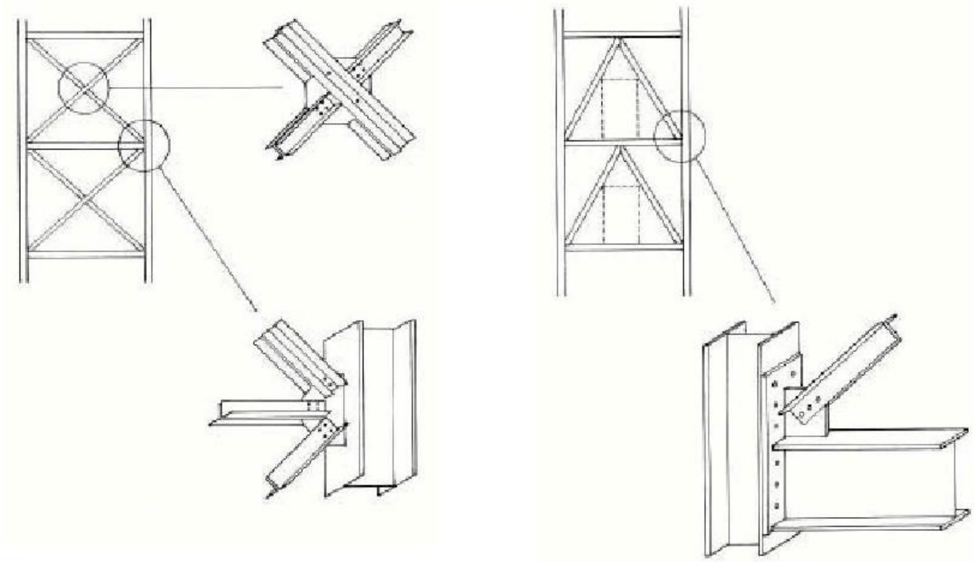
# Connection Geometry



**Centroid axis of each member should pass through the same point**

**through the same point**
**(particularly true**
**for axial force structures like trusses.)**

# Steel Bracing Connections

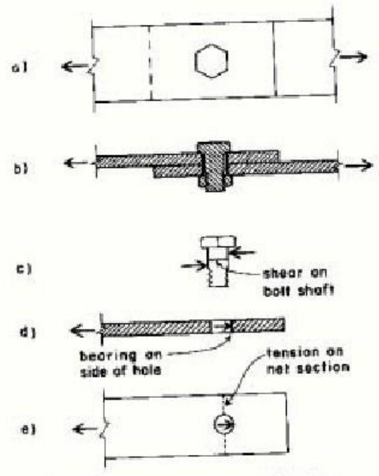


**Centroid axis of each member should pass through the same point**

# Bolt in Single Shear

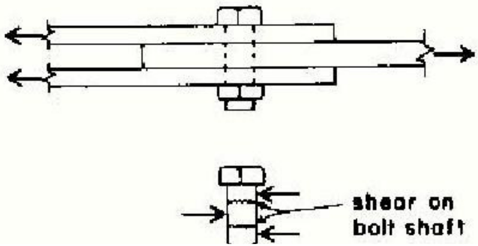
Shear stresses try to slice the bolt

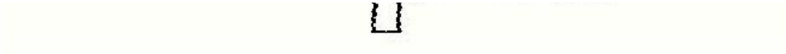
Stress equals shear force divided by the cross-sectional area of the bolt



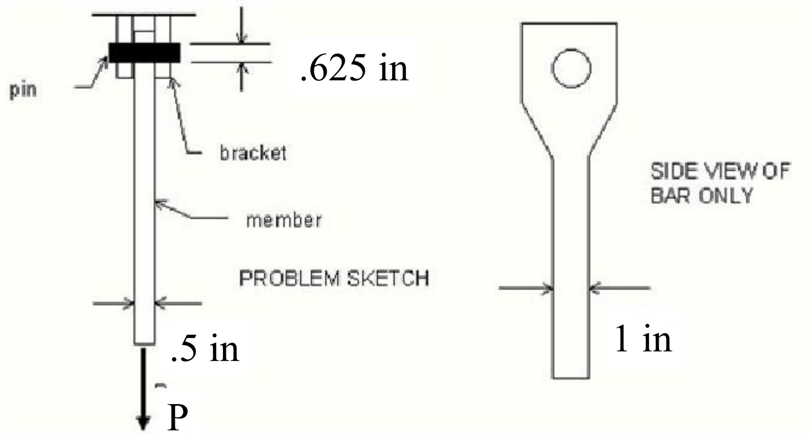
# Bolt in Double Shear

**Shear stress is one *half the value of* the applied load**





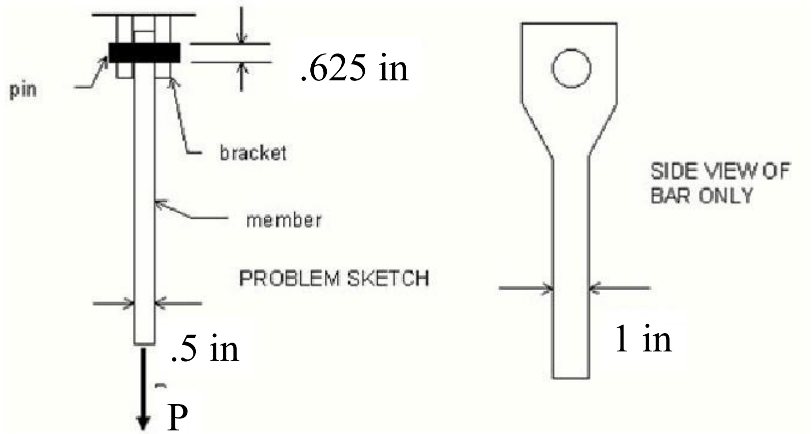
# Example problem




**What are the ways this connection**

**could fail. (allowable stress = 10 ksi)**

# Example problem

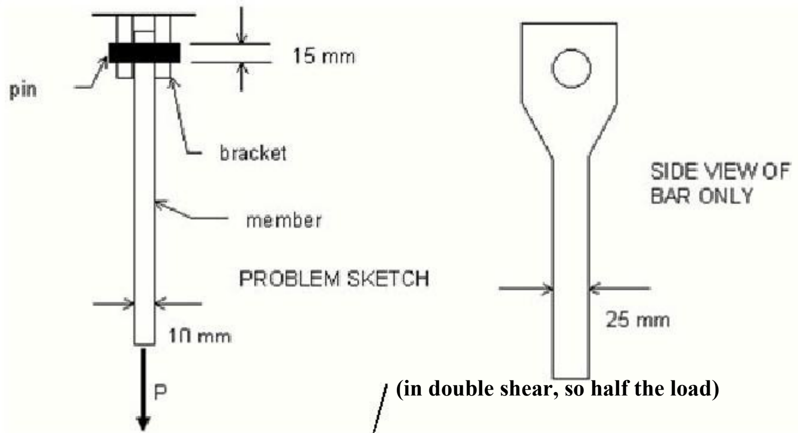



**1. Maximum axial stress on the bar:**

**F = (Stress)(Area) = (10 ksi)**

**F = (Stress)(Area) = (10 ksi)(1 in)(0.5 in) = <u>5 kips</u> (5000 pounds)**

# Example problem




(in double shear, so half the load)

**2. Maximum shear across the pin: (area = 0.31 in $^2$)**

**F = (Stress)(Area) = (2) $^2$)**

P = (Stress)(Area) = (2) )

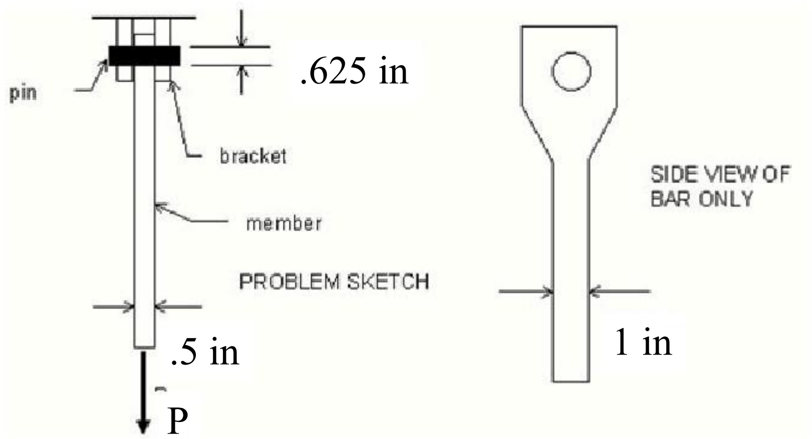
(10 ksi)(0.31 in

**kips** (6,200 pounds)

=

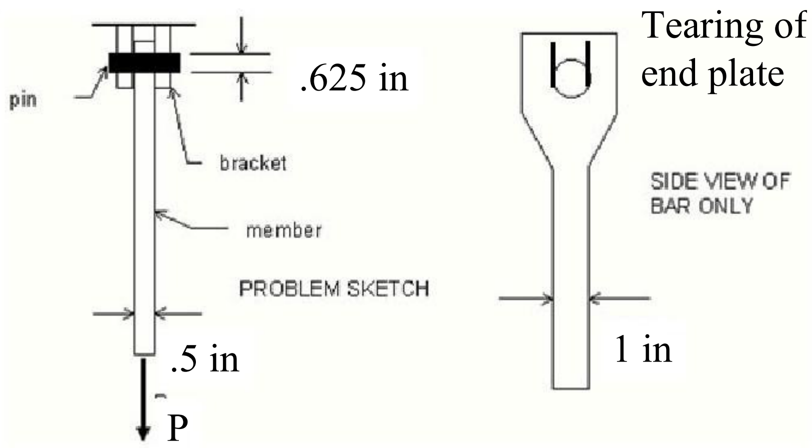
6.2

# Example problem




**Other modes of failure. (at least 3)**

# Example problem




# Other modes of failure.

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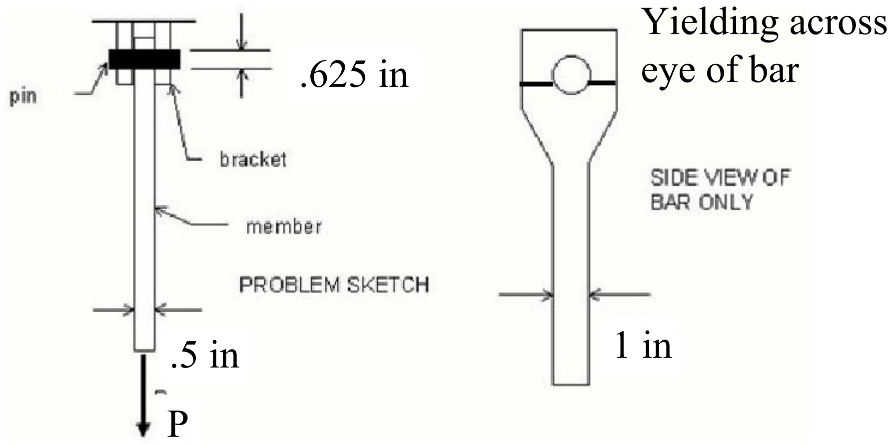
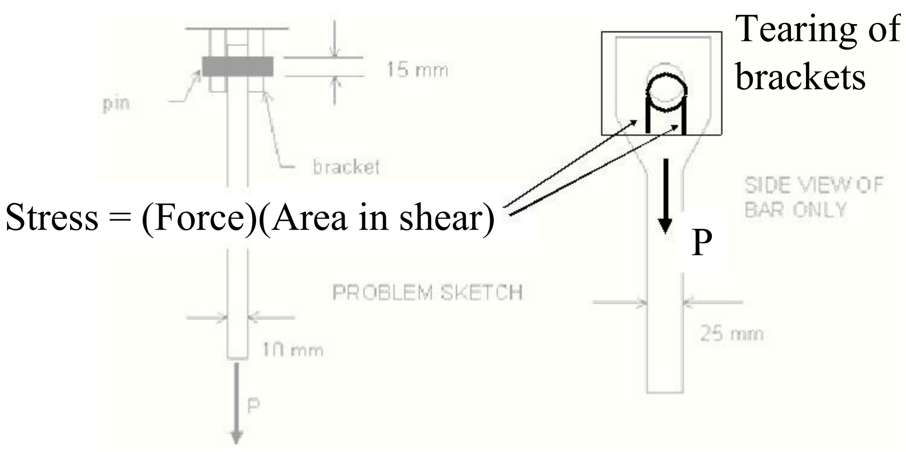
# Example problem



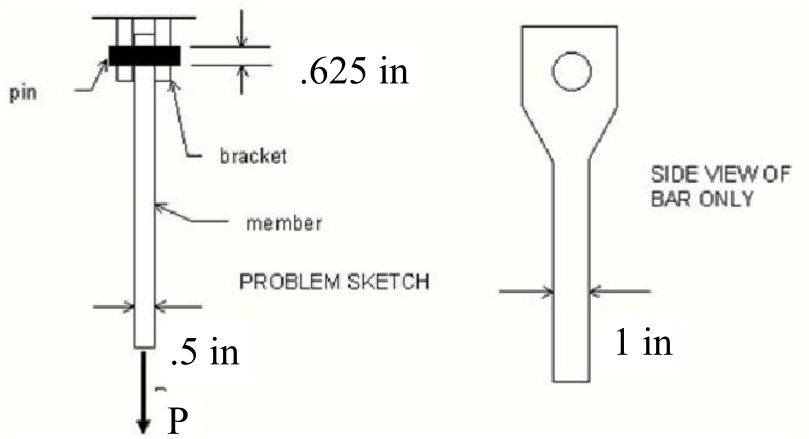

**Other modes of failure.**

# Example problem




**Other modes of failure.**

# Example problem




**Conclusion: Even the simplest**

**connections can fail
in many ways**

# Axial Force Connections

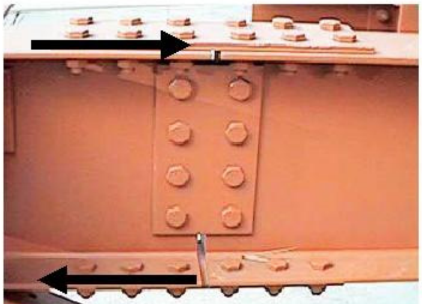
Consider all sections of material where failure could occur

Compare allowable force for each section, and the lowest force value governs the design load capacity

If the joint acts in

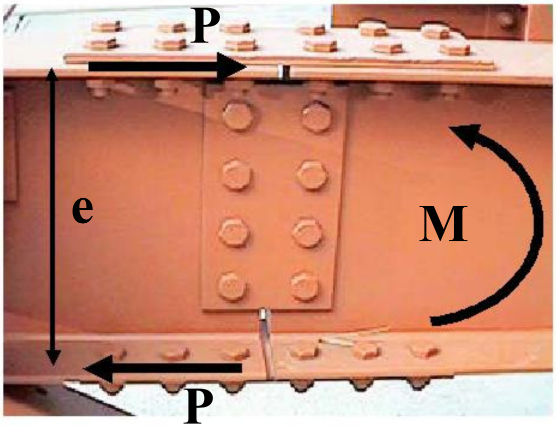
- compression, beware of buckling (typically in plates)

# Moment Connections

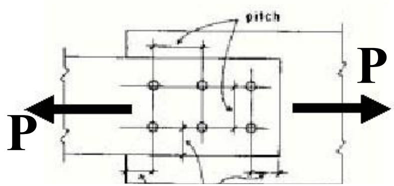


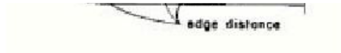
# Tie flanges together to transfer moment

# Moment Connections




**Moment, M = Pe**



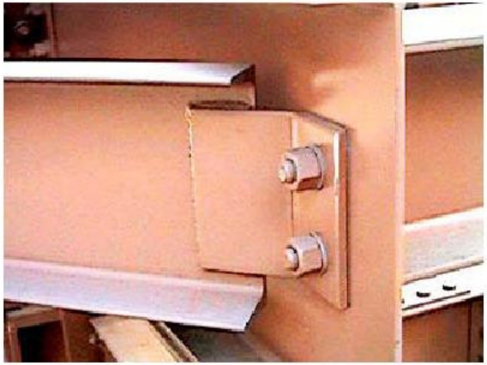



# Design for axial force, P

# Shear Connections

## Use the web of the beam to transfer shear

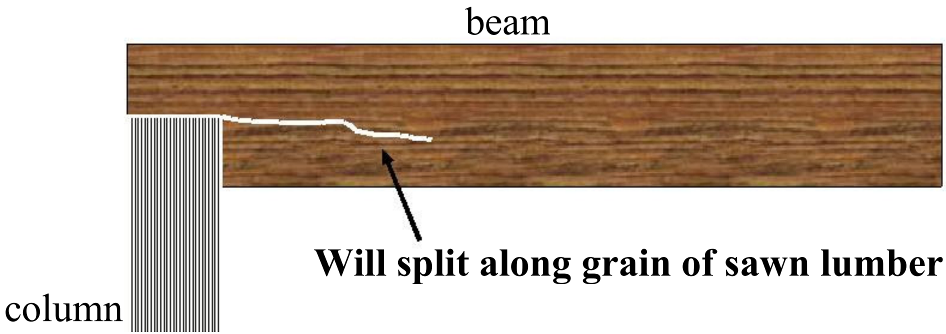
# Shear Connections



# Use the web of the beam to transfer shear

# Connections: Beware!

2. **Wood has different properties with and against the grown: beware of splitting**



# Properties of Timber

- Cellular structure is very efficient
- Handles both compression and tension well
- Different strengths with and against the grain
- Inhomogeneous material with imperfections

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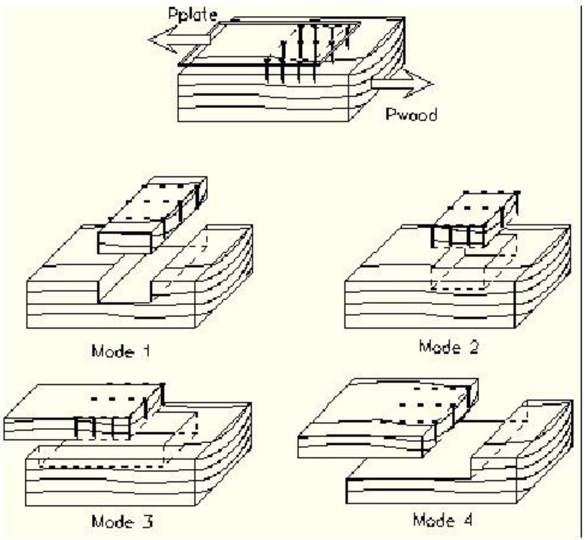
# Metal Shear Plate on Wood



**Must consider various possible failure modes**

# Connections: Beware!

4. **Someone will have to disassemble your connection in the future: your construction today will be somebodys problem in the future**

**Case study:**

**Williamsburg Bridge**

# Williamsburg Bridge

Carried traffic and trains throughout the 20th century

But maintenance was neglected badly for decades

In 1988 the poor condition of the bridge became

**became an emergency**

# Decay of Williamsburg Bridge

Main cables had corroded badly (were not galvanized)

Pin joints in the main trusses were corroded

Rusted girders

# 1990-2005: Rebuilding the Williamsburg Bridge

- **New cables, new girders, new roadways, new bearings, new paint, etc**
- **Original designers didnt consider how to repair many elements**

# Designing for Maintenance and Deconstruction

**Develop a maintenance plan for your structure**

**Design components which are accessible and replaceable**

**Avoid toxic materials which are hazardous for future repairs or demolition**

# Connection Conclusions

**Design for strength: how could it fail.**

**Design for serviceability: can it be maintained easily.**

**To design a good connection you must know exactly what it has to do: seek clarity in design**

# Steps in Finite Element Analysis

1. **Define geometry**
2. **Connect nodes with members**
3. **Assign section properties (A, E, and I)**
4. **Define fixity of nodes and connections**
5. **Apply loads**

## 6. Run analysis and examine output

# Structural Failure

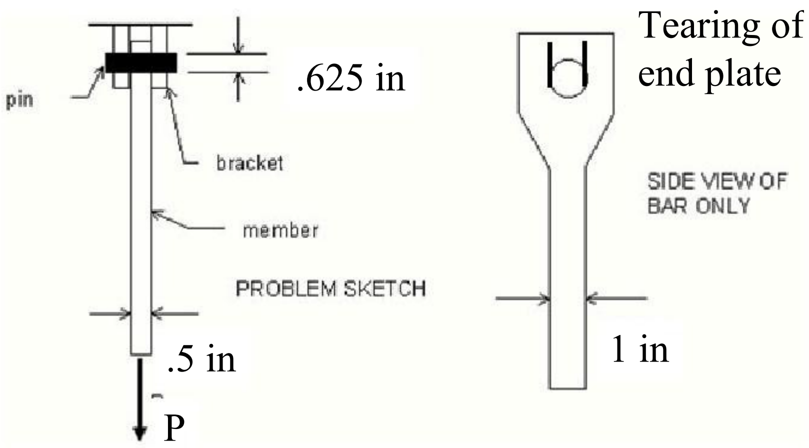
**Be clear in the function of the connection**

What loads does it have to resist.

**How could it fail.**

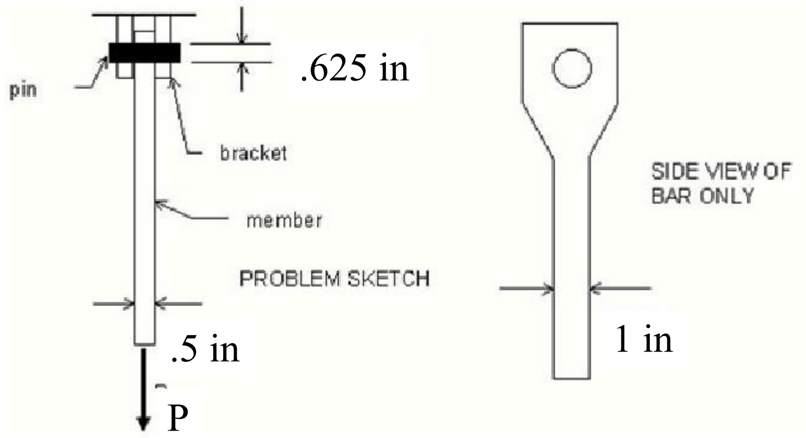
**Will it be easy to maintain in the future.**

# Example problem




# Other modes of failure.

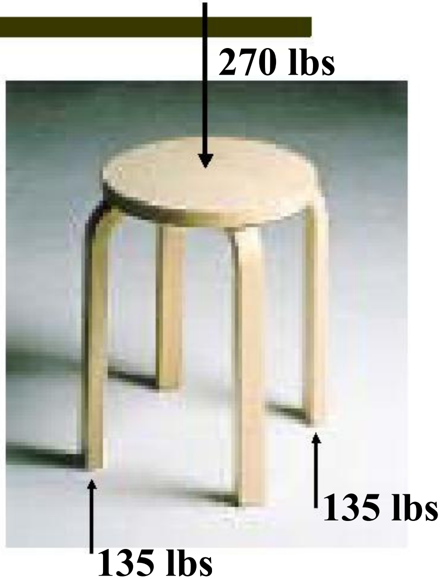
# Example problem




**Conclusion: Even the simplest**

**connections can fail in many ways**

# Four-Legged Stool Example



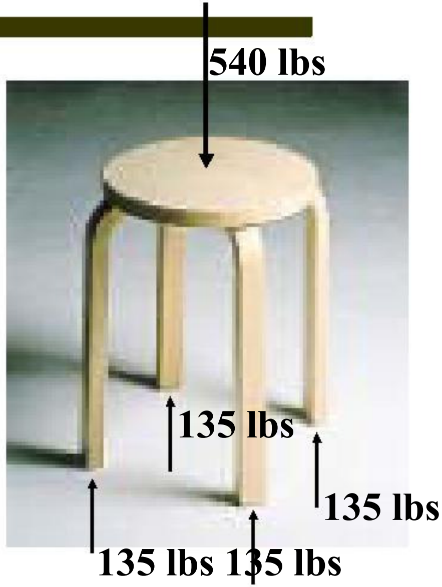

Now imagine the load is increased to cause failure

When load is 270 lbs, the two legs will begin to fail

As they squash, the other two legs will start to carry

**carry load also**

# Collapse of a 4-Legged Stool




**At final collapse state, all four legs carry 135 pounds and the stool carries 540 pounds.**

**This occurs only if the structure is ductile (ie, if the legs can squash)**

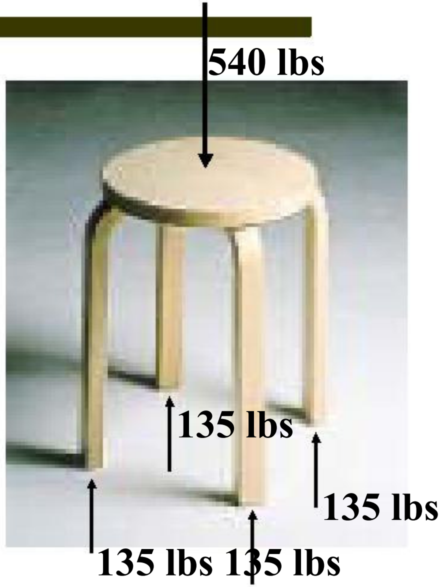
**Is NOT valid if**

**is NOT valid if**
**buckling occurs,**
**because one leg will fail suddenly**

# Ductile Collapse

So small imperfections do not matter, as long as the structural elements are ductile

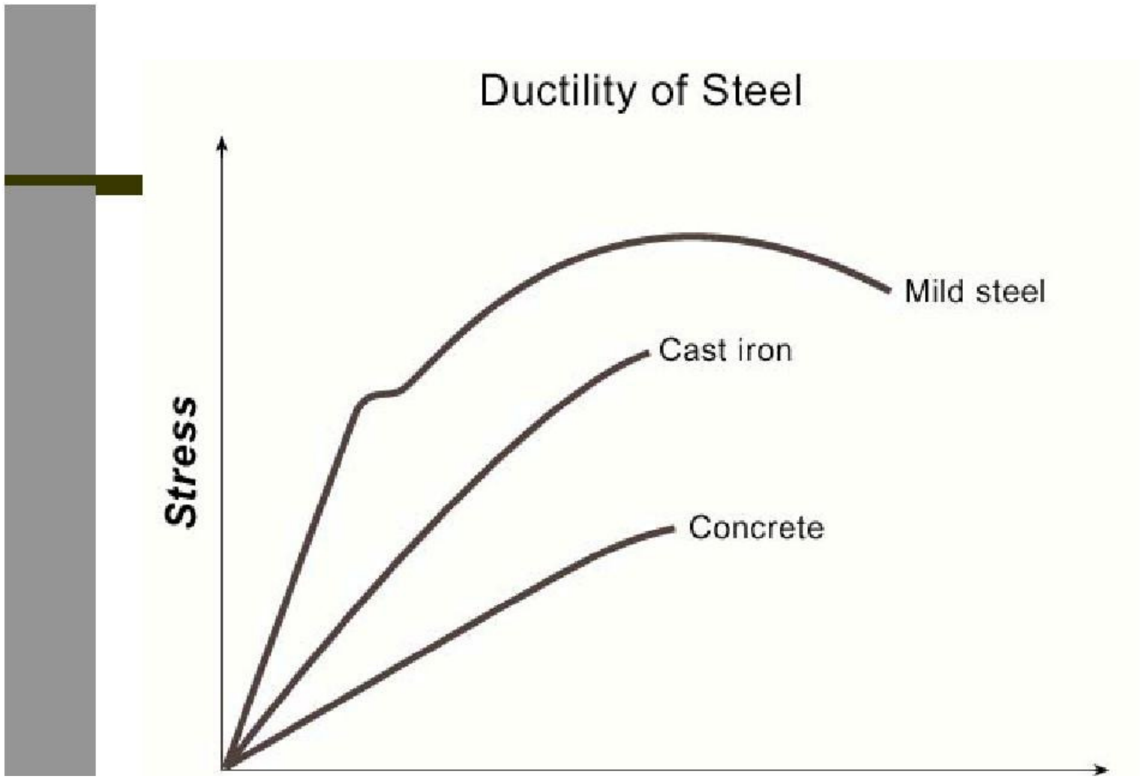
The forces in a hyperstatic structure cannot be known exactly, but this is not important as long as we can predict a ductile collapse state



# Why is steel a good structural material.

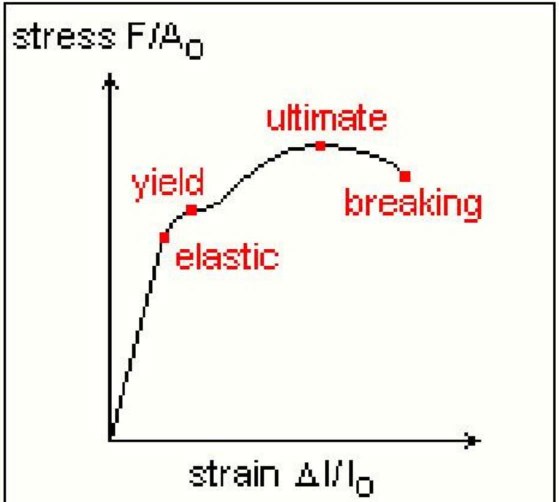
High strength

Ductile material


Ductility of Steel
Stress
Mild steel
Cast iron
Concrete

## Strain

# Yield Stress of Steel




**Stress-Strain Relation**

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# Failure of Independent Elements

**Tension element: breaking stress exceeded**

**Compression element:**

Crushing stress exceeded

Buckling occurs

**Truss:**

Statically determinate: one element fails

Indeterminate to n degrees: n elements fail

**Beam:**

Either flange fails in compression or tension will form a

**hinge (Indeterminate to n**

**hinge (indeterminate to n degree: n hinges form)**

Shear failure

# Parallel Axis Theorem

**To calculate the moment of inertia, I, of a built-up section with respect to an axis other than its centroid:**

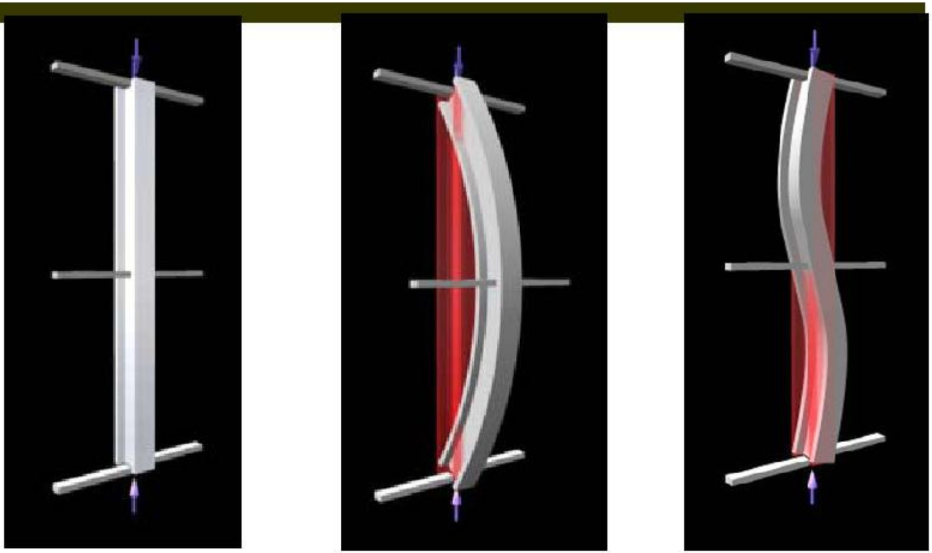
$$I = SI + SAd^2$$

**Where:**

**A is the area of the segment**

**d is the distance from the centroid of the area to the axis being considered**

# Buckling About a Different Axis



Unbuckled Strong Weak

Unbuckled Strong axis Weak axis

**Must brace columns against weak axis buckling**

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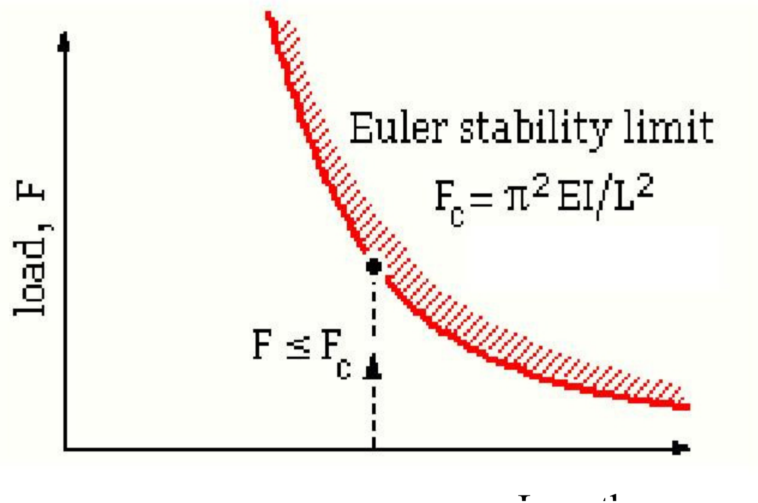
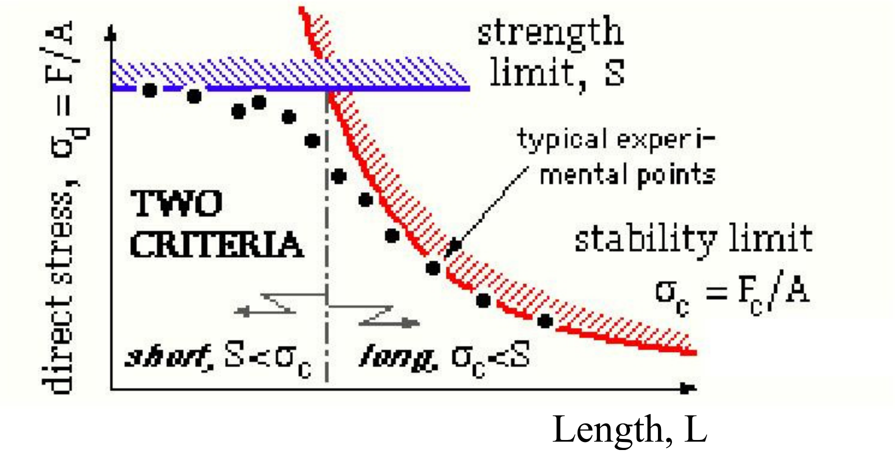
# Buckling Load vs. Length of Column



Length,
L

# Failure of Compression Members



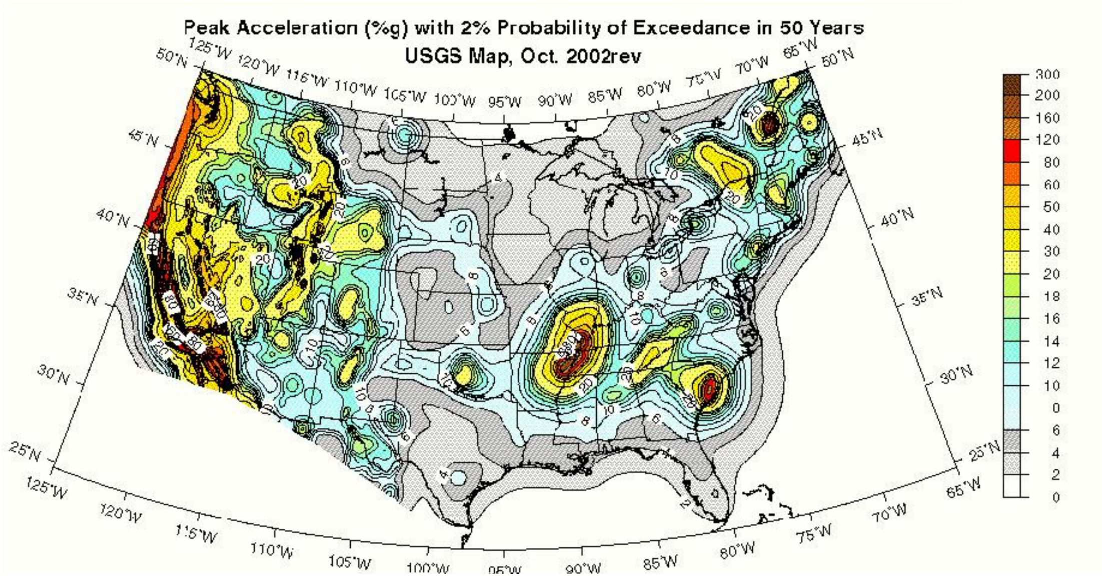
**Failure by buckling or crushing**
**Reality may be in between the two modes**

# Importance of Ductility

Large displacements before collapse (as **opposed to a brittle material, which fails suddenly)**

Energy dissipation as the steel yields **(important for resisting earthquakes and other overloading)**

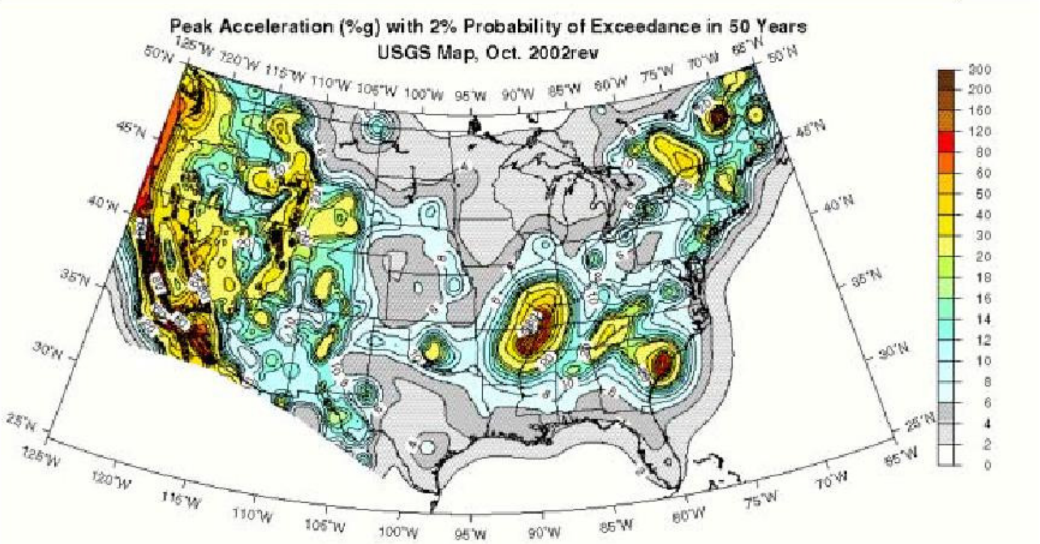
# Is there a danger of earthquakes in Boston and other East Coast cities.



# US Seismicity

**Which state in the mainland US has had the largest earthquake.**

# US Seismicity



## Missouri: 8.2 in New Madrid, MO, 1812

# Increased Earthquake Risk

Growing cities and infrastructure

Many existing buildings are untested in a major earthquake

Earthquakes are not dangerous, but our infrastructure is dangerous

# Structural Failures

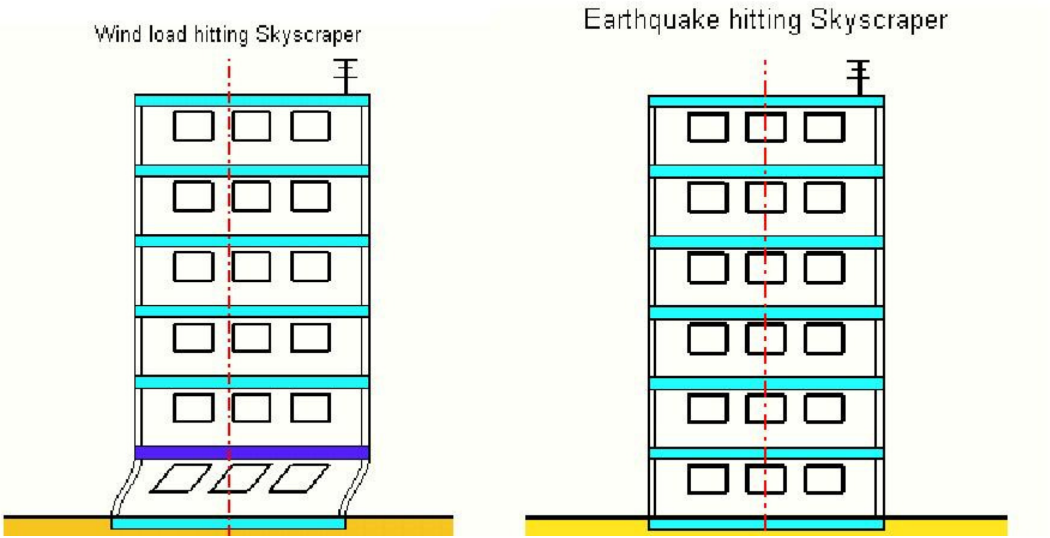
How could it fail. What is the weak link in the system.

Buckling is difficult to predict due to sensitivity of the parameters

Some failure modes are combined modes, i.e., local crushing can

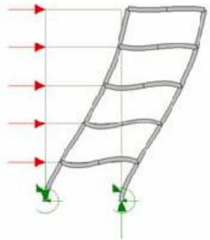
**i.e., local crushing can lead to global buckling**

# Loading + Failure



# Lateral Load Systems

**1. Frame** **rigid joints**



**2. Bracing** **diagonal elements**

**3. Shear wall** **diaphragm**

# Good Practice in Wind Design

**Provide greater resistance along shorter dimension**

**Careful attention to detail**

- Continuity of structure
- Provide ties for each element

**Greater weight can provide greater wind resistance**

**Protect inhabitants from flying projectiles**

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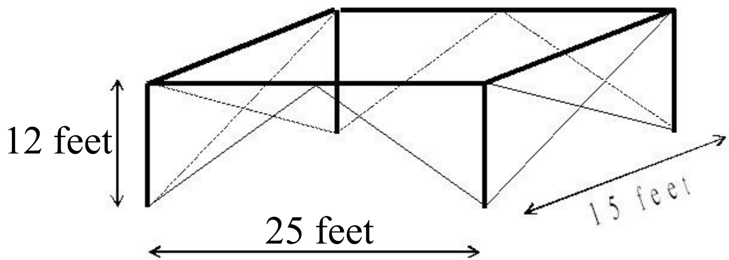
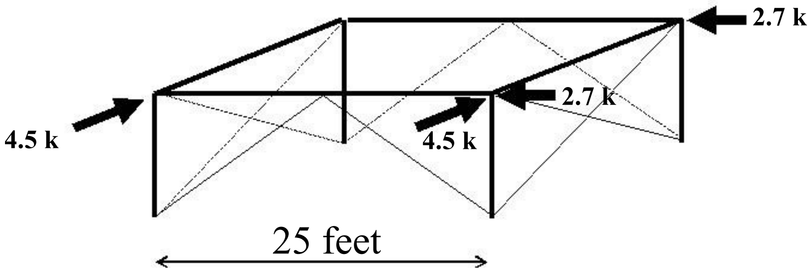
# Wind Bracing Example




**Wind loading of 30 pounds per square foot applied on**

**square feet applied on each side**

# Wind Bracing Example

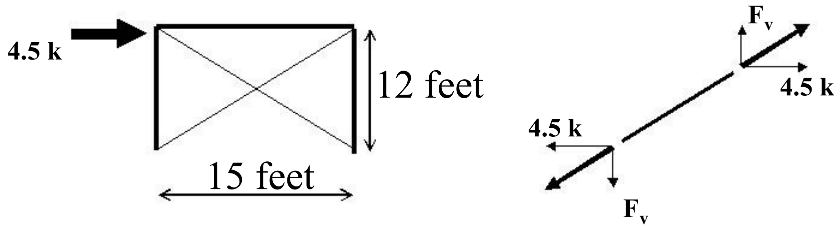



**(25 ft)(12 ft)(30 psf) = 9,000 lbs**

**Applied at top of wall, 4,500 lbs/frame (4.5 k)**

**(15 ft)(12 ft)(30 psf) = 5,400 lbs**
**Applied at top of wall, 2,700 lbs/frame (2.7 k)**

# Wind Bracing Example

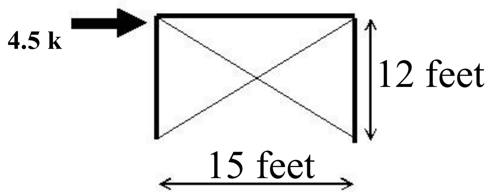


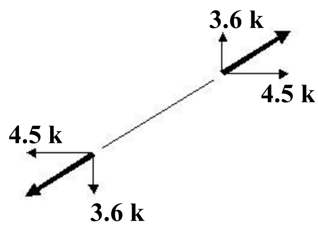

**If the cable carries 100% of wind load, then the horizontal component of force in the cable must be 4.5 k**

$$F_v/(4.5\ k) = (12\ ft)/(15\ ft)$$

$$F_v = 3.6\ k$$

# Wind Bracing Example

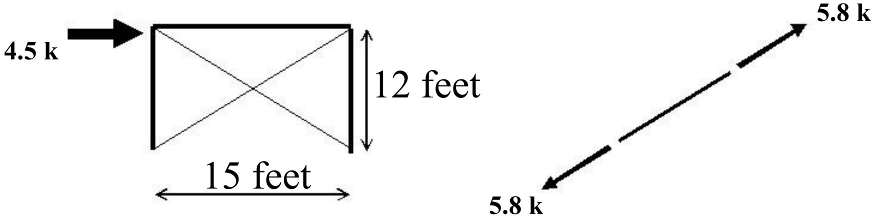



**Internal force in the cable is found from Pythagorean Theorem**

$$F_{cable} = \sqrt{(4.5\ k)^2 + (3.6\ k)^2} = 5.8\ k$$

# Required Area of Steel Cable




**Maximum allowable stress in cable is 15 ksi (given)**

**Stress = Force/Area**

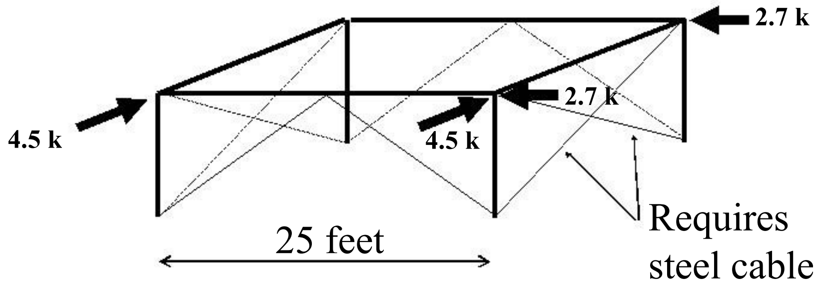
$A_{reqd}$ **= Force/Stress = 5.8 k/15 ksi = 0.38 in** $^2$

**Cable diameter, d**

**Cable diameter, d = 0.7 inches (A=p(0.7)$^2$/4 = 0.38 in$^2$)**

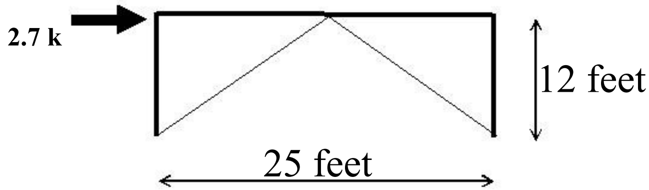
**Specify steel cable (A = 0.44 in$^2$)**

# Wind Bracing Example




**What about bracing in other direction.**

# Wind Bracing Example

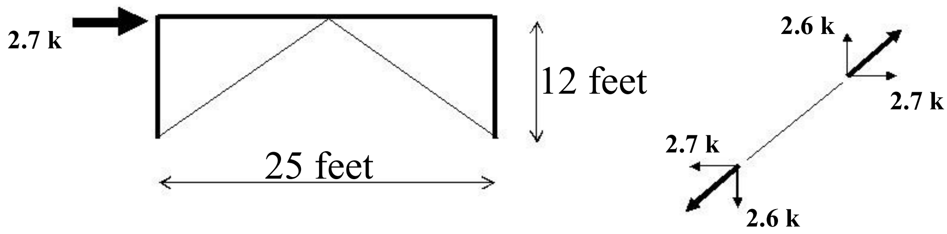



**Assume bracing carries 100% of wind load, then the horizontal component of force in the cable must be 2.7 k**

$$F_v/(2.7\ k) = (12\ ft)/(12.5\ ft)$$

$F_v = 2.6$ k

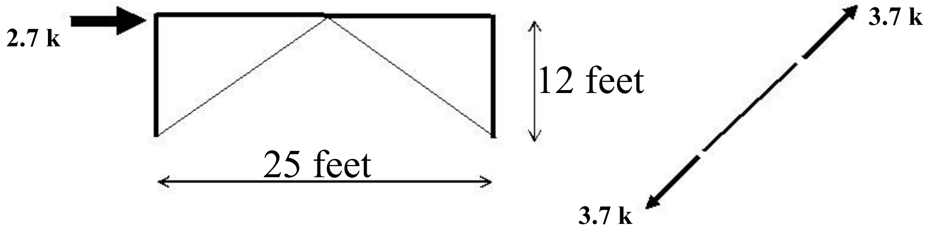
# Wind Bracing Example




**Internal force in the cable is found from Pythagorean Theorem**

$$F_{cable} = \sqrt{(2.7\ k)^2 + (2.6\ k)^2} = 3.7\ k$$

# Required Area of Steel Cable




**Maximum allowable stress in cable is 15 ksi (given)**

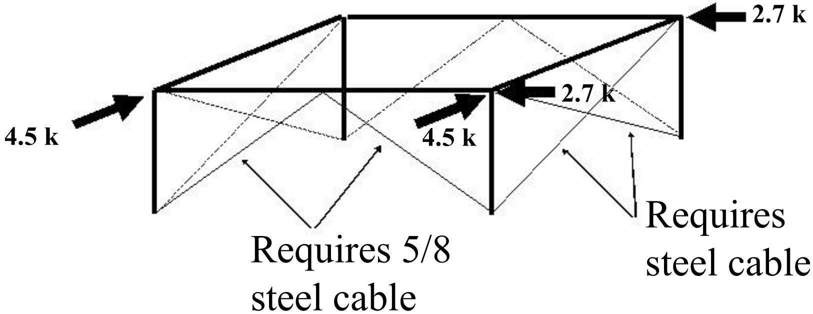
**Stress = Force/Area**

**$A_{reqd}$ = Force/Stress = 3.7 k/15 ksi = 0.25 $in^2$**

**Cable diameter, d = 0.56 inches (A=p (0.56)$^2$/4 = 0.25 in$^2$)**

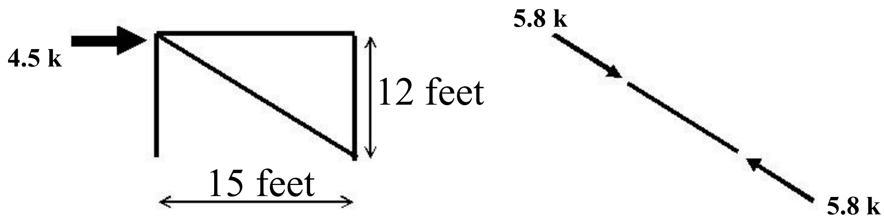
**Specify 5/8 steel cable (A = 0.31 in$^2$)**

# Wind Bracing Example




**Design of wind bracing for cables**

# Compression Element as Wind Bracing




**Now one element must carry 5.8 k in both tension and compression**

**For tension, must have an area of 0.38 in $^2$ (3/4 in diameter bar)**

**So cross-sectional area must be greater than 0.38 $in^2$**

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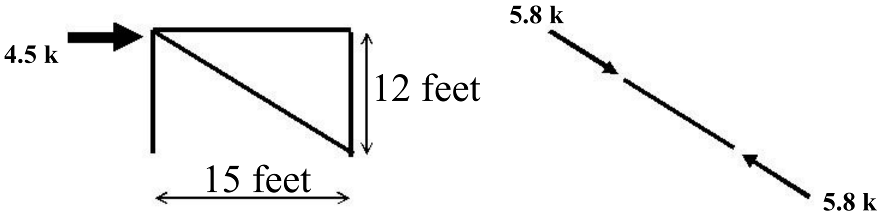
# Compression Element as Wind Bracing




**Compression element requires about 6 times the material (to resist buckling)**

# Design Considerations

**Tension braces use less material than compression braces for lateral loads**

**Compression members must resist buckling which requires extra material**

**Must consider buckling about either axis, and should brace**

**and should brace**
**the weak axis**

# Design Considerations

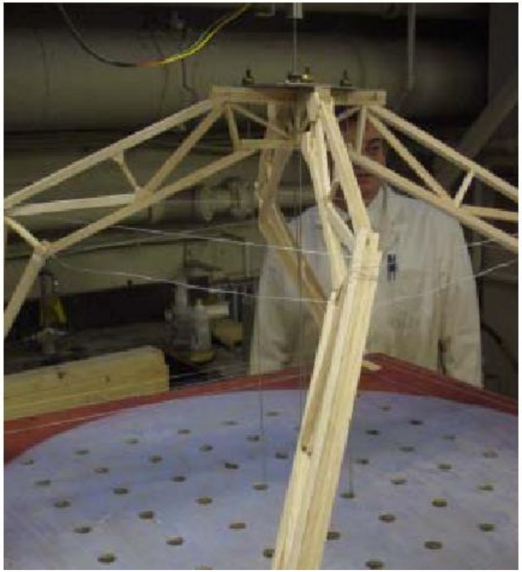
Want to have ductility in our structures so that sudden collapse does not occur

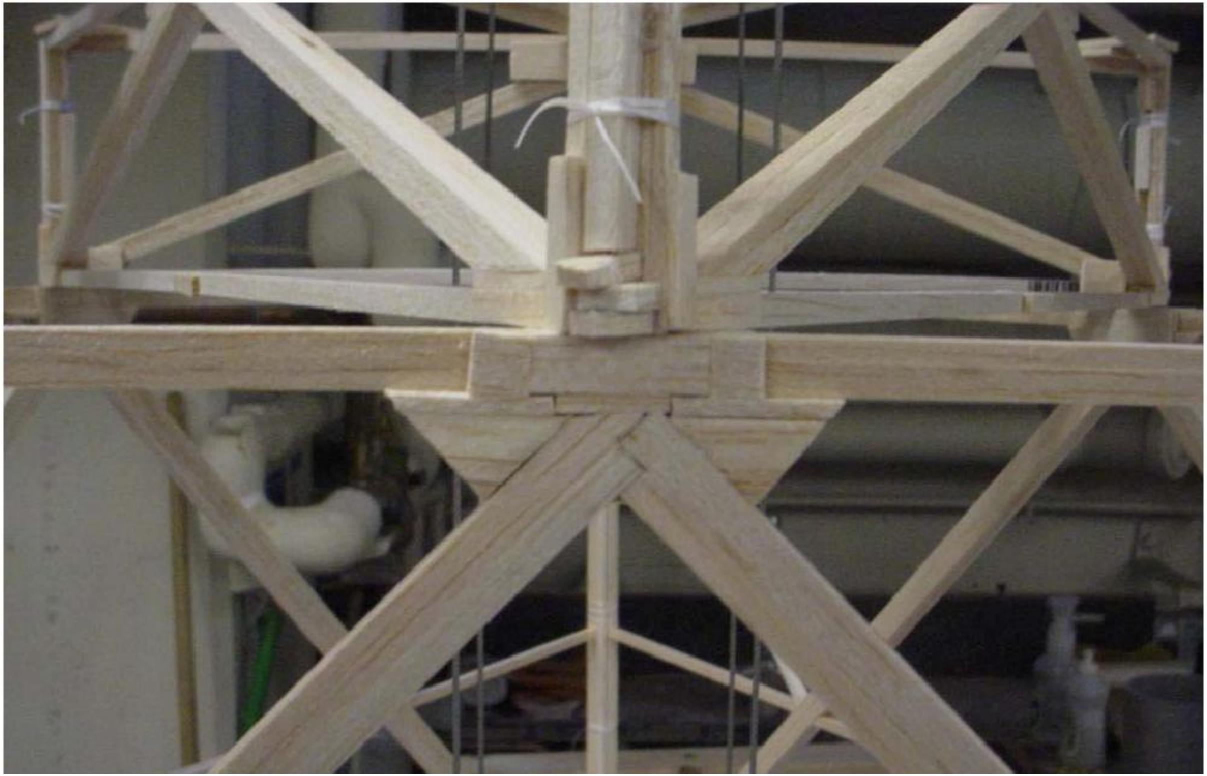
Failure by buckling may be sudden and unexpected not a ductile failure

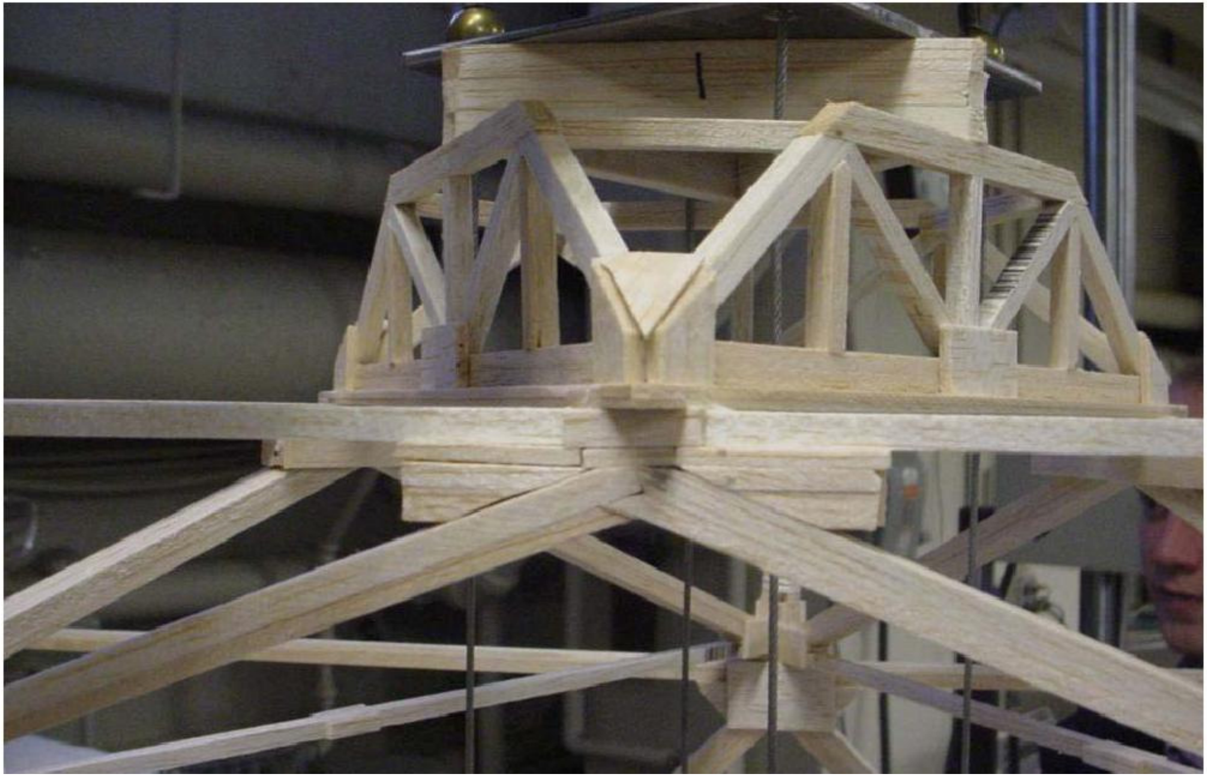
Statically determinate structures are easier to design because you can know the

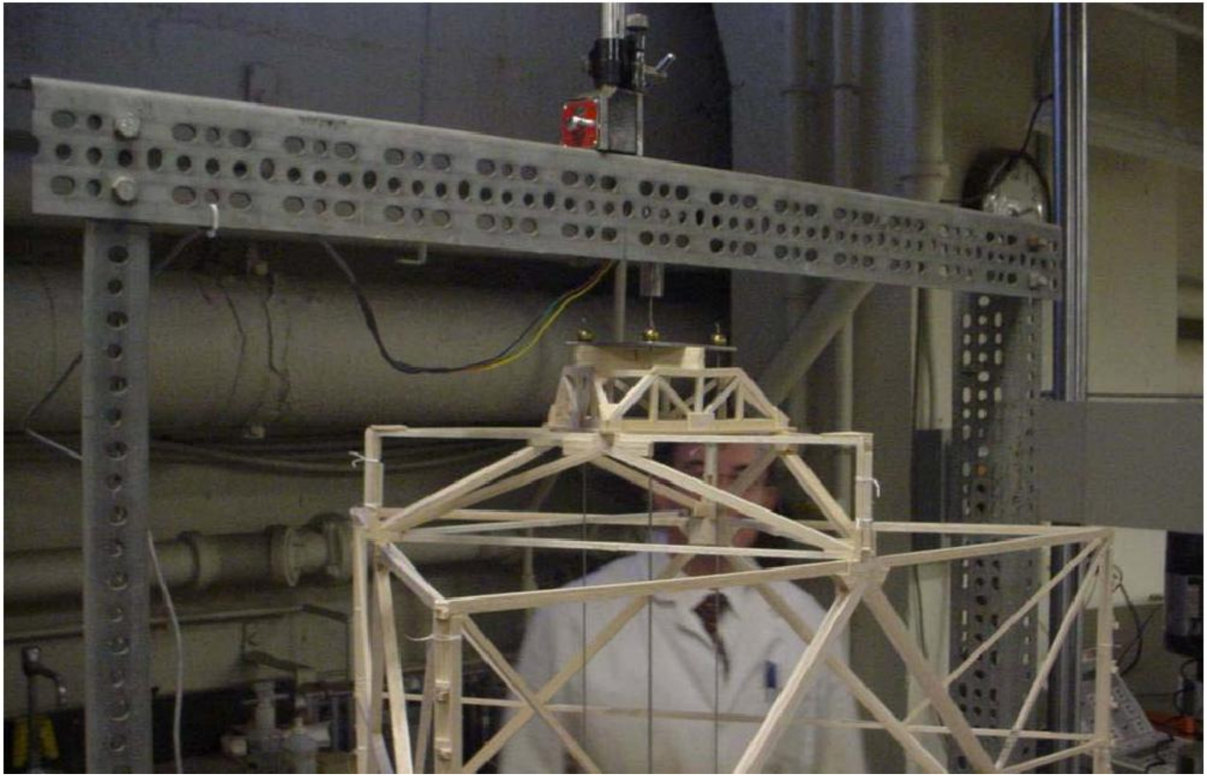
**internal forces exactly**

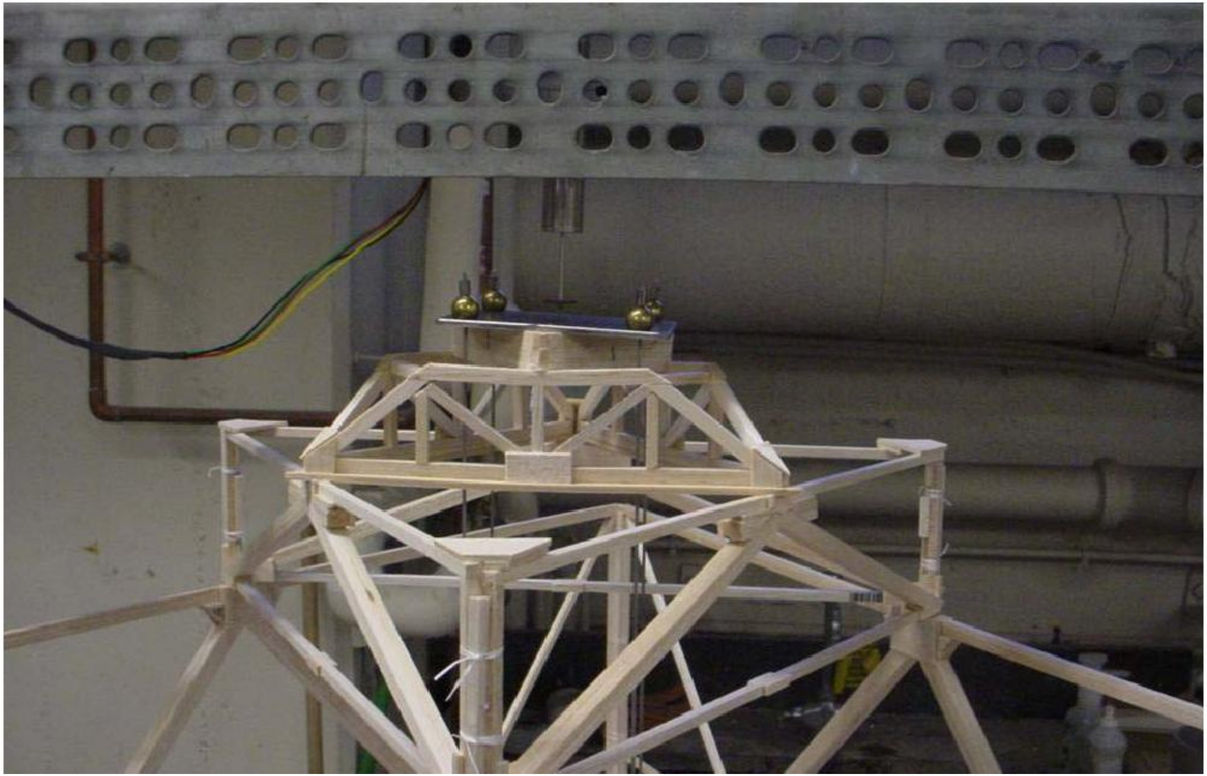
# Balsa Dancing

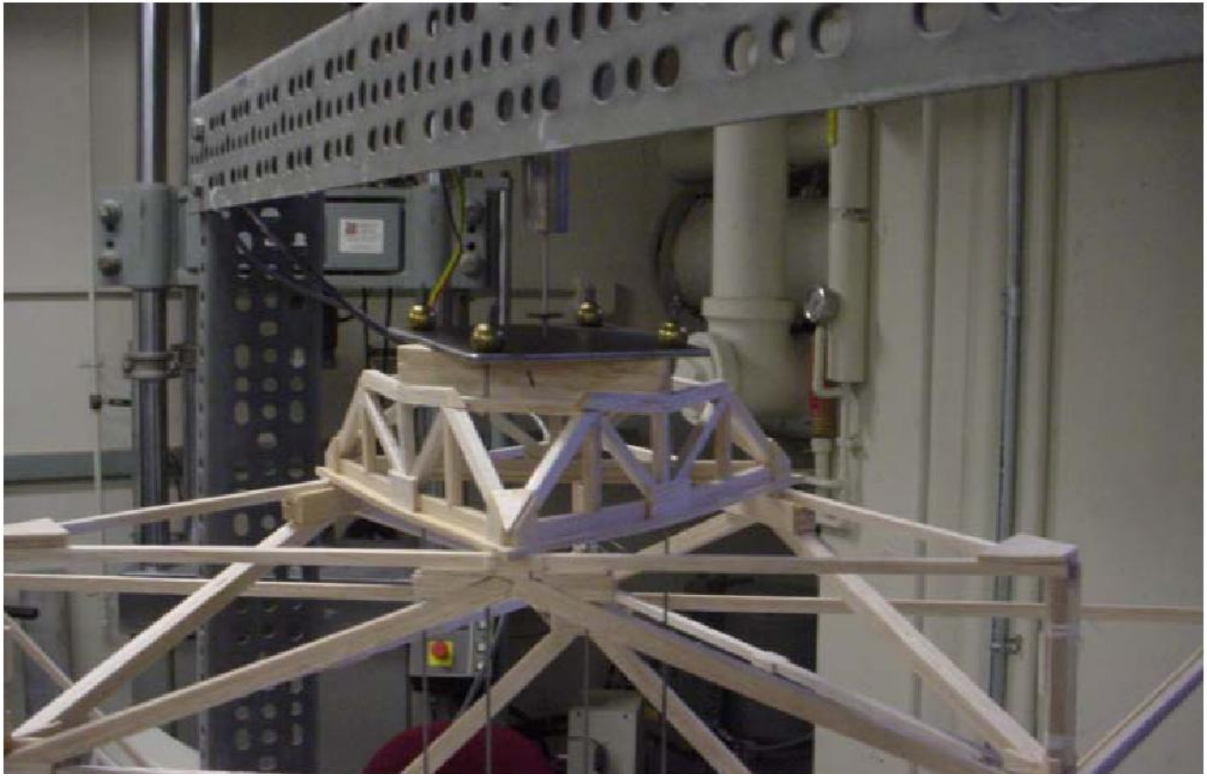


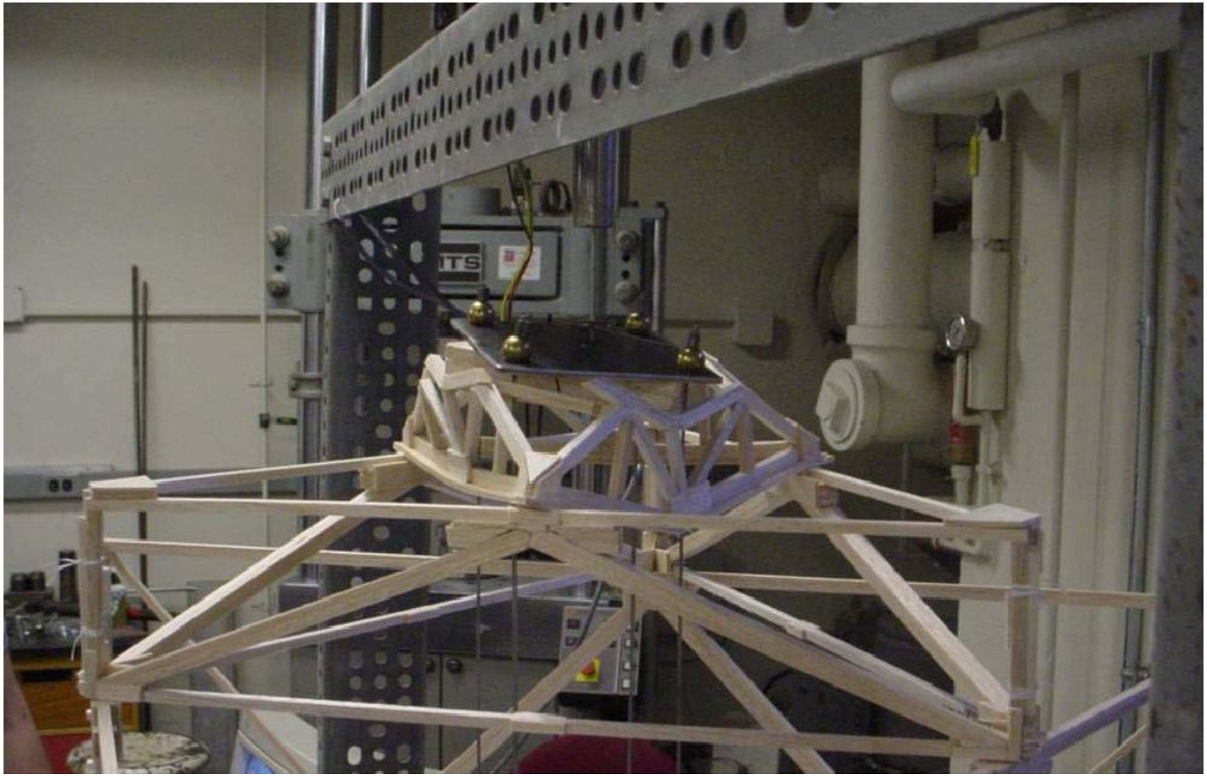








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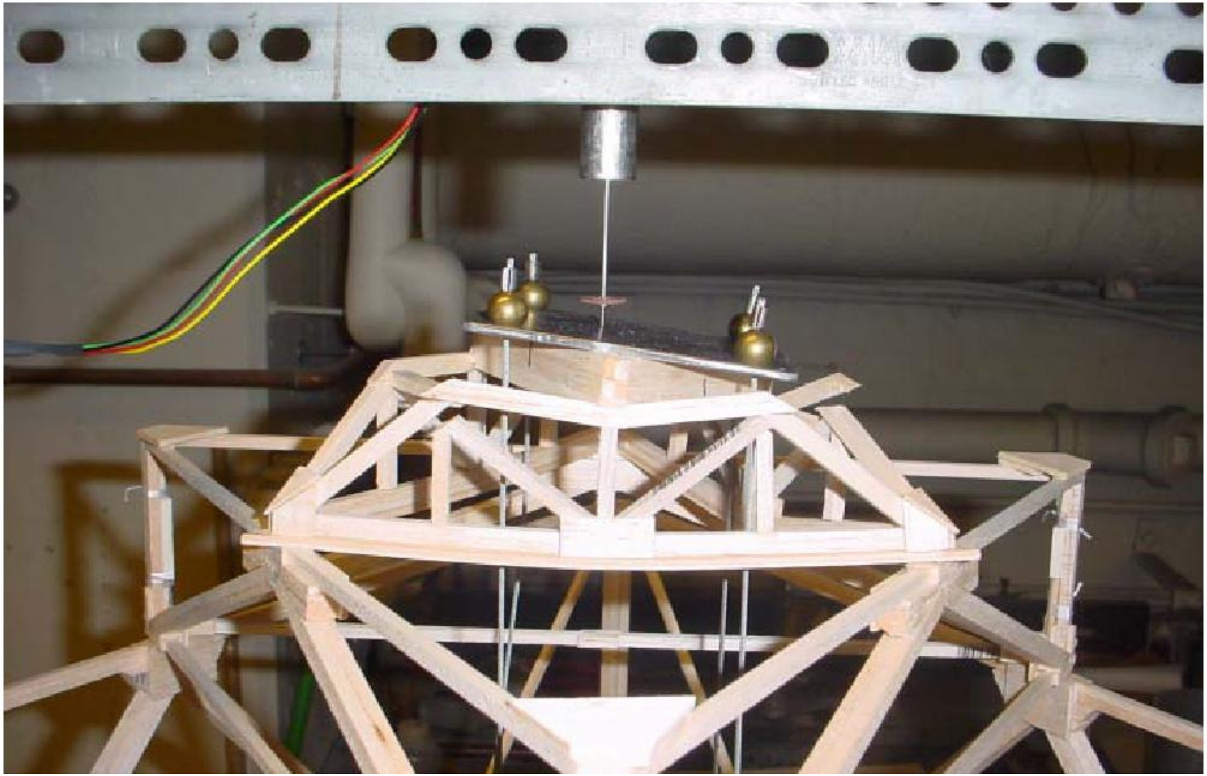
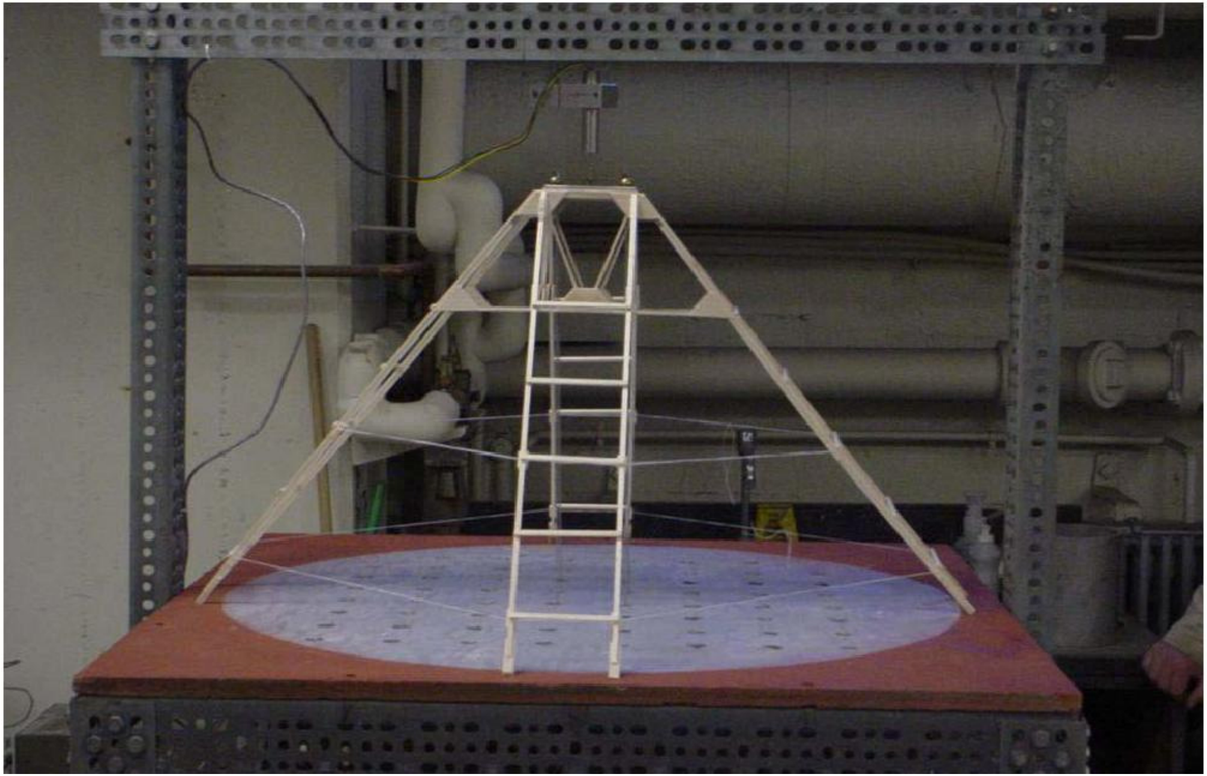
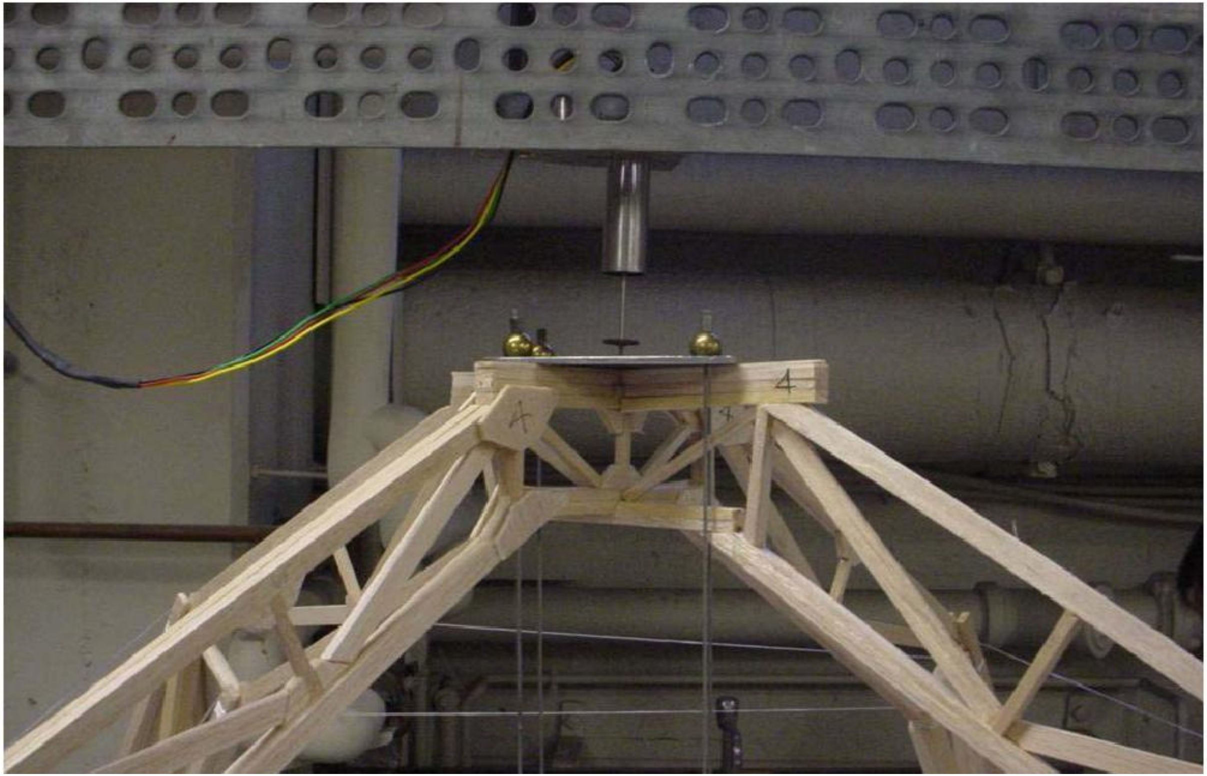
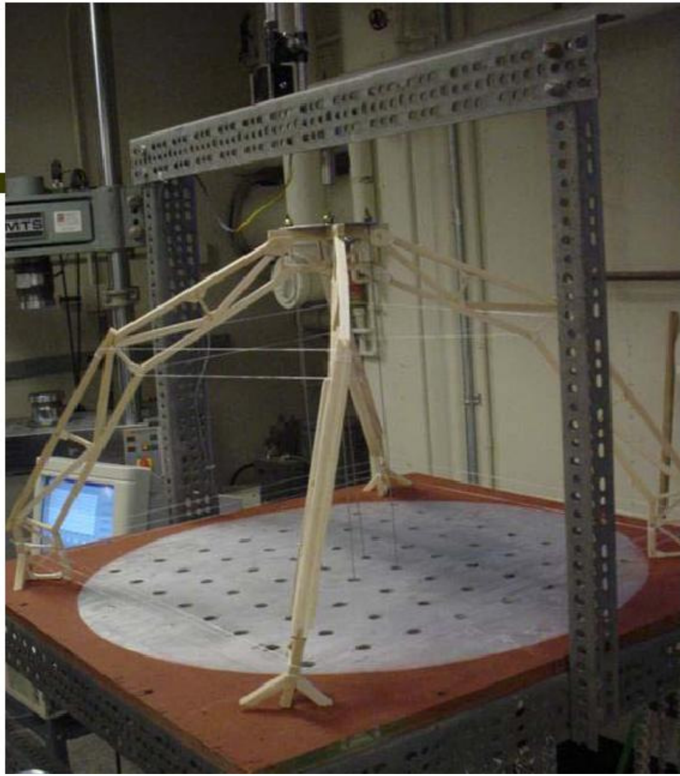
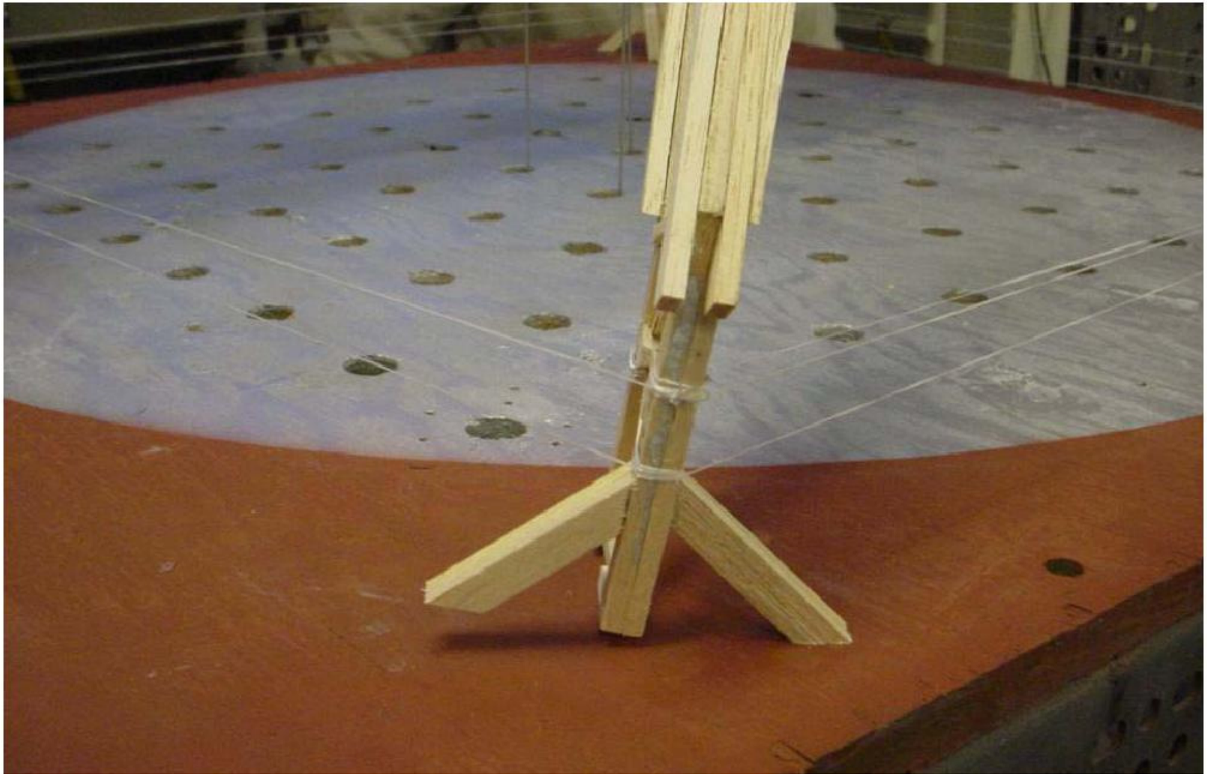
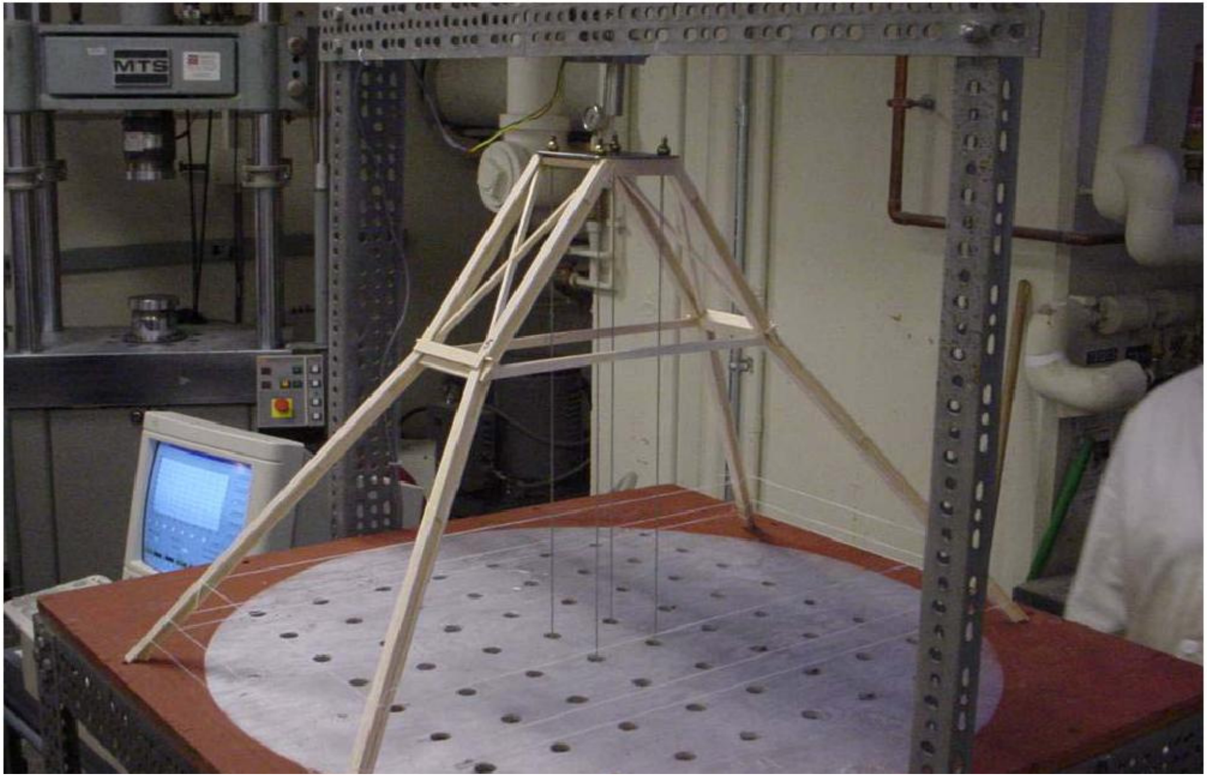







MTS

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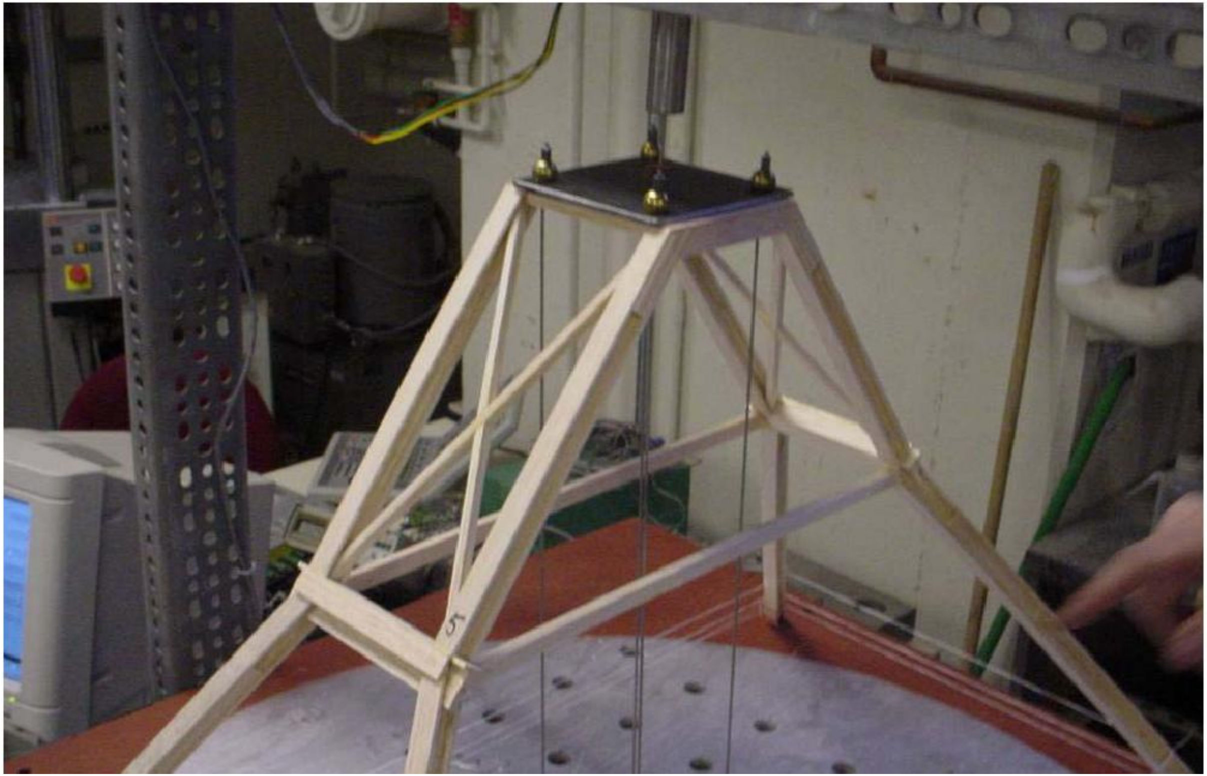
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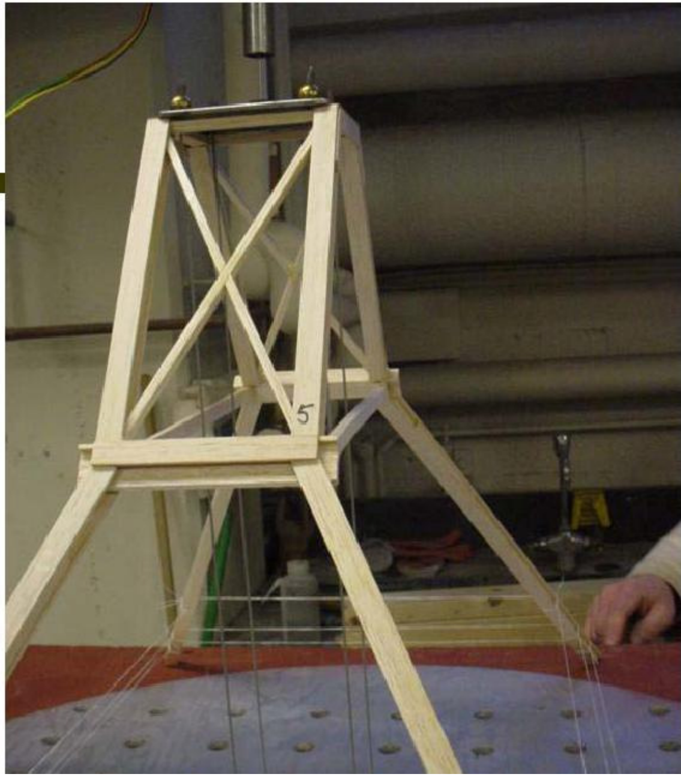
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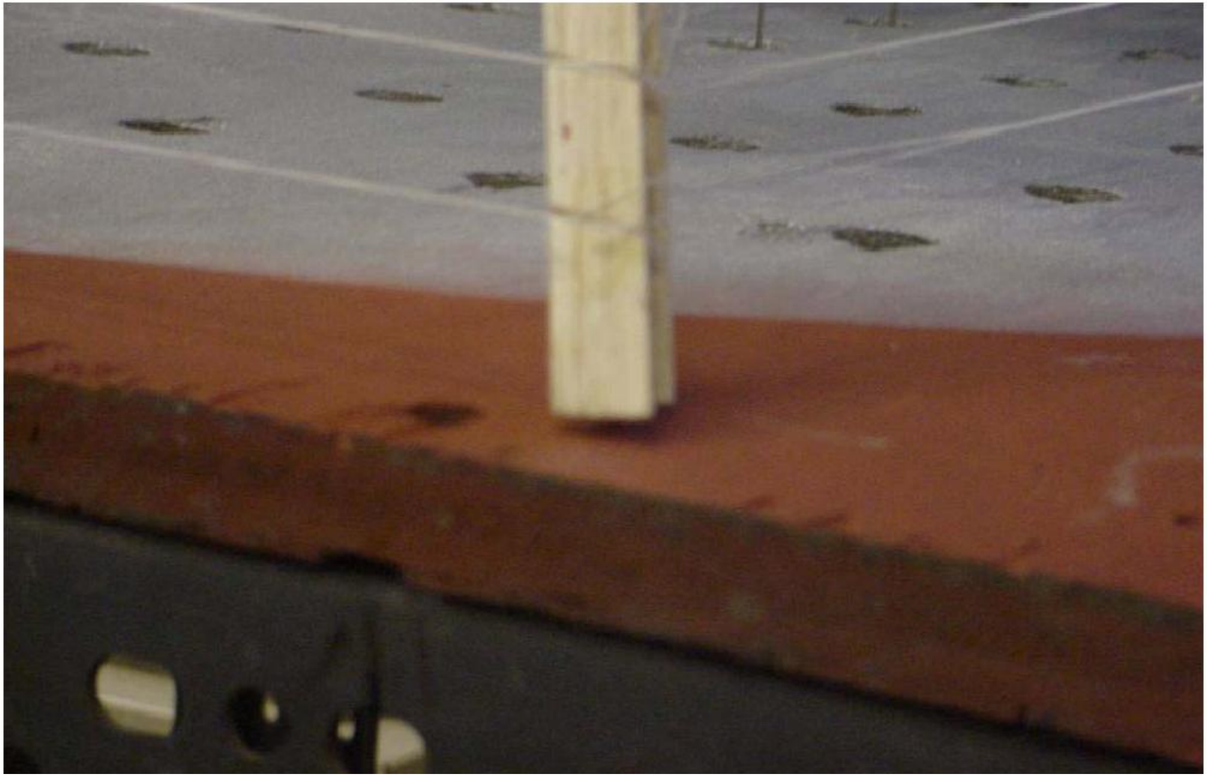
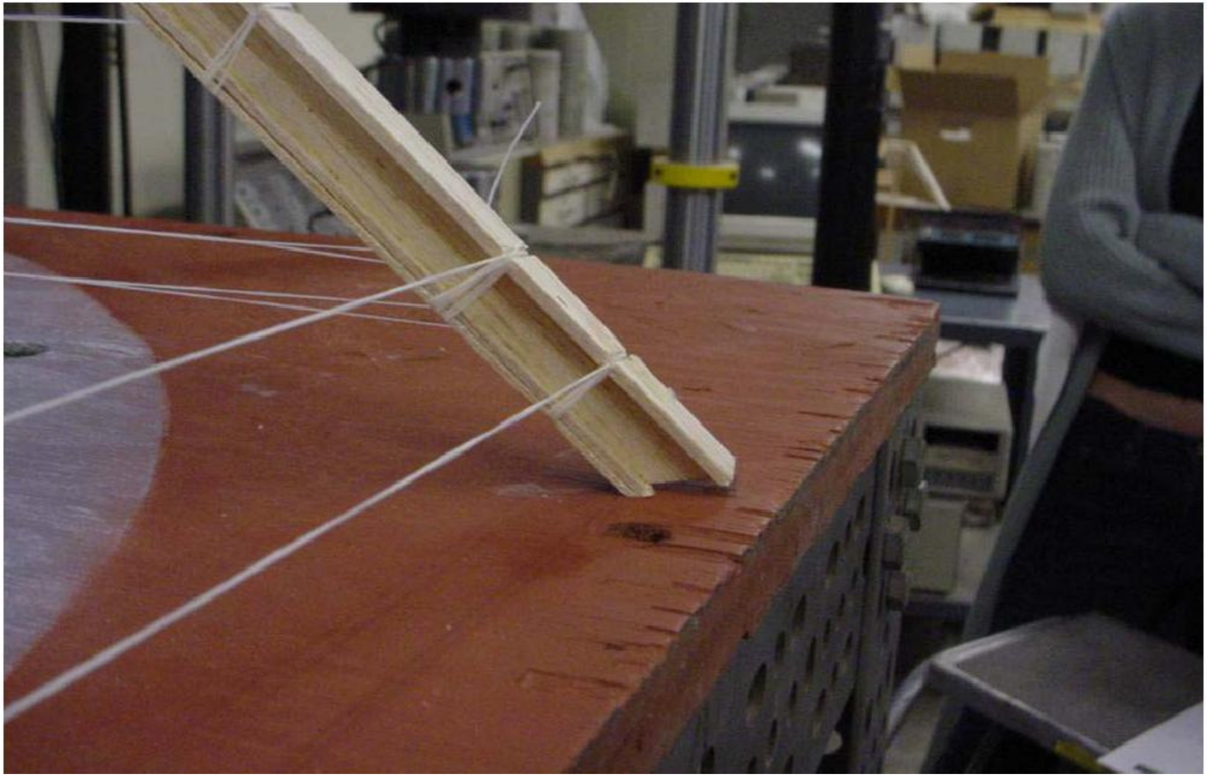
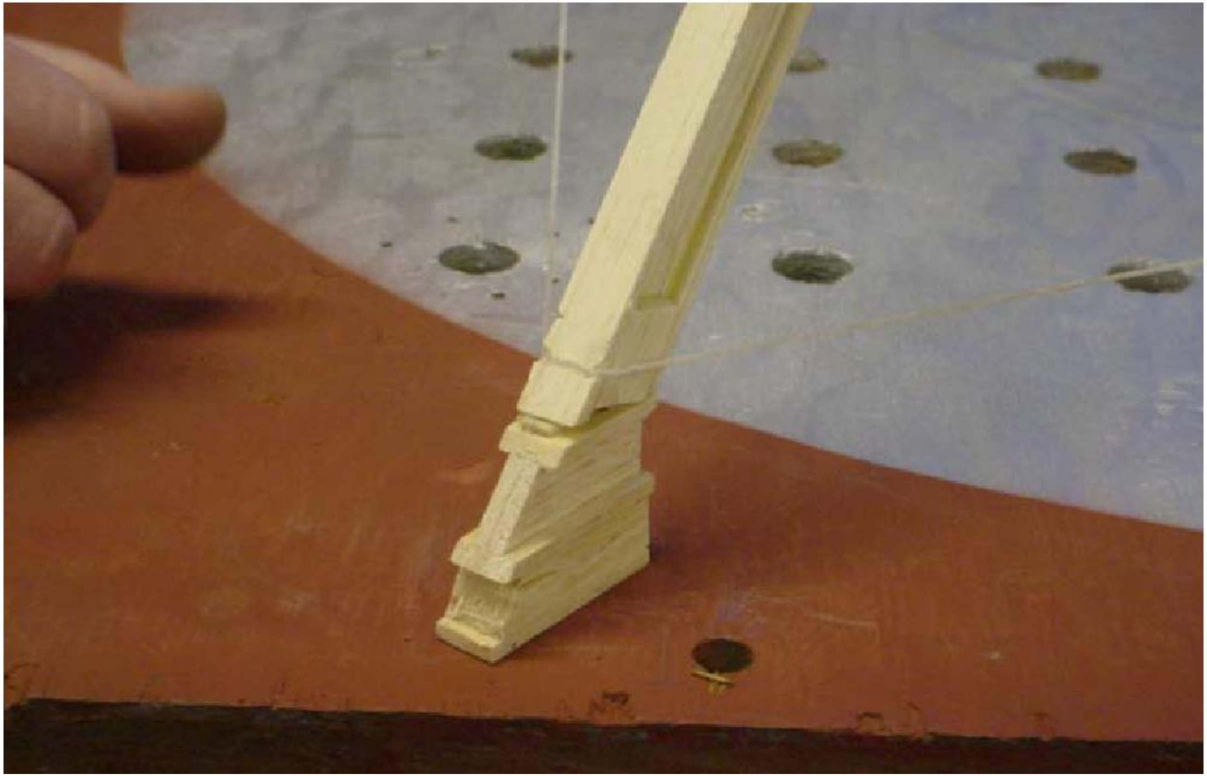
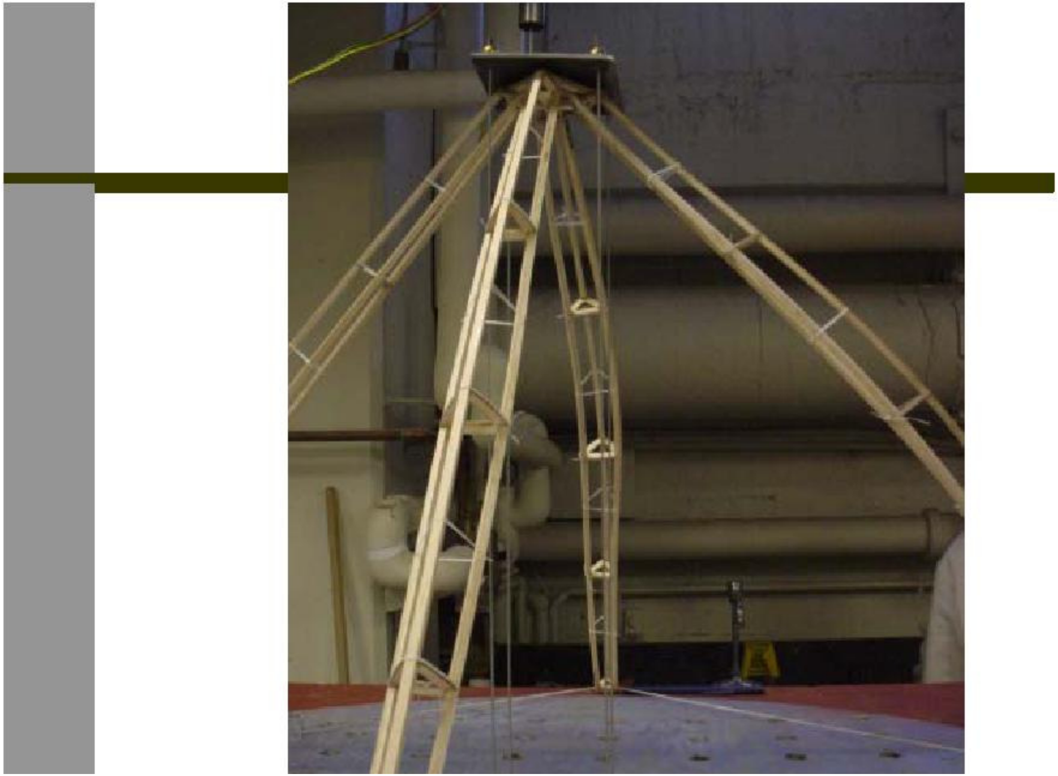
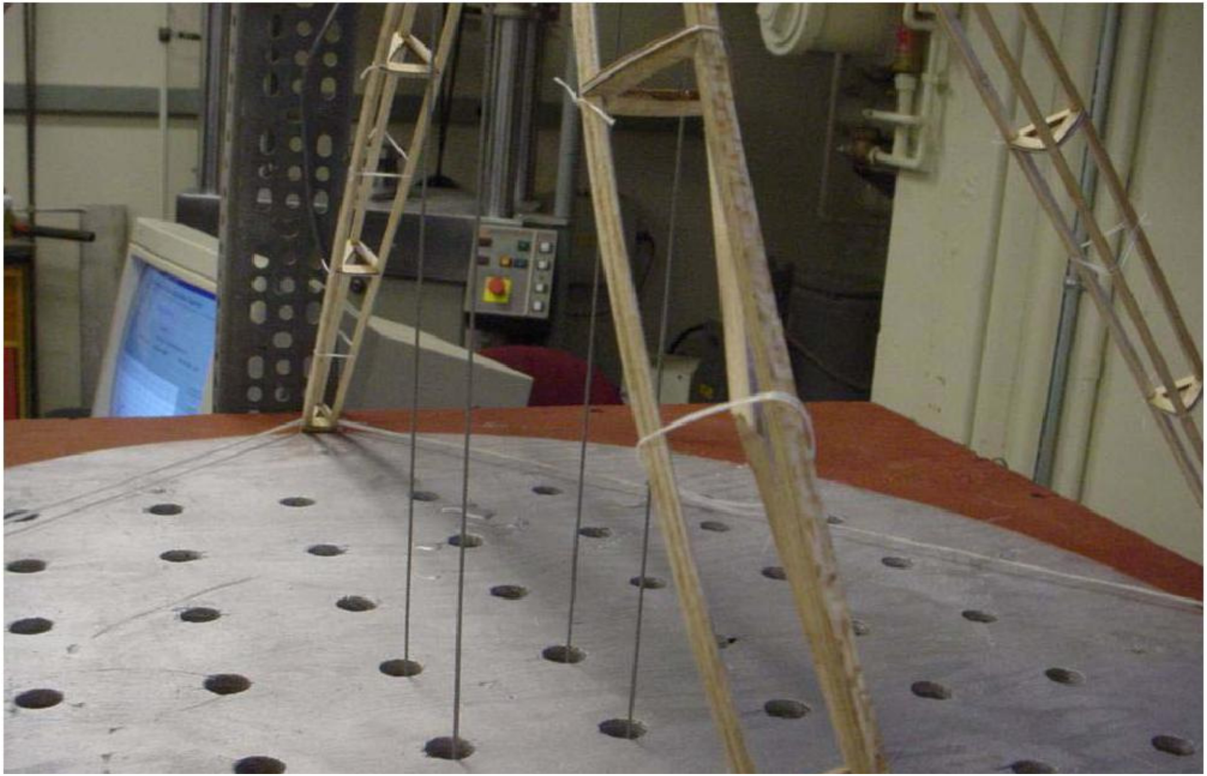
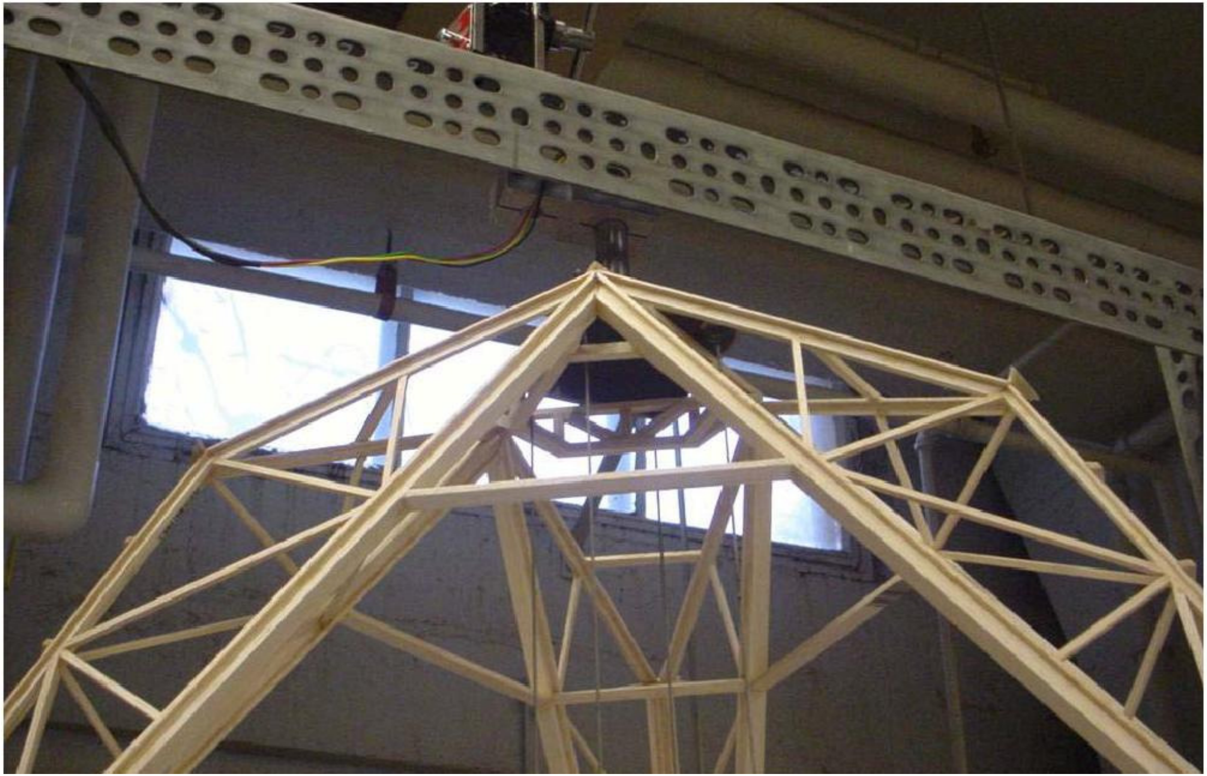


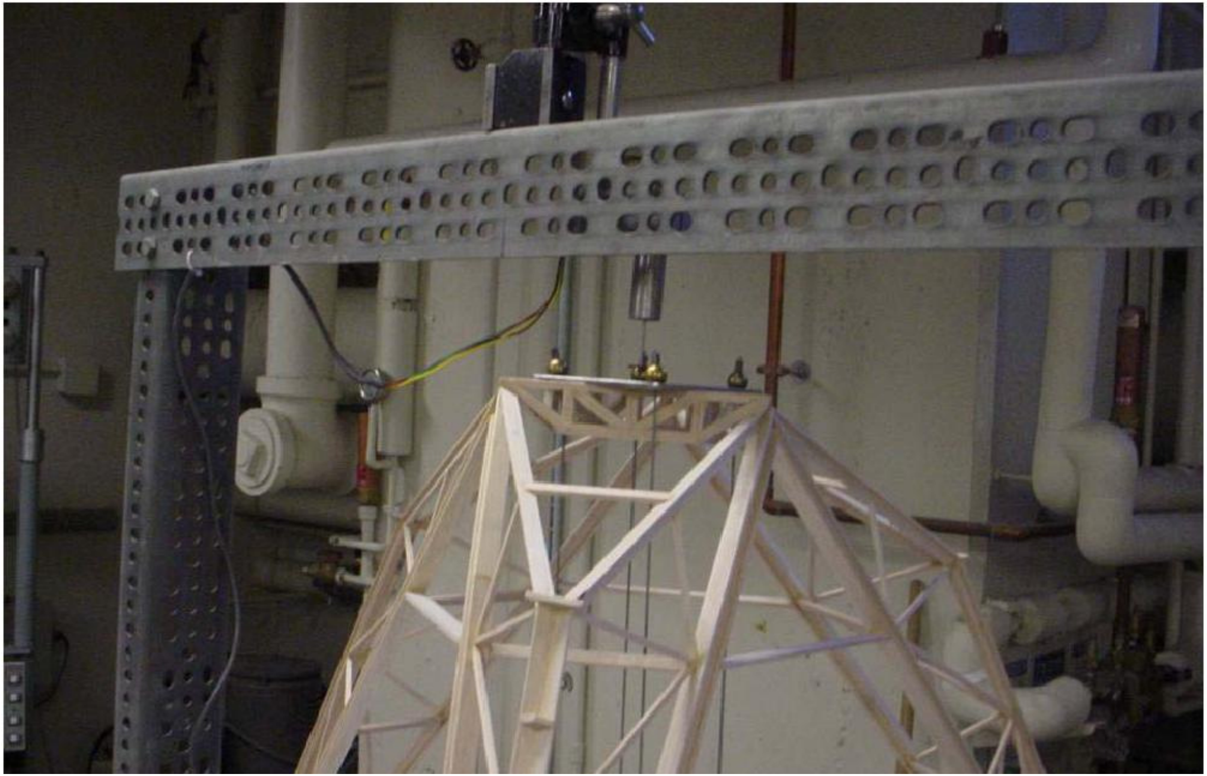


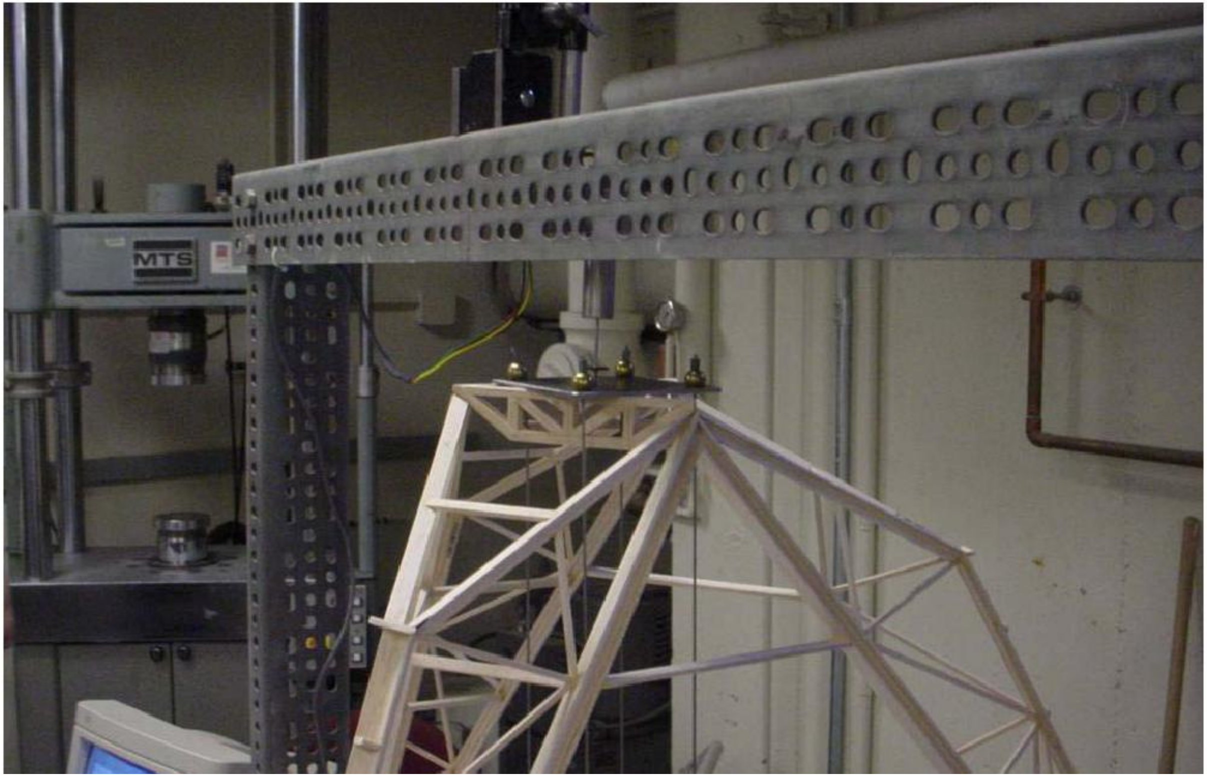


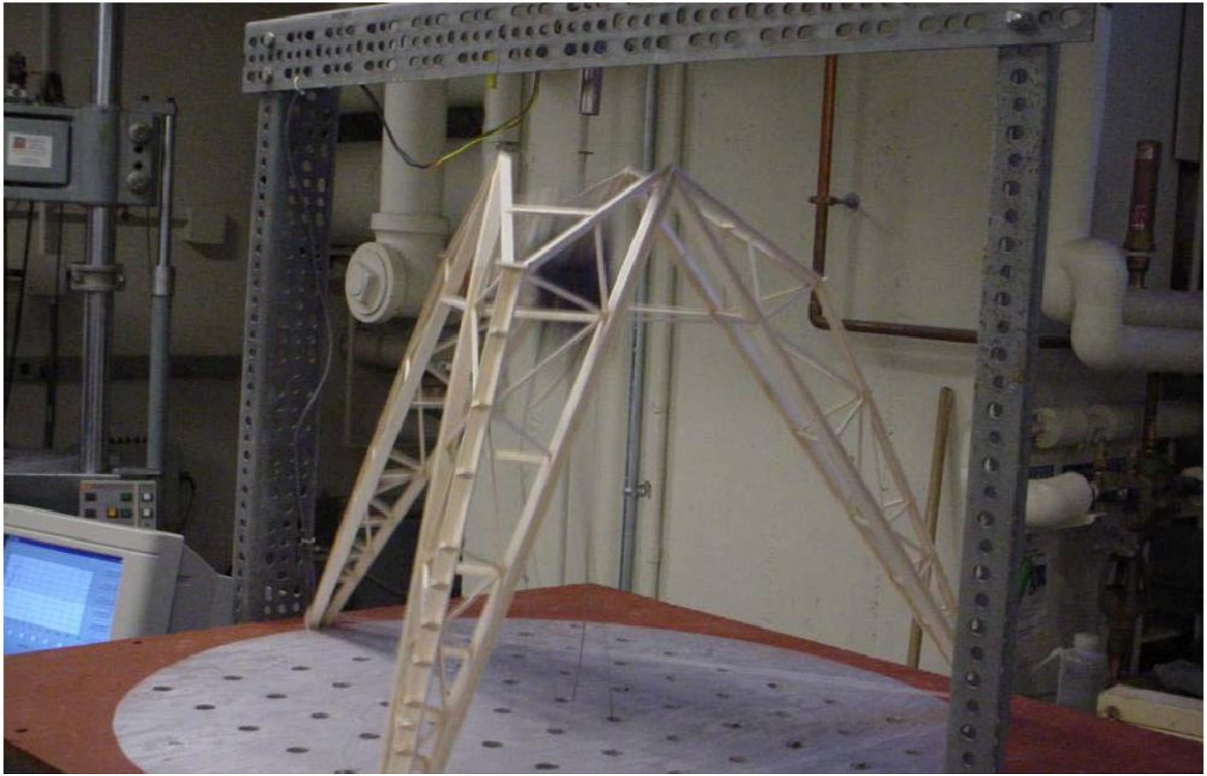









MTS



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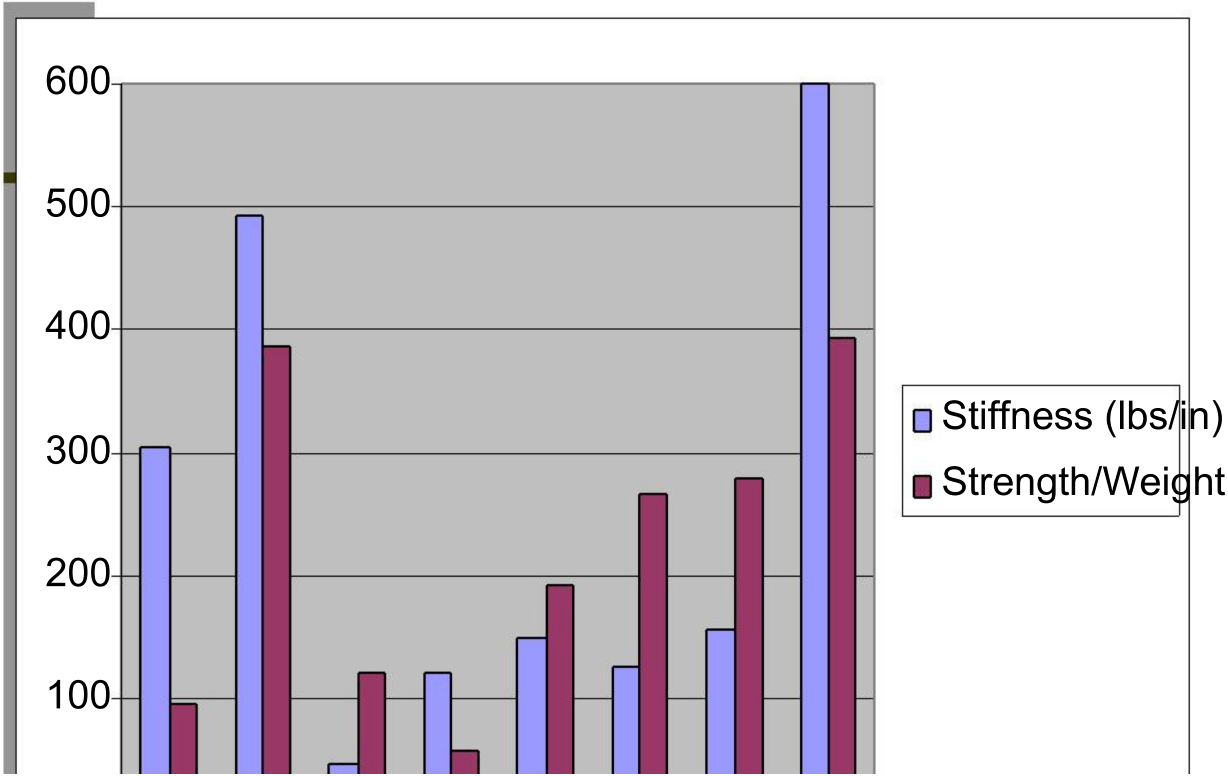


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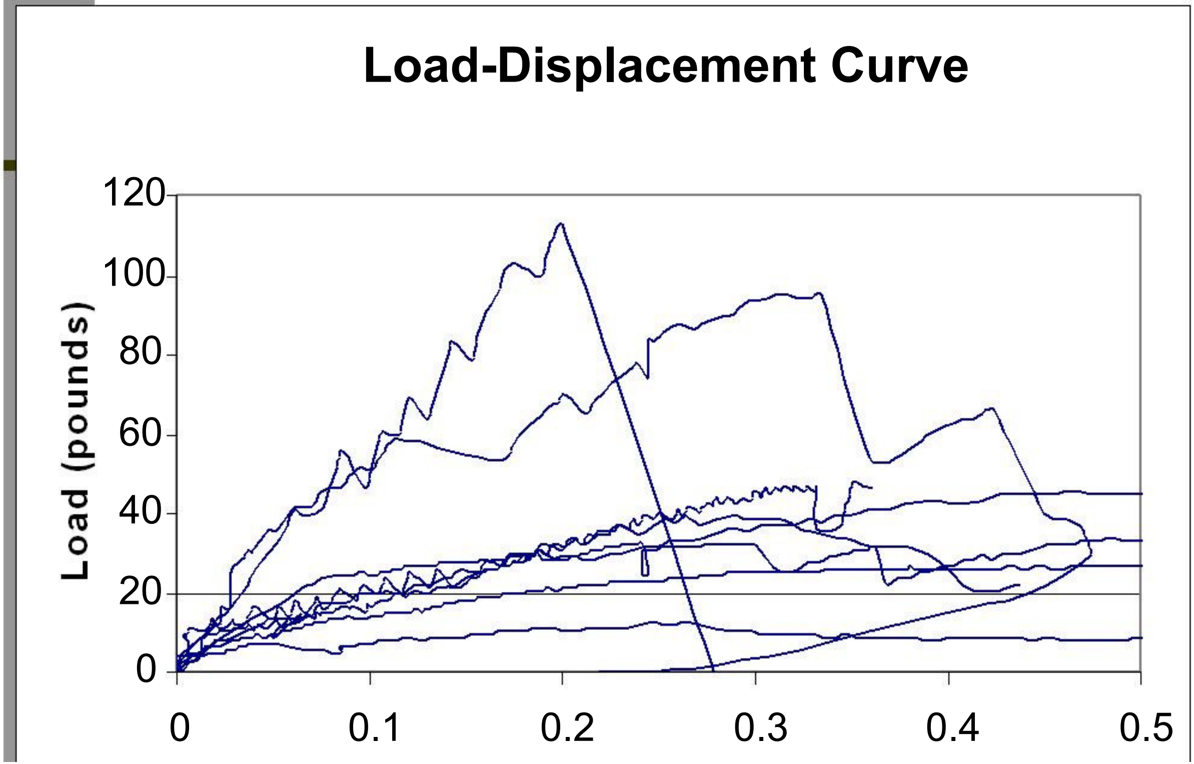
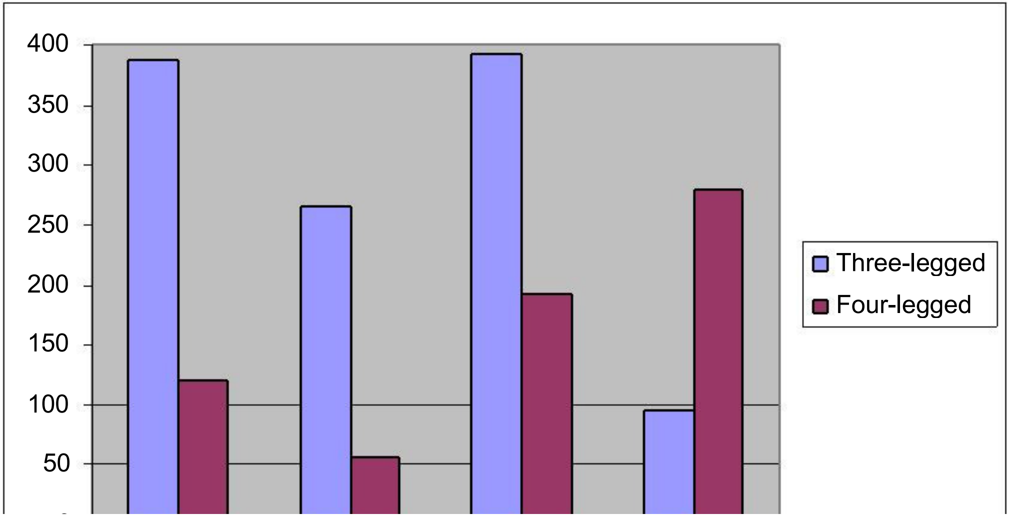

Load-Displacement Curve
Load (pounds)
120
100
80
60
40
20
0
0
0.1
0.2
0.3
0.4
0.5


Vertical Displacement (inches)

# Strength to Weight Ratio




0

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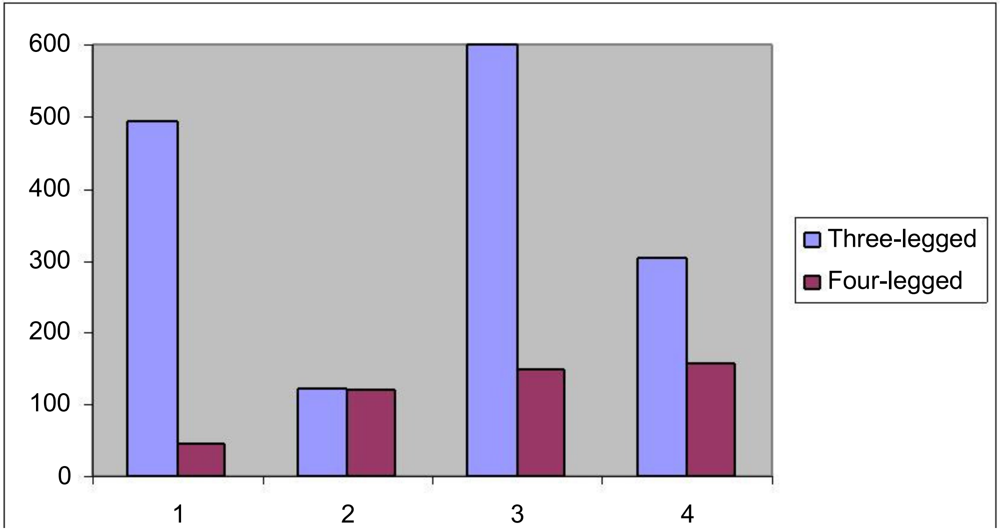
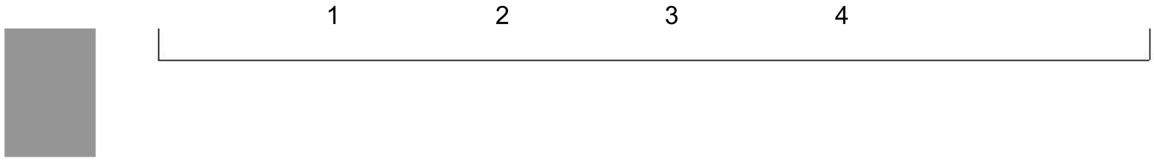
# Stiffness (slope of load-displ curve)




1
2
3
4

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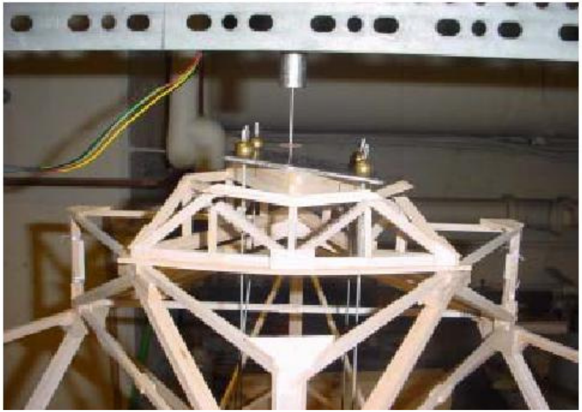
# Lessons: Concept

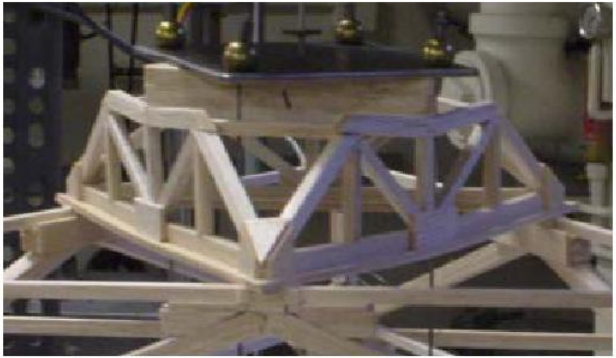
Systems with many unknowns are difficult to predict

Structures which are simple and clear in their load paths are easier to design



# Lessons: Construction

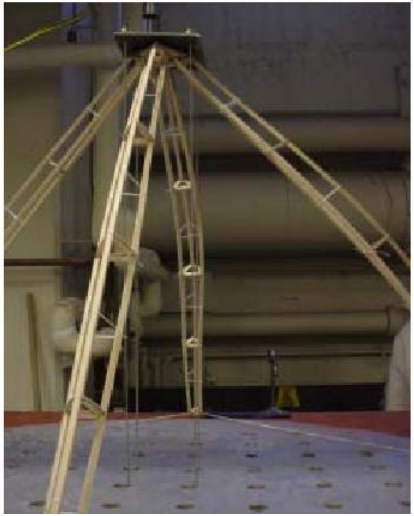
- Details are critical
- Repetition helps
- Small differences add up to big differences
- 3D joints are not easy!



# Lessons: Buckling

**Failure occurred significantly below calculated values:**

- Sensitive to **imperfections**
- Support conditions
- Insufficient bracing
- Lower load in post-**buckled state (not a ductile failure)**
- Effective buckling **length was typically much longer than assumed**



# Sustainable Engineering: The Importance of Structures

Professor John Ochsendorf

# End of Life Design

30 million computers are thrown away each year (only ~14% are recycled now)

Tackling waste flows can reduce environmental impact and save money

The electronics and automobile industry are beginning to design for the end of life (MIT

**Materials Systems Laboratory)**

# Outline of Lecture

Introduction

Materials Selection

Case Studies

Sustainable Structural Design

Conclusions

Future Challenges

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# Construction and the Environment

**In the United States, buildings account for:**

**37% of total energy use**
**(65% of electricity consumption)**
**30% of greenhouse gas emissions**
**30% of raw materials use**
**30% of waste output (136 million tons/year)**
**12% of potable water consumption**

**Source: US Green Building Council (2001)**

# Construction and the Environment

**US Primary Energy Consumption:**

| | |
|---|---|
| Buildings | 37% |
| Industry | 36% |
| Transportation | 28% |

**Source: US Dept. of Energy**

# Spending on Construction

***In industrialized nations, construction contributes more than 10% of the Gross Domestic Product (GDP)***

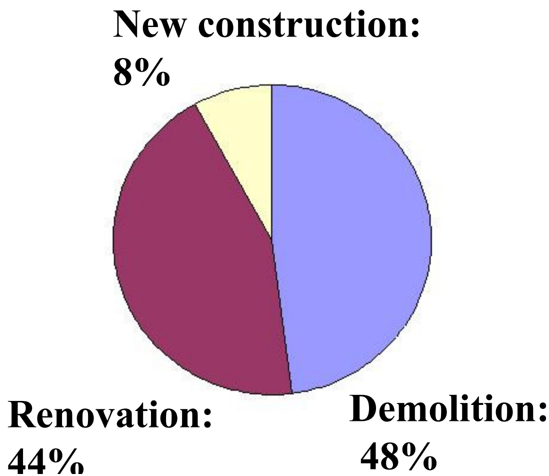
***An estimated 47% of total spending on construction is for renovation.***

**Source: Daratech (2001)**

# Construction Waste

US Environmental Protection Agency (EPA) estimates 136 million tons of waste generated by construction each year

Most from demolition or renovation and



**nearly half**
**the weight**
**is cement**

# Goals of Structural Design

Efficiency

Economy

Elegance

But all must consider the environmental impact as well

# 19th Century Design Concern

**EFFICIENCY IS IMPORTANT: New materials in construction, such as wrought iron and steel, lead to greater concern for efficiency**

# 20th Century Design Concern

**MAINTENANCE IS IMPORTANT:**
**The initial design is important, though we must also design for maintenance throughout operating life**

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# 21st Century Design Concern

**END OF LIFE IS IMPORTANT:**
**Waste from the construction industry is a vast consumer of natural resources on a global scale**

# Buildings are Not Permanent

**Stone pinnacles of cathedrals are replaced ~200 years**

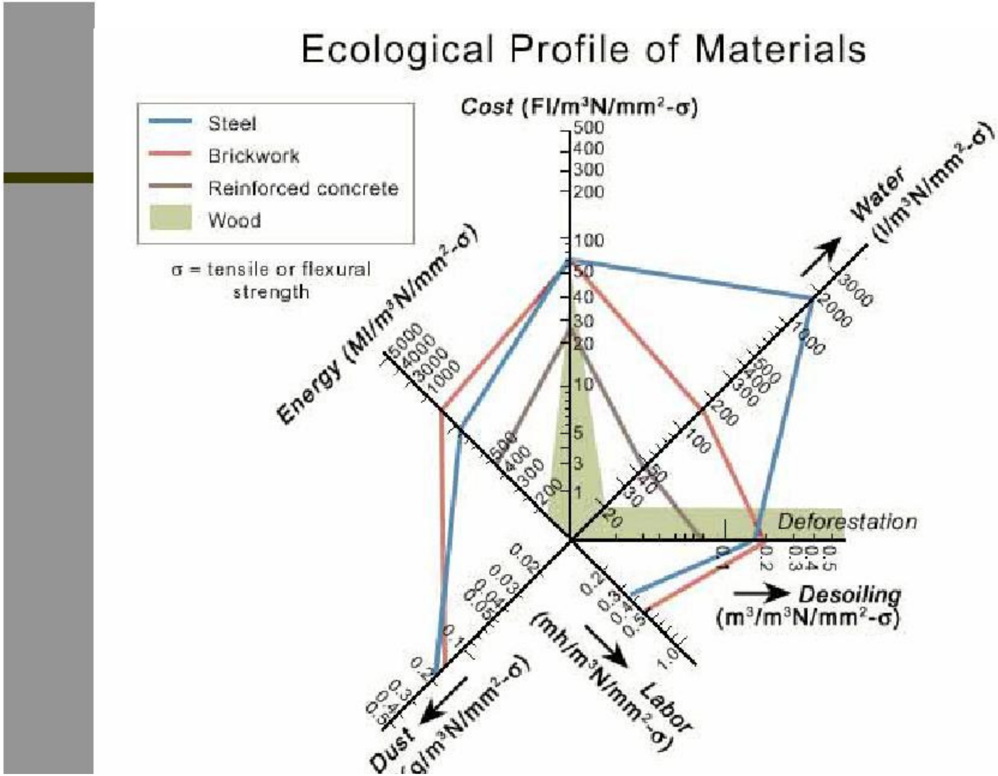
**Buildings are *waste in transit***

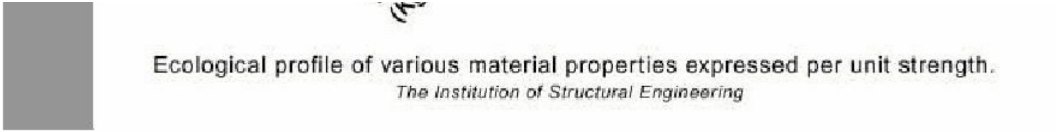
# Choosing Materials

**Environmental Impact**

**Durability**

**End of Life**


Ecological Profile of Materials
Steel
Brickwork
Reinforced concrete
Wood
σ = tensile or flexural strength
Cost (Fl/m³N/mm²-σ)
Water (l/m³N/mm²-σ)
Energy (Ml/m³N/mm²-σ)
Deforestation
Desoiling (m³/m³N/mm²-σ)
Labor (mh/m³N/mm²-σ)
Dust (g/m³N/mm²-σ)



Ecological profile of various material properties expressed per unit strength.

*The Institution of Structural Engineering*

# Is concrete a green material.

**Concrete is made from local materials.**

**Concrete can be made with recycled waste or industrial byproducts (fly ash, slag, glass, etc).**

**Concrete offers significant energy savings over the lifetime of a building. Concretes high thermal mass moderates temperature swings by storing and releasing energy needed for heating and cooling.**

# Energy Required for Concrete

| Component | Percent by weight | Energy % |
|---|---|---|
| Portland cement | 12% | 92% |
| Sand | 34% | 2% |
| Crushed stone | 48% | 6% |
| Water | 6% | 0% |

**Each ton of cement produces ~ 1 ton of $CO_2$**

# Environmental Advantages of Steel

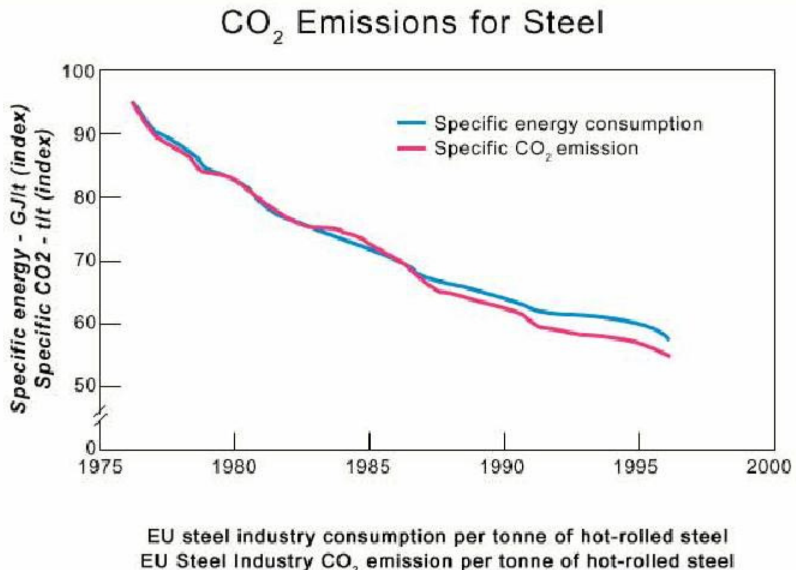
Lower weight reduces foundation requirements

Highly recycled and can continue to be recycled indefinitely

Durable, if protected from corrosion

Can be salvaged for reuse

# Energy Consumption for Steel



*(3 year moving averages)*

Source: Eurostat

# Environmental Disadvantages of Steel

Very high energy use, predominantly from fossil fuels produces pollution

Lightweight, so lower thermal mass compared to concrete requires more insulation

Is susceptible to corrosion

# $CO_2$ Emissions in the US

**US: 5% of world population, 25% of greenhouse gases**

**UK: commitment to cut CO2 emissions 60% by 2050 (well beyond the goals of the Kyoto Protocol)**

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# Kyoto Protocol and $CO_2$

**To meet Kyoto Protocol: ~33,000 lbs of $CO_2$/year/person (-7% from 1990)**

**But individual contributions are only 1/3 of per capita contributions rest is industry, agriculture, etc.**

**So individuals annual goal would be 11,000 lbs (though many scientists are calling for much greater reductions)**

# Kyoto Protocol

**Aims to reduce $CO_2$ emissions by 7% over 1990 levels (though the UK has just committed to going much further 60% reductions of current emissions)**

**Would limit personal carbon emissions to 11,000 pounds of $CO_2$/year**

**This quantity of $CO_2$ is produced by:**

- Two coast-coast flights (economy class)
- Driving 11,000 miles (with 20 mpg fuel efficiency)
- Casting 16 cubic yards of concrete

About 14 cubic feet of structural steel

About 5 cubic feet of virgin aluminum

# Kyoto Protocol

Aims to reduce CO2 emissions by 7% over 1990 levels (though the UK has just committed to going much further)

This requires approximate CO2 emissions of 33,000 lbs/year for each person in the US

Only about 1/3 comes from personal decisions, the rest is due to industry and services

# Architects and engineers

**Architects and engineers contribute to the industry and services**

# The Greenest of ThemAll.

Only one primary building material:

-comes from a renewable resource;
-cleans the air and water;
-utilizes nearly 100% of its resource for products;
-is the lowest in energy requirements;
-creates fewer air and water emissions; and is
-totally reusable, recyclable and biodegradable.

And it has been increasing in US net reserves since 1952, with growth exceeding harvest in the US by more than

**30%.**

**-American Wood Council**

# Planting trees.

A healthy tree stores about 13 pounds of $CO_2$ per year -- NOT MUCH!

Would require nearly 3,000 trees per person to offset $CO_2$ emissions

Specifying timber reduces $CO_2$ emissions compared to steel and concrete, but carbon sequestration is a small contribution to this reduction

Main advantage is that wood does not produce nearly

**as much $CO_2$ as steel and concrete**

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# High vs. Low Embodied Energy.

Materials with the lowest embodied energy intensities, such as concrete, bricks and timber, are usually consumed in large quantities.

Materials with high energy content such as stainless steel are often used in much smaller amounts.

As a result, the greatest amount of embodied energy in a building can be either from low embodied energy materials such as concrete, or high embodied energy materials such as steel.

# Steel and Concrete

**Energy intensive materials**

**High associated CO2 emissions**

**Dominant structural materials**

Industry standards
Many engineers have not designed with other materials
Economies of scale
Steel provides ductility, the ability to absorb energy before **failing**

**Many other materials can serve in**

**Many other materials can serve in place of steel and concrete**

# Energy Savings fromRecycling

| | Energy required to produce from virgin material (million Btu/ton) | Energy saved by using recycled materials (percentage) |
|---|---|---|
| Aluminum | 250 | 95 |
| Plastics | 98 | 88 |
| Newsprint | 29.8 | 34 |
| Corrugated Cardboard | 26.5 | 24 |
| Glass | 15.6 | 5 |

***Source:Roberta Forsell Stauffer of National Technical Assistance Service (NATAS), published in Resource*** *Recycling, Jan/Feb 1989).*

# Electronics Industry

**30 million computers thrown away annually in the US**

**Only 14% recycled**

**Initial design must consider end of life**

# Embodied Energy vs. Operating Energy (3,750 sf home)

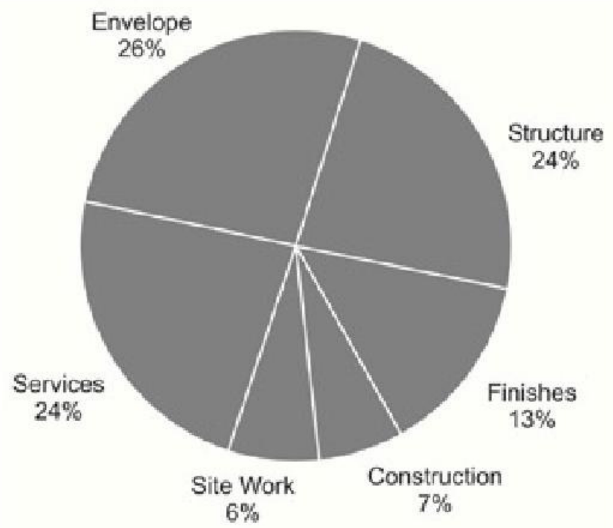
| Home type, location | Heating Energy MM Btu/year (Gj/year) | Embodied Energy MM Btu (Gj) | Embodied Energy in years of heating energy |
|---|---|---|---|
| Conventional, Vancouver | 101 (107) | 948 (1,000) | 9.4 |
| Energy-efficient, Vancouver | 57 (60) | 1019 (1,075) | 17.9 |
| Conventional, Toronto | 136 (143) | 948 (1,000) | 7.0 |
| E... | | | |

| | | | |
|---|---|---|---|
| **Energy Toronto efficient,** | 78 (82) | 1019 (1,075) | 13.1 |

**Source: Ray Cole, Univ. of British Columbia**

# Typical Building Embodied Energy

**Breakdown of Initial Embodied Energy by Typical Office Building Components Averaged Over Wood, Steel and Concrete Structures [Cole and Kernan, 1996].**



Average Total Initial Embodied Energy 4.82 GJ/$m^2$

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# Range in Embodied Energy

| Material | Density | Low value | High value |
|---|---|---|---|
| | kg/m³ | GJ/m³ | GJ/m³ |
| Natural aggregates | 1500 | 0.05 | 0.93 |
| Cement | 1500 | 6.5 | 11.7 |
| Bricks | ~1700 | 1.7 | 16 |
| Timber (prepared softwood) | ~500 | 0.26 | 3.6 |
| Glass | 2600 | 34 | 81 |
| Steel (sections) | 7800 | 190 | 460 |

| | | | | | |
|---|---|---|---|---|---|
| **Plaster** | **~1200** | | **1.3** | | **8.0** |

Source: BRE, UK, 1994

# Reducing Waste

**Design for Less Material Use**
**Use materials efficiently and maximize program use by combining spaces. (i.e., build smaller)**

**Design Building for Adaptability**
**Design multipurpose areas or flexible floor plans which can be adapted for use changes.**

**Recycle Construction Waste**
**Wood, metal, glass, cardboard etc. can be salvaged in the construction process. Materials should be used and ordered conservatively.**

# Use Recycled Content Products and Materials

**High recycled content:**

**Paper on both the face and the back of all drywall is a 100% recycled product.**

**Structural steel uses mostly recycled material (though it is still energy-intensive and responsible for harmful pollutants.)**

**Example of an item that you can specify:**

**Armstrong ceiling tiles contain 79% recycled material (cornstarch, newsprint, mineral wool, recycled tiles). Both the ceiling tiles and the suspension systems can also be reclaimed and recycled rather than dumped**

**dumped in a landfill.**

# Separating Waste

# Australia: Waste Avoidance and Resource Recovery Act (2001)

**Web site dedicated to Construction & Demolition waste minimization: onSITE**

**http://onsite.rmit.edu.au/**

(Source of material for this lecture.)

# Steel and Concrete

Can be designed for reuse (concrete pavers)

Can reduce required quantities through efficient design

We will return to the design of indeterminate structures and the importance of structural form

Designers can use the constraints of economics, efficiency, and the environment to

**find new forms**

# Ecological Comparison of Materials

Each material has environmental advantages and disadvantages

Choice of material will depend on the site and design problem

Embodied energy is only one of manv

**considerations**

# Design Matters

**19th Century: Efficient use of materials**

**20th Century: Maintenance matters**

**21st Century: End of life matters**



# Designing for Maintenance

Develop a maintenance plan for your structure

Design components which are accessible and replaceable

Avoid toxic materials which are hazardous for future maintenance

**operations**

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# Demolition: Lessons from History

Sustainable structures must consider the end of life of the structure

~24% of solid landfill waste in the US is generated by the construction industry

Up to 95% of construction waste is recyclable, and most

**most**
**is**
**clean**
**and**
**unmixed**

# Two Extreme Approaches to Sustainable Structures

1. **Permanence:** Very high quality construction, with materials which can be reused in future construction

2. **Temporary:** Less expensive construction, with a short life span. Materials must be low-impact.

**impact.**

# Two Sustainable Bridge Types

**Inca suspension bridge**

- High stresses
- High maintenance
- Short lifetime
- Low initial cost
- Renewable materials
- Low load capacity

**Roman arch bridge**

- Low stresses
- Low maintenance
- Long lifetime
- High initial cost
- Reusable materials
- High load capacity

# Conclusions

Each material has environmental advantages and disadvantages: good design is local

Recycle or reuse materials to decrease waste

Consider end of life in the initial design

History suggests sustainable solutions: Inca structures (temporary) and Roman structures

**(permanent) can both be sustainable**

# Conclusions

Construction industry generates enormous waste annually

Individual designers can reduce this waste significantly

Energy intensive materials like steel and concrete can be used more efficiently

**Alternative materials should be explored**

# Future Challenges

**Education of architects and engineers**

Teaching design and analysis

Assessment of existing structures

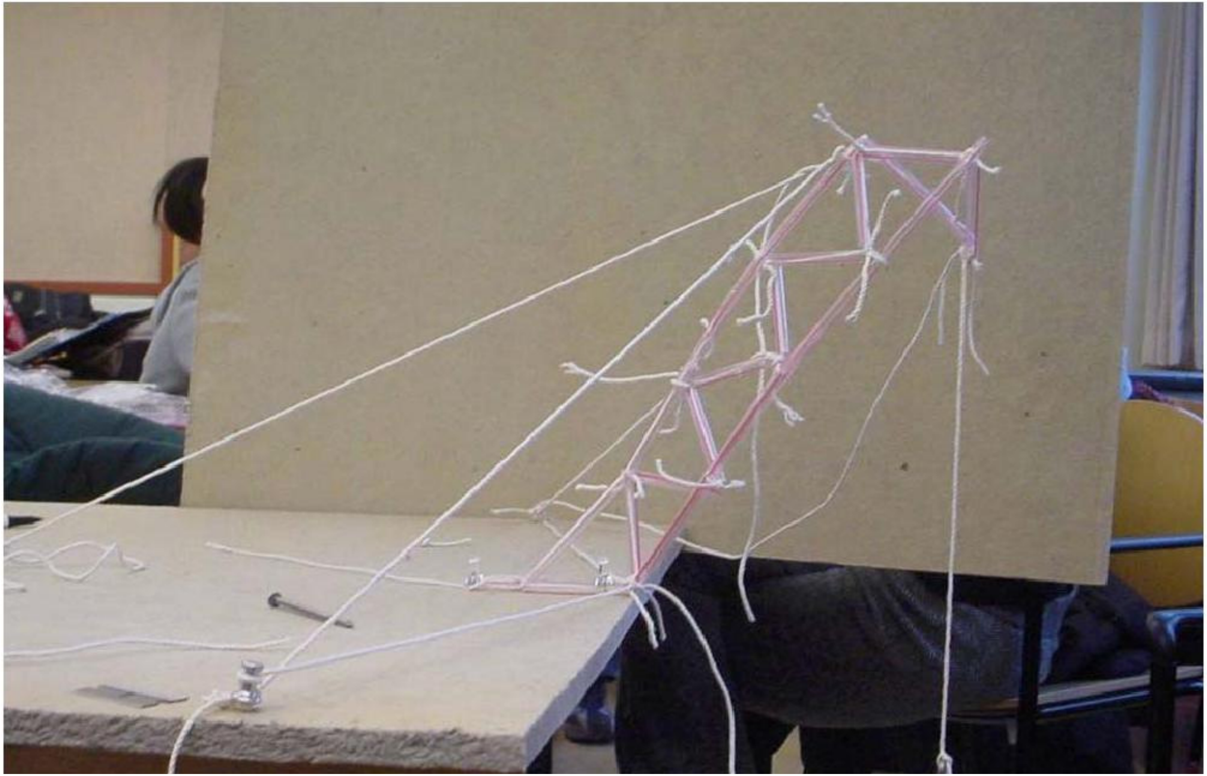
Environment as a design constraint, not an opponent

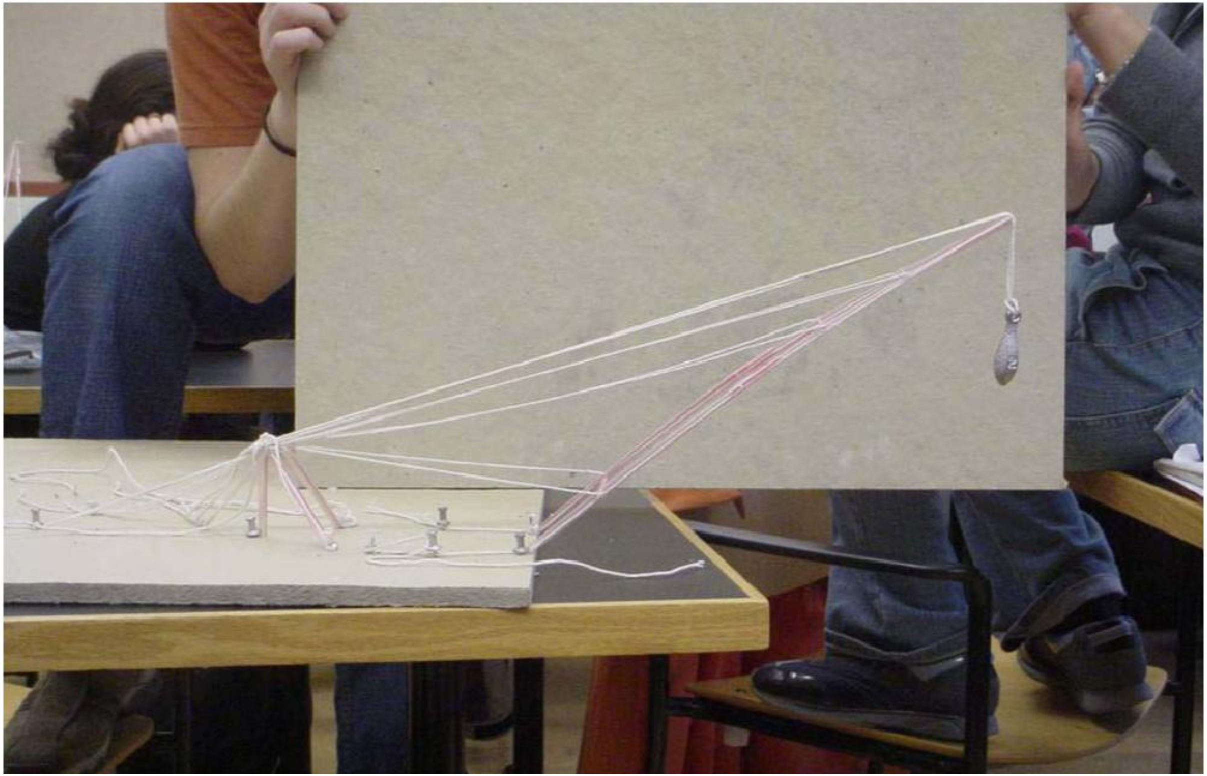
**Maintenance and disposal plan for new structures**

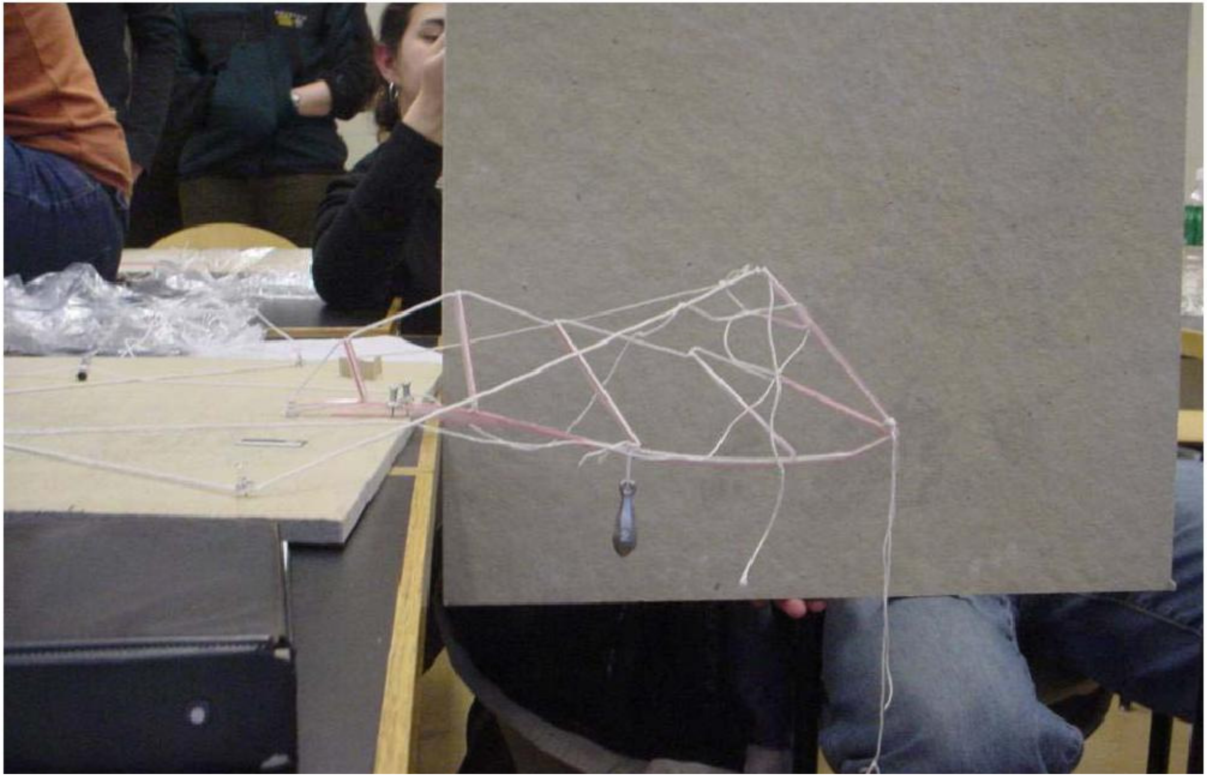
**Code improvements for the reuse of salvaged structures and new uses of traditional materials**

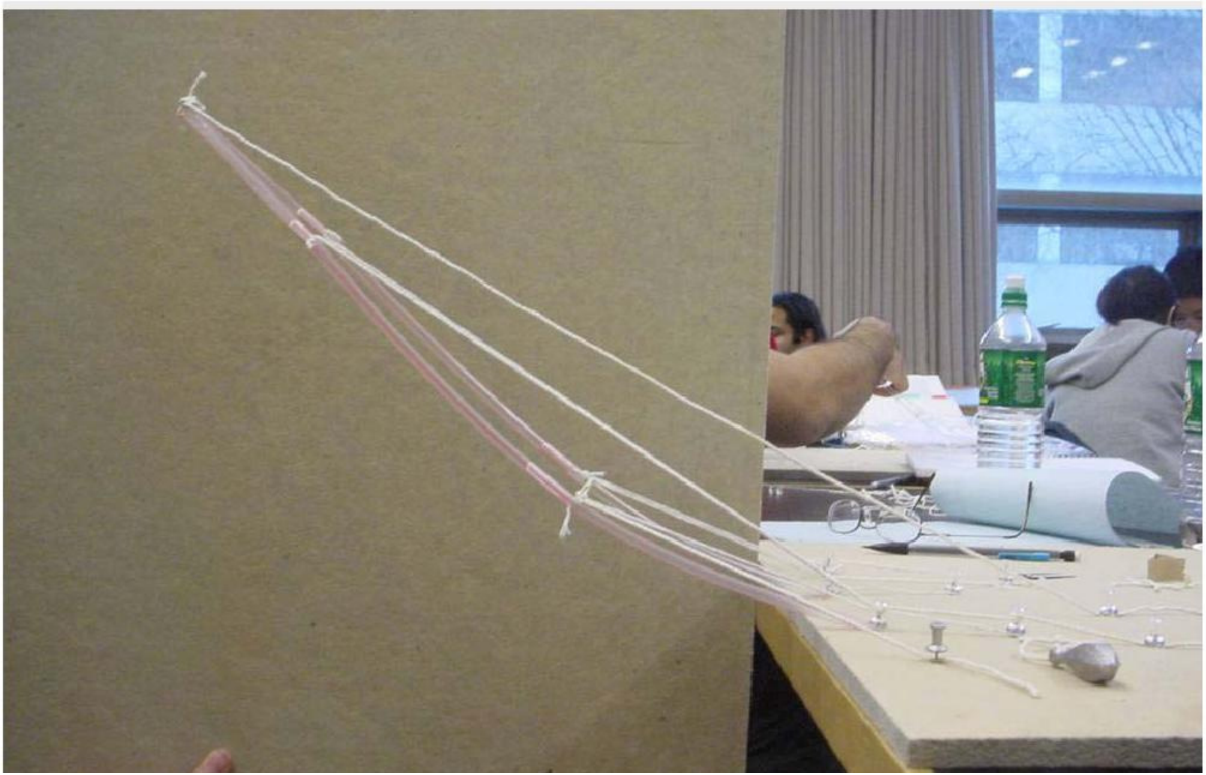
# Tension Structures

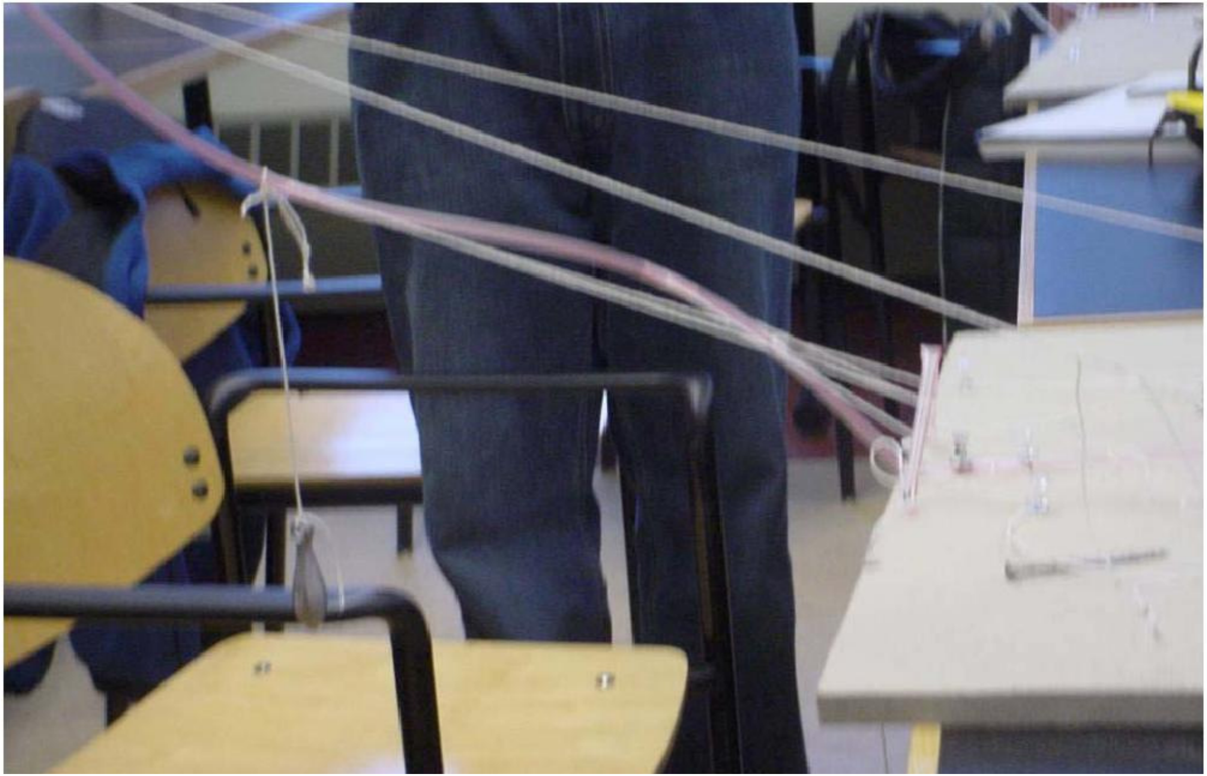
## 4.440 Basic Structural Theory

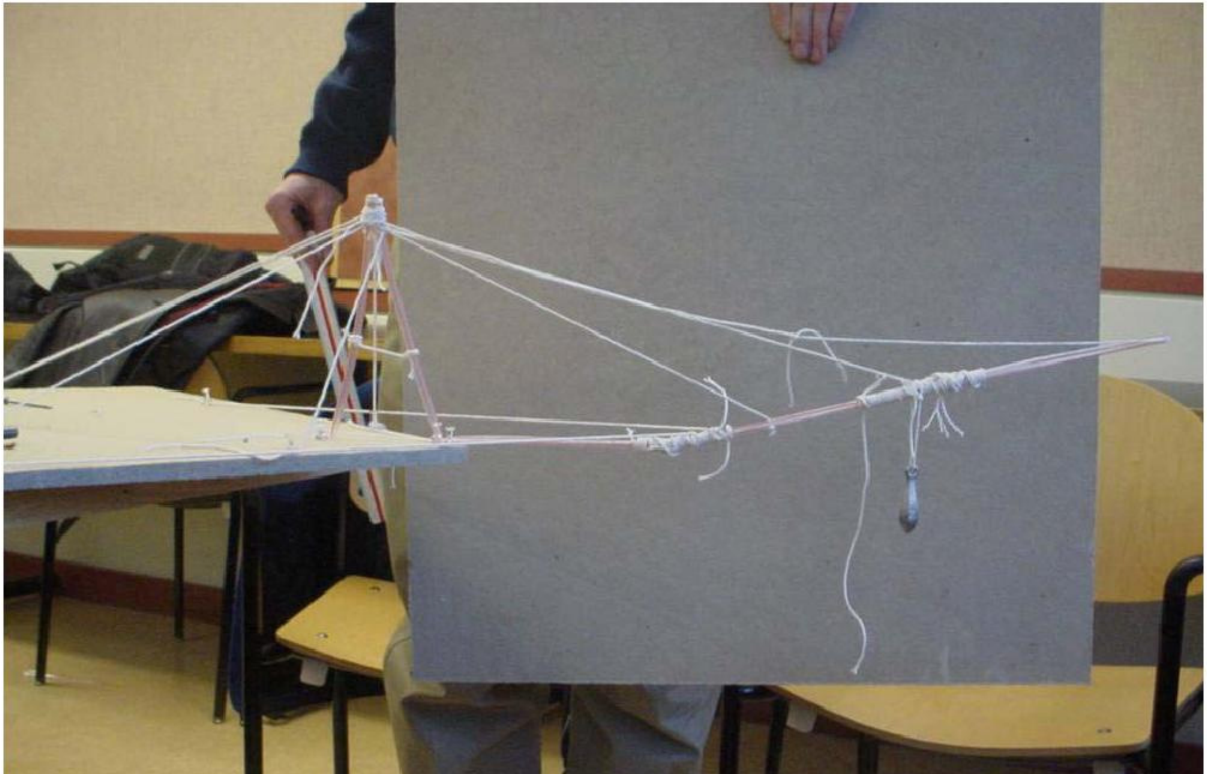






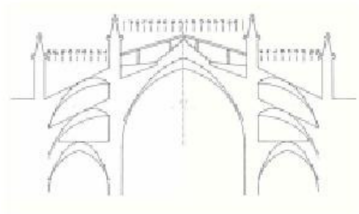




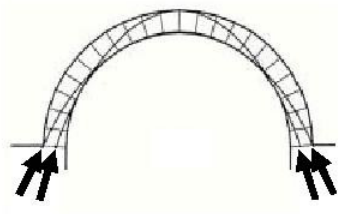


# Review of Compression Lecture

Masonry structures must contain lines of compression within the material



Arches can provide a range of thrust values



Efficient

**structures follow a funicular shape**

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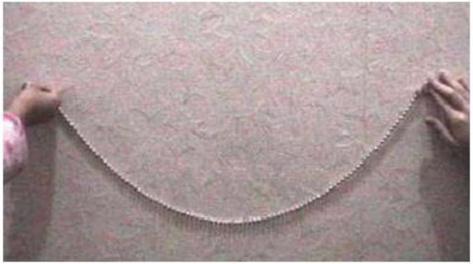
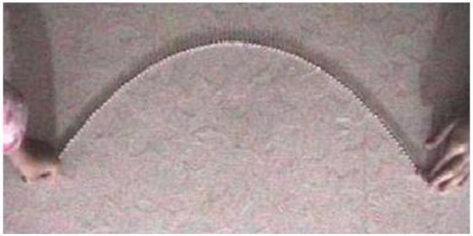
# Hookes 2 nd Law (1675)

**ut pendet continuum *flexile, sic stabit contiguum rigidum inversum***





**As hangs the flexible line, so but inverted will stand the rigid arch**

arch.

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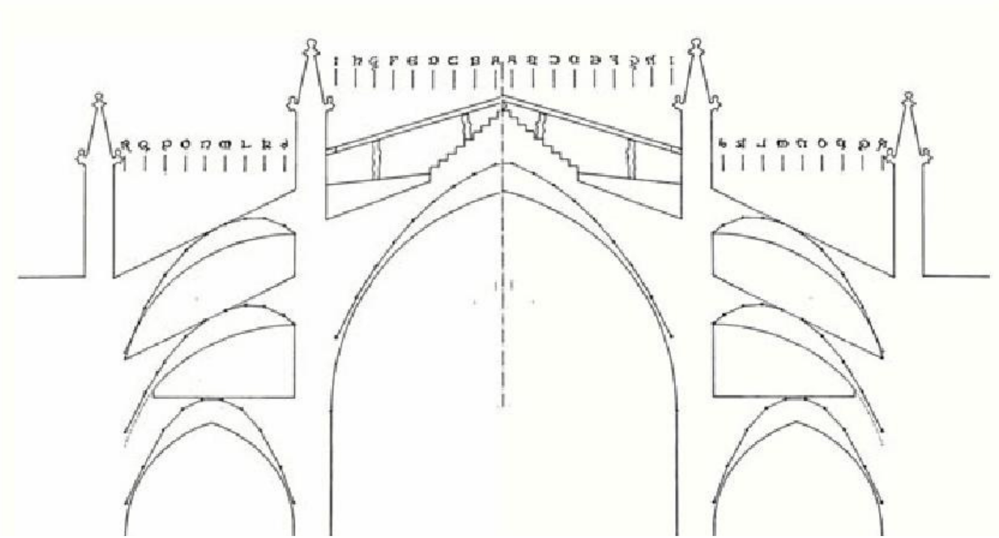
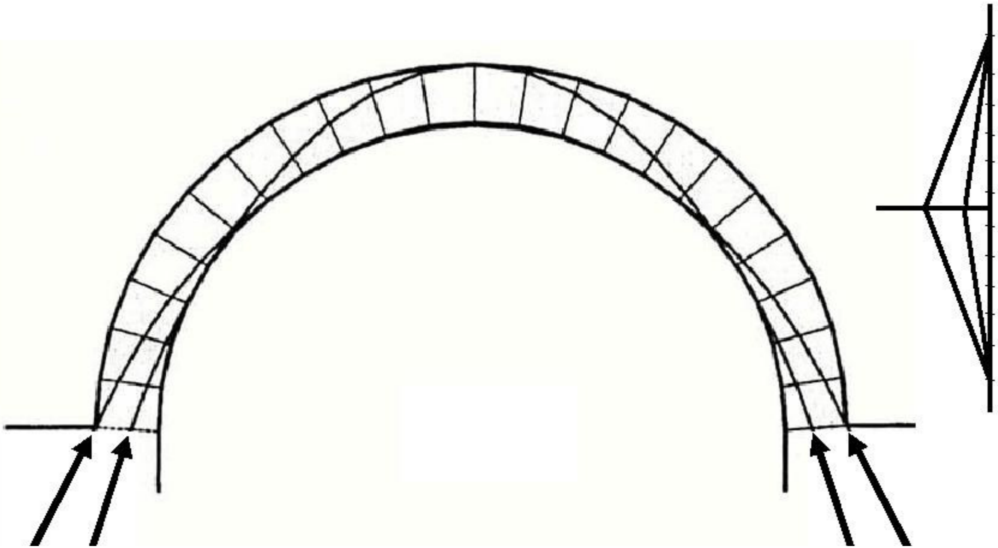
# Cathedral of Palma de Mallorca, 16th C Spain



# Range of Arch Thrust



## COMPRESSION

# Tension Structures

Tension structures must have a structural form: cables dont lie

Due to their light weight and long spans, tension structures are susceptible to vibration and other dynamic problems

For really long spans (like suspension

**bridges), the self weight of the structure is the dominant load**

# Truss Analysis

# Review: Member Design

Compression elements have lower stresses due to buckling

$$P_{cr} = p^2EI/(kL)^2$$

When using graphic statics for truss analysis, use clockwise convention to determine if an element is in tension or compression.

# Truss Lecture

**Moments of forces for finding reactions**

**Method of joints for analyzing trusses**

**Graphical analysis for analyzing trusses**

# Three Equations of Equilibrium

**1. Sum of vertical forces must be zero**

$$SF_y = 0$$

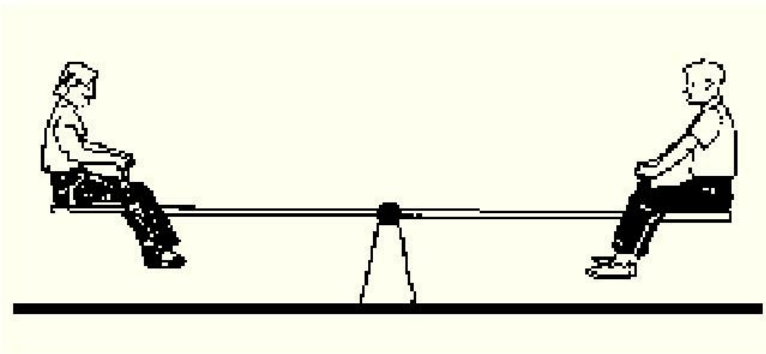
**2. Sum of horizontal forces must be zero**

$$SF_x = 0$$

**3. Sum of moments must be zero**

SM = 0

# Moment Equilibrium



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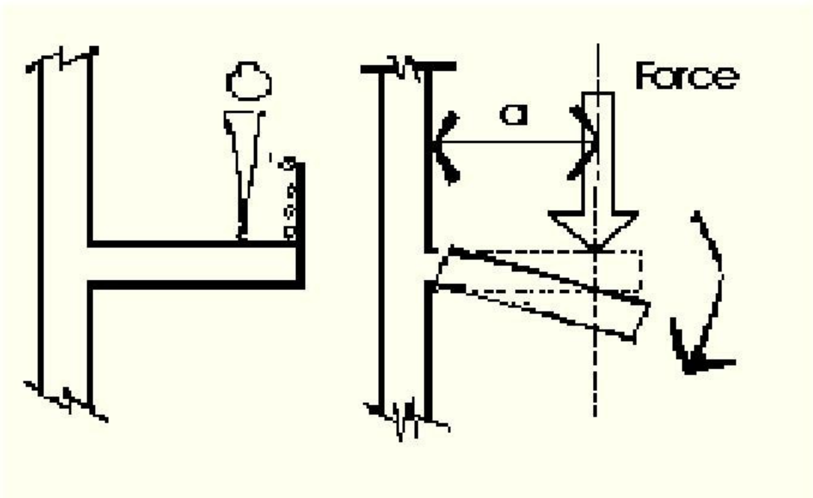
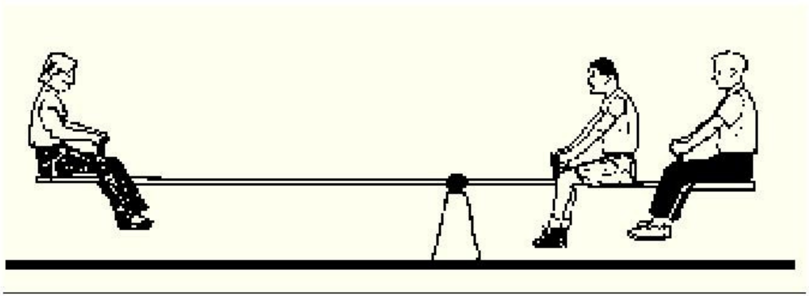
# Moment of Force

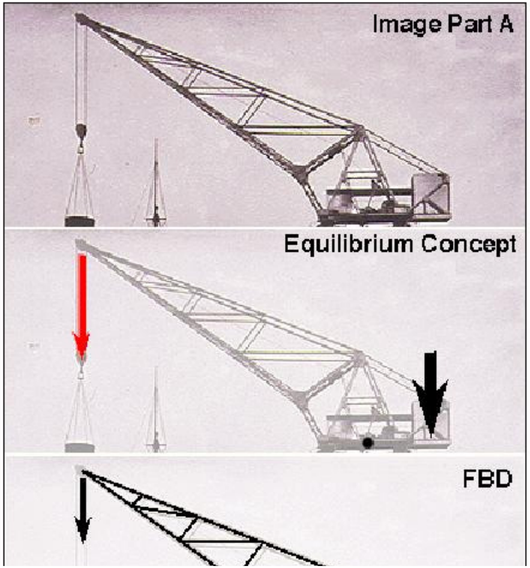


M
=
Fa

# Moment Equilibrium



# Crane Counterweight



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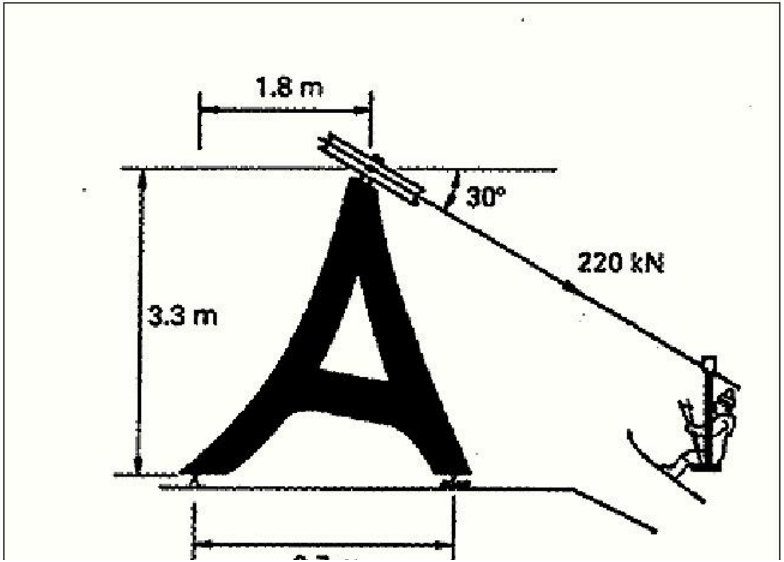
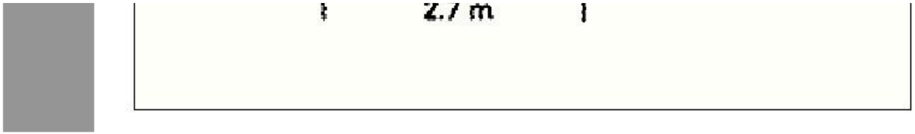
# Equilibrium of Ski Lift Tower




2.7 m

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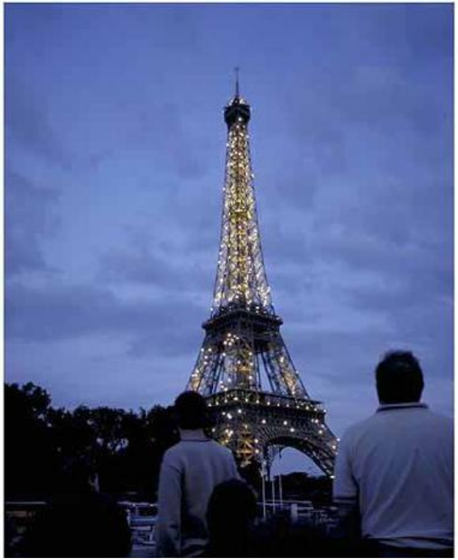
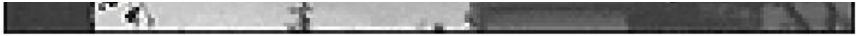
# Eiffel Tower

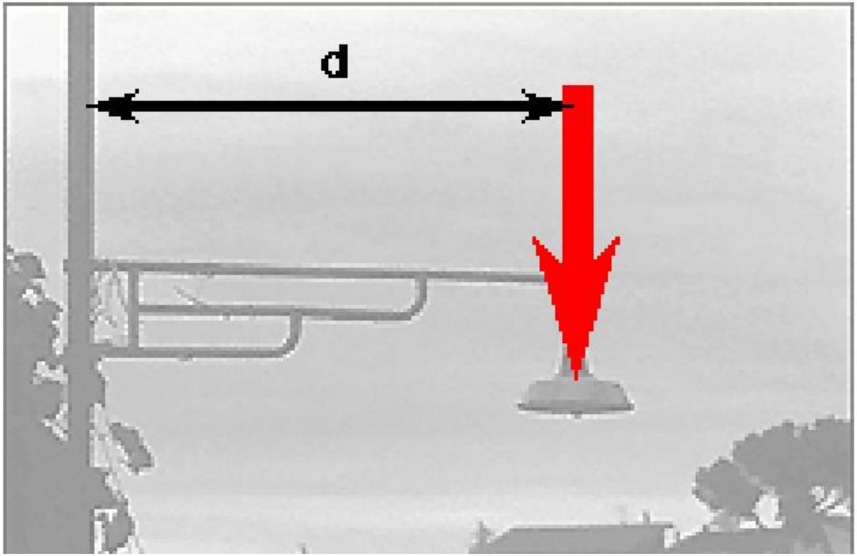


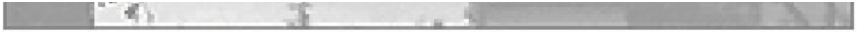

copyright 2002 keith@epifice.com

# Cantilevered Streetlight



# Weight of Lamp





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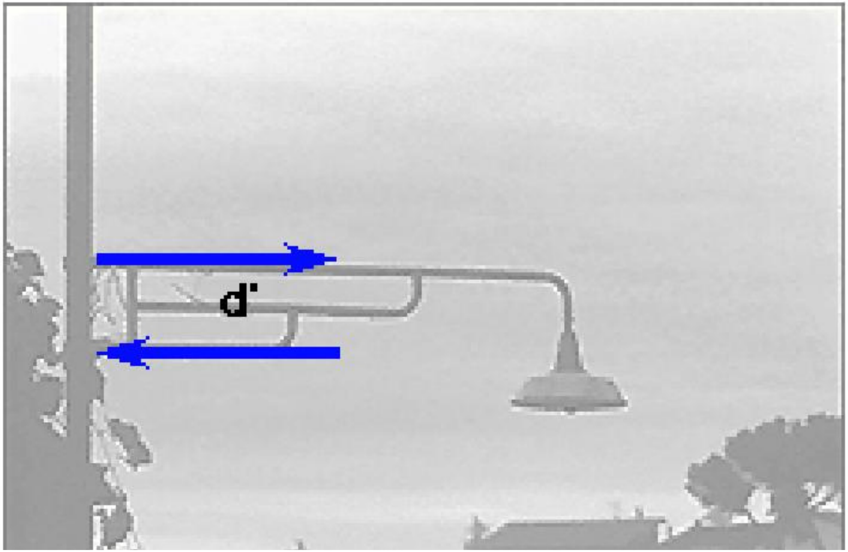
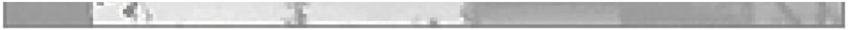
# Reactions at Supports





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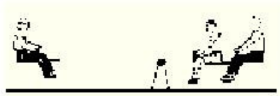
# Trusses

**Rotational Equilibrium**

Sum of the moments must equal zero.

Use to calculate reactions at **supports and to find internal forces**



**Trusses are an efficient way to carry loads with minimal material**

**Look for examples of moment**

**equilibrium around you**

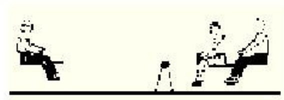
# Beam Design

# Review of Lecture 5: Trusses

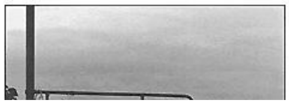
**Rotational Equilibrium**

Sum of the moments must equal zero.

Use to calculate reactions at **supports and to find internal forces**

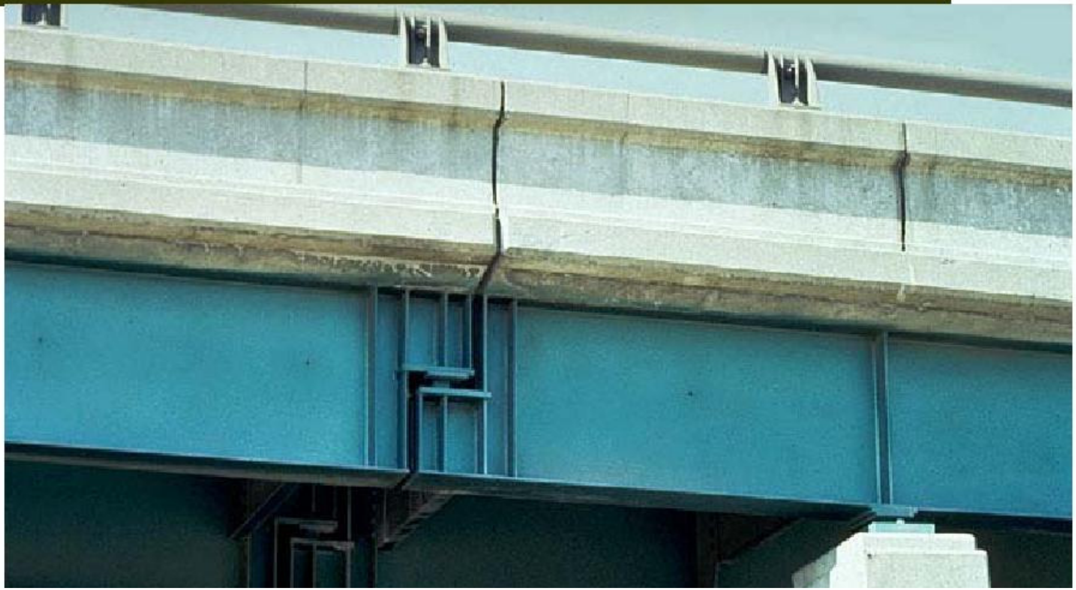


**Trusses are an efficient way to carry loads with minimal material**



**Look for examples of moment**

**equilibrium around you**



# Concrete beams

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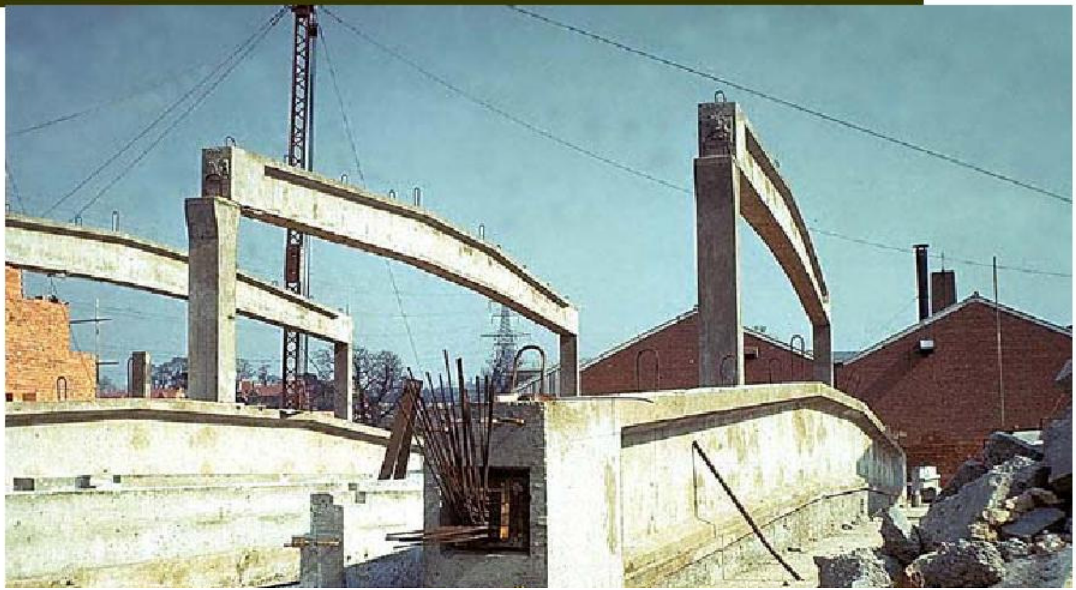
# Concrete connections



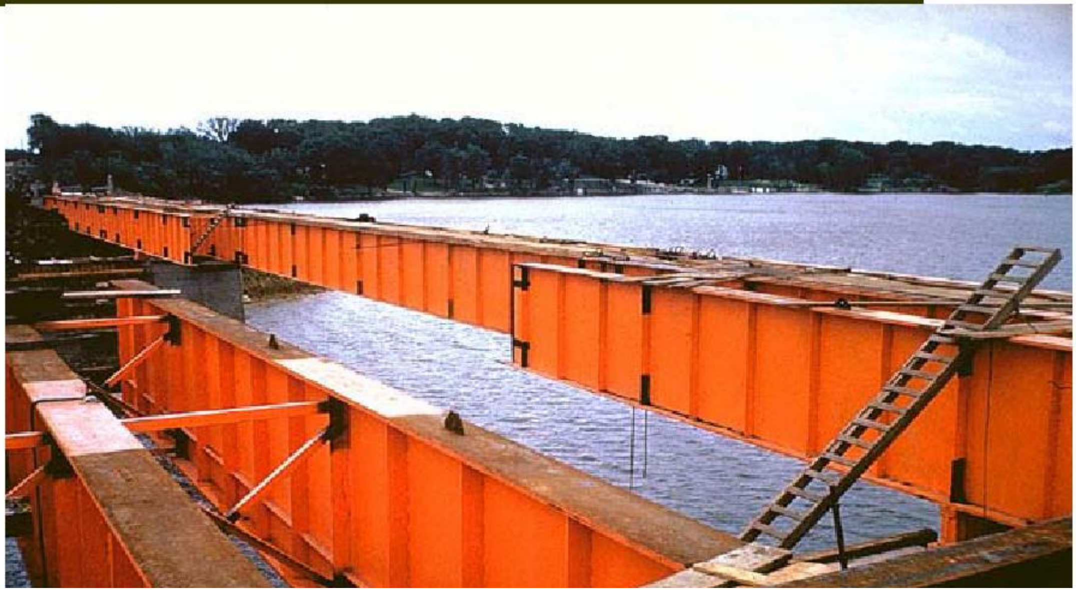
# Reinforcing rod connections

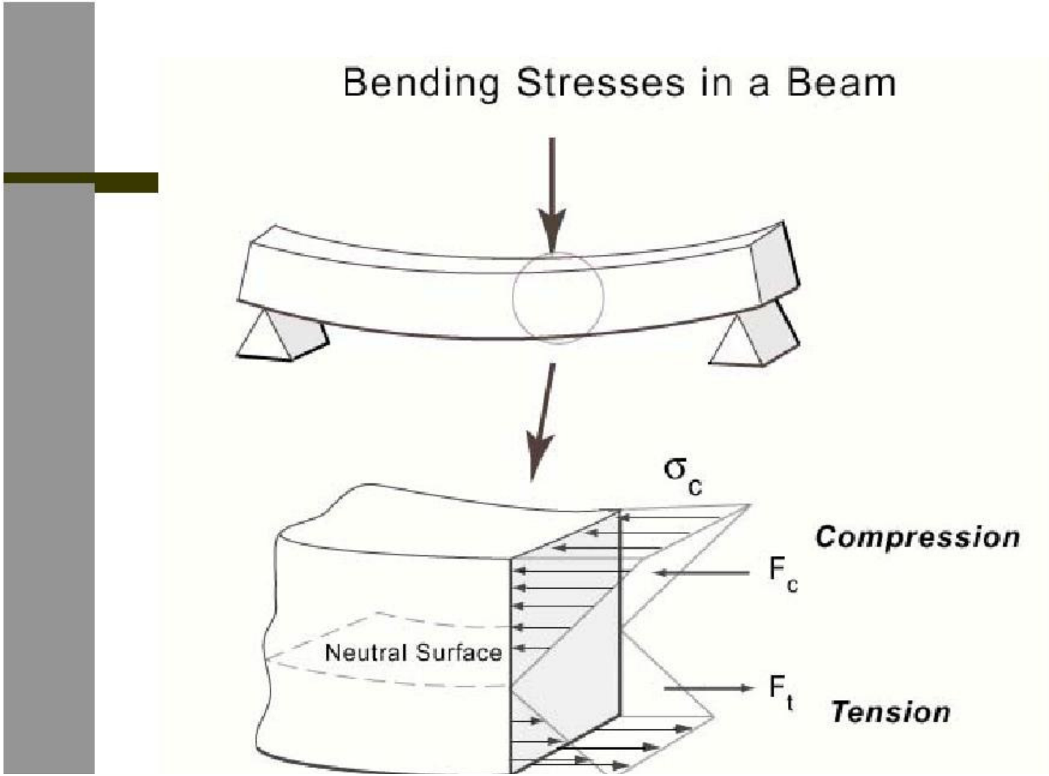
# Concrete Y-beams

# Interior View

# Castellated Beams

# Timber Cantilever Beams




Bending Stresses in a Beam
$\sigma_c$
Compression
$F_c$
Neutral Surface
$F_t$
Tension


σt

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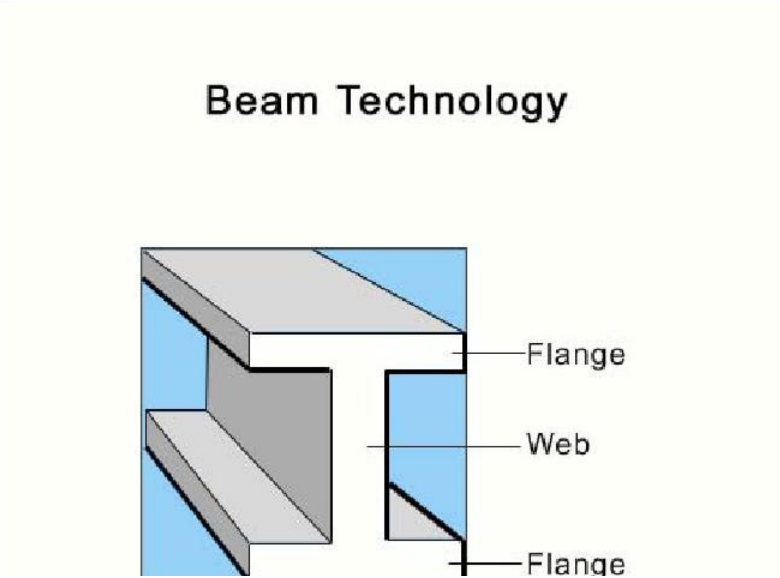
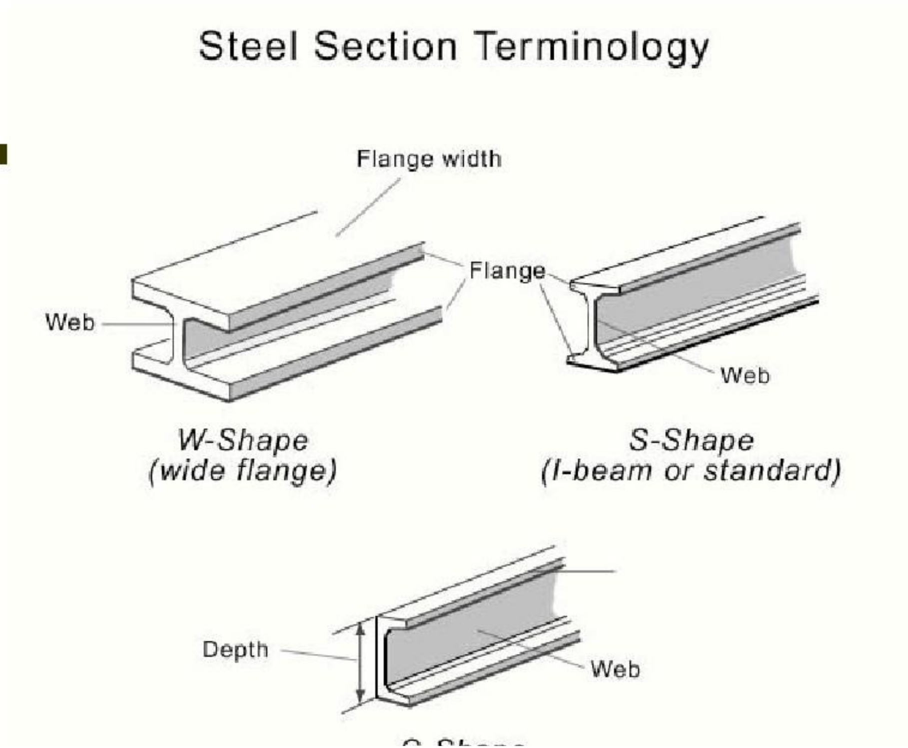
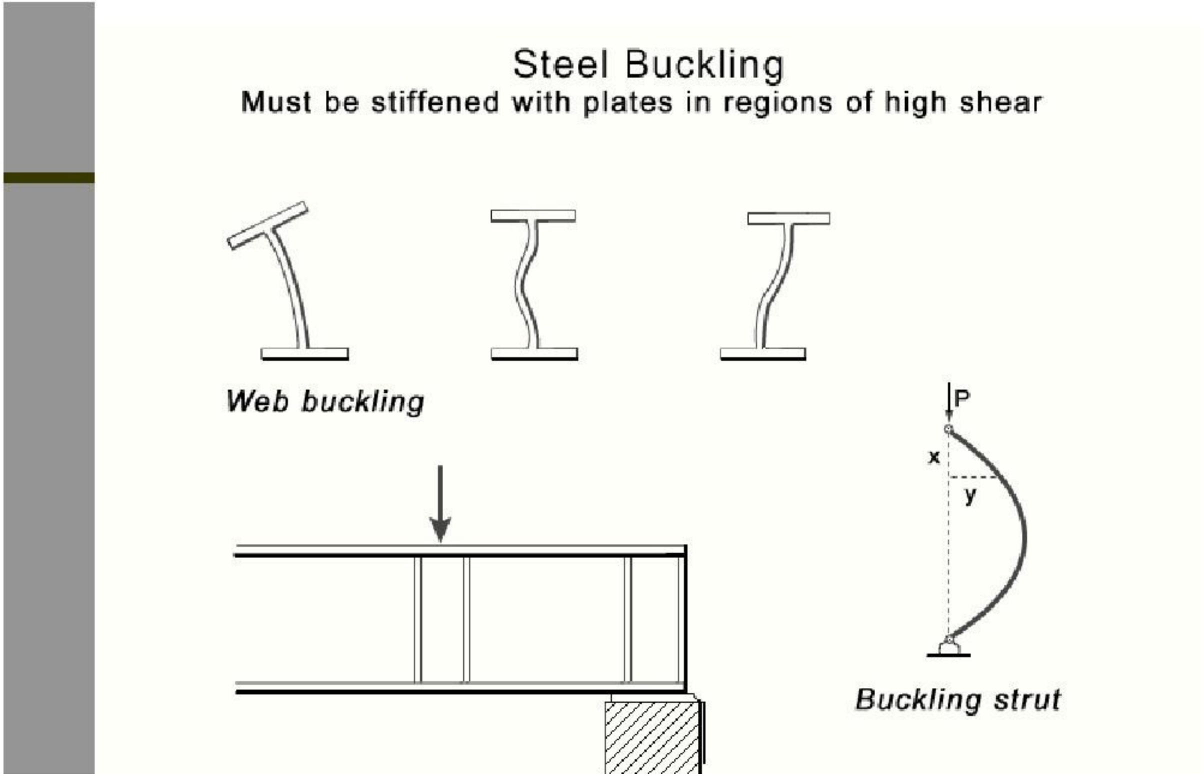
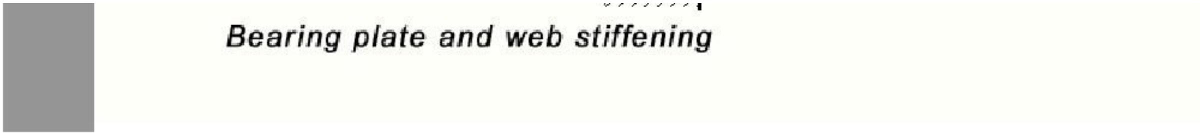
# BeamTerm inology




Steel Section Terminology
Flange width
Flange
Web
W-Shape
(wide flange)
Web
S-Shape
(I-beam or standard)
Depth
Web

C-Shape
(channel)


Steel Buckling
Must be stiffened with plates in regions of high shear
Web buckling
P
x
y
Buckling strut


Bearing plate and web stiffening

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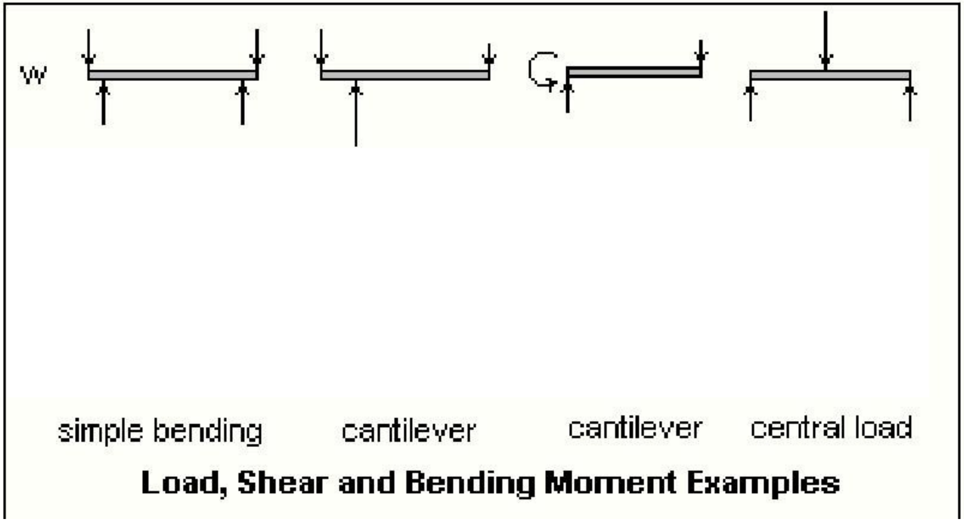
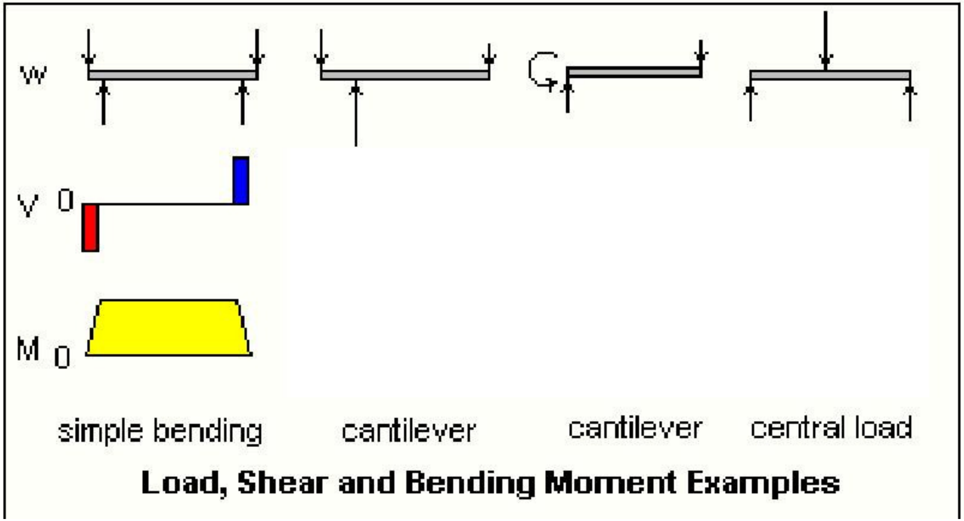
# Shear Diagrams



# Shear Diagrams



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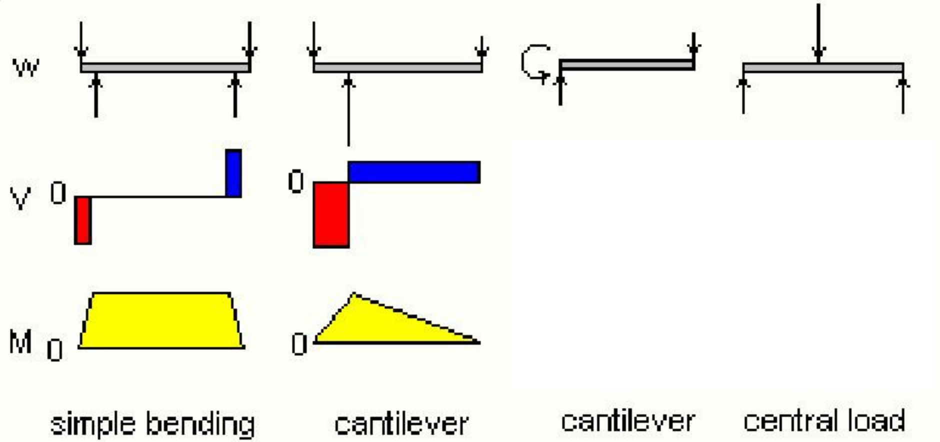
# Shear Diagrams




**Load, Shear and Bending Moment Examples**

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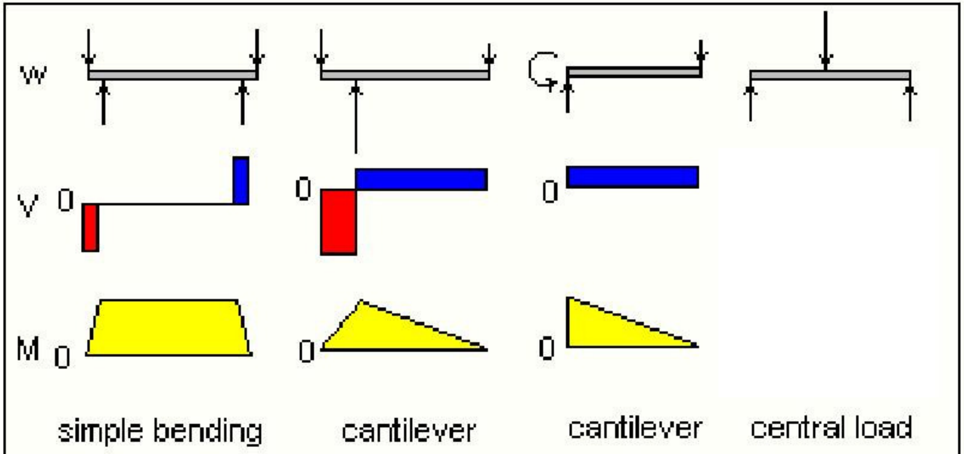
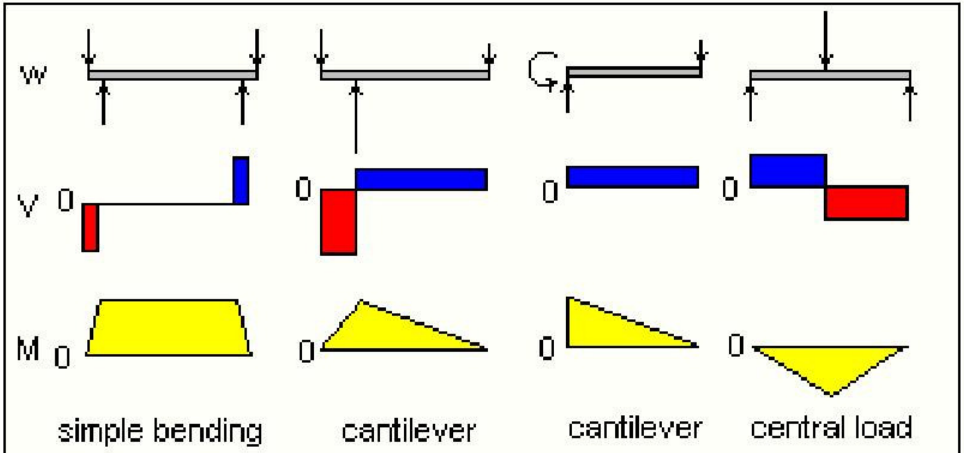
# Shear Diagrams




Load, Shear and Bending Moment Examples

# Shear Diagrams




**Load, Shear and Bending Moment Examples**

# How to draw a shear diagram

1) Determine external reactions on beam

2) Walk along beam with your pen

3) Pen goes up and down with the loads

4) Must close diagram at the ends of the beam

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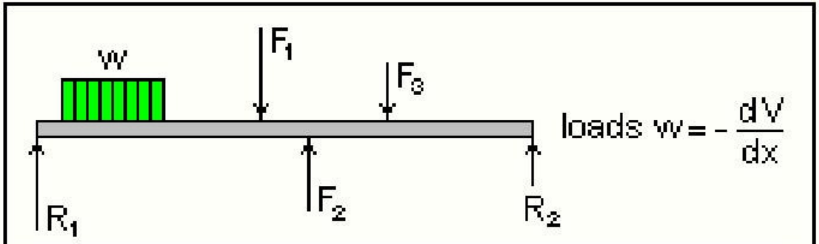
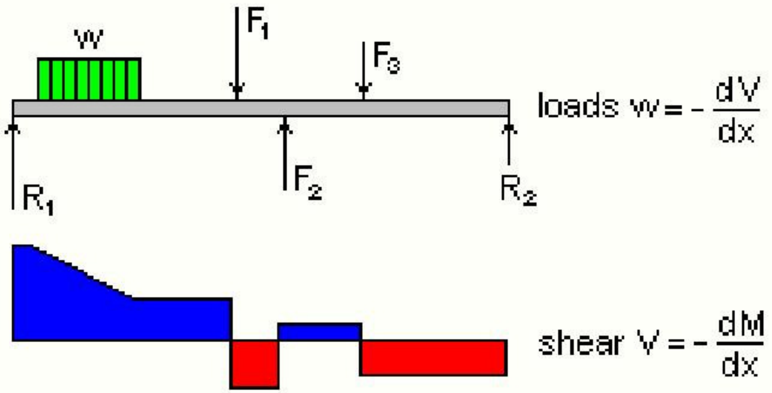
# Shear Diagrams



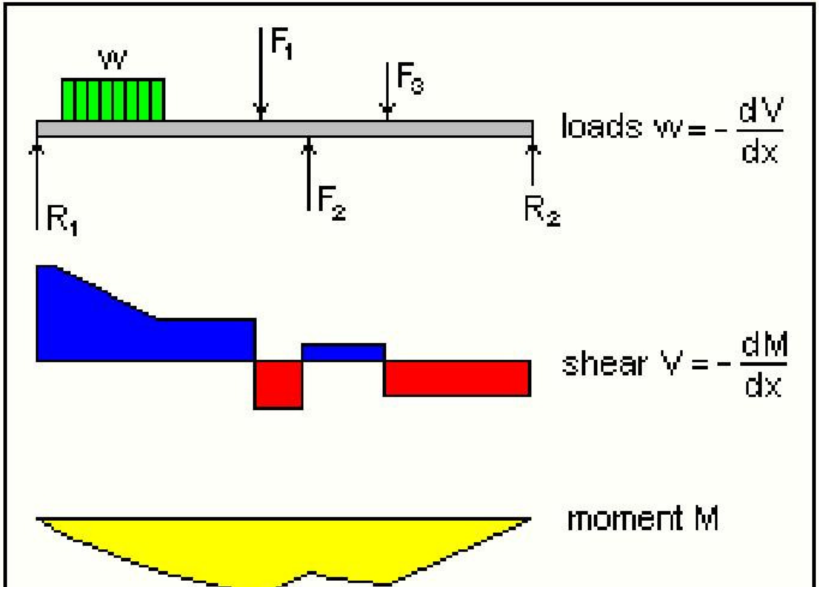
**Load, Shear and Moment Diagrams**

# Shear Diagrams



## Load, Shear and Moment Diagrams

# Shear Diagrams




Load, Shear and Moment Diagrams

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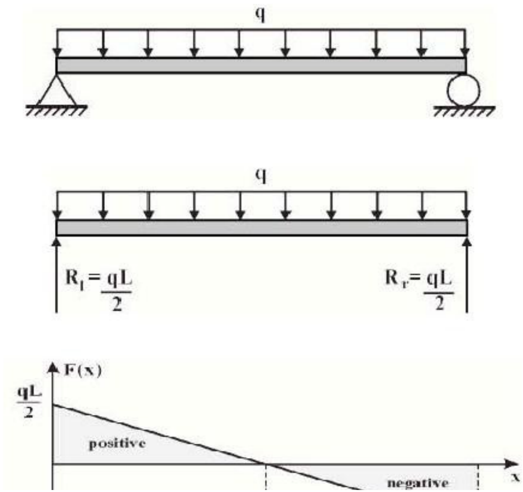
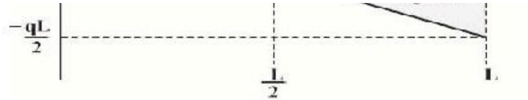
# Shear Diagram for Uniform Load




−qL/2
L/2
L

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# Lecture 6: Beams

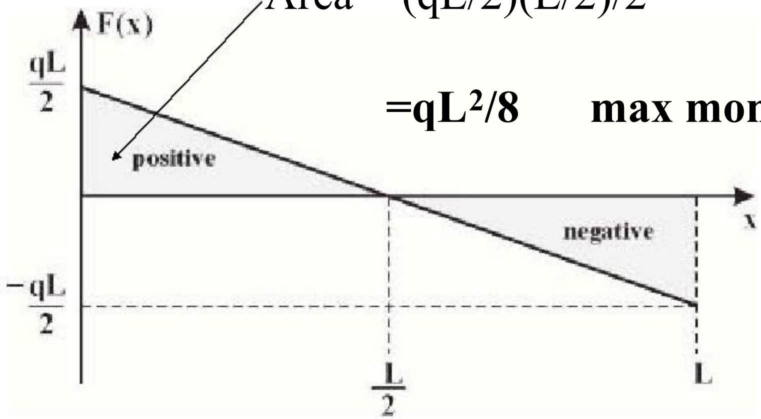
**Beams carry loads in bending, with compression and tension on opposite sides**

**Visualize trusses within the depth of a beam**

**Shear and moment diagrams are used to illustrate internal forces in beams**

# Shear Diagrams

Area = (qL/2)(L/2)/2




**$=qL^2/8$ max moment value**

# Shear diagram equals the slope of moment diagram

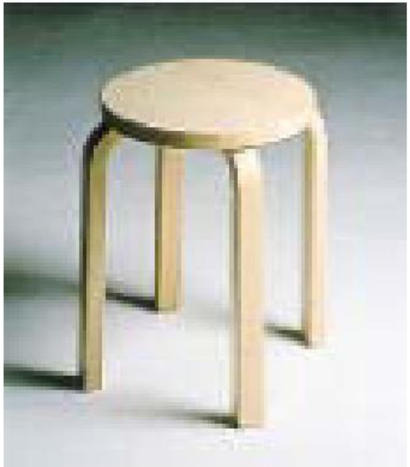
# Indeterminate Structures

# Architecture
# 4.440

# Outline

- Introduction
- Static Indeterminacy
- Support Conditions
- Degrees of Static Indeterminacy
- Design Considerations
- Conclusions

# Forces in the Legs of a Stool



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# Three-Legged Stool

Statically determinate

One solution for the axial force
in each leg

Why.
3 unknowns
3 equations of equilibrium

Uneven

**floor has no effect**

# Four-Legged Stool

**Statically indeterminate**

**A four legged table on an uneven surface will rock back and forth**

**Why.**

**It is hyperstatic:**

**4 unknowns**

**3**

**3**
**equations**
**of**
**equilibrium**

# Four-Legged Stool

Infinite solutions exist

Depends on unknowable support conditions

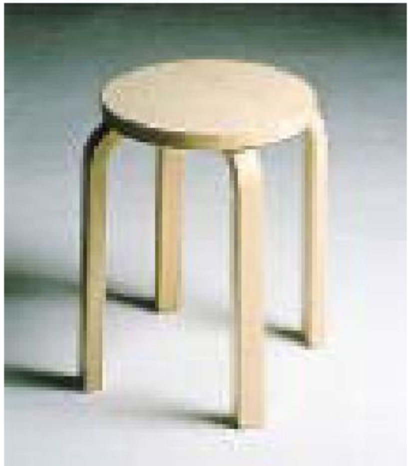
A four legged table on an uneven surface will rock back and forth

The forces in each leg are constantly changing

**Fundamental difference between hyperstatic and static structures**

# Forces in the Leg of a Stool

Statically



Statically
Indeterminate

**determinate**

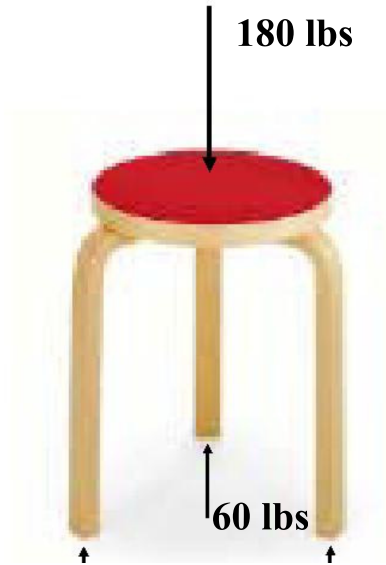
**indeterminate (hyperstatic)**

# Three-Legged Stool

**Design for a person weighing 180 pounds**

**60 pounds/leg**

**Regardless of uneven floor**




60 lbs
60 lbs

# Collapse of a Three-Legged Stool

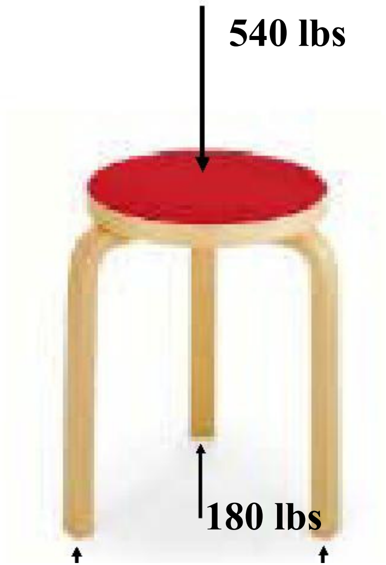
Design for a person weighing 180 pounds

If the safety factor is 3:

$P_{cr} = 3(60) = 180$ lbs

And each leg would be designed to fail at a load of 180 pounds

The stool would carry a



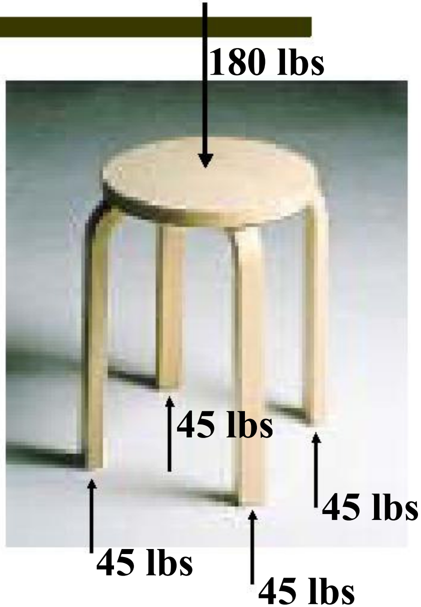

total load
of 540
pounds
180 lbs
180 lbs

# Elastic Solution for 4-Legged Stool

Design for a person weighing 180 pounds

45 pounds/leg

But if one leg does not touch the floor

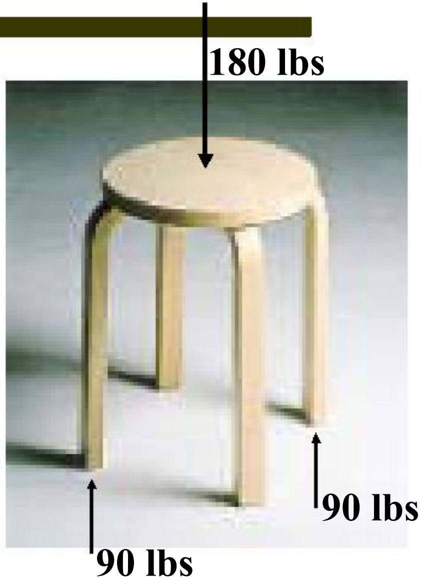


# Four-Legged Stool

If one leg doesnt touch the floor, the force in it is zero.

If one leg is zero, then the opposite leg is also zero by moment equilibrium.

The two remaining legs carry all of the load:

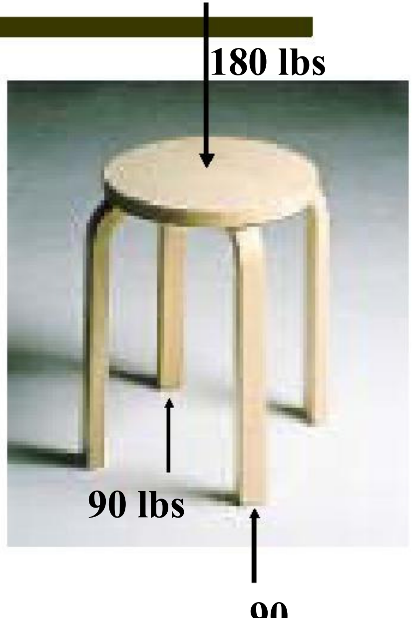


**90 pounds/leg**

# Four-Legged Stool

Therefore

**All four legs must be *designed to carry the 90* pounds (since any two legs could be loaded)**



**90**
**lbs**

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# Four-Legged Stool

If the elastic solution is accepted, with a load in each leg of 45 pounds, then assuming a safety factor of 3 gives:

$P_{cr}$ = 3(45 lbs) = <u>135 lbs</u>

And each leg would be designed to fail

**designed to fail**
**at a load of**
**135 pounds**

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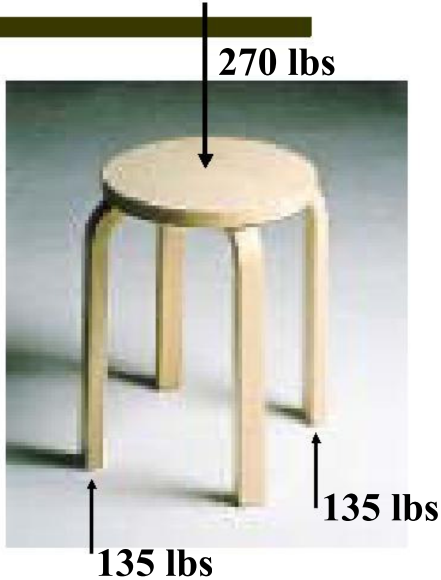
# Four-Legged Stool

Now imagine the load is increased to cause failure

When load is 270 lbs, the two legs will begin to fail

As they squash, the other two legs will start to carry

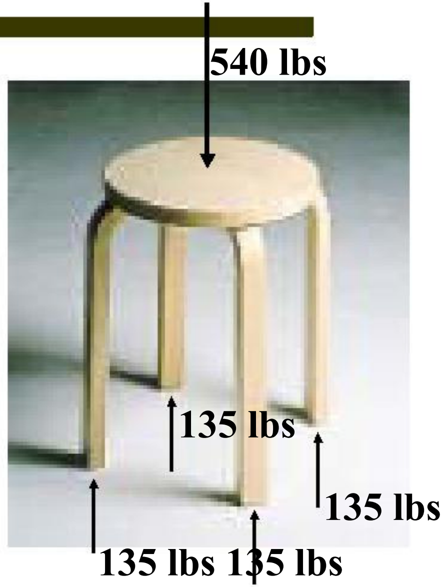


**carry load also**

# Collapse of a 4-Legged Stool

At final collapse state, all four legs carry 135 pounds and the stool carries 540 pounds.

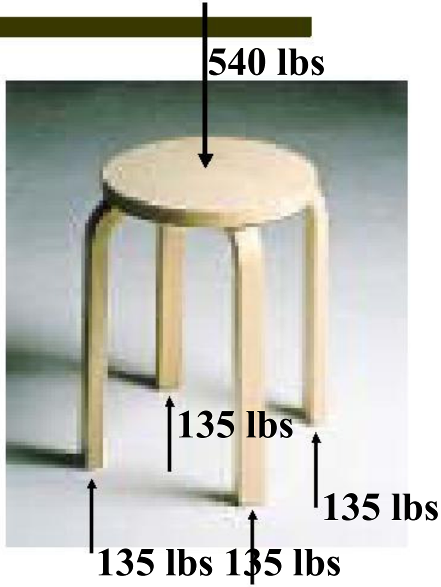
This occurs only if the structure is ductile (ie, if the legs can squash)



# Ductile Collapse

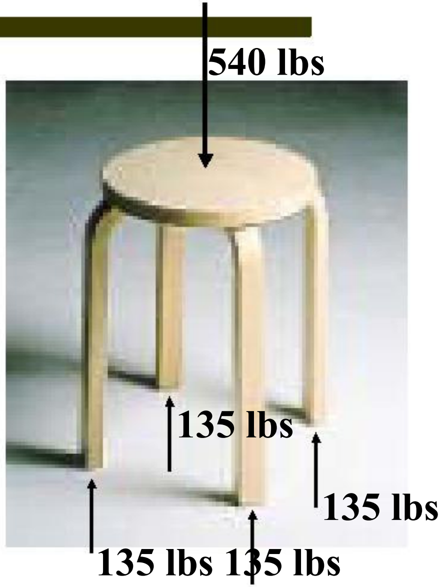
So small imperfections do not matter, as long as the structural elements are ductile

The forces in a hyperstatic structure cannot be known exactly, but this is not important as long as we can predict the collapse state



# Lower Bound Theorem of Plasticity

If you can find one possible set of forces, then the structure can find a possible set of forces




It does not have to be correct, as long as the structure has capacity for displacements (ductility)

For indeterminate structures, we

**cannot be certain of the internal**
**state of the forces**

# Examples of Statically Determinate Structures

## Unstressed by support movements or temperature changes

Three-legged stool

Simply supported beam

Cantilever beam

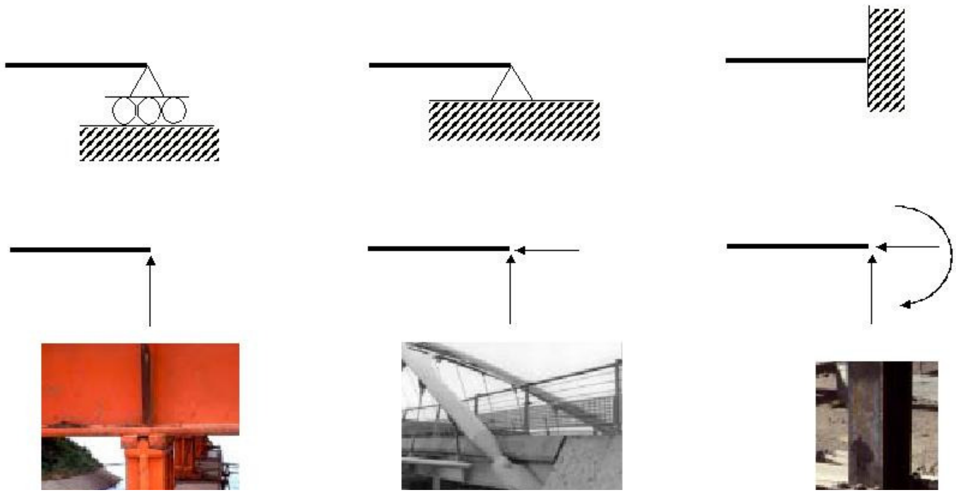
Three-hinged arch

# Simply Supported Bridge

**Can adjust to support movements and temperature changes**

# Support Conditions

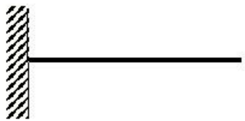
## Roller Pin (hinge) Fixed



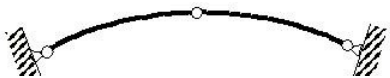
# Statically Determinate Structures

## Simply supported beam

## Cantilever beam



## Three-hinged arch



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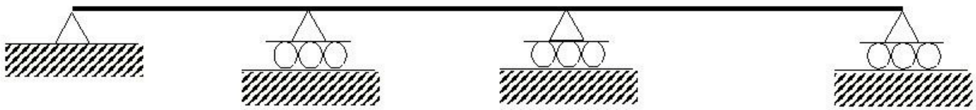
# Simply Supported Beam

| Statically Determinate | Indeterminate (hyperstatic) |
| --- | --- |
| Simply supported beam | Continuous beam |
| Cantilever beam | Propped cantilever beam |
| Three-hinged arch | Fixed end arch |
| Three- | Rigid |

**hinged frame**

**frame**

# Continuous Beam



**How many unnecessary supports.**

**What is the degree of static indeterminacy.**

# Pin-Ended Beam

**Will temperature changes cause forces in the beam.**

**How many unnecessary supports.**

**What is the degree of static**

**What is the degree of static indeterminacy.**

# Fixed-End Beam

**Will temperature changes cause forces in the beam.**

**How many unnecessary supports.**

**What is the degree of static**

**What is the degree of static indeterminacy.**

# Fixed-End Arch

**Will temperature changes or support movements cause forces in the arch.**

**How would you make this structure statically determinate.**

**What is the degree of static indeterminacy.**

# Two-Hinged Arch

**Will temperature changes or support movements cause forces in the arch.**

**How would you make this structure statically determinate.**

**What is the degree of static indeterminacy.**

# Pinned Frame

**Will temperature changes or support movements cause forces in the frame.**

**How would you make this structure**

**statically determinate.**

**What is the degree of static indeterminacy.**

# Fixed Frame

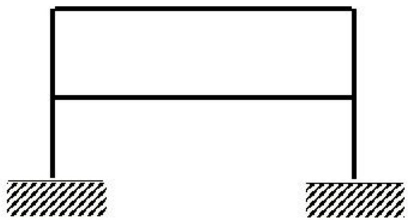
**Will temperature changes or support movements cause forces in the frame.**

**How would you make this structure**

**statically determinate.**

**What is the degree of static indeterminacy.**

# Fixed Frame



**Will temperature changes or support movements cause forces in the frame.**

**How would you make this structure**

**statically determinate.**

**What is the degree of static indeterminacy.**

# How to find forces in statically indeterminate structures

**Approximate hand calculations**
Make simplifying assumptions

**Computer: Finite Element Methods**
Solve for internal forces based on relative **stiffness of each element and many other assumptions (elastic analysis)**

**Analyze limiting cases to determine one possible state of internal forces**

# Finite Element Analysis

Divide structure into a mesh of finite elements

Solves for internal forces based on relative stiffness of each element

# Finite Element Analysis

But cant account for imperfections in supports and construction

Like a four-legged stool, it is impossible to know the exact forces

Finite element analysis is more sophisticated, but is not necessarily better

# Design Considerations

**Statically indeterminate structures offer greater redundancy, i.e. more possible load paths**

**But are less clear in their structural action**

- More complicated to design and assess
- May be more difficult to repair

# Static Indeterminacy

For a given set of applied loads, any possible equilibrium state is acceptable (internal forces in the legs of the stool)

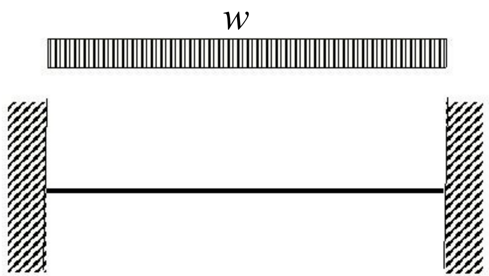
Find extreme equilibrium cases by releasing the extra supports (i.e., assume two legs dont touch the ground)

You can choose any internal equilibrium state as long as buckling

**does not occur (lower bound theorem)**

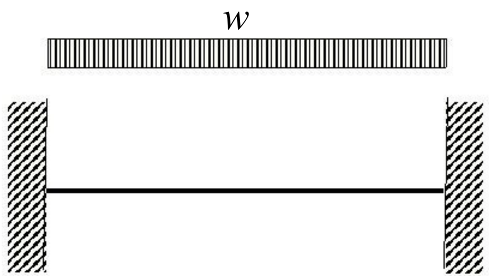
# Statically Indeterminate Beams

**What is the moment diagram for this beam under a uniform load, w.**



# Statically Indeterminate Beams

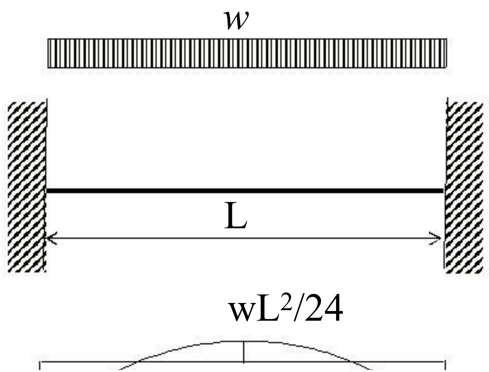
**What is the moment diagram for this beam under a uniform load, w.**



**Is there one answer.**

# Statically Indeterminate Beams

**What is the moment diagram for this beam under a uniform load, w.**




Elastic solution (perfect world)

$wL^2/12$

$wL^2/12$

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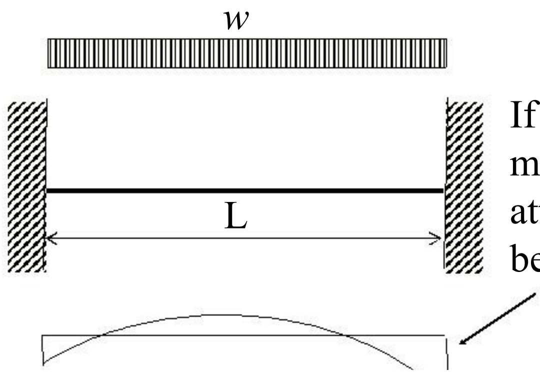
# Statically Indeterminate Beams

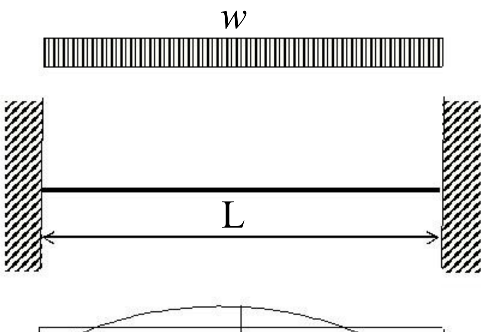
**But what did we learn from the 4-legged stool.**




If this support is more rigid, it will attract more of a bending moment.

# Statically Indeterminate Beams

**The difference between the midspan moment and the closing line is always $wL^2/8$ due to a uniform load.**

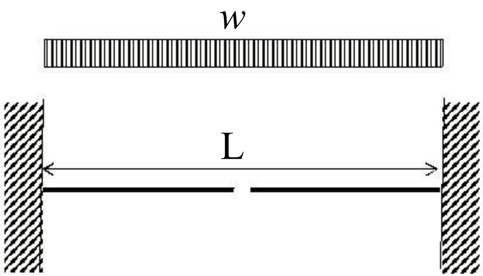



If this support is more rigid, it will attract more of a bending moment.


wL²/8

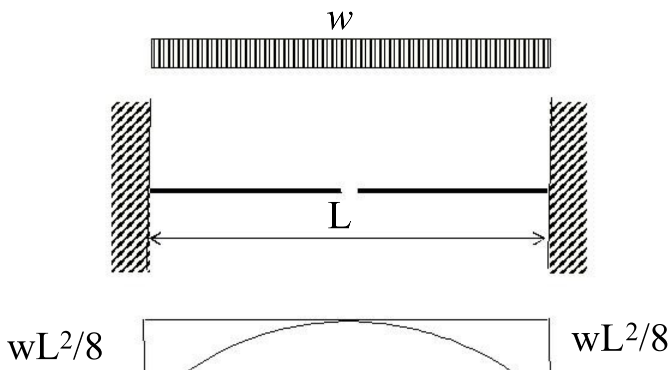
# Statically Indeterminate Beams

**What is the moment diagram for this beam under a uniform load, w, if we make a cut at midspan.**



# Statically Indeterminate Beams

**What is the moment diagram for this beam under a uniform load, w, if we make a cut at centerspan.**



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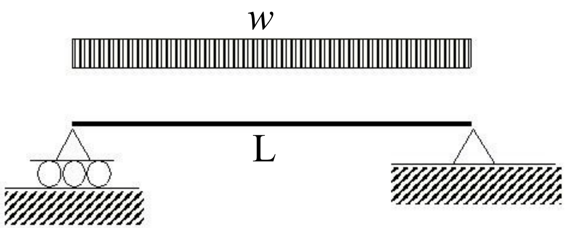
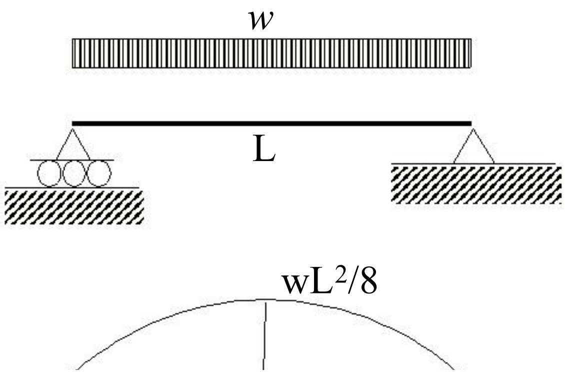
# Statically Indeterminate Beams

**What is the moment diagram for this beam under a uniform load, w, if it is simply supported.**



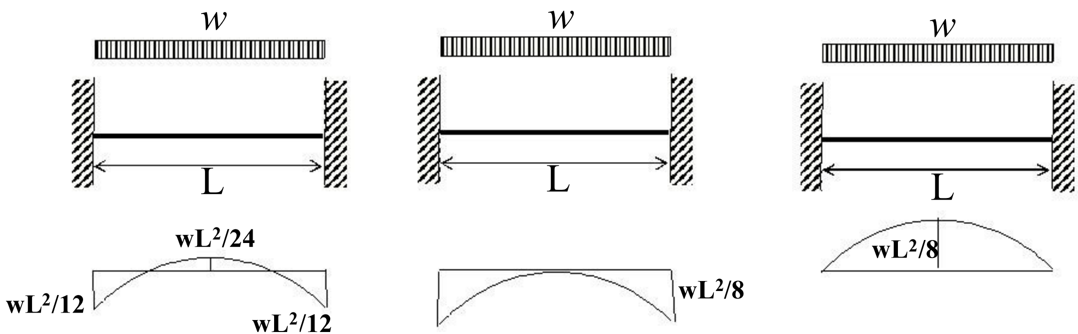
# Statically Indeterminate Beams

What is the moment diagram for this beam under a uniform load, w, if it is simply supported.



# Statically Indeterminate Beams

**Various possible bending moment configurations for a beam under uniform load**



**Moment diagram shifts up and down as the supports change their degree of fixity**

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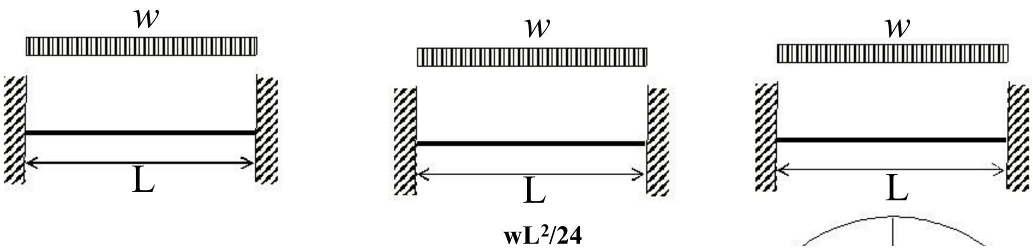
# Statically Indeterminate Beams

**Which is correct. All of them!**

**As a designer, you choose the function by choosing the form**

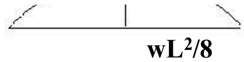
**Shape the structure to reflect the load acting on it**

**Articulate the role of each structural connection**



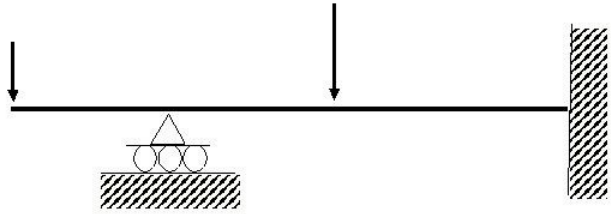

wL²/8
wL²/8


wL²/12


wL²/8

# Statically Indeterminate Beams

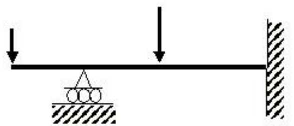
**What is the moment diagram for this beam under two point loads.**



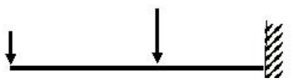
# Statically Indeterminate Beams

**Release unknown reactions until the structure becomes statically determinate.**

**Draw moment diagram for statically determinate structure.**



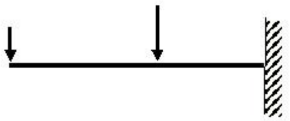
**Remove roller support to make it a cantilever beam**



# Statically Indeterminate Beams

**Release unknown reactions until the structure becomes statically determinate.**

**Draw moment diagram for statically determinate structure.**



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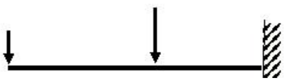
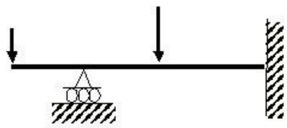
Draw moment diagram for statically determinate structure.



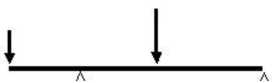
# Statically Indeterminate Beams

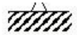
**Release unknown reactions until the structure becomes statically determinate.**

**Draw moment diagram for statically determinate structure.**



**Remove fixed support to make it a simply-supported beam.**

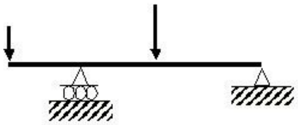




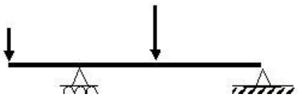
# Statically Indeterminate Beams

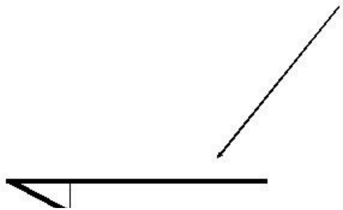
Release unknown reactions until the structure becomes statically determinate.

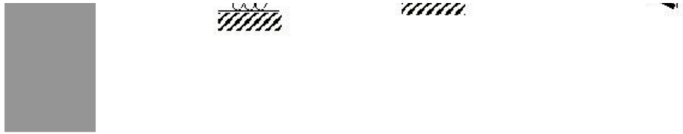
Draw moment diagram for statically determinate structure.



**What shape is the moment diagram here.**



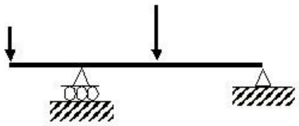




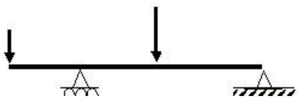
# Statically Indeterminate Beams

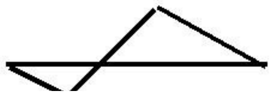
Release unknown reactions until the structure becomes statically determinate.

Draw moment diagram for statically determinate structure.

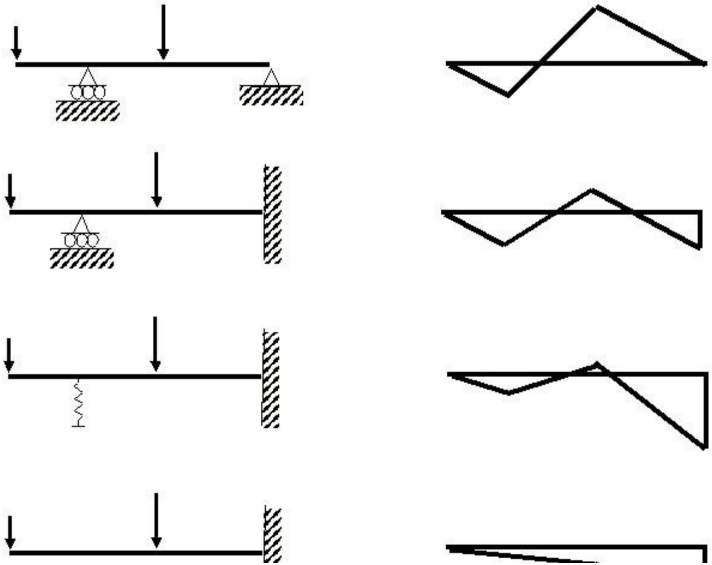


**A: The shape of the hanging cable**





# Statically Indeterminate Beams



Simply-supported

Indeterminate

Indeterminate

Cantilever

**Again, moment diagram shifts up and down**

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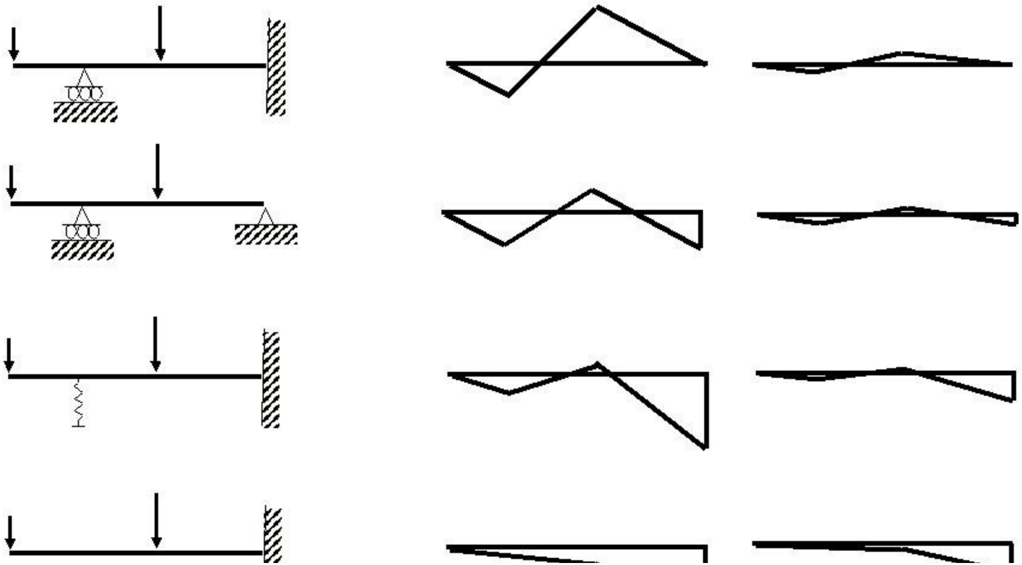
# Statically Indeterminate Beams



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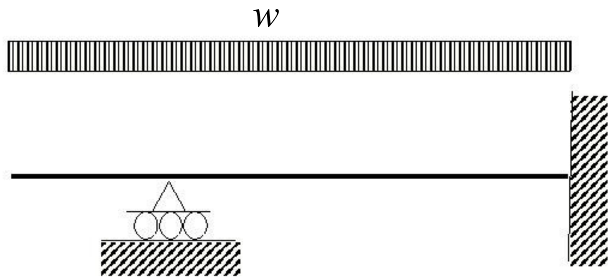
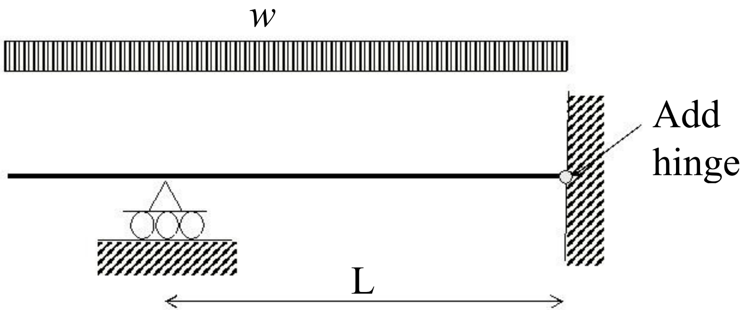
# Statically Indeterminate Beams

**What is the moment diagram for this beam under a uniform load, w.**



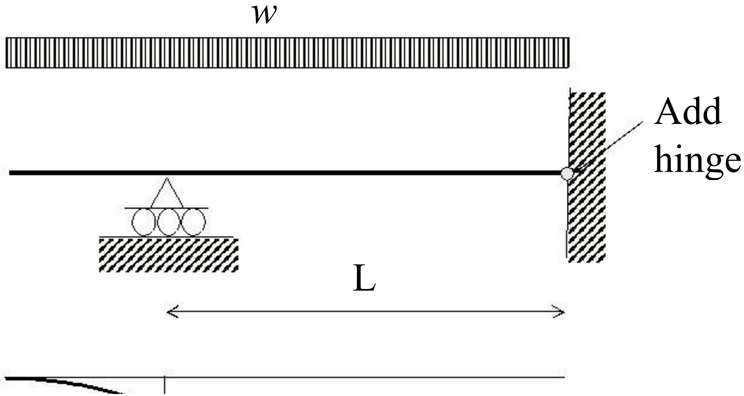
# Statically Indeterminate Beams

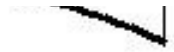
Release the right hand support by adding a hinge



# Statically Indeterminate Beams

## Release the right hand support by adding a hinge





# Statically Indeterminate Beams

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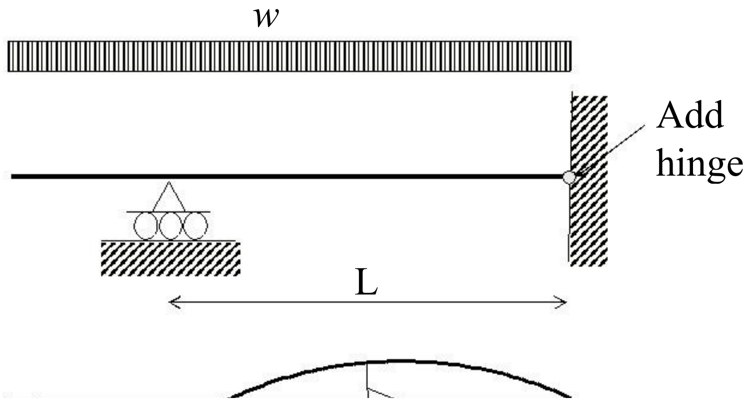
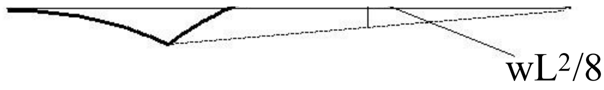
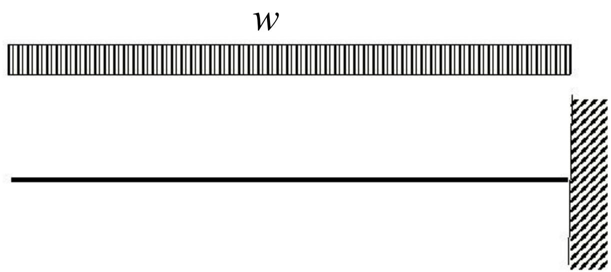



$wL^2/8$

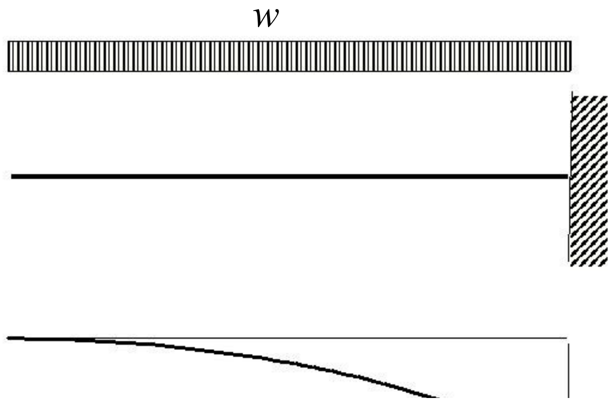
# Statically Indeterminate Beams

Make statically determinate by removing the roller support



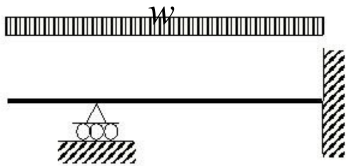
# Statically Indeterminate Beams

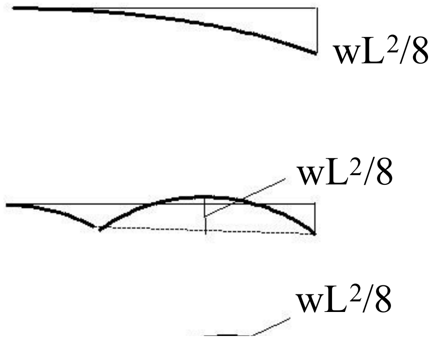
What is the moment diagram for this beam under a uniform load, w.

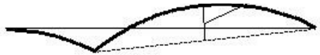


# Statically Indeterminate Beams

**What is the moment diagram for this beam under a uniform load, w.**





# Conclusions

**You choose the function by choosing the form      function follows form**

**For a given loading, the moment diagram simply moves up and down as you change the support conditions**

**Must**

**Must prevent buckling**

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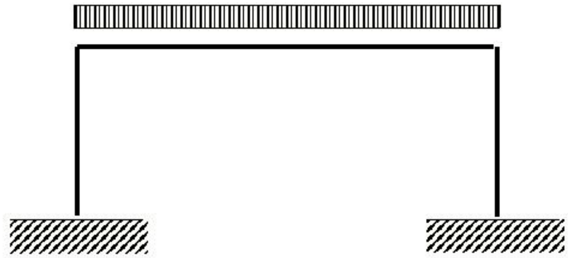
# Fixed Frame Under Uniform Load



**Propose three possible moment diagrams for this frame**

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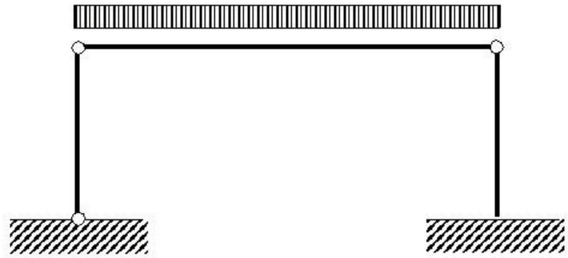
# Fixed Frame Under Uniform Load



## Simply-supported beam on posts

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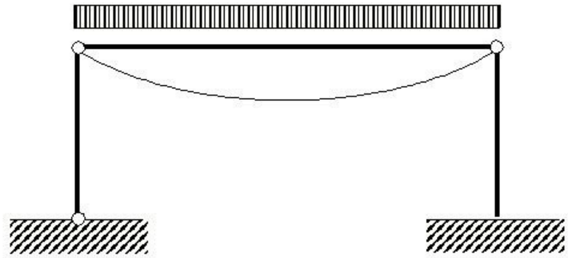
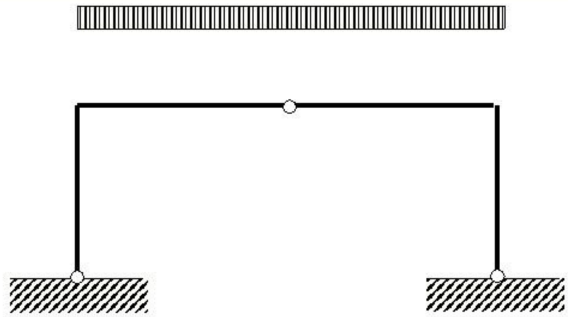
# Fixed Frame Under Uniform Load



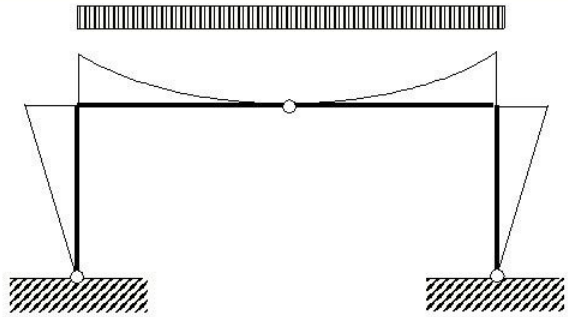
**Simply-supported beam on posts**

# Fixed Frame Under Uniform Load



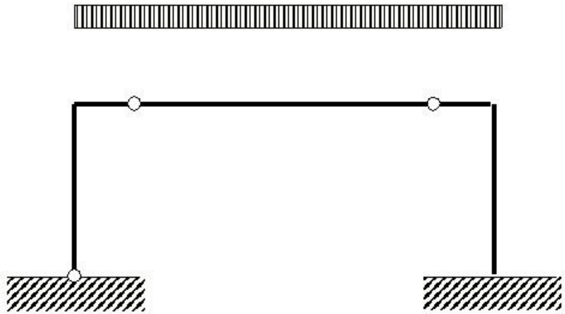
## Three-hinged frame

# Fixed Frame Under Uniform Load



## Three-hinged frame

# Fixed Frame Under Uniform Load



## Alternative three-hinged frame

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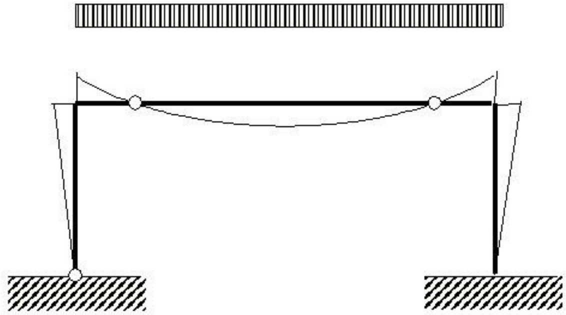
# Fixed Frame Under Uniform Load



## Alternative three-hinged frame

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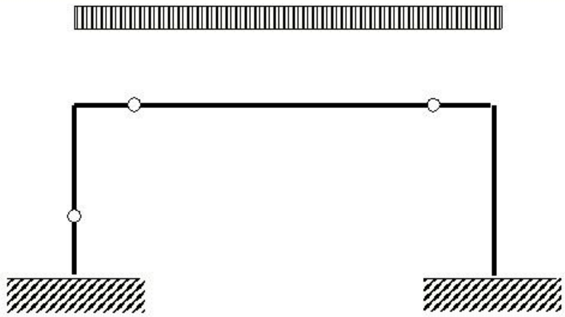
# Fixed Frame Under Uniform Load



## Alternative three-hinged frame

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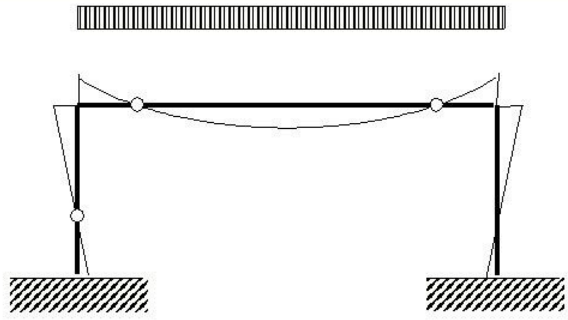
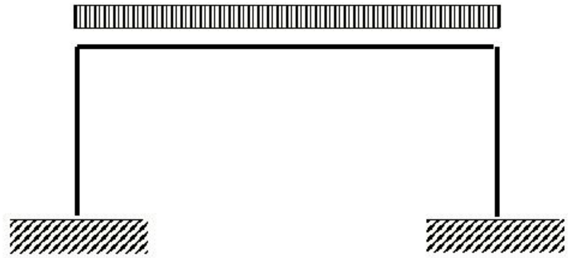
# Fixed Frame Under Uniform Load



## Alternative three-hinged frame

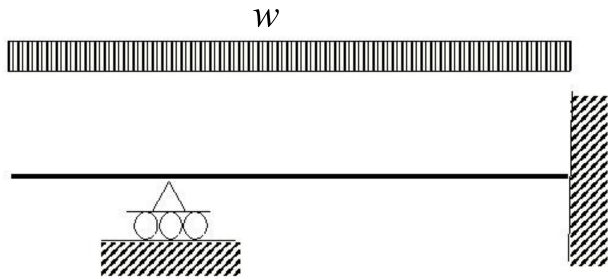
# Fixed Frame Under Uniform Load



**What type of structural forms would work for this load case.**

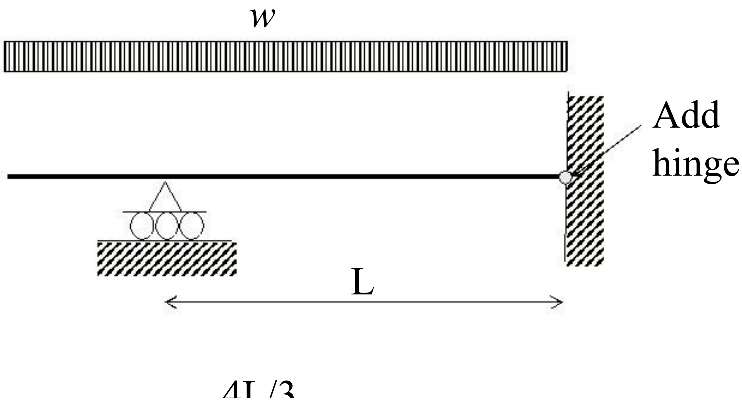
# Statically Indeterminate Beams

**What is the moment diagram for this beam under a uniform load, w.**



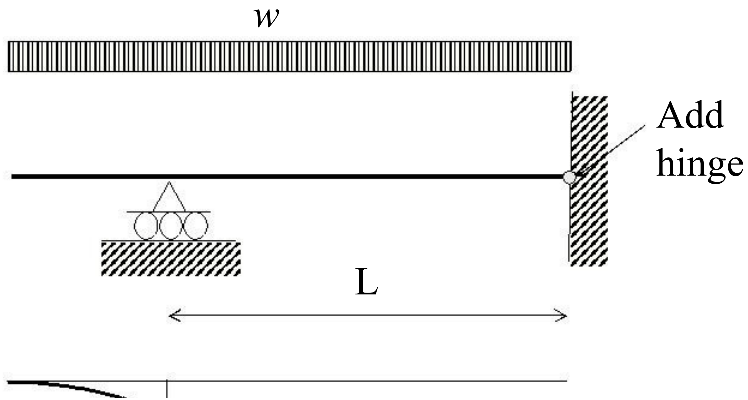
# Statically Indeterminate Beams

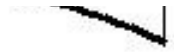
Release the right hand support by adding a hinge



# Statically Indeterminate Beams

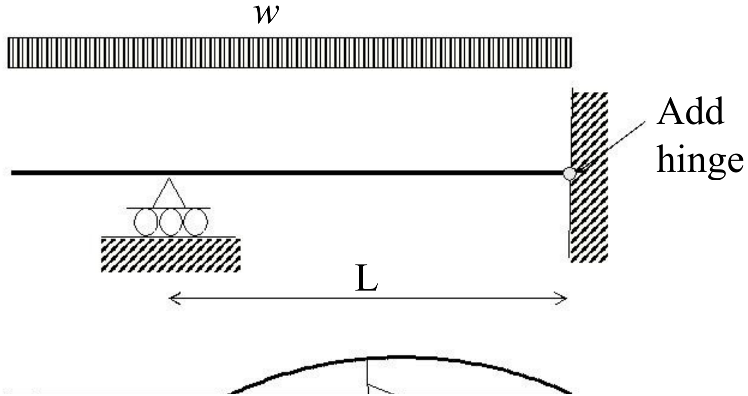
**Release the right hand support by adding a hinge**

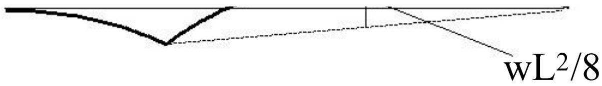




# Statically Indeterminate Beams

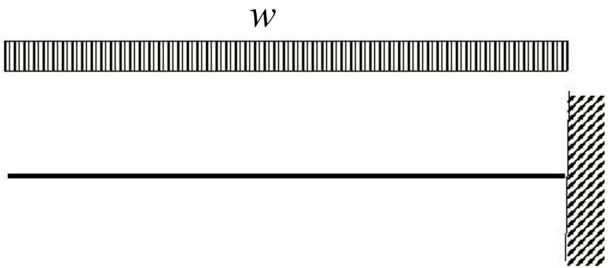
Release the right hand support by adding a hinge




wL²/8

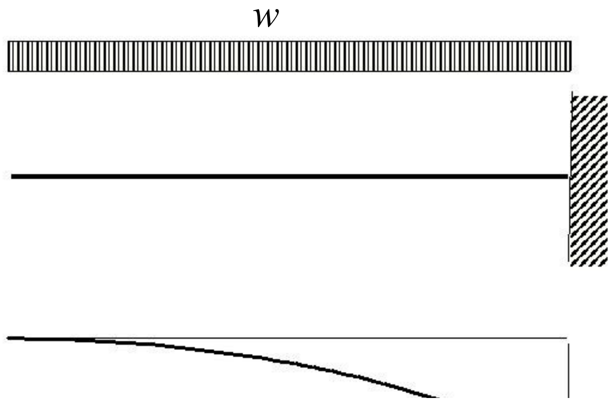
# Statically Indeterminate Beams

**Make statically determinate by removing the roller support**



# Statically Indeterminate Beams

What is the moment diagram for this beam under a uniform load, w.



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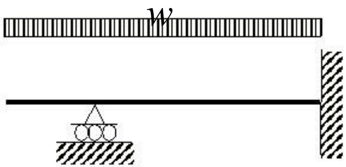
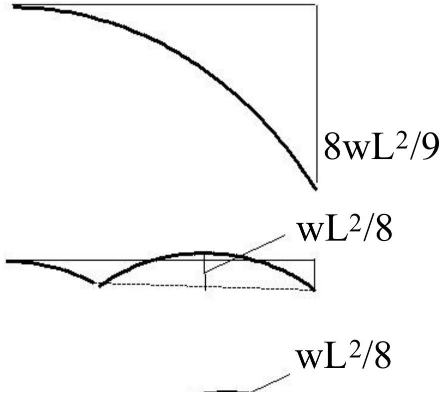
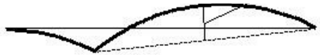
# Statically Indeterminate Beams

**What is the moment diagram for this beam under a uniform load, w.**





# Review: Indeterminate Structures

For a given loading on a beam, the moment diagram simply moves up and down as you change the support conditions

You choose the function by choosing the form
function follows form

Must prevent buckling (think of three-legged stool example)