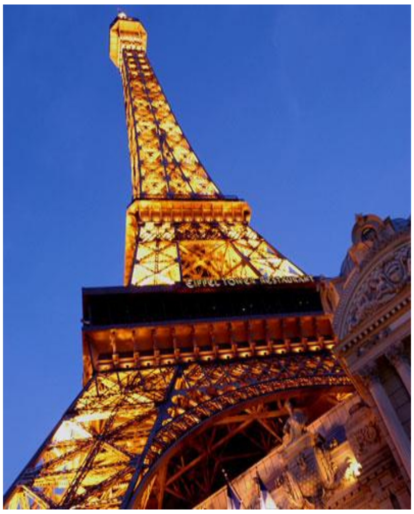
Structures

A structure can be defined as an arrangement of parts joined together in a manner which provides strength in order to facilitate the carrying of loads. There are many different types of structure in existence. Examples of these include; buildings, bridges, cranes and chairs.

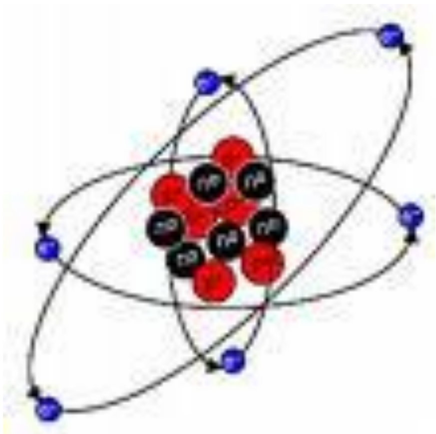


The Eiffel Tower

The Golden Gate Bridge

Most objects are arrangements of parts, e.g. atoms, crystals, cells.

Crystals



Atoms / Cells

Similarly, structures are objects made up of parts which, when combined, create solid structures.

What, do you think, contributes to strength in structures?

Hint: *Structures are designed to be able to withstand loads, which may distort or break them.*

This picture shows a variety of structures, including; buildings, a tower crane and scaffolding.

Factors which contribute to strength in structure are as follows:

- The strength of the material
- The shape of the parts
- The method used to join the parts together
- The manner in which they are arranged

This Florentine Bridge and Thai Tribal Home incorporate all of the aforementioned factors in order to contribute to their strength.

Naturally Occurring Structures

Nature provides us with the template to many of our strongest structures.

How many can you name?

Honeycomb

Trees

Spiders Webs

These naturally occurring structures must, in order to serve their purpose **as structures**, be able to withstand loads. The forces of nature also provide an everyday challenge to these structures.

Engineers have studied these naturally occurring structures, which have proven their strength and durability against the forces of nature time and again. They have learned from them and incorporated many of their features into useful designs with several applications in our various man-made structures.

Bee's Honeycomb

Honeycomb Floor Mat

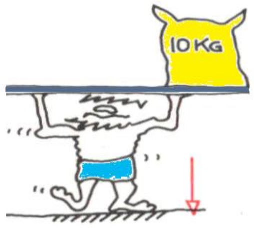
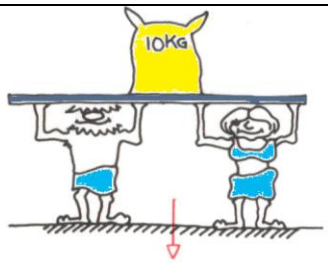
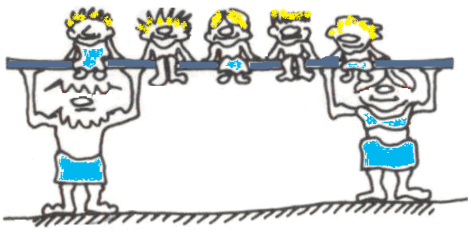
Mount Everest

Egyptian Pyramid

Forces

Force changes the state of rest or uniform motion of a body.

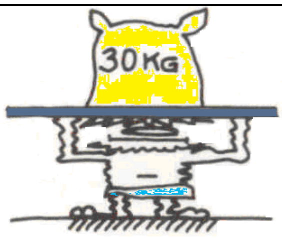
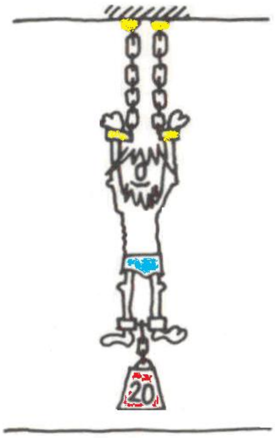
Force is measured in units of weight.

	Point Load – A load acting on a point
	Stable pair – When forces are equal
	Unstable pair – When forces are not equal
	Stable combination – When opposite forces are balanced
	Universally distributed load – When the load is spread evenly across a supporting member

The effects of force on a structure

Stress is caused within a structure by any force trying to change the shape of the structure.

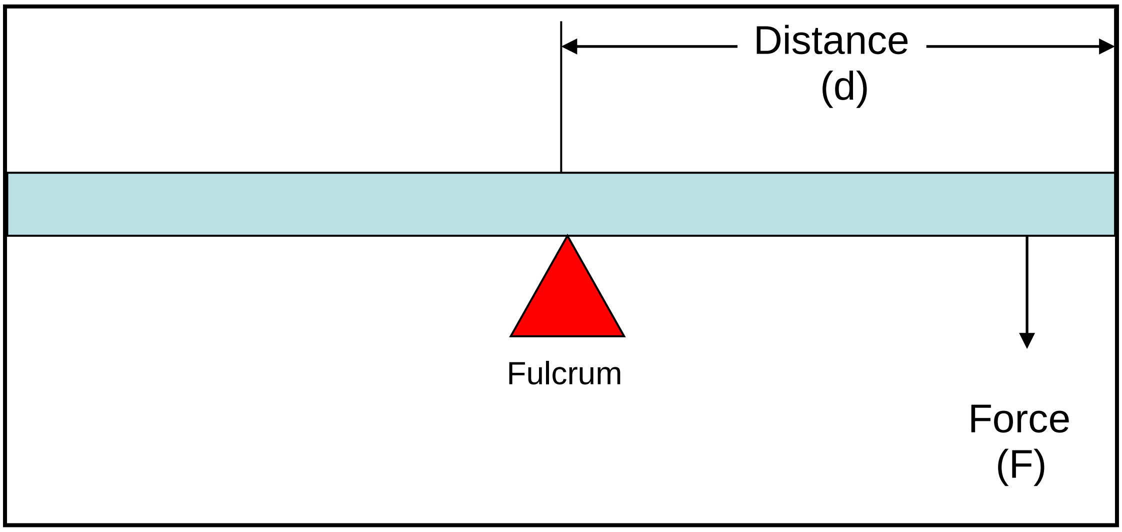
Strain is the actual change in shape that is caused.

	Compression – is when something is squeezed and can result in crushing.
	Tension – is when something is pulled and can result in stretching
	Shear – is when something is cut or slides and results in sliding or shearing
	Torsion – is when something is twisted
	Bend – is when something is bent and can be permanently deformed

Moments

Moments are any movement or action about a point or fulcrum. A moment is obtained by multiplying the load by its distance from the point being considered.

Moment = F x d

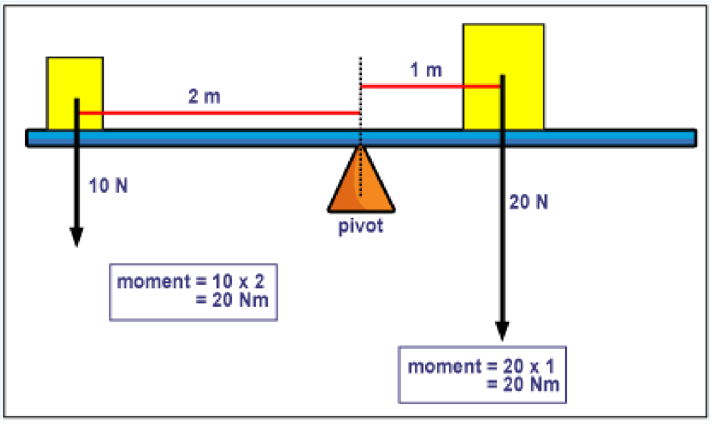


When something is in equilibrium, the moments of a force are balanced.

The **Principle of Moments** states that for there to be equilibrium, the clockwise moments must equal the anti-clockwise moments.

Calculating Moments

Example 1



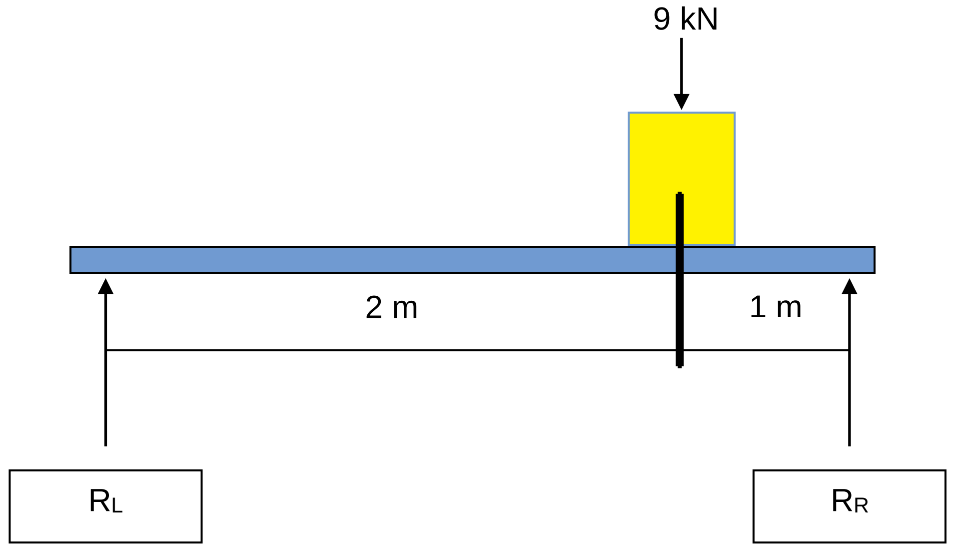
Taking moments about the pivot:

Clockwise Moments = 20N x 1m   Anti-Clockwise Moments = 10N x 2m

20Nm = 20Nm

Therefore, the scales is in equilibrium.

Example 2



Taking moments about point R_L

$R_R \times 3m = 9 \times 2m$

$R_R = \frac{9 \times 2}{3}$

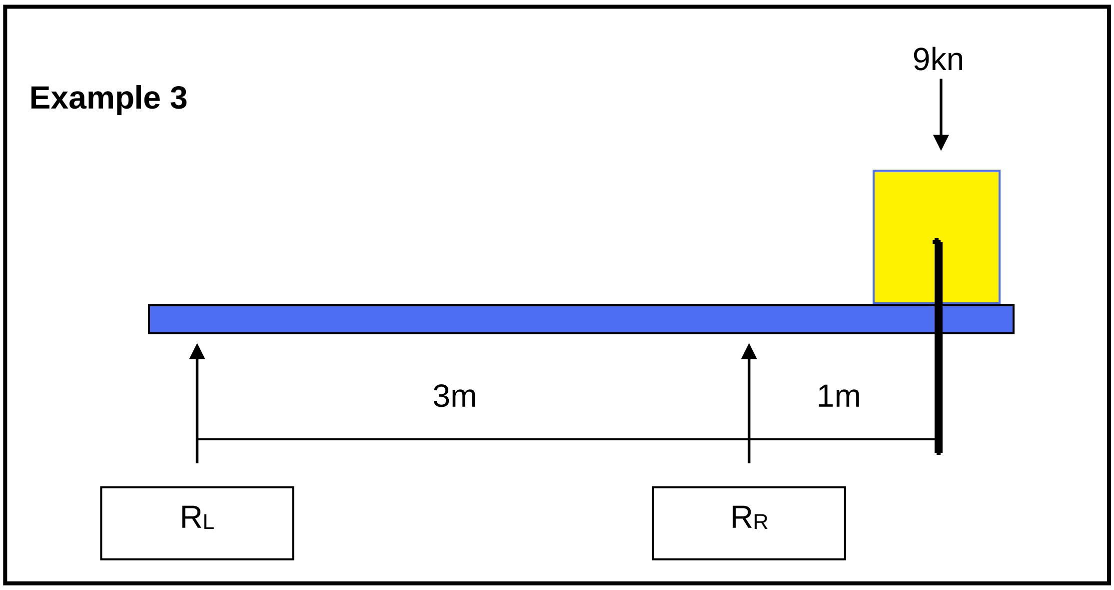
$R_R = 6kN$

Taking moments about point R_R

$R_L \times 3m = 9 \times 1m$

$R_L = \frac{9 \times 1}{3}$

$R_L = 3kN$



Taking moments about R_L

$R_R \times 3m = 9 \times 4m$

$R_R = \frac{9 \times 4}{3}$

$R_R = 12kN$

Taking moments about R_R

$(R_L \times 3m) + (9 \times 1m)$

$R_L = \frac{-9}{3}$

$R_L = -3kN$

So, in summary, ***equilibrium*** can be described as a state of balance which occurs when both sides are equal.

Observing the picture on the left, each of the stones is of a different size and non-uniform shape. However, these stones have been stacked in a manner which allows them to balance and remain upright. How is this possible?

Explanation: Each of these stones has an individual *'point of balance'* which, when placed in line with the *'points of balance'* of each of the other stones, allows the stack of stones to remain upright and unwavering. This *'point of balance'* is known as the ***Centre of Gravity***.

TAP 203- 2: Centre of gravity of a student

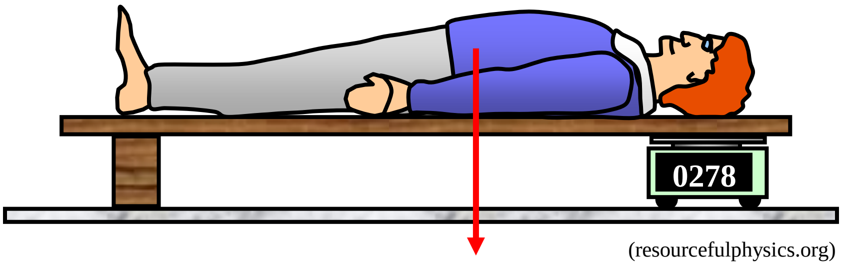
Task: Find the centre of gravity of a student.

Use a strong wooden plank, a pair of bathroom scales and a brick (or block of wood the same height as the scales).

Place the plank with one end on the block of wood or brick and the other on the bathroom scales.

Lay the student on the plank with their heels over the pivot (brick). Record the reading of the scales.

Take moments about the brick having weighed the pupil first.



Theory:

Reading on scales × distance of scales from pivot = (Weight of student × distance of student's centre of gravity from the pivot) + (Weight of plank × distance of centre of gravity of plank from the pivot.)

The Centre of Gravity is crucial to engineers, when designing large scale structures, such as high rise buildings. It is vital that the building be in equilibrium, in order to ensure that forces such as strong winds, earthquake tremors, or even traffic shudders, do not cause the building to shake on its foundations and collapse.

In order to better understand the influence of structures in nature on manmade structures, we will examine the following natural occurrences, and establish a link between natural and everyday manmade structures:

- A grass leaf
- A water lily
- A palm tree leaf
- A sea arch
- A snail shell

Water Lily

Palm Tree

Snail Shell

Grass Leaves

Sea arch

Grass Leaf

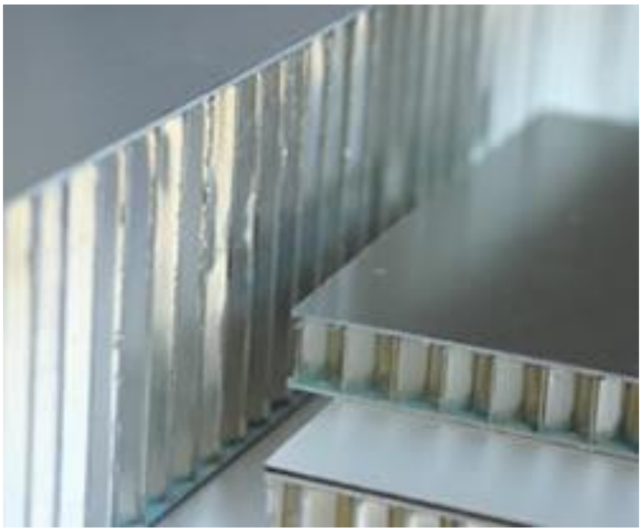
Plants often provide structural inspiration for engineers because they manage to achieve characteristics which are simultaneously lightweight and strong

Grass leaves combine these two characteristics. The area between the two outer surfaces of a grass leaf is made of a ***honeycomb*** or ***mesh*** structure. This honeycomb structure creates a material which is very strong and stable, yet simultaneously thin and lightweight.

Grass Leaf under a Microscope

This image shows how the internal honeycomb structure of a grass leaf provides it with its strength

Manufactured Honeycomb Structures



Honeycomb is predominately used as a core in sandwiched structures to meet design requirements for highly stressed structural components. When sandwiched between layers of carbon fibre, honeycomb exhibits extreme resistance to shear stresses.

Water Lily

Water lilies are naturally very fine, yet their structural properties enable them to maintain their shape, even in adverse weather conditions.

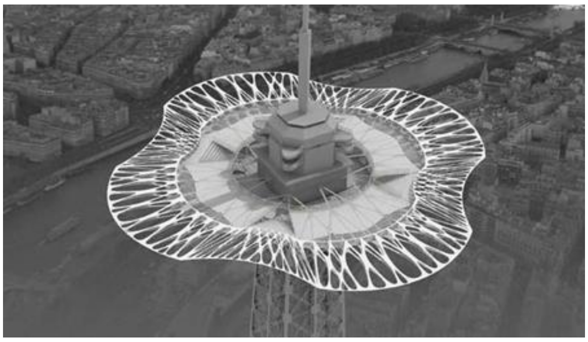
On observation, the underside of a water lily consists of a web-like structure, which grows from the centre of the leaf outwards. This structure effectively scaffolds or supports the surface of the leaf.

Supporting Structures

Can you think of any man-made structures which support platforms in the way that the water lily does?

Sports stadiums, multi-storey car parks and modern factory roofs all use the water lily structure as a model on which to construct and manufacture their structures.

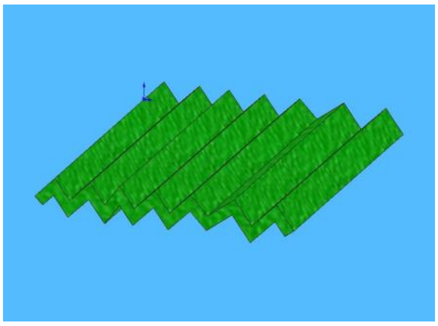
A structure made with parts that extend to meet each other.



The Eiffel tower's giant Lily Pad
- design of the future.

Palm Tree Leaves

Palm tree leaves can grow to over 10m in length and 1m in width, yet in spite of this magnitude they are very light in weight. This combination of characteristics allows the palm tree leaves, which gain their strength from thin corrugated sheets, to be supported by their stalks.



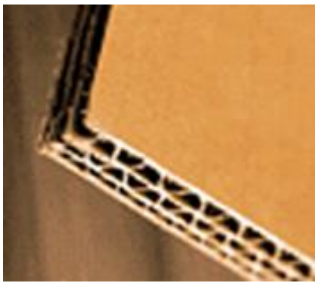
This cross section of a palm tree leaf shows a *zigzag* pattern. This folded characteristic gives the leaf its thin yet durable and hard-to-tear properties.

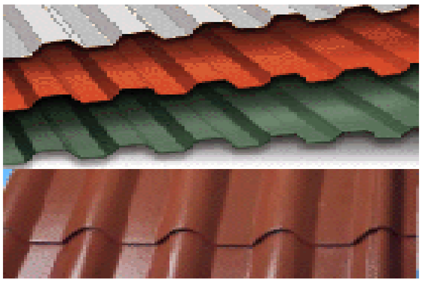
Corrugated Structures

Can you think of any man-made structures which take their inspiration from the palm tree leaf?

Shed and garage roofs and cardboard packaging all use the palm tree leaf as a model on which to base their corrugated structure, providing strength and durability without the hindrance of excess weight.

Corrugation used in packaging



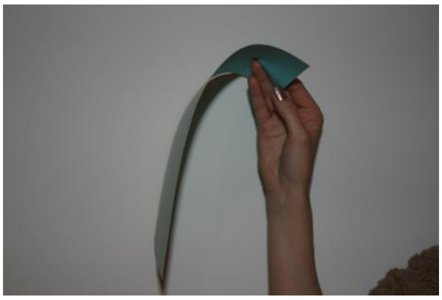


Corrugated roofing

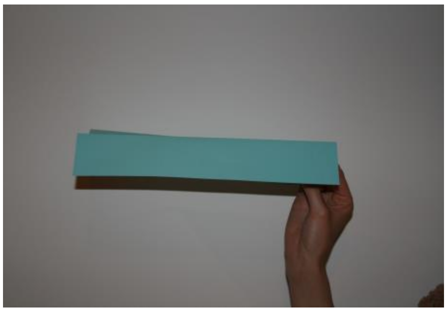
In the sections above, we examined the honeycomb structure and the zigzag pattern of the palm tree leaf. Designers have always tried to recreate these structural forms.

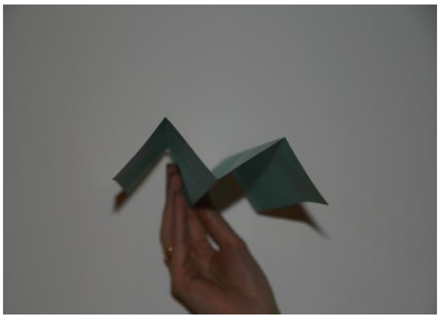
Task

If you hold a sheet of paper at one end, the other end will flop and bend over.



What happens if the sheet is folded to recreate the zigzag structural form of the palm tree leaf?





In designing and building these structures, engineers have many factors to consider. Engineers have found that by bending sheets into shapes, as in the above example, they are increasing the rigidity of the material.

This can also be achieved through the square form.

Recreate these paper forms, as demonstrated above.
Experiment with creating a square form fold, in addition to the zigzag.
Examine, through experimentation, the maximum load each structure can bear.

Sea Arch

Coastal features, such as pillars, caves and arches, formed naturally by weathering and marine erosion, have inspired engineers for centuries. One of the most inspirational of all of these is the arch.

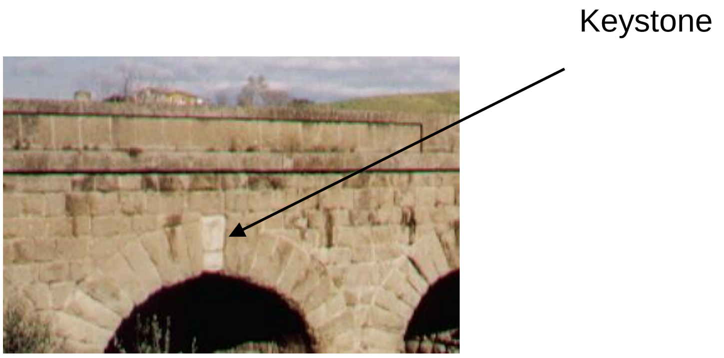
The arch can be described as a curved opening in a mass of rock resulting from the erosion of rock by wave activity and chemical weathering.

Structural Arches in Buildings

Can you think of any man-made structures which take their inspiration from the sea arch?

The arch is a central and defining feature of many of our most famous and easily recognisable building, such as the Colosseum in Rome.

In more everyday applications, arches can be seen in fields and over rivers all over the countryside in the form of bridges. Builders use stone to form these arch shapes. These bridges have their origins in Ancient Rome and are, therefore, sometimes known as ***The Roman Arch Bridge***. The main feature of this style of bridge structure is a keystone, as shown in the image below.



Why do you think stone-built bridges use the arch as their structure?

What would happen if the keystone were removed?

Task
Using 40mm wooden cubed blocks, cut / shape / form them into a Roman Arch.
Experiment with different means of supporting the stones in place.

In more modern times, as technology has advanced, road bridges are occasionally of the ***suspension design***, as shown below.

As illustrated, the bridged roadway is carried by wire cables, which are supported by towers.

Other bridges are constructed using concrete. These are known as ***beam bridges***, an example of which can be seen below.

As can be seen below, different types of frame structure can be joined together, using a variety of material shapes, to construct ***girder bridges***.

Shells

'Shell' is a word commonly used to describe the hard covering of eggs, crustaceans, tortoises, etc. A shell serves to protect and provide shelter from the elements, whilst also being lightweight. A shell is usually curved in form.
The snail's shell, as shown, embodies all of the aforementioned qualities.

Can you think of any man-made structures which take their inspiration from the shell?

Man-made shell structures are used in various sectors of engineering. Masonry or stone domes or vaults in the Middle Ages facilitated the construction of more spacious buildings. Nowadays, the use of reinforced concrete has made the use of shell-like structures commonplace.
Shell structures can usually be understood as a set of beams, arches and catenaries. They are capable of carrying large point loads. The shape of a shell, rather than the materials used, is the key to its strength. There are many examples of shell structure to be found in modern building design. The Sydney Opera House is one such example. Shell structures play a very important part in mechanical design as shown below.

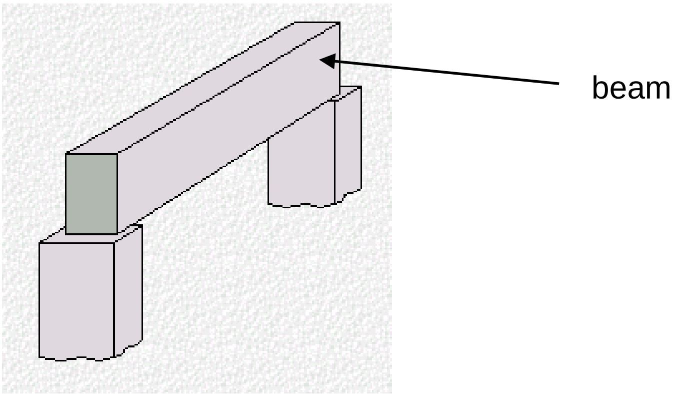
Sydney Opera House

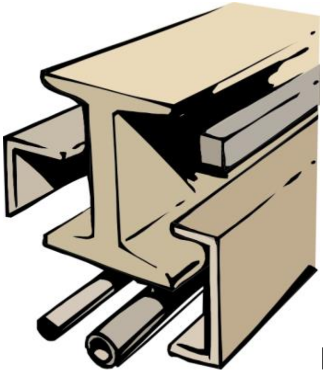
Car Shell

Shells serve to protect and provide excellent strength.

Beams

A beam is a strip or section of material used to span a distance and support a load. They can be used to add strength to a structure.



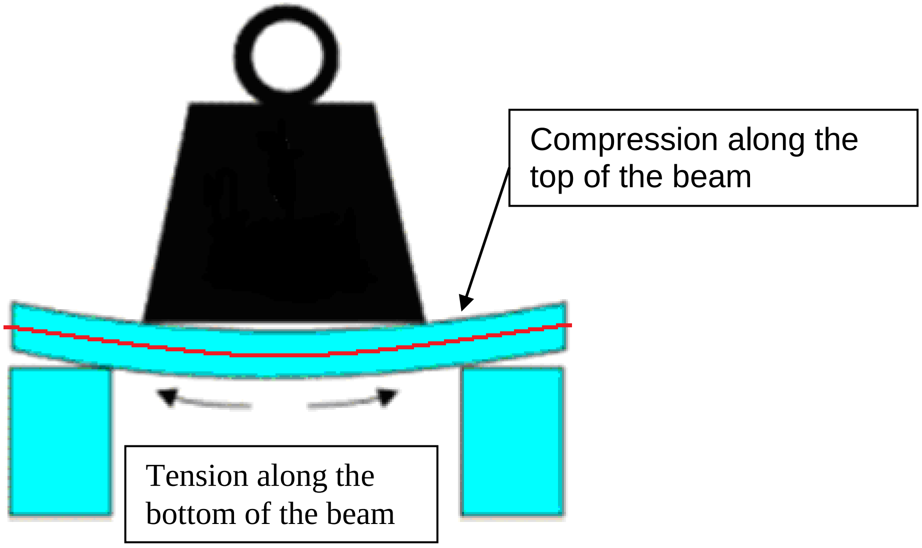


Beams come in many different shapes.

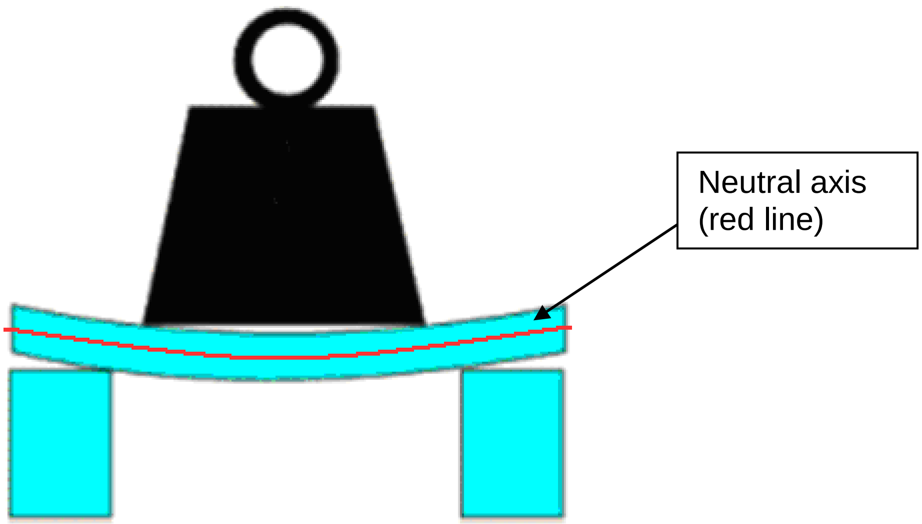
Task: How do beams support?

- Using a standard 300mm ruler and two blocks, arrange the materials as shown in the diagram above.
- With the ruler positioned flat on the two blocks, add a weight to the centre of the ruler.
- Now, reposition the ruler on its edge and add the same weight to the centre of the repositioned ruler.
- Discuss the results…what happened and why?
- What do you think would happen if a number of rulers were to be positioned on the flat on the two blocks? Repeat the test under these conditions.
- Replace these with a single piece of wood of equal dimensions (approx.) to the rulers being removed.
- Again repeat the test under these new conditions.

It can be concluded from these tests that a beam will bend under a downward load. On close inspection, it can be seen that the top of the beam is being compressed, whilst the bottom of the beam is being pulled apart and, is therefore said to be under tension.

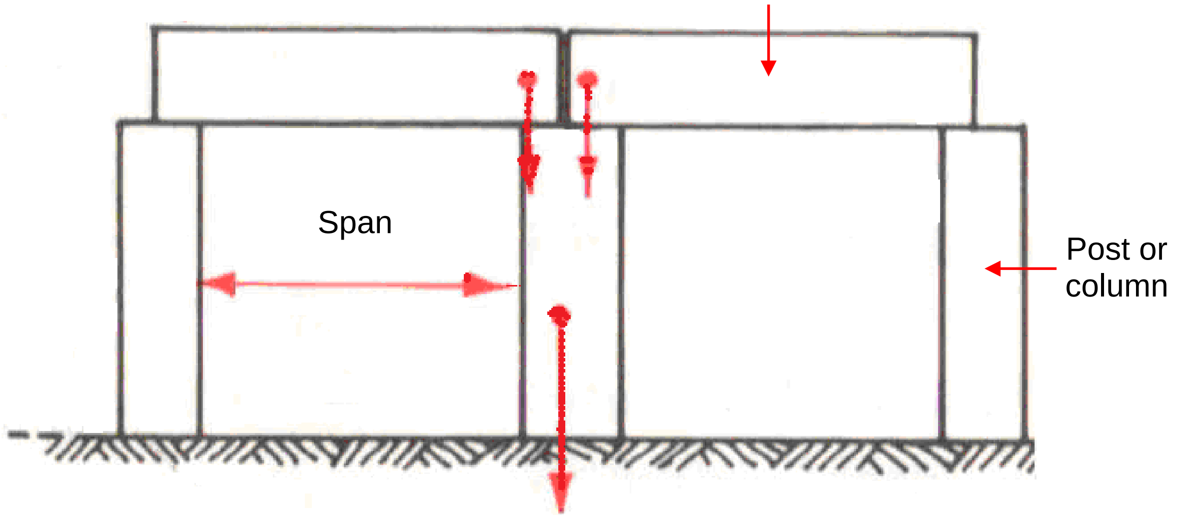


As we move from the bottom of the beam to the top, we change from tension to compression. But what happens at the very centre? The answer is – somewhere in the middle, very little happens. This area is known as the 'neutral axis'.



As we know, a beam must work hard on both top and bottom to resist the forces of tension and compression. Engineers designing beams know that

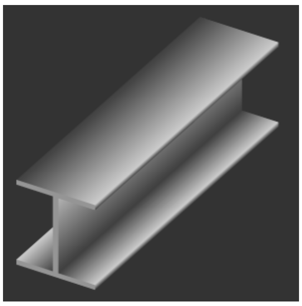
very little happens along the neutral axis. For this reason, beams are designed in order to be strongest along their top and bottom.



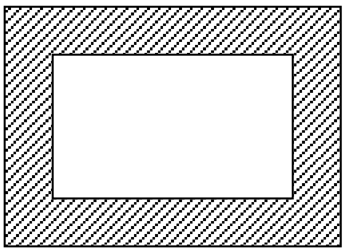
Beams are usually used in conjunction with what are known as posts or columns. These compose the upright element of the structure, as illustrated above.

Why might it be important to have different sections of beam?

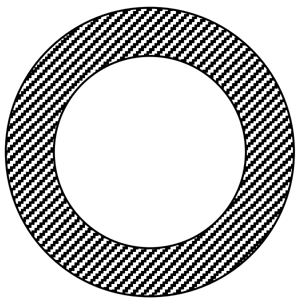
1. to save material
2. to reduce cost
3. to reduce weight
4. to maintain strength



In saving material, some beams can be constructed in hollow sections, as illustrated below



Box section



Circular section

Can you identify some of the uses of these sections in everyday life?

One such example of this is a bicycle. It is necessary for a bicycle to be lightweight, in order to make cycling it easier. For this reason, the amount of material used needs to be reduced. Therefore a bicycle is constructed using a circular section.

Classroom tables are often constructed on a square or box section. Reducing the amount of material used by constructing a hollow beam or beam section, accordingly reduces the cost of the product, thereby making it more appealing to the consumer.

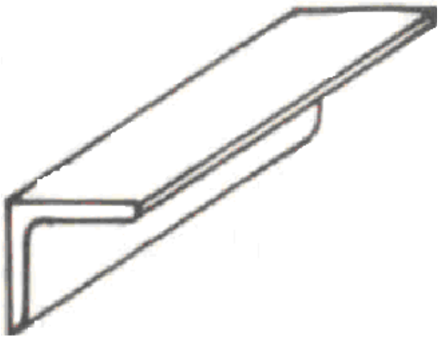
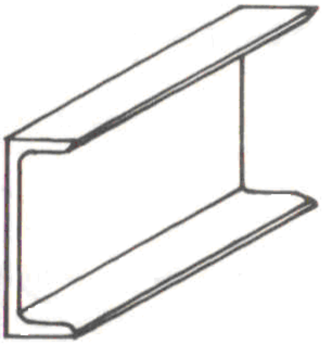
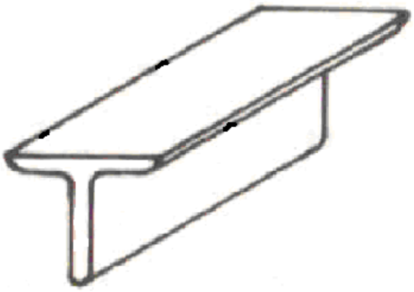
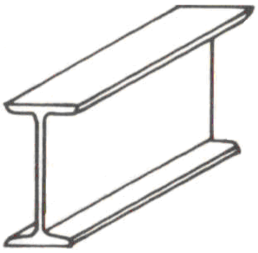
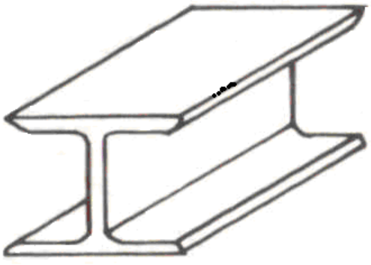
These circular or box sections are sometimes referred to as ‘tube’.

Classroom Table

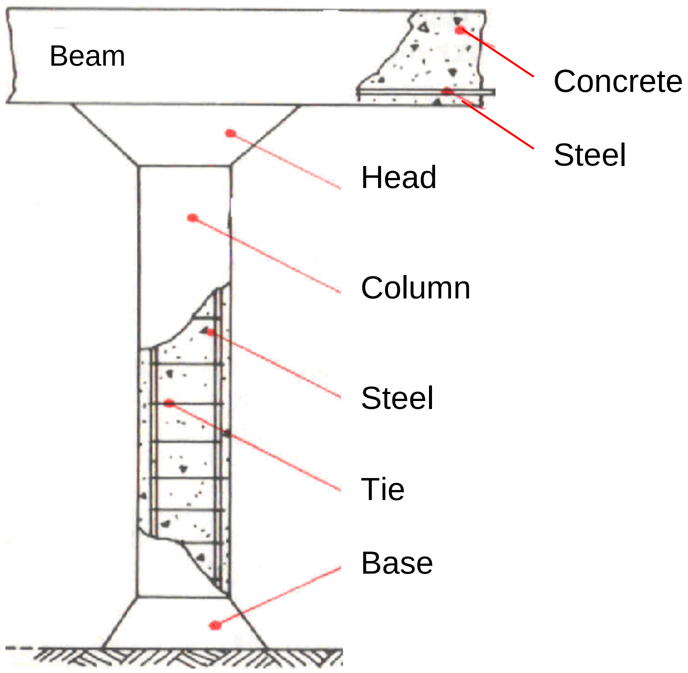
Bicycle Frame

Beams can be manufactured in many different shapes and sizes, and when fixed together, they can lend enormous strength to a structure.

Some examples of different beams shapes are illustrated below:

	Angle Beam
	Channel Beam
	Tee Beam
	Universal Beam *or* I Beam
	Universal Column or H Beam

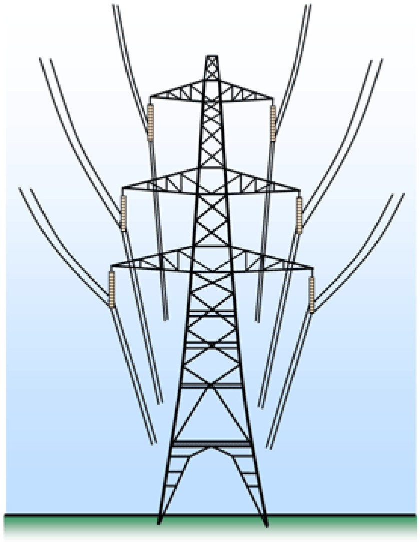
As already stated, there are many different types of beam section, which have a diverse range of functions in addition to the construction of buildings and bridges. Strength of beam and weight of load are important factors to consider when choosing a beam. Beams and columns are not always constructed using steel. Some beams are manufactured in wood, as seen in timber framed houses. Beams can also be reinforced to provide additional strength, as illustrated below.



Can you identify some of the uses of beams in everyday life?

Frames

Frames are structures made from sections of materials.



Frames are used as the basis for the construction of many different artefacts, such as gates, stools and picture frames. Their advantage is that they enclose spaces without filling them with solid material.

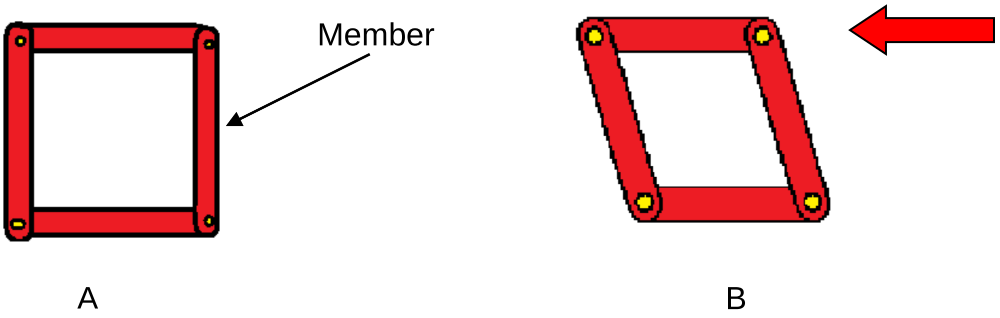
However, the question must be asked…Are frames always rigid?

If the frame is examined in more detail:

A **member** is said to be a part of a complex structure.

The point which the members meet or join is called a **joint**.

Joints can be either fixed or pivoted. Pivoted joints are not very stable and if a large force is applied to a corner the frame may lose its shape. A fixed joint is much stronger and can resist larger forces than a pivot joint.



How do you know if joints are **fixed** or **pivoted** – apply a force. As shown above.

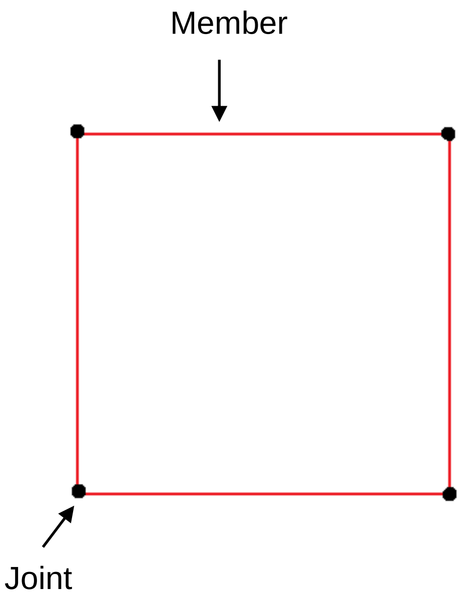
Task

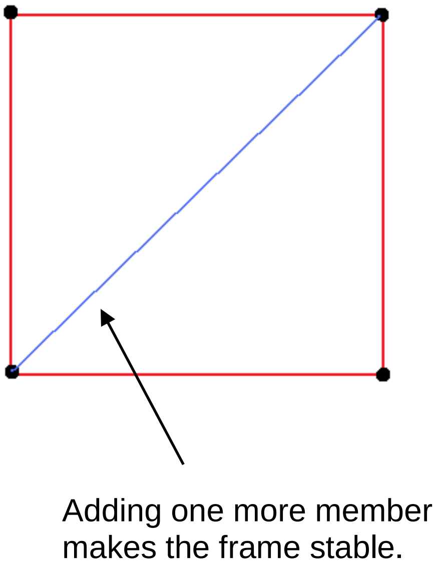
Take thin strips of card, plastic or wood and some pins, screws and nuts. Make up some polygon frames, e.g. square, rectangle, pentagon, hexagon, etc.

What happens when force is applied to a corner of the constructed frame? Can any conclusions be drawn from these tests?

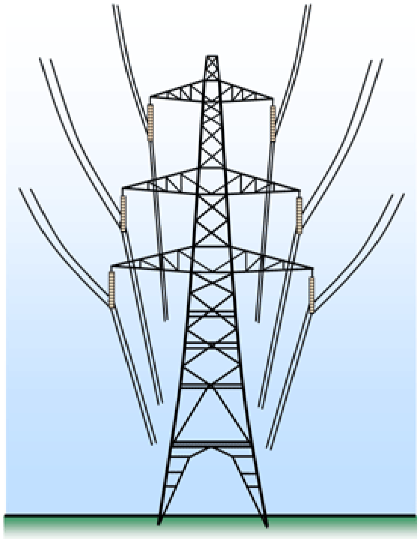
A rectangular or square frame is not a rigid structure. It relies on the strength of the joints for its rigidity.

Now, either remove or add a strut to create triangular shape within the structure. What happens?...The triangle does not distort. We can conclude from this that triangles are more stable and rigid structures.





Can you identify the main shape which is repeated in the image below?

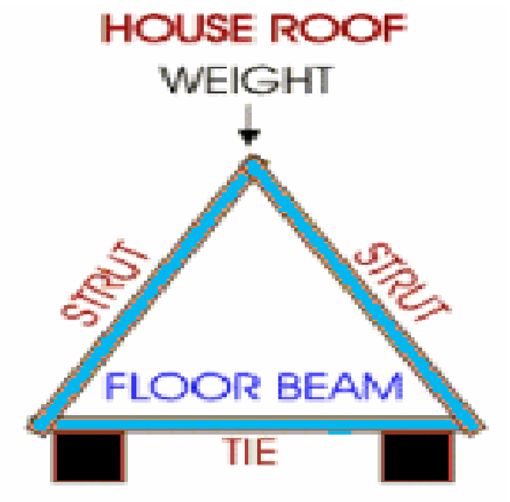


A ***triangle*** is one of the strongest frame shapes known to man. The implementation of this concept in design is known as ***triangulation***. The term ***triangulation*** is used to describe the arrangement of triangles together in the formation of a frame. Square, rectangular and other frames can be made more rigid by ***bracing***. In other words, bracing involves placing a diagonal piece or strut to create a triangle.

The construction of roof trusses is based on the principle of triangulation.

The parts of a roof truss are identified as ties and struts.

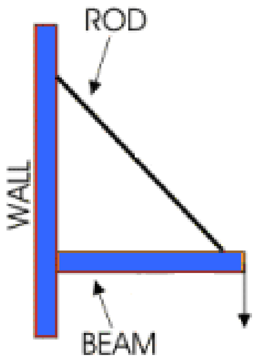
All structures have forces which act upon them.

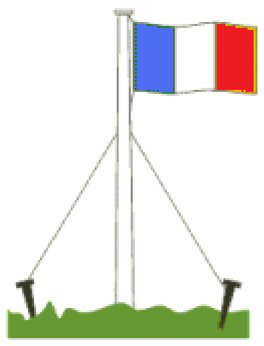


A ***tie*** is the part of a structure which has ***tensile forces*** acting upon it.

A ***strut*** is the part, which has ***compressive forces*** acting upon it.

Identify the struts and ties in the following images.



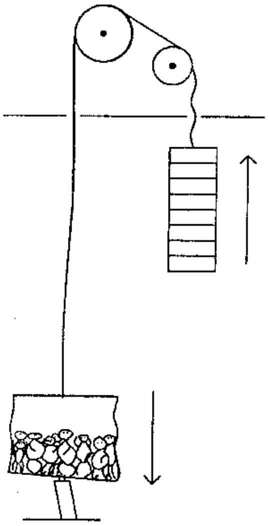


Task

Take photographs or make sketches of triangulated structures.

Identify the struts and ties within these structures, bearing in mind that a **tie** has tensile forces acting upon it and a **strut** has compressive forces acting upon it.

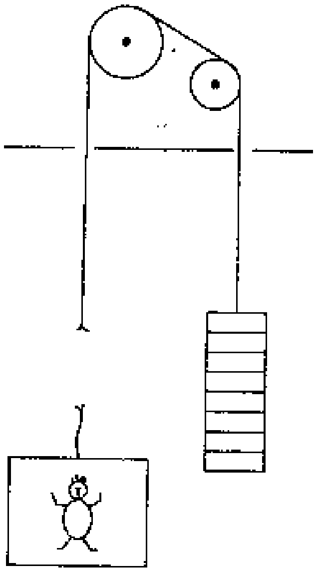
Factor of Safety



Overcrowding

Imagine the following scenario; an elevator with a maximum load capacity of 6 people is carrying a load of 8 people.
What do you think might happen in these circumstances?
The lift should not 'give way' as something known as a ***Factor of Safety*** is implemented to ensure that the overloading of a lift will not result in disaster. Factor of Safety is used to provide a margin of lee-way of flexibility over the theoretical capacity of the item in question.

This is to allow for any uncertainty in the product.
This uncertainty could be attributable to any number of things, from the strength of the material to the manufacture quality to human disregard for regulations.
When allocating a Factor of Safety, the trustworthiness of the product is examined. The more trustworthy a product is, the lower its Factor of Safety will be, due to the fact that the margin of lee-way is less uncertain.
However, the less reliable a product is, the higher its Factor of Safety will be, due to the uncertain nature of its maximum functioning capacity.



Disaster!

So, referring back to the previous scenario of the elevator; If the cable supporting the elevator will break under a load limit of 1000kg, but is listed as having a maximum load limit of 100kg, it is listed as having a Factor of Safety of 10.
Factor of Safety is crucial in structural design, as component failure could result in substantial financial loss, serious injury or even death. The use of Factor of Safety does not, however, imply that a structure or design is safe.

Incidences exist in our past which highlight the importance of factor of safety. One of the many reasons for the failure of structures is its inability to withstand loading and unloading. For example a crane hook lifting and dropping heavy loads continually. What should happen if the hook is not up to the job? Which factors exist that lead to the hook being checked? As with all structures the responsibility of making sure they are safe falls to the engineer. Tests are carried out to ensure the structure is safe. This can be easy to do when the structure can be taken away and checked. However, what about the likes of a bridge? Natural disasters, such as earthquakes, occur all the time, but what about the disasters that occur due to the failure of the structure? One such example occurred in 2003 in Minneapolis, U.S., when the Interstate 35 Bridge collapsed, so tragically, during the height of a Minneapolis rush hour. Investigators found that two factors contributed to its failure: age and heavy use. The constant loading and unloading of the traffic across the bridge coupled with the increasing volumes of traffic led to the eventual collapse of the bridge.

Aerial views of the Interstate 35 Bridge collapse

Destructive and Non-Destructive

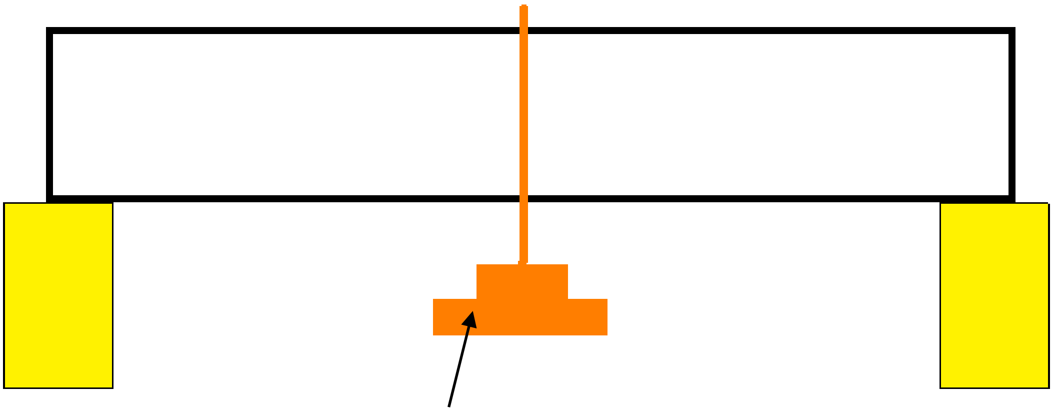
Referring back to the example of the bridge above, what type of tests do you think could be carried out to examine the strength of the bridge?

Task

Investigate the different types of bridge trusses that exist for example – Box girder, or Warren girder.

Construct the trusses from 6mm square wood strips or equivalent.

(The maximum length of the truss to be 600mm and height 60mm.)



Weight suspended from the truss.

1. Add increasing weights as a point load as shown above until the truss fails. Which type of truss could withstand the greatest load?
2. Add increasing weights as a universally distributed load until the truss fails. Which type of truss could withstand the greatest load?
3. This time load and unload the weights at different points and times, attempting the replicate traffic on the bridge. Record all positions and times. Repeat for all the trusses in the same order and measure the amount the trusses bend and draw some conclusions.