9 Structures

HAVE YOU EVER WONDERED…

- what holds a building up?
- what tension and stress are?
- why house frames are made of wood or steel?
- how skyscrapers can be built so high without falling down?
- how bridges can span huge distances without breaking in the middle?

After completing this chapter students should be able to:

- recall that a stationary object, or a moving object with constant motion, has balanced forces acting on it
- use Newton's second law to predict how a force affects the movement of an object
- apply Newton's third law to describe the effect of interactions between two objects
- use modelling and simulations to investigate situations and events.

9.1 Forces in a structure

We live in a world of buildings. Some are large, such as skyscrapers and bridges. Others are smaller, such as houses, bus shelters and dog kennels. Buildings are examples of structures, but not all structures are buildings. The structures of ships, cars and aircraft keep their shape when they are knocked by waves, bumpy roads and wind. The structure of a tree secures it to the ground and makes it stand upright, while the structure of an animal holds it together and allows it to move about.

INQUIRY science 4 fun

Tense standoff

Can you stand a ruler on its end?

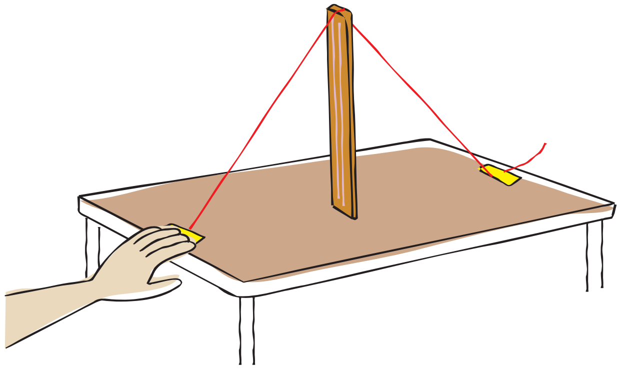
Yes

Collect this ...

- 30 cm ruler
- at least 60 cm of string
- 2 drawing pins or sticky tape

Do this ...

1. Try to stand a ruler on its end. Can you do it?
2. Secure one end of the string to the table by pinning or taping it down.
3. Stand the ruler up and pass the string over it as shown below.
4. Secure the other end so that the string is tight.



Record this ...

Describe what happened.
Explain why you think this happened.

Force

If something falls down, changes shape, changes direction, speeds up, slows down or stops, then a force caused the change. A **force** is a push, pull or twist. Examples are the push to open the front door when you get home from school, the pull of gravity as you step off a diving board at the local pool, or the twist on a towel as you try to wring the water out of it.

Most objects have more than one force acting on them at the same time. For example, the bike shown in Figure 9.1.1 has four forces acting on it. Your pedalling produces a force that pushes you forwards. The wind and roughness of the road produce another force that pushes backwards, slowing you down. (These forces are known as air resistance and friction.) Weight is a force that pulls the bike downwards while the ground produces another force called a reaction force that stops you from sinking into it. What the bike does depends on whether all those forces are balanced or unbalanced.

Newton's first and **second laws** of motion summarise what happens:

- If forces are balanced, then no change will happen—the object will stay at rest or will keep moving at a constant speed.
- If forces are unbalanced, then the object will accelerate and its motion will change.

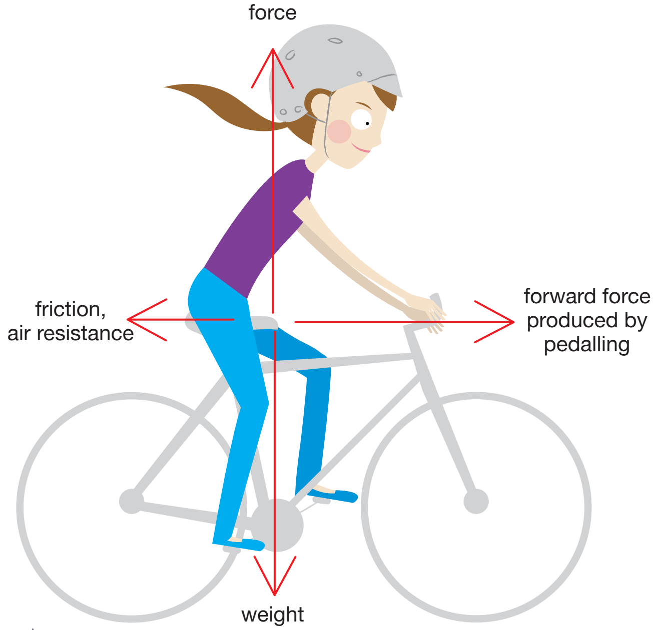


Figure 9.1.1 There are four main forces acting on a bike. The longer the arrow, the bigger the force.

Balanced and unbalanced forces

A bike resting on its stand is not moving, and so the forces on it are **balanced**. There are gravity and reaction forces acting on the bike but they balance each other, adding up to zero.

Unbalanced forces cause the movement of the bike to change. For example, the bike **accelerates** (speeds up) when there is an overall, unbalanced force pushing it forwards. This happens when you pedal harder than what is needed to overcome air resistance and friction. A bike **decelerates** (slows down) because there is an overall, unbalanced force pushing back on it that is slowing (perhaps stopping) its forward movement. This will happen when the force from the brakes, air resistance or friction is greater than the force from your pedalling, or if you stop pedalling. The bike will change direction if there is an overall, unbalanced force pushing it sideways. This happens when you turn the handlebars or are knocked sideways when you hit the kerb.

SciFile

Moving and shaking

Engineers who design buildings and bridges for earthquake-prone regions sometimes test a model of their structure on a shake table. This special platform shakes the model in several different directions at once to test how the structure could withstand a real earthquake.

Buildings normally don't move about and so are very different from bikes. Buildings are designed so that *all* the forces on them (and in every part of them) are *always* balanced. This way the structure won't move but will stay upright and retain its shape. If any of the forces on the building become unbalanced, then the building (or part of it) will change. The building might break, crack, crumple or twist. This is known as **failure**.

If the failure is minor, then it can cause parts of the structure to move a little or change shape slightly. Doors might jam or windows stick, or tiles, plaster and brickwork might crack. This has happened in Figure 9.1.2.

Figure 9.1.2 Cracks and jamming doors indicate that part of the building has shifted slightly because the forces on it have become slightly unbalanced.

If an important part of its structure fails, then the whole building is likely to collapse. For example, the failure of a wall might cause one part of the building to fall down, twisting the rest of the structure so badly that it can no longer stay upright. This is what happened to the hotel in Figure 9.1.3.

Figure 9.1.3 Buildings like this hotel can collapse if the forces on them (or on a part of them) become badly unbalanced.

Gravity, mass and weight

Gravity pulls everything towards the centre of Earth (or the Moon or Mars if you happen to be there instead). It is what makes things fall down, including buildings.

The **weight** of a building depends on gravity and on the mass (the amount of material) that is in it.

SciFile

Losing weight!

Your weight depends on your mass and the mass of the planet you are on. Smaller planets and moons generally have less mass than bigger ones, and so gravity and weight are less there too. For example, on the Moon you weigh only one-sixth what you do on Earth!

Weight is a force and so bigger buildings push down on the ground more than smaller buildings. Likewise, buildings made of dense materials such as brick, stone, steel and concrete push down on the ground more than buildings of a similar size made of less dense materials such as timber, plaster, bamboo or thatched grasses.

9.1

Compression and tension

Every part of a structure is pulled downwards by its weight. If the structure is to stay upright, then this weight needs to be balanced by another force that pushes it or pulls it upwards. **Newton's third law** states that for every force, there is an equal and opposite force. Hence, every part of a structure should have a reaction force that balances its weight. The overall force on each part is zero and so the part stays in place and the structure does not fail. This combination of weight and reaction forces causes different parts of a structure to be in compression or in tension.

Compression

Figure 9.1.4 shows a carport. The weight of the roof pushes downwards through the posts and would push them into the soil if the ground didn't push back upwards to balance it.

The downwards push of the roof and the upwards push from the ground compress (squash) the post. The post is said to be in **compression**. If the post cannot withstand all that compression, then the structure will fail.

In the same way, the weight of the column in Figure 9.1.5 and force from the ground compresses its bricks.

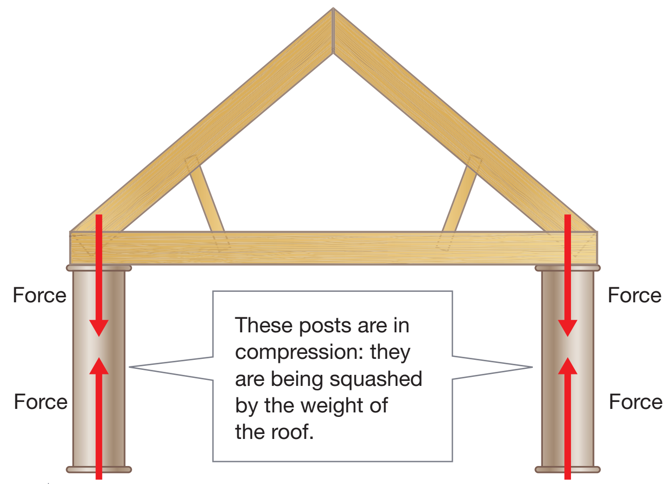


Figure 9.1.4 The forces in a post compress it, squashing it and making it a little shorter. The post is said to be in compression.

1 p300
2 p301
3 p301

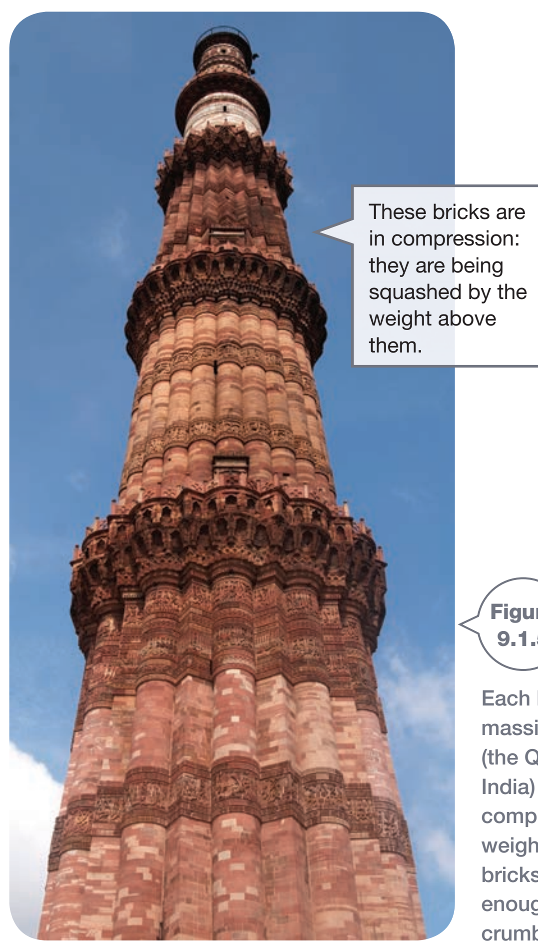


Figure 9.1.5 Each brick in this massive 73 m column (the Qutab Minar in India) is being compressed by the weight above it. If the bricks are not strong enough, they will crumble and fail.

Tension

Another way of supporting the weight of a structure is to pull it upwards by a cable, chain or rope. The Sydney Harbour Bridge (Figure 9.1.6) uses cables to support its deck of road and rail tracks. The weight of the deck pulls the cables downwards but the arch of the bridge pulls the cable upwards. These two up and down forces stretch the cable, keeping it taut (tight). The cable is said to be in **tension**. Cables in tension can also hold a roof up, like the stadium roof in Figure 9.1.7.

Figure 9.1.6 The weight of the road and rail tracks of the Sydney Harbour Bridge is suspended from cables attached to the arch overhead. Each cable is in tension and is being stretched.

Figure 9.1.7 These cables hold up the roof of the Wembley Stadium in England. The cables are in tension and engineers design them so that they can easily withstand the tensile forces on them.

SKILL BUILDER

Identifying compression and tension

Compression squashes and tension stretches. To identify which parts of a structure are under compression and which are under tension, think about what each part would do if it were replaced by a cable, chain or rope.

- If the part is under tension, then the cable, chain or rope would remain taut (tight).
- If the part is under compression, then it would collapse if it were replaced by a cable, chain or rope.

Substances used in structures

Concrete, brick, marble and granite are incredibly strong when compressed, but they break when stretched. In contrast, substances like carbon fibre, nylon and Kevlar are strong only when stretched. Other materials like steel, aluminium, timber and bone are strong when under compression or tension. Choose the wrong substance and the part it is made from will fail, possibly causing the structure to collapse.

4 p302
9.2

Stress

Force is important when discussing the materials a building is built from, but another quantity called stress is even more important. **Stress** measures how concentrated a force is on a material. High stresses are more likely to cause a material to fail than low stresses. Like forces, stress can be compressive (placing the substance in compression, squashing it) or tensile (placing it in tension, stretching it).

Table 9.1.1 shows the stress that different materials can withstand before they break. Stress can be expressed using the units newtons per square metre (unit symbol N/m^2) but its numbers are usually so high that stress is usually measured in meganewtons per square metre (MN/m^2) instead. These are also the units used for pressure when discussing liquids and gases in chemistry. For this reason, stress can be thought of as the pressure on a solid material.

Table 9.1.1 Strength of materials when placed under compression and tension

Behaviour	Material	Maximum compressive stress (MN/m^2)	Maximum tensile stress (MN/m^2)
Strong under compression only	Concrete	20	2
	Marble	80	0
	Granite	240	0
	Brick	35	2
	Cast iron	550	170
Strong under tension only	Carbon fibre	0	5560
	Nylon fibre	0	500
	Kevlar	0	3620
Strong under compression *and* tension	Steel	500	820
	Aluminium	200	200
	Brass	250	250
	Timber (pine, cut along the grain)	35	40
	Bone	170	130

Stress and area

Stress depends on the force being applied and the area the force is being applied to (Figure 9.1.8). Mathematically, stress is given by the formula:

$$\text{Stress} = \frac{\text{force}}{\text{area}} = \frac{F}{A}$$

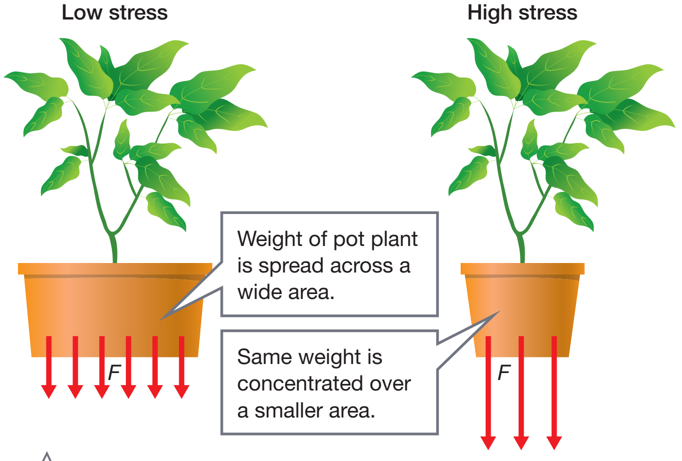


Figure 9.1.8 Stress is highest when force is high and the area to which it is applied is small.

You always exert the same weight force on the ground regardless of what shoes you wear. However, different imprints are left behind by different shoes. For example, high-heels sink deep into mud and snow while flat, wide-soled boots have far less effect. What has changed is the area over which your weight is spread. Boots spread your weight over a large area and so the stress on the mud and snow is small. Skis, snowboards and snowshoes (like those in Figure 9.1.9) spread your weight over an even larger area and have even less effect than boots. High-heels concentrate your weight into a tiny area. Stress on the mud or snow is high and down you sink.

Figure 9.1.9 Snowshoes, skis and snowboards have large surface areas and spread your weight much more than normal shoes. Stress on the snow is minimal (very small), allowing you to move easily across the snow.

Stress also explains why knives, axes and scissors all need to be sharp to be effective. Sharpening makes the cutting edge very narrow, reducing the area over which the cutting force is applied. The force is concentrated on whatever you are cutting and stress on the material is high. This makes it easier to cut.

Necking

Stress also explains why a material is most likely to break at a scratch or dent. Think of a wire with a severe scratch at one point. The cross-sectional area will be constant all along the wire except where the scratch is. There the wire is thinner and the area less. When the wire is placed under tension, stress at the scratch will be far higher than along the rest of the wire. This causes it to stretch more at the scratch than the rest of the wire, thinning it even more. As the wire gets thinner, stress increases until eventually the wire snaps at the scratch. The process is called **necking** because of the neck-shape formed just before it breaks. Figure 9.1.10 outlines how it happens.

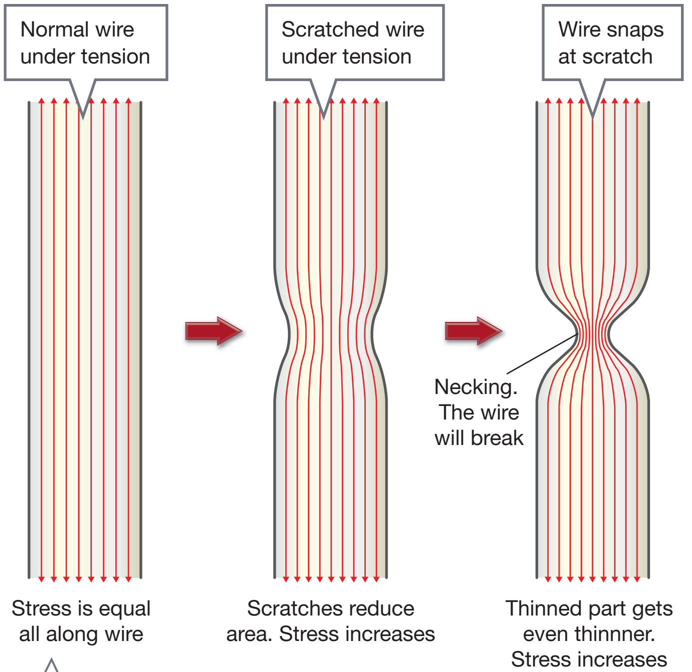


Figure 9.1.10 Scratches increase the stress on a wire. This leads to necking and eventual breakage.

9.1 Unit review

Remembering

1 **State** whether the following are under compression or tension.
   a columns
   b cables

2 **List** the following materials in order of compressive strength from strongest to weakest:
   concrete, marble, granite, brick, pine, bone

3 Using Table 9.1.1 on page 297, **name** two materials that are strong under:
   a compression but not tension
   b tension but not compression
   c both compression and tension.

Understanding

4 **Predict** what would happen if a garden hose was placed under:
   a tension
   b compression.

5 **Outline** why wires are more likely to break at a scratch than anywhere else.

6 **Describe** the property of Kevlar that makes it the ideal material to make sails from for a yacht.

Applying

7 Figure 9.1.11 shows a bird's-eye-view of three cars driving down a road and the overall forces acting on them. **Identify** which car would be:
   a accelerating
   b decelerating
   c changing direction.

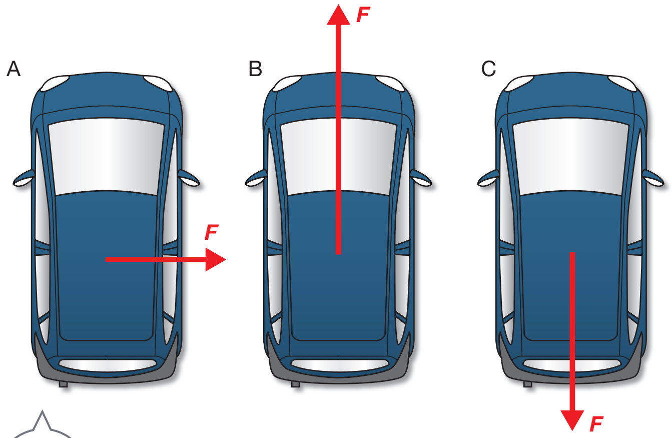


Figure 9.1.11

8 **Identify** whether the following are under compression or tension.
   a earlobes that have heavy earrings in them
   b the legs on a table
   c the string of a guitar
   d your legs when you are standing
   e a child's arms when hanging from the monkey bars or climbing frame

9 Being poked by someone's finger hurts more than being pushed with an open hand with the same force. **Use** the concept of stress to **explain** why.

10 **Calculate** how much stronger granite is under compression than:
   a concrete   b marble.

11 **Calculate** how much stronger carbon fibre is under tension than:
   a nylon   b pine.

12 Different forces were applied to different areas of a building material. **Calculate** which of the following samples is under the greatest stress.

   Material A: 2 MN applied over 1 m^2

   Material B: 2 MN applied over 0.5 m^2

   Material C: 4 MN applied over 2 m^2

   Material D: 1 MN applied over 0.5 m^2

Analysing

13 In the Science4fun activity on page 293, a ruler is held upright by a string. **Identify** whether the following are in compression or tension.
   a the string   b the ruler

14 In force diagrams like those in Figure 9.1.12, longer arrows indicate larger forces. Forces of equal size are drawn as arrows of the same length. **Use** this information to **analyse** the force combinations shown. **State** which are balanced and which are unbalanced.

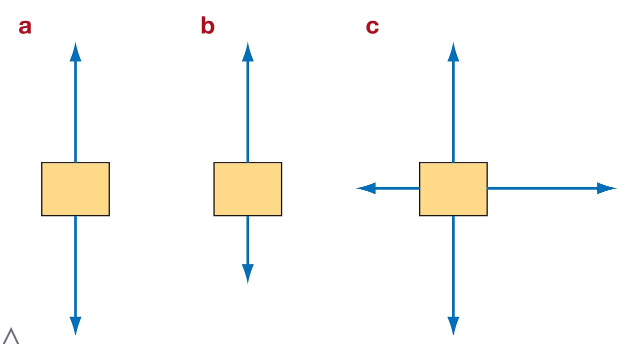


Figure 9.1.12

15 **Classify** the force combinations shown in Figure 9.1.13 as compression or tension.

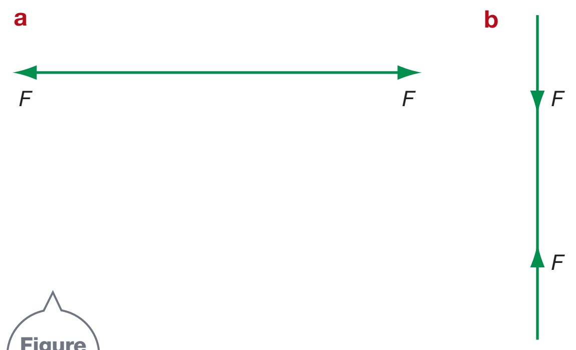


Figure 9.1.13

16 **Analyse** the components in the structures holding up the signs in Figure 9.1.14 and **classify** the forces in them (labelled I–VIII) as either tension or compression.

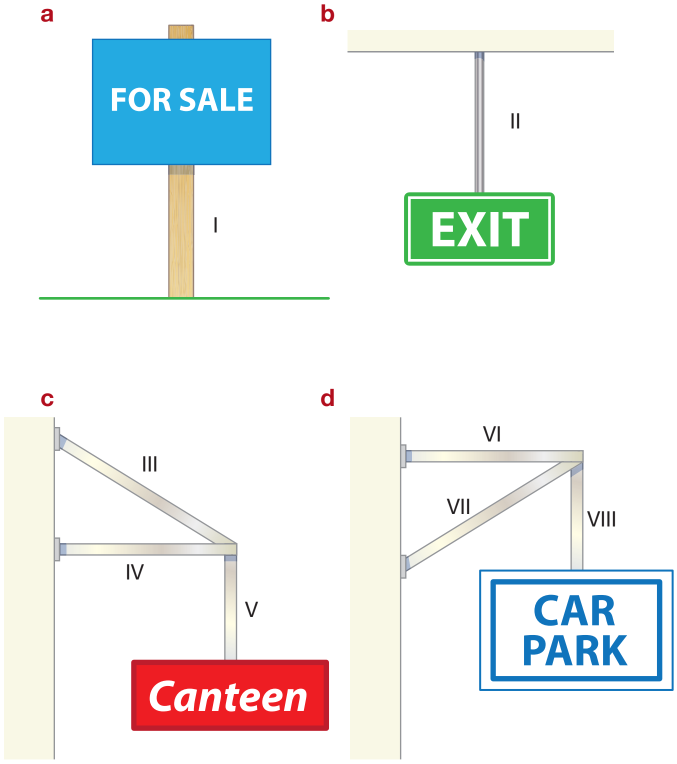


Figure 9.1.14

Evaluating

17 If something is not moving, then there are no forces involved.

- a **Analyse** the above statement and decide if you agree or disagree with it.
- b **Justify** your answer.

18 The frames that make up the structures of many houses are commonly made of timber. **Propose** three reasons why.

19 The frames and outside of many aircraft are made from aluminium. **Propose** reasons why.

20 People wearing high heel shoes are sometimes required to remove their shoes before walking across polished wood floors. **Propose** a reason why.

21 Nails have sharp tips and are not blunt. **Use** the concept of stress to **propose** a reason why.

Inquiring

1 a Find out what a pile driver is, where and why it is used and what forces are involved.

- b Find videos showing a pile driver in action.

2 Search the internet for videos showing how a house is built from the foundation up. Possible key words are *build house video*.

3 Columns often have fancy tops called capitals. Explore the internet to construct a portfolio of images showing different types of capitals. Find images of capitals known as:

- Ionic
- Corinthian
- Egyptian
- Doric
- Byzantine
- Romanesque.

4 Research one of the following substances: Kevlar, fibreglass, steel. Whichever one you look into, find:

- a what its properties are
- b how it is manufactured
- c what it is used for.

5 Use the key words *earthquake shake table* or *earthquake simulation* to find animations and video on structures being tested under earthquake conditions.

6 Mudbricks aren't made of just mud. Research what else is added to them, find a 'recipe', and use it to make a brick.

9.1 Practical activities

1 Investigating column shapes

Columns and pillars have been used since ancient times to support structures. Their strength depends on a number of factors.

Purpose

To test the strength of columns with cross-sections of different shapes.

Materials

- small tub (e.g. margarine tub)
- sheet of cardboard, large enough to support the tub
- 50 g masses
- multiple sheets of A4 paper (uncrumpled scrap A4 is fine)
- sticky tape
- access to scissors

Procedure

1. Curl an A4 sheet to construct a cylinder as shown in Figure 9.1.15.

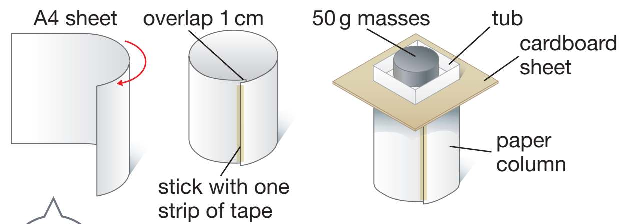


Figure 9.1.15

2. Join the edges of the cylinder by overlapping a maximum of 1 cm and using one strip of sticky tape along the outside edge.
3. Set up the column, cardboard sheet and tub as shown.
4. Add 50 g masses to the tub until the column 'fails'.
5. Now construct columns with the shapes shown in Figure 9.1.16. Make sure that:
   - the paper is folded so that the columns are all the same height
   - the creases are 'crisp' and parallel
   - the overlap is roughly the same each time (maximum 1 cm)
   - one single strip of tape is used each time along the outer edge of the join.
6. As before, test each column by adding 50 g masses to the tub until the column fails.

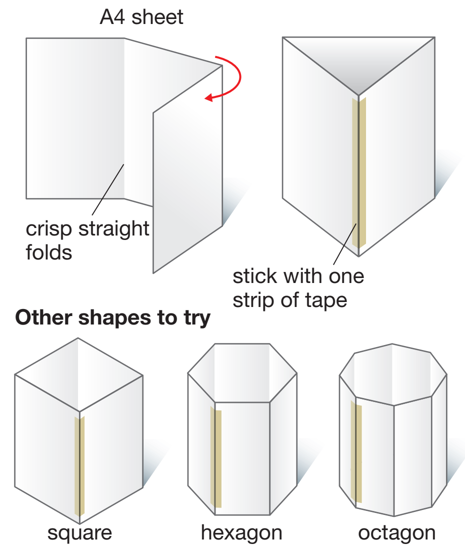


Figure 9.1.16

Results

In your workbook, construct a table like that shown below and use it to record your results.

Cross-section shape	Number of 50 g masses required to cause failure	Mass required to cause the failure (g)
Circle (forming a cylinder)		
Triangle		
Square		
Hexagon		
Octagon		

Discussion

1. **Describe** what happened to each column as it failed. Did it crumple evenly, split or bend?
2. **Compare** the results you obtained by ranking the columns in order from strongest to weakest.
3. **Describe** what happened to the column strength as the number of sides increased.
4. Cars do not have flat sheets of metal making up their bonnets, boots and doors, but have creases and folds in them. **Use** the results from this experiment to **propose** a reason why.

2 Investigating column diameter

Purpose

To test the strength of columns with different diameters.

Materials

- as per Practical activity 1

Procedure

Design an experiment that tests the strength of cylindrical columns of different diameters.

Results

Construct a table and line graph to display your results.

Discussion

1 **Rank** your columns in order from strongest to weakest.
2 **Describe** how this pattern is displayed in the line graph.

3 Loads on bridge columns

Purpose

To observe what happens to the compression in the columns of a bridge as a load passes over it.

Materials

- 1 m length of light wood (e.g. balsa, pine)
- 1 m ruler
- felt-tip pen
- 2 scales or electronic balances (representing 2 columns)
- large mass (e.g. 100 g, 200 g, 500 g)

Procedure

1 Use the 1 m ruler to place a mark on the length of wood every 20 cm.
2 Set up the apparatus as shown in Figure 9.1.17. The scales are the columns of your bridge.
3 If the scales have a 'tare' button, tare the scales so that they read zero.
4 Place the mass on the wood directly above one of the scales. (Call this Scale 1.)
5 Take the readings off both scales and record them in a table similar to that in the results section.
6 Shift the mass to the next 20 cm marking and repeat until the mass is directly above the other scale. (Call this Scale 2.)

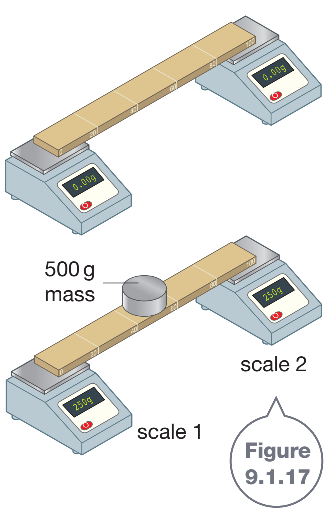


Figure 9.1.17

Results

In your workbook, construct a results table like that shown below.

Distance from Scale 1 (cm)	Distance from Scale 2 (cm)	Reading on Scale 1 (g)	Reading on Scale 2 (g)	Total mass reading (g)
0	100			
20	80			
40				
60				
80	20			
100	0			

Discussion

1 The scale readings you took are related to the compression forces in each column. The higher the mass, the higher the compression force in the column. As the mass is moved across the bridge, **describe** what happens to the compression in:
   a column 1
   b column 2.

Loads on bridge columns continued on next page

Loads on bridge columns continued

2 Imagine a heavy truck passing over a bridge like that tested in this experiment. **Identify** where the truck would be if the compression was:
  a the same in both columns of the bridge
  b zero in one of the columns.

4 Material testing

Purpose

To test the behaviour of a material.

Materials

- retort stand, bosshead and clamp
- fishing line
- 30 cm ruler
- 50 g masses and holder (with hook)
- foam rubber or something similar to act as a cushion

Procedure

1 Set up the apparatus as shown in Figure 9.1.18.

2 Lightly stretch out the fishing line as it hangs from the retort stand and accurately measure its natural length (in millimetres) before any masses are added to it.

3 Use the hook to add masses to the line. Each time a new mass is added, measure the new length of the fishing line. Record the masses (in gram) and length (in millimetres) in a table like that shown below.

4 Keep adding masses until the fishing line snaps or you have added 1 kg.

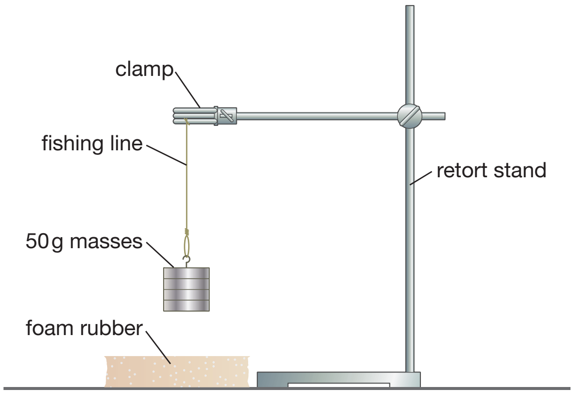


Figure 9.1.18

Results

1 In your workbook, construct a results table like the one shown below.

Mass added (g)	Length (mm)	Extension (mm)
0		
50		
100		
150		
200		
250		

2 Calculate how much the fishing line has extended each time a mass is added by subtracting the length of the line with no mass. That is:

extension = length of line with mass attached – length if line with no mass

3 Accurately plot a line graph of the line's extension against the mass added.

Discussion

1 **Assess** whether the following were under compression or tension in this experiment:
  a the fishing line
  b the upright on the retort stand

2 Imagine a fish being reeled in on this fishing line. **State** the mass of the fish that would snap the line.