TOPIC 3

Mass and Forces

Not long ago, circus elephants were trained to balance on tiny stools. The stool had to be very strong or it would collapse under such an enormous load. However, if an elephant were taken to the Moon, even a flimsy stool would support it. The elephant's matter — the amount of material in the elephant — would be the same in both places. The load force (weight) that the elephant exerted on the stool would be very different.

If you understand how mass causes a load force on a structure, you will find it easier to make strong, efficient designs.

DidYouKnow?

The metric system of measurement was created in 1795 in France. It replaced many traditional systems of measuring with just one system. The modern International System of Units (in French, *Le Système International d'unités* or SI) is based on the original metric measures. Standard SI units were set up in 1960 by an international committee called the General Conference on Weights and Measures. Experts meet regularly to review and revise SI.

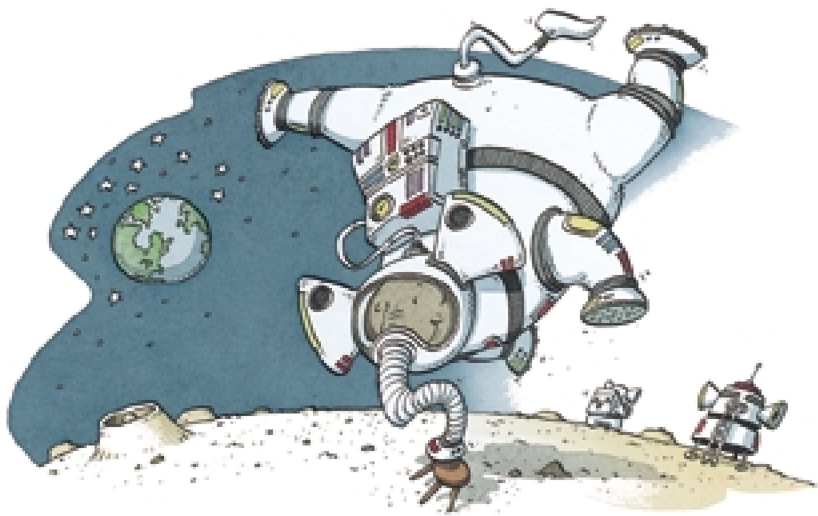


Figure 4.28 If an elephant was on the Moon, what would stay the same? What would change?

Mass

The **mass** of an object is the measure of the amount of matter in it. As you learned in Unit 3, all objects are made of tiny particles. An elephant is made of a very large number of particles, so it has a large mass. An egg-sized lump of lead contains fewer particles than an elephant, so it has less mass.

When the metric measuring system was first designed, scientists decided to measure mass by comparing objects to a particular small cylinder of metal. They called this cylinder the **primary standard** of mass, and the amount of material in it was called one **kilogram (kg)**. Exact copies of the primary standard kilogram are kept in various countries, including Canada.

Smaller masses are usually expressed in grams (g). "Kilo" means "thousand," so one kilogram (1 kg) is just another way to say one thousand grams (1000 g). Very small masses are usually expressed in milligrams (mg). "Milli" means "one thousandth," so a milligram is one thousandth of a gram (0.001 g). How many milligrams would be needed to make one gram (1 g)?

Skill FOCUS

To find a summary of basic SI units, turn to Skill Focus 4.

A **balance** is the most common type of measuring instrument for mass. Many balances compare the pull of gravity on the object being measured with the pull of gravity on standard masses. If the pull of gravity is equal, the masses must be equal, too. Figure 4.29 shows a common type of laboratory balance.

Mass is a very useful property to measure because it stays the same no matter where an object is located. An elephant has a mass of about 5000 kg whether it is on Earth, on the Moon, or in space. Its mass will change only if it gains extra matter (by eating a large meal, for example) or if it loses matter (perhaps by converting body fat into energy through exercise).

Figure 4.29 Triple-beam balance

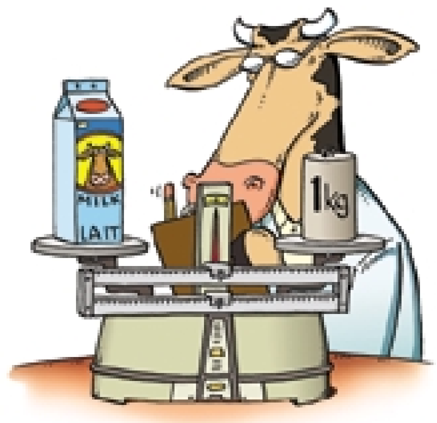


Figure 4.30 The standard kilogram has about the same mass as 1 L of water, milk, or juice.

Forces and Weight

You have just learned that the elephant's mass of 5000 kg would not change whether it was on Earth or on the Moon. This is because the amount of matter making up the elephant would be the same wherever it is in the universe. So why does its weight change? To understand how mass and weight are different, you must first learn more about forces. In Topic 1, you learned that **forces** are stresses such as pushes or pulls.

The standard SI unit of force is called a **newton (N)**. One newton (1 N) is only a small force, just enough to stretch a thin rubber band a bit. Some other examples are shown in Figure 4.31. To understand and predict how forces affect structures, you need to find the size of the force.

DidYouKnow?

In everyday talk, "mega" means "really big." In science, "mega" means one million. Whenever you see the prefix "mega," you can replace it with the word "million" or the number 1 000 000.

1 N: force that can lift a flashlight battery (D-cell)

10 N: force that can lift a 1 L carton of milk

200 N: force of a hard-thrown baseball hitting your hand

Figure 4.31 Some forces of different sizes

Did You Know?

Isaac Newton (born on December 25, 1642) was a British mathematician and scientist. By the time he was 24, Newton had begun to develop differential calculus, a powerful type of advanced mathematics, and had used it to analyze the gravitational forces between objects. In 1687 Newton published a book called *Principia Mathematica*. In this book, he showed how to use mathematics to analyze and predict the motion of any object and the forces that caused the motion. In 1699 Newton became Master of the Mint and was in charge of producing coins for the British government. Newton was disagreeable to work with, but his books and ideas revolutionized science and mathematics. He died in 1727 and is buried in Westminster Abbey, a famous church in London, England.

Study Figure 4.32 to find out how to use a **force meter**, or spring scale, a common laboratory instrument for measuring forces. Force meters are not very accurate, but they are less expensive and more sturdy than electronic sensors. Some forces are very large or otherwise difficult to measure, such as the force exerted by a rocket engine. Forces like these can often be calculated by observing their effect on the motion of an object.

To completely describe a force, you need to determine both its direction and its size. To lift a box, for example, you might have to exert a force of 50 N upward. A book falling on your toe might exert a force of 15 N downward.

Figure 4.32 A force can be measured by seeing how far it stretches the spring in a force meter.

Weight

Weight is a force and, like other forces, it is properly measured in newtons. Did you notice that we said the elephant's *mass* is 5000 kg, not the elephant's *weight*? Weight was carefully investigated by Isaac Newton in the seventeenth century. According to a famous story, Newton once sat under an apple tree and began to wonder why the apples always fell down, toward Earth. They never fell up into the sky or just floated in mid-air. Newton realized that there is a force between any two objects, anywhere in the universe, that tries to pull them together.

Using his mathematical skills, Newton analyzed the size of this force, which he called gravity. He found that the **gravitational force** between two objects depends on the masses of the objects and the distance between them. The force of gravity is very small between ordinary-sized objects. You do not notice gravity pulling you toward trees or other people as you pass by them, but the force is there. If objects are very massive, however, the gravitational forces near them become much larger.

Earth is big enough for the gravitational force between it and nearby objects to be important. In everyday language, we call this force **weight**. Instead of saying that there is a gravitational force of 10 N between a 1 kg mass and Earth, we would say that the mass has a weight of 10 N. (It actually has a weight of 9.8 N, but we will use the rounded value of 10 N to make calculations easier.)

Skill FOCUS

For tips on measuring mass, turn to Skill Focus 5.

Because gravitational force depends on the distance between objects, an object's weight changes depending on where it is. In an airplane or on a high mountain, where you are farther from the centre of Earth, your weight is a little bit less. However, your mass remains the same. Gravitational force also depends on the mass of an object. On the Moon, your weight would be about one sixth what it is on Earth, because the Moon's smaller mass exerts less gravitational force than Earth's mass. In space, very far from Earth or any other large body with a gravitational force, you would be essentially weightless!

It is easy to confuse mass and weight. As you have just learned, mass is the amount of matter that an object is made of, while weight is the force with which gravity pulls on an object. Read the following sentences and decide whether the terms and units of mass and weight are used correctly:

- The spring scale in the super-market was used for finding the mass of the fruit to be purchased.
- After a rigorous exercise program, Bob's weight decreased by 5 kg.
- As the space shuttle returned to Earth, the mass of the astronauts' bodies returned to normal.
- The Olympic weight lifter competed in the 100 kg weight class.

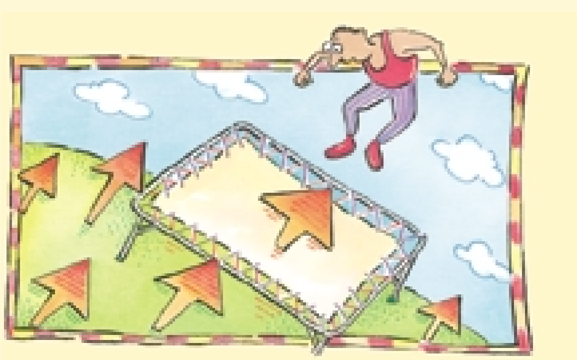
Cool Tools

Precision balances are basic tools in modern laboratories. You will use them a lot in later courses. If your school has balances and spring scales, you may be able to practise measuring small objects with them now.

Figure 4.33 A standard bathroom scale is a type of spring scale. Springs within the scale are stretched when a person stands on the scale. The springs are connected to parts that move a numbered scale below a fixed needle.

Find Out ACTIVITY

How Forceful!



Procedure

Stretch a rubber band between two fingers. Do you feel a pulling force on just one finger, or on both?

What Did You Find Out? Analyzing and Interpreting

Now think about gravity. Like the rubber band, it acts between two objects. So — does it pull on both objects, or just one? If your weight is 400 N, is that just the force pulling you toward Earth? Is there also a force of 400 N pulling Earth toward you?

Why do we always see things falling down toward Earth? Why is Earth not pulled up toward them? Or is it? These are the kinds of questions Newton tried to answer 300 years ago. Write a short paragraph to explain your ideas about them.

INQUIRY

INVESTIGATION 4-C

SKILLCHECK

- Initiating and Planning
- Performing and Recording
- Analyzing and Interpreting
- Communication and Teamwork

Crush It!

You can find out about a structure's strength by gradually adding weight to a structure until it breaks. In doing so, you observe the ability of the structure to withstand a force. Observations of when and how a structure fails can help a scientist understand the strength of a particular material or design. In Topic 1, you learned that this point of failure is called the ultimate strength of a structure. In this next investigation, you will use your skills in making a hypothesis and prediction, performing tests with controlled variables, recording data, and analyzing results.

Question

Which types of shell structures can withstand the most force before they fail?

Hypothesis

Before beginning your investigation, form a hypothesis about which structures will withstand the most force before they fail.

Safety Precautions

- Work on newsprint or a plastic drop cloth to simplify clean-up.
- Wear safety goggles and an apron during this investigation.

Apparatus

15 x 30 cm piece of wood

assortment of objects to use as weights (i.e., bricks, masses from mass kits, pennies, washers, ceramic tiles)

force meter

Materials

newspaper; 3 or 4 shell structures to test: ice-cream cone (flat bottom); styrofoam cup; section of a cardboard or foam egg carton; paper muffin tin liner; small section of celery stalk; half an orange, eggshell, or Ping-Pong™ ball; plastic blister packaging; pieces of breakfast cereal in shell shapes; shell-shaped pasta; walnut or peanut shells; red or green pepper halves; cones made of paper

Procedure

1. Before starting your investigation, **predict** which materials will be weakest and strongest. **Rank** your test materials in order from weakest to strongest. Be sure you are testing some natural and some manufactured structures. **Explain** your ranking based on your hypothesis.

2. Copy the table shown below into your notebook.

3. **Record** the names of the structures you will be testing and **classify** them as natural or manufactured.

4. Use the force meter to **measure** the weight of the objects you will use to test the strength of the shell structure. Find the weight of the board you will use in your test.

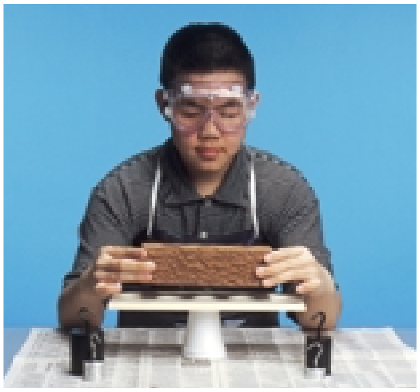
5. Place a shell structure on a flat surface covered with newspaper.

6. Balance your piece of wood on the structure.

Force to Crush the Shell Versus Type of Shell

Shell structure tested	Type of structure (manufacured or natural)	How does the structure fail?	Force needed to break the structure (N)

7. Place your weights one at a time on top of the wooden platform until the structure fails. **Observe** how the structure fails. (Does it bend first or just crack? Do small cracks appear and then spread, or does it crumble all at once? Where does it fail first?) **Record** your observations in your table.



8. **Record** the weight of all materials placed on the shell structure prior to collapse. Remember to count the weight of the board.

9. Repeat steps 5 through 8 for all shell structures to be tested.

10. Clean up your work area.

Skill FOCUS

To learn how to make a bar graph, turn to Skill Focus 10.

Analyze

1. What was the manipulated variable (the feature you changed for each test)? What was the responding variable (the feature you observed in each test)? What variables did you control for each test?

2. **Rank** the objects from weakest to strongest.

3. **Draw a graph** that clearly shows the strengths of the different objects. A bar graph would show these data clearly.

Conclude and Apply

4. **(a)** Did any shapes seem stronger than the others? Give examples and **explain**.

   (b) Did any materials appear stronger than the others? Give examples and **explain**.

5. What might have happened if you had suddenly increased the weight on the test object, or put all the weight on a tiny part of it? How can the way in which you apply force affect the results?

6. Think of a shell structure in which strength would be

   (a) very important

   (b) not particularly important

Math CONNECT

Forces are measured in newtons, but most bathroom scales are marked in kilograms or pounds. (A pound is a unit of force but it is not an SI unit.) Each kilogram represents a force of almost 10 N and each pound represents a force of about 4.5 N. Using the results of your investigation and your weight in newtons, calculate how many ice-cream cones (or egg cartons or styrofoam cups) would be needed to support your weight. If you have enough materials, try this out to check your calculations. (Remember to distribute your weight evenly over all of the objects.)

Picturing Forces

A **force diagram** is a simple picture that uses arrows to show the strength and direction of one or more forces. As you can see in Figure 4.34, a circle or rectangle stands for the object on which the forces act. Each force is shown by an arrow. The length of the arrow shows the size of the force: a longer arrow represents a larger force. The direction of the arrow shows the direction of the force. The arrow is usually drawn pointing away from the place where the force is acting, like a rope pulling an object.

Diagrams are especially useful to find the combined effect of several forces acting on the same object. A neat sketch is often enough to solve a simple problem. Even when many forces are acting together, mathematicians have found ways to use exact scale drawings and calculations to predict what will happen.

Math CONNECT

Very precise measurements show that the gravitational force at Earth's surface is a bit smaller than 10 N on each kilogram of matter. (The actual figure is close to 9.81 N.) Try recalculating the predicted weight of each object you measured in *Cool Tools* on page 301, using 9.81 N as the force on each kilogram instead of 10 N. Are these predictions closer to your measurements than your original predictions?

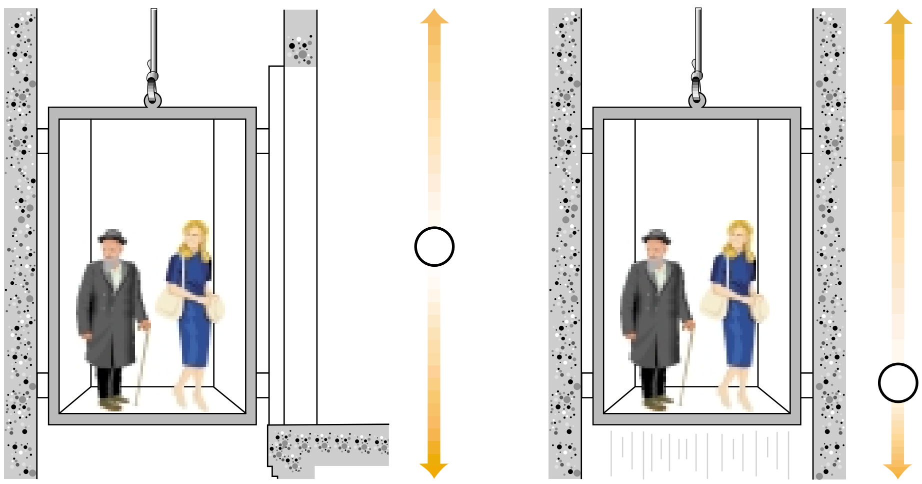


Figure 4.34 When the elevator is standing still, the force of the cable pulling it up is the same as the force of gravity pulling it down. When the force of the cable becomes greater than the force of gravity, the elevator begins to rise.

TOPIC 3 Review

1. Suppose you want to measure the weight of a pencil.
   (a) What measuring instrument should you use?
   (b) What units should you use for your answer?
2. In a lab report, two students reported that they had applied a force of 6.5 N to a brick. Their answer received only half marks. What extra information should they have reported?
3. Write three sentences that show you know how to use the terms "mass" and "weight" and the units of mass and weight.
4. **Apply**
   (a) Express the mass of a 125 g tube of toothpaste in kilograms.
   (b) Calculate the weight of the tube of toothpaste.

TOPIC 4 Forces, Loads, and Stresses

Figure 4.35 A train derailment produces a number of effects on the cars that collide with each other.

You do not have to witness a train crash to know that it creates dangerously large forces. Look closely at Figure 4.35. What effects did the forces in this collision have on the colliding objects? List as many effects as you can.

Now imagine a smaller "collision," such as kicking a soccer ball. When your foot applies a force to the ball, or any small object that is free to move, three things can happen. The object's motion can speed up, slow down, or change direction. When you kick something larger, such as a building, it does not usually move, but the force still has an effect. A force, such as your kick, on the outside of the building is called an external force. **External forces** on structures are stresses that act on a structure from outside it. These forces produce **internal forces**, or stresses, within the materials from which a structure is made. Such internal stresses can change the shape or size of a structure. This change to the shape or size of the structure is called **deformation**. Deformation can lead to either repairable damage or the complete failure of a structure. Engineers must design structures strong enough to withstand damaging changes. Therefore, they must understand external forces and the internal forces that they cause.

Ask an Expert

Read about Alan McColmon, on pages 342–343. Alan uses forces to tear down and demolish structures.

External Forces

DidYouKnow?

Although the mass of the CN Tower in Toronto is over 130 000 t, this hollow concrete structure is still flexible. In 190 km/h winds, which are thought to occur only once or twice every 100 years in Toronto, the glass-floored observation deck near the top of the tower would move 0.46 m (about the width of this open textbook) off centre. Instead of making the tower unstable, this movement would press the specially shaped foundation even more firmly into the ground.

Engineers divide the forces that affect buildings into two groups.

A **dead load** is a permanent force acting on a structure. This includes the weight of the structure itself. Over time, this gravitational force can cause the structure to sag, tilt, or pull apart as the ground beneath it shifts or compresses under the load.

A **live load** is a changing or non-permanent force acting on a structure. This includes the force of the wind and the weight of things that are in or on a structure (people, furniture, and snow and rain on the roof). Impact forces, caused by objects colliding with the structure, are another type of live load. Most structures are designed to withstand forces at least two or three times larger than their expected live load. Sometimes, though, live loads become extremely large for a short time, as in a storm or a collision, and the structure can be damaged.

When you act as a live load on a teeter-totter, you create forces that spread through the whole apparatus. Your weight pushes down on the seat and the bar to which the seat is fastened, but the opposite seat is lifted up. The centre of the teeter-totter twists around its pivot. One external force (your weight) creates several internal forces. These stresses affect different parts of the structure in different ways. Study Figure 4.36 on the next page to learn about four of the most important internal forces.

INTERNET CONNECT

www.mcgrawhill.ca/links/sciencefocus7

For information about how the CN Tower was designed and built, and some of the records it has set, go to the web site above. Click on **Web Links** to find out where to go next. Or submit "CN Tower" to an Internet search engine. Compare your findings with facts about other tall buildings around the world.

INTERNET CONNECT

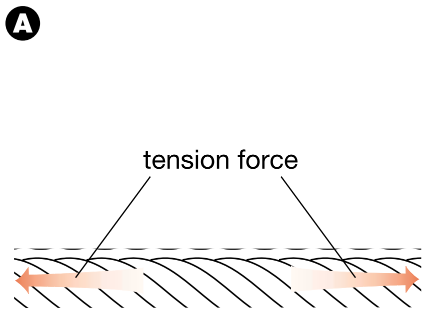
www.mcgrawhill.ca/links/sciencefocus7

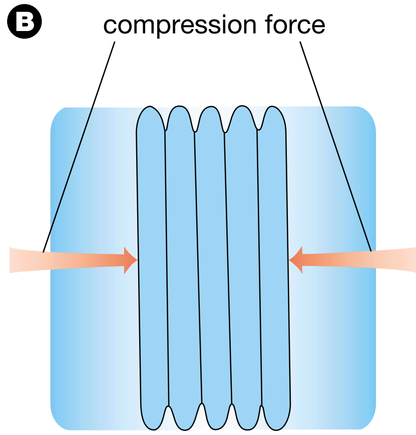
Find out more about the Leaning Tower of Pisa by going to the web site above. Click on **Web Links** to find out where to go next. Based on what you learn, how would you suggest the city of Pisa prevent further leaning?

DidYouKnow?

The Leaning Tower was designed to be a beautiful bell tower for a church in the Italian town of Pisa. Construction began in 1173, but after the first three storeys were built, the ground beneath the heavy stone building began to sink unevenly. Even before the 55 m tower was completed (around 1370), it had developed a noticeable tilt. By 1990, when the tower was closed to the public, the edge of the top storey was about 4.4 m outside the edge of the foundation and the tilt was increasing by about 1.3 mm each year. In 2000, engineers had corrected the tilt by 23 cm by carefully removing the soil from under the tower. They hope to bring the tower back another 23 cm, to the tilt it had in 1838. Then it will be safe to climb the tower again.

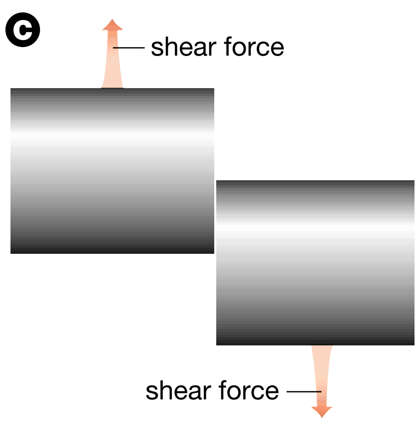
Internal Forces

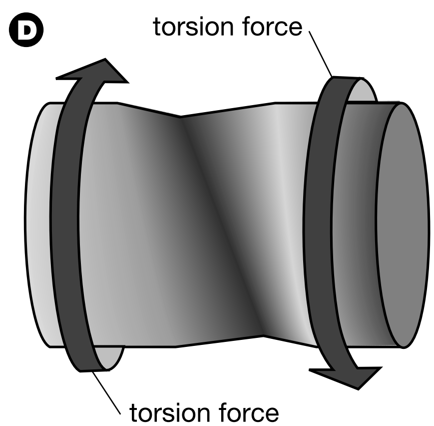




Tension forces stretch a material by pulling its ends apart. **Tensile strength** measures the largest tension force the material can stand before breaking.

Compression forces crush a material by squeezing it together. **Compressive strength** measures the largest compression force the material can stand before losing its shape or breaking into pieces.





Shear forces bend or tear a material by pressing different parts in opposite directions at the same time. **Shear strength** measures the largest shear force the material can stand before ripping apart.

Torsion forces twist a material by turning the ends in opposite directions. **Torsion strength** measures the largest torsion force the material can stand and still spring back to its original shape.

Figure 4.36 Internal forces

Pause & Reflect

In your Science Log, write a short paragraph explaining the difference between external forces and internal forces. To illustrate your explanation, give an example of each type of force when a strong wind blows on a flag.

Word CONNECT

The same words that name internal forces are used in other situations.

- How is a metal pair of cutting *shears* similar to a *shear* force?
- How is a *tension* headache similar to a *tension* force?
- How is a *compressed* computer file similar to a *compressive* force?

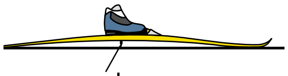


Figure 4.37 Cross-country skis are designed to bend when a force is applied. Bending allows the middle, or camber, of the ski to contact more snow and give the skier a better grip when pushing off.

Hold a ruler with one hand at each end and bend the ends gently toward the ground. (You will find this easiest if you begin by holding the ruler flat in front of you.) Describe the kinds of forces that are acting on a ruler when you exert a **bending force**. Draw a diagram with arrows showing how the forces are acting on the ruler. Bending is a combination of tension and compression forces. In Topic 5, you will learn how shear and torsion forces are also a combination of tension and compression. You will also learn why bending the ruler in one direction is much easier than bending it in another!

Find Out **ACTIVITY**

Bend That Bike!

If you know the types of internal forces that stress part of a structure, you can design that part with the kind and amount of strength it needs to support the forces efficiently. In this activity, you will identify the forces acting in a bicycle and the effect each force has.

Procedure

Performing and Recording

1. Set up a data table to record your observations for five parts of a bicycle. Include columns for the name of the bicycle part, its letter on the diagram, the force acting on it, and the type of strength it needs. Give your table a title.
2. Study the diagram of the bicycle.
   (a) Read the descriptions of the forces acting in each part of the bicycle.
   (b) Fill out one row of the data table for each labelled part of the bicycle.

What Did You Find Out?

Identify one more part of the bicycle that might fail because it has too little

- tensile strength
- compressive strength
- shear strength
- torsion strength

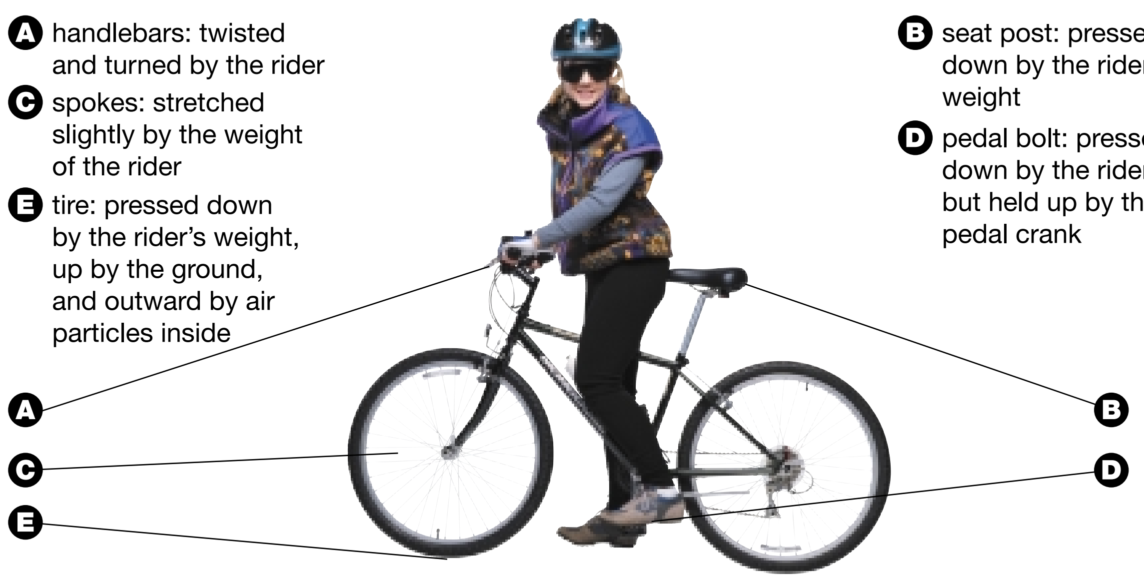


Figure 4.38 Examine the illustrations to find examples of live loads, dead loads, tension, compression, shearing, bending, and torsion. How many examples can you find of each?

Looking Ahead

What kinds of forces and loads will affect the reverse bungee ride you are planning for your unit project? Write down your ideas and add the best ones to the group file or notebook.

Cool Tools

Have you ever wondered how dental braces work? You probably think of your jawbone as a very solid and strong material. However, when you are young, you can stretch your jaw by applying forces to it. This is because your body's bones are still growing.

It is common for a person's jaw to be too small for its owner's teeth. If your jaw is too small, specialized dentists called orthodontists may insert a structure in your mouth that will pull on your jaw. As your body grows, your jaw will grow in the direction of the pulling force, making your jaw larger.

Most people grow fastest when they are around 8 or 9 years old. This is the best time to expand or reshape your jaw. When you are an adult, your jawbone will have hardened. By the age of 20, you may even need surgery to reshape your jaw.

Dental braces can also move your teeth. The best time to move your teeth into the correct positions is after you get your permanent teeth, when you are 12 or 13. Permanent teeth are still a bit loose when they first come in, so they are easier to move. When you are older, your teeth are more firmly set in place. You can get the same dental treatments when you are older, but it will hurt more!

The materials used for dental braces have specific performance requirements. Braces are designed to apply tension forces to out-of-line teeth, so the materials need high tensile strength. Braces also need a strong adhesive to make sure they are solidly anchored to teeth. Everything making up the braces — bands, brackets, cement, and elastics — has to be able to withstand the hostile environment of the mouth. All mouths have bacteria that produce acids that attack both metal and teeth. Even saliva is a chemical designed to break down other materials.

INQUIRY

INVESTIGATION 4-D

SKILLCHECK

- Initiating and Planning
- ✸ Performing and Recording
- ✸ Analyzing and Interpreting
- Communication and Teamwork

Examining Forces

If you know the types of internal forces that stress part of a structure, you can design that part with the strength it needs to resist the forces acting on it. In this investigation, you will identify the forces acting on a variety of structures and materials and the effect each force has.

Question

What forces create stress in various structures, and where does the stress occur?

Part 1

Stressed-out Marshmallows

Apparatus

black non-permanent overhead felt pen

30 cm ruler

Materials

5 large-sized marshmallows

Procedure

1. As shown in the photograph below, use a felt pen to **draw a grid** on 5 marshmallows. Use a ruler to draw the lines as straight as possible. The squares formed by the grid should have sides of equal length. (Do not draw rectangles.)

2. **Prepare a data table** similar to the one shown, with sufficient space to record your observations for each part of this activity.

3. Hold a marshmallow between two fingers as shown in the photograph to the right. Squeeze the marshmallow. **Observe** changes to the horizontal and vertical lines. In the appropriate section of your data table, **draw a diagram** that represents the change in the size and shape of the grid. **Describe** the changes to the grid lines using words such as "shortened," "lengthened," or "stayed the same."

Force Versus Action

Action	Grid diagram	Description of grid changes	Type of force(s) observed
Squishing			
Stretching			
Bending both ends			
Bending one end			
Twisting			

4. As shown in the photograph below, hold a second marshmallow firmly at both ends. Pull outwards. **Record** your observations as you did in step 3.

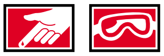
5. Holding a marshmallow with your hands positioned as they were for step 4, bend the ends of the marshmallow upward. **Observe** and **record** any changes to the grid on your data table.

6. While holding one end of a marshmallow on the edge of a desk or table, push the other end downward over the edge of the desk. **Record** your observations.

7. Firmly grip a marshmallow on each end as you did in step 4. By turning your hands in opposite directions, apply a twisting force to the marshmallow. **Record** your observations.

Part 2
Shear Excitement

Safety Precautions



Take care using both sharp and dull scissors.

Apparatus

sharp scissors

dull scissors (or scissors with a loose central screw)

Materials

toothpicks

2 (10 × 15 cm) pieces of blue polystyrene

sheet of paper

Procedure

1. Read this procedure completely, then **draw a data table** with sufficient space to record your observations for each part of this activity. You will need a column for an observation diagram and a column for a description of your observations. Give your data table a title.

2. Slowly tear a sheet of paper from top to bottom. In your data table, **draw** and **describe** what happened to the fibres that make up the paper when it was torn. Include arrows to show the direction of the forces acting on the paper.

3. Using the sharp scissors, cut a sheet of paper from top to bottom. **Record** your observations as you did for step 2.

4. Repeat step 3, this time using the dull scissors.

5. Place the two pieces of polystyrene together and connect them by pushing two or three toothpicks through both pieces. Holding each block firmly, rapidly slide the blocks apart, snapping the toothpicks. Observe the broken ends of the toothpicks. **Record** your observations on your data table.

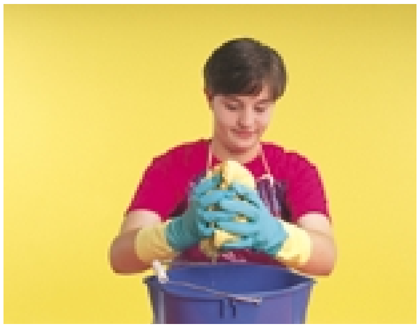
CONTINUED

Part 3
Twist That Towel

Apparatus
small towel or washcloth
plastic bucket or basin full of water
empty plastic bucket or basin
graduated cylinder
rubber gloves

Procedure

1. **Prepare a data table** to record your results. Headings should include Action (squeezing or twisting), Amount of water collected (mm), and Type of force(s) involved. Give your table a title.



2. Soak the towel in water. Hold the towel above the bucket of water until it stops dripping.
3. After dripping has stopped, hold the towel over the empty bucket. Squeeze, *but do not twist*, as much water as possible into the empty bucket.
4. Use the graduated cylinder to **measure** the volume of water squeezed out. **Record** your answer and the type of force or forces in the data table.
5. Repeat steps 2 through 4, but this time twist the wet towel tightly to squeeze out the water. **Record** your answer as in step 4.

Part 4
Tug-o'-war

Apparatus
2 desks or tables
retort stand bar or other strong metal bar
plastic bucket (with a handle)
paper clips
assorted masses of known weight

Materials
30 cm lengths of at least four types of materials to test (e.g., sewing thread, fine fishing line, knitting wool, crochet cotton, strips of scotch tape, masking tape, paper)

Procedure

1. **Prepare a data table** in which to record the total weight held by each material before breaking.
2. Loop the first material being tested through the handle of the plastic bucket and over the metal bar that has been placed between two desks. Securely tie or connect the loose ends of the material together.
3. Gradually add masses to the bucket until the material being tested breaks. Hold your hands just below the bucket as masses are added, to prevent the bucket from falling quickly when the test material breaks. **CAUTION** Keep your feet clear of falling buckets.

4. In your data table **record** the amount of weight supported by the material before breaking. Remember that weight must be recorded in newtons.
5. Repeat steps 2 through 4 for all materials to be tested.
6. After all materials have been individually tested, braid three pieces of one of the materials together and repeat the test.

Skill FOCUS
To learn how to measure with a graduated cylinder, turn to Skill Focus 5. For tips on making data tables by computer, turn to Skill Focus 9.

Analyze

1. Use your observations to decide whether each statement below is true or false. In your answers, **explain** which part of the investigation gives evidence for your decision.
   - **(a)** Only one force can act on one part of a structure at a time.
   - **(b)** Torsion forces reduce the size of the spaces between particles in a substance.
   - **(c)** A piece of yarn or rope made by twisting several fibres together has much higher tensile strength than a single fibre.
   - **(d)** The top of a structure that is being bent may be placed under tension or compression.

Conclude and Apply

2. In this investigation, you tested a variety of materials for strength against tension, compression, torsion, shear, and bending. For each type of force, **list** at least two examples of materials that would be well suited to resist that particular force. Give at least two examples of materials that would be poorly suited. **Explain** your examples.

3. For each of the forces you investigated, give an example of a "real life" structure or part of a structure that must be able to resist that force. **Explain** how you think these structures have been designed to resist those forces. Hint: Think about structural features such as the type of materials used, the shape of parts, and how the parts are connected.

4. For each example below, **describe** which force(s) would cause internal stress:
   - **(a)** playground swing set
   - **(b)** playground seesaw
   - **(c)** full garbage bag held shut with a twist tie
   - **(d)** front bumper on an automobile
   - **(e)** member of a school's wrestling team during a match
   - **(f)** snowboard with bindings

INTERNET CONNECT

www.mcgrawhill.ca/links/sciencefocus7

Find out more about the most recent efforts to manufacture fibres as strong as spider silk by going to the web site above. Click on **Web Links** to find out where to go next. Or submit "spider silk" and "strength" to an Internet search engine. Write a brief report based on your findings.

***Computer* CONNECT**

If you have access to a computer, you could use it to prepare data tables for the investigation.

Did You Know?

One kind of spider silk is the strongest material known. Dragline fibres are spun by spiders when they make the frame of a web and when they drop from high places. Because the fibres have high tensile strength and are also very stretchy, it takes a great deal of energy to break them. The web of the golden silk spider is strong enough to trap a bird!

Measurements of the dragline fibres show that they are at least five times stronger than an equal mass of steel. That is even stronger than Kevlar™, the fibre used to manufacture bulletproof vests. If a strand of this spider silk were as thick as a pencil, it could stop a speeding 747 passenger jet! Scientists are currently using genetic engineering to develop a bacteria containing the gene for spider silk. They hope to someday produce large quantities of this "super strong" material.

Resisting Stress—The Inside View

What determines the strength of a material? Scientists trace strength, and many other properties, to forces between the tiniest particles of the material. Examine Figure 4.39 to learn what scientists have been able to infer about particles that are far too small to see.

- Steel has high tensile strength. It has strong forces pulling its particles together. A very strong tension force is needed to separate the particles and break the material.
- Graphite (a form of carbon) has low shear strength. Its particles are arranged in layers, but the forces between the layers are relatively weak. Because the layers slide over one another easily, graphite is slippery and makes a good dry lubricant. The layers of graphite in a pencil "lead" rub off and leave a mark on the paper when you write.
- Rubber has high torsion strength. Each particle is attracted in all directions to the other particles around it. The particles hold together even when a piece of rubber is twisted out of shape.

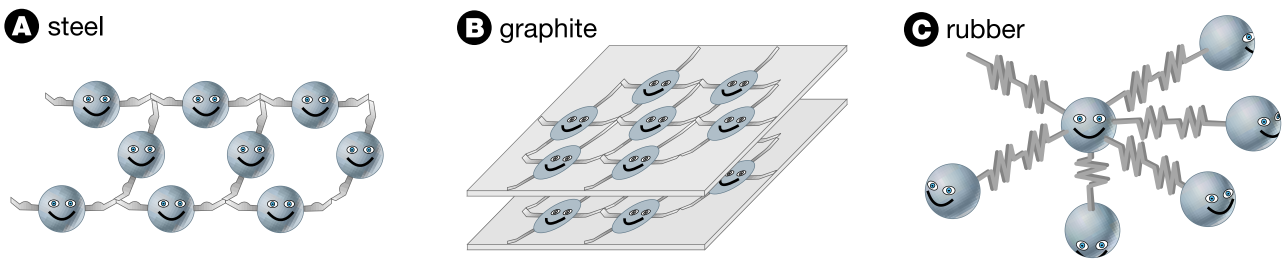


Figure 4.39 Each metal particle attracts a few other particles very strongly. The forces are quite directional, so the particles form a regular arrangement in space.

Graphite particles attract strongly in some directions, but hardly at all in other directions.

Each rubber particle attracts many other particles in all directions.

TOPIC 4 Review

1. List examples of deformation that you investigated or read about in this topic.
2. Name three types of stress that a force can cause inside an object.
3. (a) What is the difference between a live load and a dead load?
   (b) Study the following loads that are acting on a tree. Classify them as "live" or "dead."
   - wind blowing against a tree
   - the weight of the tree
   - the weight of a bird in the tree
4. Identify the type of strength that is shown by
   (a) the chain that connects a ship to its anchor
   (b) a piece of very tough dried meat you are chewing
   (c) a bolt you are tightening with a wrench
   (d) the legs of the chair you are sitting on
5. How well can chewing gum withstand internal forces? Explain differences between a dry stick of gum and chewed gum.

TOPIC 5 How Structures Fail

No structure is perfect. No material is perfect. If a great enough force acts on a structure, it will begin to fail. Even small forces, acting in a vulnerable place, can cause damage. Learning how structures could possibly fail helps engineers design strong, durable structures.

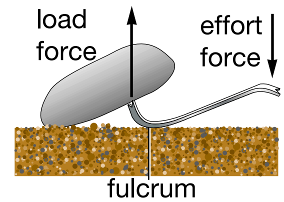


Figure 4.40 With a crowbar, you can lift very heavy objects or separate pieces of wood nailed together.

Levers Create Large Forces

Frame structures that are made of long, rigid lengths of lumber or steel can fail when force is applied to them. Such failures can result from the force created by the action of a lever. A **lever** is a device that can change the amount of force needed to move an object. Some types of levers consist of a long arm that rests on a pivot, or **fulcrum**. When effort is applied as an external force to the lever, a large enough force is created to lift a heavy load. A crowbar used to lift a rock shows such forces at work (Figure 4.40).

Figure 4.41 shows how unintentional lever action can damage a structure. Strong winds can exert an external force that bends the frame structure of a flagpole. Even a slight bend can exert a large force on one side of the flagpole's base. Then, the base acts like a lever (see Figure 4.41). As the external force pushes down against one side of the base, the other side pushes up against the load of the flagpole. Eventually, the bolts holding the frame structure to the base weaken, and the flagpole falls over. Strong winds can produce other forces that can result in structural failure (see Figure 4.42).

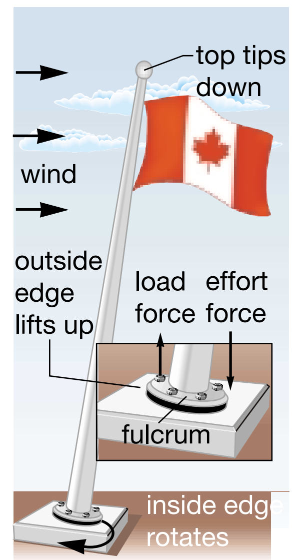


Figure 4.41 Strong winds can tip a flagpole.

How Materials Fail

External forces can cause internal forces in the structure (see page 305). Each type of internal force can cause certain types of damage.

- **Shear** Solid materials are never perfectly uniform. They nearly always have microscopic cracks or weaknesses. When a solid material is compressed, the crack can enlarge or break apart. One section may shear (slide over another section along the weakness). The weight of a building can compress the soil causing the soil to shear or slip sideways. The ground beneath the building sinks, and the building tilts or collapses.

Figure 4.42 Winds in a tornado produce twisting, bending, and compression forces so strong that no structure can escape damage.

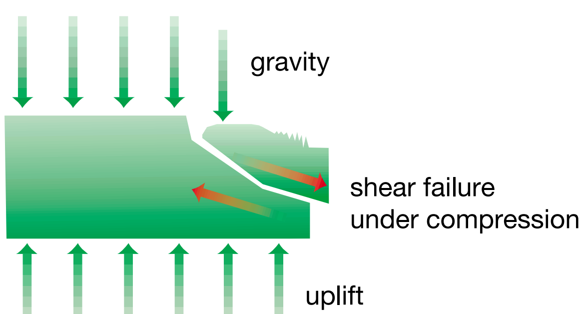


Figure 4.43 Compression causes sections of material to slide sideways, causing shear failure.

Figure 4.44 Even if the ground beneath a building was uniform when the building was constructed, shear damage can occur. An earthquake caused this damage.

- **Bend or Buckle** If you put pressure on a metal can, the thin metal folds and the can buckles (gives way) under the compressive force you apply. The same thing happens to a piece of paper when you push the ends together. All thin panels tend to bend and buckle when they are compressed. Compression forces cause material to bend on the inside of the curve, and pull and snap on the outside of the curve. Shell structures that use thin panels to support their entire load, such as boats and aircraft, are reinforced to prevent buckling. Examine Figure 4.46 to see some common methods of reinforcement.

- **Torsion** Twisting forces can cause material failure, too. Brittle structures, such as dry spaghetti and plastic cutlery, often shear when they are twisted. Sections of the structure slide past each other, and the structure cracks or breaks in two. Very flexible structures, such as rubber bands, hoses, and electrical cords, shear less easily. Instead, torsion forces make them fold up and twist into tangles and knots. Although the structure is unbroken, it has lost its shape, which is a form of failure.

Figure 4.45 How could an engineer design buildings so they would not bend or buckle during an earthquake?

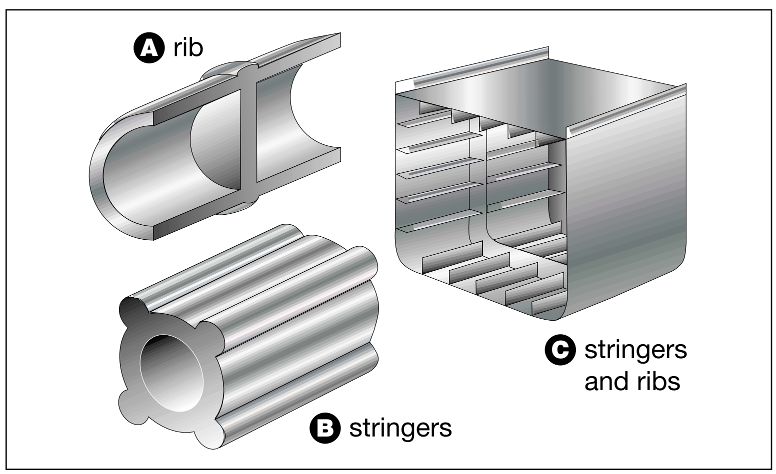


Figure 4.46 These three common designs reinforce structures in order to prevent shear, bend, buckle, and twist failure. Stringers and ribs are used to reinforce large vessels such as cargo ships, aircraft, and many rockets. Sometimes they are hidden beneath an exterior skin, so they are not easy to see.

INTERNET CONNECT

www.mcgrawhill.ca/links/sciencefocus7

Find out how engineers design structures that are resistant to earthquake damage. Click on **Web Links** to find out where to go next.

Making Use of Stress

Snap, twist, buckle, bend, and shear: that is what materials and structures do when they fail. These same behaviours can also be put to good use. You already saw bending put to good use in cross-country skis (see Figure 4.37 on page 308). Other examples include:

- *Buckle* Car bumpers and sheet metal can be designed to buckle in a collision. As the metal deforms, it absorbs some of the energy of the impact. The car may be badly damaged, but the occupants are less likely to be seriously hurt. Blades of grass on a sports field buckle as athletes land on them, absorbing some of the energy of the impact. Certain kinds of panels, such as the bellows in an accordion or the flaps on a cardboard box, are designed to buckle in specific places when you press on them.
- *Shear* In a boat's outboard motor, the propeller is held to the drive shaft with a shear pin. If the propeller becomes tangled in weeds, the shear pin will break, allowing the motor and the gears to spin freely instead of being damaged. The clutch and automatic transmission of a car are designed so that shear forces allow parts to slip past each other, speeding up or slowing down gradually until they are moving at the same speed. This produces a much smoother ride than connecting the engine directly to the wheels.
- *Twist* Spinning wheels twist cotton or wool fibres tightly so that they lock together. The twisted yarn is much stronger than a bundle of straight fibres and is long enough to knit or weave into cloth. If the fibres are twisted too much, they tangle and shorten unless you keep pulling on them. That's one way to make stretchy fabrics. Controlled twisting turns hair into braids, string into ropes, and wires into cables.

Figure 4.47 Car designers increase the margin of safety for vehicles by using principles of material failure.

Across Canada

One day, Sandford Fleming (1827–1915) invited some governors to have lunch under a bridge. Fleming was chief engineer on the construction of the railroad across Canada. He was trying to convince the governors that iron was the best material for building train bridges because it would stand up well to fire, moisture, and cold. Everyone else wanted to use wood, fearing that iron beams would crack from the weight of the trains.

When a heavy train thundered across the bridge during lunch, the governors shook with fear, and some ran away from the table. Of course, nothing happened; the bridge was safe. Fleming went on to build more iron bridges across Canada.

Solving problems was always one of Fleming's passions. In his late teens, in 1845, he sketched a design for a type of rollerblade! Later he created the first Canadian postage stamp. It featured a beaver and was issued on April 23, 1851. Hard work and determination helped Sandford Fleming become one of the most respected scientists in Canadian history.

Sandford Fleming

Metal Fatigue

Looking Ahead

In your Science Log, write a point-form outline to summarize the main ideas about structural failure that you have studied so far. What kinds of failure might your reverse bungee ride design need to overcome?

Early railway cars often developed a serious problem after they had been used for several years. Their solid metal axles broke and their wheels fell off, even though the parts were designed to be much stronger than necessary. About 150 years ago, a German railway official identified the problem. Metals weaken when they are bent or twisted over and over again.

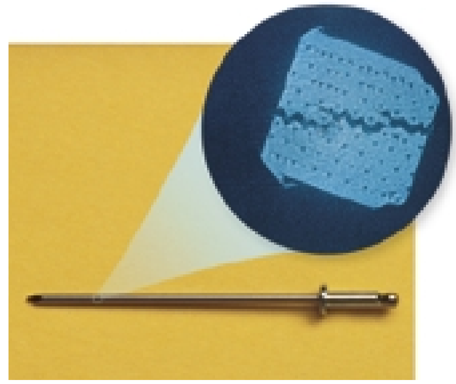


Figure 4.48 The material around this rivet shows signs of metal fatigue.

You can explain this loss of strength using the particle model, which you learned about in Unit 3. In a bent or twisted part of a metal structure, the arrangement of particles is changed. Where particles move apart, the forces holding them together become weaker. If enough particles are affected, small cracks develop. Eventually the material may fail under only a small stress, one that it could easily resist when it was new. Engineers call this weakening **metal fatigue**, and it is still a problem, especially in lightweight, flexible structures such as aircraft.

Find Out ACTIVITY

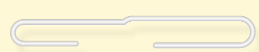
Bend and Break

Materials

2 silver-coloured metal paper clips

Procedure Performing and Recording

1. Straighten one paper clip as shown. Touch it to your inner forearm. Note the temperature.
2. Bend the paper clip back and forth quickly ten times. Can you feel it weaken? Record how many bends are needed to produce noticeable metal fatigue. Immediately touch the paper clip to your forearm again. Record whether you noticed a change in temperature.
3. Repeat step 2 until the paper clip breaks. Record how many bends are needed. Take care not to puncture your skin with the broken paper clip.
4. Straighten the second paper clip. This time, twist the ends of the paper clip back and forth. Count the number of twists needed to produce noticeable metal fatigue. Count the number of twists needed to break the metal.



What Did You Find Out? Analyzing and Interpreting

Answer the following questions:

1. Which type of stress seems to cause metal fatigue sooner, bending or twisting?
2. Did you notice any change in temperature after bending or twisting the paper clip? If so, what provided the energy to warm or cool it?
3. Describe the force or forces that led to the failure of the paper clips. Explain your answer.

Career CONNECT

- chemical engineer
- electrical engineer
- mechanical engineer
- aerospace engineer
- civil engineer
- materials science engineer
- structural engineer

There are many different types of engineers. Using a dictionary and logic, try to guess what type of engineer each of the people below is. Note that there may be more than one person for some branches of engineering.

Stanley Arthurson: designs custom tools for assembly line industries

Tom Cardinal: developed a new metal alloy for a lighter, faster bicycle frame

Josh Cohen: oversees smelting operations at a large mining company

Tony Chung: designs and modifies equipment to lower pollution from a large processing plant

Susan Erickson: develops circuitry for stereo components

Bob Gonzales: designs and oversees construction of roads and overpasses

Karen Ouimette: oversees the operation of the equipment needed to process petroleum into its components

Sasha Salinsky: creates new wing designs for a small airplane manufacturer

Tammy Nguyen: designs building frames capable of withstanding earthquakes

Find a partner and compare your matchings. Then, as partners, devise a plan to check your accuracy. Perhaps you will look in your telephone book for information, or your local college or university course calendar. The Internet or the guidance office in your school could provide some clues as well. Keep a journal of the steps in your plan and what information you gain at each stage. Share the journal, as well as your original and revised matchings, with the other partnerships in your class.

Skill FOCUS

For tips on using the Internet to do research, turn to Skill Focus 9.

INTERNET CONNECT

www.mcgrawhill.ca/links/sciencefocus7

Find out more about engineering by going to the web site above. Click on **Web Links** to find out where to go next. Can you discover why many Canadian engineers wear a special ring, what metal it is made of, and what famous disaster it commemorates? Write a short article about your findings.

TOPIC 5 Review

1. **(a)** Identify three dead loads and three live loads that are acting on your classroom.
   (b) Explain your reasoning for deciding which loads are "dead" or "live."
2. Name three ways that materials fail, and identify the type of internal force that causes each kind of failure.
3. **(a)** Which type of structure (mass, frame, or shell) is most likely to be damaged when its parts act as levers and create very strong forces?
   (b) Why are the other two types of structures not also weakened by lever action?
4. Which type of material failure occurs when you
   (a) leave a trail of footprints in a carpet?
   (b) sprain your ankle in a soccer game?
   (c) accidentally hit a baseball through a window?
   (d) crinkle a new $5 bill as you stuff it into your pocket?
   (e) twist the lid of a partly opened tin can back and forth until it breaks off?
5. Write a technical description of a time when you knocked something down or demolished a structure. Use the terms you learned in Topics 1–5. For example, to describe kicking over a sand castle, you might begin, "I applied an external force to a small mass structure. As a result, …"

Wrap-up TOPICS 6–7

If you need to check an item, Topic numbers are provided in brackets below.

Key Terms

mass
primary standard
kilogram (kg)
force meter
gravitational force
weight
balance
forces
newton (N)
force diagram
external force
internal force
deformation
live load
dead load
tension forces
tensile strength
compression forces
compressive strength
shear forces
shear strength
torsion forces
torsion strength
bending force
bend (buckle)
twist
shear
metal fatigue

Reviewing Key Terms

1. Copy the puzzle below into your notebook. Do not write in the textbook. Use the clues to complete each line. The number of blanks gives the number of letters in the word. If your answers are correct, the letters in the box will spell the name of an important force.

(a) _ _ _ _ ▢ _ _ _
(b) _ _ ▢ _ _
(c) _ _ _ _ _ _ _ _ ▢ _ _ _ _
(d) _ _ ▢ _ _ _ _ _ _
(e) _ _ ▢ _ _ _
(f) ▢ _ _ _ _ _ _
(g) _ _ _ _ _ _ ▢ _
(h) _ _ _ ▢ _ _
(i) _ _ _ _ ▢ _ _
(j) _ _ _ _ _ _ _ _ _ ▢ _
(k) _ _ _ _ _ _ ▢

(a) primary standard of mass (3)
(b) push or pull (3)
(c) picture of forces on an object (3)
(d) force that causes extra stress on a structure (4)
(e) force that pulls you against Earth (3)
(f) force for turning off a water tap (4)
(g) forces that resist outside forces (4)
(h) standard unit of force (3)
(i) kind of strength that spider silk has (4)
(j) forces that develop when you squeeze something (4)
(k) type of material failure that occurs when you twist plastic cutlery (5)

Understanding Key Concepts

2. Classify each statement as referring to force (F) or mass (M). (3)
   (a) measured in newtons
   (b) stays the same no matter where the object is located
   (c) measured with a balance
   (d) your weight

3. Describe two ways that material failure can be put to good use. (5)

4. What two factors affect the gravitational force between two objects? (3)

5. Using the diagram below:
   (a) Name the type of force stressing the top of the bookshelf. (4)
   (b) Name the type of force stressing the bottom of the bookshelf. (4)
   (c) Describe what might happen if more books were piled on the bookshelf. (4)