CHAPTER 11

Structural Strength and Stability

KEY QUESTION: What factors make structures strong and stable?

Looking Ahead

- A stable structure maintains its shape and position over an extended period of time.
- Beams, trusses, arches, and domes are used to help structures support loads.
- The skills of scientific inquiry can be used to investigate the factors that affect the ability of a structure to support a load.
- The skills of technological problem solving can be used to determine the most efficient way for a structure to support a load.
- Structural failure occurs when all or part of a structure loses its ability to support a load.
- The skills of scientific inquiry can be used to investigate methods used to ensure that structures are safe.

VOCABULARY

stability	cantilever
centre of gravity	truss
beam	arch
I-beam	dome
corrugation	structural failure

The Ritual of the Calling of an Engineer

In 1922, Canadian Herbert Haultain created a ceremony for new engineers. New engineers are asked to recite an Obligation to their profession. They also are given an iron ring to wear on their little finger. The ring is a symbol to new engineers. It reminds engineers of their pride in their profession and their responsibility to safety.

The idea that engineers needed to be more responsible may have come from the Quebec Bridge disaster. The Quebec Bridge collapsed in 1907, killing 75 workers. The cause was an engineering error. In 1917, the rebuilt bridge collapsed. This time, 11 people were killed.

Haultain wrote to author and poet Rudyard Kipling for help with creating the ceremony. Kipling responded with *The Ritual of the Calling of the Engineer*. The first ceremony was held in 1925. The yearly ceremony continues to this day.

The words of the Obligation of *The Ritual of the Calling of the Engineer* are secret. However, Kipling is well known for his poetry on engineering and building subjects. This example was written in 1911:

Modern Machinery

We were taken from the ore-bed and the mine,
We were melted in the furnace and the pit—
We were cast and wrought and hammered to design,
We were cut and filed and tooled and gauged to fit.
Some water, coal, and oil is all we ask,
And a thousandth of an inch to give us play:
And now, if you will set us to our task,
We will serve you four and twenty hours a day!
("The Secret of the Machines," verse 1)

LINKING TO LITERACY

Making Inferences

Texts can have "literal" meanings or "inferred" meanings. "Literal" means that the text means exactly what it says. "Inferred" means that a text says something, but really means something more.

Readers make inferences by thinking about what they have read in a text. Then, they make a connection to what they already know to make an informed guess about what a text really means. See if you can infer the meaning of the text for each situation.

1. In 1922, Herbert Haultain created a ceremony for new engineers. What inference does this text suggest for why he created this ceremony?
2. The words of the Obligation are secret. Kipling wrote this example of a poem about something that engineers would build. What can you infer about the words in the real Obligation?
3. The poem that is included in this text is from *The Secret of the Machines*. This is verse 1. What can you infer about the actual length of this poem?

11.1 Stability of Structures

Imagine you are standing on a public bus (Figure 1). The bus is speeding up and slowing down. You probably would feel more stable with your feet flat on the floor and spread apart. Why is this so?

Figure 1 How do you keep from falling when you are standing on a moving bus?

LINKING TO LITERACY

Reading for Meaning

When reading science texts, look for explanations or definitions of difficult or scientific words as you read. Sometimes, explanations are in the main text; sometimes they will be given in a sidebar or caption under a picture. Locate two definitions that are given on this page. How do these help you to better understand your reading?

Your body is a structure that is able to maintain its position when external forces try to push or pull it out of balance. **Stability** is the ability of a structure to maintain, or regain, a stable (balanced) position when external forces act on it. When engineers design structures, they must make sure that the structures are stable. Stable structures are safer because they do not easily topple over or fall down. Almost all structures, from small toys to huge buildings, are designed to be stable. Some toys and rides at amusement parks are designed to appear to be unstable to make them seem exciting and unpredictable.

stability: the ability of a structure to remain in or return to a stable, balanced position when forces act on it

An important characteristic of any structure is its centre of gravity. Finding a structure's centre of gravity helps designers determine its stability. **Centre of gravity** is the point around which a structure's mass is equally balanced in all directions. The centre of gravity is also the point at which the entire mass of an object seems to be concentrated.

centre of gravity: the point around which an object's mass is equally balanced in all directions; the point where the mass seems to be concentrated

TRY THIS: Finding the Centre of Gravity

SKILLS MENU: predicting, analyzing, evaluating, communicating

SKILLS HANDBOOK 2.B.3.

Locating the centre of gravity in an object is complicated. However, it is possible to find the horizontal balance point of long, thin objects. The horizontal balance point is very close to an object's centre of gravity. In this activity, you will predict, locate, and test the horizontal balance point of various objects.

Equipment and Materials: metre stick; tape; large rubber stopper; various long, thin, rigid objects; scissors; cardboard; pencil; 216 × 279 mm (8½ × 11 in.) piece of scrap paper; tape; pin; metal washer; string

Part A

1. Hold a metre stick by placing your index fingers near the two ends of the stick (Figure 2). *Slowly* slide your fingers toward each other until they meet. The location where they meet is the horizontal balance point of the metre stick. Record your observations.

Figure 2 Step 1

2. Tape a large rubber stopper at one end of a metre stick. With one hand, hold the metre stick with the rubber stopper to get a sense of how the metre stick's mass is distributed. Predict the location of the horizontal balance point of the metre stick with the stopper attached. Record your prediction. Test your prediction: repeat step 1 with the metre stick–stopper combination. Record your observations.
3. Predict and then find the horizontal balance point of other long, thin, rigid objects. Record your observations.

Part B

4. Work with a partner for Part B. Carefully cut a piece of cardboard into an L-shape. Tape a piece of scrap paper onto the shape so that the paper covers the shape, and also covers the space where the cardboard was cut out (Figure 3). Predict the location of the horizontal balance point of the shape, and mark it with a pencil.

Be very careful when using sharp objects.

Figure 3 Step 4

5. With a pin, make a hole near the edge of the shape. Make the hole slightly larger than the pin so that when the object is held up by the pin, the shape can rotate.
6. Make a plumb line by tying a washer to the end of a piece of string. Hold the shape by the pin, and hang the plumb line from the pin (Figure 4). Using a pencil, trace the line made by the hanging plumb line on the shape. Label this line AB.

Figure 4 Step 6

7. Make a second hole in the shape. Repeat step 6, but this time, label the new plumb line CD (Figure 5).

Figure 5 Step 7

8. Identify the point where line CD crosses line AB. Label this point X. Point X is very close to the shape's centre of gravity. Try to balance the shape horizontally by placing the blunt end of a pencil on point X. Will the shape balance on point X? Record your observations.
9. Repeat steps 4 to 8 with other unusual shapes cut out of cardboard. Record your observations.

A. Evaluate each of the predictions you made in the activity.

B. Write your own definition for "horizontal balance point."

C. Can the horizontal balance point of an object be outside the object itself? How do you know?

The Centre of Gravity of Common Structures

All structures have a centre of gravity. In the previous Try This activity, you used several different methods for locating an object's horizontal balance point. (Remember, the horizontal balance point is close to the centre of gravity.) An object's centre of gravity is usually located deep inside the object, not on its surface. For example, when you are standing upright, your centre of gravity is located deep inside your body, just below your belly button (Figure 6).

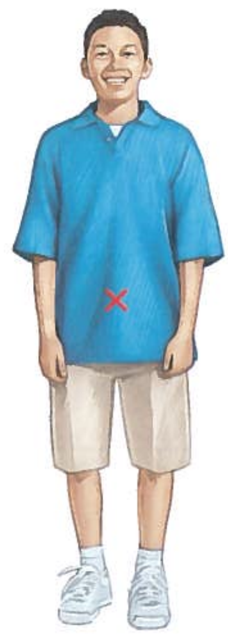


Figure 6 Centre of gravity of the human body when standing

However, your body's centre of gravity changes every time you move or bend your body into different shapes. The centre of gravity of an object depends on the shape of the object and how its mass is distributed. In some cases, the centre of gravity is outside the object itself (Figure 7).

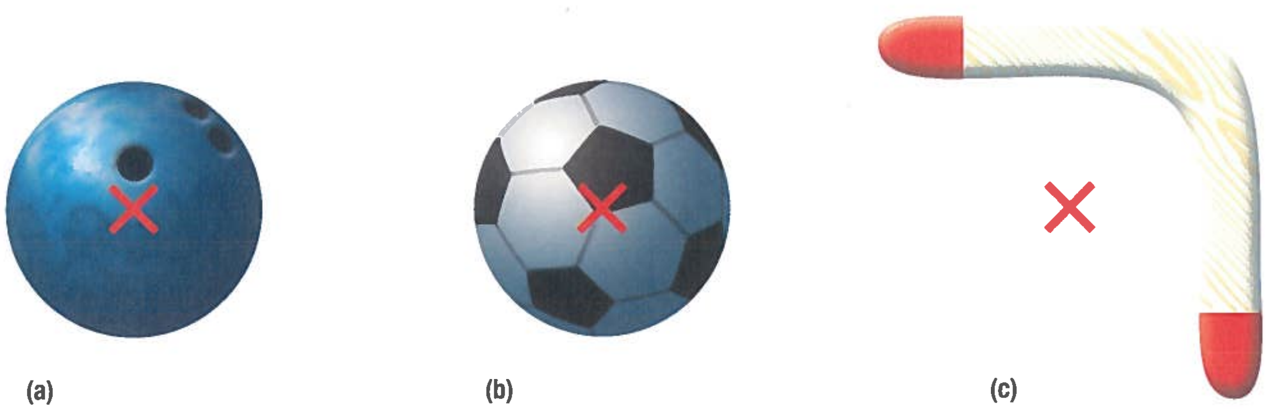


Figure 7 The centre of gravity of various objects
(a) middle of a solid ball
(b) middle of a hollow ball
(c) outside of a boomerang

TRY THIS: Centre of Gravity and Stability

SKILLS MENU: predicting, analyzing, evaluating, communicating

If you bend forward and let your arms hang in front of you, you may feel as though you are going to fall forward. Your body feels less stable in this position because its centre of gravity has moved in front of the centre of its base (your feet). In this activity, you will learn how a structure's (your body's) stability relates to its centre of gravity and its support base.

Equipment and Materials: object that can be lifted with one hand (for example, a dumbbell or textbook)

If you have any problems in lifting objects or bending over, be careful in deciding which steps to follow. These activities should be performed with a partner, with one partner acting as a spotter. Work on a gym mat.

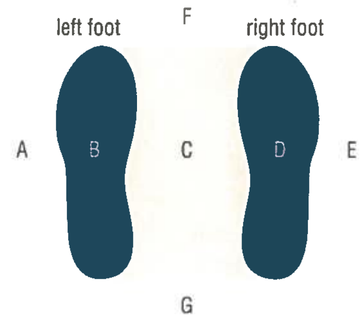


Figure 8

1. Refer to Figure 8. The region enclosed by the footprints is shaded and represents the support base of a person standing upright.
   - **(a)** Stand upright with your arms at your sides and your feet about 50 cm apart. Have your partner look at you from a place in front of position F. Above which point, A to G, does your body's centre of gravity feel like it is positioned?
   - **(b)** Slowly raise your right foot off the floor. Above which point, A to G, does your body's centre of gravity feel like it is positioned now?
   - **(c)** Stand erect with your feet together. Hold a heavy (but not too heavy) object in one hand near your stomach. With your partner still in front of position F, determine what happens to your body, especially to your hips, as you move the object out to one side (toward either A or E). Where does your centre of gravity appear to lie now?
2. **(a)** Stand sideways against a wall with the side of one foot pressed against the wall. *Slowly* raise the other foot off the floor. Describe what happens. Where is your body's centre of gravity relative to your support base?
   - **(b)** Stand with your back to the wall and your heels pressed against the wall. *Slowly* bend over to try to touch your toes. Describe what happens. Where is your body's centre of gravity relative to your support base?

A. Which provides greater stability, a high centre of gravity or a low one? Support your answer with an example.

B. Which provides greater stability, a small support base or a large one? What evidence supports your answer?

C. Explain the observations you made in step 2. (Hint: Think of how your centre of gravity moved with each position that you attempted.)

Conditions for Greatest Stability

Consider the sports car and the truck in Figure 9. The truck is more likely to tip over. The car has greater stability because of two features: it has a low centre of gravity, and it has a wide support base (when compared to its height). Objects with a low centre of gravity and a wide support base tend to be stable.

Figure 9 Which vehicle is more stable?

To maintain stability, the centre of gravity must lie directly over the support base. Stability decreases as the centre of gravity rises. If the centre of gravity rises higher and is no longer above the support base, the object will fall over. This is shown in Figure 10 for a truck going around a banked curve with different-sized loads. The truck on the far right will tip because its centre of gravity (the red X) lies outside of the two wheels.

LINKING TO LITERACY

Compare and Contrast

Good readers gain meaning from texts by analyzing the information they read. One way to analyze is to look for ways that information is the same or different. On this page, the author gives four examples of how stability works: trucks, boats, a bird, and an acrobat.

After you read this page, take a moment to reflect and analyze what you have read. How are these examples the same? How are they different?

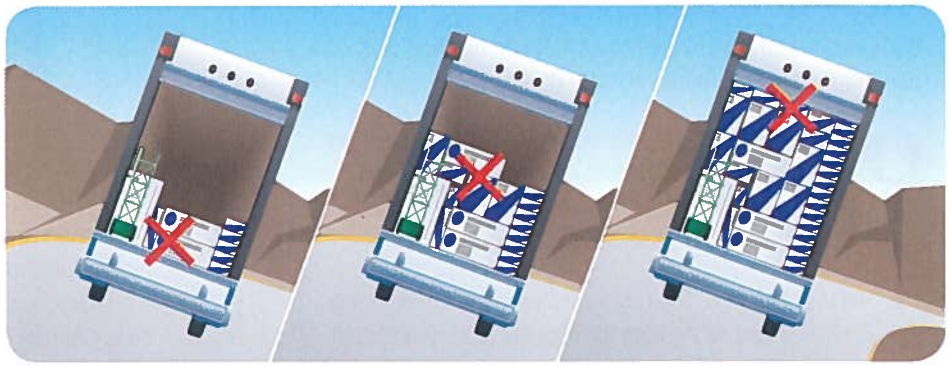


Figure 10 The truck is unstable when its centre of gravity does not lie above its support base.

Stability is also important for ships, boats, and canoes. Canoeists know how important it is to maintain a low centre of gravity. Standing in a canoe is dangerous. It raises the centre of gravity, and the canoe could easily tip over.

Examples of stability are also found in nature. The loon is a bird that is well adapted to water. The loon's feet help it to dive and swim quickly. However, on land, the loon is very awkward. Its centre of gravity lies ahead of its feet. The loon has to lean backward as it walks forward.

Thinking about how your own body reacts to external forces helps you to understand other structures. When you carry a backpack on your back, hold a suitcase by your side, or stand on your toes, your body has to adjust to help you keep stable. An acrobat walking on a tightrope applies a similar principle. The acrobat carries a downward curving pole that is heavy at both ends (Figure 11). The pole helps to lower the centre of gravity, and that means greater stability.

Figure 11 The long pole helps lower the acrobat's centre of gravity.

Unit Task How will you use what you learned about centre of gravity and stability when designing your playground equipment?

CHECK YOUR LEARNING

1. Describe how you would find the approximate centre of gravity of
   (a) a golf club
   (b) a framed painting
   (c) a coat hanger
   (d) a tennis racquet
2. State the location of the centre of gravity of
   (a) a golf ball
   (b) a bagel
3. What two features of an object provide good stability?
4. State the conditions needed for stability.
5. Which is more stable? Explain why in each case.
   (a) a turtle or a giraffe
   (b) the CN Tower or your school building

Making Structures Strong: The Beam

11.2

Many structures have similar features. You may have seen many bridges that look similar. You may also have seen many buildings being constructed that use similar features—most house frames look very similar, even if the finished house looks very different. One of the features common to many structures is the beam.

A **beam** is any reasonably level structure that is designed to support a load. The frame of a typical doorway consists of a horizontal upper beam and two vertical supports (Figure 1). One of the oldest beam structures was probably a log lying across the banks of a river—a log bridge. In this case, the log is a beam that is supported by the banks of the river.

beam: a horizontal structure designed to support a load

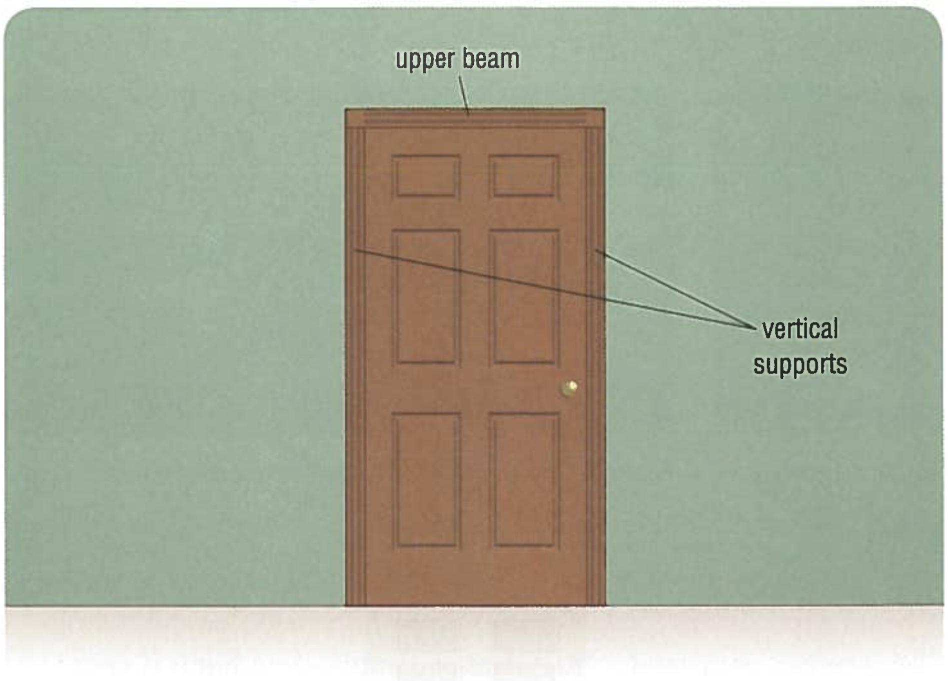


Figure 1 A typical doorframe is a beam structure.

Strengthening the Beam

On its own, a beam may not be able to support a large load. Some beams can bend or break if the load on them is too great. Beams can be strengthened in several ways. One way is to change the material that a beam is made of. A beam made of balsa wood is not as strong as one made of steel. Beams can be made out of many different materials, such as wood, stone, concrete, or steel, depending on the load requirements of the structure. Choosing the right material is an important factor in building a strong and stable structure. Steel is stronger than wood, but steel is also heavier. An engineer needs to consider both strength and mass when selecting the material for any structure.

LINKING TO LITERACY

Making Predictions

Prepare for reading by making a prediction about the information that will be explained or described on this page. Start by scanning the page for the most visible information: the title, subtitles, pictures, and margin information. Then, skim the first sentence of the first one or two paragraphs of the text.

What do these tell you about this text? What kind of information will be described or explained on this page?

Make a prediction about the text. As you read, confirm or change your prediction. Make new predictions about what will come next.

Making predictions will help to make reading informational text easier.

I-Beams

I-beam: a beam that is in the shape of the letter "I" when seen from the end

Another way to strengthen a beam is to change its form. A stronger beam shape is the **I-beam**. When you look at the end of an I-beam, it looks like the letter "I." I-beams are commonly used in the construction of buildings, including houses (Figure 2). Wooden I-beams, sometimes called I-joists, are now being used as the structural support for ceilings and floors in homes. These beams are much lighter than steel beams, but they can still support very heavy loads. They also make use of wood chips, rather than solid wood. This means that they could reduce the amount of trees needed in construction.

Corrugation

corrugation: multiple folds in a material that provide additional strength

Folding the beam also adds strength. Placing triangular ridges, grooves, or folds in a structure is called **corrugation** (Figure 3). Corrugation is common in cardboard boxes. Corrugation is applied to plastic and metal, particularly for roofing, to provide additional strength.

Figure 2 A steel I-beam is used to provide structural strength.

Figure 3 The corrugation in a steel roof provides added strength.

LINKING TO LITERACY

Reading for Meaning

Scientific words are defined or explained on this page: I-beam, corrugation, and rebar. What do these mean? How do these explanations help you to better understand your reading?

Rebar

Concrete beams are often strengthened with steel reinforcing rods. A beam experiences compression on top and tension on the bottom. Concrete can withstand a great deal of compression, but it is very weak when it experiences tension. Steel reinforcing bars called rebar are placed in the concrete to help it resist the forces of tension. Concrete that contains rebar is known as "reinforced concrete" and is able to resist both compression and tension (Figure 4).

Figure 4 Steel reinforcing bars (rebar) serve to strengthen concrete by allowing it to resist both tension and compression.

The Cantilever

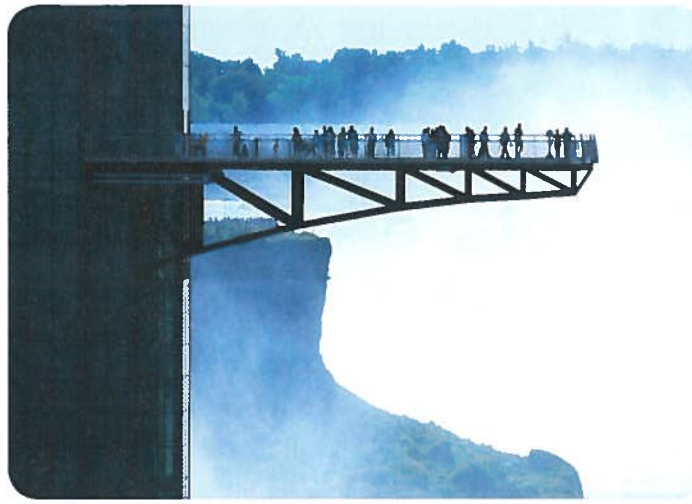


Figure 5 A cantilever is a beam that is supported at only one end.

cantilever: a beam supported at only one end

Beams are not always supported at both ends. A **cantilever** is a beam that is supported, or fixed, at only one end (Figure 5). A branch on a tree and a diving board are examples of simple cantilevers. Cantilevers are very common. Canopies over entrances to buildings and apartment balconies are also examples of cantilevers.

Cantilevers are useful in spanning great distances without the use of a central support. Cantilevers are used in areas where a central supporting structure would be unrealistic, such as over a deep gorge. Look at Figure 5. This cantilever is on the Observation Tower over the American Falls at Niagara Falls. Can you imagine trying to build a supporting structure at both ends of the cantilever at this location?

Supporting the Beam

Adding structural support also strengthens a beam (Figure 6). A tie is a structural support that is part of a framework and is designed to resist tension forces. A tie is usually set at an angle between a beam and its support base (the wall in this example). A strut is similar to a tie, but it is placed below a beam where it provides resistance to the forces of compression. A gusset is a flat, plate-like device, often triangular, that supports a beam by reinforcing the connection between the beam and its support base.

Figure 6 The tie, strut, and gusset add support to the beam.

Unit Task How will you use what you learned about the beam in the design of the playground equipment for the Unit Task?

CHECK YOUR LEARNING

1. Briefly describe four ways that a beam can be strengthened.
2. How is a cantilever different from a fully supported beam?
3. Provide two examples of cantilevers that you have seen in your neighbourhood.

11.3 CONDUCT AN INVESTIGATION

Factors Affecting a Structure's Ability to Support a Load

SKILLS MENU

- ☐ Questioning
- ☑ Hypothesizing
- ☑ Predicting
- ☐ Planning
- ☑ Controlling Variables
- ☑ Performing
- ☑ Observing
- ☑ Analyzing
- ☑ Evaluating
- ☑ Communicating

Imagine that you have to design a bridge to span a stream. What design provides enough strength but the least mass of materials? How can you perform a fair test to discover how factors affect the strength of a beam? In this investigation, you will develop answers to these and other questions.

Testable Question

How do the mass, shape, and form of a beam affect the beam's ability to support a load?

Hypothesis/Prediction

SKILLS HANDBOOK 2.B.3.

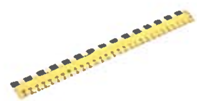
Read the Experimental Design and Procedure, and examine the figures to see the different beam designs you will be testing. Make and record a hypothesis about which design will be the strongest and which will be the weakest. Your hypothesis should include a prediction and reasons for your prediction.

Experimental Design

Your group will build six different beam "bridges." Four have the same mass, while the remaining two have twice as much mass. You will test each beam's strength by pulling down on its centre with a spring scale. Use as little masking tape as possible, and recycle the cardboard after completing the investigation.

Equipment and Materials

- ruler or metre stick
- scissors
- spring scale
- 2 stools or movable desks
- 8 pieces of file-folder cardboard
- masking tape
- string

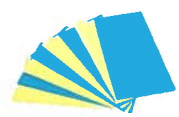


ruler or metre stick

scissors

spring scale

stools or movable desks



pieces of file-folder cardboard

masking tape

string

Be very careful when using sharp objects.

Procedure

SKILLS HANDBOOK 6.A.3., 6.D.1.

1. Mark and cut out eight pieces of cardboard, 24 cm long × 12 cm wide. Draw lines on five of the pieces of cardboard, and fold the cardboard as shown in Figure 1 on the next page. Tape the edges together to close the beam. Make three flat beams, one triangular beam, one cylindrical beam, and two rectangular beams.

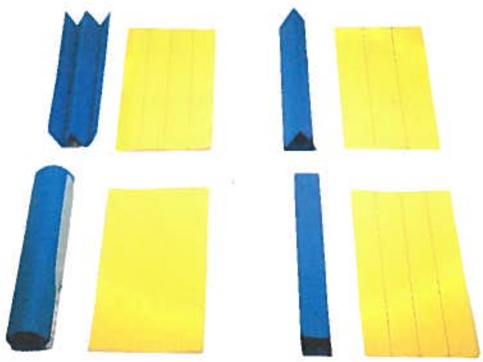


Figure 1 The four beam designs

2. Design a table to record the measurements taken during the tests you will be performing.
3. Set up a single flat beam as a bridge supported at the ends by two stools or desks separated by 18 cm. The overlap at the ends of the beam should be equal. Tie a loose loop of string around the middle of the beam. Suspend the spring scale from it. As you read the force on the scale, very gently pull straight down until the beam fails (Figure 2). Record the force that caused the failure.

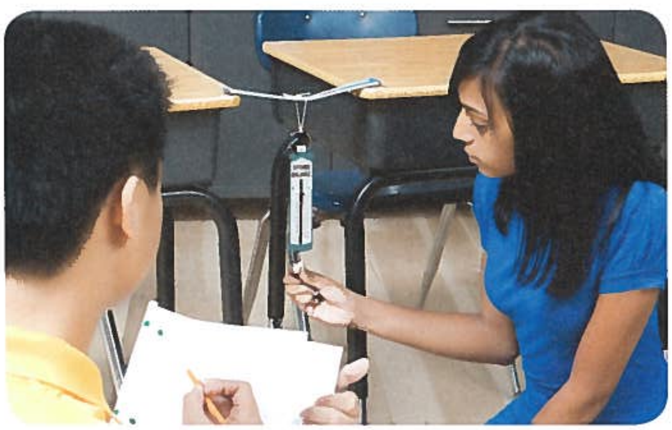


Figure 2 Setup for testing the strength of a beam bridge

4. Tape two flat beams together to double the mass. Repeat the test in step 3.
5. Repeat step 3 for the triangular beam, the cylindrical beam, and a rectangular beam.
6. Mark and cut the last piece of cardboard into four equal strips 24 cm long and 3 cm wide. Fold these strips width-wise. Tape them together to form a corrugated row about 24 cm long. Place this row into the second rectangular beam (Figure 3). Use tape to secure it to the ends of the beam. Close the sides of the beam, and tape the edges that meet. Test this beam as you did in step 3.

Figure 3 Reinforcing a rectangular beam

Analyze and Evaluate

(a) Rank the beams in order of weakest to strongest.

(b) Describe three independent variables you tested in this investigation. State how each variable affected the beam's ability to support a load.

(c) Answer the Testable Question.

(d) About how many flat (or solid) beams would be needed to provide the same strength as a single reinforced rectangular beam? How would the masses compare?

Apply and Extend

(e) If you were allowed four 24 cm × 12 cm pieces of cardboard, what design would you use to maximize a beam's strength? Draw a sketch of your design.

(f) Metal support beams are made in the shape of a capital L or a capital I. Describe the advantages of this design.

11.4 Making Structures Strong: The Truss, Arch, and Dome

Designers sometimes want to use shapes other than beams to make structures stronger and more interesting looking. They can do this by adding triangles (trusses) or curves (arches and domes).

The Truss

truss: a network of beams arranged in triangles

A **truss** is a network of beams that form triangles. A truss can be used as a bridge or a cantilever, and for many other applications. In the following Try This activity, you will learn how trusses can be strengthened and how their mass can be reduced.

TRY THIS: Building and Testing Trusses

SKILLS MENU: **performing, observing, analyzing, communicating**

SKILLS HANDBOOK 4.C.1.

In this activity, you will learn how to build trusses and reduce their mass while maintaining their strength. You will test for strength, not for failure, by gently pushing on your structures. In each step, record your observations.

Equipment and Materials: 11–15 equal-sized strips of stiff cardboard or large craft sticks with a small hole drilled near each end; paper fasteners (brads); string

1. Construct a four-piece structure using cardboard and fasteners (Figure 1(a)). With the structure resting upright, determine how sturdy it is.
2. Add a fifth component to create a bridge truss made of two triangles (Figure 1(b)). Place the truss to span a small space between two textbooks. Gently test how sturdy this truss is, but *do not* break it.
3. Make a larger truss using the triangular design (Figure 1(c)).
   (a) Test the sturdiness of the truss as a bridge spanning a space.
   (b) Test the sturdiness of the truss when used as a cantilever (over the edge of a book).

Figure 1 Structures used in steps 1 to 3

4. Reduce the mass of your truss bridge by replacing beams with pieces of string (Figure 2). Start by replacing one beam, and then two beams, and so on. Draw a diagram of your final design. Gently test its strength.

Figure 2 Reduce the mass of a suspended truss

5. Turn over the truss you made in step 4. Describe what happens to its sturdiness.
6. Put the long truss back together and support it at one end only (as a cantilever). Discover how to reduce the mass of the cantilever by replacing at least one beam with string (Figure 3). Draw a diagram of the cantilever truss with the least mass.

A. What basic form provides a truss with strength?

B. How can a spanning truss be reduced in mass while maintaining strength?

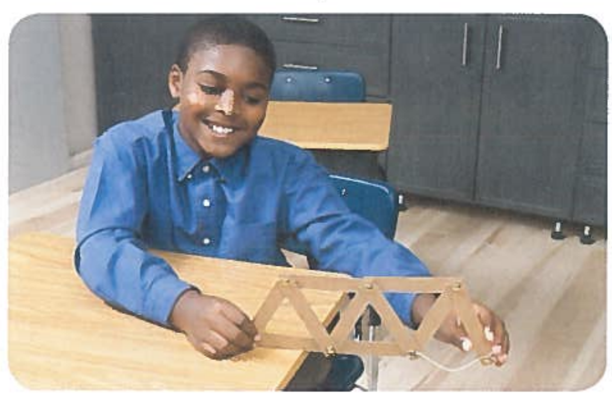


Figure 3 Reduce the mass of the cantilever

Most people are familiar with the trusses used in the roofs of home construction (Figure 4). You can see examples of trusses in many places. Construction cranes, communication and hydro towers, bridges, and the International Space Station all contain trusses.

Trusses can be bent or curved and still retain their strength (Figure 5). Trusses take advantage of the strength of triangles to make structures strong. In a truss, forces are distributed between the points of the triangles that make up the truss. The triangles help the structure support more weight. Notice the complex truss structure that makes up the circle of the Ferris wheel. A beam used in this application could be too heavy. Remember that the structure needs to support its own weight as well as the weight of the passengers. Using trusses allows for different structural designs. Trusses can be used for applications that other types of supports, such as beams, cannot be used for.

Figure 4 Trusses are used in the construction of many structures.

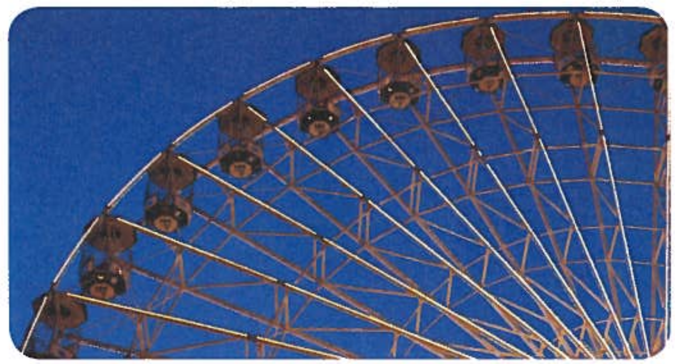


Figure 5 Trusses provide strength to this Ferris wheel.

The Arch

An **arch** is a curved structure often used to support loads. Arches are used in spaces where supporting beams are not practical. Such spaces include doorways or windows, bridges, or places of worship. An arch's curved design transfers compression force downward (Figure 6). Like the beam and the truss, the arch is one of the basic components of structures.

arch: a curved structure used to span a space while supporting a load

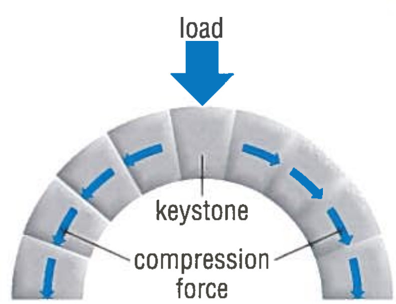


Figure 6 The arch transfers compression force downward from each stone to the next.

Many early civilizations, such as the Romans, used the arch when building structures. Some of the arches that the Romans built over 2000 years ago are still standing. Today, arches are still used to span long distances (Figure 7).

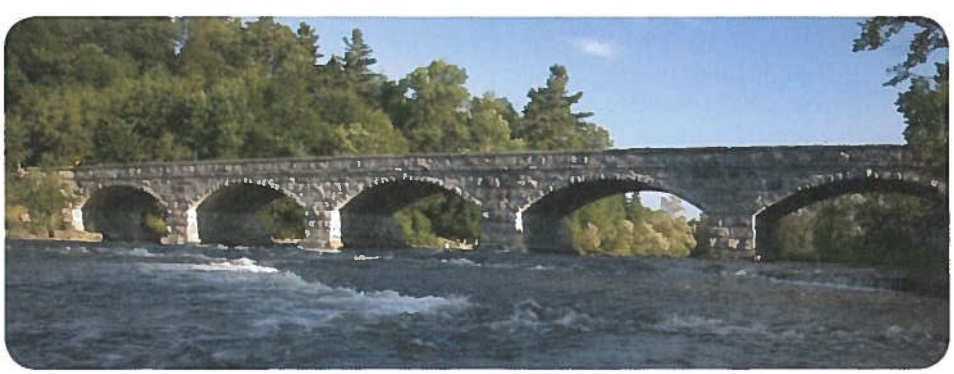


Figure 7 Arches can be used to make bridges stronger.

The Dome

dome: a shell structure that looks like the top half of a sphere

A **dome** is a structure that looks like the top half of a sphere or an egg. Like an arch, a dome directs compression force downward. In an arch, the compression force occurs in only one plane of application (Figure 8). However, in a dome, the compression force is directed downward in many planes at once (Figure 9). You could consider a dome to be a series of arches that have been connected at a centre point.

Figure 8 The compression force on this arch is directed downward in a single plane.

Figure 9 The compression force on this dome is directed downward in many planes at once.

Domes are popular structures because they are strong and can still enclose a large volume of space. Planetariums, churches, mosques, and many stadiums use domes in their design (Figure 10).

Figure 10 The Pantheon in Rome, Italy, is an example of a dome.

Unit Task Will you be able to use trusses, arches, or domes in your playground design for the Unit Task?

CHECK YOUR LEARNING

1. What are some advantages of using trusses?
2. List four examples of structures that use trusses.
3. Describe the similarities and differences between arches and domes.
4. Explain how compression forces are different in arches and domes.

Tech CONNECT

Carbon Nanotubes

Carbon nanotubes are made of a single layer of carbon atoms. The atoms are arranged in a hexagonal (six-sided) shape (Figure 1). They are 10 000 times thinner than human hair but stronger than steel! Their light weight and extreme strength make them ideal for structures that will face extreme conditions.

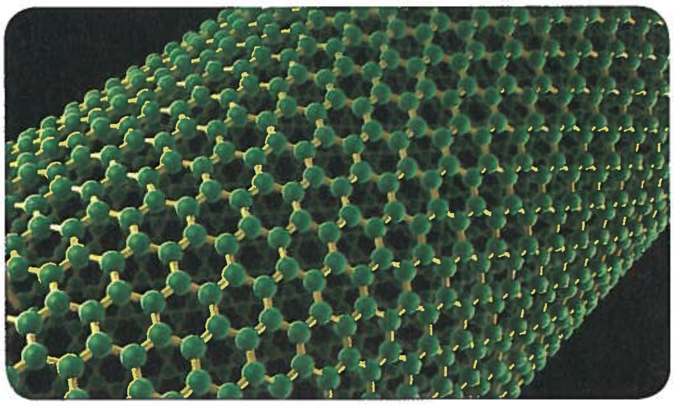


Figure 1 This diagram of a carbon nanotube shows its hexagonal structure.

Carbon nanotubes (Figure 2) have great potential in many areas, from designing sports gear to fighting infection in medicine. Carbon nanotubes can be used to build better and smaller electrical circuits. These circuits operate on the level of the individual particles of matter. Nanotube technology has even been developed to make solar power more efficient. Microscopic solar cells can be applied to flexible plastic sheets and stuck on windows, skylights, and car windshields. Someday, even house paint may contain energy-collecting nanotubes!

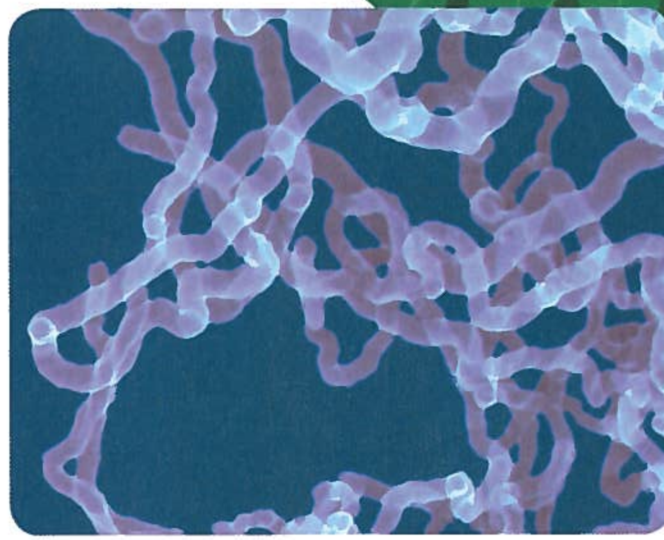


Figure 2 Actual carbon nanotubes that have been magnified 40 000 times in an electron microscope

Fibres made of carbon nanotubes may be the first commercial application of nanotube technology. These super-strong fibres could be used in vehicle armour for Formula 1 racecars and bodysuits for racecar drivers. Nanotubes could be used in other woven fabrics and textiles that would face extreme conditions, such as protective equipment for sports.

To learn more about carbon nanotubes,
Go to Nelson Science

LINKING TO LITERACY

Synthesize

Readers synthesize information by summarizing what they have read and making connections, or thinking creatively to draw a conclusion, come up with a new idea, or think about information in a new way.

Summarize your reading about carbon nanotubes. Make a connection to a similar science text you have read. What conclusions can you draw? How else might nanotubes be used? How might nanotubes be similar to or different from other technology?

Design a Scaffold

In this activity, you will consider as many of the ideas you have learned as possible as you design, build, and test a structure that is efficient and useful at supporting a load. To be efficient, a structure must be low in mass but high in strength. To be useful, a structure must be both stable and safe.

SKILLS MENU

- Identify a Problem/Need
- Planning
- Selecting Materials and Equipment
- Designing
- Testing
- Modifying
- Communicating

Scenario

At summer camp, your group has been assigned the task of painting the outside of your cabin. To make the painting easier and safer, you decide to design a scaffold. The scaffold must be strong and stable, yet light enough to move from one location to another (Figure 1). It should also have steps at one end to allow you to safely climb up to the main platform. Your group will design, build, and test a scale model of a scaffold that is 3 m long × 1.5 m high × 0.75 m wide.

Figure 1 How will the features of your scaffold compare to the features of the scaffold shown here?

Design Brief

In this activity, you will work in a small group to build a scale model of the scaffold described in the Scenario. The model will be free-standing and will have a set of steps at one end. Using a scale of 1 cm to 10 cm, your model will be 30 cm long × 15 cm high × 7.5 cm wide. As a class, you will decide on the types of materials allowed.

You will try to apply as many of the ideas as possible from earlier in Chapters 10 and 11 to design a scaffold with a low mass. Then, you will test the steps at the end of the scaffold, one at a time, to see if each one can hold a 500 g mass without breaking or becoming unstable. You will also test the scaffold to see if it can safely hold a 4 kg mass in the middle without breaking or falling over. You will then determine the efficiency of the model by dividing the live load mass (4000 g) by the dead load mass. (As an example, a 100 g scaffold that supports a 4000 g load before breaking is quite efficient, but a 500 g scaffold that supports the same load is inefficient.)

Equipment and Materials

- eye protection
- apron
- scissors
- hand drill
- screwdriver
- 4 kg mass
- 500 g mass
- spring scale
- ruler
- construction materials
- fastening materials


eye protection


apron


scissors

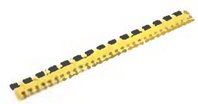

hand drill


screwdriver


4 kg mass


500 g mass


spring scale


ruler


construction materials


fastening materials

Research and Consider

Review what you have learned in this unit.

- What type of structure (solid, frame, shell, or combination) would be best for an efficient scaffold made of simple materials?
- How can a span (the top of a scaffold) be reinforced without adding too much extra mass?
- What design will ensure that the scaffold remains stable even if a person walks up the steps at one end of the scaffold?

Use these notes, research, and brainstorm with others to generate ideas. You may wish to use the Internet to see designs of different scaffolds. Make sketches of different designs that you might use.

Go to Nelson Science

Plan and Construct

SKILLS HANDBOOK 4.B.2., 4.B.4.

1. In your group, choose the model that you will use from your brainstorming sessions. Make a working drawing of your best choice.
2. Create a step-by-step plan for building your scaffold. Include a list of materials you will use and equipment you will need.
3. Finalize your plan and have your teacher check it.
4. Construct your model.
5. Determine the model's mass in grams by hanging it from a spring scale.

Test and Modify

SKILLS HANDBOOK 4.B.5., 4.B.6.

Test your scaffold to see if each step can hold a 500 g mass without breaking and without causing the scaffold to tip. Then, test the main part of the scaffold to see if it can hold the 4 kg mass in the middle without breaking. If necessary, modify the design, and find its new mass. Perform the same tests for strength and stability. Keep a written record of the modifications you make and the results of these modifications.

Evaluate

Compare the performance of your scaffold with the criteria in the Design Brief. Answer the following questions:

1. How strong and stable was your scaffold when you first tested it?
2. What modifications did you make or would you make next time to create a stronger and more stable structure?
3. How did the efficiency of your scaffold compare to the efficiencies of the other scaffolds in class?

Communicate

Prepare a report to describe the final design of your scaffold. Include a detailed diagram and any calculations you made.

11.6 Structural Failure

structural failure: the failure of a structure as a result of the structure, or part of the structure, losing the ability to support a load

An umbrella bends out of shape in a wind gust (Figure 1). A suitcase handle breaks. A bridge collapses. A drinking glass cracks (Figure 2). These are examples of structures that have failed. **Structural failure** occurs when a structure, or part of a structure, loses the ability to support a load. Once the structure loses its load-carrying ability, it cracks, deforms, or even collapses completely. There are many reasons why a structure can fail.

Figure 1 Structural failure of an umbrella from a gust of wind

Figure 2 Structural failure of a drinking glass

Bad Design

Approximately 40 % to 60 % of all structural failures are due to bad design. Bad designs can be caused by design errors such as failure to account for load, specifying incorrect materials, or not considering important factors and stresses.

On January 28, 1986, just 73 s after takeoff, the space shuttle *Challenger* exploded (Figure 3). All seven crew members were killed. The explosion was caused by a gas leak when an O-ring failed. An O-ring is a circular piece of plastic or rubber that stops water or gases from escaping. An O-ring is usually in a connection between two pipes (Figure 4). In the case of the *Challenger*, the weather in Florida was unusually cold. The cold O-ring failed and caused the gas leak that led to the explosion.

To learn about *Challenger* Learning Centers,
Go to Nelson Science

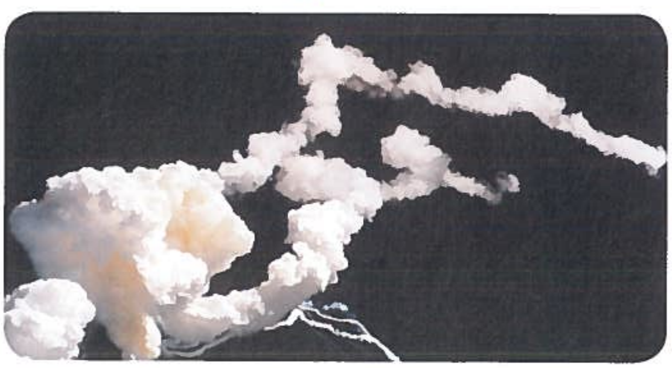


Figure 3 The explosion of the *Challenger* as a result of the failure of an O-ring

Figure 4 Inside the end of a garden hose is a round washer. This flexible washer works in a similar way to an O-ring.

TRY THIS: Observe the Effect of Temperature

SKILLS MENU: observing, communicating, analyzing

SKILLS HANDBOOK 7.B.

Different materials change at different temperatures. Materials can become more brittle at some temperatures and more flexible at other temperatures. In this activity, you will observe the effect of temperature on elastic bands.

Equipment and Materials: 2 bulldog paper clips; 2 identical elastic bands; 2 small bowls or glasses; 250 mL warm water; 250 mL ice water

1. Fold each elastic band in half and clamp it with a bulldog clip.
2. Place one elastic band and clip in the cup of ice water. Place the other elastic band and clip in the cup of warm water (Figure 5).
3. After 5 min, remove the elastic bands and bulldog clips from the water.
4. Remove the clips from the elastic bands. Examine the elastic bands. Using a graphic organizer of your choice, compare the size, shape, and texture of the two elastic bands.

Figure 5

A. What did you observe about the elastic bands? Write a brief report of your observations.

B. In small groups, discuss how the results of this activity may relate to the O-ring failure in the space shuttle *Challenger* disaster.

Faulty Construction

Faulty construction is the second most common cause of structural failure. Construction errors can result from the use of poor quality materials, poor installation from either sloppiness or lack of expertise, or a combination of these. For example, homeowners are aware of how easily shingles are blown off a roof in windy conditions. This is a bigger problem if the shingles were poorly installed by not securing them correctly with the right type of nail (Figures 6 and 7). Using the wrong nail for the job can mean the difference between a roof that lasts for 20 years and one that fails on the first windy day.

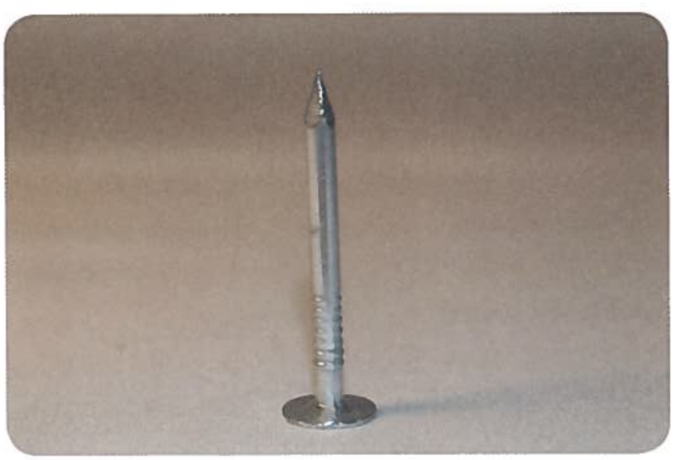


Figure 6 A roofing nail is rustproof and has a large head and a notched shank to hold down the shingles in windy conditions.

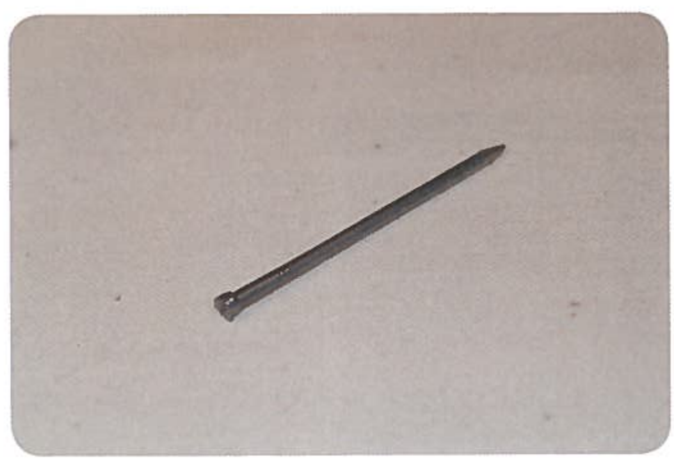


Figure 7 A finishing nail has a smooth shank and smaller head that is less visible on wood trim around doorways or cabinets. What would happen if a worker used finishing nails for roof shingles?

Faulty construction can have tragic consequences. The Sampoong Department Store (Figure 8) in Seoul, South Korea, collapsed on June 29, 1995. The collapse killed 501 people. An investigation of the disaster showed that the construction materials were inadequate, and that the installation and building methods were poor. The government allowed the structure to pass inspections that it should have failed. The chairman of the building was charged with negligence for his disregard for public safety. Several government officials were also charged with accepting bribes to conceal the building's flaws.

To learn more about the Sampoong Department Store collapse,
Go to Nelson Science

Figure 8 The remains of the Sampoong Department Store after its collapse

Extraordinary Loads

Extreme conditions can also result in structural failure. Often these failures are not the result of poor design, but the result of unexpected events that create extraordinary loads on structures.

In January 1998, North America experienced a massive ice storm. For days, parts of Ontario, Québec, Nova Scotia, New York, and Maine were drenched with freezing rain. The rain coated everything with a 120 mm–thick layer of ice. About 130 transmission towers were crushed under the weight of the ice (Figure 9). More than 4 million people in Québec, Ontario, and New Brunswick had no electricity. Some people had no electricity for more than a month. At least 25 people died, many of them from the cold.

To learn more about the 1998 ice storm,
Go to Nelson Science

Figure 9 Transmission towers toppled from the weight of the ice. Previously, the worst ice storm on record was in 1961. In that case, only 60 mm of ice accumulated and lasted only a day or two.

Foundation Failure

Failure of a structure's base, or foundation, is less common than bad design and faulty construction. However, it can also lead to significant structural problems. Foundation failure can be caused by poor soil conditions, poor installation, a foundation that is not large enough for the load of the structure, or earthquakes.

A well-known example of foundation failure is the Leaning Tower of Pisa in Italy (Figure 10). The tower was built in 1178 on sandy, unstable soil with an inadequate foundation. The soil shifted and the tower began to lean almost right after construction began. Over the centuries, the tower leaned more and more. Modern construction methods have finally slowed down the movement of the tower and returned it to the angle at which it was leaning in 1870.

To learn more about the Leaning Tower of Pisa,
Go to Nelson Science

Figure 10 The Leaning Tower of Pisa

Foundation failure is more common in smaller buildings. Cracks in the walls of a house or misaligned doors are often the result of a house's foundation shifting due to poor soil conditions. However, any structure can shift as a result of a poor foundation.

Unit Task How can you use what you have learned about structural failure in your Unit Task?

CHECK YOUR LEARNING

1. (a) List four possible causes of structural failure.
   (b) Identify a structural failure that occurred on account of each of the four causes.
   (c) Suggest one way in which each of the structural failures in (b) could have been prevented.
2. A 12-year-old student sits on a child's tricycle and one of the rear wheels breaks off.
   (a) What was the most likely cause of the structural failure?
   (b) How could this failure have been prevented?

Preventing Structural Failure

Structures are designed to certain specifications to fulfill their purpose. Safety is an important component in the design and use of structures. Engineers use several methods to ensure structural safety so that the design serves its purpose.

SKILLS MENU

- ☐ Identify a Problem/Need
- ☐ Planning
- ☐ Selecting Materials and Equipment
- ☐ Designing
- ☐ Testing
- ☐ Modifying
- ☐ Communicating

Scenario

You are the chief designer for Design Construction Ltd. The company relies on you to make sure that the structures they build meet their design requirements and are also safe. Your firm has entered a design competition for a new building. Your team will build and test a model of a structure that incorporates features that help prevent structural failure.

Design Brief

In this activity, you will work with a partner to build the tallest, most stable structure possible. Use only three sheets of newspaper and 75 cm of masking tape to build a model. You must anchor the structure to the ground. Your structure must be able to withstand the force of the wind from a fan on high power that is placed 1 m from the tower without falling over or irreversibly buckling. If the structure topples over then it has failed the test. Your structure may buckle a little bit, but if it buckles so much that the form of the structure changes permanently, then your structure has failed.

Use several techniques to ensure the safety of your design. Create a sensor using a party streamer to determine where your structure might fail.

Equipment and Materials

- electric fan
- calculator
- scissors
- 3 sheets of newspaper
- masking tape
- party streamers

electric fan

calculator

scissors

3 sheets of newspaper

masking tape

party streamers

Be very careful when using sharp objects.

Research and Consider

Use the Internet and other resources to investigate how

- wind tunnel testing is used to check a structure's integrity (The fan at 1 m will be acting as your wind tunnel.)
- structures are over-engineered with a factor of safety so that they can withstand greater forces than anticipated
- sensors can be used to detect early warnings of failure

Go to Nelson Science

Plan and Construct

SKILLS HANDBOOK 4.B.4., 4.C.

1. Using what you have learned in this unit and from your research, design a few different structures. Remember the design requirements in the Design Brief.
2. Choose the sketch that you think will be the most stable.
3. Write a step-by-step plan for creating your design. Be sure to include a scale drawing of your structure.
4. Use party streamers to act as sensors (Figure 1). Cut the streamer with a narrow centre so that it will fail with very little force.

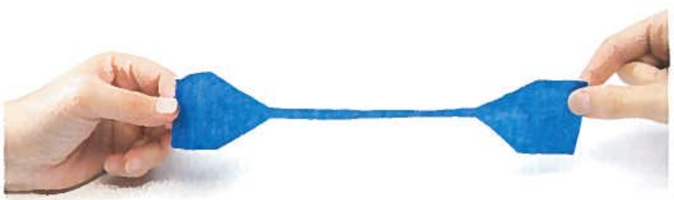


Figure 1 Use party streamers with narrow centres in your design.

5. Finalize your plan and have your teacher check it.
6. Construct your design.

Test and Modify

Test your structure to see if it is successful. Make any necessary modifications, and then retest your structure. Continue to improve your design. Now, test how well your design exceeds its engineering requirements by measuring the exact point of failure of the structure. Slowly slide the fan from its 1 m test position toward your structure until your structure fails. Measure this distance in centimetres. You may want to modify your structure again to improve the over-engineering in its design.

Evaluate

1. If your first structure failed the wind tunnel test, explain what design flaw may have led to that failure.
2. What design modifications did you make as a result of your tests?
3. Why were you asked to use sensors in your tests? How did you incorporate the sensors to create a good indicator of early failure?
4. Your tower has a design requirement to be stable in a wind at a distance of 1 m. Determine how much over-engineering was built into your tower by calculating the factor of safety for your final tower:

   Factor of safety = 1 m ÷ (distance in centimetres between fan and tower at failure)

   Hint: Convert 1 m to 100 cm before calculating the factor of safety.
5. Do you think your factor of safety was large enough for a safe design? Explain.
6. Would a tower with a factor of safety less than 1 be considered a safe structure? Explain.
7. Compare the factors of safety for all the towers in the class. Did the tower with the highest factor of safety also have the greatest height? Why or why not?
8. Can you think of other materials or designs that you could use to make your sensor more effective?

Communicate

SKILLS HANDBOOK 4.B.7.

Prepare a one-page report that describes the final version of your model, and how successfully it meets the design requirements. Include your factor of safety calculation, how you used the sensors to detect early failure, the height of your tower, and an accurate diagram of the final version of the model that you used.

CHAPTER 11 SUMMARY

Structural Strength and Stability

BIG Ideas

- ☐ Structures have a purpose.
- ☑ **The form of a structure is dependent on its function.**
- ☑ **The interaction between structures and forces is predictable.**

Looking Back

A stable structure maintains its shape and position over an extended period of time.

- A structure's centre of gravity affects its stability.
- Objects with a low centre of gravity and a wide support base tend to be stable.

Beams, trusses, arches, and domes are used to help structures support loads.

- The beam can be strengthened by changing its shape or composition (for example, I-beam, corrugation, rebar) or by adding supports (for example, tie, strut, gusset).
- The cantilever is a beam supported at only one end.
- In a truss, force is distributed through the structure at the points of contact of the triangles.
- An arch's curved design transfers compression force downward into the ground.
- A dome is a structural element that looks like the top part of a sphere. Like an arch, a dome also transfers compression forces to the ground.

The skills of scientific inquiry can be used to investigate the factors that affect the ability of a structure to support a load.

- Models can be used to determine how well structures support a load.
- The shape, mass, and form of a structure affect how much force a structure can support.

The skills of technological problem solving can be used to determine the most efficient way for a structure to support a load.

- Using structural supports and different construction materials can make a structure more efficient.
- The efficiency of a structure can be calculated by dividing the live load mass by the dead load mass.

Structural failure occurs when all or part of a structure loses its ability to support a load.

- Structures can fail due to factors such as bad design, faulty construction, extraordinary loads, and foundation failure.
- Many structural failures can be linked to human error.

VOCABULARY

stability, p. 290
centre of gravity, p. 290
beam, p. 295
I-beam, p. 296
corrugation, p. 296
cantilever, p. 297
truss, p. 300
arch, p. 301
dome, p. 302
structural failure, p. 306

The skills of scientific inquiry can be used to investigate methods used to ensure that structures are safe.

- Research skills can be used to learn more about the methods that engineers use to ensure that structures are safe.
- Technological problem-solving skills can be used to model safety tests that engineers use when designing and building structures.

CHAPTER 11 REVIEW

The following icons indicate the Achievement Chart categories: K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

What Do You Remember?

1. In your notebook, match each definition in the left-hand column of Table 1 with the most appropriate word from the right-hand column. K/U

Table 1

Definition	Term
(a) a beam supported at only one end	arch
(b) folding a material repeatedly to provide additional strength	rebar
(c) steel rod used to reinforce concrete	truss
(d) looks like the top part of a sphere	cantilever
(e) a curved structure used to support a load, or make an opening in a bigger structure	dome
(f) a network of beams that form triangles	corrugation

2. Distinguish between a simple beam and a cantilever. Provide two examples of each. K/U

What Do You Understand?

3. (a) Why are trusses so useful in structures?
   (b) List three structures that make use of trusses. K/U
4. (a) Use a Venn diagram to compare the arch and the dome.
   (b) Provide two examples of each from your home, your school, or your community. K/U A
5. (a) Why is regular maintenance important for the safety of structures?
   (b) Provide an example of regular maintenance of a structure that helps ensure safety. K/U A
6. "Human factors are the most common cause of structural failure." After reading this chapter, what do you think is meant by this statement? K/U
7. A student is leaning back in a chair. Eventually, the student falls over backward. Explain what happened using the terms "force," "centre of gravity," and "stability." K/U T/I
8. What are three factors that can affect a structure's ability to support a load? Provide an example of structural success and structural failure for each of these three factors. K/U
9. "Corrugation is just a series of connected arches." Do you agree with this statement? Explain. K/U
10. Consider the picture of the Eiffel Tower in Figure 1. What basic form is the Eiffel Tower? What structures can you identify in the tower? K/U A

Figure 1

11. Research in the library or on the Internet the shapes of traffic and subway tunnels. What is the most common shape of tunnels? Why do you think this is so? K/U T/I A

Go to Nelson Science

12. Why is rebar so common in the construction of structures using concrete? K/U

Solve a Problem!

13. Study the picture of the car in Figure 2.
    (a) Identify what structural form the cabin of the car most resembles. Why did engineers use this form?
    (b) Is this the best form to use for the cabin of a car? Why or why not?
    (c) Suggest an alternative form for the cabin of a car. Why did you choose this alternative? K/U T/I A

Figure 2

14. In the library or on the Internet, research the Quebec Bridge disaster in 1907 (Figure 3). What was the cause of its collapse? Suggest design changes that could have prevented the collapse. T/I A

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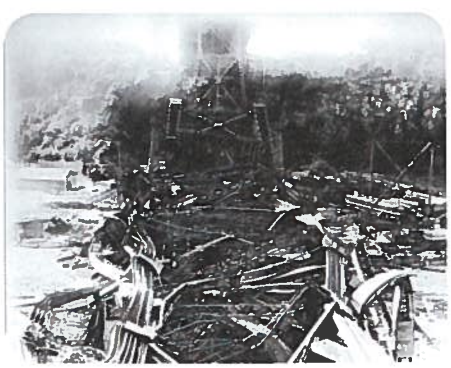

Figure 3

Create and Evaluate!

15. Most countries have building codes. These are laws that determine how certain structures should be built to withstand forces. Should building codes differ from country to country or from region to region within a particular country? Why or why not? T/I A

16. In 1999, an apartment building in Foggia, Italy, collapsed, killing 67 people.
    (a) Why might this collapse have occurred?
    (b) Tenants had complained for years about cracks in the walls. What kind of internal forces were probably acting on this building that ultimately led to its collapse?
    (c) Use the Internet and other sources to find out what caused the apartment to collapse. Could this catastrophe have been prevented? Explain.
    (d) Write your findings in a brief letter addressed to the mayor of Foggia. K/U T/I

Go to Nelson Science

Reflect On Your Learning

17. (a) Which concepts in this chapter did you find easy to understand? Explain.
    (b) Which concepts in this chapter did you find difficult to understand? Explain.
    (c) Name two things you could do to help you understand these concepts better.
18. The beam and the arch are two basic building components used to construct structures.
    (a) Were you surprised to learn that these components have been used for thousands of years? Explain.
    (b) Look at the structures around you and examine them for either the beam or the arch. Does this knowledge change how you view familiar structures? Explain your thinking on this.
19. Think back to the Key Question on the first page of this chapter.
    (a) In a brief paragraph, answer the Key Question. You may use diagrams.
    (b) Write one or two more questions about the topic of this unit that you would like to explore.