Chapter Di: Arches – The Science of Arches

AIMS & OBJECTIVES

- To introduce the arch bridge
- To learn that one way to make bridges stronger is to dissipate the forces

CONTEXT

Arches can be seen all around us. Gates, doors and windows are often shaped like arches. This is because an arch is considered to be one of the most beautiful shapes to build with and it is certainly one of the strongest. When the arch was first introduced in ancient times it was a great leap forward. Before the arch, there were mostly beam bridges but building the necessary piers in water was hard and it could be difficult for boats to pass underneath. Arch bridges solved this problem because they can be built higher than beam bridges, allowing tall boats to pass underneath.

LANGUAGE OF BRIDGES:

Abutment: the structure that the ends of the bridge rest on and can be anchored by.

Arch: semi-circular curved structure.

Beam: the simplest form of bridge, consisting of a single span resting on abutments.

Compression: a force that tries to make things shorter or smaller (a squashing, pushing force).

Keystone: the most important, wedge-shaped stone in the very centre of the arch.

Piers: the upright columns that support the bridge.

Span: the distance between bridge supports.

Tension: a force that tries to make things longer (a stretching, pulling force).

Total span: the full distance, from one side to the other, the bridge covers.

Voussoir: the special wedge-shaped pieces used in stone arches.

You will need...

Engineers have developed different types of bridges for different purposes. Here, we will learn about arch bridges and why they can be really useful.

- Handout: *Arch bridge terminology*
- Handout: *Forces in an arch bridge*
- Handout: *Arch bridge shapes template*
  - Scissors
  - Pens/pencils
- Exploring arch strength, per group:
  - Thick card (enough to cut into at least one 5x35cm strip, one 5x25cm strip and two 5x10cm strips as a minimum)
  - Scissors
  - Sticky tape
  - Ruler
  - Heavy books/supports, to act as abutments
  - Coins/washers/small masses as loads for testing

Something to Try:

INTRODUCING ARCH BRIDGES

Ask the learners to hold hands and lean out until they achieve balance. Encourage them to feel the tension in their arms.

TENSION

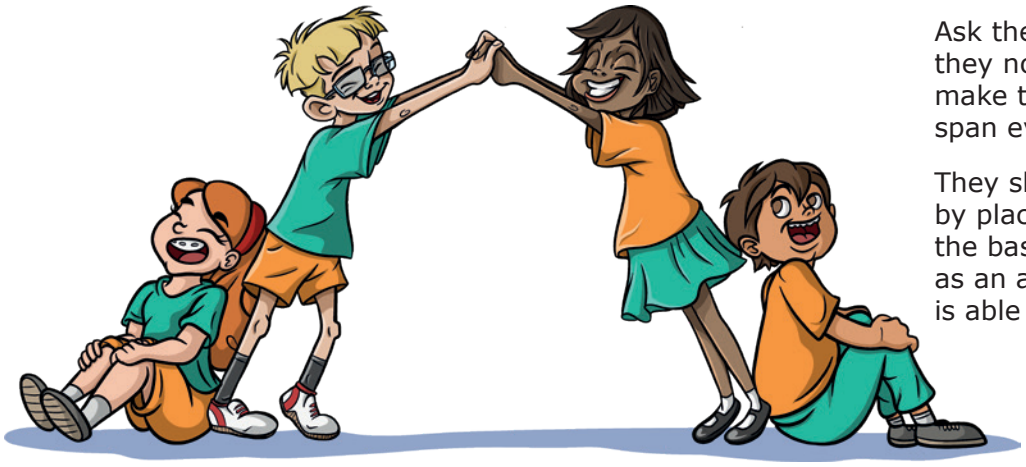
Links to *Learning About Bridges Chapter Aii: Loads and Forces*

Ask the learners to stand up in pairs facing each other with palms together to form a human bridge. Ask them to feel how much they need to push to make their bridge balanced, strong and steady.

Now ask them to (carefully) gradually increase the span by moving their feet further apart until failure occurs. Encourage them to express the view that there is a limit to how long the span of the bridge can be.

COMPRESSION

Now ask the pairs to join another pair, forming a group of four. Ask one pair to continue to create a human arch, by standing facing each other with their palms together, making the arch span as wide as possible without failing, while asking the other pair acts as abutments either side.

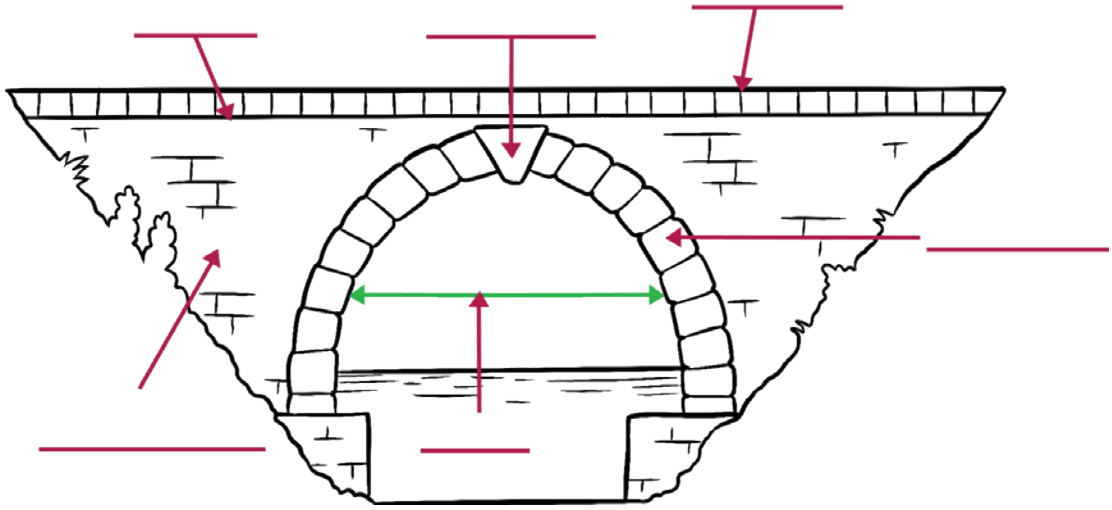


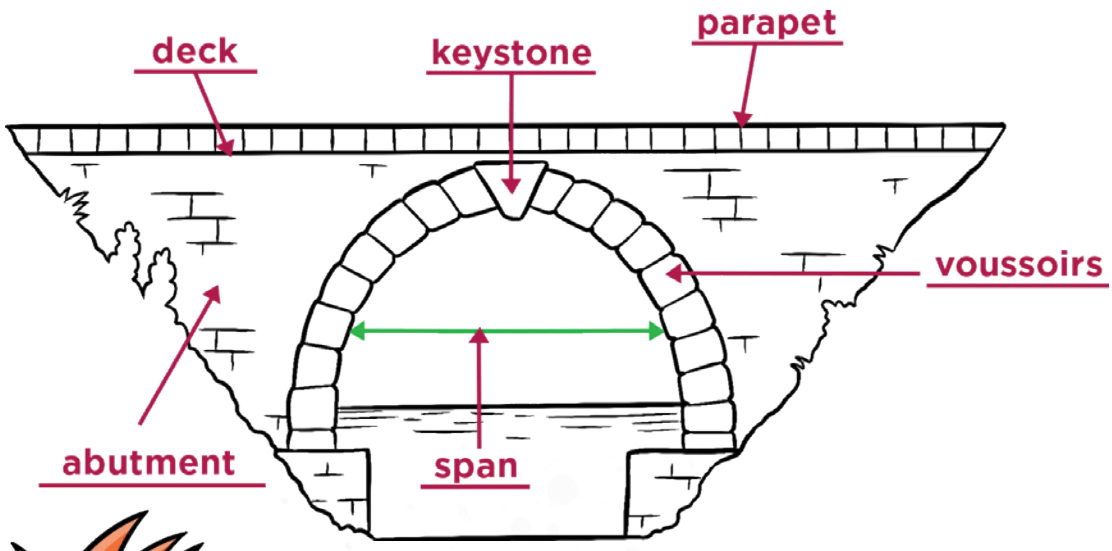
Ask the learners what they notice – can they make their arch bridge span even further?

They should realise that by placing a firm object at the base of the arch, such as an abutment, the arch is able to reach further.

THE LANGUAGE OF BRIDGES

Give learners a copy of *Arch bridge terminology* handout, and ask them to try to label the different parts of an arch bridge.

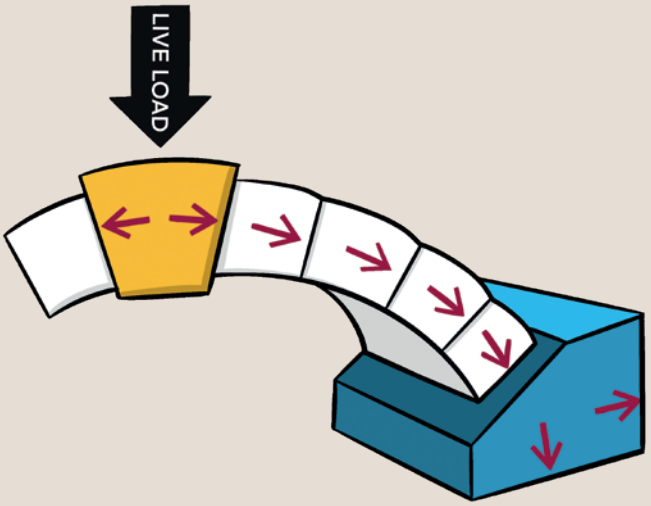




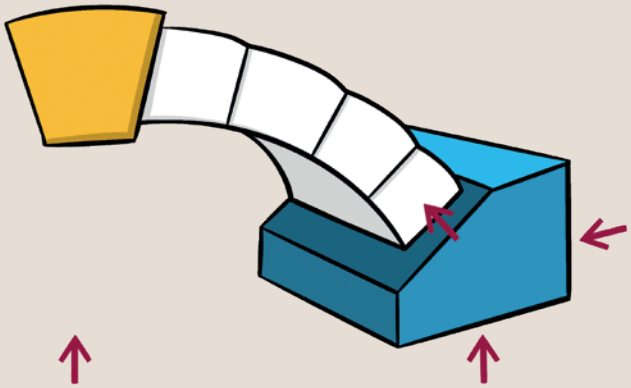
THE FORCES IN AN ARCH BRIDGE

Ask learners what they think is the main force in the arch. Explain that an arch bridge is always in compression. An arch bridge is stronger than a beam bridge because instead of pushing straight down, the load in an arch bridge is carried along the curve of the arch to the strong supports (abutments) at each end. The force is spread out or dissipated through the structure of the bridge (as shown in the *Forces in an arch bridge* handout).

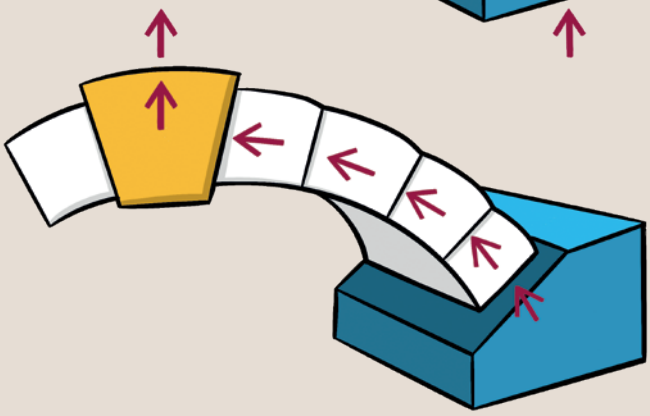
The load on the top of the **keystone** makes each **voussoir** on the **arch** of the bridge push on (**compress**) the **voussoir** next to it. This happens until the forces reaches the end **abutments** which are built into the ground.



The ground around the **abutments** is squeezed and pushes back (**compresses**) the **abutments**.

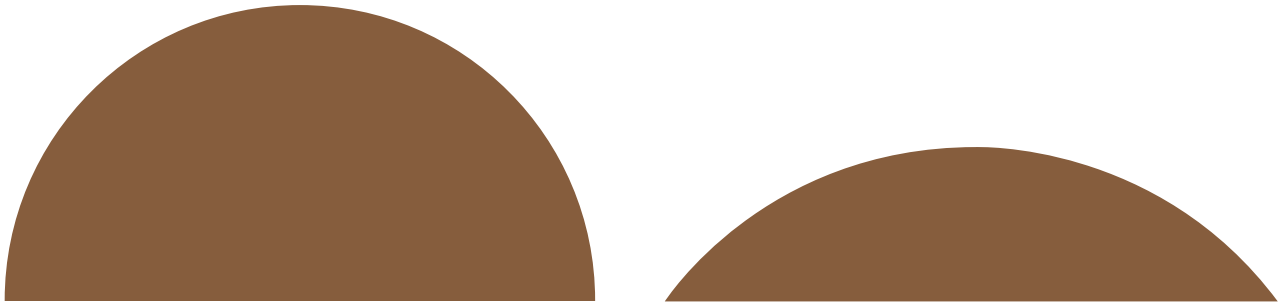


The **abutments** push back onto the **voussoirs** which pass the force back along the **arch** to the **keystone** which supports the load.

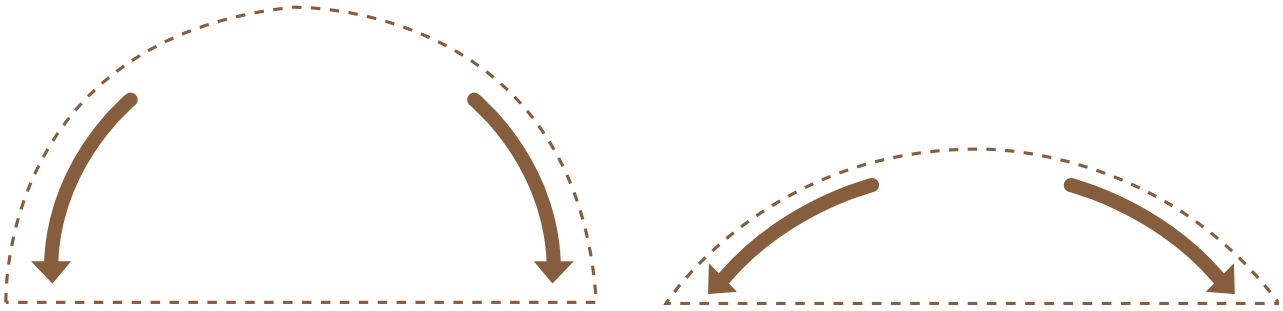


The earliest arches tend to be semi-circular. However, this limits the span of the bridge without building piers – if, for example, the river is too fast flowing for construction of piers, a semi-circular arch that crosses the wider span would have to be very tall and, as a result, very heavy. The weight could potentially put too much load on the abutments, and cause a collapse.

Using the *Arch bridge shapes template* handout, ask the learners to cut out the shapes and compare. If you compare the size and shape of the semi-circular arch and the shallower arch below, they both span the same distance, but the first arch is much taller.

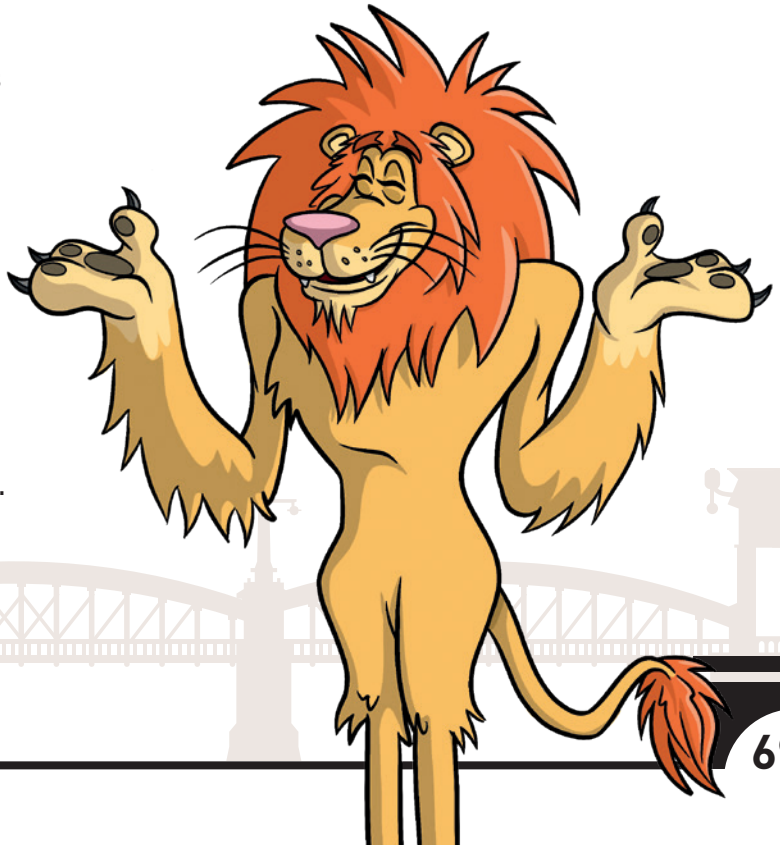


Ask the learners to draw force arrows on the shapes, as in the diagrams in the previous section.



Once learners have drawn their arrows, ask them what they notice about the pairs of arrows. They should identify that the semi-circular arrows are pointing downwards, but the shallow arch arrows are pointing out to the side.

Ask learners whether this would affect the abutments needed for the two types of arches. Which arch would need more support on the sides? The shallower arch. This is because some of the force is distributed to the sides, so the abutments would need to push back and resist this, stopping the arch from spreading outward.



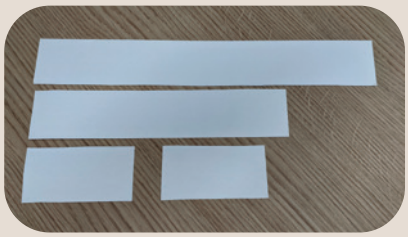
Challenge Time!

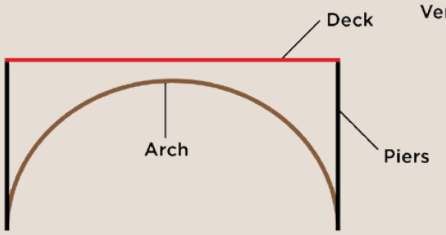
EXPLORING THE STRENGTH OF ARCHES

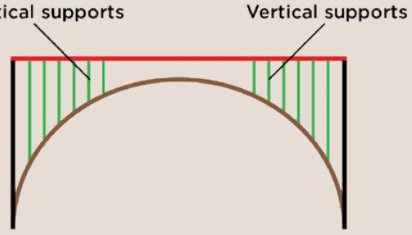
In this challenge, learners will explore the use of vertical supports in arches to strengthen bridges. Older masonry bridges usually have a series of stones creating the arch, with walls of stone to each side of them and up towards the deck and then filled. Modern bridges, of concrete or steel, often have a more open framework.

Each group should have sufficient materials to make at least one arch bridge.

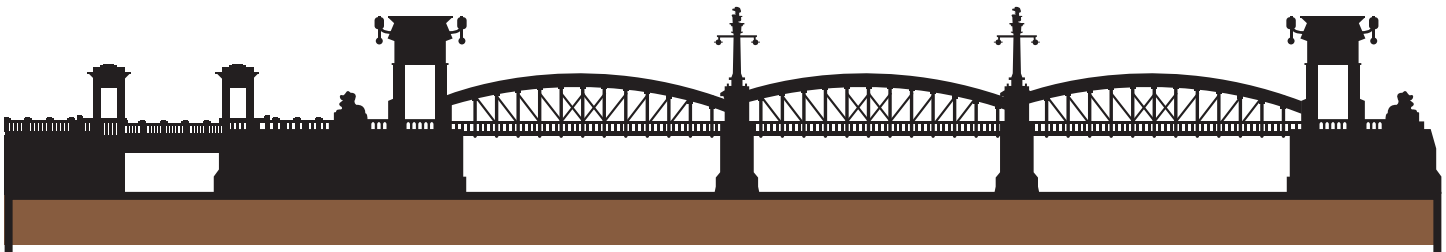
For each arch bridge, the group needs one strip of card 5x35cm long, to form the arch; one strip 5x25cm long to form the deck, and two strips 5x10cm long to form two piers. Each group should either test the basic bridge, using only these components, or add a specific number of supports to test whether the supports increase the load-bearing strength of the bridge, and whether the number of supports increases the strength of the bridge proportionally.







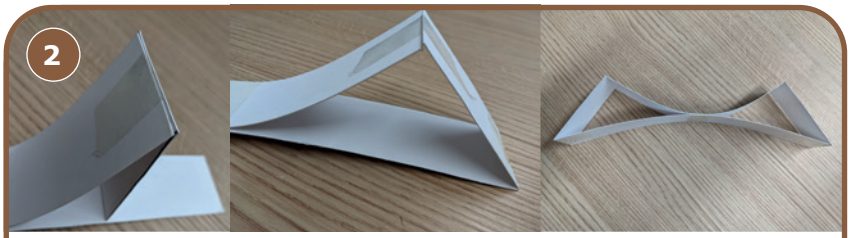
Depending on the number of groups you have, and the equipment available, you can increase the number of vertical supports to as many as can physically fit into the model.



1

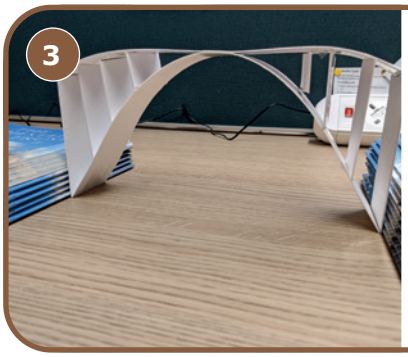
Tape the centre of the deck strip to the centre of the arch strip.

2



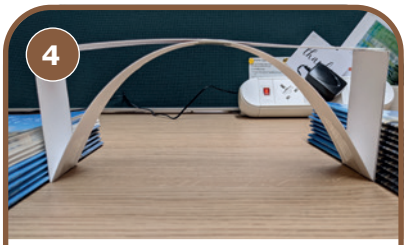
Tape a pier between the ends of the deck and arch at both sides. This will cause the longer strip to bend to form an arch shape.

3



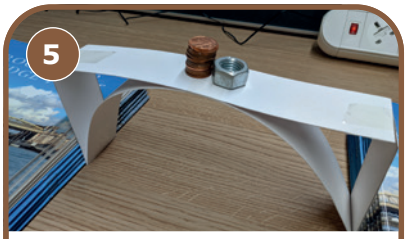
If vertical supports are to be added, tape the appropriate number of supports into position, parallel to the piers, and between the deck and arch strips. These should be symmetrical: if adding one each side, they should be as close to the same length and same position either side of the centre. If adding more than one support each side, they should be evenly spaced, and again symmetrical on both sides.

4



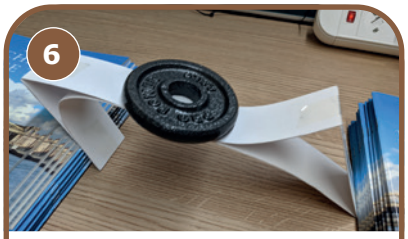
Place the arch between two large books on a table about 25cm apart (wide enough to fit the deck).

5



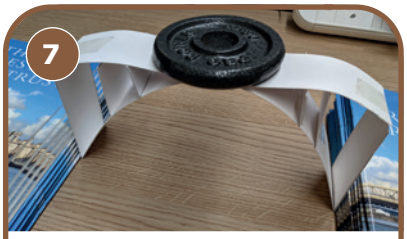
Add the small masses (coins, washers, paper clips) to the bridge, one by one, counting as they are added.

6



Take note of the number of masses in total required for the bridge to collapse.

7

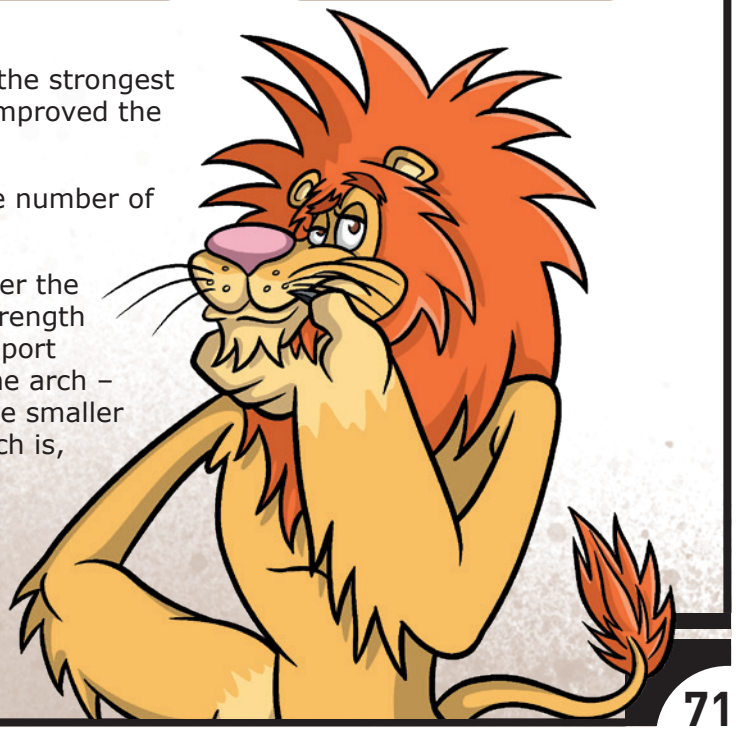


Now test each bridge with vertical supports added, recording the number of masses required to collapse each bridge in turn.

Ask the learners to describe which bridge was the strongest and why? Can they explain why the supports improved the strength of the bridge?

You could plot the results as a line graph of the number of supports on one side against the mass held.

This demonstration should show that the greater the number of vertical supports, the greater the strength of the bridge. This is because each vertical support distributes the load from the deck down into the arch – the greater the number of vertical supports, the smaller each individual load on each support on the arch is, so it is spread out more. This is then dispersed into the abutments more effectively.



HOT TOPICS!

This is the Khaju Bridge, in Isfahan in Iran. It was constructed in around 1650.

It is a stone and brick arch bridge spanning the Zayandeh Rood. It is adorned with brightly coloured tiles and 17th century artwork. This could be used as inspiration for creating geometric shape mosaics or similar artwork.

Khaju Bridge (Photo by Ninara via Wikimedia)

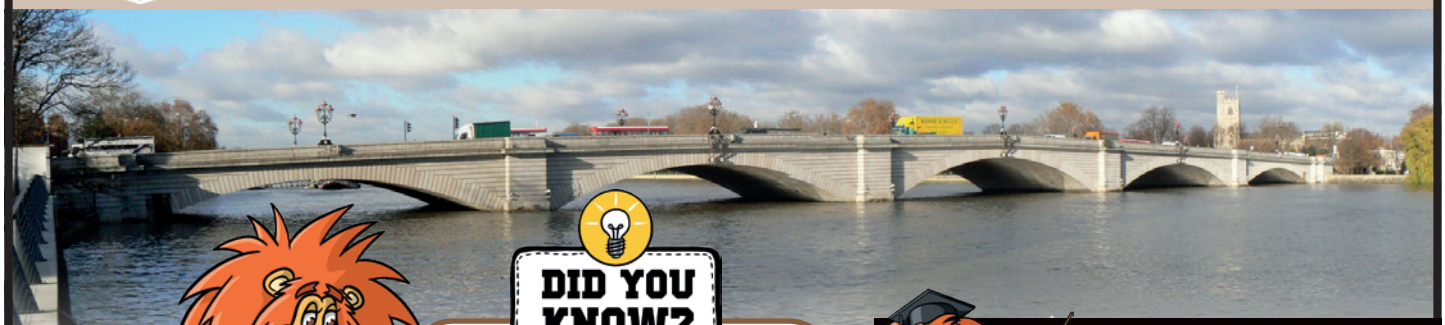
MAKING EDIBLE ARCHES

Using bitesize cake pieces from the supermarket, or making your own, can you build an arch?

Try using a whole peeled banana, cut it into voussoir shapes. You can then use toothpicks to try to secure the pieces together.

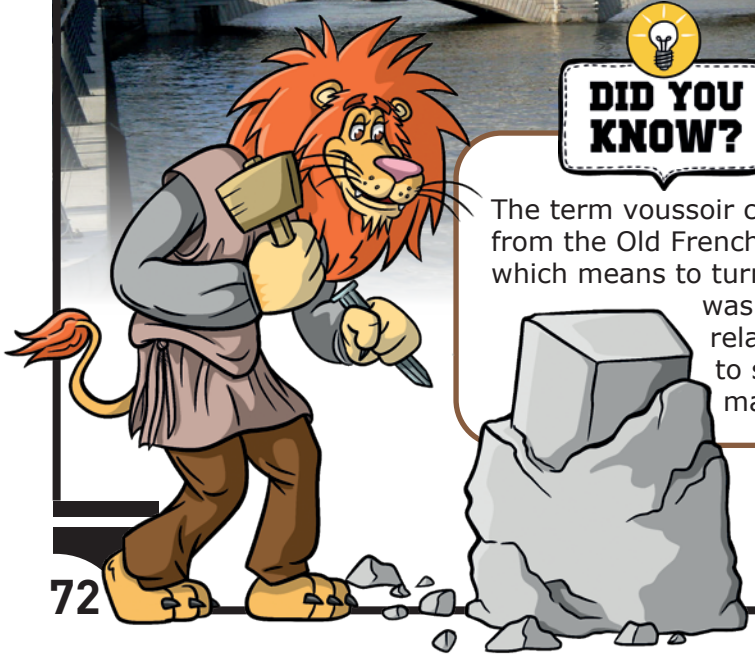
OUT & ABOUT

When walking around, can you spot any arches or domes which are a form of arch in other structures, not just bridges? Can you research different arch-containing structures from around the world? How old are they and who built them?



DID YOU KNOW?

The term voussoir comes from the Old French word which means to turn and was likely related to stone masonry.



Langdon presents:

- *Arch bridge terminology* handout
- *Forces in an arch bridge* handout
- *Arch bridge shapes template* handout

Handouts can be found at www.rochesterbridgetrust.org.uk