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PRICE £ 1,50

BRIDGES

PLON

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A physics unit for 14/15 year old students.

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PHYSICS CURRICULUM DEVELOPMENT PROJECT

* The Physics Curriculum Development Project (PLON) was started in 1972 under the auspices of the Physics Curriculum Innovation Committee (CMLN). Its terms of reference were to develop teaching packages on physics for junior and senior general secondary and pre-university schools, to evaluate such material by means of research, and to draw up a plan for directing its introduction into schools.
* The PLON is supervised by a steering group whose members have been drawn from schools, establishments of further education, educational support institutes, secondary teacher training institutions and the Ministry of Education and Science.
* The Project has been assigned to the Physics Education Department of the State University of Utrecht, which is also concerned with activities relating to the upper forms of senior general secondary schools. The development of instructional material for the upper forms of pre-university schools is carried out in cooperation with the Universities of Amsterdam (Municipal University) and Groningen and a group of teachers.
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Experimental edition.

PREFACE

This publication contains translated parts of the PLON-unit Bruggen (Bridges): the orientation, two chapters of theory (out of 4) and one investigation (out of 6). The Reading Texts have not been translated.
One of the purposes of this publication is to illustrate the structure of PLON-units for junior secondary education. The reader will also get an impression of the way the units deal with pupil activities and with physical concepts.
We would like to thank Mrs. Yolande Samwel and Mr. Robin Millar for their contributions to this translation.

A table of contents of the original unit Bruggen has been printed on page 5.

More copies of this unit are available at
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P.O. Box 80.008
3508 TA Utrecht
The Netherlands

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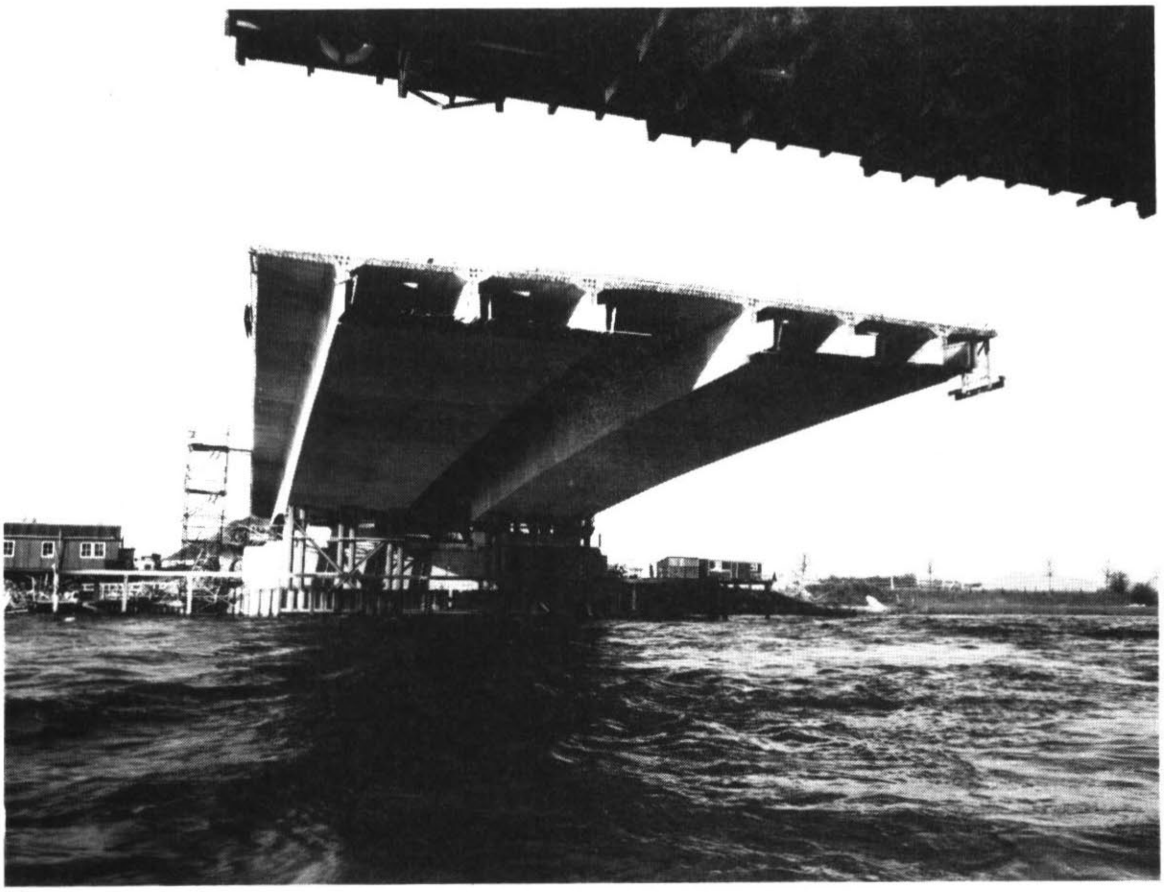
CONTENTS

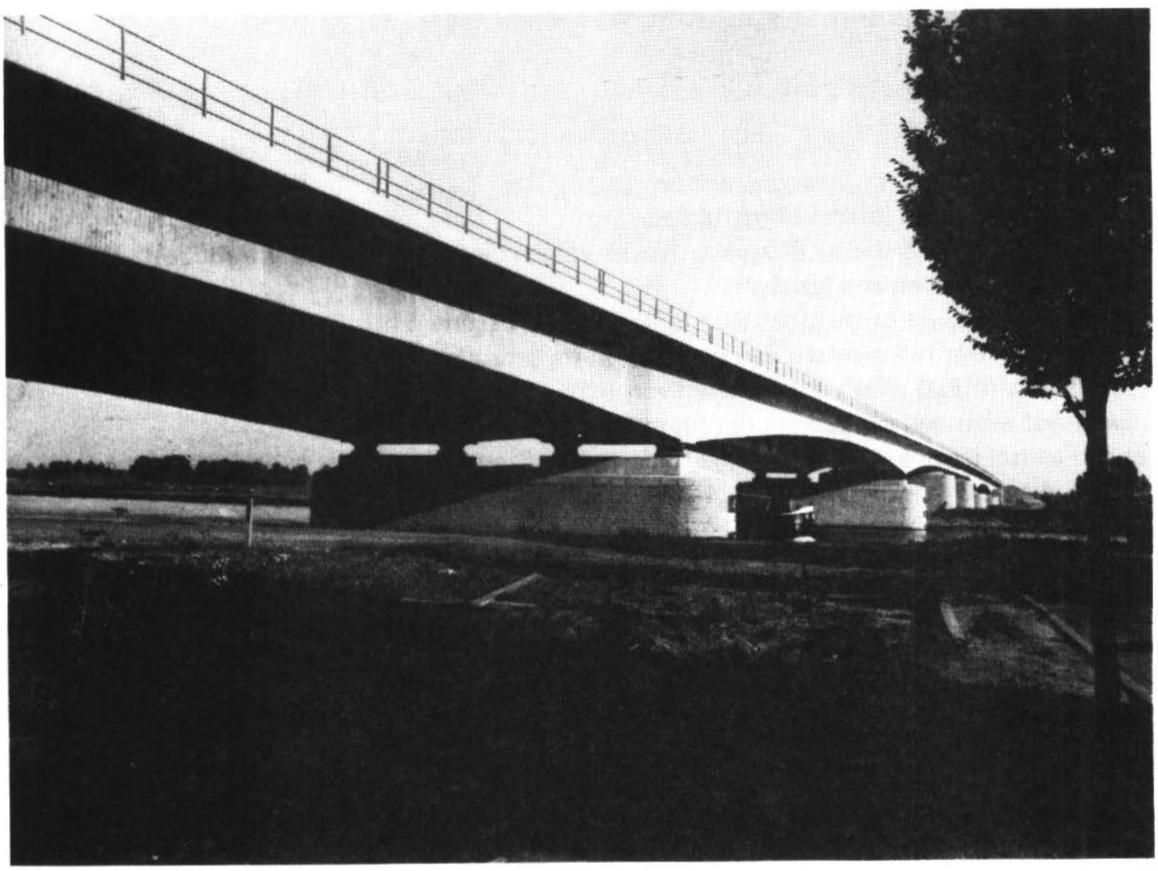
The new Willems bridge over the river Maas in Rotterdam, just before it was opened in 1981. It is a stayed girder bridge with a steel bridge-deck suspended from the A-shaped pylons.

WHAT THIS BOOK IS ABOUT

This book deals with bridges and similar constructions.
It begins with an Introduction to the theme *Bridges,* followed by four sections: Orientation, Theory, Investigations and Reading Texts.
In the Orientation section you will learn to look at bridges and cranes in a way that is probably new to you.
In the Theory section you will learn more about the shapes of bridges and cranes and the materials used in their construction. This section is essential core material which all students should complete.
Each group of pupils then chooses one investigation from the Investigation section to carry out. After completing the investigation, the groups report their findings back to the whole class.
The Reading Texts section contains a number of texts which may be useful in carrying out your investigation or in preparing your report, but you can also read them just for pleasure. These texts are not compulsory.
Each section starts with a detailed table of contents.
We hope you'll have lots of fun looking, learning, building and reading!



The bridge at Wessem under construction (above) and completed (below). By choosing the right building scheme, materials and shape, the engineers have succeeded in constructing a strong bridge without causing too much hindrance to ship traffic. The bridge consists of prestressed concrete sections (see Reading Text 2,   ) and is constructed using the "cantilever" method. The photograph above clearly shows the concrete "tubes" supporting the bridge-deck from below.



INTRODUCTION

WHY BRIDGES ?

In the Netherlands, there are bridges everywhere. They are so familiar you hardly ever notice them. Yet you can't do without them. Perhaps you cross a bridge on your way to school. Just imagine how much longer your route would be if that bridge weren't there! Every year, millions of guilders are spent on bridges. The new Willemsbrug in Rotterdam for instance, which was opened in July 1981, costs about 100 million guilders (£25 million). This tells us something about how important bridges are. But that is not the only reason for devoting a whole theme to bridges (and cranes). Bridges can teach you a lot about other constructions you use in your everyday life, not just if you happen to become a bridge-builder. For example: how can a wobbly bookcase or a television aerial be secured? How can a garden gate be strengthened?
Also, it will be enjoyable to come to understand something about bridges by working on them with your hands and your head. Enough good reasons to get started with the theme!

HOW ARE THE LESSONS ORGANIZED ?

Bridges is the first theme for the third year of the mavo-havo-vwo course. You will be working on it for about one month. In the *orientation stage* you and your group will find out about the shape of bridges and cranes and the materials used to make them by looking around in your neighbourhood and examining pictures and photographs. You will learn some theory by doing several simple experiments and tasks; this can be done as a group. Also, your teacher may wish to explain pieces of theory to the class as a whole. The *investigation stage* is organized as follows: you and your group are going to build a bridge or a crane, and then try to improve the design. Or you may investigate the strength of paper folded into different shapes to learn about balance and stability. Your group will present the results and conclusions of the investigation in a report or a demonstration to the class. The theme *finishes with* a test on the theory and on the main conclusions reached in the investigations which the different groups have carried out. Part of the test will also deal more in detail with your own investigations, so that part will be different for each group.
If your teacher decides to organize the lessons differently from this outline, he or she will tell you so.

WHAT CAN YOU LEARN FROM THIS THEME ?

In the *Orientation section* you will learn how to recognize different types of bridges, and you will become familiar with the materials used in the construction of bridges. You will also learn that bridges need to have some "play" to be able to expand on hot days.

The *Theory section* contains four chapters:
Chapter 1 deals with stresses in materials: compression, tension and bending stress.
In Chapter 2 you will learn how to make a bridge as strong as possible by choosing the right material and shape.
Chapter 3 deals with balance and counterbalance in movable bridges and cranes. You will learn how to calculate with weights, counterweights and distances from the axis of rotation.
Chapter 4 tells you how to design an object (e.g. a crane) so that it doesn't fall over (stability). You will learn how to determine the centre of gravity, and what the relation is between the position of the centre of gravity and the stability of an object.

In the *investigations* you need to use this theory to improve the constructions which you make yourself.
Investigation 1: Building and loading a bridge. Try to make it as strong as possible; think of how parts of a bridge deform and what stresses the material is exposed to.
Investigation 2: Building a crane and improving it as described in Investigation 1.
Investigation 3: Working out the maximum load of a crane at different places. Noting the effect of the counterpoise.
Investigation 4: Making piers, beams and bridge-decks of different shapes (e.g. out of paper), loading and improving them.
Investigation 5: Exploring rotation.
Inestigation 6: Making different objects and stabilizing them using all sorts of tricks.
The different groups tell each other about the results and conclusions of their investigations by presenting *demonstrations*.

WORKING IN A GROUP

As in the second year, you will spend a lot of the third year working as a member of a group. One of the major tasks for the group is working out a plan together and deviding up the tasks. You will need to discuss things

together, and this may turn out to be rather difficult at times.
To make the discussion successful,
it is often necessary to:

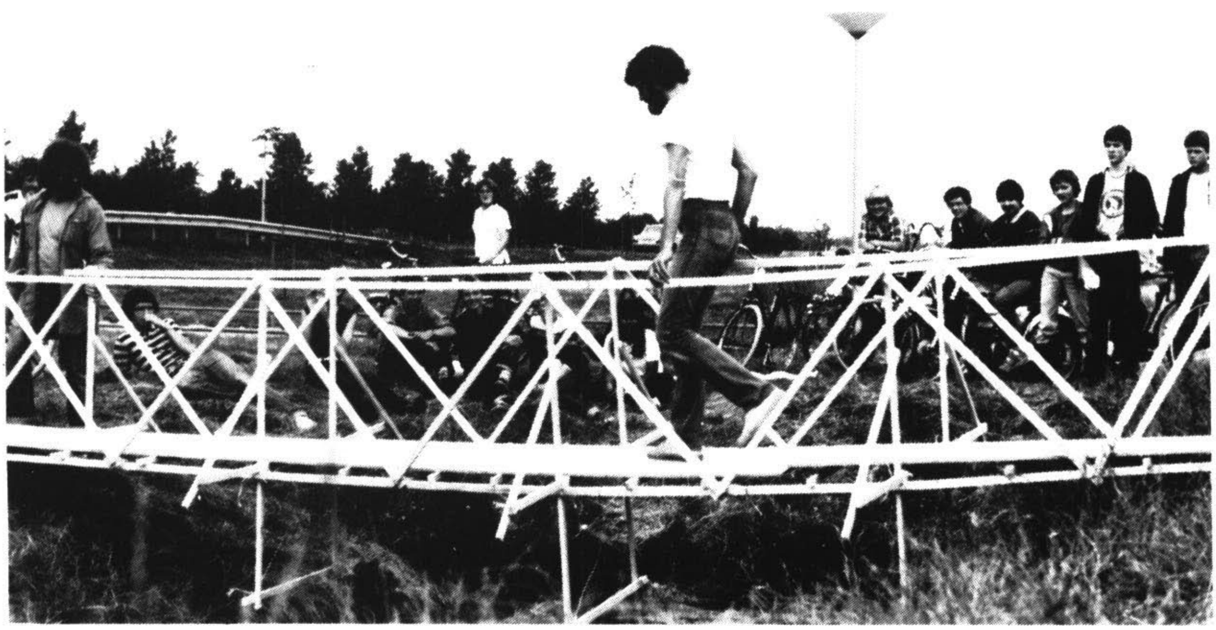
- prepare the discussion thoroughly
- stick to your subject
- see to it that the group members don't speak all at the same time
- keep an eye on the clock
- see to it that the group members don't just talk, but also listen to each other.

You can try to do all this as a group, but you may decide to choose one member of the group to keep the discussion in order. If you are a large group, this may be the best way to do it. If one or two of your discussion sessions have been unsuccessful, you really should think about appointing a "discussion leader". This doesn't have to be the same person every time.

- *See to it that you are all clear about what you are going to do.*

The discussion leader can try to state this clearly
but he or she can also ask:
"Is there anybody who wants to summarise what we are going to

Afterwards, you can ask if it's clear to everyone, and if there are any questions. Don't go on before you're certain that everybody has grasped what it's all going to be about!

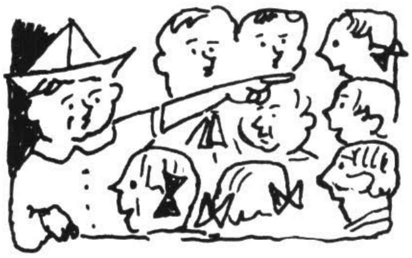


Students of the "Rijksscholengemeenschap Schagen (a High School) have constructed a real bridge, spanning a ditch of 7,5 m wide. The bridge is loaded with the teacher!

- *See to it that everyone understands what is being said.*
  It often happens that people just don't understand each other: someone says something, and someone else replies in a way that doesn't make any sense at all. You can help to make clear what other people say by asking, for instance, "I don't understand what Peter said. Could you repeat what you were just saying, Peter?"

- *See to it that everyone has the opportunity to express his/her opinion.*
  You may have someone in your group who isn't good at listening and is always talking. In the end, no-one else has been able to say a word. You can prevent this by asking every now and then "All right, that's your opinion; what do the others think about it?" Try not to make anybody feel embarassed. If someone doesn't want to give his or her opinion, he or she shouldn't be forced to.

- *At the end sum up what the results of the discussion are.*
  When the discussion is nearing its end (because a decision has been taken or because time is running out), you will have to sum up the results. You can start like this: "So we've decided to.."



"We aren't sure yet if.." "We don't yet agree about.." If the group is large you can split up the task of the discussion leader by appointing someone to see to it that everybody sticks to the subject, another to make sure that everyone understands what's going on, and another to keep an eye on the clock. Just try it and see how it works out.

You should also try to keep all this in mind when you are doing your investigations and making your actual bridge. You will be working as a group, and everyone should take part in the construction and give their ideas on the subject. And of course everyone should know what is going on during the investigation. After you have planned and carried out an investigation, every member of the group should be able to tell what the results are. So keep each other informed and let the whole group prepare the demonstration together!

INVESTIGATION IN THE THIRD YEAR:
MORE ABOUT "WORKING"QUESTIONS AND "SEARCH"QUESTIONS

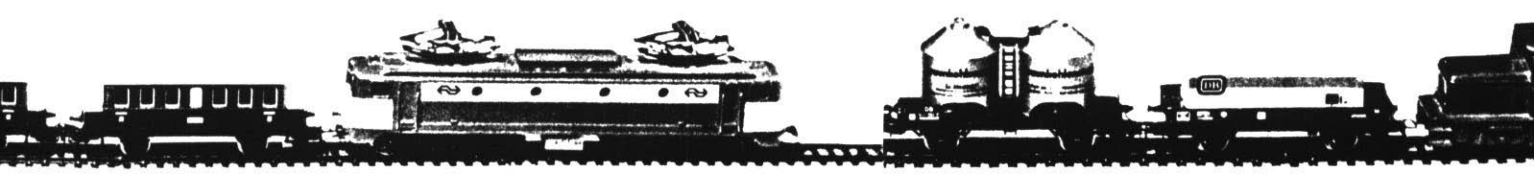
In the second year you have learned how to plan and carry out an investigation. One of the main things you learned was to make sure that the problem you were to investigate was well defined. You did this by asking "working" questions and "search" questions.

- Try to explain what is meant by "working" and "search" questions.

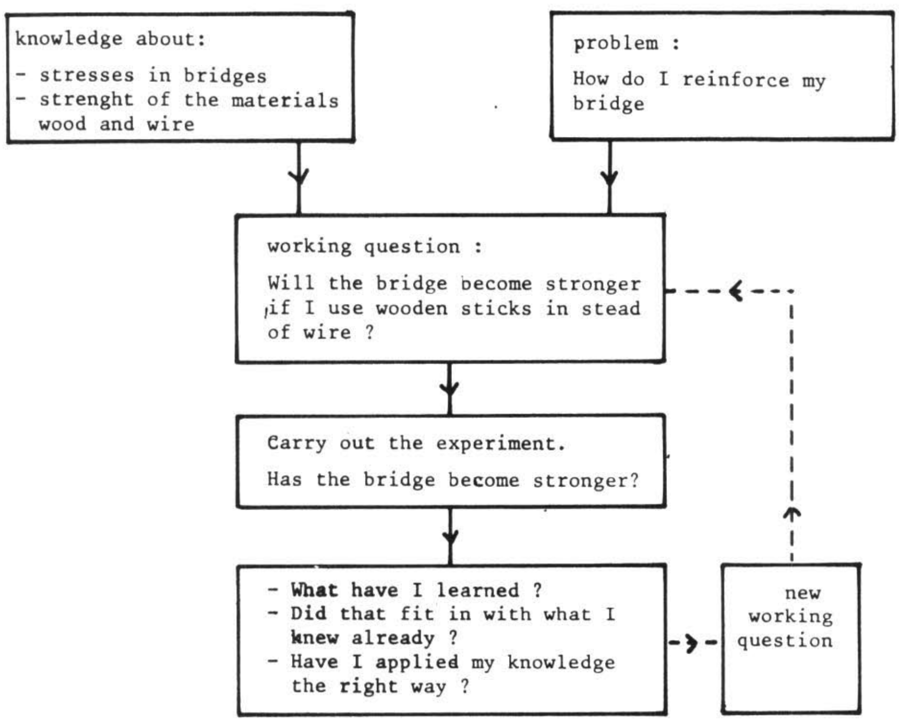
While you were carrying out experiments, the working questions turned out to be most important. For instance, when investigating a water pistol, you could ask the working question: Will the water squirt further if I widen the nozzle?

In *Bridges* and also in the other themes in the third year course, the working questions will again play an important role in the investigations. But as you know a lot more about physics now, you are able to ask working questions which are more difficult, as you can see in the next example:

Eric and Jacob want to build a bridge for their model railway, and they start looking around to find the best way to do it. They discover that most railway bridges are made of iron beams, and wonder if they should also use iron beams in their own railway bridge. But how can they get iron beams small enough to fit into their model bridge? Maybe they should use another material, but if so, what material? To find out, they must know what the advantages are of iron beams in the construction of railway bridges. "Well", Jacob says, "I know from a theme we did earlier, *Man and Metal*, that iron is a strong material. So let's use wire for our bridge". "Wire isn't strong enough. It bends easily and it isn't elastic. Why else do you think they use iron beams? Couldn't we use wooden sticks and paint them to look like iron?"



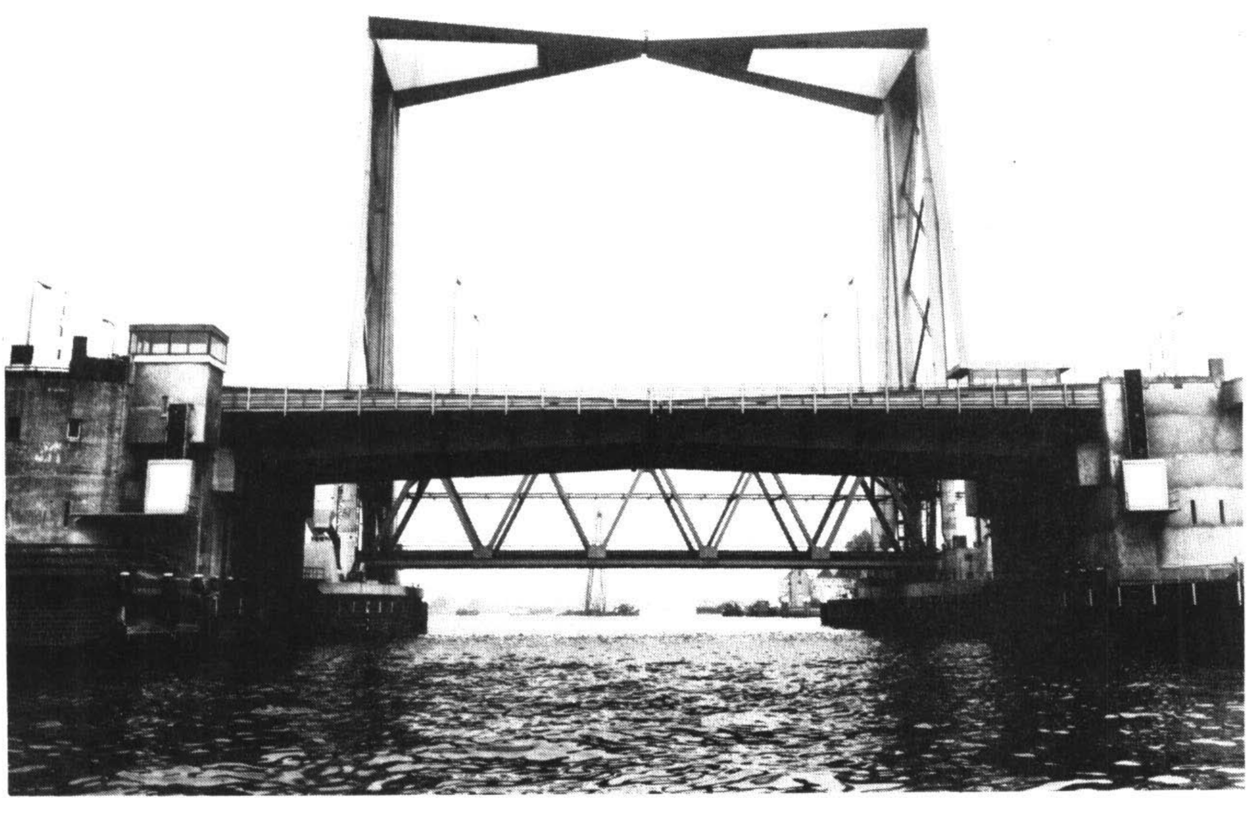
This example shows that Eric and Jacob use the knowledge they've acquired to draw up a working question. In this theme you will also learn new things (e.g. about stresses in materials) that you can use later to ask a new working question. If, for instance, you want to reinforce a bridge, you can ask yourself: Will my bridge become stronger if I use wood instead of wire, since wood is better at withstanding bending? You can put this in a diagram like this:



ORIENTATION

contents

This photograph shows some of the things discussed in this theme: different types of bridges (a double bascule bridge and a lifting bridge) and a big floating derrick crane by a tug-boat. The photograph was taken in Dordrecht.



1 bridges in your neighbourhood

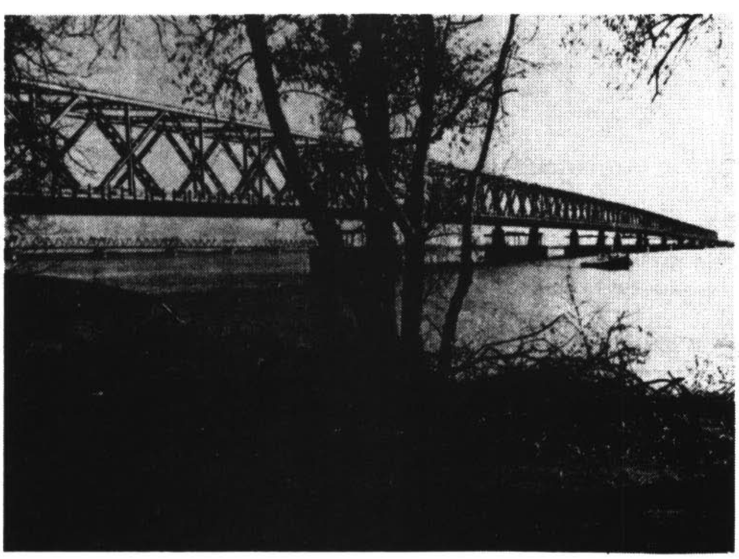
In any town or village you are likely to find bridges: bridges over waterways or roads, draw-bridges, railway bridges, flyovers, etc. There are many different types of bridges and you can see that they all have their own characteristic shape. The shape of a bridge depends on:

- the period when the bridge was built
- what was fashionable during that period
- the material the bridge is made of
- the length of the span
- the amount of traffic which passes over the bridge
- whether the bridge has to be movable
- (if the bridge is over a waterway) whether its construction will interfere with shipping.

In this theme, you are going to look at the shapes of bridges and at the materials used in their construction. You will learn something about the stresses occurring in a bridge and about materials which are able to withstand these stresses. When building your own bridge, you will put into practice what you have learned. You will also learn about weight and counterweight in a swing bridge. Stability is the last topic in this theme. A bridge should be stable enough to withstand strong winds. The notions of weight, counterweight and stability are also applied to other constructions, such as cranes and derricks.

task 1

1. Examine the bridges you see on your way from home to school, and any other bridges in your neighbourhood.



What is the name of this very well-known bridge? It looks totally different now, but this is how it looked until a few years ago. The bridge is one of the important links between the north and the south of the Netherlands.

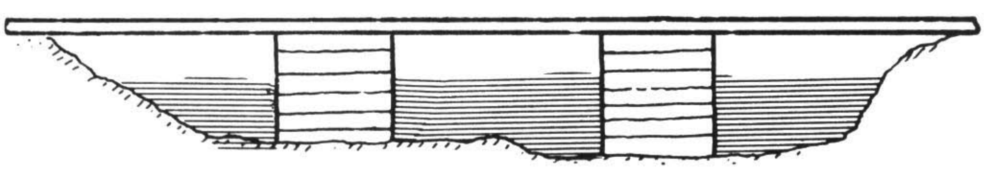
2. Make sketches of a few of these bridges in your exercise-book. Try to see exactly how the bridge is made. How are the different parts connected to one another? In which direction do the bars, the cables or the beams run?

3. Which materials are most commonly used in the bridges you have drawn? Are there any materials that can be used for one part of a bridge, but are unsuitable for another part? What differences do you notice between the materials used in modern bridges and in older bridges?

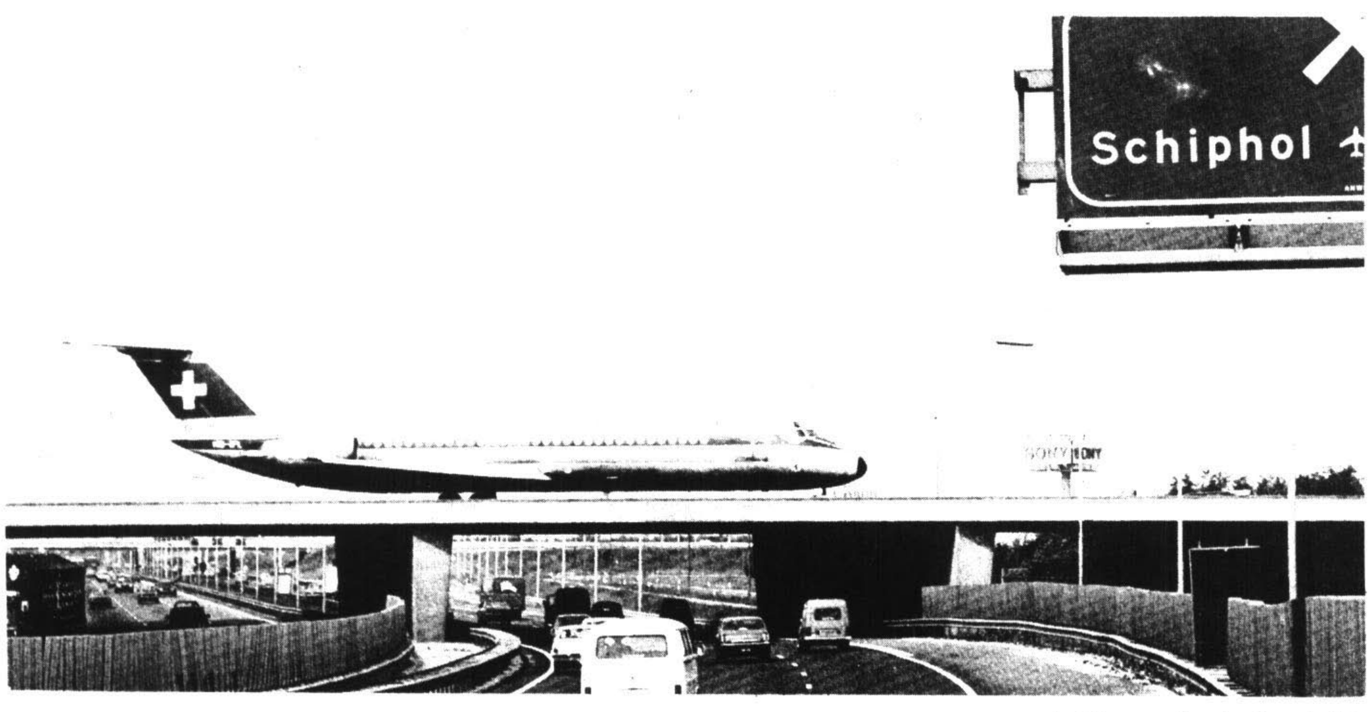
task 2 Answer the same questions for a crane (the kind that is used on a construction site).

2 the shape of bridges

The simplest type of bridge is the beam bridge: a beam that runs from one bank to the other. If the span is too long, the beam can be supported by a number of piers. In Reading Text 1, you will see a photograph of a very old English beam bridge.

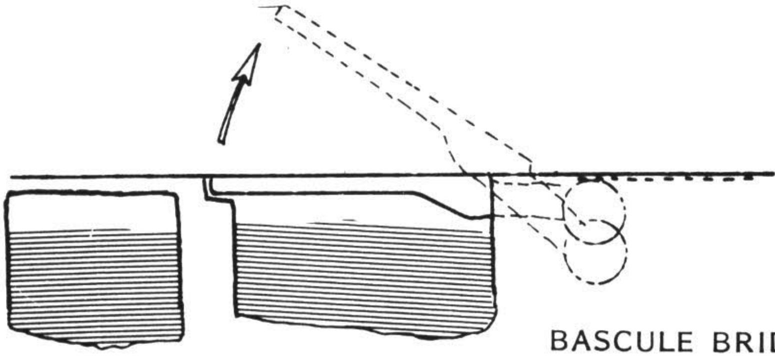


BEAM BRIDGE

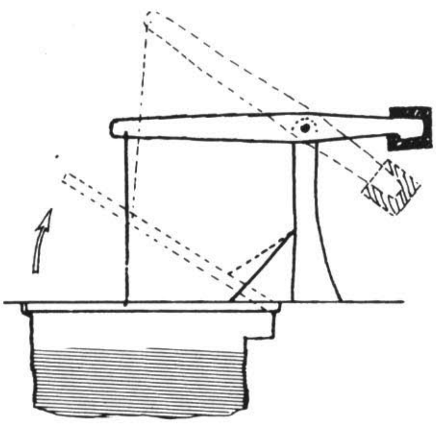


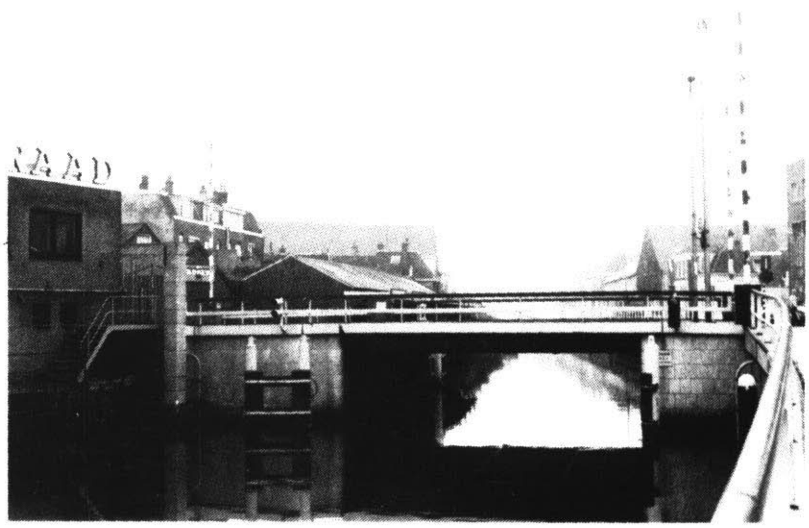
a striking example of a beam bridge

If the bridge must be movable, a bascule bridge is one of the possibilities.

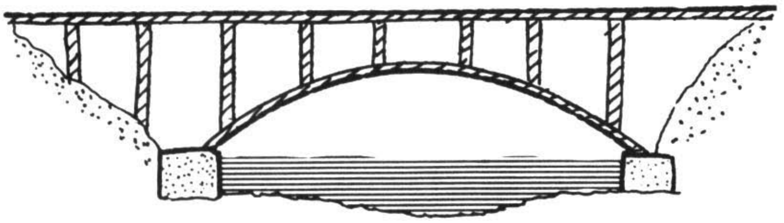

BASCULE BRIDGE

Another one is the drawbridge.

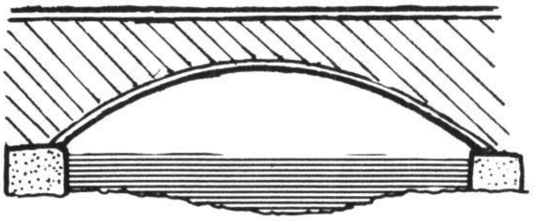

DRAWBRIDGE


a bascule bridge in Utrecht

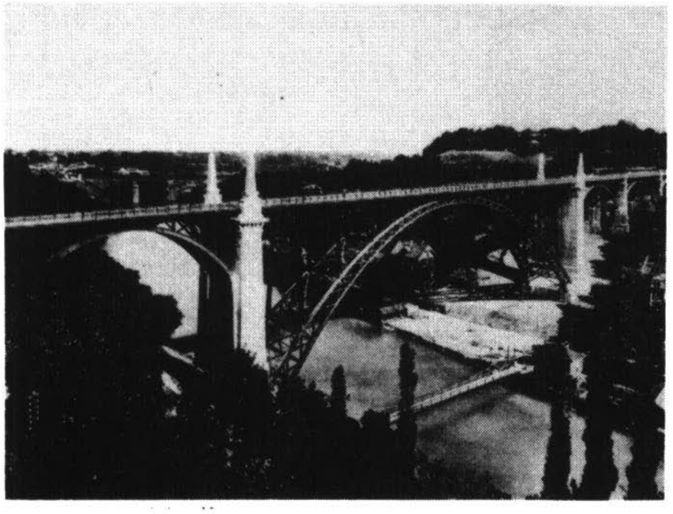
The roadway can be strengthened by supporting it with additional beams or an arch.



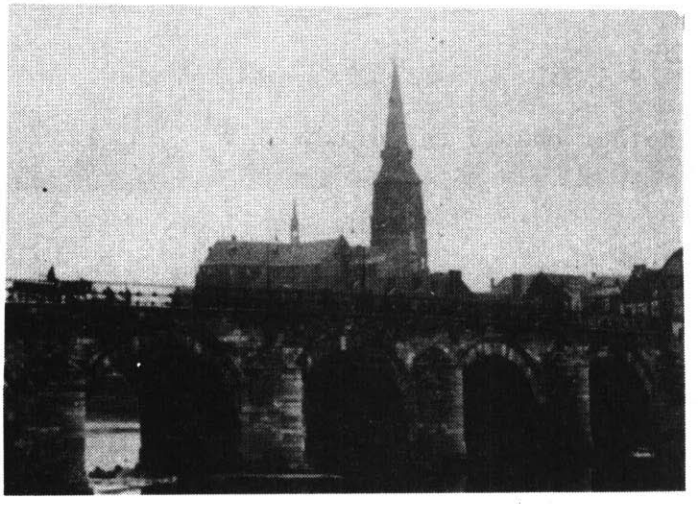
OPEN ARCH BRIDGE



CLOSED ARCH BRIDGE

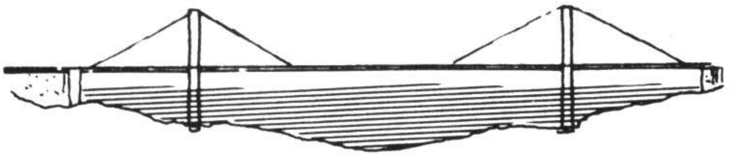


In the mountains you can find many open arch bridges

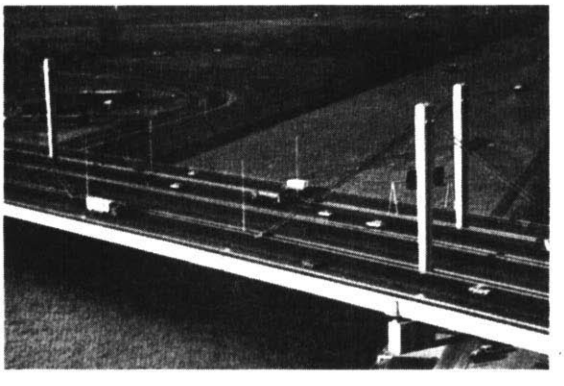


The medieval stone arch bridge in Maastricht

A bridge can be strengthened (and the span increased) when a superstructure is used. This is a stayed girder bridge (the roadway is suspended from cables called stays).

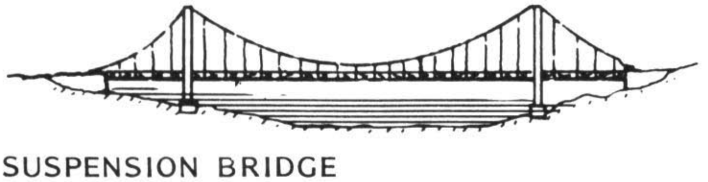


STAYED GIRDER BRIDGE



The Galecopper bridge over the Amsterdam-Rhine canal near Utrecht (stayed girder type)

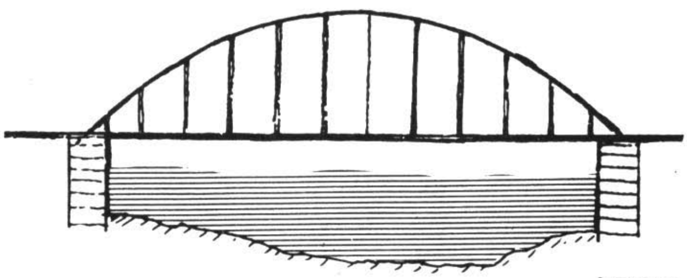
and this is a suspension bridge.



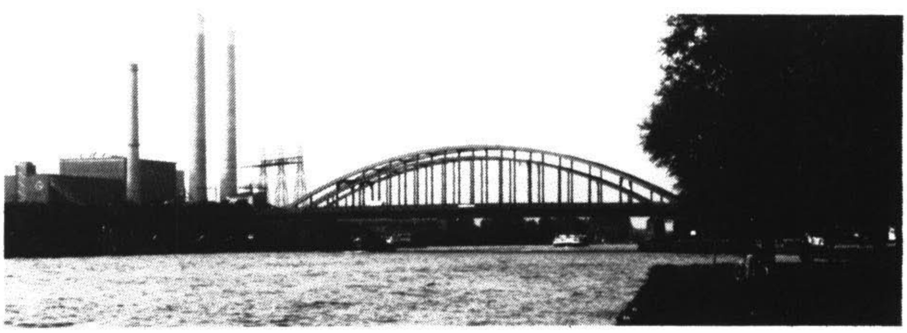
SUSPENSION BRIDGE

There are not many suspension bridges in the Netherlands

Another way of strengthening a bridge is suspending the deck from an arch. The arch is usually made of concrete or iron, and the deck is suspended from steel cables.

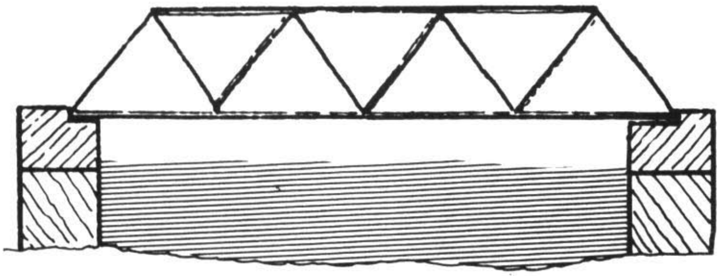


ARCH BRIDGE



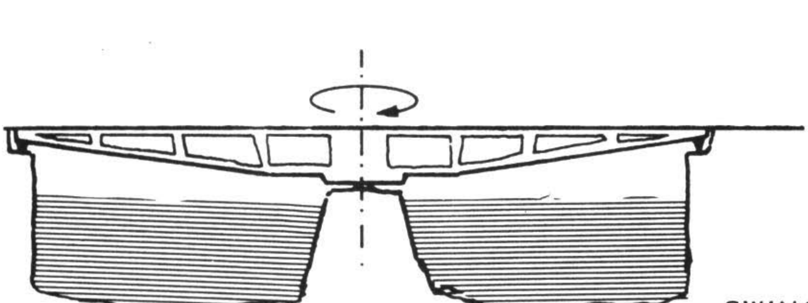
Two arch bridges side by side: the railway bridge and the road bridge over the Amsterdam-Rhine canal near Utrecht. The chimneys belong to a power-station.

In steel bridges, the superstructure often consists of steel triangles. This makes the bridge much stronger. There are several forms.

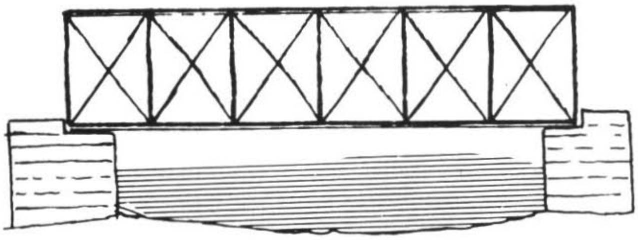


TRUSS BRIDGE

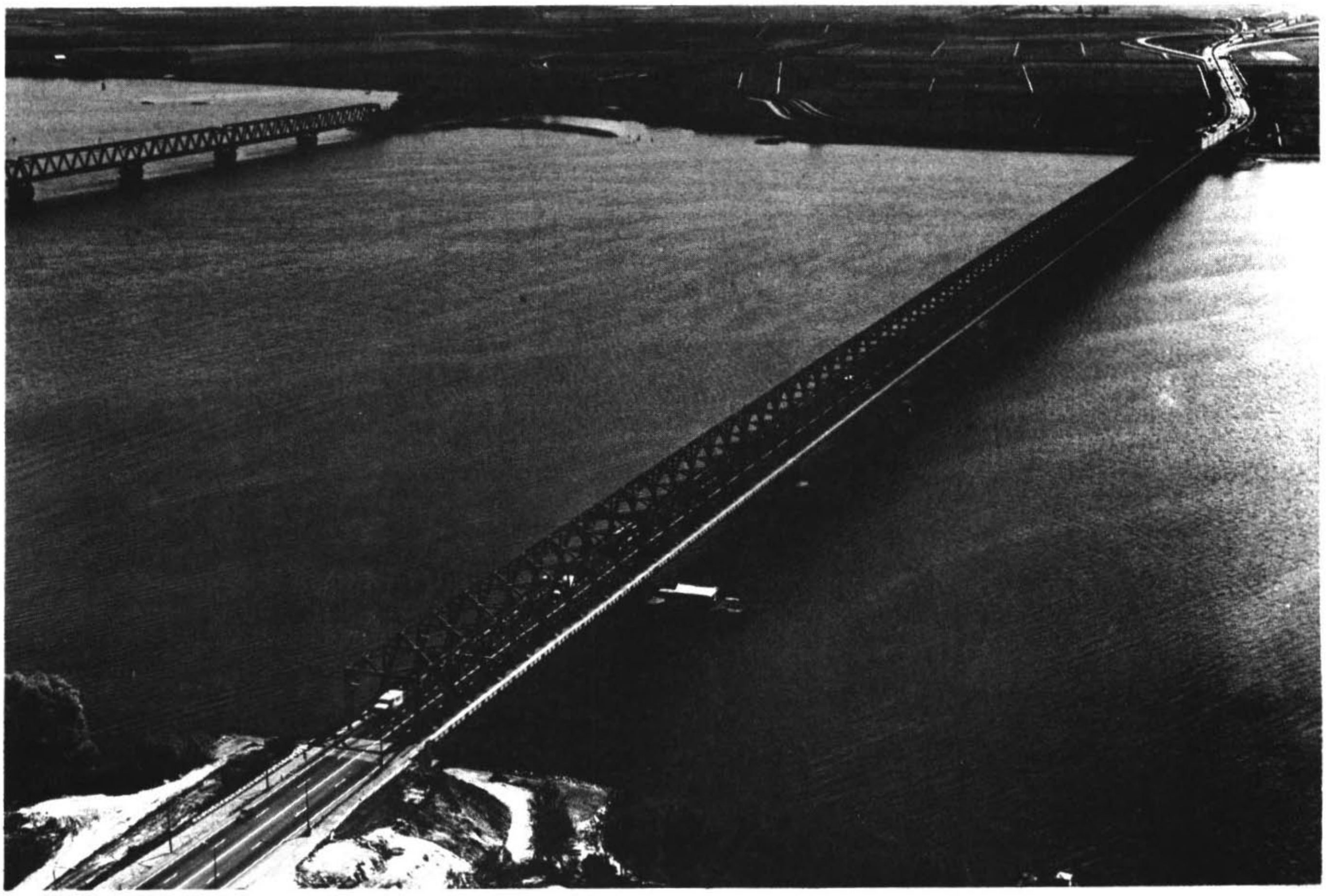
This truss bridge near Sluiskil rotates round the central pier



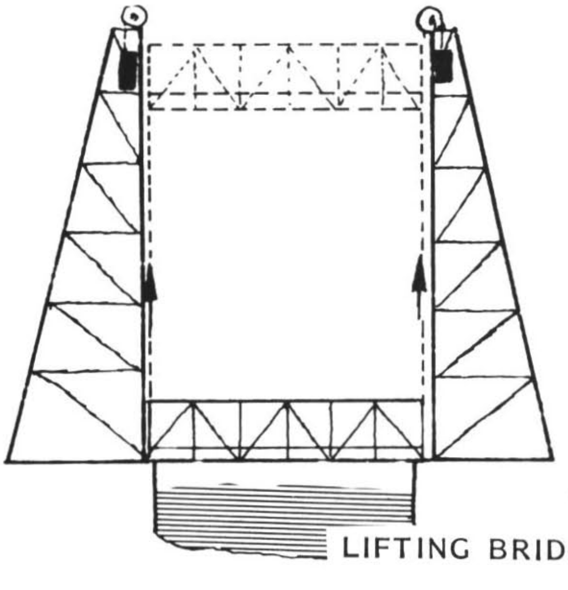
SWING BRIDGE



LATTICE GIRDER BRIDGE



The Moerdijk bridge the way it looked until 1978 was a lattice girder bridge. Now, the entire bridge has been replaced by a much wider beam-type bridge, consisting of sections of prestressed concrete (see Reading Text 3). The truss bridge in the background is a railway bridge.

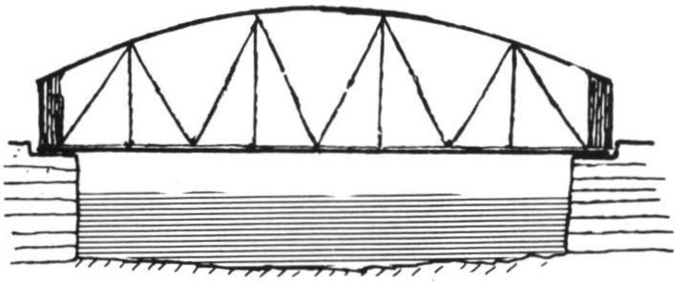


LIFTING BRIDGE

If there has to be room for tall ships to pass under a truss bridge, the lifting bridge is the commonest type. Part of the bridge is lifted by means of counterweights.

This lifting bridge can be found near Boskoop, spanning the river Gouwe.

There are still other types of bridges. Usually they combine characteristics of the ones already mentioned. One of these is the trussed arch bridge.



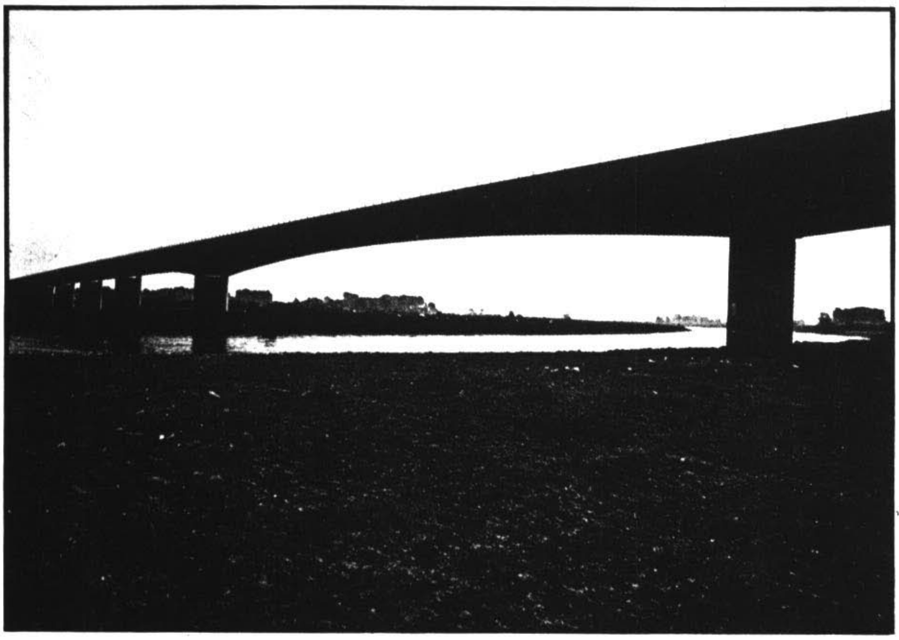
TRUSSED ARCH BRIDGE

The old road bridge at Keizersveer was a trussed arch bridge. Now, this bridge has been replaced by sections of the Moerdijk bridge (see Reading Text 3).

task 3 Try to make out from the photographs of bridges in this chapter which materials are used in their construction. How can you tell?

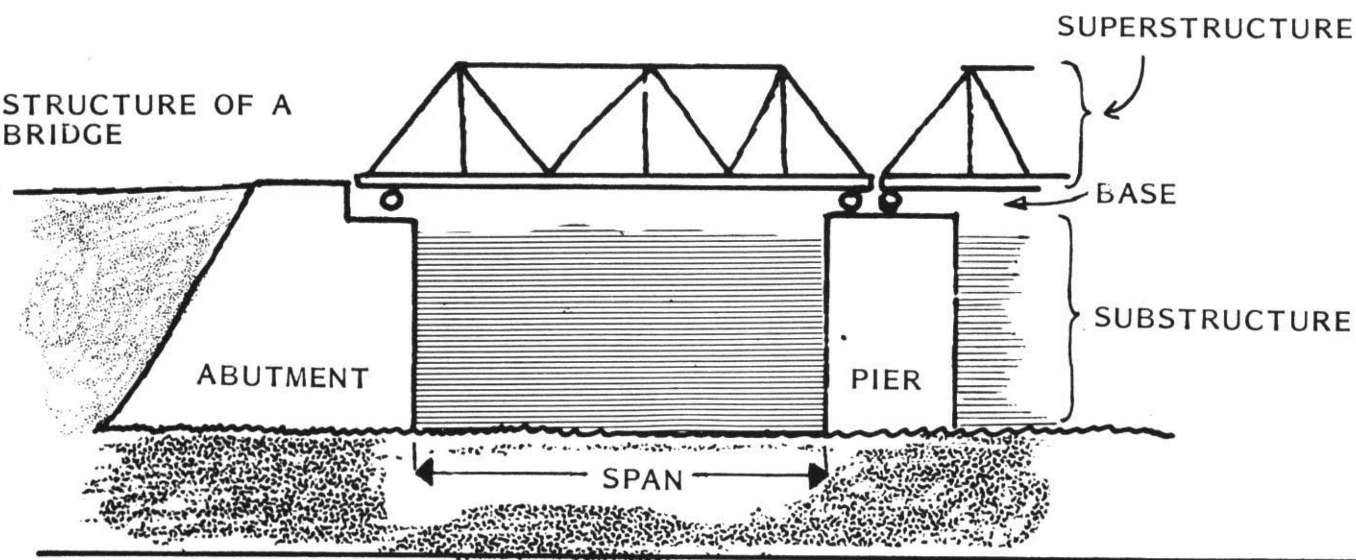
The shape of a bridge is very much determined by the material used. Until around 1800, almost every bridge was made of stone or wood. Their span could never be very long. But then steel bridges came into use, and this created a lot of new possibilities.

Since 1945, steel has been progressively replaced by reinforced concrete. Nowadays by using prestressed concrete (see Reading Text 2) and the so-called "light-weight" concrete, spans can be increased considerably without the need of a super- or a substructure.



The bridge over the river IJssel at Zutphen is made of prestressed lightweight concrete. Its maximum span is 126 m.

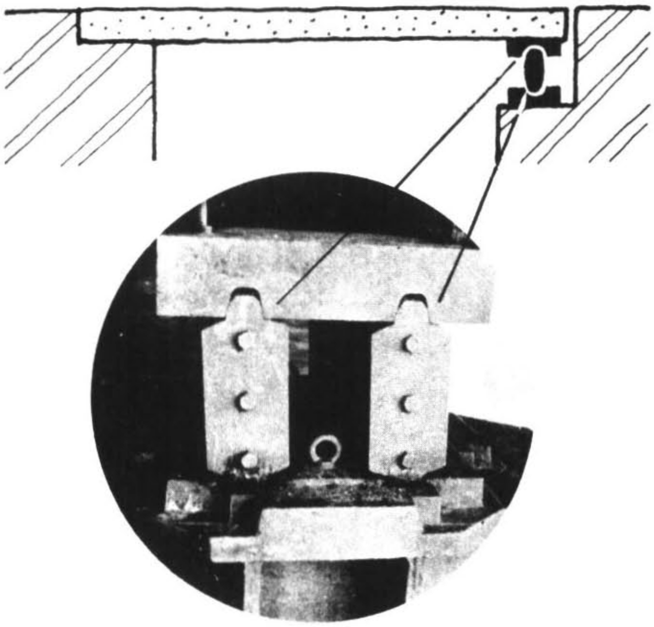
In the sketch below, you see a diagram of the structure of a bridge and the materials used in bridge-building.



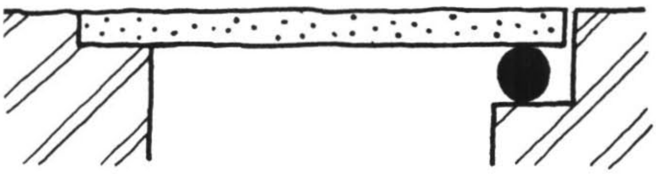
BUILDING MATERIALS : WOOD, STONE | CAST IRON, WROUGHT IRON, STEEL | CONCRETE — REINFORCED, PRESTRESSED

3 expansion and contraction in bridges

Like all other materials, bridge materials expand and contract when the temperature changes. To prevent damage when the bridge expands on hot days, the deck is fastened only at one end. At the other end, there is room for it to expand. Hinges or rollers are used to allow this to happen.



When the bridge expands (i.e. when the temperature rises), the hinges or rollers move along with the expanding deck.

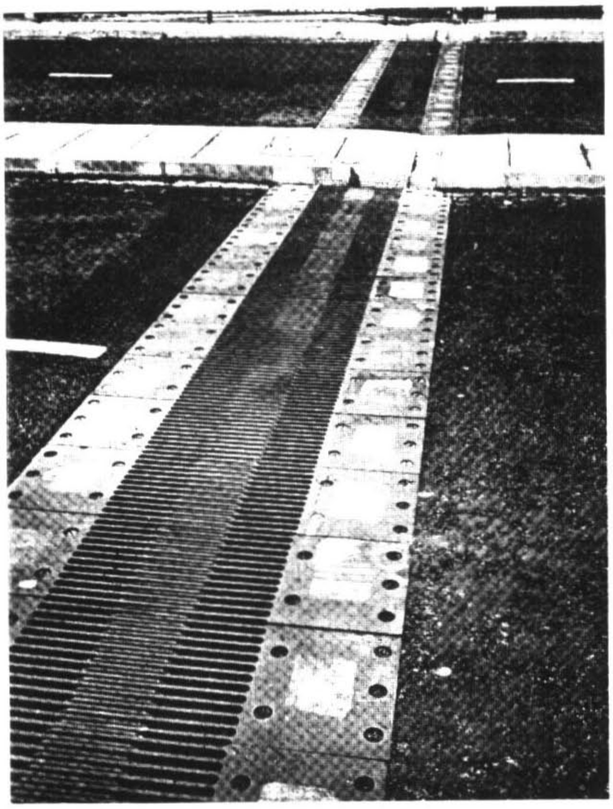


Choose a bridge near school. On several days (choose a warm and a cold day), measure:

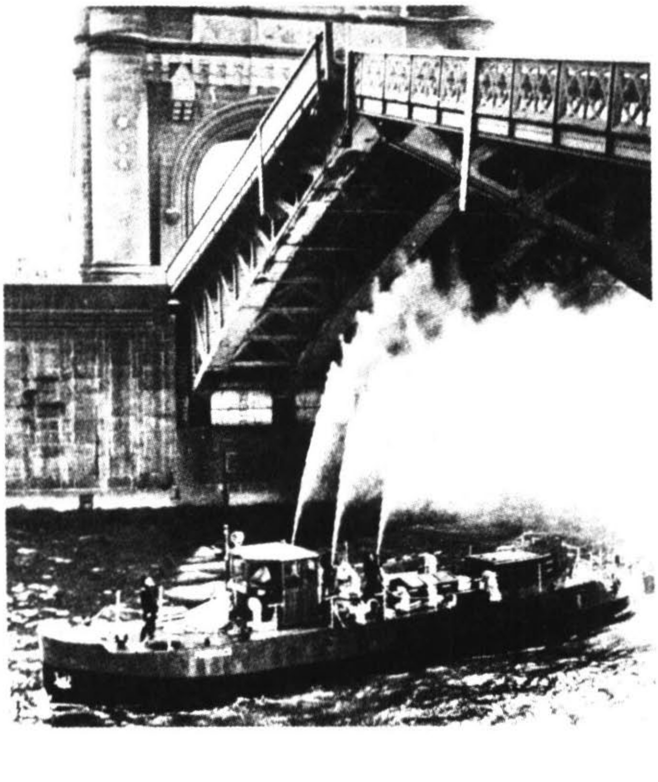
- the temperature of the bridge-deck, by carefully fitting a thermometer against it
- the space between the bridge-deck and the road-way, using a calliper.

Do you get different results on warm and on cold days?

Draw a sketch (or take a photo) of a movable deck of a bridge in your neighbourhood.



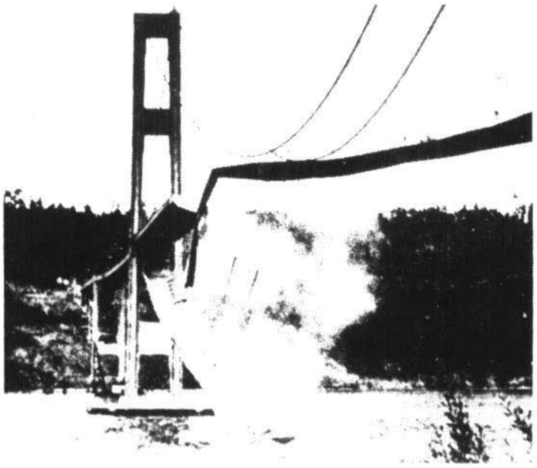
When the parts of a bridge-deck expand, the steel edges move towards each other.



Tower bridge in London during a heatwave. The bridge-deck had expanded so much that the bridge couldn't be closed. It was cooled by water from the river.

THEORY

contents



On 7th November 1940, during a gale, the new Tacoma Bridge in the United States collapsed. It could not withstand the enormous stresses.

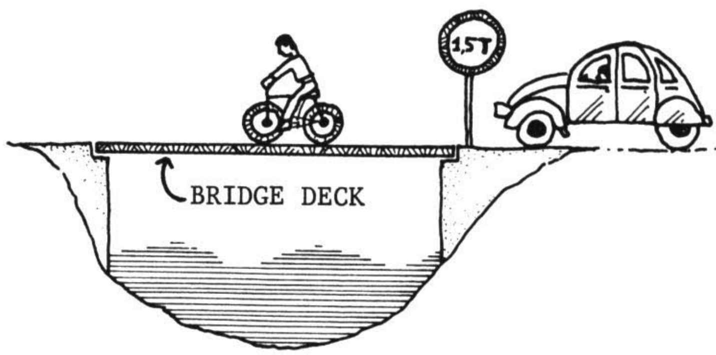
The Van Brienenoordbrug in Rotterdam has the longest span in the Netherlands: 287 m. The arch transfers the stresses in the bridge-deck to the piers.

1 stress in bridges

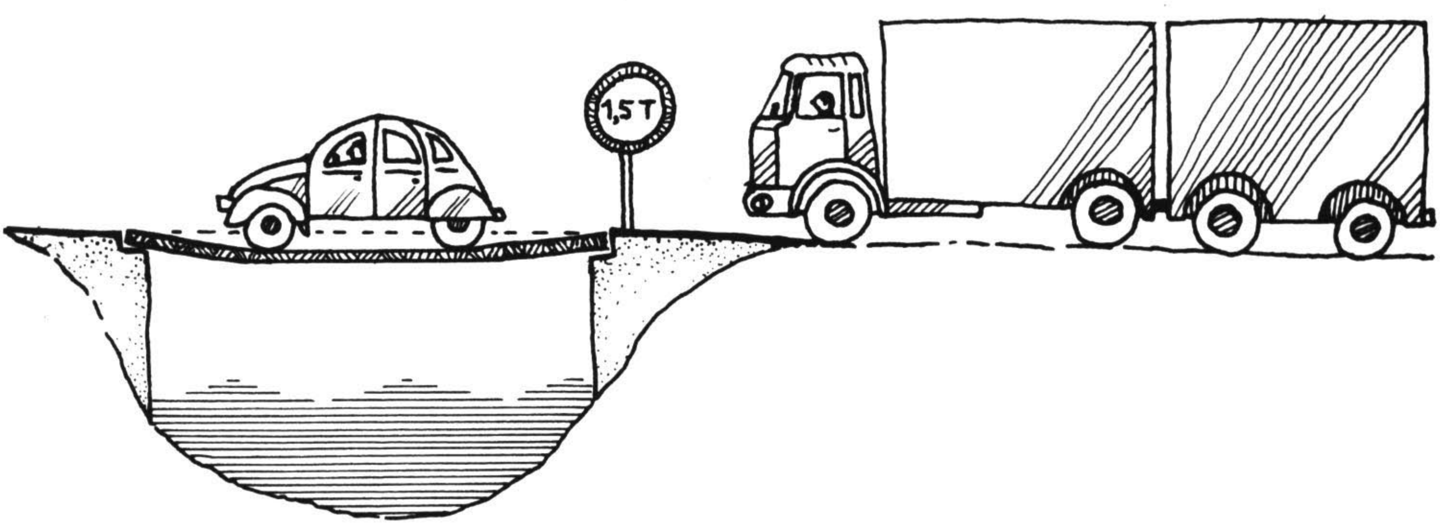
In this chapter, we will examine the stresses on the different parts of a bridge. The type of material chosen for the construction of each part depends upon the stresses which it has to withstand.

1.1 BENDING OF THE BRIDGE DECK

A load on a bridge makes the bridge bend. This causes stress in the bridge-deck.



This simple bridge will easily hold the cyclist (mass 80 kg); a car (mass 1000 kg) will make the bridge bend a little more.
The bridge will not hold a 6-ton lorry. It will bend so much under the lorry's weight that it will break. It cannot withstand such large stresses.



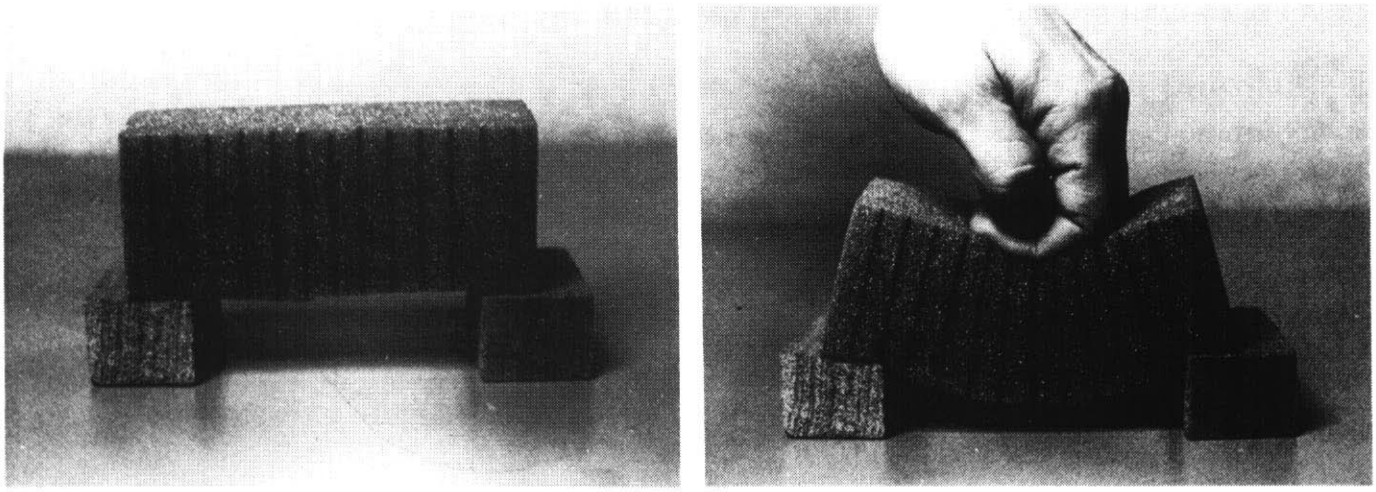
The weight of the car makes the bridge bend.

Would it help if the bridge-deck were thicker? Maybe, but a thicker bridge-deck is also heavier. Its own weight would make it bend. If the bridge-deck is too heavy, it can barely support its own weight.

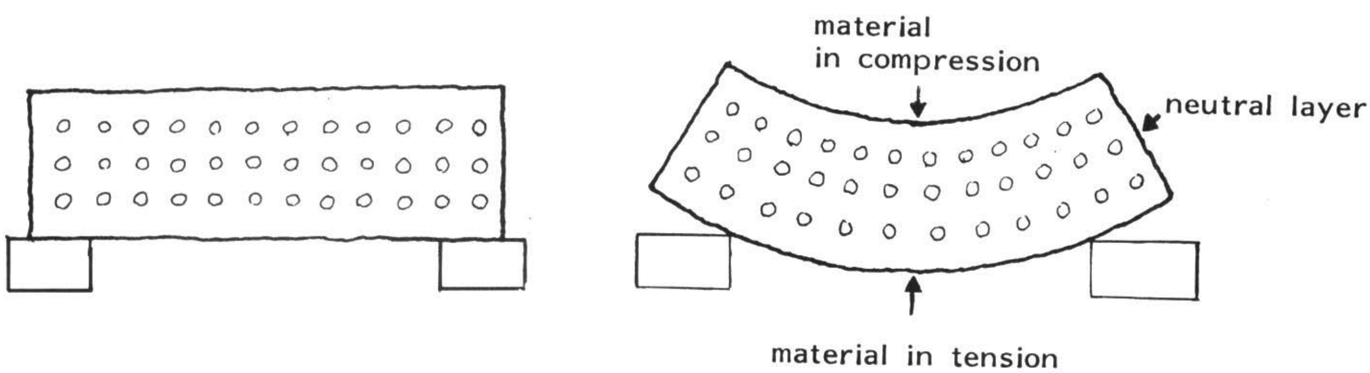
What exactly happens to the bridge-deck when it bends?
You can find this out by doing the following experiment.

experiment 1 Bending of a foam-rubber bridge

Draw some vertical lines on a piece of foam-rubber, as shown in the following photograph. Make a bridge using the foam-rubber, and put a load on it. Watch the lines. What do you see?



In this experiment you learn that the foam-rubber is compressed (pushed in) at the top and stretched at the bottom. The foam-rubber is under *bending stress.*

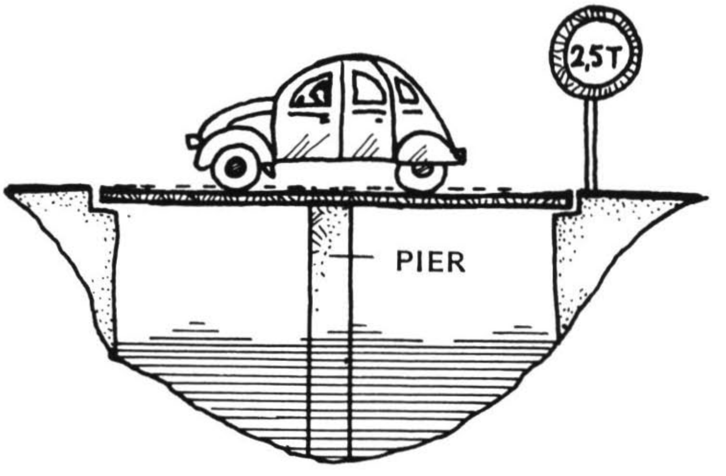


In a real bridge the same thing happens. You usually don't see it, because bridges are made of a stronger material than foam-rubber. The bending stress in the bridge-deck is able to prevent it from collapsing under the weight of the car, by transmitting the car's weight to the supports (or piers).

1.2 STRESS IN DIFFERENT PARTS OF A BRIDGE

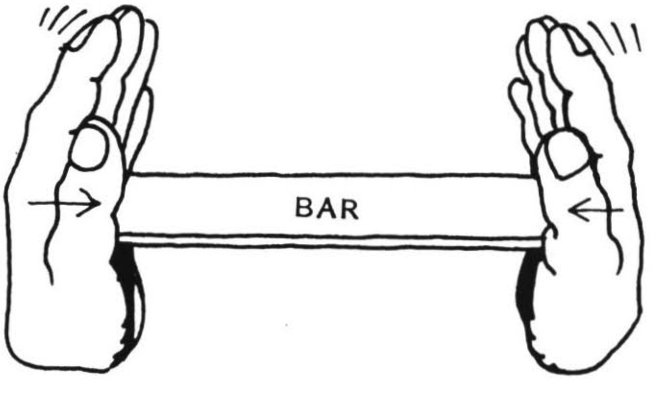
Compression

Many bridges not only have supports on both sides but are also supported by a pier in the middle. This makes the bridge much stronger, because the pier won't let the bridge-deck bend too much. The pier is compressed by the car's weight, but the material the pier is made of can withstand this stress, and will keep the bridge-deck in place. The stress which the pier undergoes is called *compressive stress* or *compression*.



The pier keeps the bridge-deck from bending too much.

You can exert compression on a bar by pushing against both ends with your hands, as shown in the drawing. The bar (and your hands too) are pushed in a little bit, but the bar does not collapse nor bend nor break, unless it is a very thin one. This means that the bar is good at withstanding compressive stress.



<u>experiment 2</u> **Compression and materials**

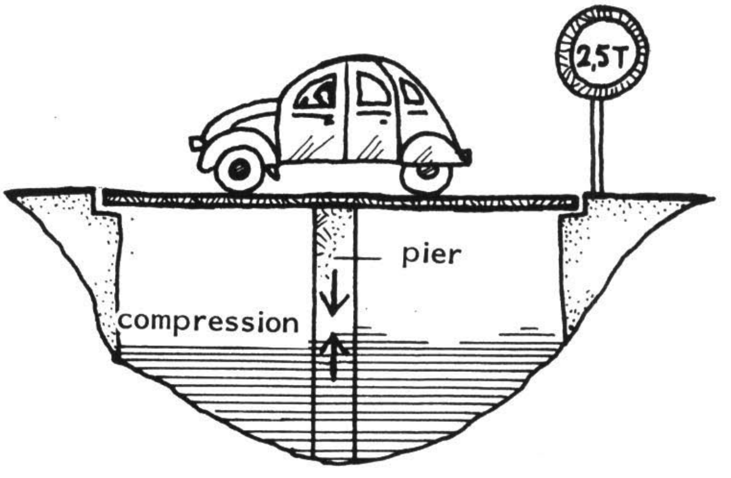
Investigate which of the following materials are good and which are bad at withstanding compression:

- wood
- paper
- cardboard
- modelling clay
- elastic
- rope

Which of these materials would be most suitable for building a pier for a bridge-model in the classroom?

task 1 The materials most frequently used in the construction of bridges are wood, stone, iron and reinforced concrete. Which of these materials are most commonly used for bridge-piers in bridges near your school (or in the photographs in this book)?

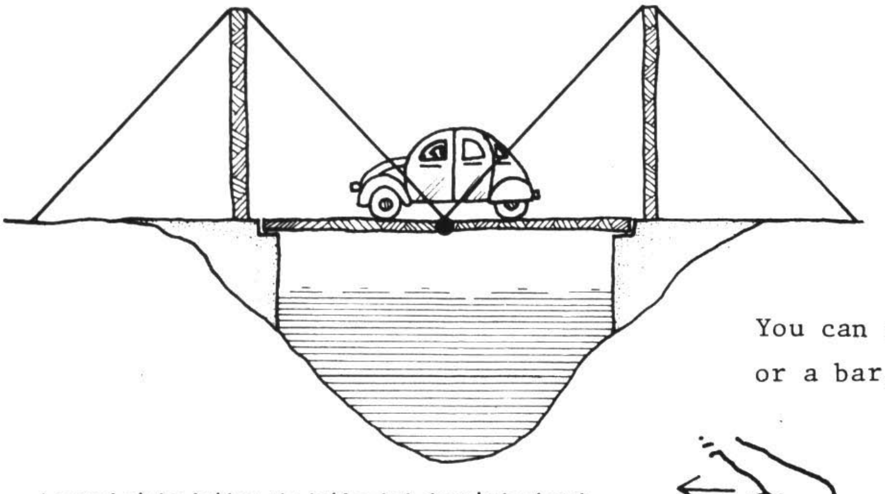
If a bridge element is subjected to compression, we will indicate this by two arrows pointing towards each other.



The pier is under compression

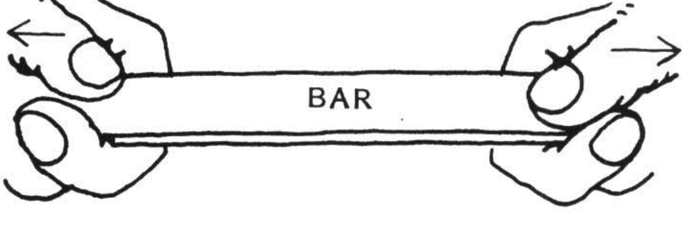
Tension

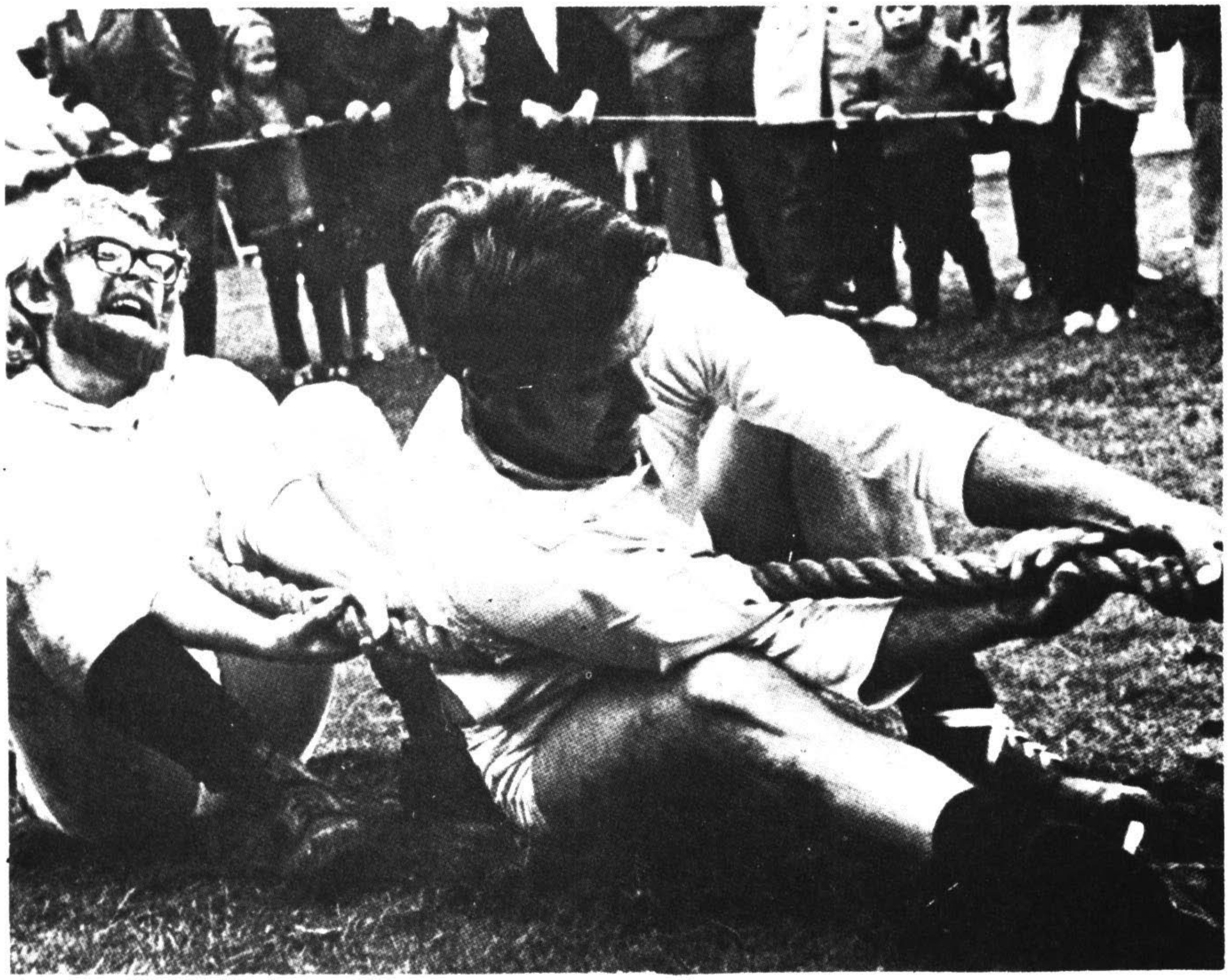
Another way of strengthening bridge-decks is suspending them from cables. These cables (sometimes called stays) are attached to towers called pylons. A bridge constructed this way is called a stayed girder or a cable cantilever bridge. The stress which the cables undergo when they are stretched is called *tensile stress* or *tension*. This transfers the weight of the load onto the pylons.



A stayed girder bridge: the bridge-deck doesn't bend much, because the stays carry part of the car's weight.

You can exert tension on a rope or a bar, as shown in the drawing.





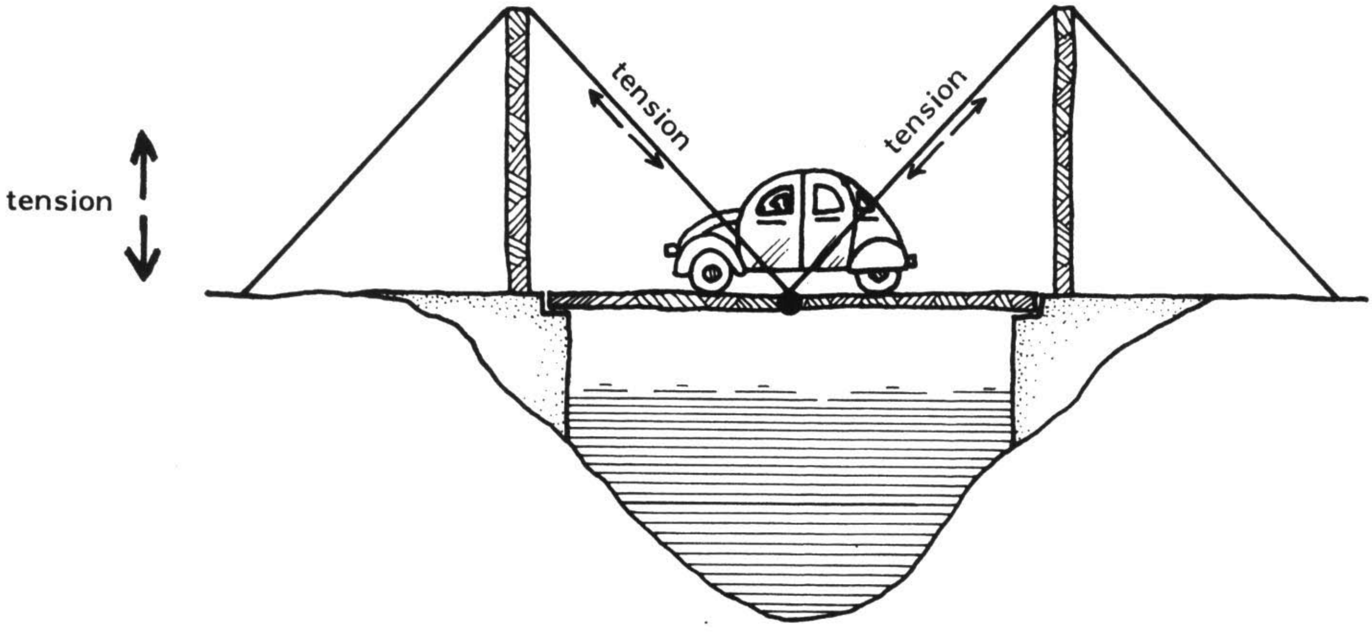
The men in the photograph are involved in a tug-of-war. The men at the other end of the rope are also pulling as hard as they can. The rope between the two teams is under a lot of stress, but fortunately it is good at withstanding tension.

experiment 3 **Tension and materials**

Test the materials listed in experiment 2 for tensile stress. Which of these materials would you use to make the stays of a stayed girder bridge?

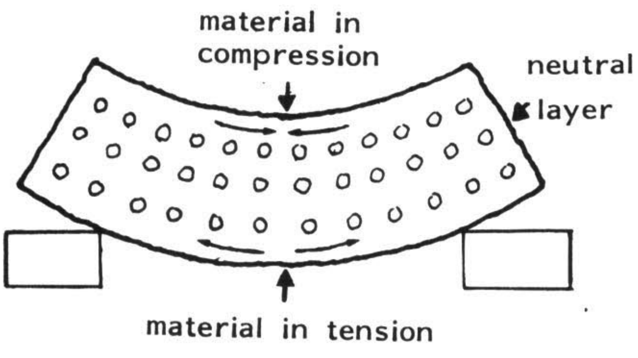
task 2 Which of the materials listed in task 1 are suitable for use in stayed girder bridges and which are not? What is your conclusion about the resistance of these materials to tensile stress?

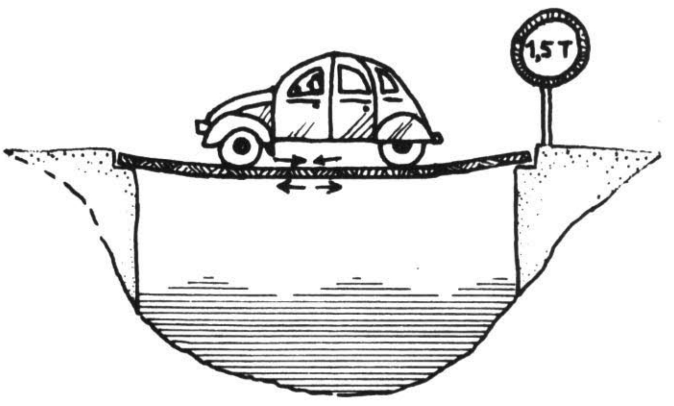
If a bridge element is subjected to tension, we will indicate this by two arrows pointing away from each other.



1.3 BENDING

In Experiment 1 we found that a load on a foam-rubber bridge-deck compresses the top layers of the bridge-deck and stretches the lower layers: the material is in compression at the top and in tension below.

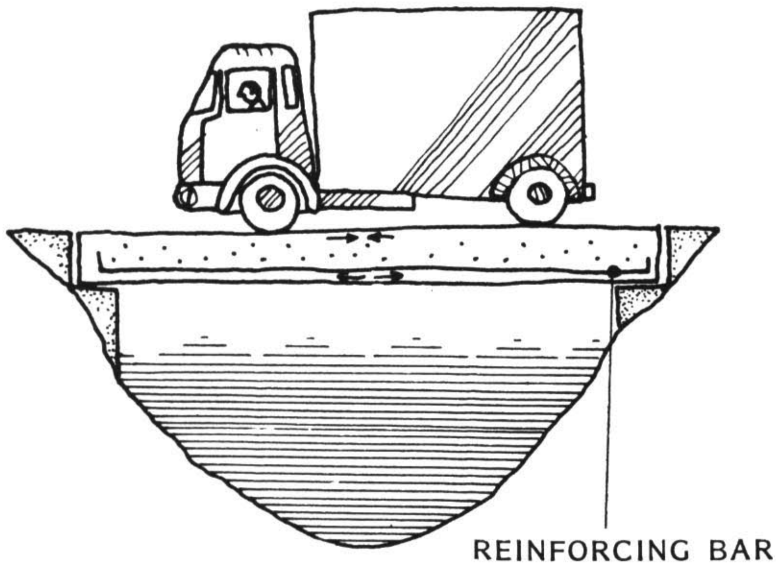




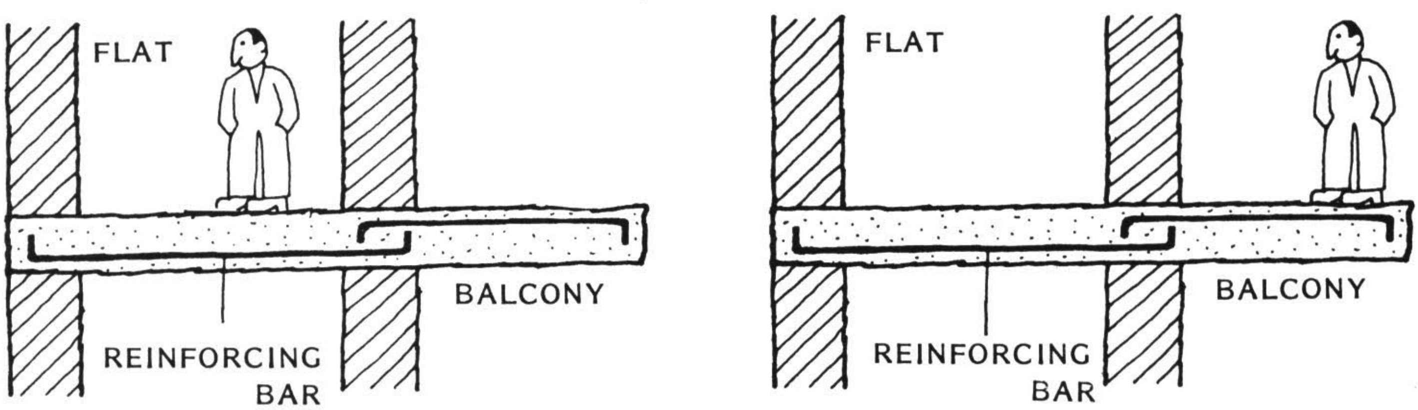
When a bridge-deck bends, it undergoes compressive and tensile stresses.

Bending is a combination of compression and tension. A material which is not good at withstanding compression (e.g. paper) or tension (e.g. stone) is also bad at withstanding bending stresses. Only materials which are strong under both compression and tension (e.g. wood or iron) are suitable for the construction of bridge-decks.

Concrete is weak under tension, and therefore weak when made to bend. Yet many roadways are made of concrete. This concrete needs to be reinforced with steel rods, which are positioned in the lower layers of the concrete to absorb the tensile stress. The compressive stress in the top layers of the roadway can be easily handled by the concrete itself. Reinforcement makes the concrete much stronger. Text nr. 2 in the Reading section deals with the technology of "prestressed" concrete.



Iron bars or rods are also used in concrete floors of houses, and in concrete beams.



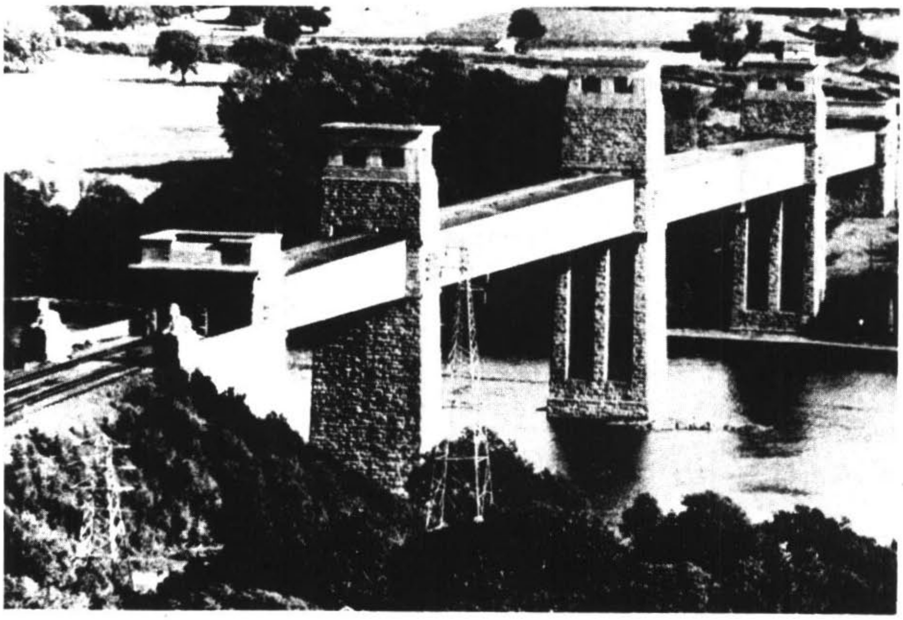
task 3 Explain why the reinforcing rod is positioned at the top of the balcony beam but at the bottom of the floor beam.

2 strength and shape

In this chapter you will find out how bridges can be strengthened, and you'll learn how important the shape of a bridge is.
Also, you are going to apply what you have learned about stresses in materials in chapter 1.

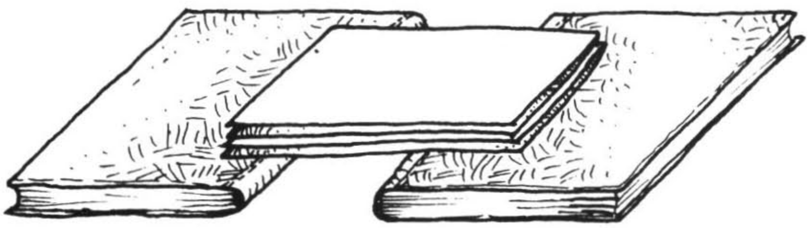
2.1 ROOFED BRIDGES

In the bridge on the photograph, the railway is roofed. This is not just a shelter against the rain, it also makes the bridge stronger. In the next experiment you will find out why.



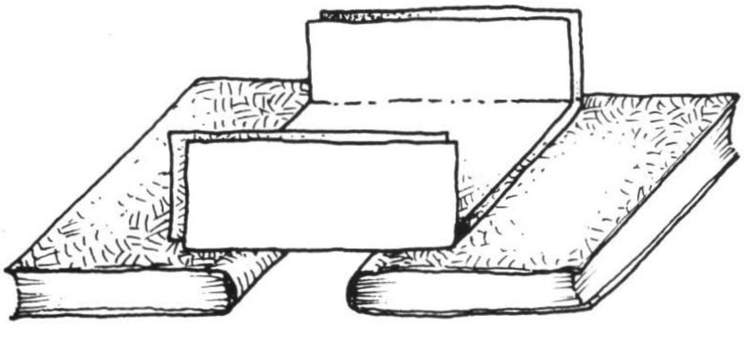
Brittannia bridge in England (see Reading Text 5)

experiment 1 A paper bridge

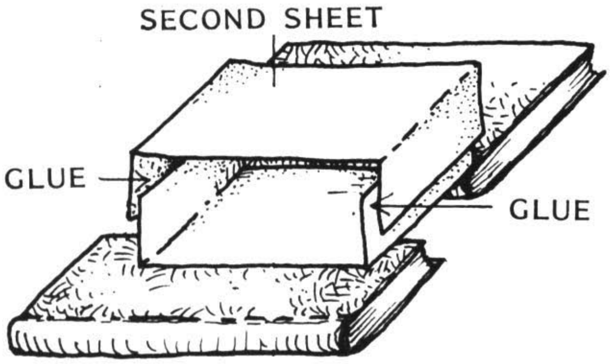


You should use the same amount of material, otherwise you won't be able to make a fair comparison.

- Make a "bridge" of two folded sheets of paper, resting on two books. Will this make a strong bridge?
- Then fold the sheets as shown below.



Will this make the bridge stronger?
What will happen to the raised edges if you put too much load on the bridge?
In what part of the edges do you notice tensile stress?
Where do you notice compressive stress? How can you tell?



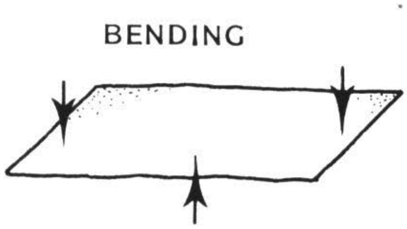
- Now reinforce your bridge by glueing the two sheets of paper together to form a tube.

Has the bridge become stronger?

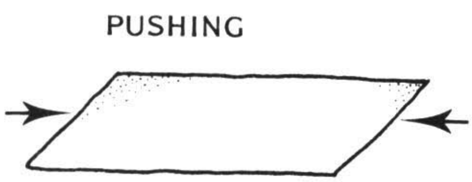
- How can you reinforce your bridge even more?

In this experiment, you have strengthened a flat sheet by folding it into a rectangular shape. Paper isn't a very strong material, yet it is strong enough to make a fairly strong bridge. There are many ways you can change the shape of a sheet of paper; some are difficult, some are easy.

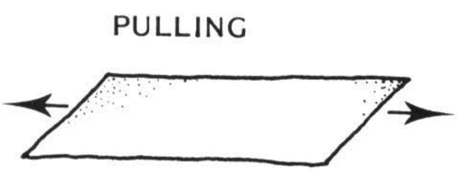
Deforming paper



Paper bends easily

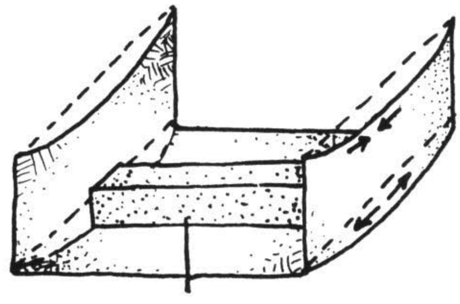


Paper buckles easily when compressed (pushed)



Paper will tear only if you pull hard. It doesn't deform easily under tensile stress.

These characteristics of paper explain how, in the experiment, your bridge became stronger when the edges were raised. You created tensile stress in the lower part of the edges. This prevented the bridge from bending, since paper withstands tension better than compression and deflection. So to make your bridge as strong as possible, you must choose the shape which is best at subjecting the paper to tensile stress.



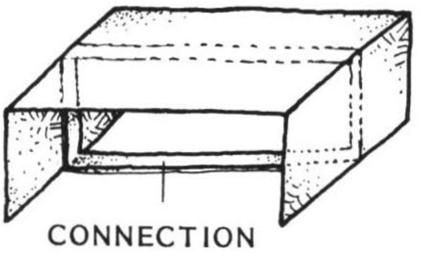
When the bridge is too heavily loaded, the upper part of the paper starts to buckle. You can help to prevent this by glueing the second sheet of paper on top of the first one. Part of the tensile stress will be transmitted to the second sheet. As you see, paper is fairly strong, so long as it is tube-shaped.

In other materials too, shape can add considerably to strength. The Brittannia bridge (reading text 5) has a tube made of steel. Steel is much stronger than paper and also withstands compression much better. In the reading text you will read how a big fire affected the strength of the Brittannia bridge.

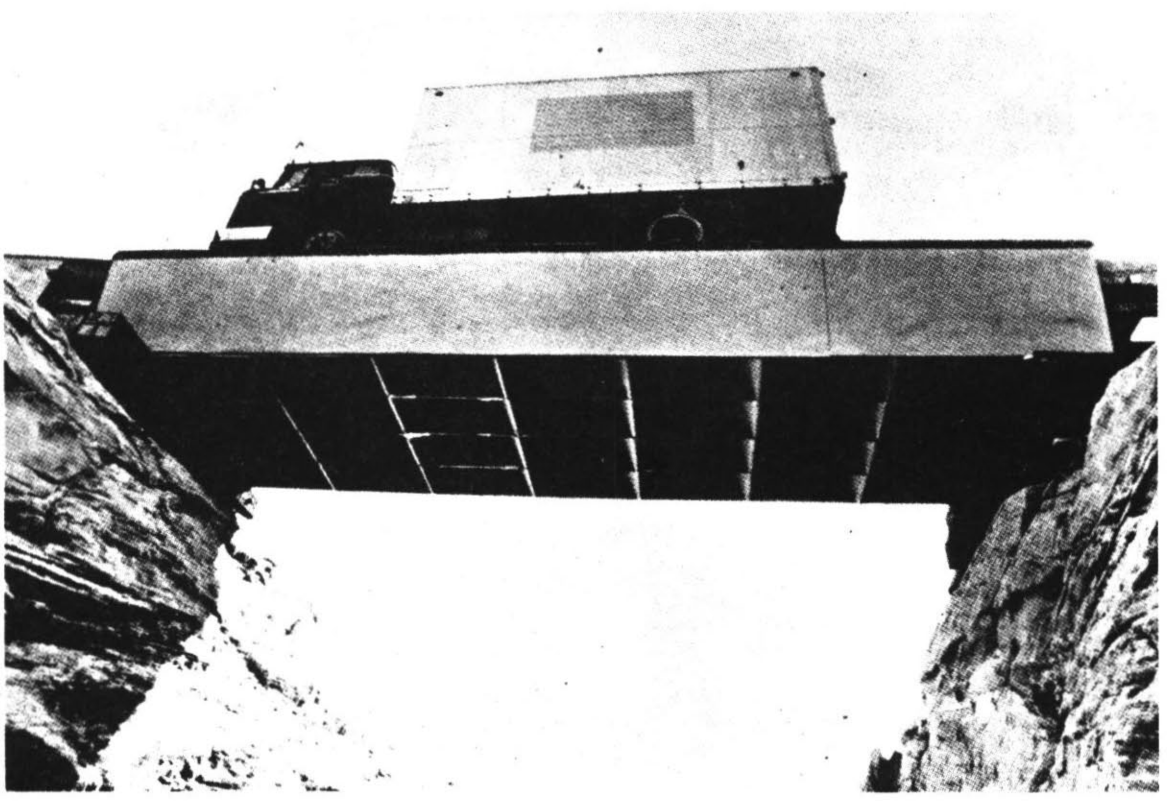
task 1 - Is the bridge in this photograph stronger with the railings than without?
- Are the railings under tension or under compression when the bridge is loaded?

2.2 BRIDGE-DECKS

Bridges are stronger when the bridge-decks have raised edges. Connections between the edges make them even stronger.

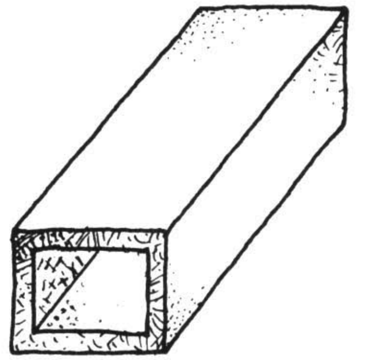


task 2 Point out the edges and the connections on the photograph
What would happen if there were no connections?
Indicate which parts are under tension and which under compression.



A bridge made from paper and glue only! It is about 10 m long and 5 m wide; it can hold a 4-ton lorry. Its own weight is 200 kgs.

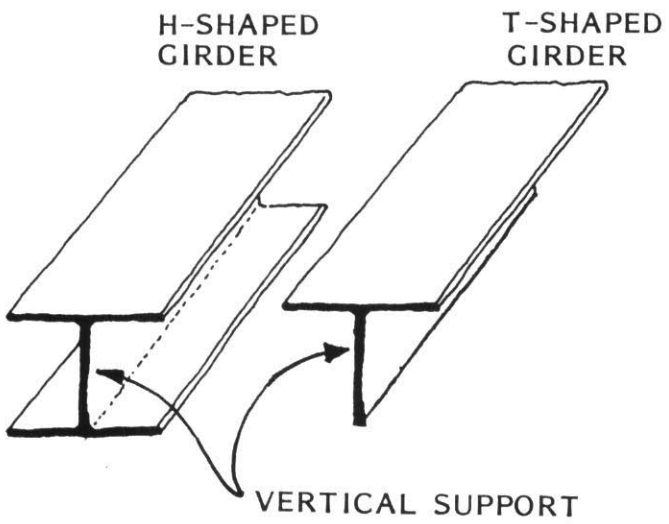
Under the concrete decks of some bridges you can see concrete tubes, which prevent the deck from bending. They make the bridge-deck thicker withoud making it too much heavier.

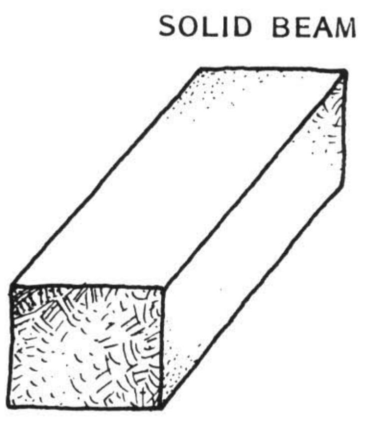


Concrete tubes underneath a motorway flyover in Utrecht.

task 3 Where exactly do you think the steel rods are in the concrete tubes: in the upper part, in the lower part or in the sides?

In iron bridges, you'll often see H or T-shaped girders. These are almost as strong as solid beams, but much lighter and far less bulky. A great deal of the strength of solid beams is used to support their own weight, so they are not often used.



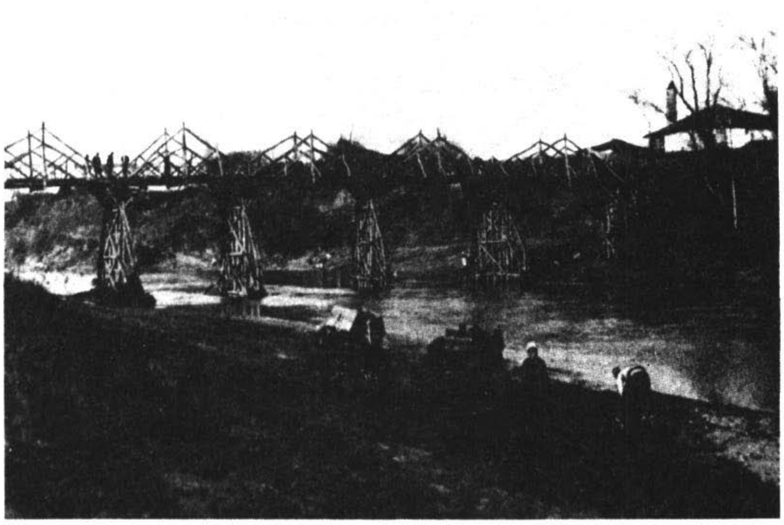


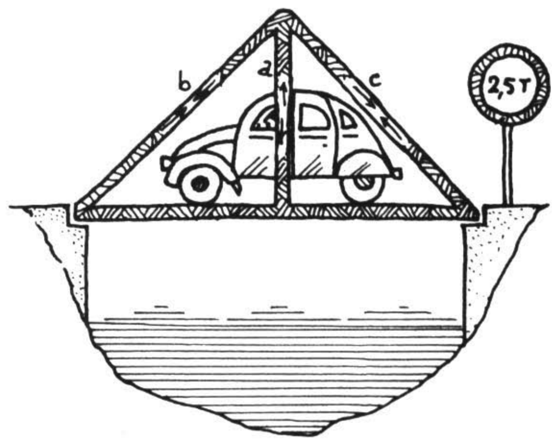
<u>experiment 2</u> Make an H-shaped paper girder and load it. Where is it exposed to tension and where to compression? How can you tell?
What can you do to prevent the paper flattening?

task 4 Why do you think iron bars or cables are used in bridge elements under tension, and H or T-shaped girders in elements under compression or bending stresses?

2.3 TRUSSES

The Brittannia bridge (see page 36 and reading text 5) is strengthened by raised sides made of steel plates, for which a lot of iron was required. Strong sides can also be made using less material. This is done in the construction of truss bridges (see p. 45).
The basic shape of the truss bridge is shown in the photograph and the drawing below.



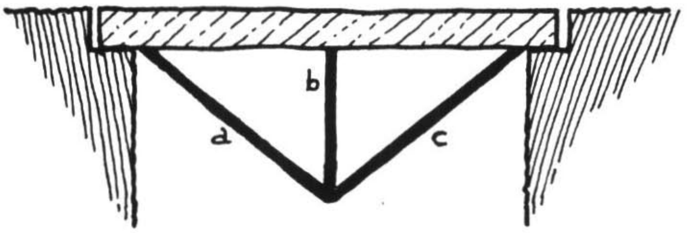


Primitive wooden truss bridge in Albania

The sides of the primitive truss bridge are made of wooden stakes, reinforcing the bridge-deck at the centre (the drawing shows how the forces work).
The weight of the car makes the bridge-deck bend down. Member A moves down too, but is held back by members B and C; therefore, the bridge-deck does not bend so much. Member A is under tension, B and C are under compression.
The weight of the load is transmitted to the piers by the truss and also by the roadway.

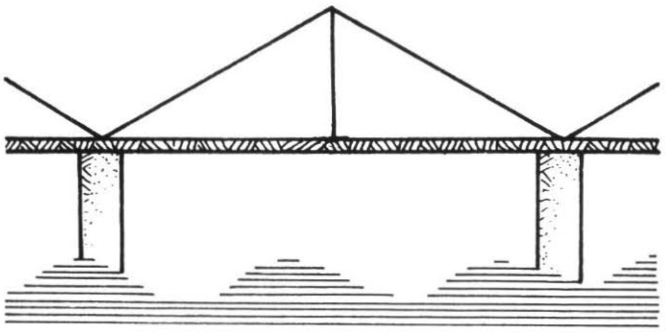
task 5 Which of the members A, B and C could be replaced by a cable?

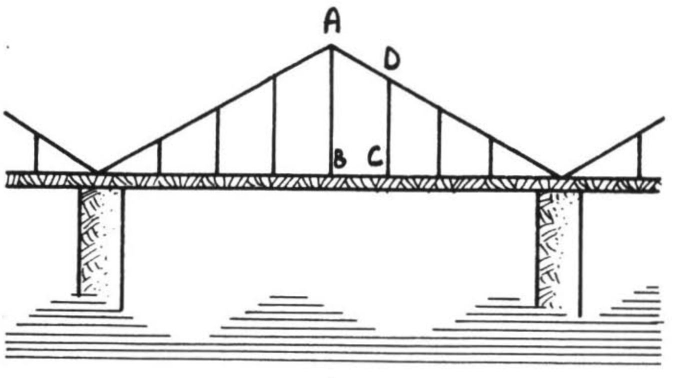
task 6 A bridge-deck can also be reinforced by a truss on the underside. Indicate which members, in the drawing below, are under tension and which are under compression.

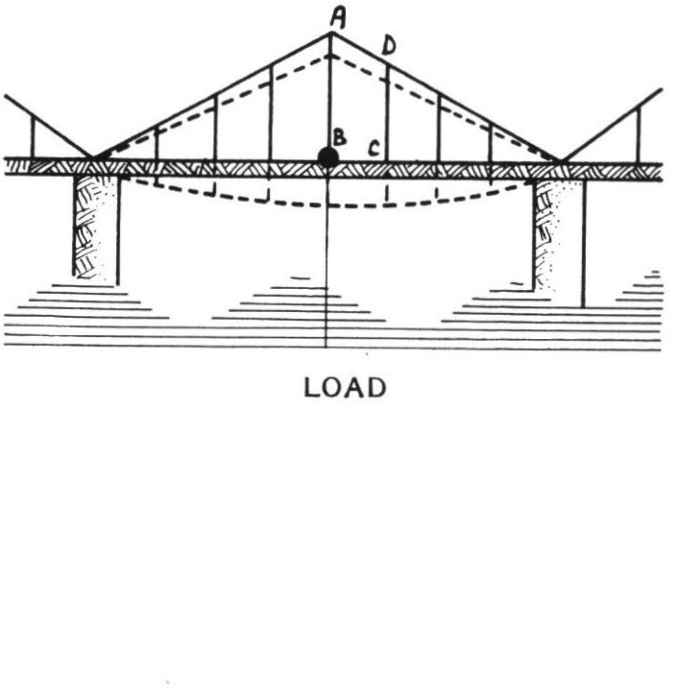


When the span is very long, additional vertical connections give extra strength to the truss.

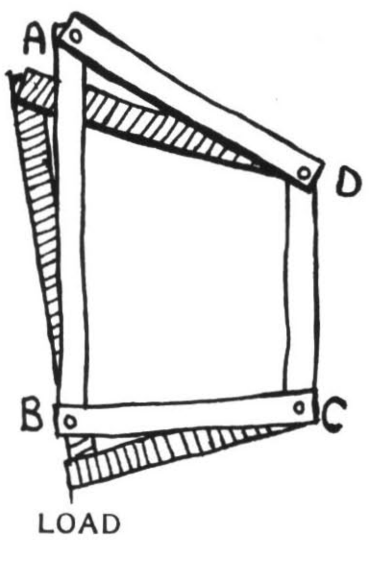
Look at the shape ABCD in the drawing below. Shapes like this tend to deform easily, but it is easy to make them stronger. You will see how in the next experiment.





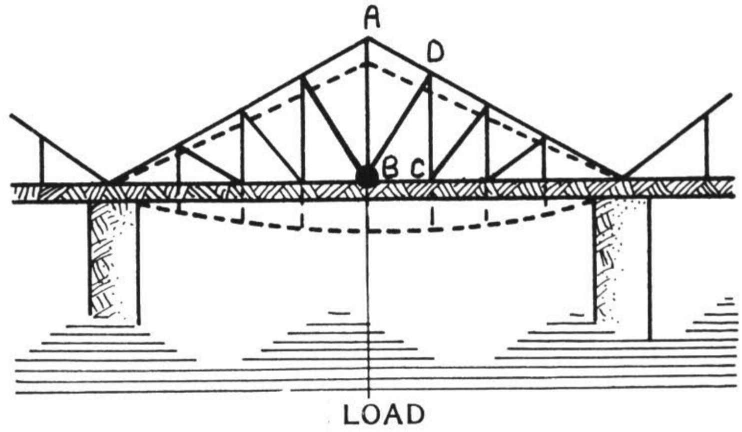


experiment 3

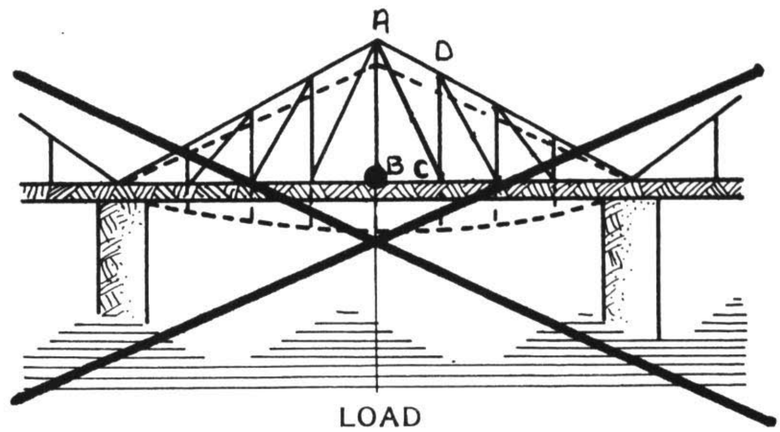


- Pull down at B while holding CD. See how the shape deforms.
- Fit in a bar BD and compare the strength of this construction to the former one.
- Fit in a bar AC and compare again. Can bar BD be replaced by a rope? And AC? Try it.

By fitting a diagonal bar, you create two triangles. A triangle is a very strong shape, which is why it is often used in bridges and other constructions such as cranes, roofs etc.
So the bridge can be strengthened like this:



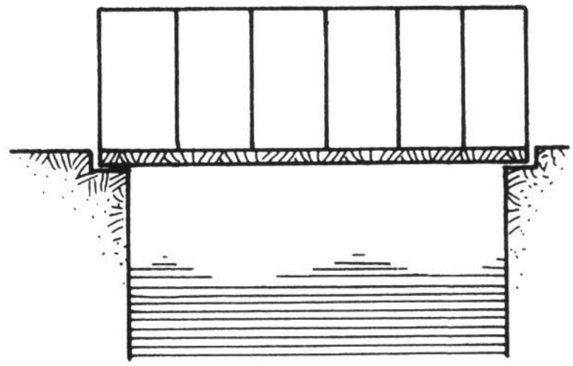
but not like this:



If the bridge is loaded at point B - e.g. by a car - the shape ABCD deforms, AC becoming shorter and BD longer. (Check this with your results from experiment 3.)
This means that member AC is under compression, whereas BD is under tension. Iron is strong under compression, but even stronger under tension. Besides, tension can be absorbed by a simple bar, whereas compression usually requires an H-shaped beam, which makes the bridge bulkier and heavier. That is why it makes more sense to use a bar BD. Besides, BD transfers the weight of the load towards the piers, unlike AC!

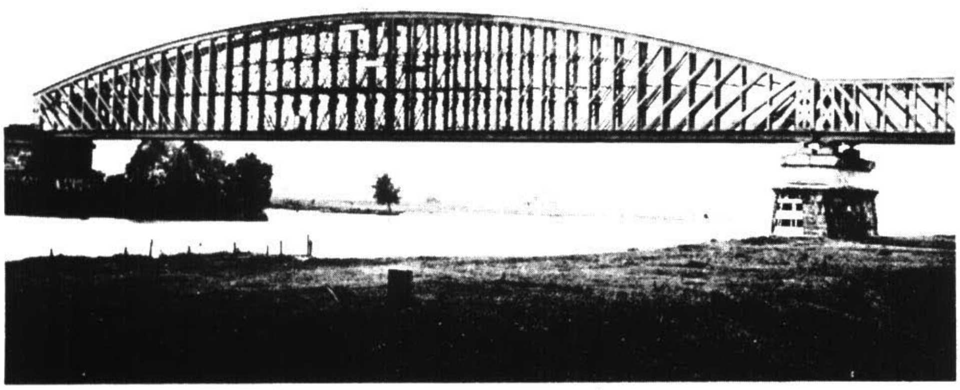
task 7

How could you fit in additional bars to reinforce the bridge in the drawing on the right? Will these bars be exposed to tension or to compression? Compare your solution to the photograph of the Moerdijk bridge in Reading Text 3.



2.4 ARCHES

In a trussed arch bridge, the triangular shape of the truss is replaced by an arch. An example of a trussed arch bridge is the railway bridge at Culemborg.

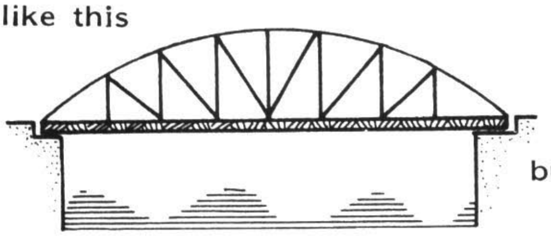


The railway bridge at Culemborg (1865) is the oldest railway bridge in the Netherlands. This trussed arch bridge is still in use.

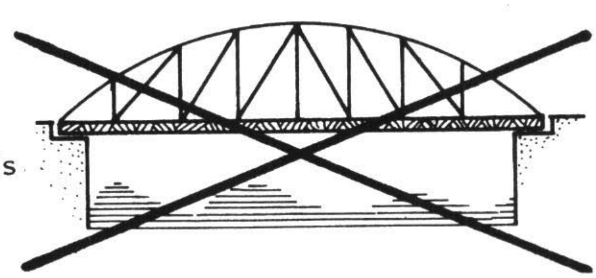
task 8 Explain why the bars towards the outside are thicker than those in the middle.

task 9 As you can see in the photograph of the Culemborg bridge, the bars are positioned to both left and right of the centre, pointing towards the centre of the bridge-deck. Explain why they are positioned like this:

like this

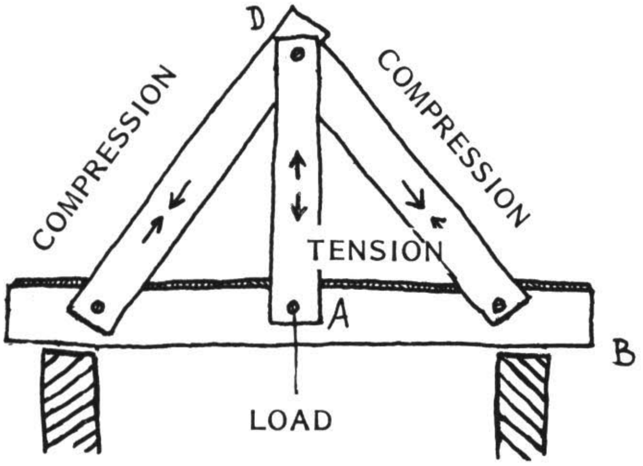


but not like this



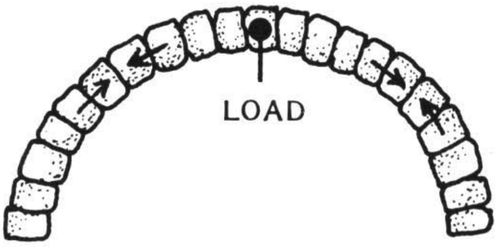
The arch is a stronger shape than the triangle. The experiment below tells you why:

experiment 4 Make a model of a truss bridge, as in the drawing. Load the triangle by suspending weights from A. Find out which are the weakest points in the triangle.

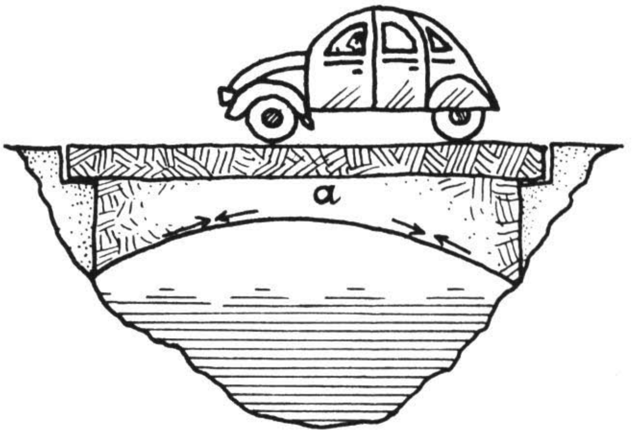


The bridge is loaded at A, generating tensile stress in AD and compressive stress in DC and DB. This has the effect of transferring the weight to the piers. Points B, C and D are exposed to stress from different directions and must be able to withstand all this stress.

In an arch, the compressive stress is spread over the arch as a whole. This is true both for arches above bridge-decks and for arches underneath bridge-decks.



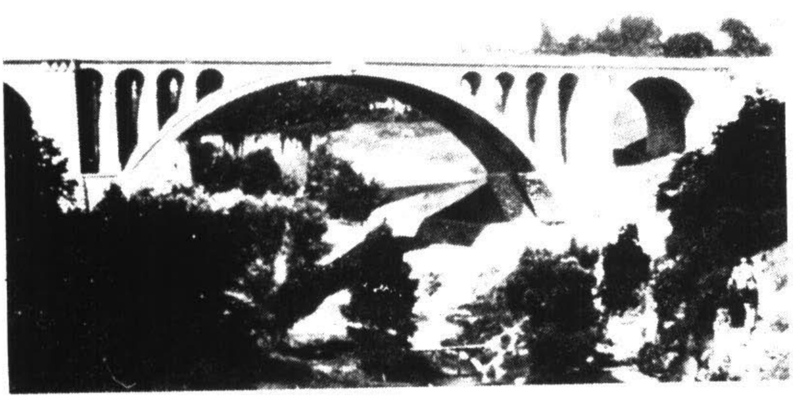
The bridge-deck is compressed a little by the car's weight, resulting in a slight compression of arch A. If the material the arch is made of is strong enough, the bridge-deck will not be affected by this compression.



This principle (with suspended as well as supported bridge-decks) is widely used in the construction of bridges.

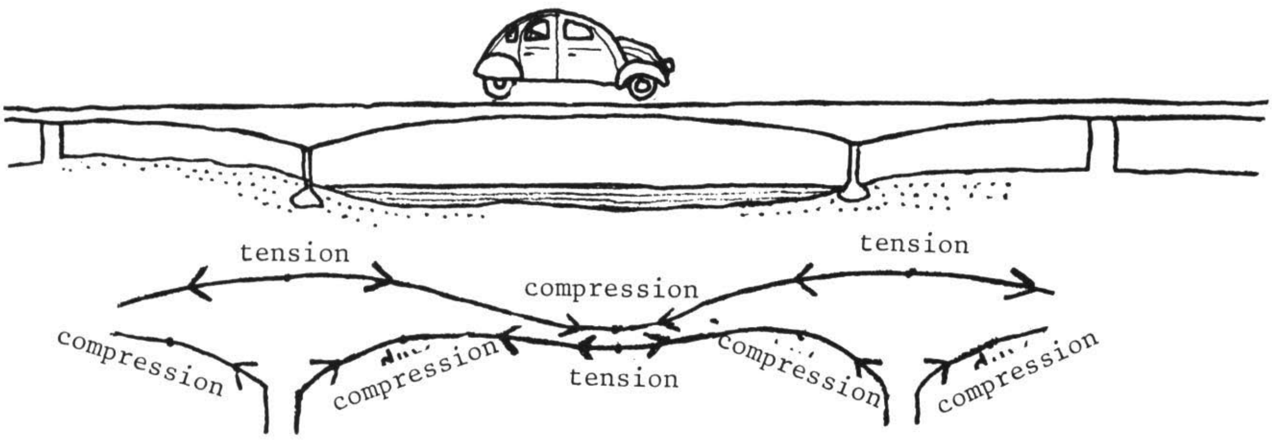
task 10 Examine these two bridges and work out what stresses the different elements are exposed to.

The Twente-canal bridge. The bridge-deck is suspended from the arch. Notice how the arch is supported by the piers.



Stone arch bridge, Pont Adolphus, Luxemburg, 1903.

In the drawing below, you see an (axaggerated) diagram of the forces occurring in a special type of arch bridge.



The combination of forces prevents the bridge collapsing under the car's weight. The weight is transferred to the piers.

task 11 Indicate the places where the concrete in the bridge above needs to be reinforced with iron rods.

2.5 STRENGTH AND MATERIAL

You have learned from the experiments that strong bridges can be made using "weak" material such as paper of cardboard. Yet these materials are never used in real bridges. The reason is not only that real bridge materials need to be much stronger still, but also that the materials in real bridges need to satisfy other requirements as well. They should, for instance, be highly resistant to fire and to moisture. That is why cardboard is not used at all, and wood only rarely, in bridge-building.
Two other reasons for not using wood are the maintenance it requires and the way it swells when it gets wet. A wooden bridge deforms considerably when the wood swells due to moisture.
A final factor which is important in the choice of material is the cost.
Materials commonly used for bridge-building are:

stone: very durable, strong under compression, but weaker under tension.

concrete: very durable, strong under compression, but weaker under tension. An advantage over stone is that it can be cast in any desired shape and can be reinforced with iron rods.

iron or steel: strong under both compression and tension. Requires quite some maintenance.

The qualities of iron and concrete are often combined in reinforced concrete. The reinforcement is positioned where the bridge is exposed to tension. So the iron instead of the concrete absorbs the tension.

Often, the steel bars in bridges are positioned in such a way as to experience tension; stone and concrete to experience compression. Cables are used only where they will experience tension. Steel under compression is usually in the form of T of H-shaped girders rather than bars.

task 12 Check this by looking at some of the bridges in the photographs in this book.

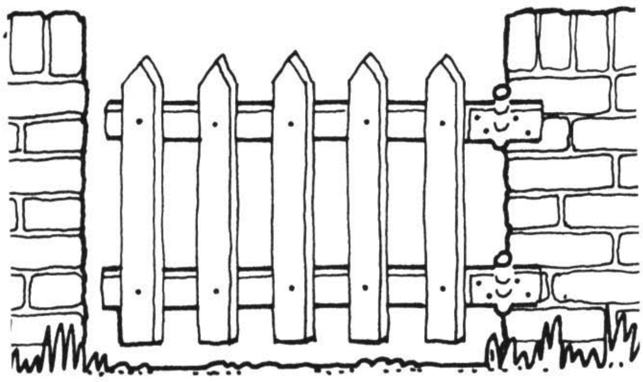
exercises

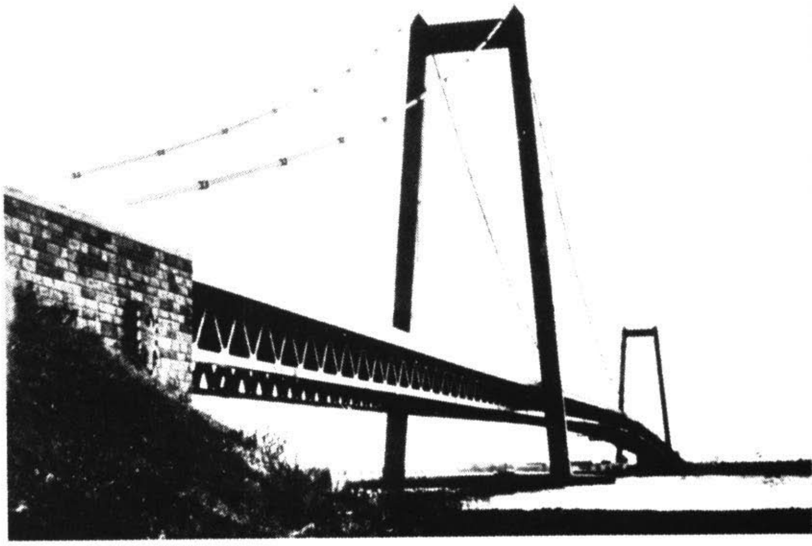
1. Explain why the arch of the Twente canal bridge is made of concrete. Why are the cables made of steel?
2. Why was an arch chosen instead of two slanting beams?

Trussed arch bridge

3. The bridge in the photograph above has strong upright "edges". In the central part, the edges point upwards, in the right part downwards, below the roadway. Explain (using your knowledge of tensile and compressive forces) why it makes more sense to construct bridges with downward edges. Why then were upward edges used in the central part of this bridge? Why is the support in the central part higher than in the righthand part?

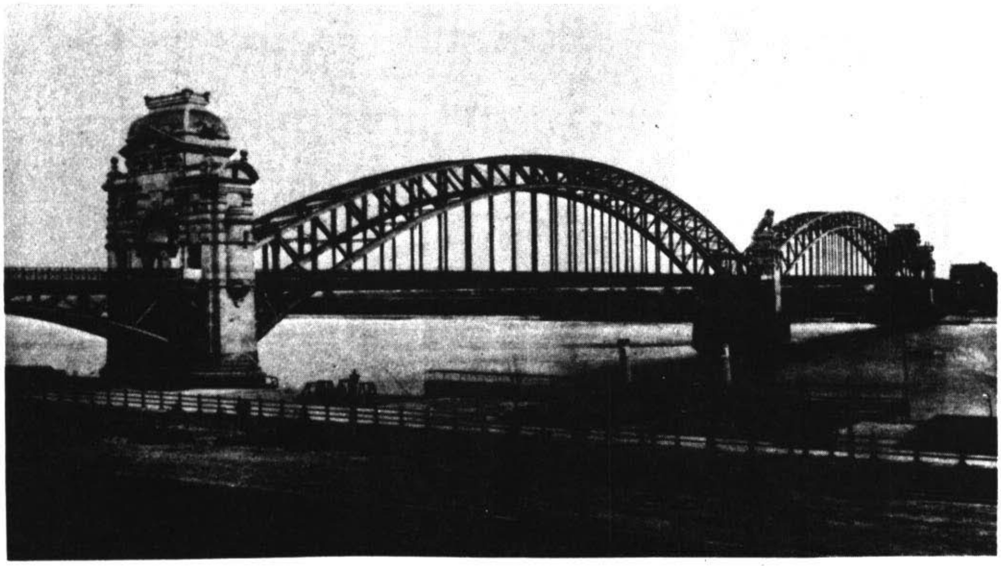
4. The carpenter has made a hinged garden gate using loose boards (see the drawing). How can this gate be strengthened by fitting in just one more board? Check the garden gates near school or near where you live!
6. Look at the suspension bridge below and work out which parts of the bridge are under compression and which are under tension. Consider the pylons, the suspending stays and the vertical cables between the bridge-deck and the stays. Notice the material used for each part.



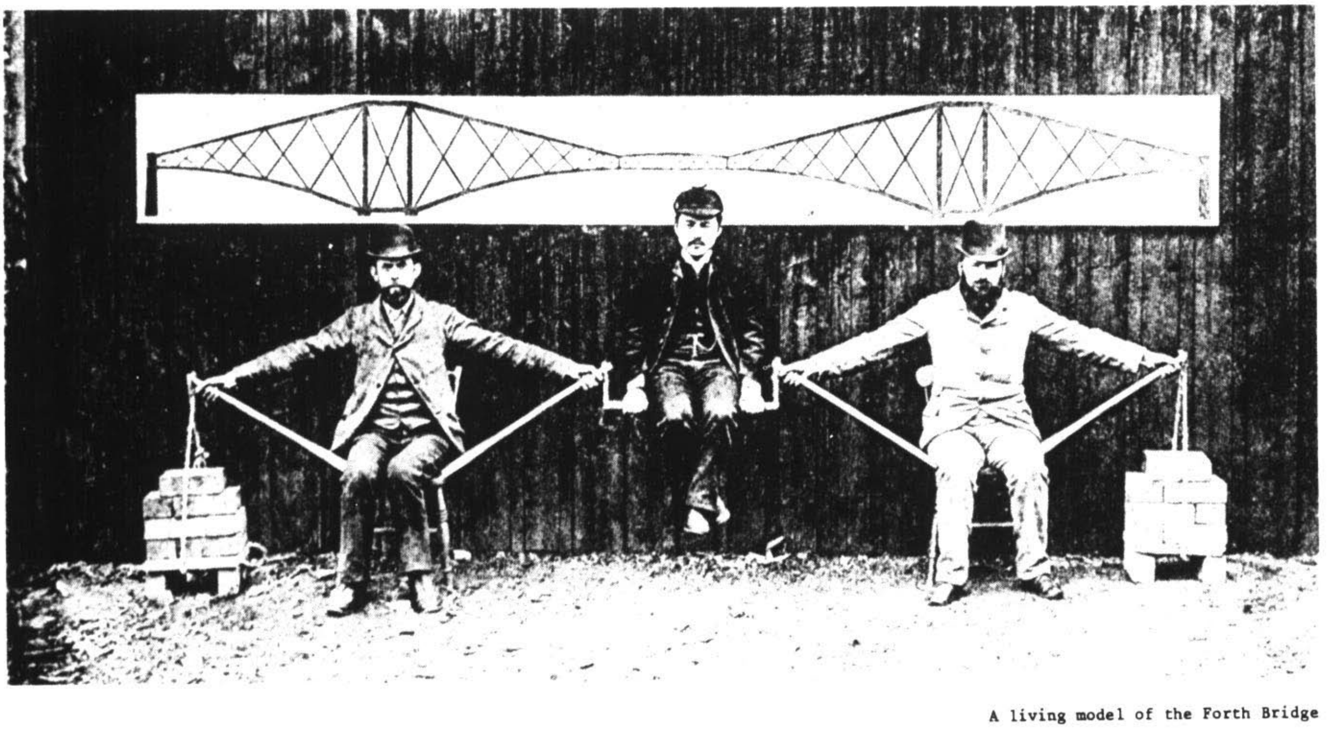


Suspension bridge over the river Rhine, Emmerich, 1965.

5. Work out which elements of the bridge in the photograph below are under compression, and which are under tension. Consider the arch, the bars between arch and bridge-deck, and the piers.
What materials are these different parts of the bridge made of? Do you see any parts that are there just for decoration, so that the bridge would be as strong without them?



The Forth Bridge over the Firth of Forth near Queensferry (constructed in 1890).



A living model of the Forth Bridge

INVESTIGATIONS

contents

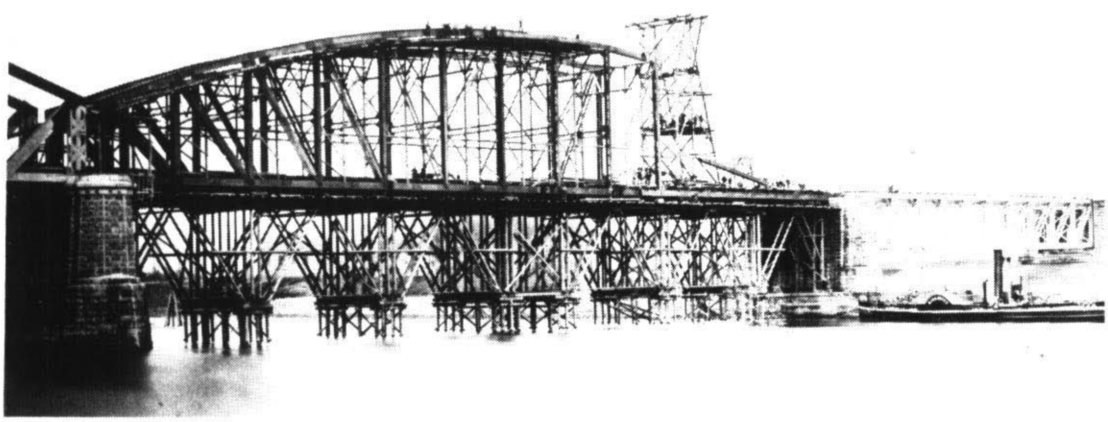
1 building, loading and reinforcing a bridge

1.1 BUILDING A BRIDGE: A BUILDING SCHEME

In this investigation, your group is going to build a bridge. You may choose one of the bridges shown in the Orientation section, or you may pick any other one, e.g. one near your school. It is important that you know exactly how the bridge is put together and what the function of each part is.

If more than one group chooses to build a bridge, you can make a competition of it. Which one holds the heaviest load?
Before starting the competition, make sure you agree on the following points:

- Length of the span
- Width of the bridge-deck
- Materials used (e.g. paper, cardboard, glue, staples, rope)
- Time allowed for the construction
- Is the bridge to be movable?
- Will bridges of the same type be compared, or of different types?

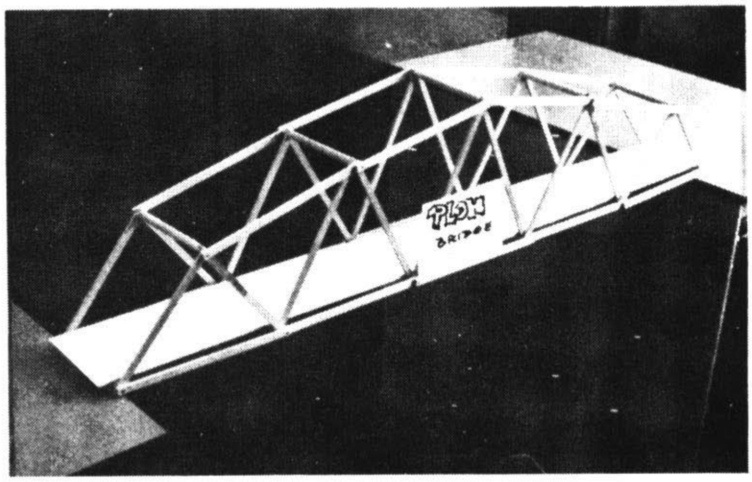


A bridge under construction around the turn of the century.
Each part delivered to the site is ready to be fitted into the structure. The construction strictly follows the building scheme.

As soon as all this has been settled, the group can proceed to draw up a *building scheme*. If you start building right away, things will certainly go wrong! Before the construction of a real bridge, there are years of designing, calculating and preparing.

A building scheme may contain the following points:

- a detailed design of the bridge. Indicate for each part the material you are going to use.
- a list of the materials needed (amounts, dimensions, etc.)
- information on where you will get the materials and who will take care of this.
- the order in which the different parts are to be constructed and assembled.
- a division of tasks within the group.
- tasks to be done at school and at home.



This is a photograph of a simple bridge-model.

- What type of bridge is it?
- What materials are used in its construction?

1.2 BUILDING YOUR BRIDGE

Building a successful bridge means: be cooperative and listen to each other! Stick to the building scheme. If, during the process, the scheme turns out to be wrong, change it together. Write down in your report why it had to be changed.

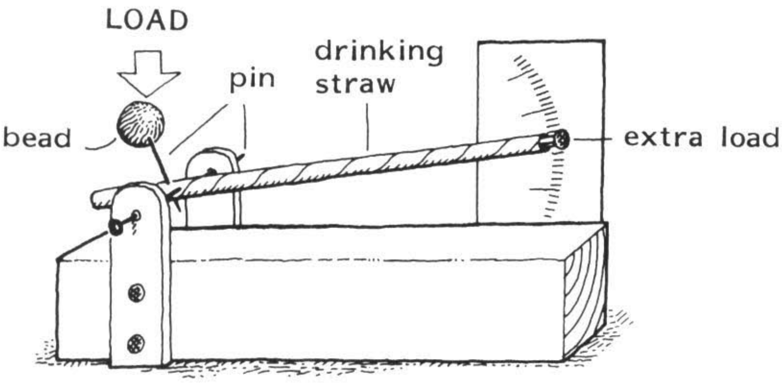
1.3 LOADING YOUR BRIDGE

When the bridge is finished, you load it by suspending from it a bucket filled with weights or sand. Measure the weight you have applied by means of a spring balance. Your bridge will bend under the load: the tensile and compressive stresses will transmit the weight of the load to the piers. You can measure the bending using a bending gauge.

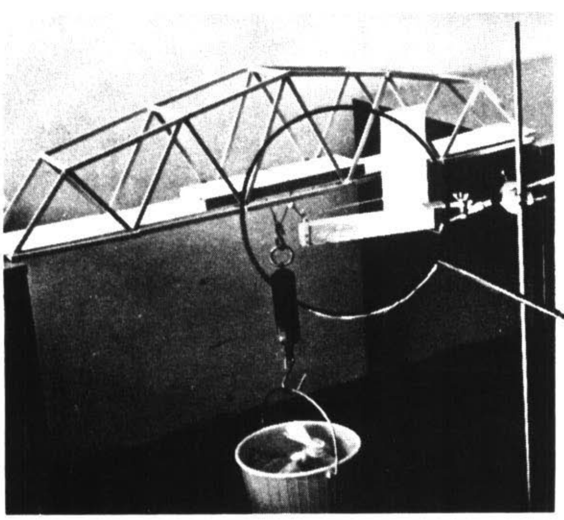
HOW TO MAKE A BENDING GAUGE

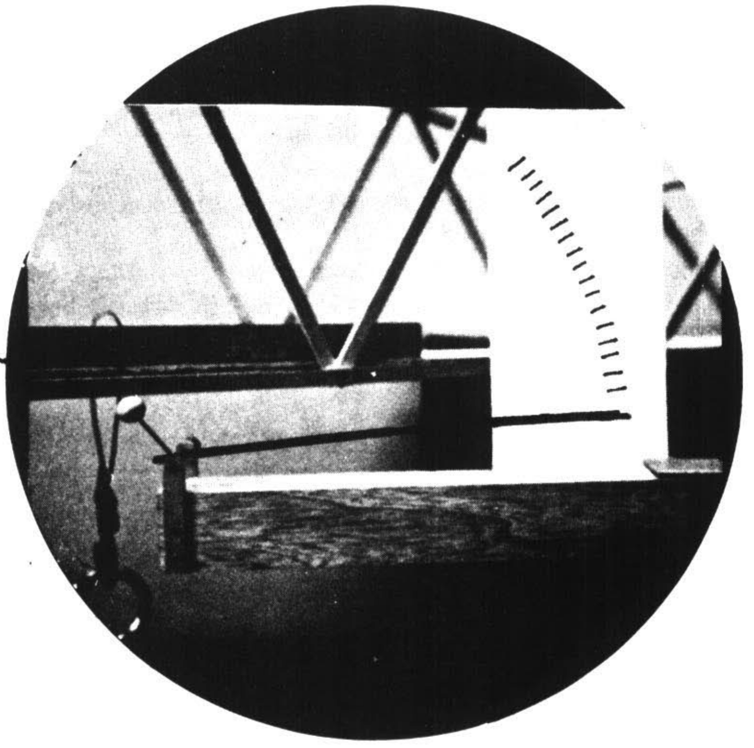
With this gauge, you can measure the bending of a bridge under load. The gauge in this drawing is a sensitive one, so that even a small amount of bending shows on the scale. This is because the axis of rotation of the drinking straw is positioned near the left-hand end.

1. Construct a bending gauge as shown in the drawing.
2. Test the gauge by pushing down the bead 1 cm and marking 1 cm on the scale at the other end of the straw. Do the same for a series of other values, 0,5 cm apart. Mark millimetre divisions on the scale.
3. Use this gauge to measure the strength of your bridge-model. If the bending is small when the load is heavy, it means that the bridge is strong.



Load the bridge until it is just on the point of collapsing (but don't make it collapse). Watch carefully how and where the parts deform. Check whether these deformations are due to tension, to compression or to bending (a combination of tension and compression).





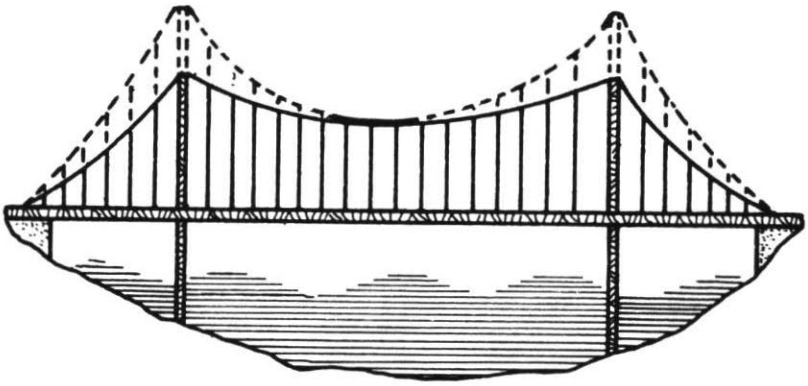
The PLON-bridge loaded. The bending gauge is clearly visible in the enlarged photograph.

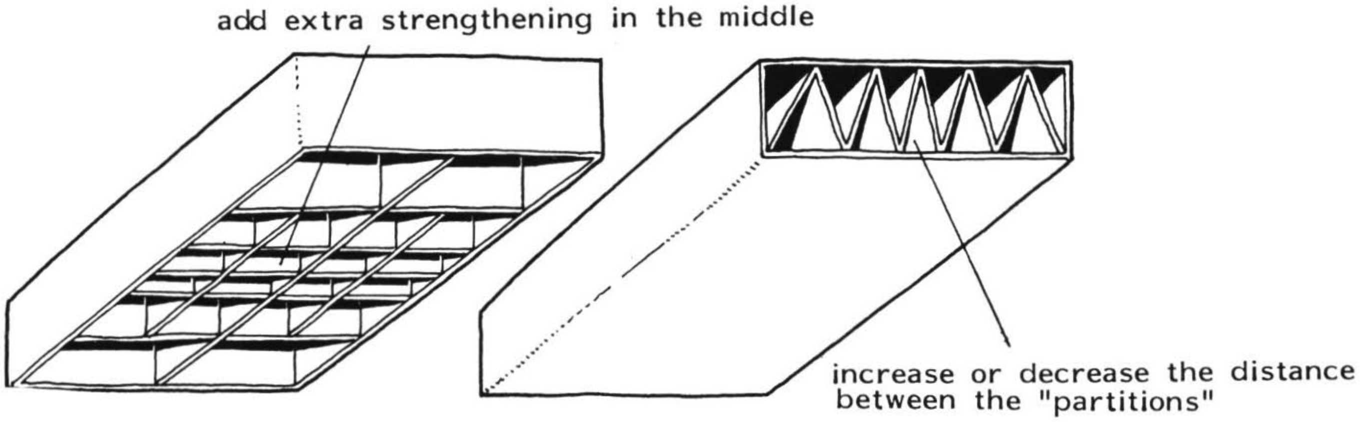
1.4 IMPROVING YOUR BRIDGE

a. *strengthening the bridge.*

Try to strengthen the bridge. It is most important to strengthen it at those places where there is most deformation. Think of ways to strengthen these parts, bearing in mind what you have learned in the Theory section about tension and compression, shapes, and the principle of moments.

A few suggestions:
- tubes underneath the roadway
- tall or short pylons (for a stayed girder bridge)
- additional cross-connections





As you make each modification check whether your bridge has really become stronger. Did your theory work? If not, what could be the reason?

b. *decreasing the bridge's weight*

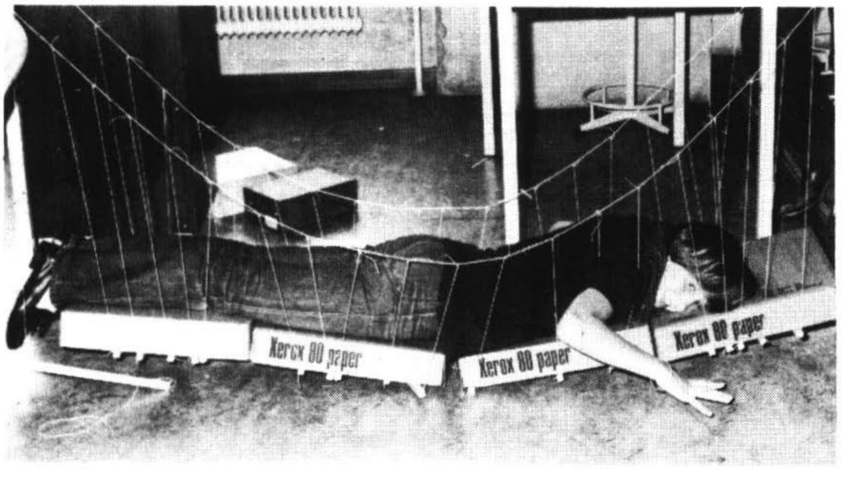
Even without any load, the bridge-deck bends a little because of its own weight. That is why you should try and make your bridge as light as possible, without, however, affecting its strength. Use what you know about the theory to think of possible modifications.

A few suggestions:
- replace bars under tension by ropes
- replace bars under compression by non-solid (H-shaped) bars
- leave out unnecessary bars and other parts

As you make each modification check that your bridge has really decreased in weight (but not in strength!). Did your theory work? If not, what could be the reason?

1.5 COMPARING BRIDGES

Is the bridge which holds the heaviest load automatically the best bridge? This would be true only if we are comparing bridges constructed from the same amount of material. So it is fair to include in your comparison the weight of the bridge itself.
Materials used for real bridges are expensive. That is why bridge designers try to build the strongest possible bridge using the least amount of material.



A suspension bridge made - and loaded - by students of the Niels Stensen High School in Utrecht.

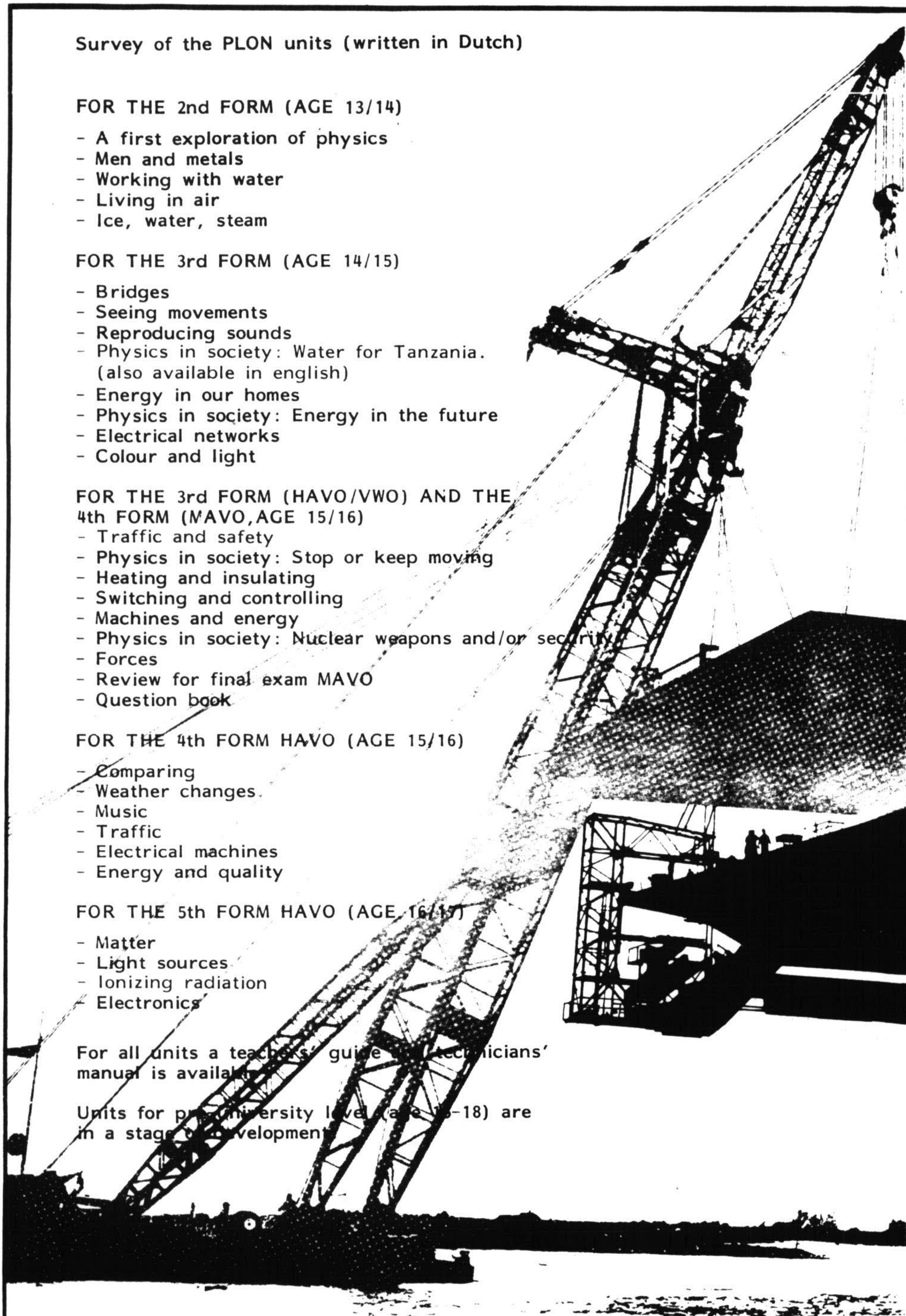
There is a simple method of comparing bridges taking into account both strength <u>and</u> weight: determining the bridge-ratio.

$$\text{bridge-ratio} = \frac{\text{maximum load which the bridge can carry}}{\text{weight of the bridge}} = \frac{\ldots N}{\ldots N} =$$

The bridge made from cardboard shown on page 39 in the Theory section has a ratio of $\frac{40{,}000N}{2{,}000N} = 20$.

- Which bridge is "the best"?
- Are there any other important factors to be included in the comparison?

The new bridge-elements of the Moerdijk bridge (see Reading Text 3) are about the same weight as the old ones. Yet, the new bridge can hold many more cars. This means that the bridge-ratio in the new bridge is better than in the old bridge.



Survey of the PLON units (written in Dutch)

FOR THE 2nd FORM (AGE 13/14)

- A first exploration of physics
- Men and metals
- Working with water
- Living in air
- Ice, water, steam

FOR THE 3rd FORM (AGE 14/15)

- Bridges
- Seeing movements
- Reproducing sounds
- Physics in society: Water for Tanzania. (also available in english)
- Energy in our homes
- Physics in society: Energy in the future
- Electrical networks
- Colour and light

FOR THE 3rd FORM (HAVO/VWO) AND THE 4th FORM (MAVO, AGE 15/16)

- Traffic and safety
- Physics in society: Stop or keep moving
- Heating and insulating
- Switching and controlling
- Machines and energy
- Physics in society: Nuclear weapons and/or security
- Forces
- Review for final exam MAVO
- Question book

FOR THE 4th FORM HAVO (AGE 15/16)

- Comparing
- Weather changes
- Music
- Traffic
- Electrical machines
- Energy and quality

FOR THE 5th FORM HAVO (AGE 16/17)

- Matter
- Light sources
- Ionizing radiation
- Electronics

For all units a teachers' guide and technicians' manual is available.

Units for pre-university level (age 16-18) are in a stage of development.