Simple Bridge Structures

by: Schools Council, Project Technology

Published by:
Heineman Educational Books Ltd.
Schools Council Project Technology
22 Bedford Square
London WC1B 3HH
England

Paper copies are $ 4.25.

Available from:
Heineman Educational Books Ltd.
Schools Council Project Technology
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Project Technology Handbook

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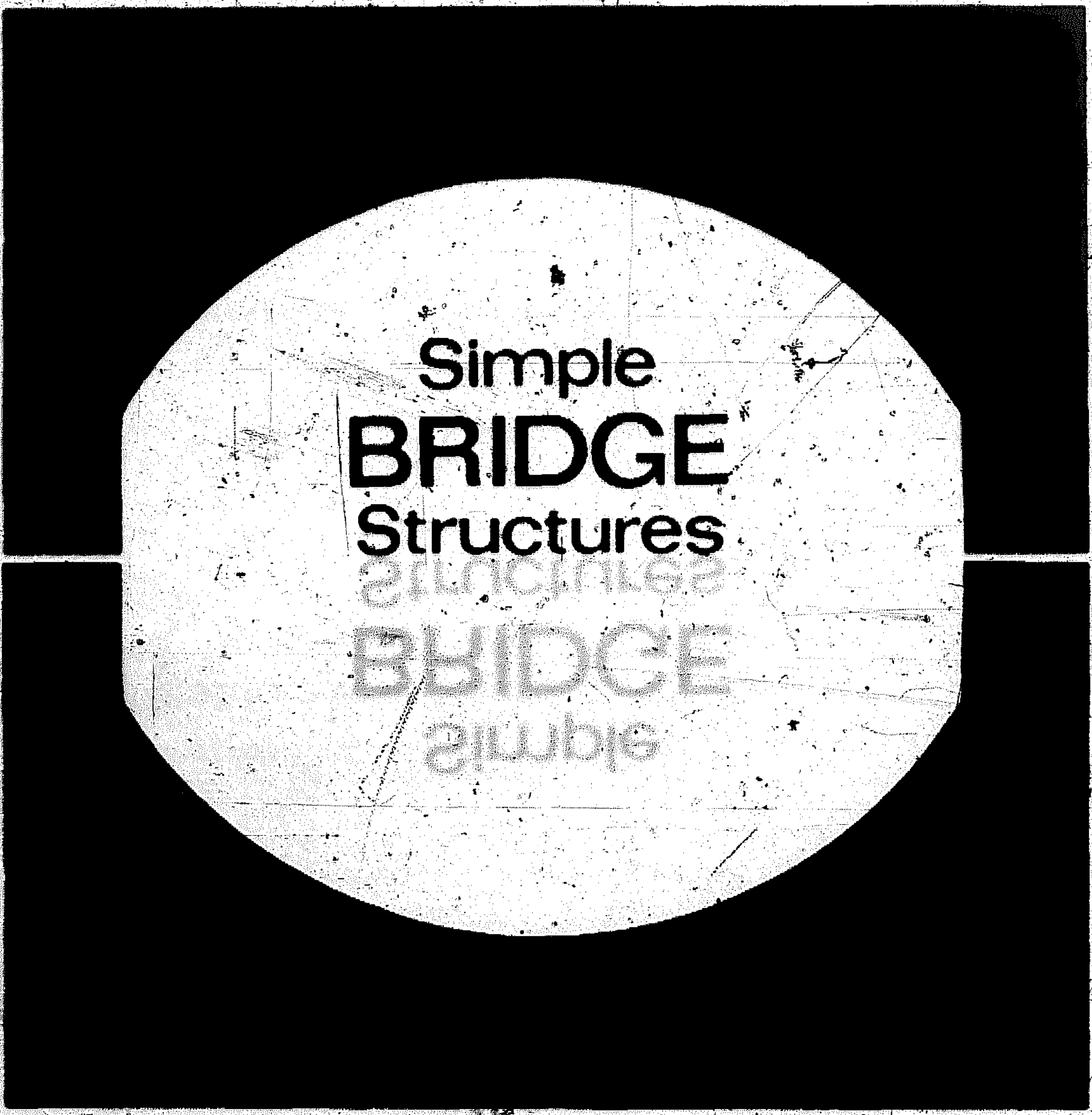

Simple BRIDGE Structures

Foreword

Technological activities are now firmly established in many schools. They have been introduced by diverse methods, and they are here to stay – and to develop further, given the help of publications such as this. Project Technology has at first hand seen the educational value of school technology activities proved beyond all doubt.

Sometimes teachers turn to Project Technology publications for general guidelines, at other times for more specific guidance. Some teachers aim to put over a body of knowledge, while others are concerned to develop in their pupils an attitude of mind and technological know-how invaluable in problem solving. Sometimes technological activities have originated in science departments, sometimes in school workshops, but usually they have developed to embrace or touch upon every department of the school. Project Technology seeks to help teachers achieve the balance natural in their school; and the whole range of teaching material produced by Project Technology should be seen as a means to this end, not the end in itself.

These publications play a vital role in realising the central aims of Project Technology to see that all children become aware of the technological forces of significance for society, to give as many children as possible an opportunity to become involved in the technological design process, and to help all children push forward the frontiers of their own technological resources in terms of both theoretical knowledge and practical skills.

It is hoped that guidance on the construction of equipment will be used, not as explicit directions for teachers to pass on to their pupils, but as a general guide to indicate ways in which such equipment can be developed and used under varying school circumstances.

Similar equipment, having been built, should not then determine the subsequent teaching in any narrow sense. It should be used in a liberating way to enable other work to develop, further investigations to be carried out, and improvements to be made to the basic design.

Many people, particularly those responsible for the diversity of activities in the regional groups of Project Technology, have played important parts in developing and writing our teaching material. To all of them whether they be in the schools, in industry, or in college or university, we are grateful.

This particular publication, *Simple Bridge Structures*, has been based particularly on the work of Mr John Leeks, formerly Trials Development Leader with Project Technology. We are also especially grateful to the staffs of the schools whose work is reported in Section 2.

Schools Council Project Technology
160, Great Portland Street
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August 1972

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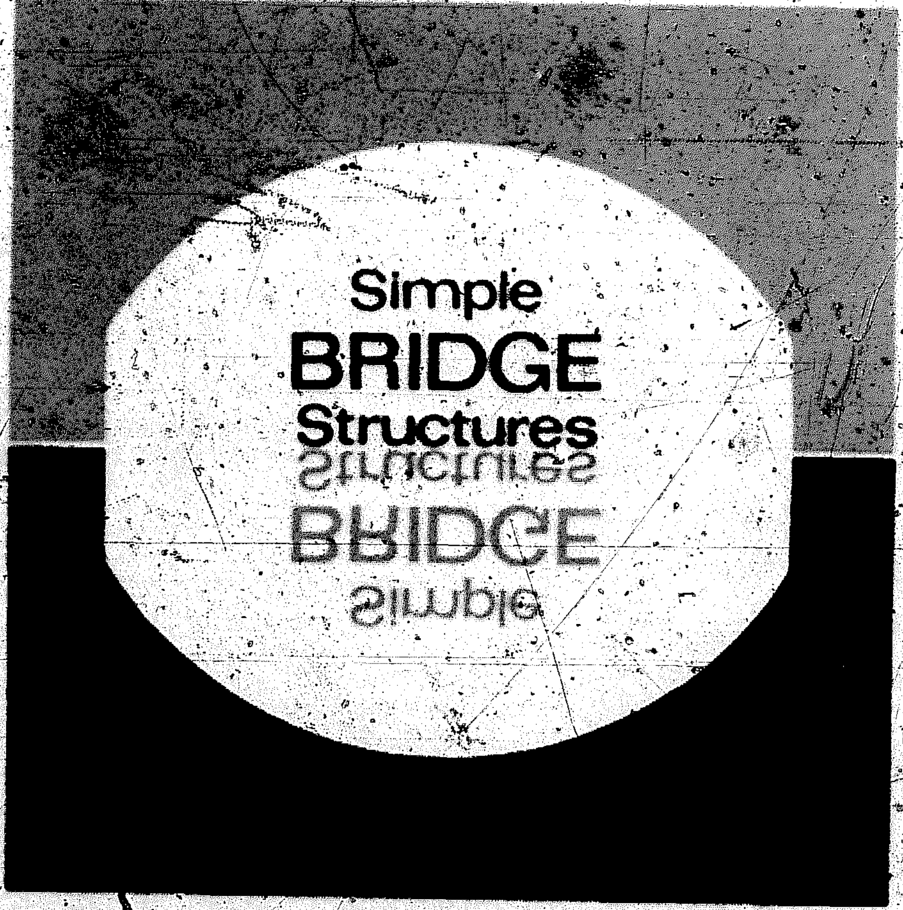

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Heinemann Educational Books
Schools Council

Heinemann Educational Books Ltd
London Edinburgh Melbourne Auckland Kingston Toronto
Hong Kong Singapore Kuala Lumpur New Delhi
Ibadan Nairobi Lusaka Johannesburg

ISBN 0 435 75901 9

First published 1972
Reprinted 1978

Published on behalf of the Schools Council by
Heinemann Educational Books Ltd
48 Charles Street, London W1X 8AH

Produced in Great Britain by Tecmedia Ltd, Loughborough LE11 3DU

Contents

Introduction

Bridges are commonplace, perhaps generally taken for granted, throughout the world today. They vary greatly, of course, from the tree trunk or stone slab across a small stream to the mighty steel or concrete structure across a broad river or forming part of a modern motorway complex.

The story and the romance of bridges goes back to Stonehenge and beyond. Even the suspension bridge, perhaps the most technologically far-out type of bridge in today's state of the art, goes back to primitive man's use of unstiffened suspended cables made of rope; by the seventeenth century, in China, man was already using iron-link chains in suspension bridges. However, for many types of bridge now known to, and developed by, man – types including suspension, cantilever, vertical lift, bascule, girder, swing, stone arch and steel arch – the eighteenth and nineteenth centuries were the period of the real beginnings of the technology of bridge structures.

But the twentieth century, particularly this latter half of it, has seen tremendous and rapid steps forward in the technology of bridge structures – for example, in the development of materials such as pre-stressed concrete or new metals and in the application of aerodynamic principles to suspension bridges.

Schoolboys and girls have marvelled at such structures as the Medway, Forth and Severn bridges and have been inspired to embark upon project work employing the principles embodied in these creations of mid-twentieth century man. They have seen visible evidence, too, of the swiftness of development of the technologies contributing to the imagination-capturing qualities of these structures. This rapid advance can be seen, even superficially, in the difference between the hulking Chiswick flyover (1958) and the relatively elegant Hammersmith flyover (1961) two or three miles away on the same road, between the Forth bridge (1964) and the Severn bridge (1966), and between the early bridges across the M1 and the later, more northerly ones. The thinking and purpose behind such advances can often influence, albeit somewhat unsophisticatedly, approaches to project work in schools.

In considering bridge structures it is also possible for some of the social significance of technology to be seen and appreciated. All such structures serve a socio-economic purpose; aesthetically, they can also be significant in environmental terms. The social consequences of the failure of technology also hit the headlines on those rare occasions of collapse in bridges. The whole question of the social impact of technology is often, and laudably, a topic of considerable importance in the minds of boys and girls involved in school technology.

The purpose of this booklet, *Simple Bridge Structures*, is to suggest, from the experience of various teachers, ways in which the pupil's awareness of the bridges in his or her locality can be used as a basis for developing an understanding of the bridge as a structure.

1 Looking at bridges

Bridge construction has a continuous history from prehistoric man's attempts to cross streams to the present achievements. Different types – beam, arch, cantilever, suspension and lifting bridges – have evolved according to the particular requirements, local conditions, state of knowledge and the materials available. The forerunners of some of these were built thousands of years ago and with modern refinements the same types are used today. The problem is always one of increasing the length of span with due regard to safety, longevity and cost. At the same time, all the factors and contingencies such as the elements which affect the loadings on the structural members have to be considered.

Bridges are an essential part of communications, affording the direct route where practicable. Therefore periods of intensive building occur at times of transport construction. Many bridges were built during the eighteenth century for improved roads and canals, in the nineteenth century for railways, in the 1930's for trunk roads and finally in the last fifteen years for motorways.

Different types of bridges were selected according to the conditions of the time. In the railway era, our civil engineers favoured [illegible] structures – the arch, beam and cantilever – and [illegible] the suspension bridge which was developed on the Continent and in America. Recently our engineers have built two fine suspension bridges across the Forth and Severn estuaries as road bridges.

Requirements for bridges

When an engineer is faced with the problem of spanning a river, roadway or valley, he must consider a number of factors before deciding which type of bridge to recommend. The most important factors are terrain and local environment, loading, soil condition, cost and method of construction.

The position of a new road may be determined by existing obstacles such as buildings, railways, areas of particular value or importance, etc, and the site of the bridge will depend on the road position. There are examples however, where the position of the road has been determined by the site of a particular bridge, eg the Severn suspension bridge. The position of a long span bridge is often dependent on local terrain and site condition rather than a consideration of the most convenient road position.

When the site of a bridge has been chosen design can proceed by considering the load to be carried, this is laid down in a British Standard. Load conditions for two types of roads are covered by this: *heavy duty* and *standard* roads. The requirements for a standard road bridge are a uniform load distributed over the entire span, and a knife edge load positioned at the point where its effect will be the greatest. Additional load requirements have to be considered for heavy duty bridges.

The soil conditions obviously affect foundations and these may be crucial in deciding the type of bridge chosen for a

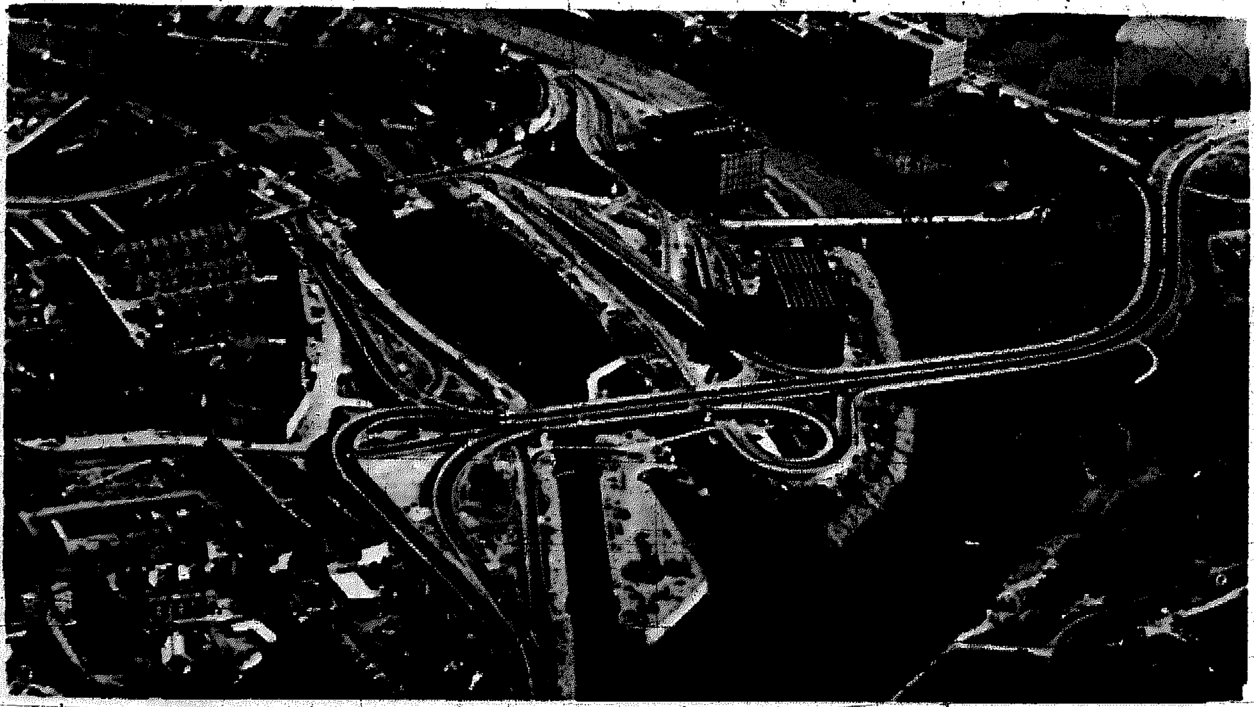

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Fig 1.1. The swing bridge pivoted on the island in the middle distance spans the entrance to the City Docks at Bristol particular site. When the load-carrying properties of the soil are poor it will be necessary to spread the load and this could lead to the choice of a multi-span bridge rather than one of single span.

When the site, loading and soil conditions are known, alternative types of bridges can be considered on the basis of cost and method of construction. While cost is clearly important the method of construction may be the deciding factor influencing the type to be chosen. For instance it may be important that access beneath the bridge is kept as clear as possible during construction. This is likely to influence the choice away from an arch bridge towards a simply-supported or cantilever bridge. Most arch bridges are built on formwork which could cause serious obstruction. A study of local bridges will often show how the factors discussed above have dictated the choice of type.

Communications in this country, because of the hilly terrain and wet climate, require many long high spanning bridges to cross numerous navigable rivers and estuaries, particularly as populations are centred near the coast or on river banks (part of our maritime heritage).

In addition each new railway track or road has to cross over or under existing communications entailing many short span bridges. The canal and railway eras left us many hump-backed road bridges. To save costs where roads crossed existing canals and railway tracks the road was made to cross at right angles, resulting in a short span bridge and an S-bend in the road. This was unimportant in the days of slow moving traffic but today these bridges are the cause of many motor accidents.

Because of the terrain and our densely populated country with the large number of existing waterways, roads and railways, each new motorway requires on average at least two bridges for every mile so that traffic is unimpeded. In urban areas, space is often saved by constructing elevated roads and flyovers which are in effect, long spanning bridges, eg the M4 over Brent.

In the future, many more long high spanning bridges will be constructed to cross the numerous estuaries in the United Kingdom, such as the Humber, Exe, Mersey, Clyde and Thames. Bridge designers, given the opportunity, would gladly submit designs for crossing the Solent and the English Channel. Proposals for the latter were submitted in the early nineteenth century. Whether these are ever built depends on future transport requirements and would be balanced by savings in time. On the other hand, improving city networks by building long spanning elevated roads and pedestrian walks is becoming a necessity and this undoubtedly will be a feature of new bridge constructions in the coming years.

MAIN TYPES OF BRIDGES

Beam with ground supports

A beam (tree or stone slab) resting on the banks of a river or on piers (piles of stones) is the earliest type of bridge (fig 1.2). The span is the distance between supports, it is limited by the load, the resistance of the beam to limited bending, and especially in days past, by the length of beam available. The length of the bridge is increased by having a number of spans on piers, hence multi-span as shown in fig 1.3.

If the piers interfere with navigation or if the bed is too deep, the span is increased by using other materials, another type of bridge or by constructing the beam differently.

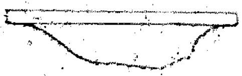

Fig 1.2 Single-span beam bridge

Fig 1.3 Multi-span beam bridge

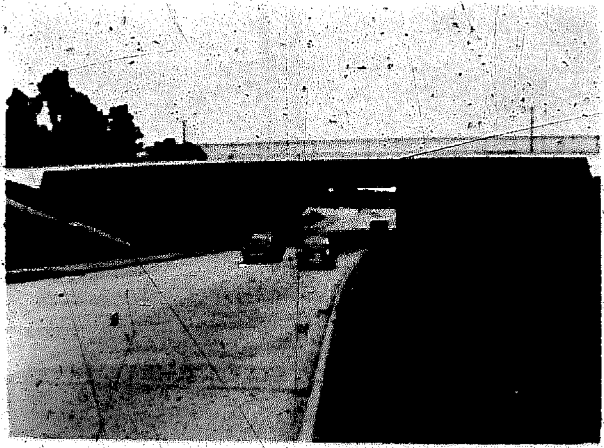

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Fig 1.4 Single-span bridge, near Basildon

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Fig 1.5 Simple multi-span bridge at Postbridge, Devon, with an arch bridge in the background

Trusses

The truss can be used to support heavier loads and span greater distances than a solid beam of the same weight and material. Essentially the truss is a system of individual members forming a series of triangles which act together as a single rigid element like a beam. (The shape of a triangle cannot be altered without deforming one of the sides, hence it is a rigid structure and is seen in steel towers, pylons, roofs of factories, pithead gear, gates etc.)

Trusses of wooden members have been used for many years to support roofs and bridges where there is an abundant supply of timber, numerous wooden bridges were built in North America to carry railways. As wrought iron and, later, steel came into general use, these were incorporated in bridges and today many examples of bridges with metal trusses are seen, particularly those carrying railways which require a rigid structure. Many types of truss have been developed, the simplest being the King truss (or inverted, the Queen) as in fig 1.6.

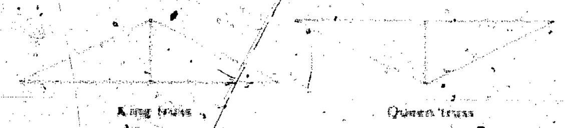

Fig 1.6

These form the principle of nearly all braced girders. Examples of other trusses are shown in fig 1.7. (Note the Fink truss used in America is simply a multiplication of the Queen truss.)

The upper and lower members of these braced girders are called 'chords', 'booms' or 'ribs'. Upright braces are 'posts', sloping braces withstanding compression are 'struts' and those in tension are 'ties'. Members in tension can generally be of smaller section than those in compression because the latter tend to buckle and must be suitably stiffened.

The bending moment of a beam carrying uniformly-distributed loading varies from zero at its supports to a maximum at mid-span. By making the beam deeper in the centre than at the supports, the stress induced in the beam can be kept within close limits. The shearing forces have also to be taken care of however; these are usually greatest at the supports.

Similar lattice arrangements to those shown in the trusses and girders above are used in tower cranes, roof girders, long articulated lorry chassis and bicycles. Pupils could be asked to sketch some of these frameworks and to consider the type of force in each of the various members.

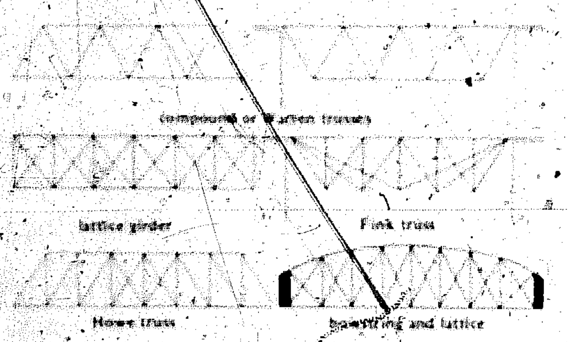

Fig 1.7

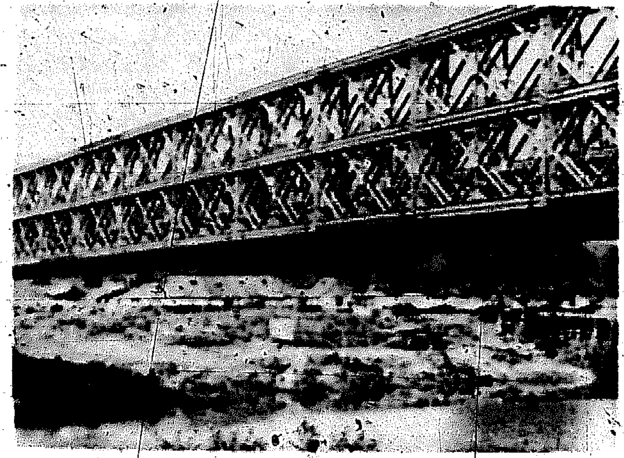

Fig 1.8 Bailey bridge

Cantilevered beam

The principle of the cantilever has been traced to ancient Chinese civilisation. The weight on one side of the pier is *counter-balanced* by the weight on the other, thus all the weight of the structure and the load is carried by the piers. This is achieved by having arms or half-spans extending from each side of the pier on the double cantilever and a short beam completing the span. The single cantilever is anchored to the pier on the bank. One striking difference with the beam bridge is that when the load exerts a downward thrust on one arm, an upward thrust is experienced on the *counter-balancing side*.

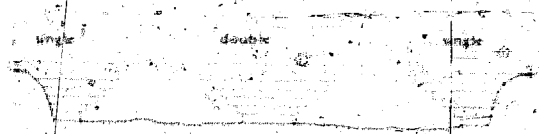

Fig 1.9

Fig 1.10 Firth of Forth bridge, double cantilever

The cantilever permits a longer span between piers and is used where the extra piers required for a beam bridge interfere with water navigation or where piers are difficult to construct in deep or fast flowing water. The famous example of this type in Britain is the Firth of Forth railway bridge which was built in the late nineteenth century. There are two main spans (520 m) requiring three double cantilevers and two girder spans, the cantilever towers, bracing and arms are 3.7 m diameter steel tubes which give the maximum support for the minimum weight.

Today the cantilever principle is applied in elevated roads built of reinforced and stressed concrete blocks. Two miles of the M4 motorway over Brent, spanning the Great West Road, use cantilevers and hence fewer piers are required. Future urban developments will undoubtedly use the same principle causing fewer obstructions to the traffic below.

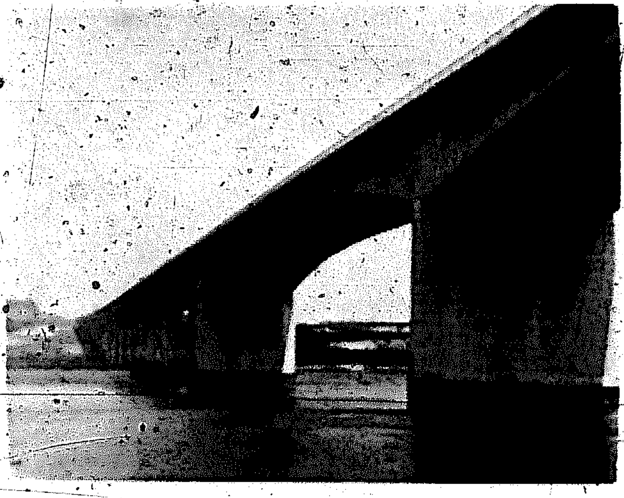

Fig 1.11 Medway bridge, a double cantilever beam bridge opened in May 1963

Elevated pedestrian walks can be cantilevers built out from adjacent buildings. Buildings requiring large spans with unimpeded ground space, such as aircraft hangers, frequently use the same device.

Arch

The Sumerians, many centuries BC, developed brick arches, for tomb portals and probably for bridges, because stone and timber beams were scarce. Later the Romans perfected the semi-circular arch which they incorporated in bridge construction. Examples of their bridges are still in existence. The span of a Roman arch was lengthened by increasing the height. Where a long low bridge was required, a series of small spans were built. To cross a ravine with a tall safe bridge, rows of arches were built one on the other, the three-tiered Pont du Gard is one such example.

Fig 1.12 Three-tiered Roman aqueduct at Pont du Gard

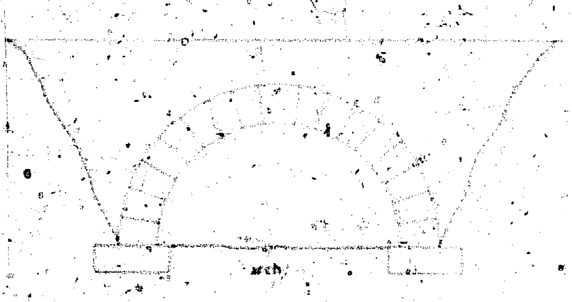

Fig 1.13 Masonry arch bridge

The simple masonry arch is built of wedge-shaped stones, which are held in place by radial forces applied by infilling under the roadway. The load and weight of the bridge are supported by the foundations, sometimes called the *arch springs*.

The Victorian railway constructors built many masonry and brick arched bridges. The hump-backed bridge is very common in rural areas, while longer spanning bridges crossing valleys and rivers used a series of arches which carry the heavy loads of today. The arch is a sturdy, safe structure.

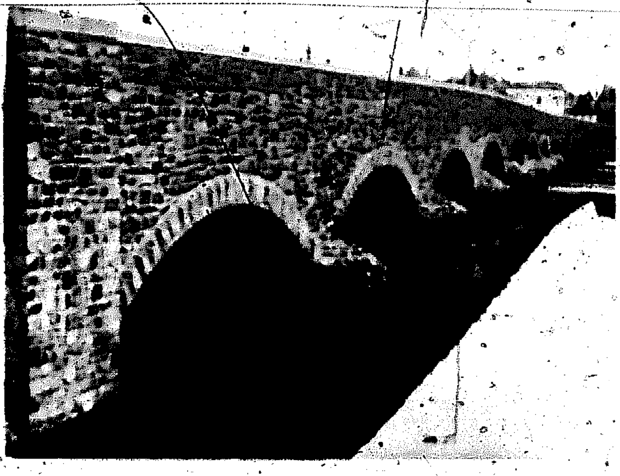

Fig 1.14 Multi-arch bridge 'Barnstaple' Bridge, eighteenth century

Fig 1.15 Barley bridge

Developments have occurred in the shape of masonry arches. Shallow ellipses, instead of semi-circles, have been used in many elegant bridges. Perronet built flatter arches with a rise-to-span ratio of 1:10 (the Roman arch is 1:2). Today, pre-stressed and post-stressed concrete provides a means whereby a greater variety of pleasing, yet safe, arched bridges may be built. One example, the M6 motorway concrete arched bridge over the River Lune, is shown diagrammatically in fig 1.16.

The use of iron and, later, steel enabled arches of much larger span to be built than those built in stone. The first iron bridge of any size to be built in England was Abraham Darby's cast iron bridge at Ironbridge in Shropshire. The deck of this bridge is supported from beneath. In later steel bridges, such as the Sydney Harbour (503 m span) and the Tyne (162 m span) bridges, the deck is suspended below the arch.

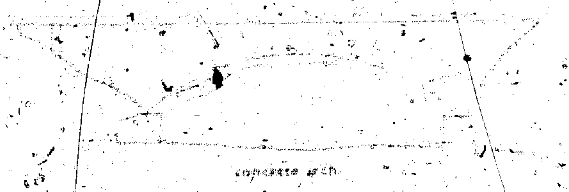

Fig 1.16 Concrete arch bridge


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Fig 1.17 Beaconhill bridge on Ross Spur Motorway

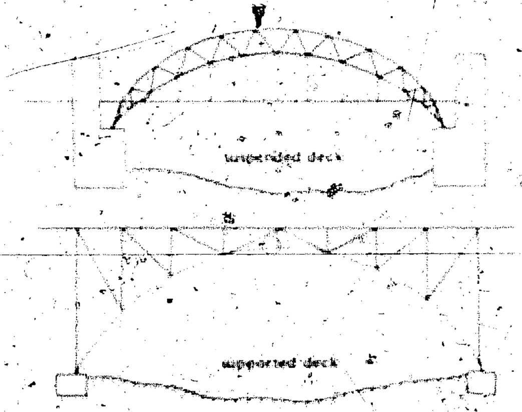

Fig 1.18 Steel arch bridge

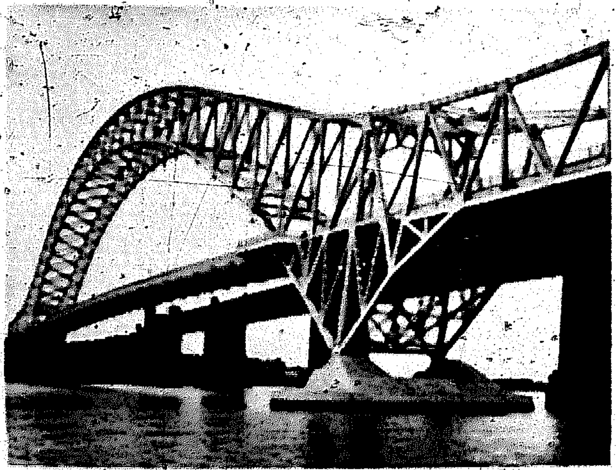
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Fig 1.19 Runcorn bridge, Widnes

The Bowstring girder

Although an arch is incorporated, it is essentially a beam type. A horizontal beam forms a tie which prevents the ends from spreading. The bridge illustrated below has been built at Scotswood. Many combined lattice (triangulated) and bowstring bridges are used to carry railway tracks.

Fig 1.20 Bowstring girder bridge

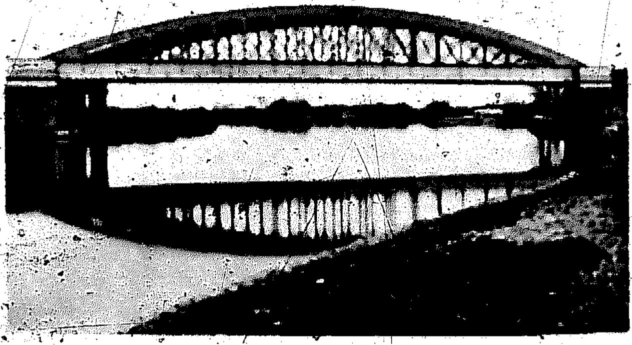

Fig 1.21 Windsor bridge

Fig 1.22 Brunel's bowstring girder bridge of 1859 and the Saltash suspension bridge at St Budeaux, Plymouth

Suspension

The suspension bridge evolved in the warmer wooded regions where liana plants flourished and where deep ravines had to be crossed. The modern counterpart is a flat deck suspended by stays at regular intervals from cables which are allowed to curve naturally from two towers. The cables pass over the towers and their ends are anchored in firm foundations. Because each part of the cable is in tension it can be constructed from stranded steel rods instead of stiffened girders.

In the nineteenth century important developments took place in America and on the Continent. Iron and, later, steel cables replaced chains resulting in a reduced weight and increased span; iron stays counteracted the pliability of the cables. Roebling and his son were the pioneers of the modern suspension bridge. Despite the forebodings of other engineers, who disliked the lack of rigidity, Roebling built a successful road and rail suspension bridge spanning 244 m over the river below the Niagara Falls. He realised the dangers of high winds and recommended adequate weight allied to a deep truss (frame) for the deck.

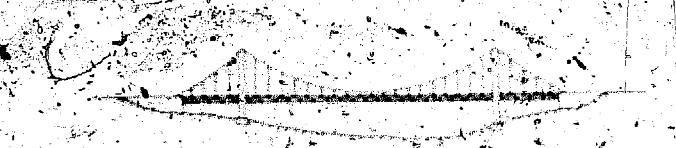

Fig 1.23 Suspension bridge

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Fig 1.24 The Severn bridge. This has a main span of just under 1000 m. Together with the bridge over the River Wye, this £8 000 000 bridge forms part of the M4 motorway from London to South Wales

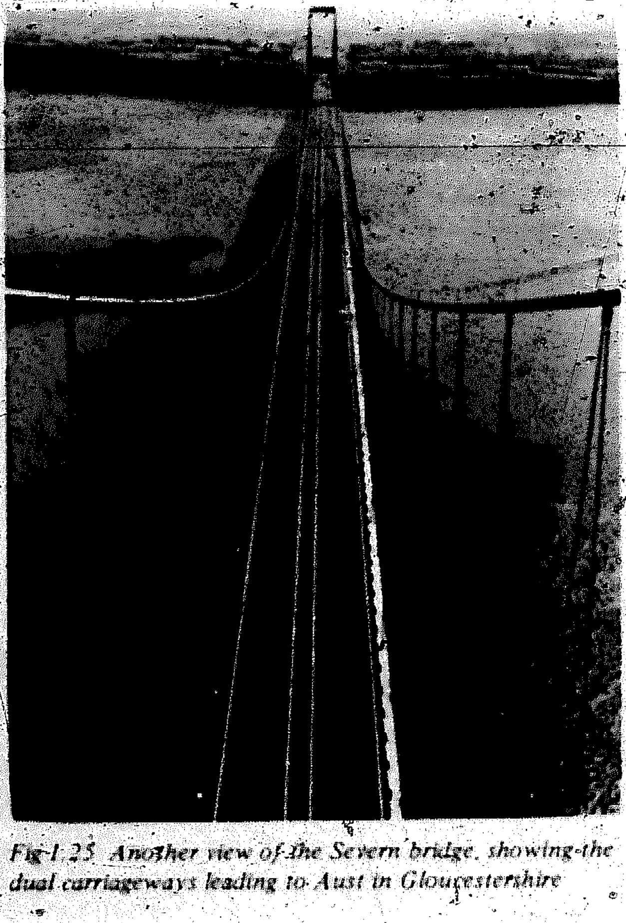

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Fig 1.25 Another view of the Severn bridge, showing the dual carriageways leading to Aust in Gloucestershire

The soundness of the advice was seen in 1940 when the Tacoma Narrows bridge collapsed. Shortly after its completion a high wind destroyed the bridge. It had a deck truss which was only 2.3 m deep. [illegible] set up oscillations about the mid-span point causing a twisting motion which was increased by resonance until the deck collapsed. Before construction of some later bridges commenced, models were subjected to wind tunnel tests. This was the case with the Forth and Severn bridges. The deck for the former has a 9.2 m deep truss, but a new design has evolved for the Severn bridge, a flattened hollow box section which is aerodynamically stable and much lighter.

Erection of the Severn bridge on the [illegible] complete sections were built downstream [illegible] then towed into position and lifted into place. Throughout the world, many fine suspension bridges have been built particularly in America, eg the Golden Gate bridge at San Francisco which is 1280m long.

The stayed girder

This is becoming a popular medium spanning bridge, although it presents problems to the constructor. It resembles a suspension bridge because of the towers, but its principle is a cable cantilever bridge; oblique stays (cables) from the towers to the span and the shore-ward side support the deck, (fig 1.26). Additional stays can be employed as, for example, with the Newport bridge, 153 m (fig 1.27).

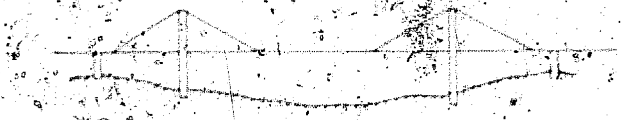

Fig 1/26 The Wye bridge is of the stayed girder type, a design new to this country, applying what is, in effect, the cantilever principle in cable form

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Fig 1.27 Stayed girder or cable cantilever bridge: spanning the River Usk at Newport, Monmouthshire

Swing and lifting bridges

The forerunner of the lifting bridge is undoubtedly the drawbridge of the medieval castle. Swing and lifting bridges of various types have been built across navigable rivers and in dockland areas. The machinery to move the sections is of interest in itself because of the heavy load which has constantly to be moved back and forth. Despite the inconvenience to road traffic, there is a need for these bridges in low-lying areas where a high spanning bridge is impracticable. Kingsferry (Isle of Sheppey) and the Cumberland Basin bridges are current examples, while the Tower Bridge, built in the late nineteenth century is an earlier one. The approaches to Tower Bridge, London, are designed on the suspension principle.

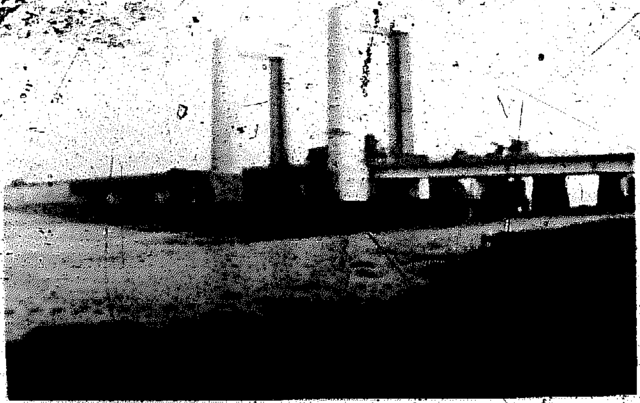


Fig 1.28 Lifting bridge at Kingsferry, Isle of Sheppey

MATERIALS

Steel, with its property of high tensile strength and relative cheapness, was seized upon by the bridge designers of the last century. Immense structures to carry heavy loads, such as railways, and to span wide rivers or estuaries were built all over the world. Many of these arch, suspension and cantilever bridges are even today engineering wonders.

This century has seen concrete being widely used to replace steel in bridge construction. Initially it was used for the shorter span arches and beams, but with the introduction of reinforcement and artificial stressing, concrete has been used for medium and long span bridges.

Concrete avoids its weakness in tension by a complicated network of steel bars arranged in the structure where the loading is tensile. Further advantage is obtained by stressing the steel reinforcing bars while the concrete is still wet, and removing the loads on the ends of the bars when the concrete sets. This stressing can be done when the beams are being made (pre-stressing) or when they are assembled on site (post-stressing).

Many elegant low-spanning arch bridges have been built using the latter technique, the cables pass through the concrete blocks and then they are tightened causing the block to curve in an arc with all sections in compression. Stressed concrete is often used in many parts of the new motorway bridges and elevated roads. The centre span (1[illegible]5m) of the Medway M2 bridge, near Rochester, is a pre-stressed concrete cantilever at each end supporting a concrete mid-section.

2 Examples from schools

Examples of work on structures and bridges which have been developed in various schools. These accounts have been revised in accordance with SI terminology

FRANCE HILL COUNTY SECONDARY SCHOOL

Age range	14 – 15 years old
Subject area	Woodwork and technical drawing
Aim	To help the pupils to develop interest in structures and the strengths of materials

The work was started in the "drawing office" by considering the topic of bridges. Pupils were asked to collect as many photographs and drawings of the various types of bridges as possible. These were arranged according to type and finally mounted to form a display. The third year then went on to draw examples of the common types of bridges.

This work was augmented by showing colour-slides of the more well known types, including motorway bridges. The following experiments and investigations were carried out in the technical drawing and the woodwork rooms.

Strength of beams made from cartridge paper

Third year pupils in the drawing office were given pieces of drawing paper approximately A4 size. These were supported at each end as beams and loaded with coins, both as concentrated and distributed loads. The paper was then folded once along its longer edge and loaded in a similar way. One further test was carried out with the paper corrugated. A record was prepared of the observations made during the various tests.

Strengths of columns made from cartridge paper

The third year pupils also made cylindrical, square and hexagonal tubes from cartridge paper. These were tested to destruction as columns under a load of uniform size text books. Records were made of the number of text books required to destroy each column

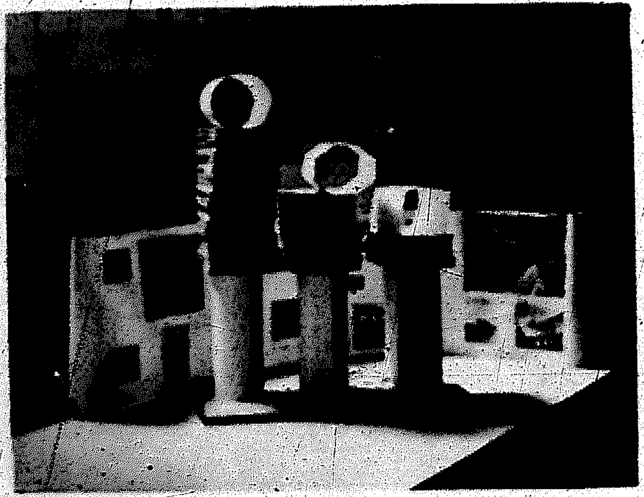


Fig 2.1 Cartridge paper columns under load

Rigidity of bridge frameworks of different types

Third year pupils in the woodwork room constructed model bridges of the Warren, Fink, Howe and Pratt types from balsa wood of uniform section. These were supported at equal spans and loaded on the carriageway. The deflection was measured by means of a dial gauge as shown in fig 2.2

The loads and deflections were recorded and the results compared for the different types of structure. The pupils were sufficiently motivated by this work to build and test further models as an out-of-school activity. After a number of different frames had been made and tested the pupils appreciated the need for cross bracing to stiffen the structure.

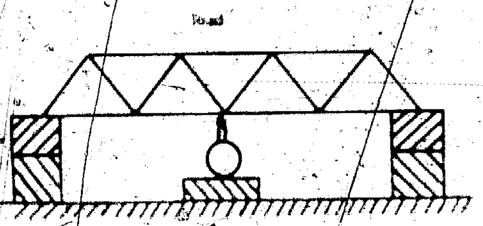


Fig 2.2 Dial gauge

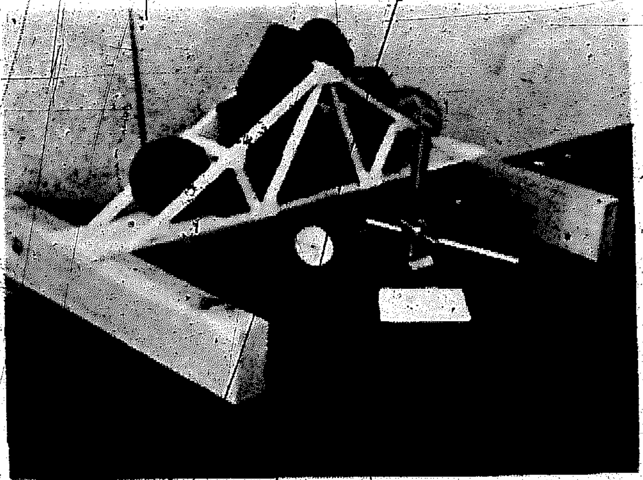


Fig 2.3 Balsa wood bridge under load

Load bearing capacity of different timbers

Fourth year pupils in the woodwork room set up an experiment to compare the load bearing capacities of timber beams. The beams were constructed from different kinds of timber, hard, soft, laminated, knotty, cross-grain, wet, seasoned etc. Each beam had a cross section of 25 mm^2 and was supported at common span. Loads were placed at mid-span and the deflections measured. The results were recorded and a comparison made.

Possible developments

Load bearing capacities of different fastenings: tests in the woodwork room on the load bearing capacities of different fastenings for wooden members in a framework eg nails, screws, butt joints, lap joints, gusset plates, various types of glues etc.

Design of a structure to accommodate a specified loading condition: pupils asked to design simple structures using the knowledge already gained of the load bearing capacities of different shapes and materials.

Box construction: problems to be set based on the design of a method for stiffening a non-rigid container, such as a cardboard box, using a minimum of material. This could lead to the consideration of car chassis and body design.

Technical drawing: the work done in the woodwork room involving frameworks and beams could be developed in the drawing office with further work on force diagrams for frameworks and bending moments and shear force diagrams for beams.

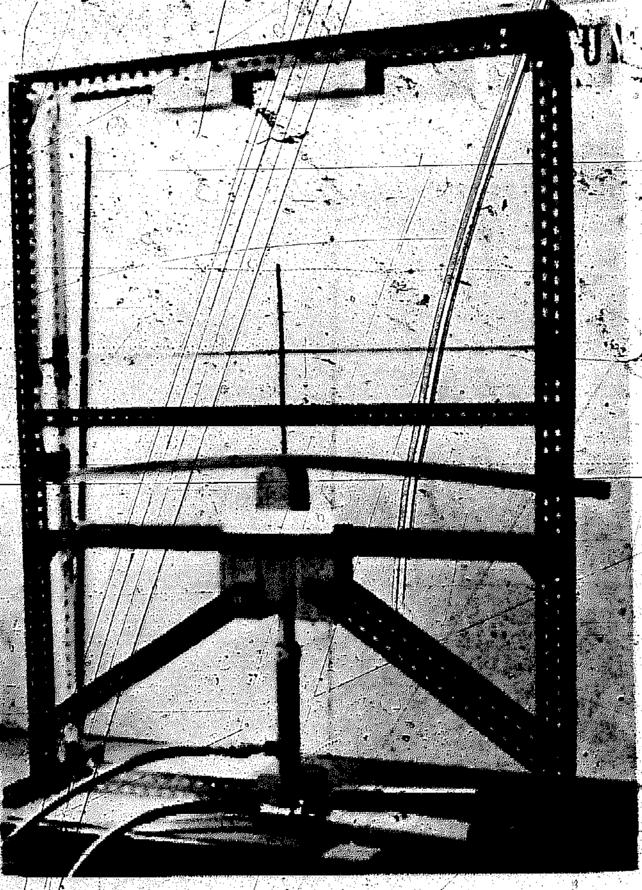


Fig 2.4 Beam testing rig

ST GEORGES SCHOOL, HARPENDEN

Age range: Sixth form

Subject area: Technical projects

Aim: To compare four roof trusses of different design on the basis of the ratio:

$$\frac{\text{maximum load}}{\text{weight of material in the truss}}$$

The following is part of the report written by the pupils. Two standard truss designs were taken from the Timber Research and Development Associations booklet and two were 'invented'. The trusses were built to the scale of 1:10 from scrap lengths of wood, sawn to a section of 10mm x 6.5mm. The joints of trusses (a) and (b) were mitred and glued but reinforcing gussets of wood were added to the joints of trusses (c) and (d).

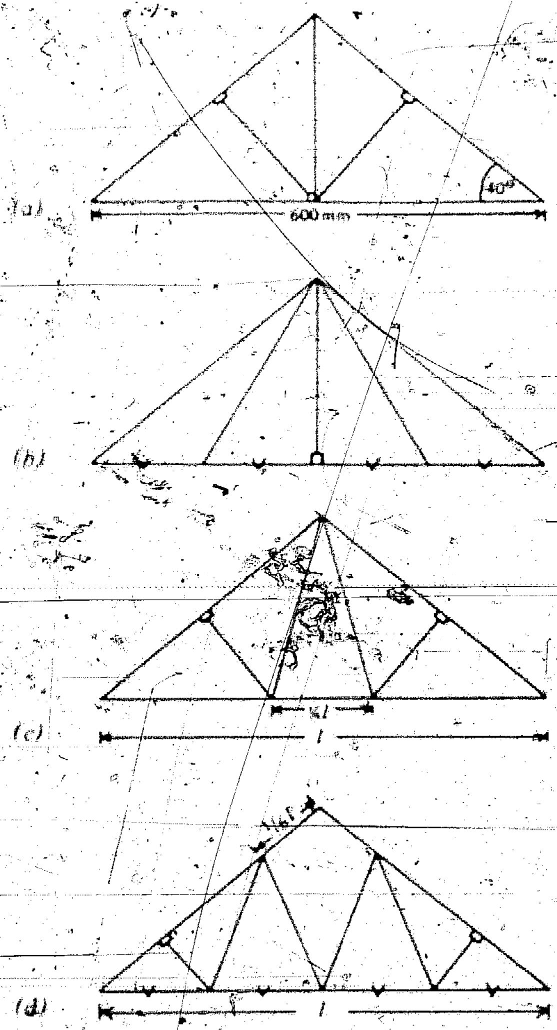


Fig 2.5

The following test procedure was adopted: the truss was supported on two stools about 530mm apart and a point load applied at its apex, by means of a saddle (fig 2.6). A bucket suspended from the saddle was filled with all the spare weights in the physics laboratory and odd chunks of metal, but the only visible result was a bent handle on the bucket. The maximum load that could be applied by this method was 440N: this was far more than we estimated the truss would carry.

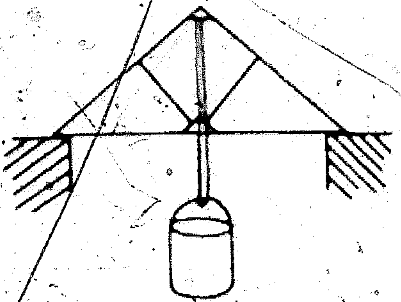


Fig 2.6

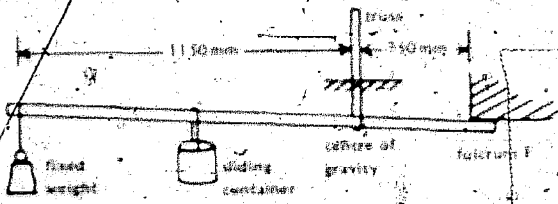


Fig 2.7

A lever system for applying the load to the truss was designed which involved the use of a woodwork sash cramp. The lever was suspended with its centre of gravity below the truss and one end connected to a fulcrum F. Along the other end a container for weights was positioned and fixed weights were hung from the free end of this portion (fig 2.7).

The load required to break the first truss was found to be over 900 N. Failure occurred in one of the upper members which was subjected to a compressive force. The result of the tests was not conclusive because a number of the glued joints failed. Tests of this nature are carried out at the Forest Products Research Laboratory, Princes Risborough, from whom the following articles can be obtained.

'Trussed Rafters for House Roofs'

'Testing of Timber Structures'

'A Laboratory for Testing Timber Structures'.

HELE'S SCHOOL, EXETER

Age range	14 years, working in groups.
Subject area	Technical subjects
Aim	To create an interest in local bridges and link this with part of the 'A' level Engineering Drawing syllabus

Introduction

Interest had been shown in the temporary military bridges built in the West Country following flood damage, and in the new bridge built over the River Exe at Exeter. In addition, pin-jointed frames are a topic in the 'A' level Engineering Drawing Syllabus and staff were interested in developing work based on bridges of various forms.

Group brief

Note the similarity between certain bridges and roof trusses, the constructional shapes necessary, and the importance of the triangular shape. Simple models of strips and pins can be used to illustrate the advantages of different shapes (fig 2.8).

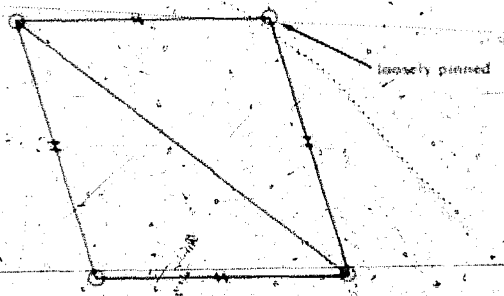


Fig 2.8 Triangular pin-jointed shapes

Obtain information about bridges and bring in cuttings, sketches, photographs, etc (homework). Bridges can be divided into various types, viz, suspension, cantilever, arch, etc. Produce a display board for each type. Visit a number of local bridges, sketch and photograph various types. Produce notes on bridges throughout the world.

Design of model bridge

Staff suggested that the group could make a simple 'girder' bridge and see how strong it could be made. Limitations were set to allow bridge to fit into test rig, ie 230 mm long, 76 mm wide, 90 mm high. Bridges were to have a mass of not more than 28 g and to withstand a downward force of 70 N.

The following brief was given to the pupils:

> Design a simple girder bridge made from 28 g of balsa which will be capable of supporting 250 times its own weight.

All bridges were to have a roadway of 1.5 mm x 76 mm. Pupils were asked 'how much 6 mm square balsa plus roadway would be needed'. The group used a chemical balance to calculate the amount of 6 mm square balsa required. Members of the group sketched out a number of possible designs and the one they considered the best was chosen. This was drawn to scale using formal drawing board techniques.

Production

Drawings were checked to ensure that no more than the permitted length of balsa had been used. The drawing was covered with tracing paper and the bridge produced in a similar way to model aircraft construction; ie cutting balsa and pinning to drawing. The size of the bridge specified would fit into a biscuit tin. The uncut lengths of balsa were marked with the owner's name and stored in a cardboard tube.

Test

A decision on the type of test rig to be used was made after discussion with the group. To act as a control, a sample piece of balsa roadway (fig 2.9), was tested to destruction and the load required recorded. A braced piece of roadway was also tested in a similar way (fig 2.10).

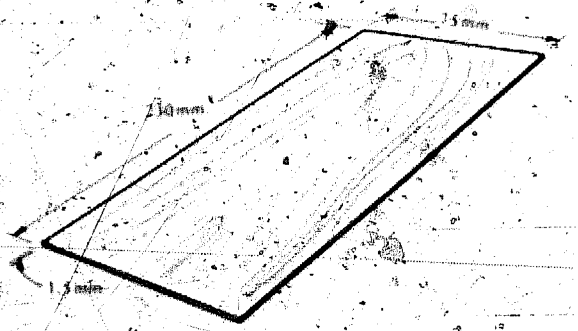


Fig 2.9 'Unsupported' roadway

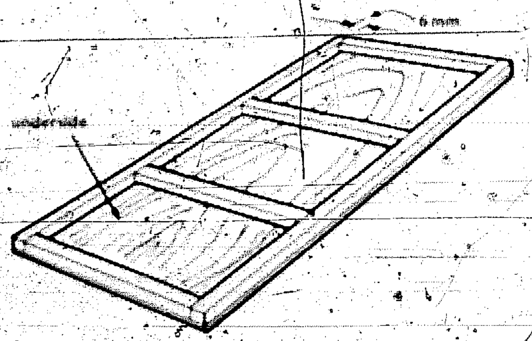


Fig 2.10 'Braced' roadway

Staff posed the problem: 'What, if any, is the relationship between the load required to bend the bridge, by, say, 0.5 mm and the ultimate destructive load?'

The bridge was set up on the test rig. The cross rig, clip, bucket and the dial test indicator were assembled. Water was added to the bucket and a reading taken from the graduated scale in the bucket when the deflection was 0.5 mm. The dial indicator was read when the bucket contained 7 kg. Further water was added and the graduated scale read when the structure failed (fig 2.11).

Further work

Histograms can be drawn comparing the loads required to deflect different structures by 0.5 mm and the loads required to destroy them. (In some cases over 250 N was required to break the structure.)

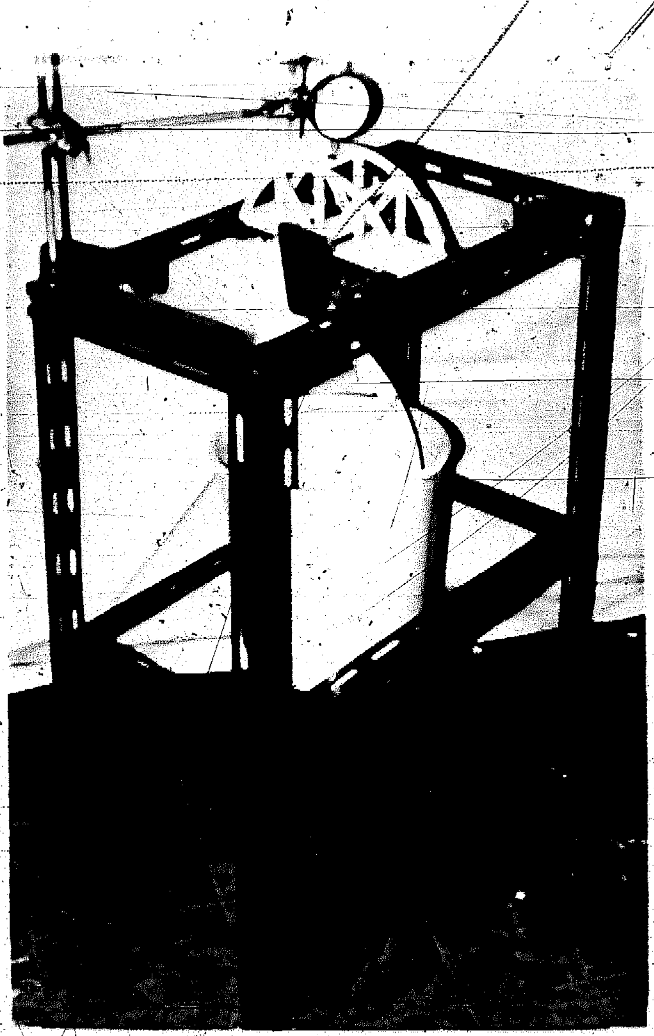


Fig 2.11

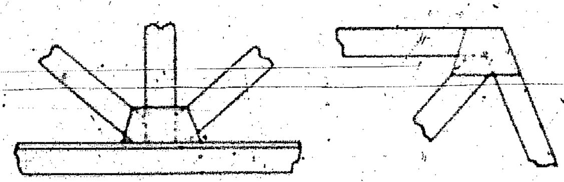


Fig 2.12 Cover plates

The force diagrams for simple frameworks such as the simple roof truss or bridge can be drawn and an estimate of the load carried by each member in the framework can be made from the force diagram. The effect of cover plates can be studied. (Are they best on the inside or on the outside of structure?) (Fig 2.12)

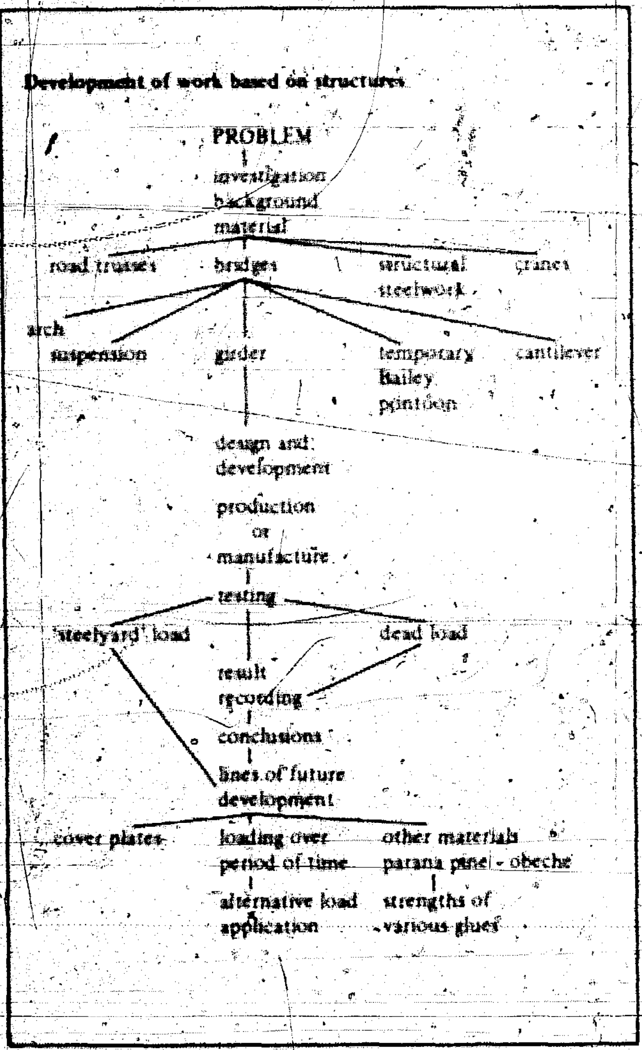
Consider the effect of leaving loads on a structure for a period of time. In addition to bridge structures consider other frameworks, eg pylons, cranes, etc. Use other materials than balsa, eg thin ply, softwood and compare the strengths. Compare the strengths of various glues. Design modifications to the test rig to incorporate a 'steelyard' mechanism for applying the load.

Benefits from the project

Interest and enthusiasm – Science Fair entry of September 1969. Illustrates the basic points of any project, ie problem, information, lines of development, decision, design, development, testing, result recording, conclusion, lines of future investigations.

Pupils developed an awareness of the structures around them.

Experience was gained in organising lines of developments, in decision making, in designing, in testing, in report writing and in planning future development.



ELLESMERE PORT GRAMMAR SCHOOL

Age range 14 years
Subject area Engineering drawing
Aim: To engender a spirit of enquiry; to encourage creativity in design; to overcome various problems in order to attain the desired end; to find a means of clearly recording and collating information; to engender a methodical and logical approach to the problems.

Introduction

The concern to provide the pupil with the opportunity to both acquire knowledge and develop his personality led to the introduction of project work within third year engineering drawing lessons. On an average, five weeks of eighty-minute periods are allocated for this work, but the time allowed is not limited, thus allowing the more able pupil to continue further if he so wishes, or the less able to obtain a good set of results.

Balsa wood project

As may be seen from the programme, the pupil is asked to design a balsa wood beam or girder, indicating the limitations on scale and material. At this stage all that is required is a pencil, paper, rule and imagination. All these ideas are recorded. Owing to the empirical nature of the work, leaving the pupil to evaluate for himself the success or otherwise of his structure, it was hoped, and subsequently proved, that the work would be self-generating. Although the programme recommends that no more than six beams are to be constructed and tested, the bright pupil has been encouraged to continue.

Stress is laid upon the need for accurate and well kept results, a folder with loose paper being supplied for this purpose. While the graph paper is used primarily for recording load and deflection, the broken beam is glued on to the sheet and some pupils have eventually mounted several chosen items on to a large piece of paper for display purposes.

The schematic outline gives, in fairly broad and general terms, an idea of the work involved. Although the value of the work may be deduced from the outline, it may be worth mentioning some impressions from observations made so far. Apart from the visual excitement engendered as a beam cracks and splits under load, much ingenuity has been displayed in attempting to design a satisfactory beam in the light of previous results.

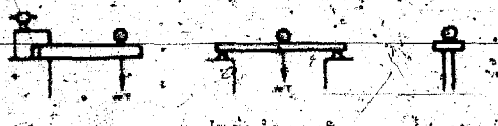
This need of forethought with anticipation of possible reaction of the material has produced an enthusiastic response. Not the least of the benefits is the pupil's need for self organisation and discipline. Good, careful preparation of the material is seen to be a prime requisite for satisfactory results. Sharing the work with the partner has revealed in many cases a generous and unselfish spirit.

The linkup with other subjects is not always obvious and may even be tenuous, but the mathematically inclined can verify concepts of equilibrium during tests, while the more artistic pupil may show more concern for the final appearance of the beam.

Schematic outline of structures work programme

Problem: find a girder beam construction which is both light and strong.

problem		*work*
must be light – using minimum amount of material – yet strong	**design**	from drawings, select simplest and possibly most efficient, make
work from simple to complex		retain drawings
obtain general set of drawings		
how to attach/apply load on to beam	**test**	use dial-test indicator to measure deflection
where to attach/apply load on beam		record all information load and deflection
why did it break where it did?	**evaluate**	was it successful, ie was there a good load/deflection ratio?
in the light of the evaluation how can the beam be modified to produce better results	**modify**	redesign/alter previous beam. Think ahead – will this be a better beam and why?
	retest	
have the tests produced a set of results which can be used to produce a final satisfactory beam?	**final considerations**	make final beam using information gathered. Say why you consider this beam to be the most satisfactory



(a) crane jib (b) bridge (c) pylon

Fig 2.13 Deflection tests on members

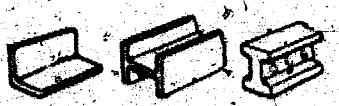


Fig 2.14 Simple rectangular beams

Fig 2.15 Simple hollow beams

Fig 2.16 Built-up beams

Testing materials – simple programme (pupils' work sheet)

Aim: to be able [illegible] to build a simple structure in balsa wood, eg bridge, [illegible] pylon, crane, etc, after first running a series of tests to find the best size, weight and cross section for the job.

Method: this is up to you – but some of the things to be determined are the best method of

weighing,
applying load
measuring deflection
supporting structure under load
constructing a graph to display information.

By carrying out the various experiments, it will also be necessary to find out the following information:

best cross section
best type of frame structure
best improvements to frame structure
best method of inclusion into final structure.

Although you may not have time to realise your final design, you should at least be able to draw a neat sketch of the final structure and state why it is correct, basing your reasons on your experiments.

Beginning the job: you should have in mind a structure which you would like to make, eg a crane jib, bridge, tower or pylon. You may have seen a picture of a structure which you wish to copy, but remember when copying this structure you are using balsa wood and not steel or concrete.

Throughout your experiments you must remember the things talked about in class, ie *stress:* tension, compression, torsion (twisting); *equilibrium of a body; elasticity*. Before testing the finished structure it is important that you look at each member and consider it as a beam, girder, tie or strut.

Testing the members: the deflection caused by different loads. In order to make useful comparisons between the various beams, girders, etc, it is important that the lengths are constant. As time is limited three tests are suggested which you could carry out on the members. Later you may want to devise further tests of your own. Each test should follow this pattern:

weight of the test piece;
cross sectional area of test piece.
test the member as shown in fig 2.13: *crane* – weight on end; *bridge* – weight in middle; *pylon* – weight on top;
If possible turn the member through 90° and test again
Make minor modifications to the shape of the member eg add sheet reinforcement, and test again.

Record other interesting information, eg cracks, noises, etc. Note: the information collected during each test should be recorded graphically.

Suggested tests:

Test 1 Simple rectangular beam (fig 2.14).
Test 2 Simple hollow construction (fig 2.15).
Test 3 'Built-up' beams (fig 2.16).

An analysis of the results has been most pleasing and modifications to the programme have been duly made. One such alteration has resulted in the pupil being thrown more upon his own resources than hitherto. Suggestions about the design and development of the beam are now only verbal, whereas previously visual encouragement had been given.

In conclusion, it should be made clear that although work of this nature is taking place in the technical department, similar activities are being pursued in the mathematics and physics departments at third form level. It is felt that both staff and pupils profit from the rethinking that the work necessitates and that it does much to integrate related subjects in a convincing and realistic manner. It also helps to prepare pupils for the project work in the upper school.

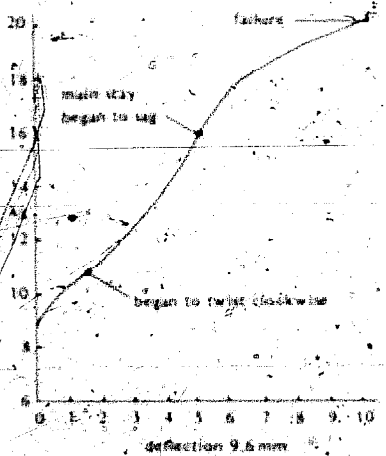


Fig 2.17 Sample result – pylon in compression

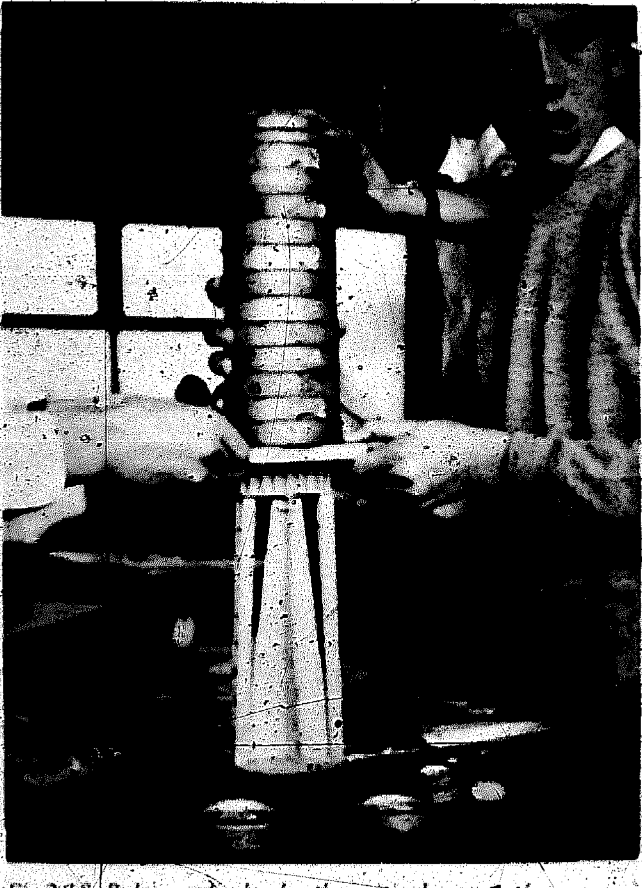


Fig 2.18 Pylon under load – the critical moment!

LA SAINTE UNION CONVENT

Age range: 14 – 15 year old girls

Subject area: Mathematics

Aim: To relate mathematics to life by carrying out work relating to structures on a project basis.

Introduction

The staff in the maths department had not attempted work of this type before, but they felt that by encouraging their pupils to observe various mathematical shapes and forms around them they would help the pupils in understanding problems relating to three-dimensional objects. The girls made models from cards, paper, cocktail sticks, string, etc, of structures both real and imaginary. The various pavilions of *Expo '67* provided the basis for many models. A local architect was persuaded to talk to the girls about his work of designing some of the local buildings. One period each week was set aside in mathematics for the project work. The models were displayed at parents' meetings in the school and also at the British Association Science Fair.

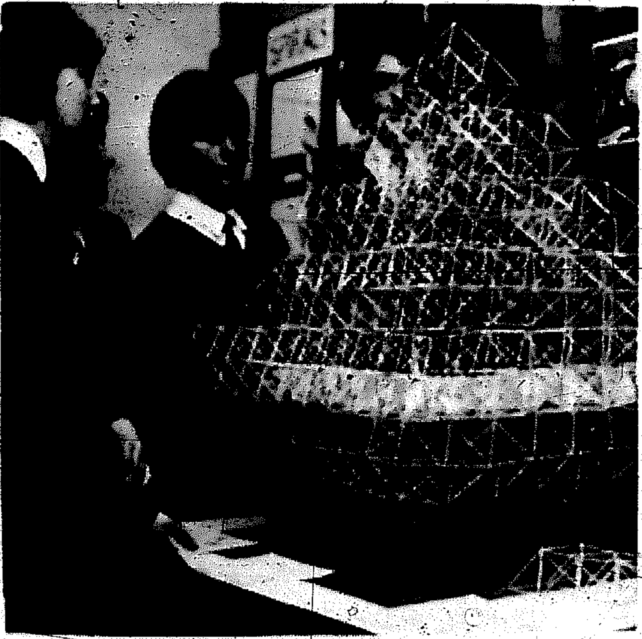
Effect on pupils

There was an increased interest in 'maths' and a feeling that everyone could do it. There was a great sense of achievement in creating a three-dimensional structure. No difficulties were experienced in imagining solids after the project had been completed.

The pupils had a greater awareness of the shapes and structures around them. They were ready to criticise and suggest alterations to the design of their homes, the school and parts of the city. Structural members were seen to have purpose when related to their structures – this understanding came after basic ideas of space had been assimilated.

Effect on the teacher

A greater appreciation of maths in the environment. An awareness of the fascination of modern architectural ideas. A realisation that girls can be interested in structures and have the ability of making good civil engineers.



Bath Evening Chronicle

Fig 2.19 Model of the Gyrotron made with cocktail sticks

The results of this work were far beyond what had been expected. The display of the work was both effective and interesting – and the enthusiasm for mathematics and the realisation of its practicability were great assets in routine classroom work.

Mathematics of structures – project work outline

Purpose of structure: to enclose a space above ground, to enclose a space underground; to span between points above the ground; to tunnel between points below ground

Restraints on structures: structure must be functional; design must be based on mathematical forms; it must be possible for the engineer to construct the structure; the design should enable economic use of space and materials

Nature of structures: structures are bounded by (a) straight lines, (b) conic curves; members and surfaces must have stability and strength

Structures bounded by straight lines: regular solids – tetrahedron, cube, etc; other solids. Draw the net of these solids on card, cut around the shape and fold to form the solid

Structures bounded by conic curves: hyperboloid roofs

Prisms as columns: relative strengths. Make columns from sheets of stiff paper or card. Load these in compression and compare the strength of different shapes

Developed shapes: study shapes of common objects and structures eg cooling towers, aeroplane propellers, turbine blades

Make models of famous structures: eg Severn Bridge, Sydney Opera House, Sydney Harbour Bridge, pavilions at Expo '67

Imaginary structures: Design a structure to meet a specification for a living area, a pylon, a flying shape. Prepare a file containing design sketches and notes based on your design

Fig 2.20 Structures of the future

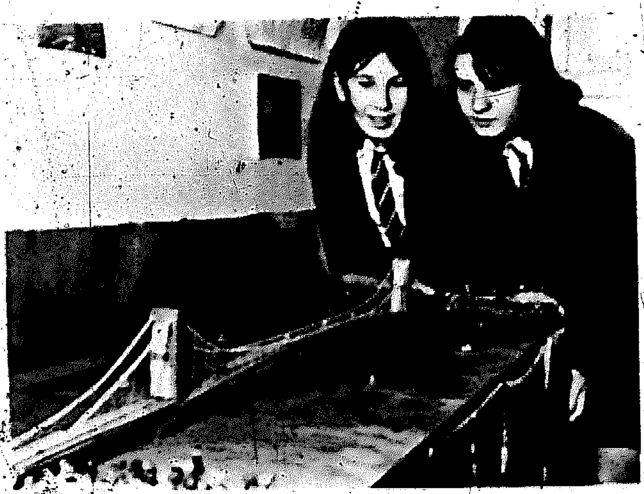


Fig 2.21 Model of the Severn bridge

3 Simple theory

Beams, frames and columns form useful topics in a study of structures. They are designed with particular features in mind such as tension, compression, shear, deflection torsion and buckling. These features are illustrated by the following simple demonstrations. Following this the three topics (beams, frames and columns) are dealt with under their respective headings.

Tension
Load a piece of rubber cord with increasing weights and notice the degree of stretch. The material is in tension. The load divided by the cross sectional area of the material is the tensile stress present in the material, ie *stress = load/area.*

The increase in length divided by the original length is the strain, ie *strain = change in length/original length.* Remove the weights, and the cord will reduce in length. This material has an elastic property.

Compression
Squeeze a piece of pencil rubber. The material is shortened and the stress and strain can be determined in a similar way to the material in tension. When the squeezing force is released the material elongates indicating that it has an elastic property. If this demonstration is carried out with a piece of putty, when the force is removed the material does not elongate. Putty has a plastic property.

Shear
Load a simple riveted joint as shown in fig 3.1. The rivet will break along the joint by one half sliding across another. The rivet is in shear.

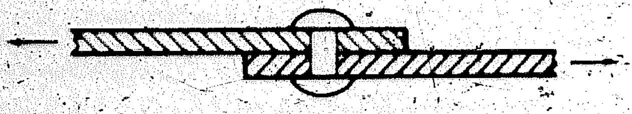


Fig 3.1

Deflection
Place a ruler on supports near its edges and load it at the centre. The ruler is seen to bend (deflect) and the deflection increases as the load increases.

Torsion
Grip a ruler in a vice (fig 3.2). Load the free end of the ruler and observe that as the load increases the ruler will twist, so that it can bend more easily. This twisting is known as torsion.

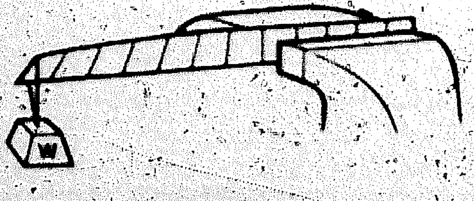


Fig 3.2

Buckling
Stand a thin strip of card vertically, held at its base. Press down on the top edge of the card. You will notice that the card buckles near its middle. The card can be made stiffer by folding or corrugating it along its length.

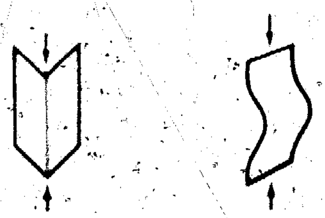


Fig 3.3

BEAMS

Simple tests on beams

When a beam is loaded it will deflect. With this form of a simple loading, material near the upper edge of the beam is shortened and that near the lower edge is lengthened. There is a layer of material near the middle which remains unchanged in length. This is known as the neutral layer.

The material above the neutral layer has a compressive force acting on it and that below the neutral layer has a tensile force acting on it. The greatest stress is present in **the material at the greatest distance from the neutral layer.**

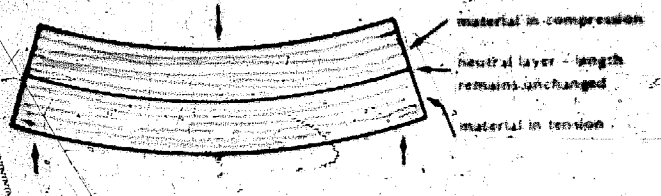


Fig 3.4

Carry out the following experiments:

- Tie a number of thin strips of timber together and load the bundle as shown in fig 3.5.
- Glue the ends of a number of similar thin strips of timber together and load the bundle as above.

Compare the results of the two experiments.

- Build a cantilever beam from a number of thin strips held firmly at one end and tied together at the other as shown in fig 3.6.

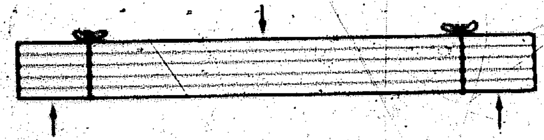


Fig 3.5

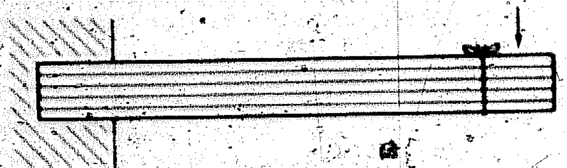


Fig 3.6

Load the tied end. Which strips suggest that tensile forces are present? How does this compare with the results in the previous experiments? When the beam is loaded, the material is subjected to shear - adjacent layers of the material tend to slide over each other. This can be observed in the experiments above; the strips slide over each other if they are free to move.

Shear will also occur along vertical planes due to loading. The cantilevered beam will tend to shear at the support. It will also, in fact, tend to shear along millions of other vertical planes between the load and the support.

The maximum load which can be safely carried by a beam is limited by the strength of the material in tension, compression and shear. The maximum load is also limited by the acceptable deflection and this can be shown to depend upon a number of different features, ie material, loading, length of span, width, depth, cross sectional shape, type of end fixing. A number of simple experiments can be carried out to illustrate the relationship between these features and the deflection.

In order to keep the mathematics of the experiments as simple as possible, we will consider a rectangular beam simply supported with a single load positioned at mid-span.

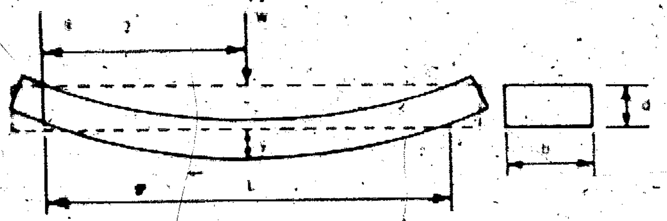


Fig 3.7

It can be shown that $y = WL^3/48EI$

where I = the second moment of area of the beam section.

For a rectangular beam, $I = bd^3/12$

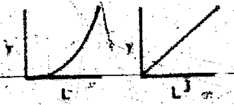
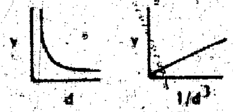
$\therefore y = WL^3/4Ebd^3$ for a rectangular beam.

Where y = maximum deflection
W = load
L = span
E = Young's Modulus of Elasticity (a constant for the material)
b = width of beam
d = depth of beam

Hence we can see that the deflection (y) varies in direct proportion with load (W) and span³ (L^3) and in inverse proportion with width (b) and depth³ (d^3).

Table 3.1 and the notes which follow detail a number of experiments which can be carried out.

Table 3.1 Effect of various properties of beams on deflection

Range of experiments	*Link with deflection*	*Typical graphs*
Load vary load applied at mid-span	$y = cW$	
Span vary span but maintain constant load at mid-span	$y = cL^3$	
Width vary width but maintain other dimensions and loading	$y = c/b$	
Depth vary depth but maintain other dimensions and loading	$y = c/d^3$	
Material use beams of different materials but identical sizes and loading		

Load

Make a steel beam from 25 mm x 6 mm material, 685 mm long. Place the beam on supports about 38 mm from the ends (600 mm). Load the beam at mid-span with various loads and measure the deflection. Plot a graph of deflection (y) against load (W). This graph should be a straight line passing through the origin and the slope of the line will be equal to:

$L^3/4Ebd^3$

since $y = L^3W/4Ebd^3$

Care should be taken not to load the beam too heavily. Too large a load will stress the material past the yield point and this will produce a permanent deformation in the beam.

Span

Place the beam used in the *load test* on supports 600 mm apart. Measure the deflection of the beam under a load placed at mid-span. Repeat the experiment for different spans, say 375 mm, 450 mm, 525 mm. Plot a graph of deflection (y) against span (L) and deflection (y) against span^3 (L^3).

It will be noticed that when y is plotted against L^3 the graph approximates a straight line, ie deflection is proportional to span^3, hence when the span is doubled the deflection is increased by (2^3) eight times.

Width

Use 6 mm deep x 685 mm long steel beams of different widths, say 25 mm, 32 mm, 38 mm and 50 mm. Place these beams on supports 600 mm apart and measure the deflection of the beam under common loads placed at mid-span.

Plot a graph of deflection against 1/width. This will give a straight line because deflection is inversely proportional to the width of the beam.

Depth

Use 25 mm wide x 685 mm long steel beams of different depths, say 3 mm, 4.5 mm, 6 mm, 7.5 mm and 9 mm. Repeat *depth test* for each beam.

Plot a graph of deflection against 1/depth^3. This will give a straight line. What indication does this give regarding the relationship between deflection and the depth of the beam? Which dimension of the beam, width or depth, would you increase in order to produce the stiffer beam ie a beam which has the least deflection?

Material

Make beams similar to that used in *load test* of other materials, eg softwood, hardwood, aluminium, etc. Place each beam in turn on the supports used in *load test*. Measure the deflection of the beam under a common load placed at mid-span. Draw a histogram of the deflection for the different materials.

Using the value for the slope of the graph obtained in *load test* it is possible to calculate a value for E (Young's Modulus of Elasticity). The value for E is a property of the material and can be used when comparing the beams.

$$\text{slope} = L^3/4Ebd^3$$

$$\therefore E = L^3/\text{slope } 4bd^3$$

Shape

Construct models in balsa or softwood of various sections eg (L, T, C, I, II, ☐) similar to those used in girders and box beams. Make all beams of equal cross sectional areas and lengths. Repeat *width test* for each beam and compare the deflections of the various beams. Note: to prevent the beams twisting under load during the tests it may be necessary to provide suitable guides. Remove material from the web (fig 3.8) and compare the deflection/weight ratio of the lightened beam with the original.

The pupils could be asked to suggest where beams having shapes similar to these can be found eg aircraft spars, floor beams in large buildings, car chassis, roofs of most older railway stations, steel bridges.

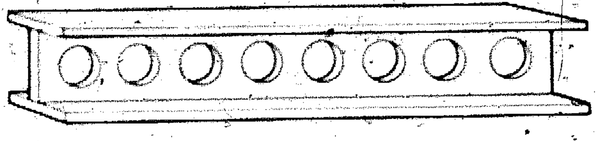


Fig 3.8

End fixing

Make two beams from balsa or softwood of equal dimensions. Support one beam on small blocks of wood or metal and build a jig in which the ends of the other beam can be fixed rigidly. The spans of the two beams should be the same.

Load the beams at mid-span and measure the deflections. Compare the results of these two experiments. Can you

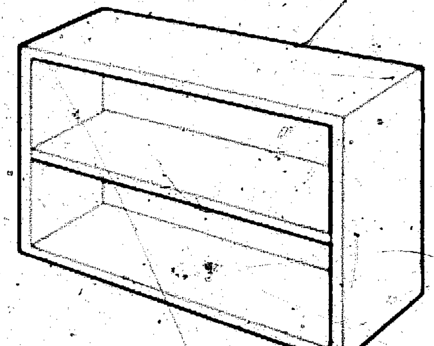


Fig 3.9

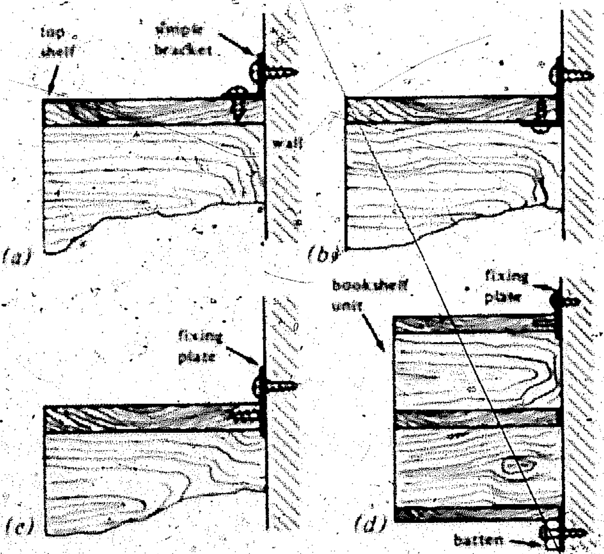


Fig 3.10

think of examples of (a) simply supported beams, and (b) encastered (built-in) beams? Which beam deflects most? Do you notice any relationship between the amount of deflection and the nature of the material?

The information gained in these experiments is useful when designing load bearing furniture such as bookshelves, chairs, stools etc. The pupils could be asked to look at a number of examples of load bearing furniture and to consider their construction from the strength aspect.

Consider a simple set of bookshelves (fig 3.9) which is to be hung from a wall. There are a number of different ways of supporting this unit on the wall, some are illustrated in fig 3.10.

The following questions might be considered:

What are the advantages and disadvantages of the various means of support?

What type of force is acting on the wall screws in (a), (b) and (c)?

What type of force is acting on the top shelf screws in (a)?

What kind of failure is likely to result in (c)?

How many brackets or fixing plates would you use in (a), (b) and (c)?

Where would you position these along the top shelf:
part way in from each end?
near the centre?

If you positioned them part way in from each end what shape will the top shelf take when the unit is fully loaded?

If you use fixing method (d) will this alter the loaded shape of the top shelf?

Will the methods of supporting the unit affect the design of the joints between the top and bottom and the sides?

If dovetail joints are used, how will these be arranged?

If after initial loading it is found that the middle shelf sags unduly, how can this be remedied without redesigning the whole unit?

Many other questions could be asked about the structural aspects of this unit, and other pieces of furniture could be treated in a similar way.

Reinforcement

Concrete beams have limited use because the material is very weak in tension; it is very strong in compression however! A concrete beam can be strengthened by reinforcing with steel rods the area which carries a tensile load.

Experiments can be carried out with beams made from plaster of paris and steel wire. The following is a suggestion for a simple experiment to indicate the principle of reinforcement.

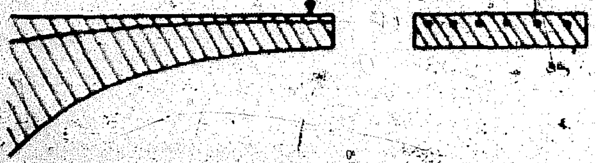


Fig 3.11 The upper portion of the cantilever is in tension hence the reinforcement will be arranged near the top of the beam

Make three beams using balsa wood and thin metal strip as shown in fig 3.12. Use 20mm x 6mm balsa wood and 20mm wide metal binding strip. Support each beam on supports of equal span and load at mid-span until destruction occurs. Compare the strength of each beam.

Another piece of simple apparatus to demonstrate the principle of reinforcement can be made from strips of 1.5mm thick balsa. From a 1m length of 75mm x 1.5mm balsa cut two strips 240mm long and six strips 80mm long.

Glue up two units similar to that shown above and cut each unit into two pieces (along the dotted line). Join the two pieces together to make a strip 240mm x 40mm x 6mm. One unit should be joined with the grain of the outside laminations running longitudinally and the other unit joined with the grain of the outside laminations running laterally as shown in fig 3.14. Each unit can now be loaded as a simply supported beam. The difference between them will be readily observed.

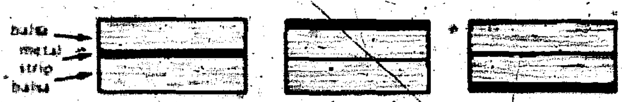


Fig 3.12

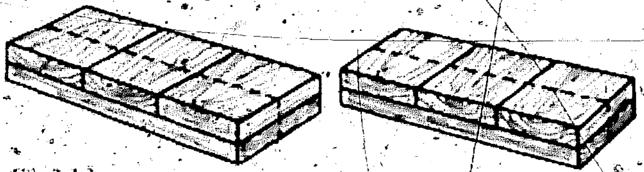


Fig 3.13

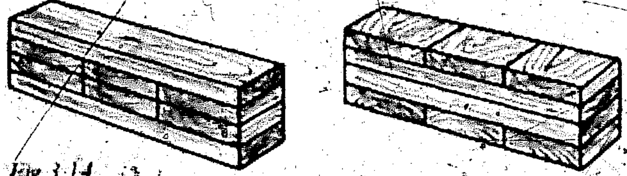


Fig 3.14

FRAMES

This topic is dealt with fully in many standard text books and reference is made to some of these in Section 5. These notes are included as a guide to indicate one approach to the to[illegible]

Forces in frameworks

Before considering the various forces acting within a framework or a single force acting on a member, it is necessary to consider what force is in general terms. A force tends to alter the state of motion of a body on which it acts, ie to set it in motion, stop it, make it move faster, or slower, or to change its direction. If the body is restrained by other forces the force will tend to alter the shape of the body.

In order to accelerate a body a force must be applied. Newton showed that the magnitude of this force is directly proportional to the mass of the body (for a given acceleration), and directly proportional to the acceleration it receives (for a given mass). That is:

force (F) $\propto$ mass (m) x acceleration (a)

= c x m x a where c is a constant.

For convenience the unit of force has been chosen such that unit force = unit mass x unit acceleration. In the SI system, the unit of force is the newton (N), of mass the kilogramme (kg) and of acceleration metres per second per second (m/s^2). Hence:

$1\,N = 1\,kg \times 1\,m/s^2$

Stress and strain

When a force is applied to a member in a framework it is resisted by forces spread evenly across the cross section of the member. The force exerted by each unit area of the member is known as the stress, ie stress = force/area.

A tensile force will cause the member to extend and the ratio of this extension to the original length (unit deformation) is known as strain, ie strain = change in dimension/original dimension.

One material will deform much more than another and a useful way of comparing the deformation properties of different materials is by a stress/strain ratio known as Young's Modulus of Elasticity, named after Dr Young who used the ratio extensively when comparing different *body* materials.

Summarising

stress = load/cross section area = L/A

strain = change in dimension/original dimension
= x/l

Young's Modulus (E) = stress/strain = Ll/Ax

A simple experiment related to force, stress and strain can be carried out with a piece of fairly strong rubber strip. Load the rubber as shown in fig 3.15 and measure the extension. A load extension graph can be produced. Further experiments can be carried out using different lengths of the strip and corresponding graphs produced. If the loads used are kept small so that the cross sectional area remains reasonably constant, the information obtained from the curves produced can be combined into one stress/strain curve. This information can be used in an experiment described later relating to force diagrams.

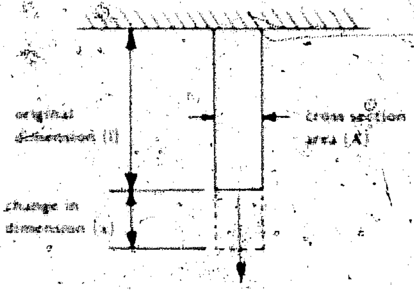


Fig 3.15

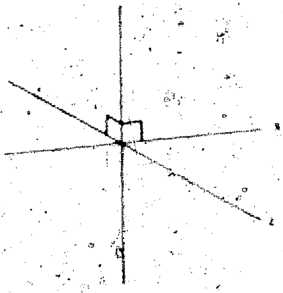


Fig 3.16

Forces in equilibrium

A body is said to be in equilibrium when the forces acting on it are perfectly balanced, ie when there is no resultant force acting on it. The body in equilibrium may be stationary or in a state of steady motion. The following conditions are necessary before a state of equilibrium can exist:

the sum of the components of the forces acting along each of three mutually perpendicular axes x, y and z must be zero.

the sum of the moments of the forces about any point must be zero.

An equilibrant is the force which must be applied to a body to keep it in a state of equilibrium. For example if a 3N force and a 4N force act on a body 'O' (fig 3.17), a third force – the equilibrant – is required to prevent the body from moving. The equilibrant E can normally be found by either graphical or mathematical methods.

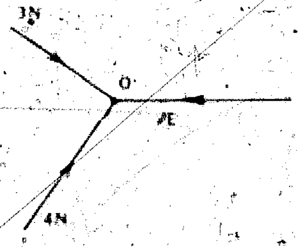


Fig 3.17

Graphical method

If the forces acting on a body are in equilibrium, when their vectors are plotted, a closed figure is obtained. A force vector is a line which represents the force in both magnitude and direction. The space diagram (fig 3.18) indicates the relative positions of the forces, ie their positions in space.

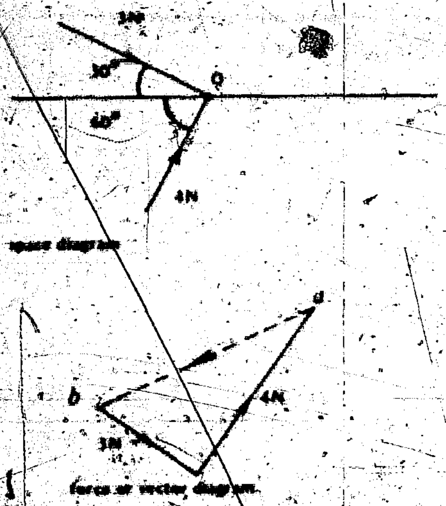


Fig 3.18

The force or vector diagram represents the magnitudes and directions of the forces acting in the system. It will be noted that the arrows on the vectors follow each other around the figure. The dotted line represents the force which is needed to produce a state of equilibrium – the equilibrant *(ab)*. The line also represents the single force which could replace the 3N and 4N forces and produce the same effect at O – the resultant *(ba)*. It will be obvious that a scale (mm represents N) is necessary in order that the force diagram can be drawn.

Mathematical method

The first condition for equilibrium stated that the sum of the components of the forces acting along perpendicular axes must be zero. The forces in this example act in one plane only – they are co-planar – hence they have no components along the z-axis.

Let us consider the perpendicular axes in the plane of the forces to be xx and yy. Both the forces can be considered to act partly along the xx-axis and partly along the yy-axis. These parts are known as their xx and yy components, and for equilibrium the sum of these components must be zero. Hence the xx component of the equilibrant can be found by subtracting the sum of the xx components of the 3N and 4N forces from zero. The yy component of the equilibrant can be found in a similar manner. These components can then be compounded to give the equilibrant in magnitude and direction.

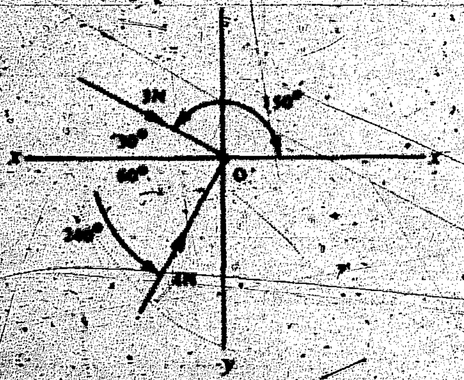


Fig 3.19 Calculating the xx components

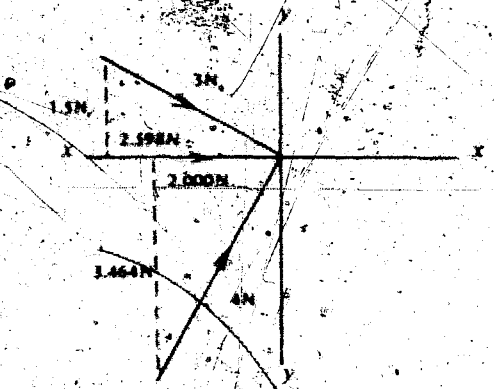


Fig 3.20 Calculating the yy components

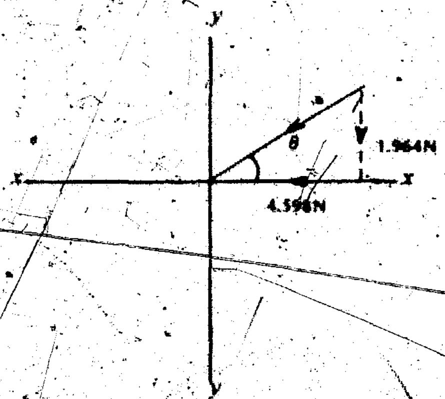


Fig 3.21 Calculation of equilibrant force

xx components

3N force = $3\cos 150^{\circ} = 3 \times -0.866 = -2.598$N

4N force = $4\cos 240^{\circ} = 4 \times -0.500$ [illegible] 2.000N

combined components = -4.598N

xx component of equilibrant = $0-(-4.598) = 4.598$N

yy components

3N force = $3\sin 150^{\circ} = 3 \times 0.500 = 1.500$N.

4N force = $4\sin 240^{\circ} = 4 \times -0.866 = -3.464$N

combined components = -1.964N

yy component of equilibrant = $0-(-1.964) = 1.964$N

By Pythagoras (see fig 3.21)

$E = \sqrt{(1.964^2 + 4.598^2)}$N

$= 5$N

$\theta = 23^{\circ}13'$ $(\tan\theta = 1.964/4.596)$

hence the equilibrant is a force of 5N acting at 23°13 to xx.

An example where three forces act at a point is the jib crane (fig 3.22). The tie, the jib and the applied load are joined by a pin. The forces acting on the pin and the corresponding forces acting on the tie, jib and load link are shown in fig 3.23 and fig 3.24.

The forces acting on the pin are in equilibrium and their vectors can be plotted to form a force triangle as shown in fig 3.25. The applied load and the angles between the forces are known, hence the jib and tie forces on the pin can be found. Each force on the pin will have an equal and opposite

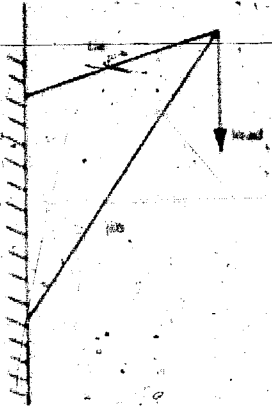


Fig 3.22 Jib crane

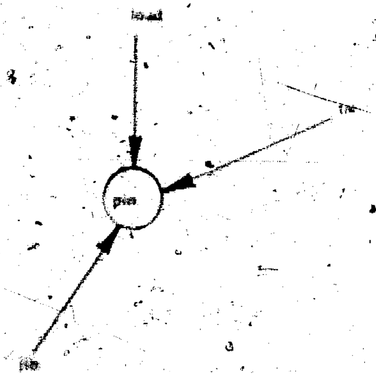


Fig 3.23 Forces acting on the pin

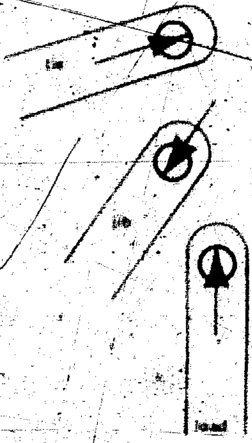


Fig 3.24 Forces acting on the member

Fig 3.25 Triangle of jib crane forces

force on the corresponding member, hence when the pin forces have been determined, the forces in the members are established.

The mathematical method may be used also to find the pin forces, and a third method is by experiment using the information gained from the stress/strain experiment described earlier. Set up a jib crane using a piece of the rubber from the stress/strain experiment for the tie and a suitable piece of timber for the jib. Load the crane and measure the extension of the tie. The force in the tie can now be found from the load/strain graph plotted earlier.

A framework can be made from a number of Meccano links bolted together at their corners. It will be obvious that some frames built in this way will be unstable, for example the quadrilateral shown in fig 3.26 will tend to collapse when force F is applied.

Triangular frames, however, are more stable, and if a diagonal member is used in the frame shown in fig 3.27, making two triangles, a more stable structure will be obtained. The forces acting on the frame tend to extend or shorten the links from which it is made. The forces in these links are *tensile* and *compressive* respectively.

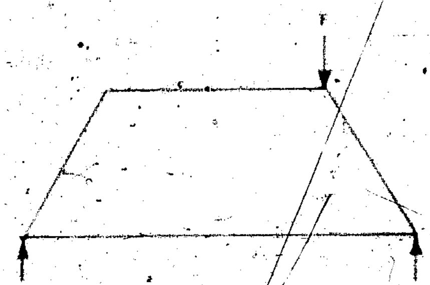


Fig 3.26 An unstable quadrilateral framework

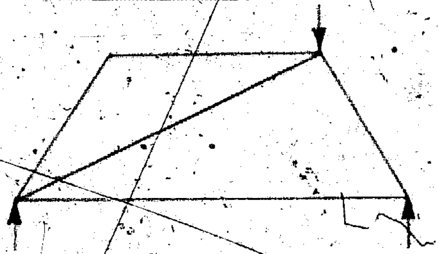


Fig 3.27 Stability provided by diagonal member

Bow's notation
Most frameworks have more than one joint where a number of members meet. The forces acting at these joints can be found by dealing with each one in turn or by a quicker method. Both these methods will be described in order to show the relationship which exists between them.

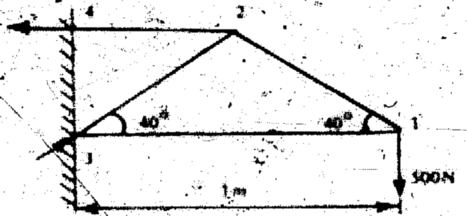


Fig 3.28 Calculation of forces

The forces acting in the framework shown in fig 3:28 can be found by applying the graphical or mathematical method already dealt with to each joint in turn. Deal first with joint 1 and then from the information obtained progress to

other joints until all the joints have been considered. Note the force diagram for joint 1 in fig 3.29. This enables the force in member 1 – 2 at joint 2 (fig 3.28) to be stated.

The force acting towards joint 1 at the lower end of the member must be balanced by an equal and opposite force at the upper end acting towards joint 2 in order to maintain a state of equilibrium within the member. Having discovered the other forces acting at joint 2 we can then proceed to joints 3 and 4.

This is a rather tedious procedure. A much quicker method using Bow's notation can be used. By this means the separate force diagrams are combined to produce one composite diagram as shown in fig 3.30. The Bow's notation method identifies a force by letters with space diagrams on each side of the member on which it acts. For instance the 500N force in fig 3.28 is known as *ab* or *ba* depending upon the convention used. The convention refers to whether one moves clockwise or anti-clockwise around the joint. If the clockwise convention is used the 500N force will be *ab* and vice versa. Once a convention has been chosen, it must be adhered to throughout the problem. A clockwise convention will be used for this solution.

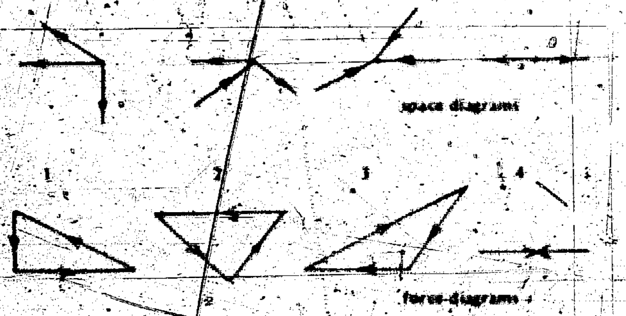


Fig 3.29 Forces at joints of framework shown in fig 3.28

Fig 3.30 Composite force diagram

Fig 3.31 Force diagram

Having chosen a suitable scale, draw a line to represent the 500N force *ab* (fig 3.31). Next draw a line through *b* to represent the force in the lower horizontal member, force *bd*. Then a line through *a* to represent the force in the right hand sloping member force *da*. Where these two lines intersect is point *d*.

Similarly deal with the forces in the upper horizontal member and the left hand sloping member, ie forces *dc* and *ca*. Force *bc* (the lower reaction) can be found by joining points *b* and *c*.

The directions of the forces acting in the members can be found as follows. Consider the forces acting at joint 1. Moving clockwise across the horizontal member we pass from space B to space D. Refer now to the force diagram; force *bd* acts towards the right, hence the force acts towards the joint. Similarly moving clockwise across the sloping member we pass from D to A. Referring to the force diagram, force *da* acts upwards hence the force is acting away from the joint.

The direction of the forces acting at other joints can be determined in a similar manner and the appropriate arrows marked on a space diagram. From these arrows it is possible to establish the kind of forces, tensile or compressive, acting in the members. If the arrows are pointing towards each other, this indicates that external outward forces are present. These forces are tending to pull the member apart and hence the member is in tension *(tie)*. Conversely members with arrows pointing away from each other are in compression *(struts)* as shown in fig 3.32.

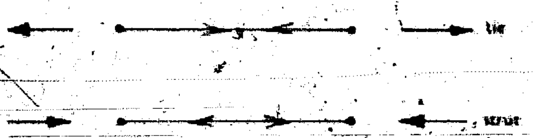


Fig 3.32 Representation of tie and strut forces

Moment method for finding reactions

Before the force diagram for a simply supported framework can be drawn, the reactions must be found. The simplest method of finding these reactions is by moments (fig 3.33).

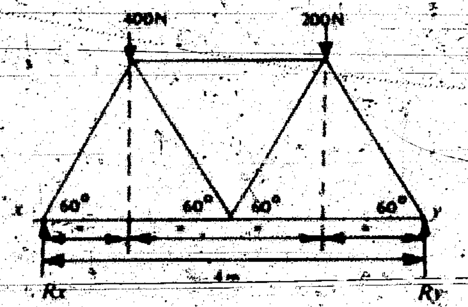


Fig 3.33 Simply supported framework. Before the force diagram is drawn the reactions Rx and Ry must be found

Consider clockwise moments as positive and anti-clockwise moments as negative. Consider downward forces as positive and upward forces as negative.

To find Ry consider moments about x (the sum of the moments of the forces acting on the framework about any point is zero):

$$\text{clockwise moments} + \text{anti-clockwise moments} = 0$$

$$(400\text{N} \times 1\text{m}) + (200\text{N} \times 3\text{m}) - (\text{Ry} \times 4\text{m}) = 0$$

$$\therefore \text{Ry} = (400 + 600)\text{N}/4 = 250\text{N}$$

To find Rx (the sum of the vertical forces acting on the framework is zero):

$$-\text{Rx} - 250\text{N} + 400\text{N} + 200\text{N} = 0$$

$$\therefore \text{Rx} = 350\text{N}$$

Other methods of finding the reactions at X and Y are possible. One of these alternatives is a graphical method, known as the funicular polygon. Forces in single members in a framework can be calculated using the 'method of sections'. This method and the funicular polygon method are described in *Practical Geometry and Engineering Graphics*, by W Abbot.

Work on simple frames

Construct the simple framework referred to earlier from four strips bolted at the corners (this is a pin-jointed frame, fig 3.34). Support the framework at corners C and D and apply a load at corner B. The framework will collapse. Join corners B and D with a member made from string (fig 3.35).

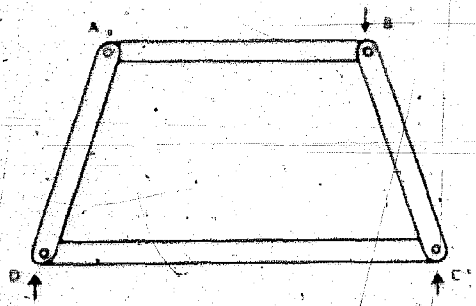


Fig 3.34

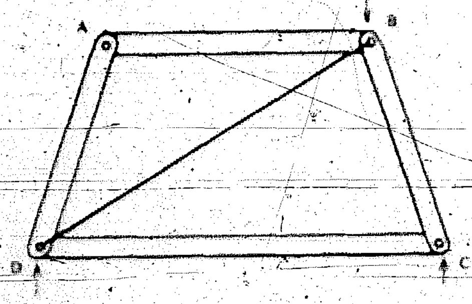


Fig 3.35

Does this strengthen the framework? Try joining corners A and C, the framework is now rigid. Why? Member BD would be in compression, and member AC in tension. The value and nature of the loads in the framework can be determined by using the Bow's notation method in producing a force diagram.

It can be seen from the above example that:

- members in compression must be stiffer than those in tension.
- the triangular frame is rigid whereas the quadrilateral frame may not be rigid.

Few real frameworks are actually constructed with pin-joints, the members are usually held rigidly together by gusset plates, thus the forces obtained from the Bow's notation diagram are only approximate in practice. However, with caution the force diagram can be used to give a useful guide to the magnitude of the forces involved in a structure. By studying the force diagram it is often possible to see how the shape of the framework can be altered in order to reduce the forces in certain members.

Example: design a simple framework to carry a load of 500N at a distance of 1.5 metres from a vertical wall

By studying the space diagram (fig 3.36) it is clear that the force in member AB can be reduced if it is repositioned so that its vector is shortened, eg move a to position a_1 as shown in fig 3.37. This also has the effect of reducing the force in member AD. By positioning AB perpendicular to AD the force in AB is minimised. This change in design also changes the nature of the force in AD from compressive to tensile, which may be advantageous.

There may be reasons, of course, why it is not possible or desirable to reposition member AB, and in this case, the member must be made strong enough to carry the load which the configuration demands. There are other aspects to design than the forces carried by the members in a framework; general appearance of the finished structure and the need for the structure to fit into its environment are also important.

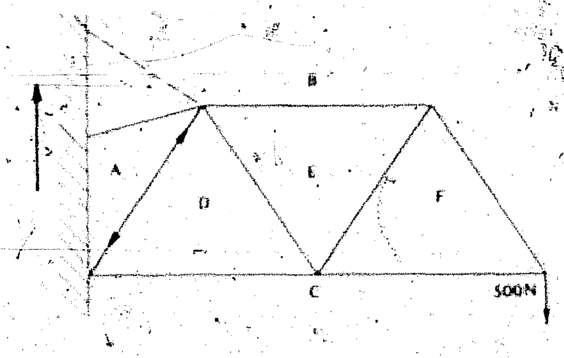


Fig 3.36 Space diagram

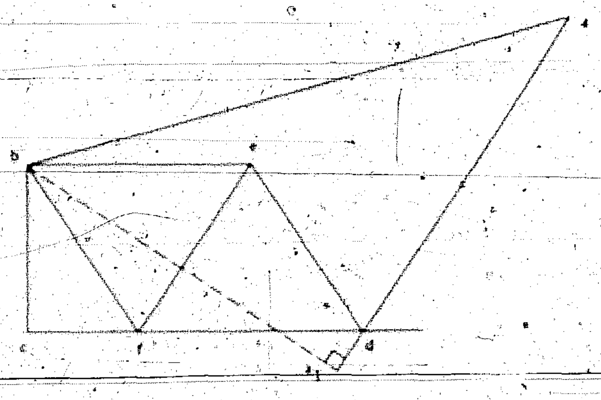


Fig 3.37 Force diagram

Before considering the size (cross sectional area) of each member it is necessary to know something about the strength of the material from which the member is made. When a member is loaded it is assumed that the force produced within it is shared evenly by all parts of the cross section. The force accepted by each unit of area is known as the stress (load/area).

The stress within the material as it breaks is known as the maximum or ultimate stress; this is determined by dividing the breaking load by the cross sectional area of the material. The safe working stress used for design purposes is based on the ultimate stress and the factor of safety, ie safe working stress = ultimate stress/factor of safety.

The factor of safety is governed by the nature of the material and the nature of the loading. A simple rig to obtain the ultimate tensile stress for balsa or other soft wood is shown in fig 3.38.

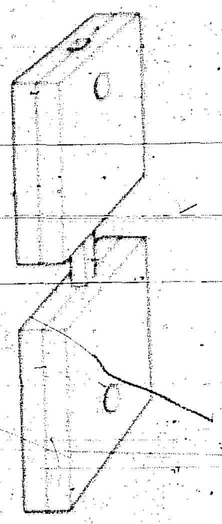


Fig 3.38 Balsa wood rig for tensile stress test

A balsa test piece 24mm^2 cross sectional area will break at approximately 800N force. Hence the ultimate tensile stress is approximately $33 \times 10^6 \text{ N/m}^2$ and if a factor of safety of 4 is used, a reasonable safe working stress would be

$$(33/4) \times 10^6 \text{ N/m}^2 = 8.25 \times 10^6 \text{ N/m}^2$$

A tie (a member in tension) carrying a load of 600N should have a cross sectional area of:

load(N)/safe working stress(N/m^2)

$= 600/8.25 \times 10^6$

$= 0.72 \times 10^{-4} \text{m}^2$

$= 72 \text{mm}^2$ (say 6mm x 12mm).

Example of further work on frameworks: *design a lattice beam from balsa wood with a span of 0.5m and maximum depth 0.2m to carry a load of 300N at mid-span*

Consider the following points:

Have you arranged your members to carry minimum load?

What is a suitable method of applying the load?

Does your framework look pleasing?

The beam is likely to twist when it is loaded. What provision should be made when designing a test rig to prevent excessive twisting in the beam when it is loaded during test?

A number of different trusses and girders are illustrated elsewhere; models based on these could form the basis for further tests.

COLUMNS

Columns have to be large enough to support the applied compressive load and to provide rigidity. The load bearing property of the member is governed by the nature of the material and the cross sectional area, whereas the ability of the member to remain rigid under load depends also on the disposition of the material, eg a tube may be more rigid than a rod of equal cross sectional area.

Suggestions for work based on columns:

From pieces of cartridge paper, say A4 size, construct columns of different sections. Design the column to support the largest possible load. Books can be used to load each column. Consider examples of tubes used for load bearing structures - bridges, cycles, scaffolding, stems of plants etc.

Make a column from plaster of paris reinforced by four 3mm diameter rods. Load the column to destruction. Make similar columns with the rod arranged in different positions. Compare the results for each column.

4 Suggestions for further work

Structures brief 1

Design a balsa wood structure within the space limits shown in fig 4.1

During test the structure will be restrained between buttresses X and Y and the load will be suspended from it along the axis AB

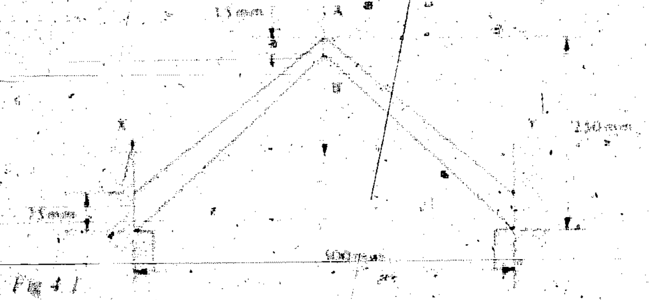


Fig 4.1

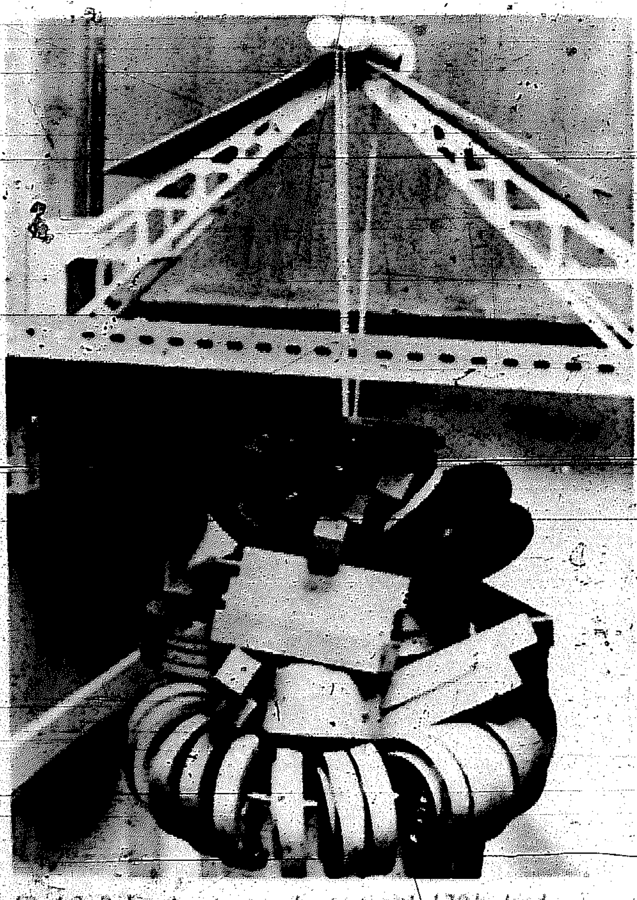


Fig 4.2 Balsa structure under test with 120 kg load

Structures brief 2

Design a bridge structure with clearances, headroom, etc, as shown in fig 4.3

The clearance between the supports is 2m, carriageway 150mm wide with minimum headroom 90mm. The centre section of the carriageway is to be moveable to clear the dotted area shown (500mm × 150mm). The carriageway is to be not thicker than 1.5 mm but may be reinforced by thin wire mesh and it must be able to support a dead load of 150N m run. The ground pressure under the supporting piers must not exceed [illegible] × 10[illegible] N m[illegible].

The structure is to be manufactured from balsa wood and no member is to be greater than 50mm² in cross sectional area. The structure must include a suitable device for raising the centre section. The design of the structure must be based on the pin-jointed frame principle.

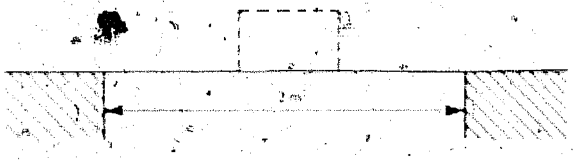


Fig 4.3

Fig 4.4 One solution by sixth form boys

Structures brief 3

The following is an outline for a project on the topic of bridges, which could be carried out during history lessons.

Objectives

To encourage individual enquiry, reading and presentation of results. To show the progress in bridge construction, particularly in recent years, and the importance of bridges in communications.

Introduction

Lecture and discussion on when and where bridges were built from earliest times to the present. The classification of bridges according to the method of construction: arch, cantilever, suspension and beam. (*Bridges and Men* by

J Gies and *The World's Great Bridges*, by H Shirley Smith are useful for the historical aspect and the development of different types.)

The films 'Tacoma Narrows' and 'The Slender Span' illustrate wind effects, research, loading and planning of a modern bridge. These could be shown at this stage.

Topics

Small groups of three or four pupils choose or are set a problem as a topic for development by reading and research. Folders with notes, sketches and drawings should be kept to illustrate the progression of the particular type of bridge; also include notes on some famous bridge builders, the different materials used and the methods of construction. After discussion and guidance, outline scaled drawings can be prepared and models constructed in balsa and/or clay. Models set in a landscape showing the river, terrain, access roads/rails, etc are more realistic, if time permits.

Some suggestions for bridge topics

True arch and pointed arch (Roman and Turkish)

Girder (bowstring, arch – Volta and Sidney Harbour)

Suspension (Severn, Clifton, Golden Gate, Early Tibetan)

Moving (Tower Bridge, Kingsferry)

Cantilever (Early Chinese, Forth rail, Waterloo)

Stayed girder (Wye, extended from Severn complex)

Motorway flyovers (Hammersmith and Almonsbury intersection)

London Bridge (from the earliest to model of the latest design)

Cast iron (Coalbrookdale, Telford's London Bridge design)

Reinforced concrete (Medway M2)

An alteration to an existing road bottleneck (flyover or underpass)

Design a bridge for the future, suitable for a new development in transport (hover trains, monorail, etc).

Further talks and films may be arranged to give a wider understanding of bridge construction and development on these lines:

the benefits and social effects of some notable bridges

famous bridge designers

railway bridges

modern materials and methods – including pre-stressed concrete

suspension bridge – aerodynamics, wind tunnel tests for Severn, roadway is top surface of a hollow steel box with streamlined sides. The lightest bridge for its length. See *Project* magazine No 6 (COI)

motorway bridges – M1 entailed a bridge every mile or so – contrast the rather ugly bridges crossing the early sections of the M1 with later ones built across, say, the M6. Is it simply a matter of cost or new developments in the intervening period?

English Channel bridge – feasibility, problems. Proposals date back to the end of the nineteenth century. Dorman Long submitted a design some seven years ago.

stayed girder bridges – construction; advantages. Examples - Wye, proposed Alvsborg bridge (Sweden), Erskine bridge

Milford Haven box girder design – failure during construction; accident report is of interest. Compare the saving in time with old ferry and road around the reach. Interesting contrast with the Britannia tubular bridge over the Menai Straits (destroyed by fire) where trains pass through the box and not across the top; new materials and methods are applied to old concepts.

Note. Outside speaker from engineering firm or county engineer would enhance the work.

5 References

REFERENCE MATERIAL

Information Division, Department of the Environment, Nevile House, Page Street, London SW1

The Institution of Civil Engineers, Gt George Street, London, SW1 for reports of proceedings of particular bridge constructions. Tel 01 839 3611.

The Cement and Concrete Association, 52 Grosvenor Gardens, London SW1. Tel 01 235 6661

The Forest Products Research Laboratory, Princes Risborough.

The Timber Research and Development Association, High Wycombe.

Dorman Long 7 Co Ltd, Terminal House, Grosvenor Gardens, London SW1.

George Wimpy & Co Ltd, Hammersmith Grove, London W6.

The Petroleum Film Bureau, 4 Brook Street, Hanover Square, London W1. Tel 01 493 3333

FILMS

16mm films may be borrowed from the following:

The Institution of Civil Engineers (free)

The Failure of the Tacoma Narrows Bridge (silent) 20min. (Shortened version) Ref Film 5. Collapse of a suspension bridge under the influence of lateral wind forces.

Bridge across the Tagus. Colour sound 20min. Ref Film 38. The erection of the superstructure of the highway bridge which is the longest bridge in Portugal. Shows the employment of a floating trussed steel service span as a temporary support for each permanent span.

Construction of the Forth Road Bridge Colour sound 56min. Pictorial record of the construction, including the spinning of the cables. Ref Film 85.

The Petroleum Film Bureau (free)

B P 1969 Bridges in Holland
Colour 21min.

The Cement and Concrete Association (free)

A number of very interesting colour films are available from the Association; these are listed in their catalogue 'Films available on loan'. They include:

The Medway Bridge (39min)

Elements facing Elements (30min) Europe's longest bridge.

The Hammersmith Flyover (38min)

Over the Top (25min) M4 between Chiswick Flyover and Boston Manor

Mancunian Way (30min)

Prestressed Concrete Quay Construction (28min)

Standard Beam Sections for Prestressed Concrete Bridges (10min)

For information about the availability of colour slide sets, please write to:
National Centre for School Technology
Trent Polytechnic, Burton St, Nottingham

BOOKS

Many titles are available in school and public libraries. The following may be found useful:

Roads, Bridges and Tunnels
Michael Overman, Aldus Books.
Basic principles well illustrated with many modern examples, clear diagrams. Good teacher and pupil reference book.

The World's Great Bridges
H Shirley Smith, Phoenix House.
Comprehensive, well illustrated coverage of the world's major bridges.

Modern British Bridges
D Henry and G Jerome, MacLaren & Sons.
Many plates and drawings of the latest bridges.

The Girder Bridge
P S A Berridge, Robert Maxwell.
Well illustrated book giving interesting accounts of the development of railway girder bridges in Great Britain from the start of the railway age in 1825.

Builder and Dreamer (Brunel)
L Meynell, Heinemann Educational.

Bridges (Get to Know Series)
E Fry, Methuen.
Simply written and well illustrated, children's book.

Bridges
Derrick Beckett, Paul Hamlyn.

Bridges
National Benzole

Science Builds the Bridges (World of Science Series)
C H Doherty, Brockhampton Press.
Simply written and well illustrated, children's book.

Your Book of Bridges
E De Mare, Faber.

The Appearance of Bridges
HMSO (SBN 11 550074X)

The Severn Bridge
'Project' magazine No 6, COI

Forth Road Bridge
Clerk of the Forth Road Bridge Joint Board, City Chambers, Edinburgh 1. (Official story)

Severn Bridge
E Everard Ltd, 38 Broad Street, Bristol 1.
Story of the history and construction of the bridge

Timber Construction in Bridges
L G Booth, TRADA.

An Illustrated History of Civil Engineering
J P M Pannell, Thames and Hudson.

TEXTBOOKS

Forces in Framed Structures
Morgan.

Practical Mechanical Design
Tweedale, Iliffe.

A Design Manual for Cabinet Furniture
Furniture Development Council, Pergamon.

Principles of Structural Design (2nd edition)
Niels Lisborg, Batsford, 1967.

CHARTS AND DIAGRAMS

The National Coal Board.

London Transport Executive,
180 Marylebone, London NW1.

Project Technology Handbooks

These handbooks form part of the teaching material programme of Schools Council Project Technology. They provide technological know-how, guidance on equipment, and ideas to help the teacher set up technological project work in schools and colleges.

1 *Bernoulli's Principle and the Carburetter*
2 *Simple Bridge Structures*
3 *Simple Materials Testing Equipment*
4 *Introducing Fluidics*
5 *Engine Test Beds*
6 *Muffle Furnaces*
7 *The Ship and Her Environment*
8 *Design with Plastics*
9 *Simple Fluid Flow*
10 *Industrial Archaeology for Schools Vol I*
11 *Industrial Archaeology for Schools Vol II*
12 *Food Science and Technology*
13 *Basic Electrical and Electronic Construction Methods*
14 *Computer and Control Logic*
15 *The What, Why and How of School Technology*

Heinemann Educational Books / Schools Council