Design and Construction of Bridges

Part One of a series of interest to all engineering-minded readers

By Terence Wise

THE single decker bus slewed wildly across the road towards the barrier in the centre of the dual carriageway. The automatic doors burst open suddenly and explosively. The driver forced the steering wheel hard over and slowly the bus regained its position, only for the process to be repeated a minute later. Determinedly but crazily the bus zigzagged its erratic course over the bridge.

I experienced this hair-raising ride one evening when crossing the mile of river spanned by the Severn suspension bridge, one of the many new bridges in this area and certainly, with its revolutionary aerodynamic design, the most impressive of all the numerous bridges that have been built in this country over the past decade. This journey, made during a strong gale, aroused my curiosity concerning the engineering skill that enabled such a bridge to be built and I began to 'see' the wonder of bridges everywhere that previously I had crossed hundreds of times without a second look. I started investigations.

Chambers Encyclopaedia defines a bridge as "an engineering structure carrying a path, road, railway or canal across a river, a valley or like obstacle, or across another road or railway". This is a rather drab description for creations that are rarely ugly, no matter how utilitarian, but are often exceedingly graceful, expressing in every soaring span the triumph of Man overcoming Nature's obstacles. Bridges are also classified under type of design and material, whether fixed or opening, single or continuous span. In the following months I shall deal with the various types of arch, cantilever, girder and suspension bridges, but in the present article it is first necessary to describe the basics of bridge building and span the history of the development of bridges up to the revolution caused by the introduction of iron and steel. To understand bridges one must start at the beginning, not the end!

All bridges must depend ultimately on their foundations, for any subsidence of these at a later date could be fatal. Consequently the siting of a bridge often depends on the availability of good conditions for foundations. Fig. 1 illustrates the formations that decided the position and design of the Severn suspension bridge. Rennie's beautiful Waterloo bridge in London had to be demolished—despite loud protests from the public—simply because during a period of a hundred years one of the piers, built on wooden piles, had sunk over two feet and rendered the bridge unsafe. The building of foundations is especially difficult where water or soft soil is encountered and caissons—box-like shells of timber, concrete or steel that are later filled in to become part of the permanent structure—have to be constructed.

On the foundations are built piers of stone, brick, steel or concrete, usually in the form of a slender shaft nowadays (Fig. 2) although before the Renaissance piers were thick, rather clumsy things, for they not only carry the weight of the bridge but also must resist the extreme pressures of any floods. The piers at each end of a bridge, in addition to taking the weight of the bridge, are also sometimes subjected to a horizontal thrust and they are then termed abutments (Fig. 3). In modern suspension bridges the towers carrying the cables and the anchorages at each end of the cables represent the piers. Retaining walls are also built to contain the approach embankments to some bridges and these are known as wing walls.

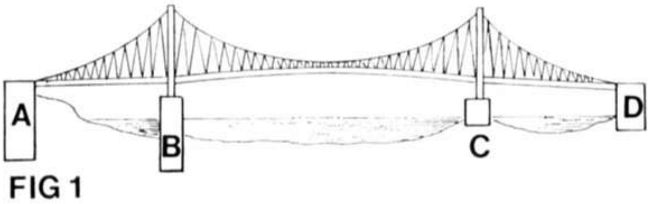
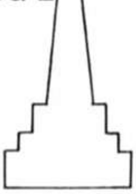


FIG 1

FIG 2



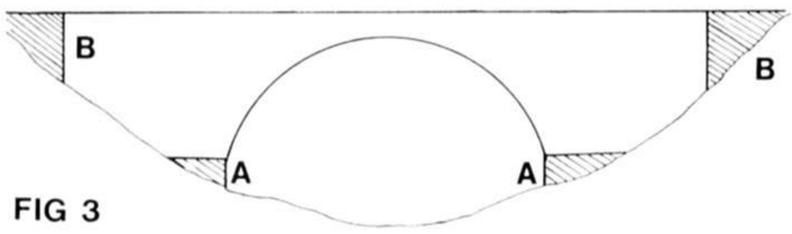


FIG 3

Fig. 1–A. Beachley anchorage, built on hard limestone after digging through 60 feet of sand.
B. Beachley pier, set 35 ft. down.
C. Aust pier, a depth of only 4 ft. before building on Ulverstone Rock.
D. Aust anchorage again only a small depth of 10 feet to the limestone.

Fig. 2–The slender shaft of a modern pier resting on the widened base of the foundation.

Fig. 3—A. Two abutments to resist the thrust of the arch ring *and*
B. Two more abutments for the bridge deck, supporting the earthwork of the bridge approaches and forming the ends of the bridge.

Heading photo, the medieval stone bridge over the River Monnow at Monmouth was built in 1272. The distinctive toll gate was added in 1296.

A 19th century stone arch bridge, carrying a railway line: this technique has remained unchanged after 2,000 years.

The type of bridge erected on the piers is often determined in the first instance by the availability of sites for the piers, the nature of the approaches to the bridge and, in the case of rivers used by shipping, the height above water level needed for navigation. Into the design of the bridge must also be incorporated a safety margin to provide for wind pressures and to cover this the designers allow for the maximum stress being exerted on every section of their bridges. Bridge loads are governed by law in most countries.

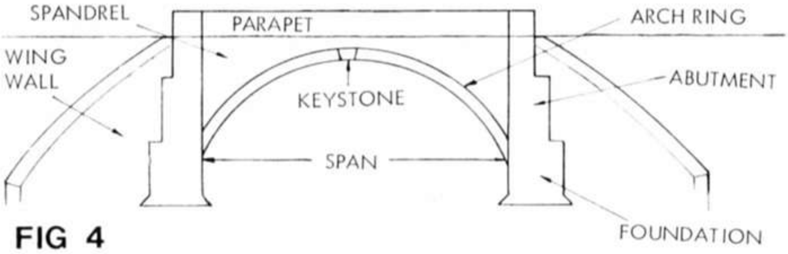


FIG 4

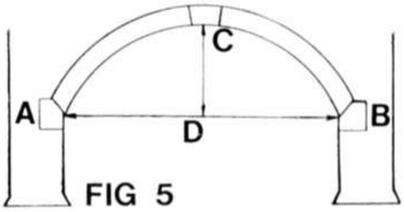


FIG 5

The first type of bridge design, usually attributed to the Romans, was the simple arch. The principle was known to the Sumerians as early as 3,600 B.C. but the oldest surviving bridge in the world is a stone arch bridge at Izmir, Turkey, dating from about 850 B.C. In the 6th century B.C. the Romans were building timber bridges, but by the end of the 2nd century B.C. were constructing stone arches. Their Ponte Fabricio over the Tiber in Rome, built in 62 B.C., is still in use today. With the fall of the Roman Empire, however, bridge building came to an end in Europe until the time of the Crusades, when communication with the East reawakened interest. About this time were built the famous Ponte d'Avignon and the infamous London Bridge, which incidentally survived 623 years until 1832! But the arches of these bridges were still steep and small, with massive piers, and it was not until the Renaissance that bridge building made its first major step forward.

The main disadvantage of close-set piers, aptly illustrated by the rapids of old London Bridge, was the obstruction to the flow of water. This caused the river to constantly swirl around the piers and by a scouring action eventually undermine them. The Italians discovered that the arch not only exerted vertical pressure on the piers, but also horizontal thrust. This discovery enabled them to develop the segmental and elliptical arches with their slender, widely spaced piers which caused less obstruction to the river and at the same time, by lowering the rise of the arch, permitted the construction of a more level roadway over the bridge.

The development of the arch reached completion with this discovery as far as design was concerned and it was only to be modified by the introduction of new materials such as iron, steel and eventually reinforced and pre-stressed concrete. Basically any stone or brick arch usually consists of part of a solid ring erected on a temporary staging to take the weight during construction, with the central keystone being placed in position last. Once the keystone is in position the staging is removed and the structure settles until the compressive forces are evenly balanced. (Telford's bridge over the Severn at Over in Gloucestershire dropped ten inches at this vital moment owing to movement at the eastern abutment. A normal drop would be perhaps two or three inches.) Thus it can be seen that all movement at the ends of an arch must be prevented. Several arches can be built to thrust horizontally against each other, but the ends of the series of arches must always be terminated by really solid abutments. Fig. 4 points out the various parts of an arch bridge. Fig. 5 shows that the arch ring 'springs' from the abutments A and B and at the springing point rests on skewbacks—special courses of brick or stone dressed to the correct angle. At the crown C the arch rises above the chord line (the straight line A–B joining the ends of the arc) to a height C–D which is called the rise of an arch. This is measured from chord line to soffit. The extrados and intrados are the outer and internal surface curves of the arch, and the soffit is the highest point of the intrados. Dressed bricks or stones that form the ring of the arch are called voussoirs, being specially tapered to shape. Today both brick an stone have been almost entirely superseded by concrete.

Many notable stone bridges were erected during the next century—the longest and flattest brick arch ever built is Brunel's railway bridge over the Thames at

Partially destroyed by floods in 1598, and further damaged in the 19th century, the Ponte Rotto in Rome was built in 181 B.C. These remaining arches are typical Roman. In the background is the Ponte Fabricio.

COMPARATIVE COMPRESSION STRENGTHS OF MATERIALS	
Brick	8-12 tons per sqare foot
Limestone & Sandstone	20 ,, ,, ,, ,,
Granite, etc.	30 ,, ,, ,, ,,
Concrete	750 pounds per square inch
Reinforced Concrete	1,000 pounds per square inch in the concrete 18,000 pounds per square inch tension in the steel.

The bridge over the Thames at Richmond, built in 1773, just before the first iron bridge. The width was doubled in the 1930s.

Maidenhead, with two spans of 128 feet each and a rise of only 24 feet 3 inches—but all these bridges were merely re-using the same construction principles. The next great advance in the art of bridge building did not come until 1776, when a Shropshire iron founder named Abraham Darby began the building of the world's first iron bridge, curiously enough once more across the Severn, near Coalbrookdale in Shropshire. Next month we shall investigate the development of the cast iron bridges and the introduction of wrought iron, reaching a peak with Brunel's Royal Albert bridge at Saltash.

NORTHWEST PASSAGE

(*Continued from page 91*)

so far through the ice-infested seas. After a long winter icebound at Melville Island, Parry continued west, sailing almost to Banks Island, the last land mass of the passage.

After Parry came the ill-fated Sir John Franklin. One of the greatest Arctic navigators, he had spent 25 years adventuring in the Far North before embarking on his last fatal voyage in 1845. The two ships, with a total company of 130 men, were last sighted by a Greenland whaler at the end of July that year as they entered Lancaster sound. Nothing more was heard of them.

With a £10,000 reward offered for the discovery of the vanished expedition, over the next ten years more than 40 others set off from both sides of the Atlantic hoping to solve the mystery. Gradually the tragic story was pieced together. After being gripped in the ice for nearly a year and a half, Franklin and many others died of exposure. Survivors abandoned the doomed ships, but all perished as they tried to cross the ice to safety.

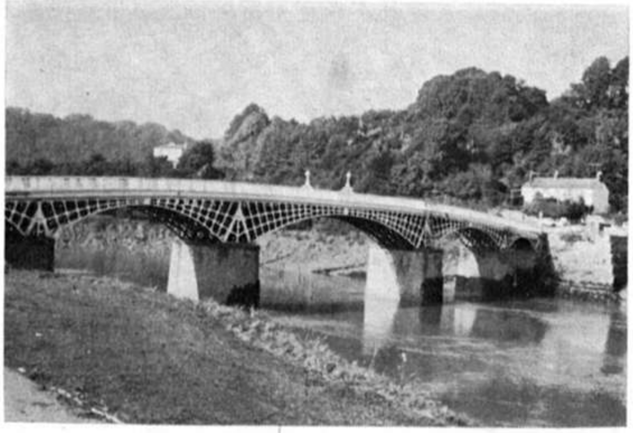
Among the searchers for Franklin was Commander Robert McClure. He rounded Cape Horn and followed Captain Cook's earlier trail from the Pacific. Beyond Bering Strait, McClure turned east and navigated the westernmost channel of the Northwest Passage. From a 1,300-foot mountain on Banks Island he looked east and could confirm the existence of a through sea route. But McClure's ship was frozen fast, and it was three years before a rescue party arrived.

McClure and his companions did actually make the first transit of the Passage, although 200 miles were made by sled. Another half century passed before Amundsen finally succeeded in making the first east to west crossing entirely by ship, reaching the Bering Strait at the end of August, 1906, after three long winters locked in the ice.

Not until 1954 did the Canadian ship *Labrador* captained by Commodore Robertson, carry out the first transit of the Northwest Passage ever made in a single season.

Now, more than 60 years after Amundsen, the *Manhattan* has pioneered what could well be the breakthrough for commercial navigation in the Arctic. Many problems still have to be solved before this is feasible. But sometime in the Seventies, mammoth icebreaking supertankers, two or three times as large as the *Manhattan*, could be shipping crude oil from the North Alaska field by the most direct route to America's east coast ports, and thence to world markets. The potential value of big-ship navigation to future development of the Arctic's natural resources is tremendous indeed.

Right, The *Manhattan* trapped in heavy ridging ice in a northern area of Baffin Bay. Beyond is the new Canadian Coastguard icebreaker *Louis S. St-Laurent* which later moved in along the tanker to ease pressure and allow the ship to move again.



Design and Construction of Bridges

Part Two—Cast Iron Bridges

By Terence Wise

THE modern bridge can really be said to date from the introduction of cast iron to bridge building, instigated in Great Britain in the latter half of the 18th century by Abraham Darby, for this caused the departure from solid arches and the use of cast iron ribs eventually led to the invention of the girder.

The design for the very first iron bridge was by an architect from Shropshire named Thomas Pritchard, who suggested to Darby the use of cast iron ribs to form a support for a masonry arch. This was not adopted, but it gave rise to the idea of forming an iron arch by the casing of a series of arch-shaped ribs, made with hollow spandrels in order to remove much of the weight which was not contributing to the strength of the members. (Spandrels are the part of a bridge between the arch ring curve and the deck.) This design was not taken up either, but a third design resulted from it and this was the one on which the bridge was finally constructed. (*Fig.* 1).

Built by Darby over the Severn River near Coalbrookdale in Shropshire—the place is now named Ironbridge—the bridge consisted of five semi-circular iron ribs cast in ten halves in open moulds. The casting of these main ribs, each one being half the length of the hundred foot six inches span, was a masterpiece of iron foundry work for those days. The rise of the completed arch was fifty feet and the bridge, begun in 1776 and completed by 1779, is still standing to this day.

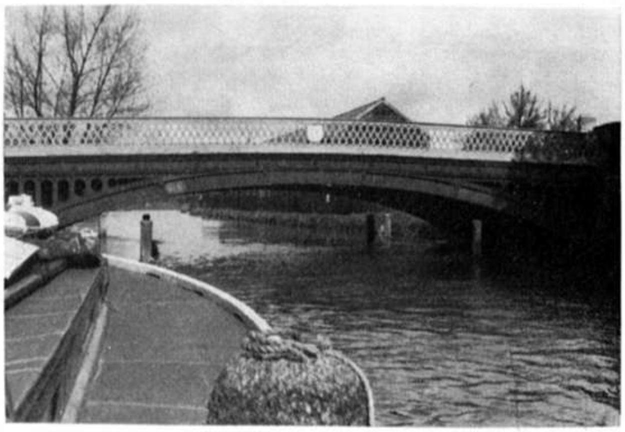
It was not long before the revolutionary new bridge was copied, appropriately by Thomas Paine, himself a revolutionary and author of 'The Rights of Man'. He drew up a design for a second cast iron bridge but he had to flee the country and it was not built until some years later, in 1796. The ribbed arches for this bridge were cast at Rotherham by Robert Wilson and for some time they were exhibited in London as a curiosity. After being returned to Rotherham, the bridge was redesigned by Wilson and erected over the River Wear at Sunderland by Rowland Burdon (*Fig.* 2). The span was a staggering 236 feet, with a low water clearance height of a hundred feet.

A third iron bridge was built in the same year at Buildwas, again over the Severn, by Thomas Telford—a foretaste of the work soon to be performed by this great engineer. The span was 130 feet. A more impressive iron bridge was that built at Southwark over the Thames by John Rennie, being completed by 1819. This bridge had a centre span of 240 feet. It was replaced by a modern bridge in 1921.

Cast iron has two factors that influenced its use in bridge building. Firstly, it had a high resistance to compressive stresses—compare its high compression strength quoted below with those of the earlier materials, shown in last month's article—and it could be cast in very large sections. Secondly, it was extremely brittle. The second factor soon led engineers and iron founders to seek economic ways of producing wrought iron which, being forged or rolled instead of cast, is more malleable and therefore better suited for the tensile, bending and twisting stresses experienced in bridges.

Wrought iron was first produced in great quantities and at an economic price in 1766 by Richard Reynolds, the son-in-law of Darby, but by 1820 the difference in prices was still so great as to restrict the use of wrought iron, cast iron selling at about half the price. It was Telford who first used wrought iron for bridge work, in his construction of Britain's first suspension system for the Menai Straits Road bridge during the years 1819–1825. (This bridge will be covered in greater detail in a later article.) It was used again by him for a second suspension bridge over the Conway River in 1826. However, his choice of wrought iron was dictated by the necessity for tensile strength in the new suspension design.

It was left to Robert Stephenson to select wrought iron for his principal material despite the extra cost when he began work on the 412 foot long tubular girder bridge over the Conway River in 1846. The bridge, completed two years later, served as a proving ground for his next bridge—the Britannia railway bridge over the Menai Straits, which was finished in 1850 and is today safely carrying loads far in excess of those estimated by Stephenson. The wrought iron tubular girders



Remarkable elegance could be captured by bridge designers using cast iron, as these two lovely examples show.

FIG 1

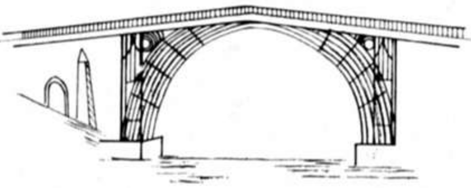


FIG 3

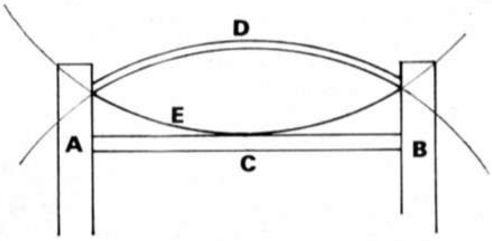


FIG 2

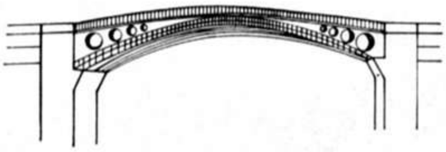
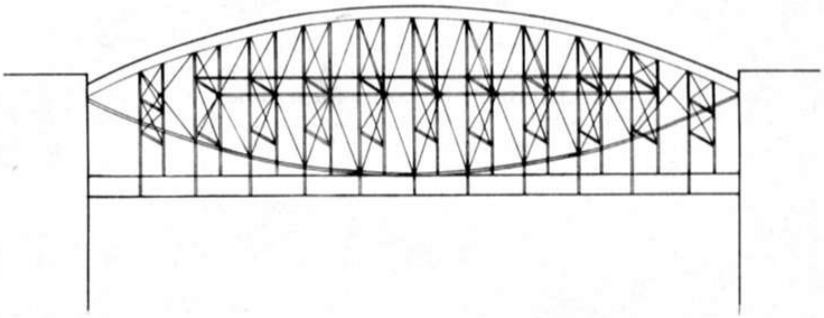


FIG 4



for the latter bridge are each 1,511 feet long and weigh 4,680 tons, the trains running *through* the tubes. The bridge has a total length of 1,380 feet and a high water clearance height of a hundred feet.

But it was Brunel's Chepstow and Saltash bridges that constituted the greatest advance in bridge building, bringing the use of wrought iron to its zenith in the 1850s, for his new designs used the material to its best advantage. The railway bridge at Chepstow provided Brunel with a chance to experiment for the Saltash bridge. The weight of the 300 foot main span was taken by two huge wrought iron tubes resting on rollers on top of iron piers. These tubes lasted a hundred years, being replaced by modern steel in 1962.

Work on his Royal Albert bridge, carrying the railway link between Devon and Cornwall across the Tamar River, was begun in 1853. In his design Brunel tried to combine the best structural advantages of the wrought iron arch and the newer suspension principle. The bridge was based on two great wrought iron trusses with tubular arches and suspension chains, both following an identical line of curvature to form a double convex shape. *Fig.* 3 illustrates this basic principle of the design. A and B are the piers, C the bridge deck, D the arch curve, and E the suspension chain curve. The arch tubes are oval in shape, being 16 feet 9 inches wide and 12 feet 3 inches high. The length of each span is 465 feet, the two trusses meeting on a central pier built on solid rock in mid river after excavating to a depth of 80 feet, with their other ends resting on piers built on the river banks. Each of these giant trusses weighs over a thousand tons.

Fig. 4 is a simplified sketch of the elevation of one span, showing the deck slung from the arch and suspension chains. The suspension links have not been drawn in in order to make the construction of the truss stand out more clearly. Each of the trusses was first built on a platform on the shore, then floated into position on pontoons and jacked to the right height. The bridge, capable of carrying the much heavier loads of today, was finished in 1859.

The Saltash bridge was to be Brunel's last work for he died in September of that year. It was also the last great wrought iron bridge, for in 1855 the English metallurgist Henry Bessemer had patented a process for producing steel from pig iron and within five years—only a year after the completion of the Royal Albert bridge—the new material was being used in the building of bridges.

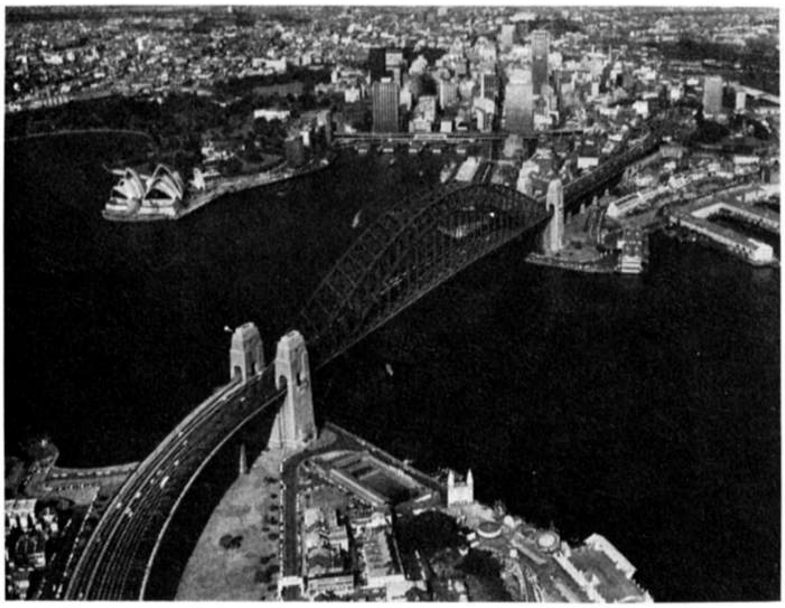
This brings us to the era of the steel arch, which we shall be covering next month.

COMPARATIVE COMPRESSION & TENSION STRENGTHS OF MATERIALS

Cast iron	3,000 lbs per square inch in	tension
	12,000 lbs ,, ,, ,, ,,	compression
Wrought iron	14,000 lbs ,, ,, ,, ,,	tension
	14,000 lbs ,, ,, ,, ,,	compression in short struts
	12,000 lbs ,, ,, ,, ,,	sheer, that is in the perpendicular

Book Review

Model Building in Meccano and Allied Construction Sets by B. N. Love is a unique publication which will appeal to model builders of all ages. The author, who is well known for his feature articles in Meccano Magazine, presents a wealth of information on Meccano models, beautifully illustrated throughout with large pictures of first class mechanisms and working models. This is a long-awaited publication which presents, for the first-time, a collection of some of the work of first-rate adult modellers from many parts of the U.K. Nevertheless, it is written in the author's easy style for young and old alike. A well-produced book which will grace any constructor's personal library shelf and which will prove both entertaining and instructive.



THE DESIGN AND CONSTRUCTION OF BRIDGES

Part 3

THE STEEL ARCH

by T. Wise

STEEL was first used in the construction of bridges as early as 1829 in the building of the Danube Canal bridge in Vienna, but it was the establishment and growth of the railway industry, creating a demand for bridges in all parts of the world, that led to the rapid new developments in the designs of bridges. These new ideas on design, coupled with the mass production of steel, resulted in iron being abandoned as the prime material in bridge building.

The benefits brought by steel were countered by only two defects: steel is extremely susceptible to rust, making constant maintenance necessary, and it expands appreciably with rises in temperature. The latter is provided for by the inclusion of expansion joints in the designs, such as the hingeing of arch bridges, explained later in the article, the use of rollers at one end of a truss instead of a fixed bearing, and in modern suspension bridges the wire adapting itself to a new curve to allow for any such increase in length.

In 1867 the American engineer Captain James Eads began work on his bridge over the Mississippi at St. Louis, using for the first time an alloy steel in bridge construction. The bridge, completed seven years later, was the largest arch bridge of its day, with two side spans of 502 feet each and a central span of 520 feet. However, the first bridge to be built entirely of steel was that carrying the Chicago-Alton railway over the Missouri at Glasgow in South Dakota. It was not completed until 1878.

The French engineer A. G. Eiffel used wrought iron, mild and cast steel when he built the Viaduc du Viaur, carrying the railway from Carmaux to Rodez over the River Viaur in the Aveyron area of southern France. Completed in 1880, the viaduct was not of a new design but very few of its kind had been built at that time. The main advance was that scaffolding, or staging, could be done away with all together, a great advantage in this particular case where the height above river level is 380 feet. Known as equilibrated or balanced arches, the system entails building out from each side of the valley, in this case covering a span of 1180 feet, the viaduct having a total length of 1515 feet. The approaches are masonry, with independent trussed girders of the Pratt type connecting to the ends of the arch ribs. (The subject of trusses is covered in article number five in this series.) The arch ribs are 187 feet deep at the piers and have a span of 227 feet, diminishing to a depth of only 10 feet at the crown. The central span remaining is 726 feet, which if divided into two gives 363 plus 227 (length of side span) = 590 feet, so that each half of the bridge represents a kind of balance beam. Once the side spans have been erected with the arch ribs, the remainder of the bridge is completed by building outwards on the cantilever principle to a meeting in the centre. The breaking stresses of the materials were (per square inch) 30 tons for steel, 23 tons for wrought iron, 27 tons for the steel used in rivets and 26 tons for wrought iron rivets. Although this great viaduct is still in use the design was too fragile for modern needs. At this time also engineers became enamoured with the cantilever principle for bridging large spans—the Firth of Forth railway bridge was begun in 1822—and for some years the arch was neglected by bridge builders.

Meanwhile concrete, which had at this time already begun to replace timber, brick and stone for arch bridges—the first concrete bridge in Britain was built as early as 1877—was improved at the turn of the century by the introduction into it of high tensile steel rods, and this reinforced concrete began to replace steel for arch construction from about 1905.

Fig. 1 is an outline of the steel bridge that in a single majestic span of 500 feet leaps over a 400 foot chasm of

Above, Sydney, Australia. In the foreground are road and rail approaches to the Harbour Bridge, linking the northern suburbs with the inner city area.

FIG.1.

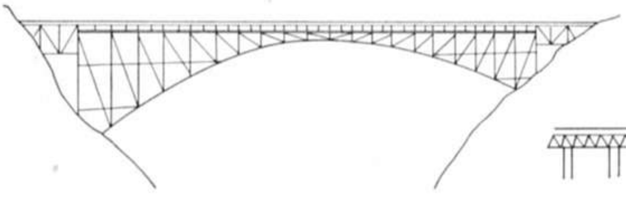
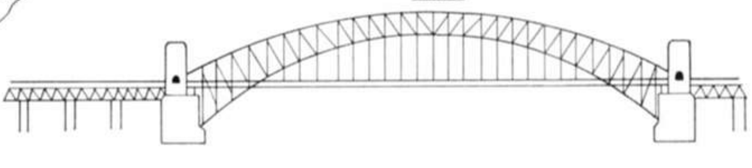


FIG.2.



the Zambesi River below Victoria Falls. Built in 1905, the Victoria Falls bridge carries a vital link in the African railways system. Only one side of the construction has been drawn in detail in order to illustrate the members more clearly.

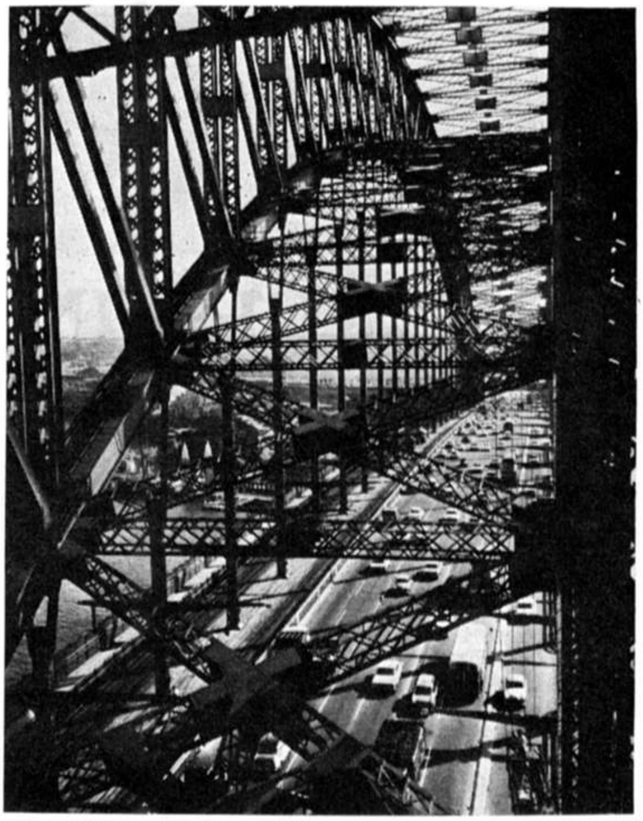
The steel arch was not yet finished, indeed the greatest examples of it were yet to be built. In 1917 Gustav Lindenthal erected a great steel arch across the East River in New York. This bridge—the Hell Gate, carrying four railway tracks over a 977½ foot span—was the pioneer of the modern steel arch bridge. In its design Lindenthal utilised the arch and suspension principle employed by Brunel for the Royal Albert bridge at Saltash, the deck of the bridge being suspended from the arch itself, instead of being supported above it. In this tied or bowstring design the curved upper member of the bridge takes the character of a linear arch, transmitting a thrust throughout its entire length, while the lower member, forming the bridge deck, is simply a straight tie uniting the ends of the bow. Once construction is complete the whole structure can become independent of the abutments and merely rest on them in the same manner as a beam. In very large bridges the uppermost member may become a curved lattice girder consisting of two concentric members braced together, see sketch of Sydney Harbour bridge. In this case the arch thrust is divided between the two members, although it cannot always be shared equally by them.

The trouble with this design arises with the changes of temperature, for the expansion of the curved member forces it to bend upwards at the crown, since it cannot expand its length. Provision for such expansion is therefore made by the introduction of pins, or hinges, at certain spots. (Hence the terms unpinned and fixed, or two- or three-pinned bridges.)

In many cases the curved member is hinged or pinned at the skewbacks. This permits a freedom of angular movement at each abutment, enabling the member to take a continuous curvature in one direction throughout its length and so accomplish the bending promoted by expansion. The resulting stresses are much less severe than if the member were secured to the skewbacks. Stress is still experienced at the crown of the arch, however, and this can be eased sometimes by the use of a third pin or hinge at the crown. The Viaduc du Viaur employed such a three hinge method. This does not damage the stability of the structure but will help to relieve the member from the expansion stresses and also those that arise from the compression of the arch.

Sydney Harbour bridge is perhaps the finest example of a two-pinned steel arch of this type. The bridge was built by Dorman, Long & Co. of Middlesbrough between 1925 and 1932 and at the time was the largest steel arch bridge in the world. The total length is 3,770 feet, total width 160 feet and the total height 437 feet, or 75 feet higher than St. Pauls. The main arch span is 1,650 feet with a high water clearance of 172 feet. The bridge was designed to carry two electric overhead railway tracks, tram tracks, vehicle lanes and two cycle and footways, although the tram tracks have since been pulled up and converted into extra vehicle lanes, making a total of eight lanes with a width of 57 feet. During the first years of use the bridge was crossed every hour by 160 trains, 6,000 vehicles and some 40,000 pedestrians: nowadays in the region of 100,000 vehicles cross every day. 50,000 tons of silicon steel were used in the construction and the total cost was £4,200,000. The main span was erected by the cantilever principle, building out towards the centre from both shores. Fig. 2 is a simplified outline sketch of the

(*continued on page* 172)



Above, Sydney Harbour Bridge pumps upwards of 40,000,000 vehicles a year in and out of the city.
Centre, the bridge has eight lanes for cars, twin train tracks and two footways.
Below, the bridge also has a 172 foot water clearance to let even the largest of ships pass, this particular one being the Matthew Flinders bound for Japan.

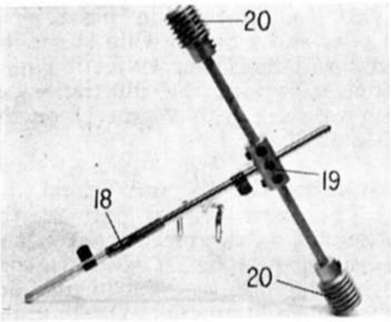


Fig. 5. The Foliot verge which makes use of the special Pivot Rods from the range of Meccano Electrical Parts Note the Spring Clips which engage with the Angle Brackets on the escape wheel.

does not wobble; (2) that it is as concentric as possible; (3) that all 15 Angle Brackets are set squarely in radial line with the shaft centre and that their tips stand off from the wheel rim at the same distance in each case. Thin Brass Washers from the Meccano Electrical Parts range are strongly recommended for setting up any discrepancies in levels in this, or any other part of the clock assembly. Remember that patience here pays handsome dividends!

When you are satisfied that it is running true, the completed escape wheel is mounted on a 4 in. Axle Rod which is passed through the central 7½ in. Angle Girder 6. The 19-teeth Pinion 7 is fixed on the shaft to mesh comfortably and without binding with 2½ in. Gear Wheel 8 on the Motor shaft. The shaft is held in place by Collars and Washers. At this stage a preliminary wind up of the Clockwork Motor should set the hour hand spinning and there will be no doubt about whether the escape wheel is running true!

Foliot Verge

Coming to the Foliot verge, this is simple by comparison with the escape wheel, as can be seen in Fig. 5, and it relies on electrical Pivot Rods for its success. A 3½ in. and a 2 in. Pivot Rod are joined by a Standard Rod Connector 18, a Coupling 19 being fixed towards the end of the longer Rod. A pair of 2½ in. Axle Rods, each fitted with a Worm 20, or similar weight bob, are fixed into the ends of the Coupling, then, finally a pair of Spring Clips are mounted on the composite pivot rod to align with the top and bottom of the escapement wheel.

It only remains now to set up the verge between the upper and lower Pivot Bolts and to screw them up gently, finally locking the Nuts when the escapement is working properly. Some adjustment of the Spring Clips will probably be required, both in height and rotation, until they are alternately caught and released by the escape wheel. The Foliot verge swings quite vigorously with a characteristic "thump, thump", so it will always remind you of its presence while it is working. This particular form of escapement, however, is notoriously less accurate than the pendulum and anchor escapement, so do not expect chronometer reliability! Nevertheless, the building of this clock is most instructive and results in a very acceptable form of antiquity!

Ornamentation

Clock ornamentation is purely a matter of constructor's choice. Fig. 1 shows the simple embellishments adopted by Pat Briggs, using four 5½ in. Perforated Strips, twelve Angle Brackets, a Boiler End, an Adaptor for Screwed Rod and some Corner Brackets. The result is extremely pleasing, but each individual builder is of course at perfect liberty to follow his own inclinations.

PARTS REQUIRED
BASIC CLOCK

1—1a
4—2
4—6a
4—8a
1—8b
7—9
3—10
21—12
1—12b
2—15b
4—16a
1—24
3—26
1—27c
4—32
6—35
52—37a
40—37b
40—38
1—63
3—90a
4—111
3—111c
1—120b
1—126
1—133
3—133a
1—120b
2—154a
1—213
1—214
1—235b

Electrical Parts

2—545
1—548
1—549
12—561

1 No. 1 Clockwork Motor

SIMPLE ORNAMENTATION

4—2
30—37
16—12
4—108
8—133a
1—162a
1—173a

HORSE-POWER (*continued from page* 175)

descended from Shires. With his remarkable muscular "forearms" and quarters, short, well-coupled back and the immense power in his frame, the Shire has moved astonishing weights.

During official trials before a properly-constituted authority, two Shires, yoked tandem-fashion, and on wet granite setts (offering a poor foothold), moved off with the huge weight of 18½ tons. They did this quietly and without any fuss, and as a matter of fact the shaft horse had shifted the mass before the leader got his chains properly tightened. On another occasion two shires moved 16½ tons of wood blocks. Another time two Shires pulled against a dynamometer. The maximum of the instrument was registered and the pull exerted was considered equal to a starting load of 50 tons. The Shire has, of course, always been noted for its strength, and its ancestors of the Middle Ages were the only horses capable of carrying the heavily armoured knights of the period.

BRIDGES (*continued from page* 177)

bridge, illustrating the design principles.

The building of Sydney Harbour bridge seemed to mark the return to favour of the steel arch, which is probably still the most elegant of all bridge designs. In 1931 the Bayonne bridge, built by the same methods as the Sydney bridge, was completed at a cost of sixteen million dollars between New Jersey and Staten Island. The arch span is 1,652 feet and 16,000 tons of steel were used in its construction. Engineers believe it possible that we may yet see steel arch bridges with spans of from two to three thousand feet, and in recent years large steel arch bridges have been erected in various parts of the world. The largest steel arch span in Britain is the Widnes-Runcorn bridge in Cheshire, finished in 1961, with a span of 1082 feet.

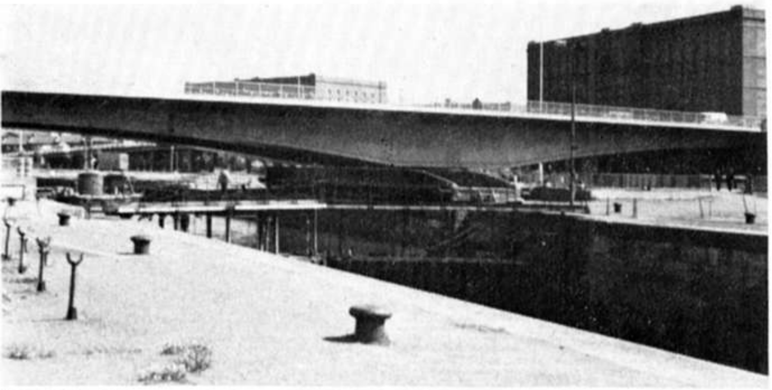
COMPARATIVE COMPRESSION & TENSION
STRENGTHS OF MATERIALS

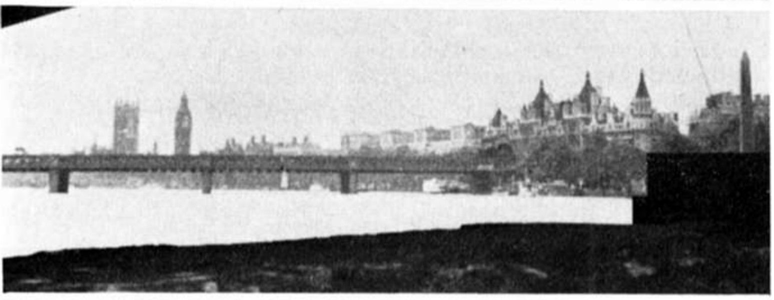
Mild Steel	18,000 lbs per square inch in tension 15,000 lbs per square inch in compression in short struts 13,500 lbs per square inch in sheer
High Tension Steel	20,000 lbs per square inch in tension with an increase for compression and sheer
Nickel Silicon & other alloy Steels	from 24,000 to 30,000 lbs per square inch in tension

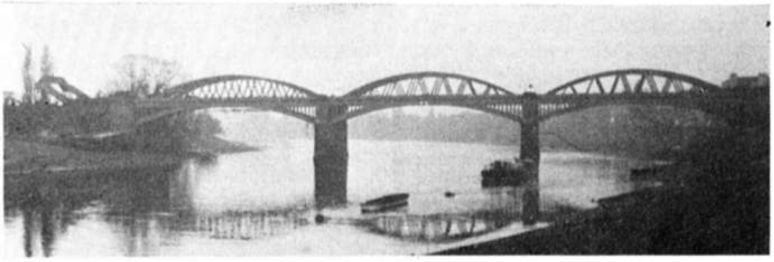
THE DESIGN AND CONSTRUCTION OF BRIDGES

PART FOUR

BY TERENCE WISE







Top to bottom, the Hawkesbury River Bridge, 35 miles north of Sydney, was designed and built by the N.S.W. Department of Railways. The Ashton Swing Bridge, Bristol, one of the many box girder bridges at present under restricted use. The Hungerford Railway Bridge over the Thames between Charing Cross and Waterloo Stations, seen from under Waterloo Bridge. Barnes Railway and footbridge, built about 1860.

A NATURAL development from the cast iron ribs used for arch bridges was the girder and the girder bridge, which in its simplest form consists of several beams laid horizontally across an opening between abutments, with some kind of deck laid on top. In larger bridges there are main girders to carry the weight of the superstructure and its loads, cross girders to connect them transversely and support the deck, while in many railway bridges a third series of small longitudinal girders runs under the rails of each track. In the last century the basic principles of girder construction were used to build such famous bridges as the Tay, Britannia tubular, Newcastle high level and London's Tower bridge, and also gave rise to the more sophisticated cantilever girder bridge. You are most likely to see an example of the girder bridge in its ugliest form, for it is more commonly used these days to carry railways over roads, usually with spans not exceeding 120 feet.

The girder bridge differs from the arch and suspension bridges in the way that the stresses are exerted on its supports. The thrust of the arch ring and the pull of the suspension chains are restricted by strongly built abutments, but the main beams of a girder bridge exert only *vertical* stress on their supports. The stresses within the bridge itself are also different. When a beam which is supported at each end carries a load it undergoes three different types of stress: the compressive and tensile stresses on the upper and lower surfaces of the beam respectively, and a shearing stress through the solid section of the beam. The modern girder is designed to resist these stresses and is built up in three parts: an upper flange, a lower flange, and between them the vertical web.

The earliest girders were made of cast iron. Because this material is stronger in compression than in tension the girders were made with a wider lower flange to increase the resistance to tension (Fig. 1A). Cast iron girders continued to be used for spans of up to about fifty feet, especially for railways, when the ends of the girders were embedded in brickwork to add to their load bearing capacity. Many of these bridges are still in service today. Figs 2 and 3 are examples of such iron bridges, built for the railways in Berlin during the last century.

With wrought iron and mild steel no such inequality of stresses exists and the ordinary girders are made up as shown in Fig. 1B. This type of girder is used for the subsidiary parts of a bridge. Main girders are made up from angle bars and plates as illustrated in Fig. 1C and these are called plate girders. Sometimes the girders are made with a double web, forming a hollow rectangle, and these are known as box girders (Fig. 1D). The massive tubular girders of the Britannia bridge are in fact box girders, carrying the railway inside the box. In this case the roof and floor of the tubes are the upper and lower flanges and the plate side walls are the double web, but in violent side-winds the plate walls perform the function of the flanges and vice versa. The depth of the girder is normally between 1/8th and 1/12th of the span, on the principle that the greater the depth of the girder the stiffer it will be.

For spans of over a hundred feet the web is built up considerably in height, but in order to save weight the girder becomes a lattice girder—Fig. 4. In this case the plate is replaced by criss crossing bars and the stresses of the web are resolved into pulls and thrusts, some of the bars acting as struts and others as ties. An even more effective method for the larger constructions is to leave out some of the crossing bars and concentrate the stresses on a smaller number of members. This gives a braced girder of inclined struts and ties, Fig. 5A, or of vertical struts and inclined ties, Fig. 5B. Another variation is the bowstring girder, Fig. 6, in which the upper flange is reinforced in the centre by an extra horizontal member with bracing between them.

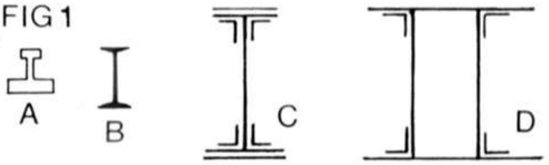
Girder bridges may be divided into deck and through deck bridges, according to the position of the deck in the superstructure, and single or continuous span bridges. Fig. 7A is a cross section of a deck bridge with the deck carried on top of four main girders, while in Fig. 7B the deck goes through the bridge, as for example in the Britannia tubes already mentioned. This method is mainly employed in larger bridges and consists basically of two main girders with braced web systems A–C and B–D forming the two sides of the bridge, the floor C–D on cross girders braced together diagonally like a horizontal web, and the overhead system filled in a similar manner by an arrangement of girders between A and B to provide wind bracing.

A single span girder bridge is one which reaches from support to support without projecting beyond those supports. Fig. 8 shows the makeup of one of the seven 416ft. spans of the Hawkesbury River single span girder bridge in New South Wales. Each span is fixed to a pedestal bolted on to the pier or abutment on which it rests, and the other end rests on rollers to allow for expansion. The total length of this bridge, which was built in sections and transported to the site by road in sections weighing up to 24 tons, is 2,900 ft. 3 in. Finding solid foundations on the thick silt bed of the river presented a problem for the builders, and some of the piers go down 183 ft. before touching a solid base.

A continuous girder bridge is one which crosses two or more spans, usually three, in one continuous length, the girder being laid upon three or more supports. In this type of bridge the stresses are rather hard to determine. The method employed to allow for expansion is to fix each span to one support and allow it to expand in both directions. However, this makes it difficult to estimate the total expansion, owing to variations at several such openings, and this type of bridge is not found much in Europe, although it is popular in America. Examples of continuous girder bridge are of course the Britannia and Conway tubular bridges built by Robert Stephenson. In the former, which has two spans of 460 ft. and two of 230 ft., the expansion and contraction variations amount to four inches at each end. The Britannia, built in 1850 over the Menai Straits, was the pioneer of the continuous girder bridge. In more recent times the Cologne-Deutz bridge, a continuous plate girder bridge with a 605 ft. span, was completed in 1948 over the Rhine at Cologne, using the piers of the 1915 suspension bridge of the same span which was destroyed in World War II. The Dusseldorf-Neuss bridge, with a span of 676 ft, was completed in 1951.

In recent years many box girder bridges have been built in different parts of the world, the design originating in West Germany. These are designed in sections, rather like the outer casing of a matchbox, which are then joined together to form the bridge deck. This method is fifty per cent cheaper than conventional designs but unfortunately several of the bridges have collapsed with great loss of life and last year restrictions were imposed on the use of 51 box girder bridges in Britain. Work on another 39 was suspended and the design subjected to investigation and rigid rulings on the standard of construction. However, the issue is still in the air and much has still to be explained, particularly in the difficult field of stress.

FIG 1



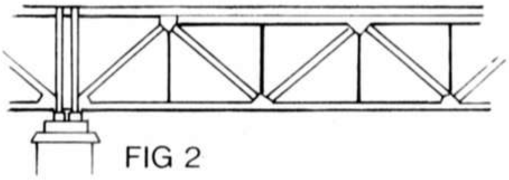


FIG 2

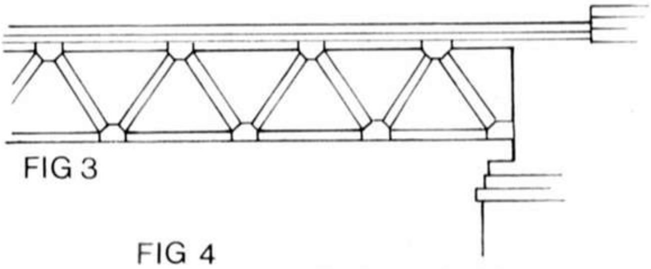


FIG 3

FIG 4

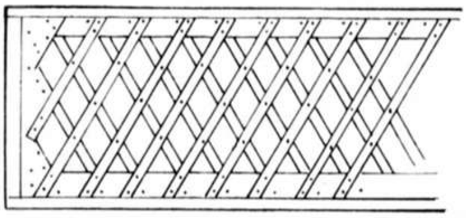


FIG 5

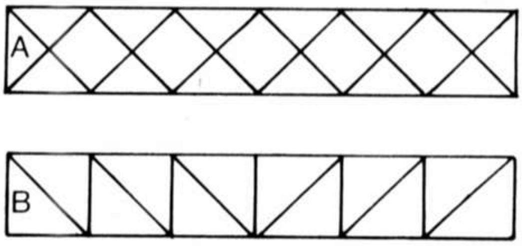


FIG 6

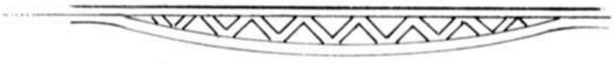
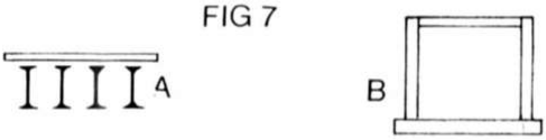


FIG 7



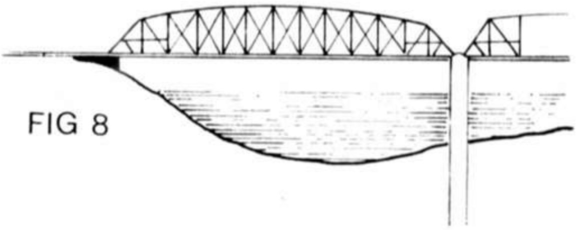
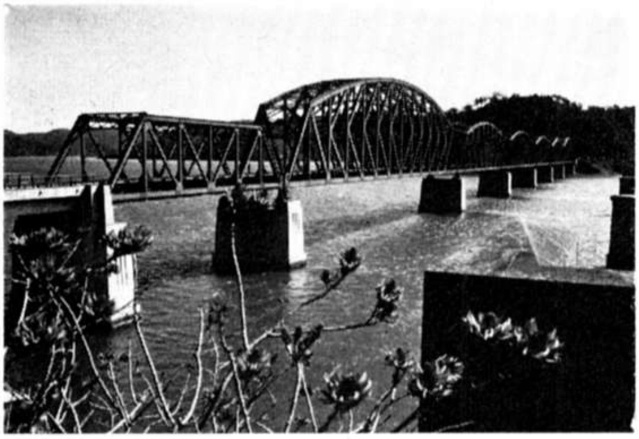


FIG 8



THE DESIGN AND CONSTRUCTION OF BRIDGES

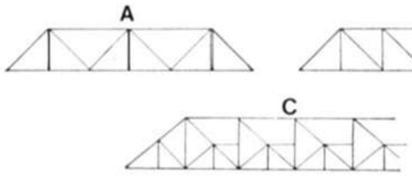
by Terence Wise

PART FIVE — TRUSSES

IN APRIL'S article (The Steel Arch) it was pointed out that it was the rapid expansion of railways all over the world which led to a demand for many new bridges, and also influenced the development of bridge design. These new bridges were required to carry heavy loads at speeds never before achieved by Man and these factors led the engineers to adopt the strong and proven method of truss construction first used in Roman times.

To begin with these truss bridges were built entirely in timber but, because of the industrial revolution in Europe, the cheapness of cast iron—and later of wrought iron and steel—soon led engineers to abandon the timber truss. By 1846 James Warren had introduced a cast iron truss design in Britain which has remained in constant use right up to the present day. The principle is shown in Fig. 1a. In 1962 Warren trusses of steel were used to replace Brunel's original railway bridge at Chepstow, building on the original piers. These trusses were machine welded in the adjoining shipyard of the Fairfield Company and assembled on the site with high strength bolts, without interfering with the train services running above. Brunel himself was famous also for the many timber truss bridges he built for the Great Western Railway. He continued to use timber here for some years after the introduction of iron trusses, but this was an exception to the rule.

FIG I



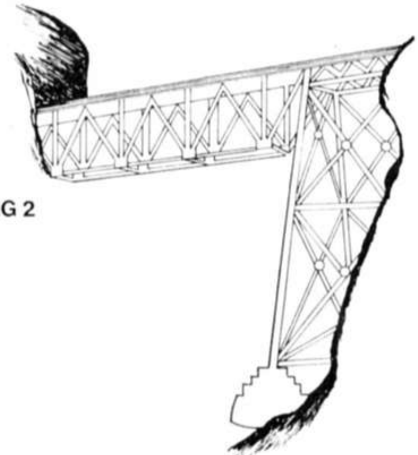


FIG 2

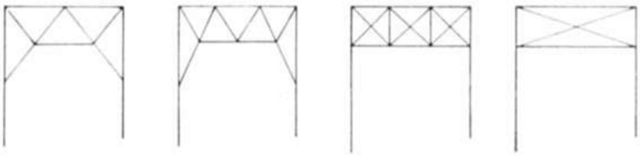


FIG 3

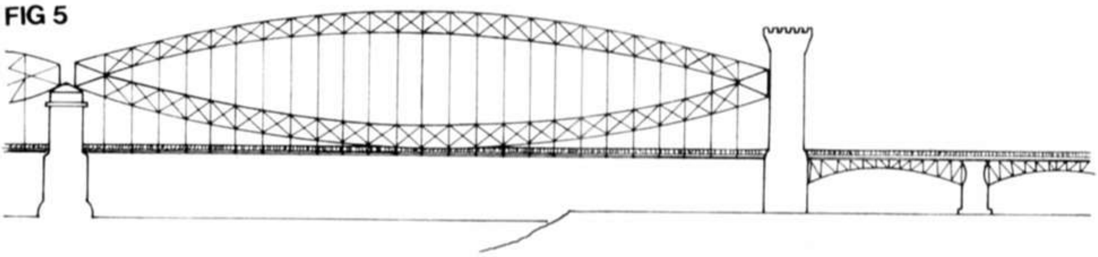
However, in other countries where cast iron was costly or not so readily available, but where timber was abundant and cheap, places such as Russia and America, then timber continued to be used. In America, especially, a great number of timber trestle and truss bridges were built for the pioneer railways. By 1840 many variations of the truss had been designed in America, but in that year William Howe patented a truss using timber diagonals with vertical tension rods of iron, and so signalled the end of the exclusive use of timber. One famous bridge using the Howe truss design was that at Havre de Grace, 36 miles north east of Baltimore, over the Susquehanna River. This was built by Nicholas Powers between 1845 and 1850. This combination of materials was soon developed, with the iron rods taking the tensile stresses and the timber employed to its best natural advantage as the compression member. Then an economical cast iron truss, patented by Thomas Pratt in 1844, began to come to the fore, and his design has continued to be used for medium sized spans right up to today. (Fig. 1B). In 1847 the Whipple truss was introduced and by 1850 iron trusses were widely used in America as well as Europe and when wrought iron became comparatively cheap this too was widely used. Fig. 1C shows a third form of truss used today when the older designs are unsuitable. This type of sub-divided truss is used for the larger spans. Fig. 2 illustrates a typical trestle and truss iron bridge of about 1870, built by the American engineer Henry Meiggs in Peru. This particular bridge is called the 'Bridge of the Little Hell' and unites two tunnels in the railway from Callao to Oraya, a 137 mile track with 65 tunnels and 67 bridges.

In Fig. 3 are shown four types of portal used to stiffen truss bridges against wind pressures.

Most iron truss bridges were functional rather than elegant at this time, but the method could lend itself to beauty and one example of the principle used gracefully was the double bow girder bridge on the Hamburg and Harburg Railway over the Elbe, completed in 1872. Fig. 4 shows the design for the entrance piers, Fig. 5 the construction of one of the main spans. The bridge carried two railway lines, with two footways outside

FIG 4

FIG 5



of them. At first an arch design was chosen for this bridge, but the low level that would have resulted was ruled out because of the river traffic. Suspension was then considered but also discarded because of the thick piers which would have been necessary—again an interference with navigation. Finally the arch and suspension design illustrated here was chosen, dividing the weight of the hanging deck between the two bows by means of vertical iron tie rods, and uniting the two curves of the bows at the points of support so that the horizontal pressure acting on them in opposite directions would cancel each other out. By this method the piers received only a vertical load and could therefore be kept reasonably slim. The bridge had three spans of 346 ft. and four of 78 ft. Into the two bows for each truss went 420 tons of wrought iron, 155 tons being used for the roadway and horizontal bracing. The approximate cost for each truss was £150,000.

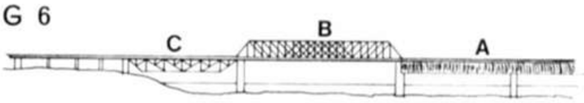
Another example of the truss bridge at this time is the Monongahela Bridge of 1874, carrying the Pennsylvania Railroad to Pittsburgh. (Fig. 6). This was a bridge of eleven spans, with a total length of 1,622 ft. exclusive of the approaches. It was at first erected entirely in timber (as marked A) except for the one span over the channel (B) which was of iron on a Linville and Piper truss design 260 ft. in length. The east span (C) was replaced in the early 1870s with a wrought iron triangulated truss of Pettit's design. This new span had a length of 182 ft., being made up of two trusses. There were six main panels in each truss and twelve sub panels. The length of the main panels was 30 ft. 4 in. and the height of the truss 22 ft. 10 in.

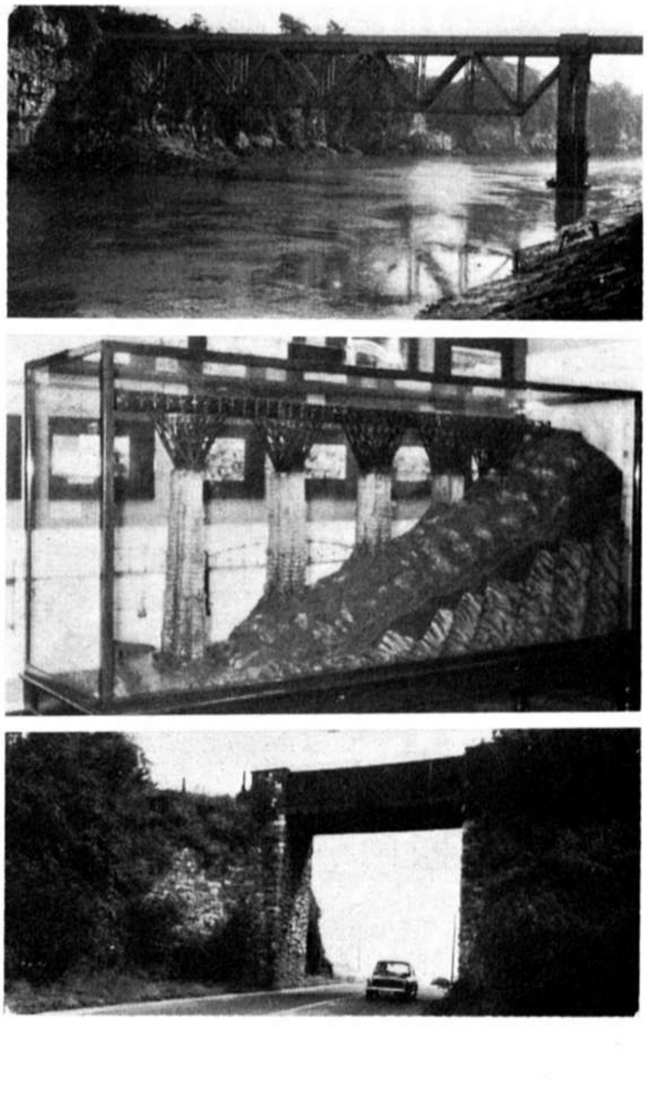
The steel truss soon superseded the lattice girder for long spans and the Hawkesbury bridge in New South Wales, discussed in last month's article on girders, is built in steel on the Whipple truss design. For this bridge the trusses are 416 ft. long, 25 ft. 6 in. wide and 58 in. high. The main girders are 40 ft. long. Each truss is divided into thirteen panels of 31 ft. 6in. each, cross girders 4 ft. 11 in. in depth are fixed between the main girders, and four rows of longitudinal girders three feet deep are fixed to these to carry the double railway lines. Between these bearers and the rails are fixed timber transoms across the bridge on 16 in. centres. Some large truss bridges have also been built in Britain, notably the Selby road bridge in Yorkshire with a span of 256 ft.

A continuous truss design was used for the Lachine bridge over the St. Lawrence, built in 1888 by C. Shaler Smith. The bridge had two side spans of 269 ft each and two centre spans of 408 ft. each. This was replaced in 1910 but until the time of its demolition it was the only example of a continuous truss bridge in America. The Metropolis bridge over the Ohio River, completed in 1917 with a 720 ft. span, was followed in the same year by the Sciotville bridge, again over the Ohio, with two spans of 755 ft. This established a new world record for span length and at the same time firmly established the continuous truss design in American bridge building. Later the Dubuque bridge over the Mississippi was built with a central truss span of 845 ft. This had a tied arch outline and a suspended roadway, utilising the artistic form introduced into Britain in 1853 by Brunel with his great bridge over the Tamar at Saltash. A newer form of truss bridge was the Wichert semi-continuous design, developed

continued on page 299

FIG 6





Heading picture shows the Hawkesbury River Bridge, N.S.W. Piers to the right are remains of the previous bridge. Right, top to bottom, the railway bridge at Chepstow, converted in 1962, model of Brunel's Ponsanooth Viaduct on the Falmouth branch, typical of the timber bridges built in great numbers by this engineer for the G.W.R. (the model is in the Swindon Railway Museum), and, lastly, seen on the A48 between Gloucester and South Wales, surely one of the last surviving wooden railway bridges, nowadays used only by quarry trains.

Left, although the transparency, the final product of the Reversal film, can be viewed on a small hand viewer, they do not offer the convenience of the colour print for casual inspection.

Far right, colour negative material offers the advantage that, with colour prints, they can be either mounted in an album or retained to be handed round among friends and acquaintances

making allowances for the variations in hue that these different conditions can give to "white light". To provide correction for the various types of light to which colour film is exposed, the "colour temperature" of the light is taken into account.

An ordinary domestic coal fire gives a fitting example of "colour temperature". The coal, if such a fire is examined, will be seen, when burning slowly, to be dark red in colour, while, as the temperature increases, the dark red gives way to bright red, and then yellow, indicating that as the temperature rises, the amount of blue in the light emitted increases as compared with the amount of red.

These facts, noticed by scientists, have made it possible to grade light according to its colour temperature, which is expressed in the terms degrees "Kelvin". Hence colour films are manufactured to give true results between certain degrees Kelvin, and providing the maker's instructions are adhered to, the "Colour Balance" of the film will give results that the human eye accepts as true.

This colour balance applies, as far as the amateur photographer is concerned to Reversal stock only, as any faults in the colour rendering of Negative films can be corrected by the laboratory at the printing stage.

Reversal films are available in Daylight type or Artificial light type.

The Daylight films, the type that most photographers use in their cameras, are, as the name implies, colour correct under outdoor conditions, also when used indoors with electronic flash and blue coated flashbulbs, both of which have a colour temperature that is within the scope of the film.

Daylight type film, however, if used without any correction facilities, in artificial lighting conditions, or with the type of photo-flood bulb used by many amateur photographers for portraits and other indoor photography, would give false hues in the final transparency so, for this reason, the makers of films provide some colour balanced for just such conditions and sold as "Artificial light" films.

It often happens that you have one type of film in the camera and wish to take the odd exposure of a subject for which it is not colour corrected. Here we turn to the maker's instructions with that particular film and under the heading of colour balance, will be found details of the filters that the maker supplies to be put over the lens of the camera, in just the same way as filters are used in black and white photography, to correct the film for the conditions under which you wish to use it.

There is another type of correction that can be applied to Daylight films used outdoors in areas where there is an excess of ultra violet radiation, such as by the sea, at high altitudes etc, and that is an ultra violet absorbing filter. Colour films, as well as being sensitive to light, are sensitive to ultra violet radiation, which records as blue on the film. Suitable filters are sold by all photographic dealers and, being colourless in appearance, do not require any increase in exposure.

Exposure, in colour photography, is the critical factor and particularly so with Reversal films, where the latitude is no more than half a stop either side of the "correct exposure". Under-exposure will result in a dark image while over-exposure will give a light image, the absolute reverse to the effects that under and over exposure give with black and white photography.

Because of this critical exposure factor in reversal colour, the use of the incident light meter has long been standard practice among professionals to whom perfection of results is of prime importance.

Without doubt colour photography can open an entirely new world for the camera owner, and if due consideration is given to the requirements of the end product, and the correct film chosen, care taken with exposure and, if conditions require it, the ultra violet radiation filter used over the camera lens, success is assured, with results that will bring admiration from both friends and other amateur photographers.

BRIDGES

continued from page 297

just before the Second World War, where the trusses are linked together over their common piers by members which form an open square. An example of this design is the Pittsburg-Homestead bridge of 1937 over the Monongahela River. It has ten semi-continuous arched trusses, the two greatest spans being 533 ft. 6 in. each.

In more recent years the joints between members have been welded instead of riveted and this had not only simplified construction but also saved weight, yet the great spans of almost 900 ft. achieved in America with this type of design are not really economical and for the large span bridges other designs are preferred nowadays. (It has been estimated that once a truss span exceeds about 300 ft. it is no longer economically competitive with other bridge designs.)

THE DESIGN AND CONSTRUCTION OF BRIDGES

Part Six in the series by Terence Wise deals with Early Cantilever Bridges

BASICALLY a cantilever may be said to be any beam or girder which projects beyond its support and carries a load on this projecting arm. It may carry the load distributed evenly along the length of the arm, or as a concentrated weight at the extreme end; in cantilever bridges the weight is usually carried in both ways. In brief this is the cantilever principle, which was used in ancient times for bridging with the aid of corbelling for support, but in more modern times it developed from the observance of the stresses exerted on continuous girder bridges.

Take for example a continuous girder bridge with four supports. Such a bridge would be subjected to two kinds of stress along its length. A beam supported at each end will sag in the middle, as shown in Fig. 1A, but a beam overhanging its support will bend in the reverse direction—Fig. 1B. Therefore the stresses in a continuous girder bridge would cause the stresses as shown in an exaggerated manner by Fig. 2. Here the girder A–J rests on four supports, and the sections B–D and F–H are bent like cantilevers, while the sections A–B, D–F and H–J sag like beams supported at each end. The points B, D, F and H, where these stresses meet, are called the points of contrary flexure. The length D–F, functioning as a beam supported at each end, transfers its load to the points D and F, where it is carried upon the projecting arms of the lengths C–D and F–G. It is therefore possible to estimate the load these two cantilever sections will have to carry at their extreme ends, in addition to the load distributed along their own length. At these points D and F there is therefore no bending stress at all and the load could be carried just as safely if the length D–F were made an independent or detached girder—a typical three span cantilever bridge in fact.

In the design of a cantilever bridge, however, the points of contrary flexure are determined before erection by hingeing the suspended span at predetermined points. These points may be located anywhere from the centre E to the limits C and G, so that the suspended span can be of any length, provided it is less than the total distance between C and G. An alternative to this method of construction is to locate these points or hinges at B and H so that the structure then consists of a rigid girder, B–H, projecting beyond the supports C and G at each end, and carrying on these projecting arms the independent girders A–B and H–J, whose outer ends would rest on the abutments. In either of these designs the bending stresses at the centre of the span C–G are far less than they would be in a continuous girder bridge and cantilever construction is therefore lighter.

The tension and compression stresses of the members, and the whole principle of the cantilever system, is perhaps most easily explained by Fig. 3. Here the chairs are the piers, the two boys sitting on them are the towers, and each boy helps to support a centre strut carrying a third (smaller) boy. His weight is counter-balanced by the anchors (A) on the extreme ends. Fig. 4 shows this principle transposed on to a corresponding design for a cantilever bridge.

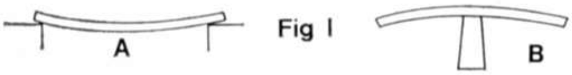


Fig I

Fig 2

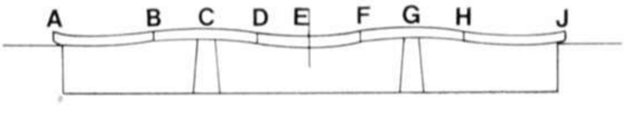
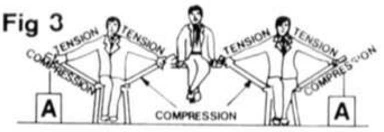


Fig 3



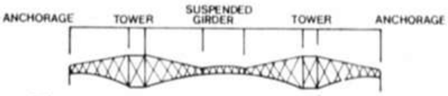
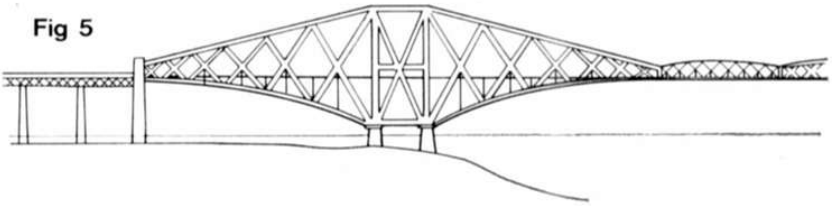


Fig 4

Fig 5



The term cantilever is derived from cant and lever, an inclined or projecting lever, and only came into use in 1883. Prior to this date the type of construction was known as a Gerber bridge, after the German engineer Heinrich Gerber who in 1867 built the first cantilever bridge at Hassfurt am Main with a span of 425 feet. The first use of the cantilever principle in America was the Kentucky River viaduct, built by C. Shaler Smith in 1876 with three spans of 375 feet each, but it was not until 1883, when C. C. Schneider built the railway bridge over the rapids of Niagara with a cantilever span of 495 feet, that the term cantilever was actually used.

The cantilever offers many advantages for the bridging of very wide openings, especially where construction takes place over a deep chasm or navigational channel, since no staging is needed once the main towers have been built. It is usually employed for bridges of three spans because it is particularly well adapted to this design, but there is a limit of around 3,000 feet for its length and the effect of wind on large bridges of this kind is very serious. In the Firth of Forth Railway bridge, the first and greatest of the British cantilever bridges, as much as 47% of all steel used was for the purpose of resisting stresses set up by the wind. Expansion on the other hand presents no problem, being allowed for in the suspended span which is hinged to one cantilever and left free to move upon the other.

The Firth of Forth Railway bridge is one of the most famous examples of the cantilever design. In its day it had the longest cantilever span in the world and was considered a great triumph of engineering. Designed by Fowler and Baker, the bridge was begun in 1882 and completed in 1889, employing a force of 4,500 men, of whom 57 were killed in accidents. Fig. 5 shows the South Queensferry pier end of the bridge with viaduct approach, tower and cantilever arms and centre span. The components for the bridge were all manufactured in large workshops built on the Queensferry shore, within sight of the bridge. The parts were carefully marked to facilitate erection, scraped, wire brushed, then coated with hot linseed oil and a layer of red lead. After erection the parts were painted with a second coat of red lead, followed by two coats of oxide of iron paint. The principal members were made up in tubular form from riveted plates and the insides of these were painted with one coat of red lead and two of white. 50,000 tons of steel were used in the construction of the superstructure alone.

After the founding of the piers the three huge towers, each 360 feet high and 145 feet wide, were built and the cantilever arms were built outwards from them by the use of platforms which were moved forward on the arms as work progressed. When the cantilevers were completed the two connecting spans were lifted into position, using the ends of the cantilever arms, to form two clear spans of 1,710 feet each, 150 feet above high water level. These smaller suspended truss spans are each 350 feet long. The total length of the bridge, not counting the approach viaducts, is 5,350 feet.

The Forth Railway bridge has been followed by many others of similar design over the years, the most notable of which is that at Quebec, (Fig. 6). This bridge links the major railway systems of the area, crossing the St Lawrence at Cap Rouge, nine miles above the city. Initially it was built to carry two railway tracks, two tram ways, two ordinary vehicle lanes and footways: the total width of the deck is 90 feet. From the river banks two 500 foot long arms, anchored to the shores, were erected to join up with the two towers, which were built on piers in the shallow water near the bank. Each of these towers is 400 feet high. The cantilever arms were then built outwards from these towers to a length of 562 ft. 6 in. and the centre span of 675 feet continued to be built outwards from these arms to a meeting point in the middle. This meant that at one stage there was as much as 800 feet of span unsupported. The total span when completed was 1,800 feet, the largest single cantilever span in the world. Total length of the bridge is 3,239 feet, so that although it exceeds the Forth bridge span by 90 feet it is shorter in overall length. The bridge was begun in 1899 but suffered two collapses during construction, costing 84 lives, and was not finally completed until 1917.

Nowadays the suspension bridge has replaced the cantilever for very long spans, and other designs are now used for bridges of under 1,000 feet, but over the years examples of the cantilever bridge have continued to be built:- the Oakland bridge in California with a span of 1,400 feet, built in 1936; the Howrah bridge in West Bengal, finished in 1946 with a 1,500 foot span and a deck 100 feet in width; and the Greater New Orleans bridge of 1958 with a span of 1,757 feet.

Fig 6

Opposite page, the famous Howrah cantilever bridge over the Hooghly River between Calcutta and Howrah. Right, London's Tower Bridge is an example of the cantilever bridge applied to movable bridges, each 'leaf' of the bridge being a 'beam or girder which projects beyond its support'.

Design and Construction of BRIDGES

BY TERENCE WISE

Part Seven — the Cantilever

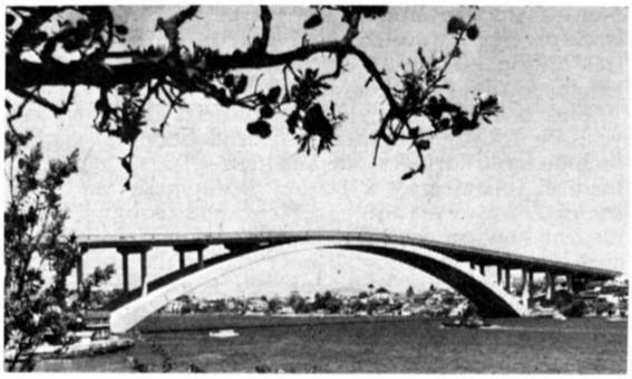
THE wide spans of 20th century bridges usually combine all types of construction and materials, including the cantilever principle, which is after all only a sophistication of the projecting beam method—one of the earliest forms of bridge known to Man. So although the heyday of the great cantilever bridges has now passed, in favour of the graceful concrete structures we see everywhere, it should be remembered that this form of construction is far from dead. The modern Waterloo bridge in London, for example, is not just a concrete shape but is in essence several girder bridges giving the appearance of arches.

This century has also seen some great steel cantilever bridges, such as the Montreal Harbour bridge over the St. Lawrence River, begun in 1926 and finished in 1930. The bridge cost 12 million dollars to build, has four lanes for traffic, two footways for pedestrians, clearance above the river of 163 feet, and, including the approaches, exceeds two miles in length.

Rivalling this is the Carquinez Straits bridge in California, 25 miles north of San Francisco, begun in 1923 and finished four years later. One of the largest steel girder cantilevers in the world, this bridge has two cantilever spans of 1100 feet, a central tower span of 150 feet, two anchor arms from the shores of 500 feet, and at the southern end a steel viaduct approach 1132 feet long, making an overall length of 4482 feet. Silicone steel was used as the main material for the towers, the trusses of the suspended spans, the cantilever arms and the anchor arms. This has an ultimate strength of 80,000 to 95,000 pounds and 45,000 pounds minimum yield point. The main tension members for the major trusses, and some of the tension members of the viaduct trusses, were built from heat-treated carbon steel eye bars, with a minimum elastic limit of 50,000 pounds and a minimum ultimate resistance of 80,000 pounds per square inch. Longitudinal expansion is allowed for at the shore ends of each anchor arm, and each suspended span is fixed at the central tower cantilever arm with expansion allowed for at the shore ends. (Expansion of the 1100 foot spans is 11 inches). To allow for the possibility of earthquakes shock, six hydraulic buffers are provided at the expansion joints between suspended and shore cantilever arms, and also between the main structure and the viaduct. The bridge has a 30 foot roadway and two footways, built from reinforced concrete slabs. Another notable point is the depth of the foundations for the piers—built in 90 feet of water to 132 feet below water level.

Another sphere in which the cantilever has remained active is the multi-span bridges, especially in America where many miles of water are being crossed. One such is the Oakland Bay bridge which unites San Francisco with Oakland across a gap of over eight miles. Opened in 1936, this bridge is one of the greatest combination bridges ever built, with a double deck throughout. The western half of the bridge consists of two suspension bridges, 2300 feet long, with towers 440 feet high, anchored into a huge concrete monument in the centre, at Yerba Buena Island. The bridge then continues over a 1400 foot cantilever span of five through truss spans and 14 deck truss spans before connecting with a viaduct from the Oakland shore. The 51 piers of this bridge, which cost £15 million to build, go deeper below water than any substructure built up to that date—some being as far as 237 feet below low tide level.

The Lower Chesapeake Bay bridge-tunnel, a multi-span bridge 18 miles long, crossing a stretch of water so wide as to look like the open sea, is the greatest multi-span bridge in the world. It consists of a series of low level trestle roads, two tunnels which go beneath the main shipping channels, and two high level bridges over the secondary channels. Four "islands" had to be built in the bay in order to link the trestle and tunnel



Top, the Albert Bridge in London, built 1873 and employing the cable cantilever technique. Left, the graceful Gladesville Bridge over the Parramatta River, linking the suburbs of Gladesville and Drummoyne with Sydney. Believed to be the world's longest of its type, it is 1,901 feet 6 inches long, including a four-ribbed concrete arch with a span of 1,000 feet, rising 120 feet above high water level. The lower picture shows this bridge during construction in 1963. Work began in 1959, and the bridge was designed to relieve the pressure on the Sydney Bridge. *(Aust. Info Service.)*

sections. The bridge replaced a ferry system which had been in service for 80 years, and cut the crossing time from 1½ hours to twenty minutes!

An unusual modern variant of the cantilever principle is the cable cantilever. The George Street bridge in Newport, Monmouthshire, completed in 1964, is an example of this method. Here the gap between abutments is 1770 feet and the main river span of 500 feet is supported from hollow reinforced concrete towers by steel wire ropes, passing over rollers inside the towers and anchored at the shore ends to the concrete approach viaducts. The towers are 165 feet above high water level. The bridge carries a 48 foot roadway with two nine foot footways, as well as the water, electrical and telephone services.

Concrete

Prior to the use of reinforced and prestressed concrete the longest arch span for a concrete bridge was the 280 feet centre span of the Rocky River bridge in Cleveland, Ohio, completed in 1910. The Swiss engineer Robert Maillard was the pioneer of reinforced concrete bridges at the beginning of this century and by the end of the First World War his work had led to reinforced concrete largely replacing steel, stone and brick for small to medium bridges. Primarily this is because of economy—spans of up to about 40 feet can be fabricated off site in the form of reinforced concrete girders, and quickly lowered into position across the abutments, the bridge deck then being laid on the beams in the form of reinforced concrete slabs.

Reinforced concrete members can be designed to take either tensile or compressive forces and it was Monsieur Freyssinet, a French engineer, who first used "prestressed" concrete for his bridge at Plougastel over the Elorn in Brittany, thus making use of the compressive strength of concrete. The principle had been known since the mid 19th century but engineers had not previously discovered a satisfactory method of anchoring the tensioned wires, nor had an economic and reliable high tensile wire become available until the 20th century. Freyssinet's Plougastel bridge had a double deck, the lower one for a railway line, and three arches with a total span of 613 feet. It was completed by 1931.

It is some indication of Freyssinet's achievement that even now his bridge over the Elorn still ranks as the fourth largest concrete bridge, after the Gladesville Bridge in Australia, the Sando bridge over the Angerman River in Sweden, built in the early Forties with a span of 866 feet, and the Elsa railway bridge in Spain, again early Forties and with a span of 690 feet. The first prestressed concrete bridge to be completed in America was a small bridge in Tennessee in 1950, and it was to be several more years before any bridges of decent size were built in this manner in the States.

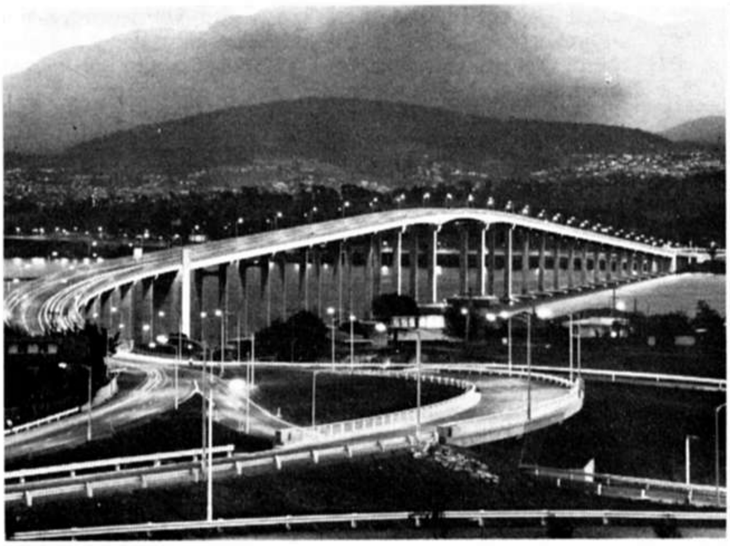
In England the largest prestressed concrete span of the Sixties was that over the Medway near Rochester for the M2 motorway, with an overall length of 3272 feet 6 inches. Of flexible cantilever construction, this bridge was remarkable for achieving a new record in size for a prestressed concrete bridge of the cantilever type. The deck is 113 feet 6 inches wide, and there is a centre span of 500 feet, 116 feet above the river. The piers taper from ten to six feet at the top, and are solid to just above water level, after which they are hollow boxes with 18 inch walls. They rest on foundations of chalk inside steel cofferdams and it was estimated that the downward pressure on the foundations would be 20,000 tons.

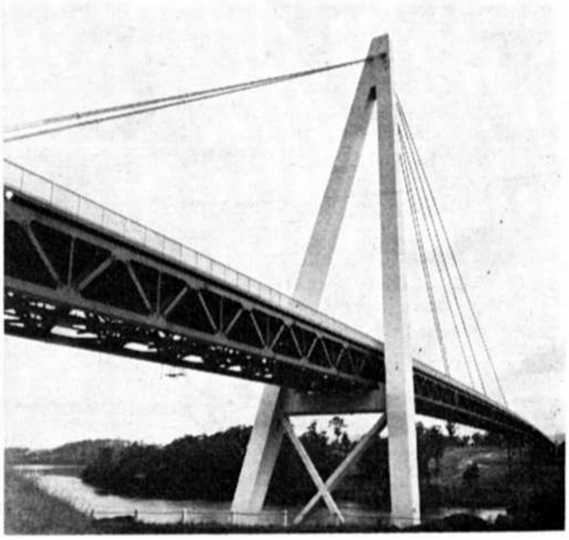
The anchor arms and main cantilevers were built outwards from the tops of the piers in ten foot sections, with working platforms slung from the structure itself. These were moved outwards as the concrete set. When the anchor arms reached 312 feet they came to rest on piers and linked up with the side spans, which are clear of the water at low tide. The main cantilever arms were built out to 200 feet and the central gap closed with 100 foot prefabricated prestressed beams weighing 135 tons.

The viaducts are basically prestressed beams supported on port and lintel frames, with the lintels projecting to form short cantilevers. The beams were made on the banks of the Medway. The west viaduct has a total length of 1350 feet in eleven spans: the east viaduct 797 feet in seven spans.

118,000 tons of concrete were used in the construction of this bridge, and over 6,000 tons of mild steel reinforcement. Another 187 miles of 1¼ in. Macalloy bar was used in the superstructure. Total cost was £2.3 millions. Until the Gladesville bridge was built, the bridge over the Medway had the longest pre-stressed concrete cantilever span in the world.

Below, left, the Tasman Bridge crossing the Derwent River in Hobart, Tasmania. One of the world's longest prestressed concrete bridges, it was completed in 1964 with a length of about 1100 feet. *(Aust. Info Service).* **Below, right, the Batman Bridge, Tasmania, spanning a 225 yard stretch of the Tamar River with a cable cantilever.** *(Aust. Info. Service.)*



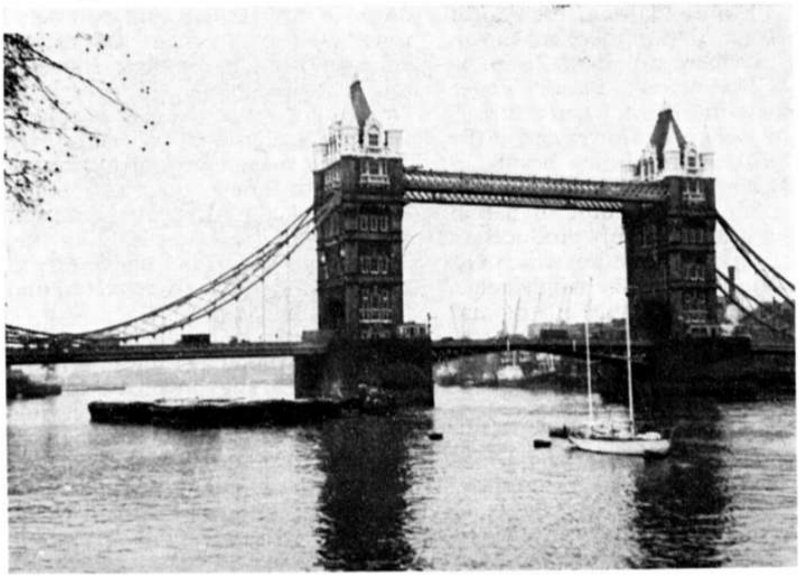


Bridge Design and Construction

PART 8

Early Suspension Bridges

By Terence Wise



SUSPENSION bridges are one of the three basic forms of bridging known to Man from the earliest times, and the principle of suspension bridges can be illustrated equally well by studying the design of the huge Severn bridge or a primitive rope and bamboo bridge erected by tribesmen in Assam. The principle is known to have been in use in China since 400 A.D. but it did not make its way to Europe until towards the end of the 16th century. It was introduced into England in 1741 in the form of a 70 foot span iron bridge over the Tees. It is significant that since 1816 the world's longest bridges have employed the suspension technique, with the exception only of the heyday of the greatest cantilever bridges—the Forth bridge and Quebec bridge, spanning the period 1889 to 1929.

Principle

The suspension principle is basically that a flexible rope or chain, whilst it has no transverse stiffness, can offer a high resistance to a direct pull or tensile stress. A rope can easily be hauled across an opening too wide to be spanned by a beam, and when that rope is made fast securely at both ends it is capable of carrying a suspended load, as in Fig. 1, or several loads as in Fig. 2, or the weight of a continuous load—Fig. 3. With each new distribution of the load the rope will find for itself a new position of equilibrium, falling into a curve referred to as the funicular polygon. When the load is uniformly distributed along the "deck", as in Fig. 3, the figure becomes a parabolic curve. It is a catenary when the rope or chain has nothing but its own weight to carry. (If the funicular polygon was inverted it would become a linear arch, or a line of struts equilibrated under the given load. The line of tension in the curved chain becomes a curved line of pressure in the arch).

A suspension bridge is the lightest form of construction which can carry loads between two points and this in itself is a great advantage. Also, the bridge deck, because it is suspended by vertical rods or wires attached to the suspended chains or cables, can be built without the use of staging, so suspension is often the choice when spanning navigable rivers.

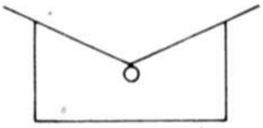
Basic Construction

The basic form of construction is a main span flanked on each side by towers. The chain or cable is laid across the tops of the towers and hangs down between them in a curve which is nearly parabolic. The dip of the chain or cable is not generally more than one twelfth to one sixteenth of the span. From the summit of each tower the chain or cable is then led down to an abutment placed at some distance behind the tower, so that on each side it extends across an opening between tower and abutment. Therefore such a bridge will span three openings, with the deck suspended from the chains or cables across the main span and two side spans.

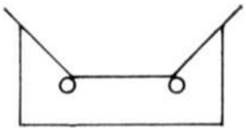
Menai Straits

An example of this type of bridge is Telford's famous Menai Straits bridge, begun in 1819 and opened in 1826 to link Anglesey to the mainland. The Admiralty were using the channel extensively at that time and required the bridge to have 100 feet headroom, with no obstruction caused by staging during the long construction. A rock near the Anglesey shore, known as Pig Island, provided a base for one tower, and the other was built on the Caernarvon shore. The span of 579 feet between the towers was bridged by a wrought iron chain of flat links invented by a Captain Brown R.N. This consisted of bars ten feet long and 3½ × 1 inch in section, with enlarged ends. Five such bars made up the thickness of the chain, and the bars were then linked together by six plates at each end, the whole

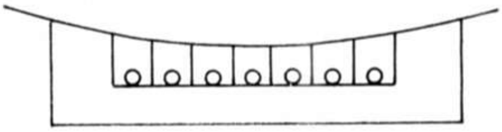
FIG 1

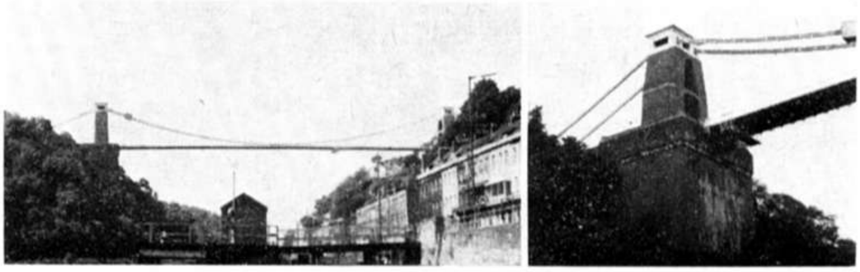


2



3





Opposite, Tower Bridge, London, designed by J. W. Barry, assisted by Brunel. The bridge is covered fully in a later article, but note how the side spans, rarely noticed by the casual observer, are in fact of the suspension principle. Right, Brunel's famous suspension bridge at Clifton, over the Avon Gorge. Note the maintenance cradles on both chain and deck. Far right, the western tower of this suspension bridge, which is one of the best-known in the world.

assembly bolted together. Sixteen such chains were used, in four sets of four. They were replaced by new ones of high tensile steel about 1940. The bridge deck was 30 feet wide with two 12 foot carriageways and a six foot footway in the centre, and was carried on suspension rods spaced at five foot intervals. These rods were one inch square in cross section and hung from the chain joints, which were staggered to suit this five foot interval.

The approach viaducts consisted of three arches spanning 52 foot six inches on the Caernarvon side, and four arches of the same size on the Anglesey side. As with most suspension bridges of that period the deck had a tendency to oscillate in strong winds, and the deck had to be strengthened soon after the bridge was opened. The same problem still occurs today and is explained at the end of this article.

Where a single span bridge was needed construction was even simpler, with a tower built at each side of the opening, the suspension cable being carried back beyond these towers to their abutments in an almost straight line. These portions of the cable, which carry no load beyond their own weight, are called backstays. The Clifton suspension bridge is an example of the single span, and here the anchorage for the backstays is obtained by tunnelling into the natural rock. The bridge was completed in 1864 and has a span of 702 feet. Until the building of the Severn Bridge, a hundred years later, it was the largest suspension bridge in Britain.

The Towers

The towers of suspension bridges are designed to act as vertical pillars and the chains or cables need not be fixed to them but may be carried over them on a "saddle" or carriage which is free to travel longitudinally upon the top of the tower. When temperatures rise, the curved cable can therefore take care of any expansion in length by assuming a greater dip. Similarly, the expansion of a straight backstay is allowed for by movement of the saddle upon its rollers. Whether a cable rests on a saddle or is fixed to the top of a flexible tower there is always a tendency when under loading for the cable to move horizontally at the tower top.

Steel Wires

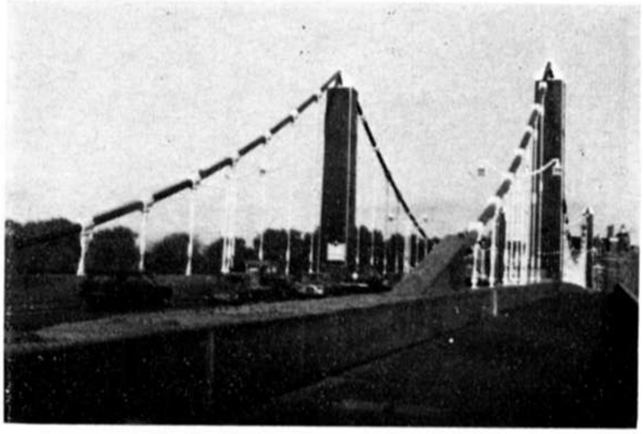
The introduction of mass produced steel in the second half of the 19th century made it possible to build much larger suspension bridges, and the use of steel wires in place of iron chains was mainly brought about by the American engineer J. A. Roebling who developed a method of spinning continuous wire cables as early as 1844, a method which has remained largely unchanged to this day. His finest achievement was the Brooklyn suspension bridge across the East River, connecting New York and Brooklyn, the first of a great series of steel wire suspension bridges in America. Now surpassed by others, in its day Brooklyn bridge was justly famous, with a main span of 1595 feet, a rise above water level of 133 feet, a total length of 5990 feet, and carrying two railway tracks, two roads and a wide footway. The bridge cost 15 million dollars and was built between 1870 and 1883, being completed after the death of Roebling by his son, W. A. Roebling.

Oscillation

The one big drawback remaining in the design of suspension bridges was the oscillation caused by high winds: in particular this ruled out the possibility of carrying railway tracks—a severe limitation. The problem was countered to a certain extent by the use of horizontal stiffening girders in the deck of the bridge, the girders sometimes being hinged in the centre to avoid temperature stresses. Another step, quite common in America at the turn of the century, was the use of a series of radiating straight ties extending from the top of the towers to a number of points along the deck. This gave some compensation for the flexibility of the chain or cable, a statement which perhaps needs clarifying.

Although the flexibility of the suspension cable is precisely what has given form and existence to the suspension bridge, it is not in itself an essential feature of the design and does not necessarily have to be retained. In suspension bridges flexibility is less harmful, but no more desirable, than in the arch design. So, for example, a suspension bridge can be designed in which the load on the suspension cables and anchorages is eased by making the bridge deck a beam girder to carry part of the load, or by making this beam sufficiently stiff for the cable to be actually anchored to its ends. This latter type of bridge is known as a self anchored suspension bridge.

We will go into this complex question of stiffening more deeply next month, when we cover the more modern suspension bridges and the lessons which were learned the hard way about this type of bridge building.



Chelsea suspension bridge, rebuilt 1935-1937.

Design and Construction of Bridges

Part 9 — Modern Suspension Bridges

By Terence Wise

Roebling's great Brooklyn suspension bridge, covered in last month's article, held the record for the worlds' longest span until the building of the Williamsburg bridge, also in New York, in 1903 with a span of 1600 feet. A notable feature here was the depth of the stiffening trusses which were 40 feet. From this time on there was a general reversal in the trend towards deeper stiffening girders and they became ever more slender and graceful.

The development of high tensile steel cables made it possible to build suspension bridges with exceptionally large spans and the sheer inertia of the dead weight of these bridges was so great that the problem of oscillation, discussed last month, was to a large extent overcome. In these new, larger bridges the weight of the traffic passing over them was almost negligible in comparison to the weight of the construction itself, and this added greatly to the ability to reduce the depth of stiffening girders.

In 1926 the Florianopolis suspension bridge, spanning the Atlantic from the mainland of Brazil to the island of Florianopolis, was completed with a main span of 1113 feet 9 inches and an overall length of 2788 feet. The span could not be called exceptional, in view of recent developments, but this bridge became famous for other more important reasons. Florianopolis saw the first use of a new form of stiffening truss, one which was four times as rigid as the conventional pattern yet only used two thirds as much steel.

In this new design the suspension cable replaced the middle half of the top chord of the stiffening truss, thus changing it from the conventional parallel chord truss with an equal depth along its length to a stiffening truss with its maximum depth at each end of the span. Another new feature was the adoption of rocker towers which, by eliminating the bending stresses, saved 20% of the steel needed for the towers and thus enabled the tower piers to be much reduced in size.

High tension heat-treated carbon steel eyebars were used instead of wire for the cables and here again there was a break from the conventional method of construction. Instead of utilising wooden framework and working platforms during erection, an overhead trolley system was used for both eyebar cables and the stiffening trusses. 4,400 tons of steel and 14,500 cubic yards of concrete were used in this bridge, which took three years to build.

Spans of ever increasing length followed in rapid succession, mainly in America, where this type of bridge was most popular. The George Washington Bridge, spanning the Hudson River between Manhattan Island and New Jersey, was opened in 1932 with a total length of 4,760 feet–the world's longest suspension bridge at that time with a length twice as great as any other. Even now, 40 years on, it still rates 4th place in the world's bridges for length. The span over the river itself is 3,500 feet. Each suspension cable contains 26,474 parallel steel wires with a total breaking strain of about 100,000 tons. The total length of wire used in the four cables reaches the staggering length of 115,000 miles.

Just after World War Two the deck of this bridge was widened to take eight lanes of traffic instead of six and during the late Fifties a new six lane deck was built beneath the existing one, making the George Washington Bridge the first 14 lane suspension bridge in the world. It is now used by more than a million vehicles every week.

Africa's largest suspension bridge is the Birchenough Road bridge over the River Sabi in (Southern) Rhodesia, with a clear span of 1080 feet. Completed in 1935 it was at that time the third largest in the world, and rises 300 feet above the river bed.

In 1937 the fantastic Golden Gate bridge at San Francisco was completed for a cost of 32 million dollars. Linking the San Francisco peninsula to North California, this suspension bridge has a main span of 4,200 feet, while each of the side spans is 1,125 feet, giving a total length of 9,217 feet. The deck width is 90 feet, with a high water clearance of 220 feet. The principal suspension cables are 36¼ inches in diameter. Even after 35 years this bridge still rates second in the world for span length, although this will soon be changed.

The Tacoma Narrows bridge, south of Seattle on the west coast of America, was built at Puget Sound in 1940 with a main span of 2,800 feet at a cost of over 6 million dollars. Four months later the main span fell during a 42 mile an hour gale. The stiffening girders had been a mere eight feet in depth. This disaster called a halt to the more and more elegant and long suspension bridges and an intensive study of the problems involved was undertaken. Out of this emerged the fact that suspension bridges could theoretically be built with spans up to 7,000 feet while, now that the special problems of suspension bridges had been thoroughly examined in the light of modern knowledge, it was thought likely that the suspension method would also be used for shorter spans.

In Britain the Forth Road Bridge was begun in 1958 and completed by 1964 with an overall length of 8,250 feet, including the approach viaducts. The centre span 3,300 feet, is at present the 6th largest in the world. The suspension cables consist of 11,618 galvanised high tensile steel wires, just under 2/10ths in diameter, with a strength of 100 tons per square inch. Warren truss

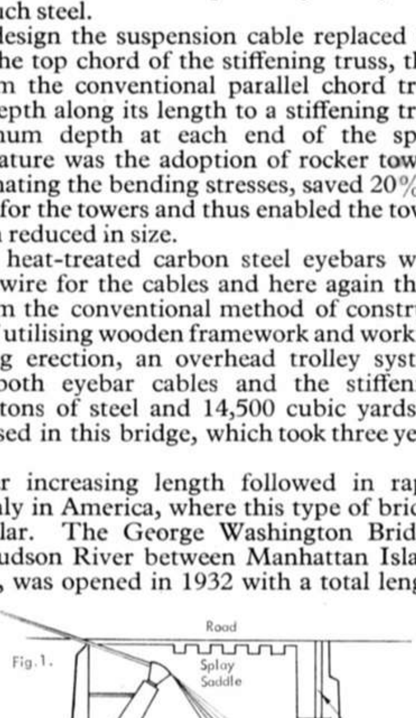


Fig. 1.

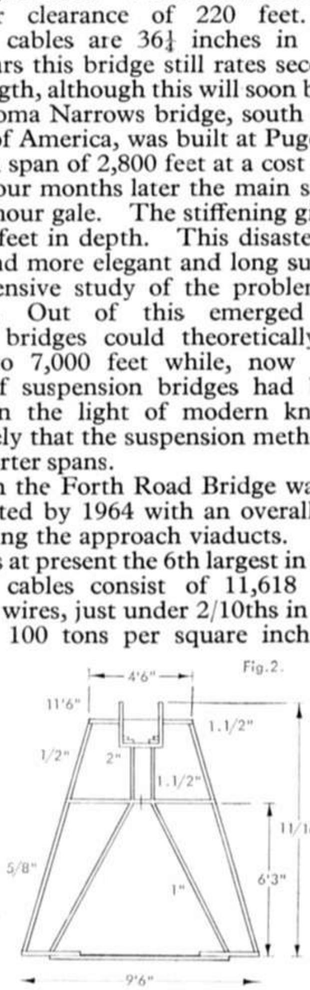


Fig. 2.