3.4

Evolution of Bridges

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Bridges are now so common that we take little notice of them; there are about 200 000 in Britain alone, with about two per mile on motorways and trunk roads. But bridges are essential to our economic well-being, something we only fully realize when one has to be closed for repairs. Their importance is also well known to the military; ever since Horatio saved Rome by defending the bridge over the Tiber, military commanders have variously sought to defend, capture or destroy bridges for strategic advantage.

To structural engineers, bridges represent the clearest expression of their art; they are usually unadorned, and the structural form is clearly seen. Big bridges are often working at the limit of what is possible, and there is a degree of national pride in having 'the world's longest span' in Britain, a record we are soon to lose.

Historically, bridges have changed in response to improvements in technology; materials have changed, understanding of structural behaviour has improved, and new manufacturing technologies have been developed. We shall follow these changes, in roughly chronological order, and look at the legacy we can see in the bridges left behind.

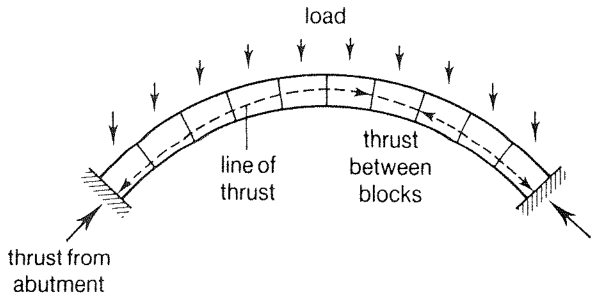
The earliest prehistoric bridges would have been beam bridges built from tree trunks; inevitably, none now remain. Stone was better, but very few stones can be cut into single pieces long enough to be useful to span a gap, while at the same time being thin enough to be lifted into position. There were never many examples like the clapper bridges on Dartmoor, which are believed to be several thousand years old (Figure 1).

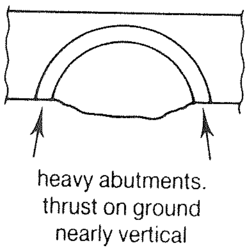
The most significant structural development in the ancient world was the invention of the arch (see Box 1). The first arches are believed to have been built in the Babylonian and Sumerian civilizations centred around the Tigris and Euphrates rivers; without suitable stone, and with insufficient trees, they needed some structural form that could be built with clay bricks. Surprisingly, the Greeks did not know about the arch, which explains why the columns on their temples are so close together; the gap had to be small enough to be bridged by a single stone. The Romans, however, made extensive use of arches,

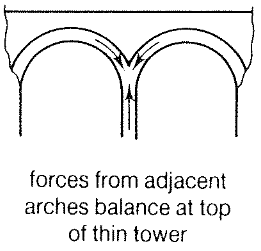
Box 1 Structural form 1: The arch

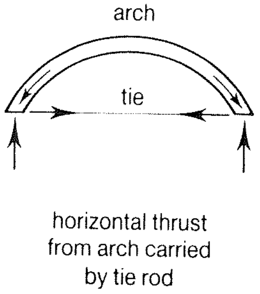
The weight of the material or loads above the arch causes a line of thrust which passes through the ring of blocks (voussoirs) which make up the arch. The exact line that this thrust follows does not matter particularly. Provided it lies within the thickness of the ring, then the arch will not fail by instability, and if it lies within the middle third of the thickness, the arch will not crack. The stresses are normally well within the capacity of the stone or concrete from which it is constructed, so failure by crushing is very unlikely.

The most important aspect of arch behaviour is that the arch thrusts against the abutment, which must be able to resist that thrust; the shallower the arch, the larger the thrust. The thrust can be resisted either by rock foundations, by the weight of a solid abutment block, by the thrust from a neighbouring arch, or by tie rods between the arch foundations.









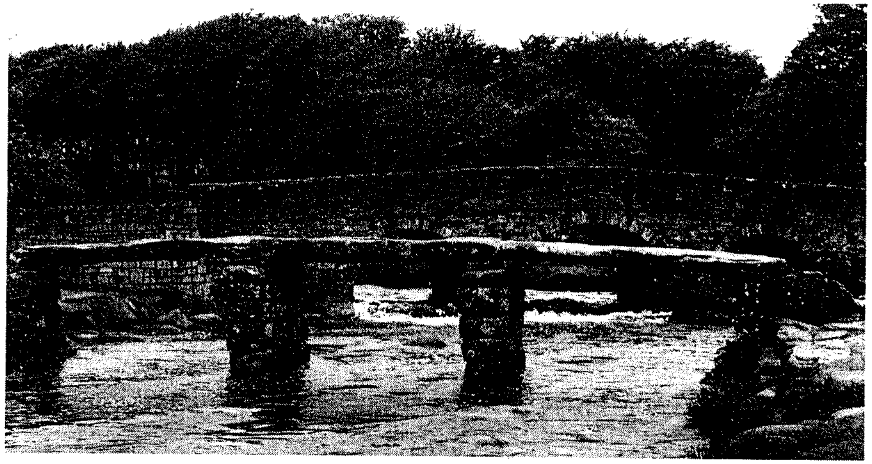


Figure 1 A clapper bridge at Postbridge on Dartmoor.

and many examples remain to this day (see Figure 2), although there are none in Britain that can be attributed to them with certainty. The Romans also made extensive use of timber bridges, with beams resting on trestles built on piles driven into the river bed. None of these remain, most having been replaced by more permanent structures on the same alignment.

In certain parts of the world, cantilever bridges were developed. If timbers are extended out from the bank of a river, they will eventually topple into the

Figure 2 An early Roman arch bridge.

water, but this can be prevented if extra weight is added on the shoreward side. By repeating this several times, spans in excess of the longest timbers can be bridged. In other places, rope bridges made from natural fibres were developed, usually to cross narrow gorges.

During the Middle Ages, most bridges would have been built from timber, or from masonry arches. One of the major difficulties with arches is that they need very firm foundations, and are not stable until complete. Massive masonry piers are needed, and the voussoirs need to be supported on timber scaffolding until the ring is complete. Then comes the delicate operation of removing the scaffolding and transferring the load to the arch; only at this stage would the mediaeval mason have known whether he had got the shape right, and whether the supports were sufficiently rigid. There was no theory about the best shape to be adopted, only masons' folklore, and many would have failed immediately (if the shape was wrong) or within a few weeks (if the abutments started to move).

If a long bridge was being built, with several arch spans, the thrusts from the arches on each side of a pier would balance when the bridge was complete, which allowed the piers to be kept fairly narrow. However, the mason would have needed to support several spans at one time to prevent the piers being unbalanced during construction. For this reason, many old masonry viaducts have massive piers which are capable of resisting the force from the arch on one side only, so they should really be regarded as a series of separate bridges placed end-to-end. The size of the piers would restrict the flow of water under the bridge, which could lead to problems of scour caused by water washing away the foundations. The water on the upstream side of the old London Bridge could be several feet higher than on the downstream side, making passage in a boat very hazardous.

In the 17th and 18th centuries, intellectual thought turned to the way loads were carried in structures. In 1675, Hooke published a Latin anagram, which when translated reads 'As hangs the flexible line, so but inverted will stand the rigid arch', which for the first time explained how the shape of the line of thrust within an arch ring could be visualized (Figure 3). But it was not until 1773 that Coulomb correctly established the principle that governs the stability of arches and the relationship between the shape of the arch and the line of thrust.

Coulomb and others also worked on the behaviour of beams, but it was Navier in 1826 who correctly analysed the general behaviour of a beam in bending, relating the internal stresses to the externally applied load. The mathematician Euler had already studied the deflected shapes taken by elastic beams under various loadings (without considering stresses), and deduced (in 1744) that beams could buckle when subjected to purely compressive loadings. Other developments built on these basic principles, most notably in theories relating to the behaviour of trusses, so that by the time St Venant solved the problem of torsion in beams in 1855, the principles which govern the behaviour of bridges were largely known.

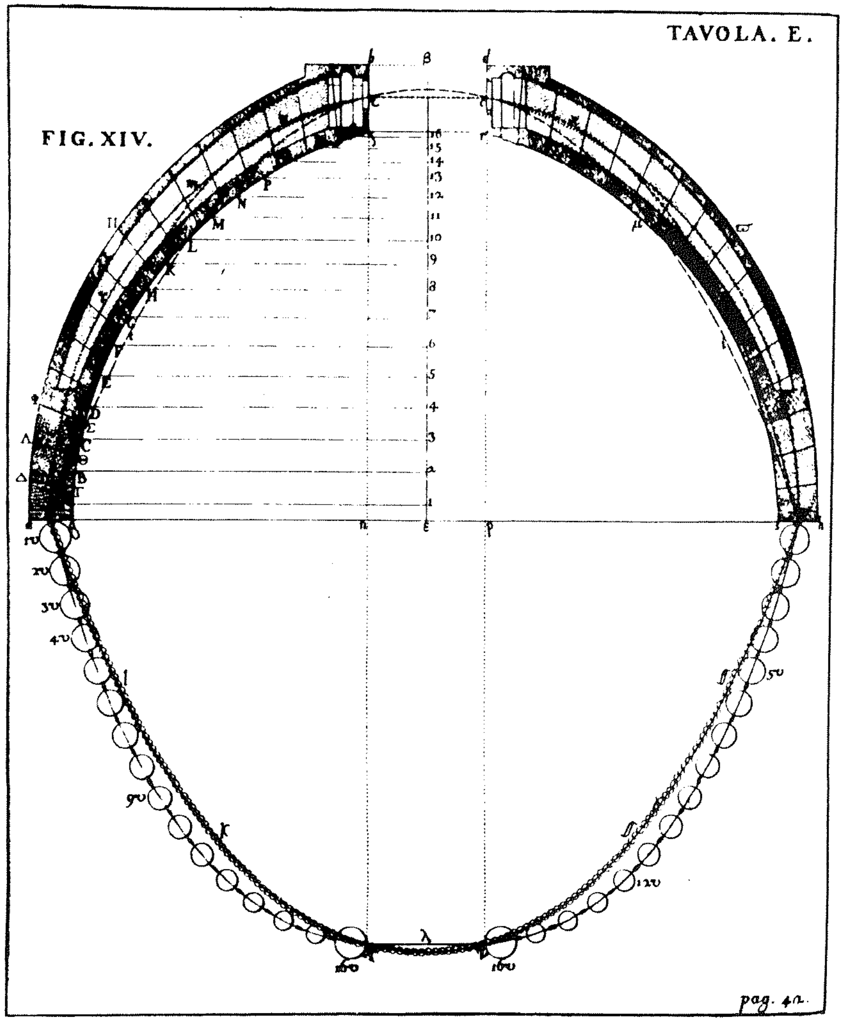


Figure 3 An illustration of the line of thrust (as a chain) within an arch ring; from an analysis by Poleni of a section of the dome of St Peter's in Rome. The thrust line was determined experimentally by loading a flexible string with unequal weights, each weight being proportional to that of a segment of the line, and due allowance being made for the weight of the lantern. [. . .] The thrust line found in this way does in fact lie within the thickness of the dome of St Peter's; the figure also shows that a uniformly loaded string would produce an equivalent thrust line passing outside the masonry.

These theoretical developments produced relatively little change in bridge building until the industrial revolution brought about the development of new materials. *Cast iron* is produced by pouring molten pig iron, made in a blast nace, into a sand mould; the pieces have to be relatively small because the iole component has to be cast in one go. The casting process leaves flaws in material in the form of air bubbles or pieces of slag, thus making it much onger in compression than in tension; in this way it is similar to stone. The ly cast iron bridges were thus arches, such as the Ironbridge in Coalbrookdale gure 4) and many of Telford's bridges, where the stone voussoirs were laced by interlocking cast iron elements. Many beam bridges were built th cast iron, but several failures caused by the lack of tensile strength, most tably the Dee Bridge disaster at Chester in 1847 (Figure 5), led to this ictice being abandoned for railway bridges.

The lack of tensile strength of cast iron could be overcome by using other type of iron, *wrought iron*. This was a more refined form of iron produced melting pig iron and then 'puddling' it in a furnace with more iron ore and ier substances to remove most of the impurities. The processing altered the ucture of the material, producing much smaller flaws and significantly reased tensile strength. Wrought iron was available in the form of bars, ips and plates, but, because it could only be made in small batches, was very pensive. It could, however, be worked by blacksmithing techniques, making ossible to produce chains from bar elements and to drill holes in plates. This ned the way for suspension bridges supported from chains, and for beam dges made from riveted wrought iron plates. These developments coincided h the development of canals and turnpike roads, which for the first time duced a demand for a large number of bridges.

The suspension bridge (see Box 2) relies on a hanging tension member ng from one abutment to the other. Ropes made from natural fibre can be d for relatively short bridges, but they are unlikely to be durable. Wrought n chains could be made to support much longer spans, and the first pension bridges in the UK were built in 1819. Early suspension bridges had ery light deck, which did not provide sufficient stiffness to prevent problems h wind-induced oscillations or excessive deflection. Most of these bridges e now been modified, but the Union Bridge over the Tweed and several all footbridges still have unstiffened decks which deflect alarmingly as a load ses over them. Telford's suspension bridge over the Menai Straits (Figure 6) fered similar problems, with the deck having to be replaced soon after it was lt, and again in the 1940s.

Iron can also be produced in the form of wire which, if drawn through a es of dies to successively reduce its diameter, can have exceptionally high ngth. This development led to the construction of suspension bridge cables n bundles of drawn wire, rather than chains, which allowed much larger ns to be constructed. The foremost exponent of this form of construction was bably Roebling, in the United States, who even built a railway suspension dge near the Niagara Falls.

Beam bridges (see Box 3) are subjected to both compressive and tensile sses, and if long spans are required, methods must be available to join nponents together. Compressive forces are easy to transmit, simply by

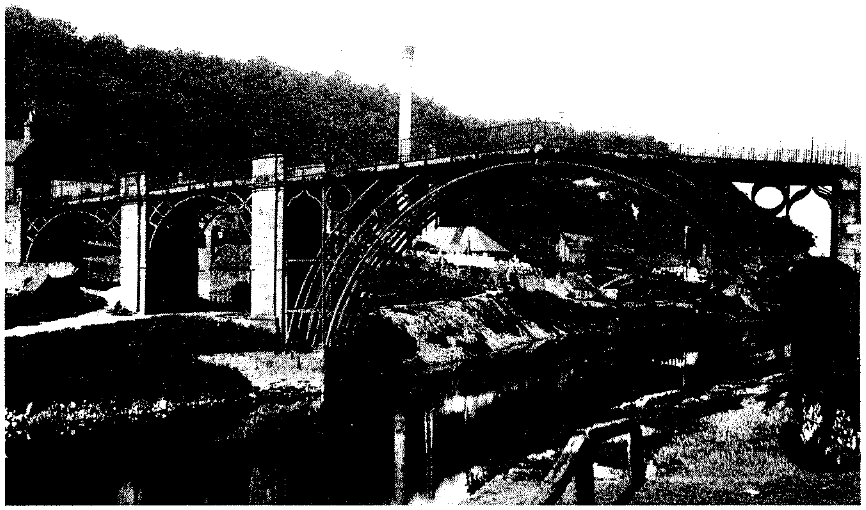


Figure 4 Ironbridge, the cast iron bridge at Coalbrookdale, UK.

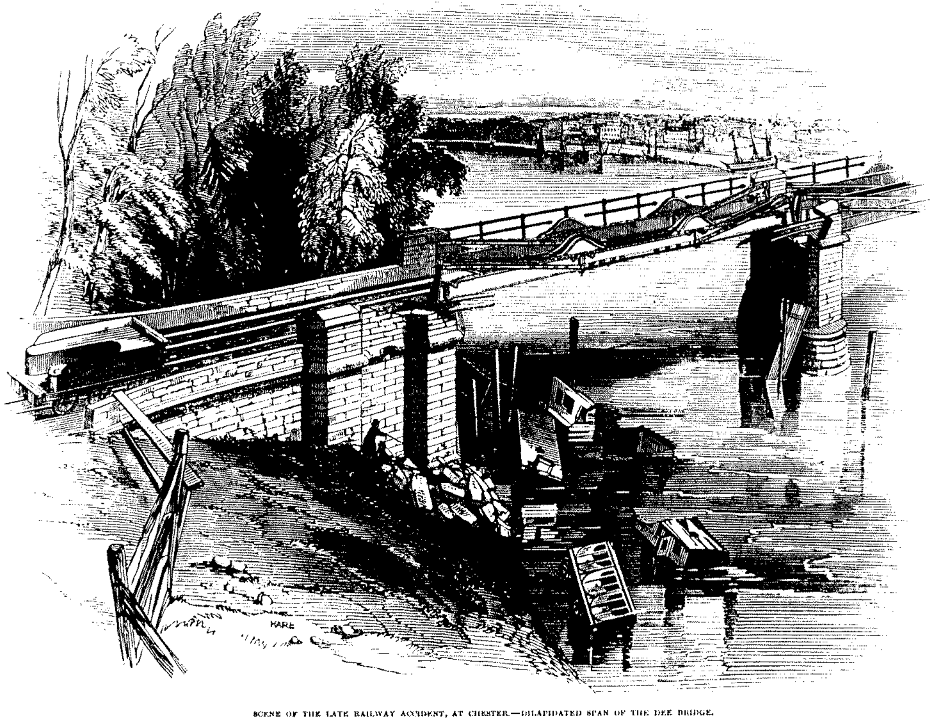
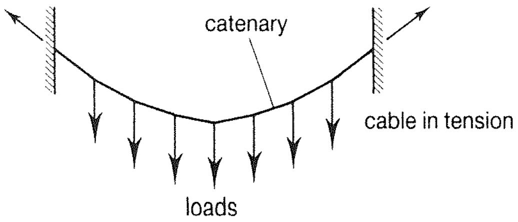


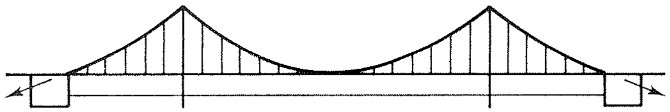
Figure 5 An engraving of the Dee Bridge disaster (1847), UK; it collapsed because a tension member broke.

ox 2 Structural form 2: The suspension bridge

f a series of weights are hung from a cable which is tied to rigid supports t the abutment, it takes up a curved profile known as a *catenary*. If a deck s suspended from the cable by means of hangers, a level roadway can be ormed. A suspension bridge built in this way is very strong, but at the ame time very flexible. The bridge can deflect significantly under heavy oads, and can vibrate under wind loadings. It must thus be stiffened by aving either a heavy truss deck, a stiff box beam deck, or by inclined angers.

The profile taken up by the suspension cable is the inverse of the ine of thrust in an arch. In the same way that the arch pushes on the butment, so the suspension bridge pulls on the abutment, which must e sufficiently massive that it can resist the cable forces.





ing one element up against the other, but tensile forces cause more lems. The ability to fabricate wrought iron by riveting plates together nt that larger spans carrying heavy loads started to become possible for the time. This was put to good use with the advent and rapid expansion of the ays, which required a large number of bridges, not just over rivers, but over roads and valleys.

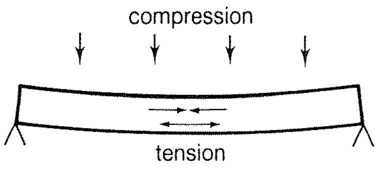
Brunel and the Stephensons, father and son, were the foremost railway neers in Britain, and indeed were influential overseas. Most railway bridges built of brick arches, but some spans became larger and flatter, such as nel's Maidenhead Bridge, which pushed conventional ideas to their limit. e early years of the railways there were a number of notable timber bridges, rally on the more remote railways, such as the trestle viaducts built by

Box 3 Structural form 3: The beam

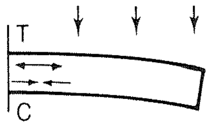
If a beam rests between two supports, with a load on the top, it will take up a slightly curved form, with the bottom of the beam getting longer, and the top getting shorter. Material in the bottom of the beam is thus in tension, and material in the top is in compression. If the beam is *cantilevered* from a wall, the situation is reversed, with tension at the top, and compression at the bottom.

If the bridge is to pass over several supports, each span can be made from a separate beam, but it is more efficient to make the beam *continuous*. Tension stresses are caused in the top of the beam over the supports and in the bottom of the beam at mid-span, with compressive stresses in the opposite faces. There are no joints (which are difficult to maintain) and the beam can generally be made lighter and cheaper than the *simply-supported* alternative.

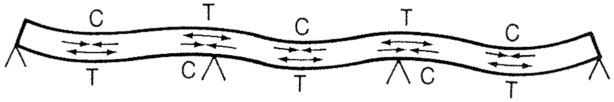
Beams have to be made from material which can resist both tension and compression, or by a combination of materials, one of which is good in tension, the other good in compression.



simply supported



cantilever



continuous

Brunel in Devon and Cornwall. Most were later replaced by more permanent structures.

The need to cross major rivers where navigation spans were required led to the biggest developments in structural form. The most important of these were over the Tyne, the Menai Straits, and the Tamar, all of which produced different innovative solutions. To cross the Tyne, George Stephenson produced a design using a *tied arch*, where the thrust of the arch is carried, not by the piers, but by tension rods tying the ends together. The bridge has two decks,

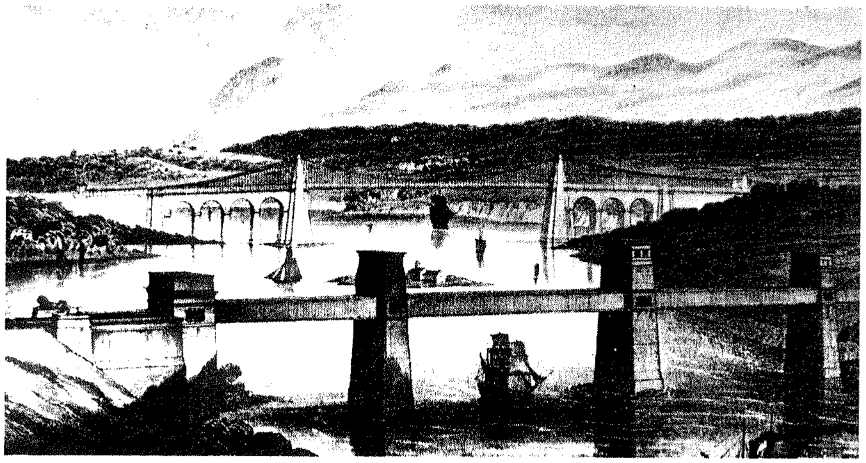


Figure 6 Two different designs in the Menai Straits in North Wales: the Menai Suspension Bridge (foreground) and the Britannia Tubular Bridge.

one for the railway supported above the arch, and a lower one for road vehicles hanging from the arch. The tie rods are incorporated just below the road deck, and can easily be seen from below.

The Britannia Bridge (Figure 6) built across the Menai Straits by George Stephenson's son, Robert, is innovative in many ways. He wanted to build large arches, but was prevented by the Admiralty who insisted on maintaining navigation clearances over the full width of the span. Instead, a wrought iron box beam was used, with the trains running on rails inside the box. One flange of the box has to carry compressive forces, but Stephenson was aware of the problems of buckling of thin plates, so the compression flange of the beam was made with stiffening cells which eliminated the problem. He built a model of the bridge, which he tested before starting construction, and built a simpler single-span prototype at Conwy. The individual box beams were fabricated on shore, floated into position, and then jacked up the piers, where they were joined together end-to-end to produce a single continuous beam. Finally, he jacked the bearings at the pier positions to induce loads in the beam which reduce the effects of the beam's weight, a technique which is regarded as advanced, even today. Stephenson had made the towers high enough to support chains which he would have used to provide additional strengthening, but in the event they were not needed. Paradoxically, when the boxes were damaged beyond repair by a fire started by vandals in 1970, they were replaced by steel arches similar to Stephenson's original design, but with sufficient strength to carry a roadway to relieve Telford's nearby suspension bridge.

At the same time as the Britannia Bridge was under construction, Brunel was tackling a similar sized structure at Saltash, where he had to cross the River Tamar (Figure 7). He adopted an equally innovative approach, with a hybrid structure consisting of wrought iron arch tubes and a suspension chain. The load on the bridge has to be shared between these two components so that the outward thrust of the arch is balanced by the inward pull of the chains; even with today's sophisticated methods of analysis that would be no mean achievement. The bridge was lighter than the Britannia Bridge, and is still in use, but significantly has never been copied.

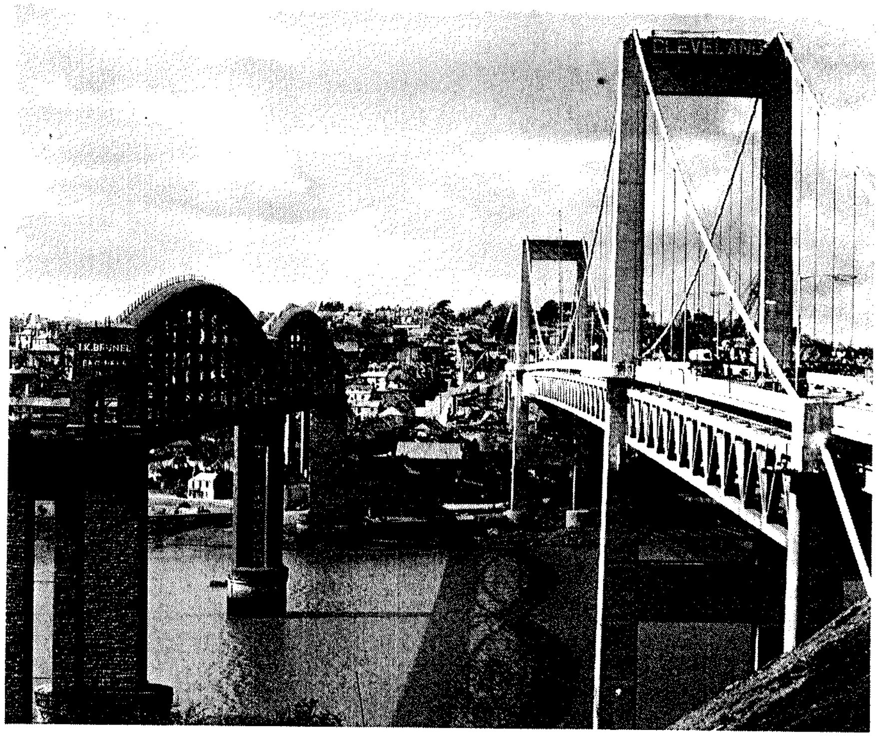


Figure 7 Brunel's bridge at Saltash; adjacent is a modern suspension bridge.

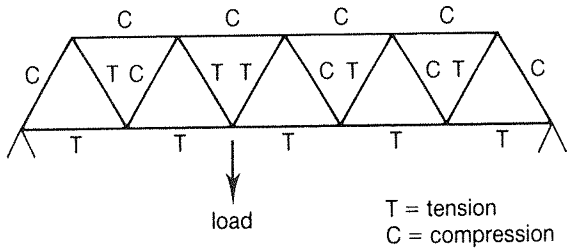
Similar achievements were made elsewhere. Wrought iron trusses (Box 4) and arches were in widespread use, the most notable exponent being Eiffel who built several large structures on the continent.

The next innovation was the development, in 1856 by Bessemer, of ways of producing steel economically in large quantities. Steel is basically iron, to which a small amount of carbon has been added. This has the effect of changing the crystal structure quite extensively and allows both tensile and compressive stresses to be carried. Steel quickly replaced both cast iron and wrought iron in bridge building, and opened the way for new developments.

A turning point in bridge design was the Tay Bridge disaster, which

Box 4 The truss bridge

A truss bridge behaves like a beam, but with most of the material removed to save weight. The top and bottom chords of the bridge carry the main tension and compression forces, but the diagonal elements transmit forces between the chords, and also brace the compression chord against buckling. The force in these diagonal elements can change from tension to compression as the load traverses the beam, and in larger trusses, the diagonals also need to be braced.



occurred in 1879. The bridge had been built of light, wrought-iron trusses, supported on cast-iron piers, with very little bracing across the structure. The loading induced by wind on the structure, especially when carrying a train, had not been properly understood, and 75 people were killed when the bridge collapsed during the passage of a train in a gale. The Forth Bridge (Figure 8) was built shortly afterwards using steel for the first time in a major bridge. It was designed with due allowance for wind loads and despite its solid appearance in a foreshortened view, it is seen to be a remarkably light structure when viewed from the side.

At about the same time as steel was first used for bridges, concrete started to be used as a structural material. The Romans knew about lime-based cements and they mixed these with crushed clay tiles to make a sort of concrete. In 1824, Aspdin produced a much stronger cement by fusing together limestone and clay, thus combining the two materials much more intimately. This cement reacts with water to produce a solid matrix, which can be used as a binder for aggregate (sand and gravel). Aspdin called his product Portland Cement, since the resulting concrete resembled Portland stone in colour and texture.

At first, concrete was considered as a means of moulding stone, rather than having to carve it. Osborne House, built on the Isle of Wight by Prince Albert, was constructed in this way. But engineers began to realize that they could cast a complete arch ring from concrete, without any joints; the first such bridge was built over the River Axe at Seaton in Devon in 1877. Concrete was developed too late for the majority of the railways but some later railway bridges such as Glenfinnan Viaduct in Scotland were built with mass concrete.

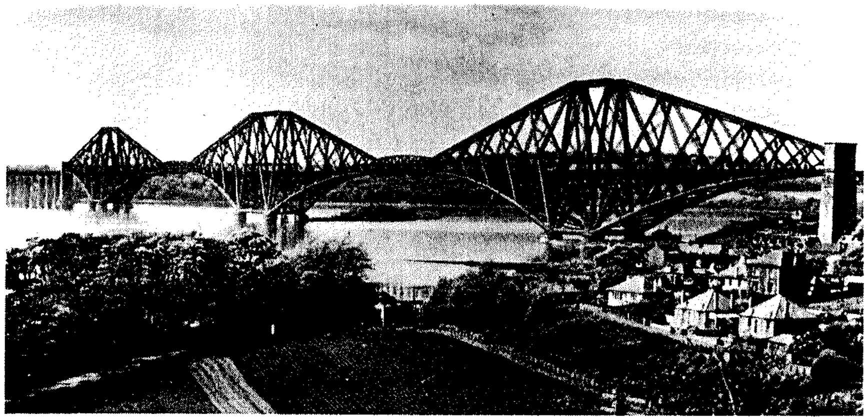


Figure 8 The Forth Railway Bridge over the Firth of Forth in Scotland, 1890, by Benjamin Baker. With two spans of 1710 feet, this steel cantilever bridge surpassed Brooklyn Bridge as the world's longest span. The steel structure rises 342 feet above the masonry piers. Although from a foreshortened view the bridge appears dense and massive, in profile it exhibits a surprising lightness.

It was not long, however, before engineers started to think of concrete as a material in its own right, rather than as a replacement. The biggest problem with stone and concrete is that they have very little tensile strength, and are brittle, although they have high compressive strength. Steel rods have high tensile strength, but a tendency to buckle when in compression. This led to the development, by Hennebique of France in 1892, of *reinforced concrete*, where bars of steel are placed in the concrete to resist the tensile forces, leaving the concrete to carry the compressive forces. We thus have an ideal material for constructing beams.

In the early years of this century many reinforced concrete bridges were constructed. At first, many of them were of the open arch type, with a relatively thin reinforced concrete ring (Figure 9). This supported columns which in turn carried the roadway. The arch was primarily acting in compression, but high point loads induced through the columns would cause bending in the arch, which could now be resisted because of the reinforcement. Smaller structures were built as simple beams, or beams supporting a thin slab. The freedom to choose the shape of the concrete section, and at the same time to vary the strength by altering the amount of steel reinforcement, at last gave engineers the chance to explore a wide range of structural forms.

The steel bars in reinforced concrete are much stiffer than the surrounding concrete, which has very little tensile strength. This means that the concrete cracks before the steel carries any significant load. In properly designed structures, these cracks are invisible to the untrained eye, but they lead to a loss

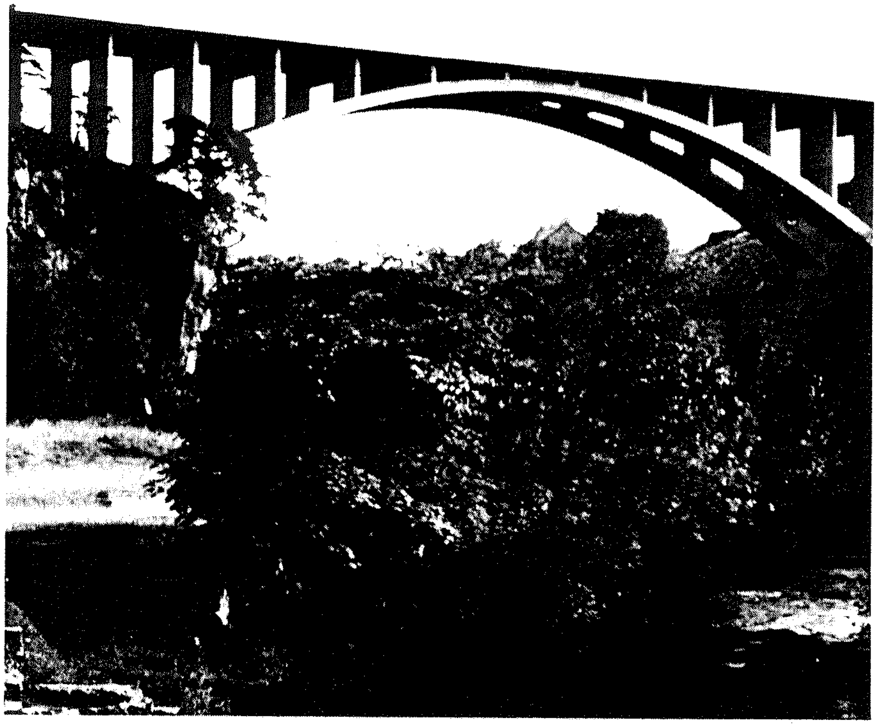


Figure 9 A thin reinforced concrete arch bridge. The Heads of the Valley Taf Fechan Bridge, Wales, UK.

of stiffness of the beam as a whole. It had long been realized that these cracks could be elminated if the whole concrete beam were subjected to an overall compressive force, so that the effect of the loads merely reduced the original compression, rather than causing tension. Attempts were made, as early as the 1890s, to do this by tensioning reinforcing bars running through the concrete, but after a few weeks the cracks reappeared.

It was only when the French engineer Freyssinet realized that concrete creeps under load, in 1927, that *prestressed concrete* was developed. He realized that if very high strength wire was tensioned, and good quality concrete cast around it, a significant compression would be left in the concrete even after the creep had taken place. Prestressed concrete bridges are normally stronger and stiffer than the equivalent reinforced concrete structures, which means that they can be made lighter. Because they have no cracks, and are made from better quality concrete, they are also more durable. Virtually all concrete bridges with spans greater than about 15 m are now built from prestressed concrete, in a variety of structural forms (Figure 10).

Developments in structural theory had matched changes in materials, but there were great difficulties in doing the calculations. The behaviour of most structural elements can be described in terms of differential equations, but in only a very limited number of cases can these equations be solved analytically; most such solutions had been obtained by the early years of this century. However, these differential equations can be rearranged into sets of simultaneous equations for more general problems. The number of calculations required to solve a set of equations increases as the cube of the number of unknowns; when calculations are performed by hand, there is a significant chance of making an error, so very careful procedures are needed. There was thus a great premium on minimizing the number of equations to be solved at one time, and a number of techniques were developed to achieve this. Various methods of finding approximate solutions, many involving iterative relaxation methods, were adopted in the first half of this century, which allowed most designers to get at least a reasonable approximation to the behaviour of the structures they were designing.

Improvements in steels have also taken place in the 20th century, with higher strengths and weldable steels becoming commonly available. Welding, where two components are combined by melting the steel at the join by means of an electric arc, does away with the need for lap joints and is much less labour-intensive than the riveting process that it replaced. But it does require special steels and skilled operators, since the welding process upsets the crystal structure of the metal near the weld, which can lead to a brittle zone and the formation of cracks. This was first demonstrated during the Second World War

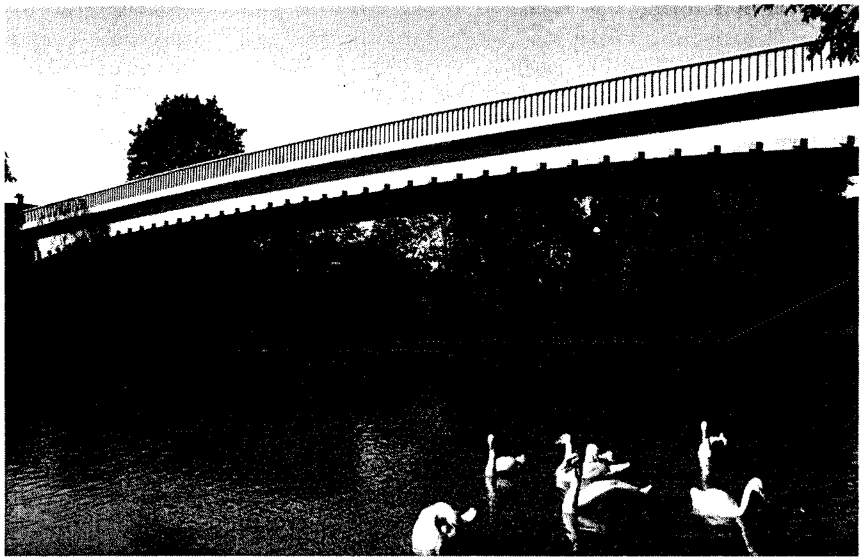


Figure 10 A prestressed concrete bridge by Freyssinet at Pont de Luzancy.

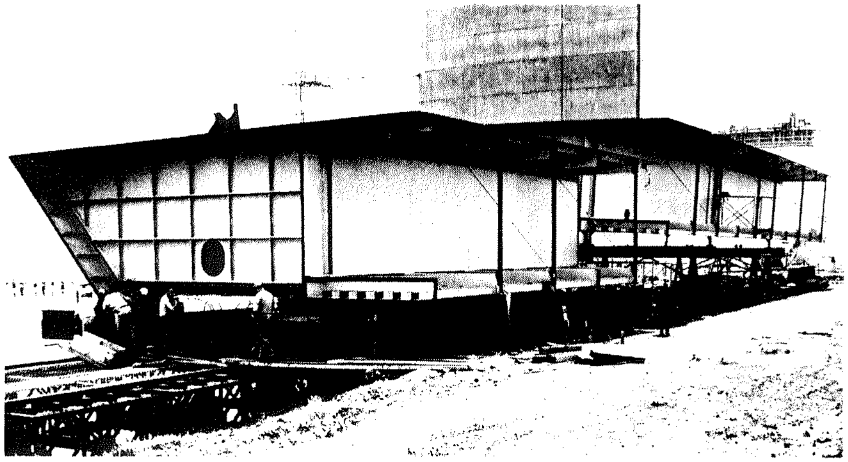


Figure 11 Box-girder bridge under construction, Avonmouth, UK.

when mass-produced Liberty ships started to break up when operating in cold waters. A number of bridge failures can also be ascribed to these effects. Welding is not usually a problem in factory conditions, but is more difficult to control on site, so hybrid methods of fabricating steel bridges are often used. Large components are welded in a workshop, and then joined together on site by high strength bolts.

Two bridge forms have come into common use in the second half of the 20th century; *box-girder* bridges, and *cable-stayed* bridges. Box-girder bridges are of cellular form, which makes them torsionally stiff, and are thus very good at distributing heavy loads placed on one side of the structure. They are economical in their use of material, but can be complex to construct (Figure 11). Steel boxes are often fabricated from flat plate components, stiffened to prevent buckling, and concrete box girders are also widely used.

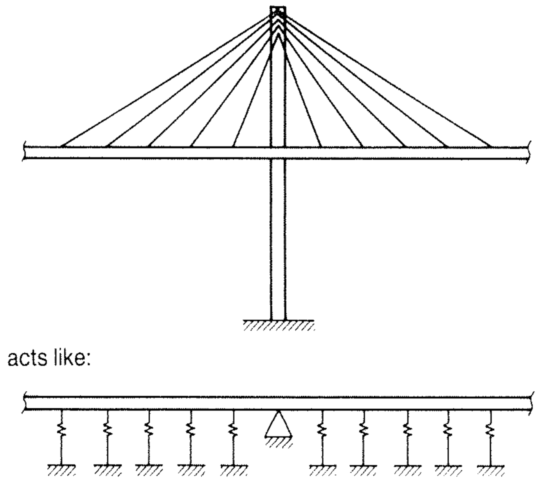
Cable-stayed bridges (see Box 5) are often confused with suspension bridges, but behave in a very different way. They have steel or concrete box decks, supported by steel wire cables which radiate out from the top of a tower (Figure 12). They do not suffer the same oscillation problems as suspension bridges, and evolved from early hybrid structures, such as the Albert Bridge in London and the Brooklyn Bridge in New York, which are primarily suspension bridges but have stay cables to improve their stiffness. Most large span bridges (but not usually the very largest) are constructed in a cable-stayed form.

All of these recent advances have been made much easier by the advent of the computer, which has removed the problems associated with solving simultaneous equations. Before 1960, solving five simultaneous equations was a major exercise, whereas today many engineers use micro-computers which can solve thousands of equations within a few minutes. It is possible to analyse a structure to any degree of detail required; the problem is becoming one of *too much* information, from which the engineer needs judgement to extract the relevant results. Future developments will almost certainly be in the field of *expert systems*, which will assist the designer in the preparation of designs and in the interpretation of the results of analyses.

Box 5 Cable-stayed bridges

The cables in these bridges act as supports for the deck structure. They serve to reduce the bending in the deck which can be made quite thin and therefore light. The beam acts as though it were continuous over a large number of spans, although the cables are extensible and do not act as rigid supports to the beam, which must be taken into account in design.

Cable-stayed bridges are normally governed by overall stiffness requirements, rather than strength conditions, and fatigue problems in the cables must be considered. They are much less susceptible to wind-induced oscillations than suspension bridges once complete, although they can be vulnerable to high winds during construction.



In the 1990s, the engineer has a wide range of bridge types to choose from, but certain standard solutions are now apparent. Arches are rarely used, except where good foundations exist to resist the thrust and where the opening to be bridged is of suitable shape. For small spans, up to about 15 m, reinforced concrete beams or slabs would normally be used, but beyond that, prestressed concrete becomes most economic. For spans up to about 25 m, which covers the large majority of structures, bridges built from precast prestressed concrete beams, lifted into place and then topped with a reinforced concrete slab, are usually used.

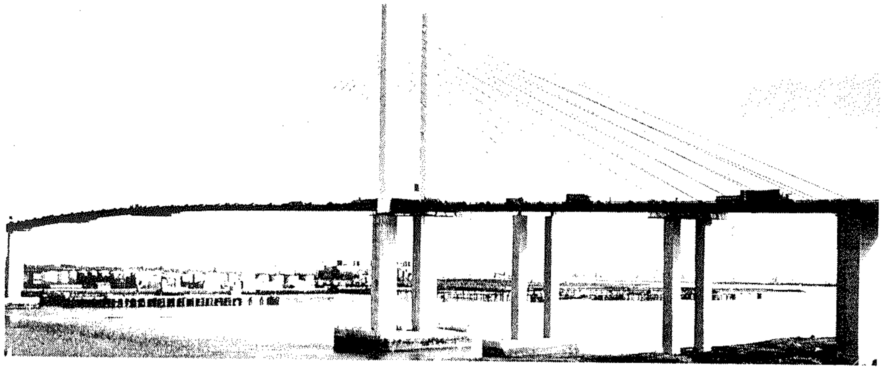


Figure 12 The cable-stayed bridge at Dartford, Kent, UK.

For medium spans, up to about 150 m, steel or concrete beam bridges are usually the most economic, built in a wide variety of ways. In *balanced cantilever* construction, sections of equal weight are added on each side of a pier until the two halves of a span meet. In *span-by-span* methods, the beam is built on scaffolding until one span is complete, when the scaffolding is moved forward to build the next span (Figure 13). *Incrementally launched* bridges are built at one abutment and pushed forward (Figure 14); this is efficient since construction takes place at one location, but requires a launching nose to be added to the structure, and often the use of temporary columns to provide additional support during launching.

Beyond 150 m, cable-stayed structures are now the most common. The deck is built out from the pier which supports the tower, with cables being added as each few metres are completed. This minimizes the amount of temporary support that is required, but the designer must take account of the varying loads on the bridge during construction, and also the quite large deflections that will take place as new pieces of the beam are added. Beam elements and cable lengths have to be adjusted so that the bridge ends up in the correct shape when complete, a problem that is only really solvable with the aid of modern computer power.

The very largest bridges are still built as suspension bridges, but only for spans that exceed about 600 m (Figure 15). Knowledge of structural behaviour and methods of analysis have improved to the extent that some of these bridges now carry railways, as well as roads. The high concentrated loads from heavy trains, particularly from the engines, were long seen as causing unacceptable deformations.

What are the problems with existing bridges? Bridges are often used at the limit of what is economically possible, so it is not surprising that a small number suffer from problems. Around 1970, four major steel box-girder bridges collapsed, three of them during erection, when the effects of interaction between buckling and yielding of the steel were not sufficiently understood.

Figure 13 'Span-by-span' construction method.

Other problems relate to durability. If water is allowed to penetrate a structure, steel can corrode, particularly if the water contains de-icing salt that has been spread on the roads. This is clearly a problem in steel structures, but the problem is usually visible and can be prevented by regular maintenance. A more insidious problem exists in concrete bridges where the corrosion of reinforcing or prestressing steel is normally prevented by the highly alkali environment provided by the concrete. However, the alkalinity can be destroyed by the penetration of atmospheric carbon dioxide or chlorides from sea spray or de-icing salts. When this occurs, reinforcement can rust, causing the outer layers of concrete to spall off, or the prestressing wires can fail, which leads to collapse of the structure. There has been only one such collapse in the UK to date, but these faults are almost impossible to detect from the outside.

What of the future? A number of new materials have been developed with the potential to overcome the durability problem, and at the same time extend the size of structures that are possible. These are all in the form of fibres, made from glass, carbon or aramids, and have strengths and stiffnesses that compare well with those of steel. These fibres can be aggregated into ropes or made into composite bars with epoxy, either of which can then be used as prestressing tendons or stay cables. Bridges have been built with all these new materials in the form of prestressing tendons, and their use is likely to increase if the durability of steel proves to be a major problem.

The real advance will be made when the largest suspension bridges are constructed from these new materials. The current largest span is the Humber Bridge at 1.4 km, but there is a 1.6 km span under construction across the

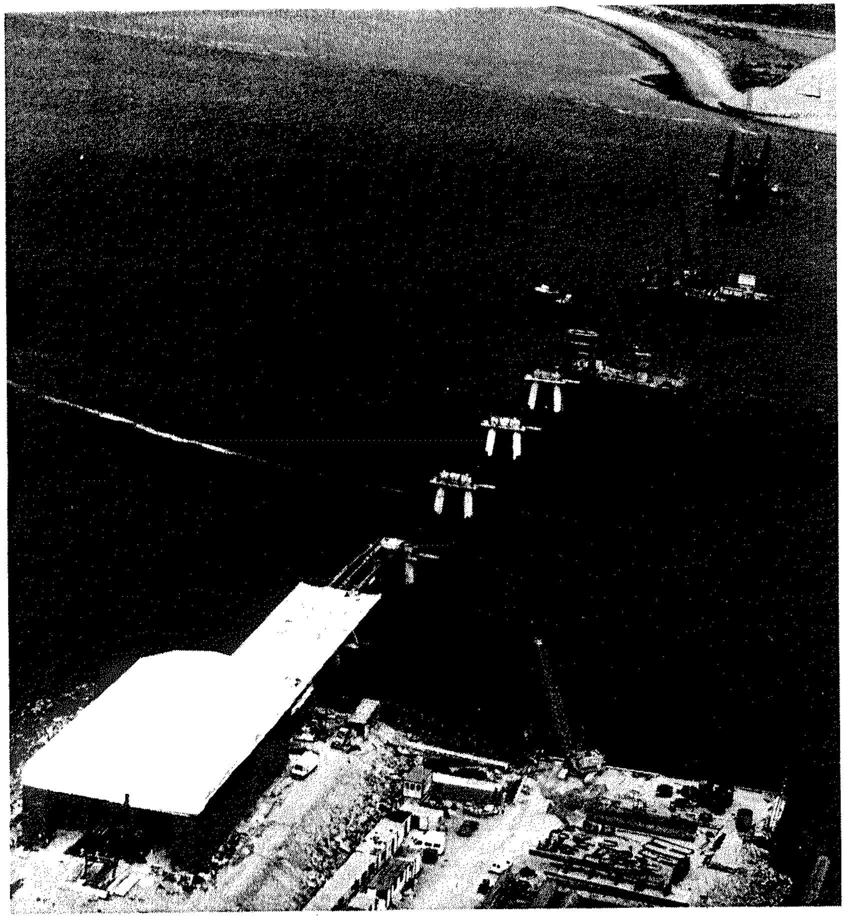
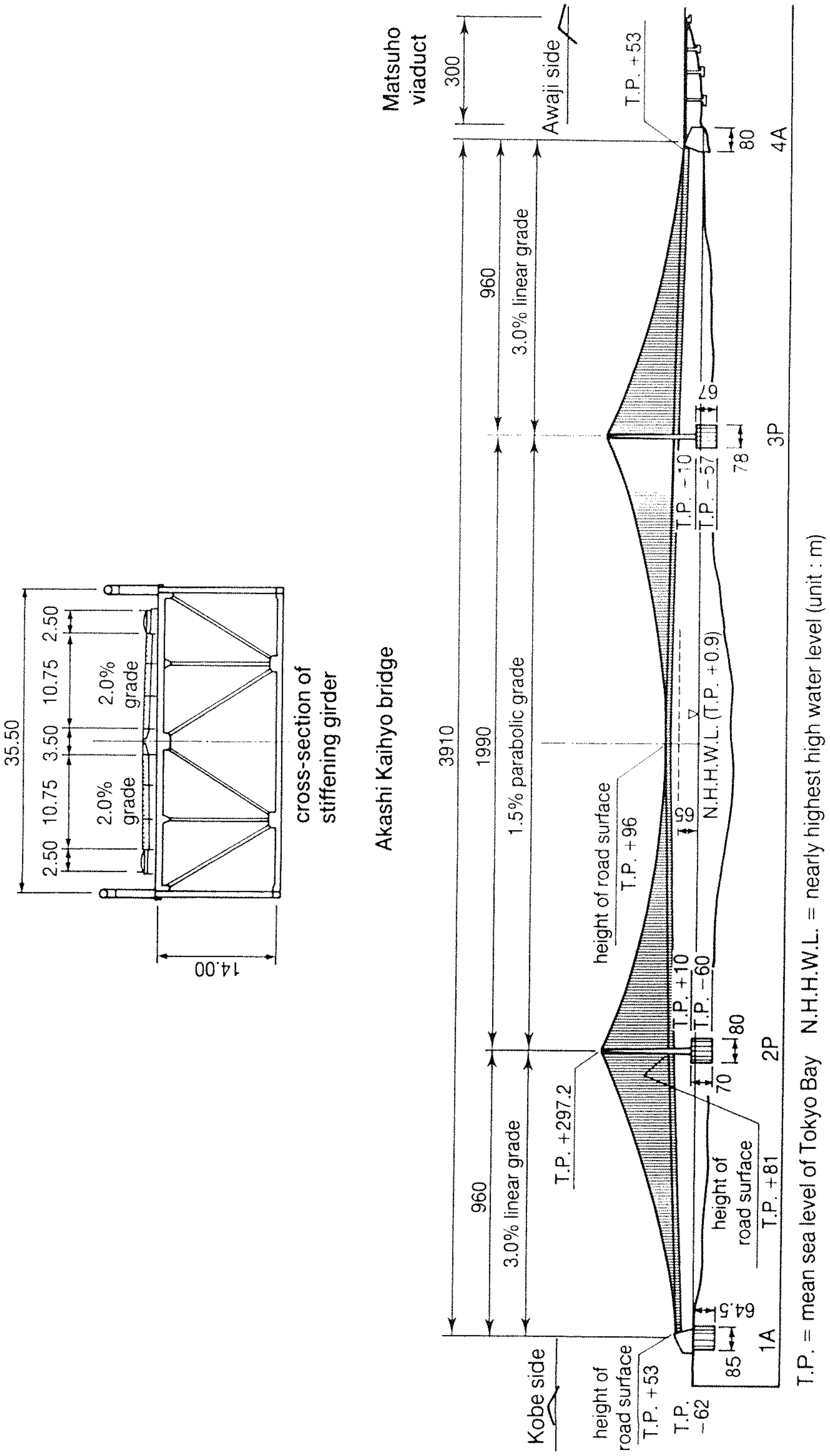


Figure 14 'Incrementally launched' bridge construction method, Dornoch Firth Bridge, Scotland.

Great Belt in Denmark, and a 2.0 km span across the Inland Sea in Japan (Figure 15). These all use steel cables, but steel is very heavy, and it is generally believed that a 2.5 km span is the largest that could be constructed with steel. Carbon and aramid fibres have a much higher strength/weight ratio, which would allow longer spans to be constructed. The Messina Bridge between Italy and Sicily would need a 3.5 km span, and a series of 4.5 km spans with aramid ropes were proposed for the Channel crossing. The largest span proposed to date is for an 8.4 km span across the Strait of Gibraltar, supported by carbon fibres.

Whether any of these bridges will ever be built remains conjecture. What is clear is that bridge forms will continue to evolve as new materials are produced, new construction techniques developed, and as we improve our understanding of the way these structures behave.



T.P. = mean sea level of Tokyo Bay N.H.H.W.L. = nearly highest high water level (unit : m)

Figure 15 The proposed Akashi Bridge (suspension) in Japan.