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Telford, Stephenson and Brunel — Pilots of the Future

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1 INTRODUCTION

Thomas Telford, Robert Stephenson and Isambard Kingdom Brunel were intellectual giants of their times - the latter decades of the eighteenth century and the first half of the nineteenth. These were men of inspiration, imagination and invention, each with a seemingly endless capacity for mental and physical endurance, who charted the courses of their lives with inquiry, precision, determination and an innate sense of beauty as they strode confidently into the future to create a bountiful heritage of "immense and glorious works of fine intelligence".

They built superbly in the old materials of stone and brick and they embraced with intense enthusiasm the new materials and processes of the new age - the Age of the Industrial Revolution. Abraham Darby at Coalbrookdale on the Severn in Shropshire used coke in place of charcoal for the smelting of iron which led to the production of cast iron in great quantities, unrestricted by the old difficulties of supplying sufficient suitable charcoal. A hitherto unknown architect from Shrewsbury, Thomas Farnolls Pritchard, designed the first cast iron bridge in the world. Cast at Coalbrookdale, the components were assembled and the bridge with a span of 30 m and a rise of 15 m was complete across the Severn in 1779 where it stands to this day at Ironbridge.

This achievement is one of the most significant, far reaching and influential attainments in the history of man as an engineer and builder and its lessons were not lost on the brilliant minds so closely to follow its example and see its implications for the future.

Wrought iron was known to the ancient Egyptians and Assyrians who made great use of it and it is mentioned in the Book of Genesis. It is surprising to see that cast iron was made as comparatively recently as the sixth century A.D. in China. Until the advent of the Coalbrookdale cast iron bridge, iron, either wrought or cast, had never been conceived as a material for engineering works in its own right. Ironbridge was the great new dawn which was to lead to the development of the science of metallurgy, controlled systems for the testing of materials and the monitoring of production methods. Telford, Stephenson and Brunel were pioneers in this work and one of their most valuable lessons for us was their use of small scale prototypes which provided the essential information allowing their great structures to follow more surely. Henry Bessemer with his converter and others made possible the mass production of steel. The Forth Bridge 1883-89, designed by Fowler and Baker was the first large steel structure to be built and we owe much to these two remarkable engineers for their frontier work on the effects of wind pressure on structures.

Our century has produced great steel wire cable suspension bridges, like J.B. Strauss's Golden Gate, San Francisco, 1933-37. Wire cable was first used in a large structure by J.A. Roebling for his superb Brooklyn Suspension Bridge in New York, 1869-83, and the principles he established for the spinning of wire cables are used today - a fascinating development from the wrought iron link chains in the bridges of Telford and Brunel.

In our century, Fritz Leonhardt of Germany has built his elegant fan and harp cable stayed bridges, which rank with the world's engineering masterpieces.

2 THOMAS TELFORD (1757-1834)

Thomas Telford was born on August 9th 1757 in a small cottage at Glendinning in the Parish of Westerkirk, Eskdale, Dumfries - the son of an 'unblameable shepherd'. He started out in life as a stonemason, with the aim of becoming an architect. In fact, during his early years in London he worked as a mason on Somerset House where he was introduced to Sir William Chambers and Robert Adam, two very distinguished architects indeed. He went on to design the Commissioner's House at Portsmouth Dockyard before moving up to Shrewsbury in 1787 to make improvements to the Castle there and to design the new prison among other works. He later built two fine churches, St. Mary, Bridgnorth and the innovative little octagonal church of St. Michael, in nearby Madeley. It was about this time that Telford was appointed Engineer and Building Surveyor to the town of Shrewsbury and the quite extensive district around about. His first task was to build a number of bridges over the Severn to replace those destroyed or extensively damaged by severe recent flooding. It was most fortuitious that he should have come to the Severn Valley, the cradle of civil engineering, just at this time. From now on, civil engineering became his career, but he never abandoned the tenets of form, line and proportion acquired during his studies of architecture - his roads, canals, bridges and aqueducts always set so harmoniously and at times in striking contrast with the diverse landscapes in which he moved, were all works of considerable beauty.

The Iron Bridge at Coalbrookdale clearly impressed Telford profoundly and this set him thinking about structural uses for cast iron. In 1793 he was appointed to design a scheme for connecting the Mersey, Dee and Severn to be known as the Ellesmere Canal System. Telford wished to reduce the flights of locks wherever possible to speed up the traffic and this presented him with the greatest challenge of the project - how to convey the Canal across the wide and deep valley of the River Dee at Pont Cysylltau near Llangollen, in North Wales.

Now just at this time, Telford was appointed engineer to another Canal, the Shrewsbury Canal which connected the town of Shrewsbury with the collieries near the Wrekin at a place called Ketley where a large ironworks had been established. The Canal had to cross the small River Tern near the village of Longdon and this is the way Telford described his idea "I have just recommended an Iron Aqueduct, ... it is approved and will be executed under my direction upon a principle entirely new and which I am endeavouring to establish with regard to the application of iron."

What Telford did was to build an aqueduct entirely of cast iron components. The trough members whilst rectangular in cross-section were fan shaped in side elevation giving the action and appearance of a flat arch. Those sections were bolted together along their flanges and sealed at the joints to make the whole assembly watertight. This continuous aqueduct trough some 55 m long and supported on cast iron columns and struts, all made at Ketley, was the first iron aqueduct in the world. Though small in scale, it was a great technological achievement. The tremendous importance of this model aqueduct was that it gave Telford the opportunity to demonstrate the soundness and practicality of his idea shortly to burgeon forth in his mighty work at Pont Cysylltau.

This majestic aqueduct is a continuous cast iron trough some 300 m in length made up of fan shaped channel sections based upon the Longdon system. The trough extends over nineteen spans, each supported by cast iron arches between tall stone piers. Telford designed these piers to be cellular from a height of 20 m upwards, thereby establishing an important new structural principle. It combined strength with comparative lightness in the masonry, it demanded excellence of workmanship and it reduced quite substantially the load upon the foundations.

The Pont Cysylltau Aqueduct was opened in 1805, to the astonishment of the people and the acclamation of the engineering world. To see canal barges being towed 40 m above the River Dee was beyond belief to the Welsh, this "Stream in the Sky" as they called it and Sir Walter Scott pronounced it the most impressive work of art he had ever seen.

Telford built his first cast iron bridge in 1796 at Buildwas on the Severn, not far from Ironbridge. The span of the arch was 40 m with a rise of only 7.5 m which very effectively resisted the thrust of the banks. This bridge, of greater span than Iron Bridge used less than half the quantity of cast iron.

Telford built a great number of cast iron bridges throughout his life. His most ambitious design was, unfortunately, never built. This was his proposal for a new London Bridge in 1801, a magnificent design spanning the Thames in one 180 m cast iron arch. It seems incredible to us that the project was abandoned on one count only - the difficulties created by the neighbouring wharf owners over the approaches to the bridge - the great chance of formal arcades lining the river in the vicinity of St. Paul's lost, if not forever, at least until the advent of an age of enlightened design.

Telford built a large number of beautiful stone bridges as well, in connection with his road and canal schemes, many of these in Scotland. It is scarcely an exaggeration to say that almost solely through his efforts, the economy of the Highlands was restored - the engineer by his considerable talents and practical skills seen as the 'redeemer of an entire society, once in apalling poverty, now starting to revive and establish once more.

Telford's achievements in wrought iron are no less important than his works in cast iron, indeed they are perhaps even more remarkable and astonishing. His greatest work in wrought iron is the supremely beautiful Menai Suspension Bridge, of 1826, conveying his London to Holyhead Road over the navigable Menai Straits linking the mainland of Wales with the Island of Anglesey.

This bridge, the longest suspension bridge of its time, has a clear span of 174 m with a clearance of 30 m between high water and the underside of the deck - a stringent requirement of the Admiralty. The two main piers, each with two archways to allow the passage of traffic, rise to a height of 16 m above the roadway deck as pyramidal towers to support the chains. The deck is approached by three great masonry arches on the mainland side and four on the Anglesey side. The stone used in the suspension towers and the approaches is a tough grey limestone, from the quarries of Penmon, at the eastern end of Anglesey. The deck, 9 m wide, was supported originally by sixteen chains made up of composite links each consisting of thirty-six bars of iron.

Telford approached the design and building of this bridge, a pilot structure for which there was no precedent in scale with the greatest caution and has given the succeeding generations of engineers much invaluable information and guidance. For example, every wrought iron link of each of the chains was given a tensile test on a machine specially designed for the purpose by Telford and installed in William Hazledine's Coleham ironworks at Shrewsbury. From protracted experiments, Telford was able to show that his bridge would in fact have the ample safety margin of 100 per cent. Corrosion of structural metals was a particular concern of his, as it is for us today. To protect the links from the very serious corrosive effect of saltwater and the salty atmosphere of the Menai, they were heated, quenched in a bath of linseed oil and then dried in a stove which gave them a protective varnish.

Telford never trusted theory alone, but checked every move he contemplated by practical experiment wherever possible. In spite of the thorough Coleham tests, the first length of chain to be assembled was suspended across a nearby valley on Anglesey and given rigorous tensile testing. He also was able to determine the power necessary to raise the chains to their appointed position on the bridge itself. Furthermore, he built a one-quarter size model of one of the chains and suspended it to enable his calculated lengths of the vertical suspension rods to be checked against actual measurement. It is especially interesting to note that a steel master link or pattern was made to allow the greatest possible accuracy in the manufacture of the chains and in the boring of the links. Our word for the process is 'jig drilling'.

The progressive raising of all the sixteen chains from the raft on the water into their positions on the towers, the linking up with the landward anchored chains and the ancillary tasks proceeded smoothly over several days, with efficiency improving as the men worked into a routine. That the entire difficult and risky operation was completed without hitch or mishap was owing, in large measure, to Telford's superb planning, rigorous testing, well chosen assistants and to his abiding concern for the safety of every man on the works.

In the middle of the night, on January 30th, 1826 the first coach crossed the Menai and the greatest suspension bridge in the world was opened without ceremony in the manner Telford saw fit.

Only a week after the opening on the night of February 7th, 1826, a ferocious gale blew down the Menai Straits, striking the bridge broadside. It induced a very pronounced movement in the structure, so much so that the coachmen refused to cross. Twenty-four of the roadway bars along with six suspension rods were broken. Twelve days later an even more violent storm at night broke twenty more suspension rods and bent another fifty. Great concern was expressed at the waving motion in the roadway deck, which was described as alarming. Clearly modifications had to be made. Stronger suspension rods were installed, bracing chains were added to steady the main chains and the deck was strengthened with heavier members. Notwithstanding these measures which appeared to have overcome the problems of movement in the bridge during bad gales, Telford with all his extreme care and concern, was gravely worried, so much so that he stated his belief that no future suspension bridge should exceed the span of the Menai Bridge. As we shall see, I.B. Brunel was soon to refute the assertion vehemently. In fact the bridge stood at the threshold of the science of aerodynamics.

The Menai Bridge, after the initial problems were overcome, served splendidly down the years. In 1940 it was modified, with the deck and chains renewed, yet it retains its original elegance of line.

The poet Southey referred to Telford as "The Colossus of Roads". He was also called "Pontifex Maximus", the supreme bridge builder. He gave us the basic form of the building contract we use to this day. He was a Fellow of the Royal Society and the first President of the Institution of Civil Engineers. Born in the Parish of Westerkirk 1757, buried in the nave of Westminster Abbey, 1834.

"And I will make all my mountains a way, and my highways shall be exhalted" - Isaiah 49:11

3 ROBERT STEPHENSON (1803-1859)

Robert Stephenson was born in 1803, son of George Stephenson, "the Father of Railways" as many called him, with little exaggeration. Robert Stephenson, unlike his father, had a formal education and distinguished himself early as a mechanical engineer. His great success with their "Rocket" at the Rainhill trials of 1829 established his reputation and the practicality of locomotive hauled railways.

In this paper we are concerned with Robert Stephenson, the celebrated civil engineer. Of his many great works, two stand out particularly, making him a pilot of the future - the Britannia and Conway Tubular Bridges.

In 1845, he was appointed Engineer-in-Chief to the Chester & Holyhead Railway. His task was to build the line and it is fascinating to see that like Telford, he too had to find a way of crossing the river estuary at Conway Castle and, of far greater moment, meet the challenge of the Menai Straits. As these were railway bridges, suspension systems with light, untrussed decks were dismissed at the outset as totally unsuitable. Robert Stephenson was emphatic about this and wrote at length on the subject. It is curious to recall that at one point his father was seriously proposing to use a lane of Telford's bridge to carry the railway over the Menai Straits!! The failure of Captain Brown's suspension railway bridge over the Tees at Stockton was a stark lesson.

For the Menai, Stephenson selected the crossing point for his bridge to align with the Britannia Rock, a natural rock outcrop almost in the middle of the Straits, about a mile south of Telford's bridge. His first proposal was for two equal cast iron arch spans each extending from its shore abutment to the central pier on the Rock. This scheme was discarded on two counts - the centering needed to construct the arches would interfere with navigation for a lengthy period and the Admiralty requirement of 30 m clearance would set the abutments so high above natural grade that the railway approaches would become prohibitively costly. His next thought for the spans was a new concept of suspension where the chains might support a form of deep trussed girder either in wood or wrought iron. His next step was to consider solid wrought iron sides and bottom made up of riveted plates, a trough in effect open to the sky, with the railway track at the bottom of the trough which would be supported by suspension chains.

Now just at this critical stage a mishap occurred during a broadside launching of an iron steamship at Blackwall on the Thames. She had jammed, quite undamaged, supported clear at two points only, at her forepeak and her sternpost. Stephenson went down expressly to have a look at her and there set before him he saw his solution to the Britannia Bridge. The vessel, her decks closed in, was in reality a long tube, supported only at the ends. He returned, put a roof on his trough and created a rectangular tube of considerable strength. The great idea was born.

Now the time for exhaustive testing had come. Stephenson believed that the strength of the tube could be such that suspension chains would not be needed. He approached two men, both experts in their field - William Fairbairn the famous engineer and shipbuilder, once an associate of his father, and Professor Eaton Hodgkinson, F.R.S., a prize mathematician and an authority on iron beams. The two reports were submitted to Stephenson. Hodgkinson considered the chains were essential, Fairbairn dismissed the need for them. "Provided the parts are well proportioned and the plates properly riveted", he stated "you may strip off the chains and have it (the bridge) as a useful Monument of the enterprise and energy of the age in which it was constructed." With characteristic caution, Robert Stephenson studied the reports exhaustively and finally decided against chains. Fairbairn and Hodgkinson worked as a close team with Stephenson on the Britannia and Conway Tubular Bridges. The basis of their work was a series of tests to destruction on large wrought iron models of the tubes set up in Fairbairn's shipyard. Progressive improvements were made after each test and the results of those tests led to the final design of the actual tubes. Cellular construction was adopted for the roof and floor of the tubes. Individual plates with stiffening "T" section ribs formed the sides.

The Britannia Bridge was designed symmetrically about the tall central pier on Britannia Rock. There were two parallel tubes each conveying a railway track. The span from the central tower to each of the intermediate towers on either side of it was 138 m and from the intermediate towers to the portal abutments 69 m. The tubes tapered slightly from the Britannia tower where the overall cross-section measured 9 m in height by 4.5 m in width. The total length of each tube from portal to portal was 454 m.

It is important to appreciate that the four sections of each tube were joined together within the towers to form one continuous tube, rigidly fixed in the central Britannia tower, but free to move over roller bearings in the intermediate towers and abutments to provide for expansion and contraction. The brilliant subtlety of this system devised by Robert Stephenson is often missed. In fact the end spans were jacked down thereby actually prestressing the tubes, an astonishing innovation for 1850, revived only comparatively recently. This continuity of the tubes and the prestressing measures greatly increased the strength of the bridge, thereby allowing it to cope easily with the heavy trains of today.

The tubular bridge at Conway though small in comparison with the Britannia Bridge provided Stephenson with the ideal opportunity for a full scale model test before he started to float the great Britannia tubes on their pontoons at the Menai. Again we see the inestimable value in having a small scale prototype to gather information and experience for the immense work to follow. The Conway bridge carried two tracks in simply supported parallel tubes of 120 m span between the portals which in this instance were decorated with roundels and battlements in keeping with Conway Castle a device used by Telford earlier in the towers of his adjacent suspension bridge. It must have been a memorable occasion to have seen Stephenson and Brunel standing together on one of the Conway tubes as it was floated into position.

In spite of all the tests and careful preparations, unforeseen problems occurred at the Menai - a hydraulic press burst, a capstan fouled at a critical time and the timber staging supporting one of the tubes during assembly gave under the weight and had to be strengthed and the camber in the tube restored. There was heroic drama in the floating and raising of the Britannia tubes.

Finally, all difficulties overcome, the great bridge was completed in 1850, one of the most astonishing achievements in the world for its time and a pilot for the future.

It is sad irony to recall how fragile the greatest structures of man can be. A few years ago young boys were smoking out ferrets, it is said, around one of the abutments. A spark from their fires flew up and lodged it seems beneath the light timber roof over the tubes which was impregnated with bitumen as a protection against the weather. In an instant the Britannia Bridge was alight from shore to shore, the once mighty tubes now sagging limp and dangerously, damaged beyond feasible restoration; one of the greatest and most innovative pieces of our Engineering Heritage was now lost forever.

In Victoria, at Shelford between Teesdale and Rokewood a small but most elegant wrought iron tubular girder road bridge of three spans crosses the River Leigh. It was designed by the engineer Charles Wilson in 1873-74.

4. ISAMBARD KINGDOM BRUNEL (1806-1859)

Isambard Kingdom Brunel, son of the distinguished engineer Sir Marc Brunel, famous for his Thames Tunnel, has been most aptly described as the Leonardo of the nineteenth century - the universal man. He was a man of vaulting intellect and unbounded imagination. In his iron steamship 'Great Britain' he proved the practicality of the screw propeller for driving ships across the oceans and his 'Great Eastern', the largest ship in the world for many years to come, laid the first successful telegraph cable across the Atlantic.

Many of Brunel's finest achievements in Civil Engineering are to be found on his superb broad gauge Great Western Railway - the Wharncliffe Viaduct; the Maidenhead Bridge with its wide span and very low rise brick arches; Box Tunnel and the prodigious difficulties encountered in boring it; the fan shaped timber viaducts in Cornwall and at the very end of his astonishingly productive life his greatest railway work of all, the Royal Albert Bridge at Saltash carrying the railway over the Tamar Estuary into Cornwall.

The Royal Albert Bridge has two great lens shaped trusses of wrought iron construction, each with a span of 140 m supported at the middle of the Estuary on a composite cast iron pier, itself consisting of four octagonal cast iron columns. The trusses are supported at the shore ends by tall masonry piers. The deck is 30 m above high water, the familiar Admiralty requirement. The approaches to the bridge are carried above the land on either side on short span wrought iron plate girders, supported on slender masonry piers. At first the bridge was to take two railway tracks, but severe economies meant that this had to be reduced to a single line.

Of particular interest to us is the method of founding the central pier and the composition of the truss system.

Brunel had a most thoroughgoing survey made of the geology of the bed of the Estuary and from the information derived, he was able to construct a model section. The survey was done by using a wrought iron cylinder, 26 m long and 2 m in diameter which was slung between two hulks and lowered vertically down to the river bed. Brunel took 175 borings at 35 different places in the vicinity of the centre of the Estuary. Finally he sunk the cylinder to bed rock, pumped out the water and excavated the mud from inside the cylinder and built a trial masonry pier founded upon the rock up to the level of the river bed, before withdrawing the cylinder.

Now in possession of essential information, Brunel proceeded to construct the great masonry column to support the central pier. This column, 10.7 m in diameter, rises 29 m from bed rock to its upper surface above high water level from which the cast iron pier is supported. Brunel decided that a wrought iron cylinder of 10.7 m diameter was to be sunk by means of compressed air with its base or cutting edge inclined to suit the slope of the rock.

About 6 m up from the cutting edge, a wrought iron dome was placed to form the roof of the working chamber from which a 3 m diameter shaft, open at both ends, reached to the surface. An innovation was the construction of an annular space 1.2 m wide inside the chamber. The idea was to pump air into the annular space only clearing the water from it so that the men could make a type of coffer dam at the bottom of the cylinder without having to use air pressure over its whole area. The cylinder was built on the river bank, floated on the tide by pontoons and lowered into position. Work proceeded steadily with some difficulties such as unexpected inrushes of water through fissures in the rock. The pumps coped, however, and by the end of 1856, the masonry cylinder and central pier it supported were complete, ready to receive the trusses. The Saltash caisson was a pilot work of the greatest consequence in civil engineering.

The trusses are a combination of beam, arch and chain, the beam being the railway deck, the arch the curved tube of elliptical section over the top and the chain below restraining the outward thrust of the tube. The arch, chain and beam are connected by vertical hangers. Each truss was prefabricated on the Devon shore and the complete assembly fully tested by Brunel before being floated out and raised into its final position.

The floating operation was meticulously organised with Brunel himself directing operations for the first tube. This great bridge was completed in what may be described as a heroic operation without mishap.

The Chepstow railway bridge, completed a little earlier by Brunel used the same truss system. Though much smaller in scale, it served as a prototype for the great work at Saltash.

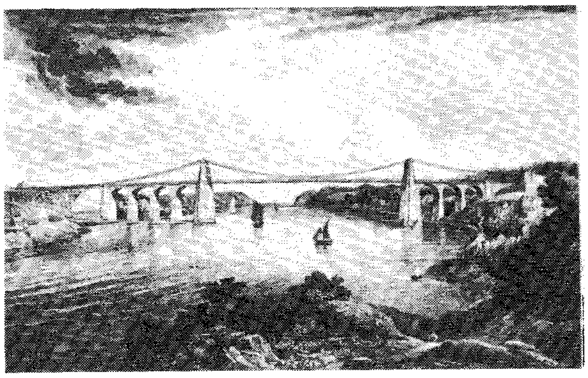
It is of some interest to recall that Brunel was retained by the Victorian Railways to inspect and certify engineering components before they were shipped to Melbourne.

As a young man, Brunel submitted his superb design for the Avon Bridge Competition. The site chosen is most spectacular, high above the Avon Gorge at Clifton, near Bristol. His conception was a single suspended span of 280 m sweeping across the sky, high above the gorge. The judge, Thomas Telford, recalling his experience at the Menai, rejected the design outright. Brunel was adamant, for he had included an opposing curve of restraining chains to steady the deck. The young, brilliant Brunel was the next generation, embracing with wisdom, the experience of the past and illuminating with inspiration the way into the future.

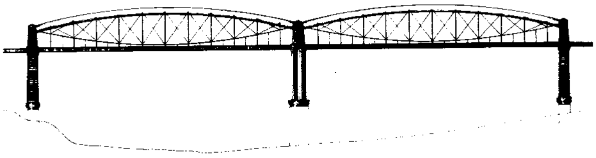
5 CONCLUSION

Telford, Stephenson and Brunel, pilots through their mighty works and enormous contribution to the knowledge and benefit of mankind, left a Heritage which has inspired the generations of engineers who have followed them. The bridges of Strauss, Steinmann and Leonhardt, some of the finest achievements of our century, reflect the essential value of that Heritage.

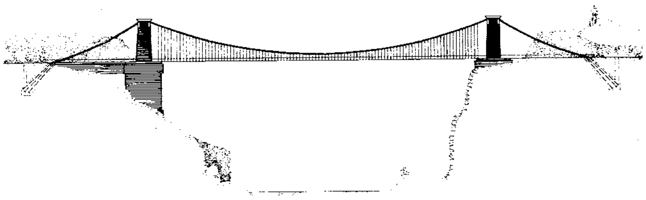
The present and future will produce an ever widening range of new materials with structural and mechanical engineering possibilities. It behoves us to heed the philosophies, procedures and approaches of the great engineers of the past and to learn from the Heritage that they have left us so that we might the more confidently and steadfastly advance into the future set before us.



Menai Suspension Bridge, Telford, 1826.



Royal Albert Bridge, Saltash, Brunel, 1859.



Clifton Suspension Bridge, 1864
Final form, Memorial to Brunel.

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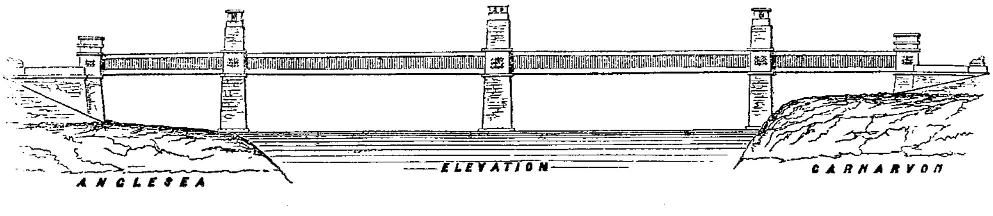

Britannia Tubular Bridge, Robert Stephenson, 1850.