The Evolution of the Forth Bridge and Its Engineering Significance

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Abstract

The Forth Bridge, arguably the greatest engineering achievement of the 19th century, carries Scotland's East Coast main railway over the Firth of Forth. This paper provides description and comment on the bridge, its evolution and significance in leading to the general adoption of steel for bridges, a brief update of *100 Years of the Forth* Bridge *(2)* edited and co-authored by the Author, and an outline of Railtrack's ongoing £70m. repair and maintenance programme.

Introduction

Earlier crossings and projects. A regular ferry operated at Queensferry at least as early as the 12th century using natural rock landings. By 1760 although it was the busiest ferry in Scotland, its users found it slow, disagreeable and dangerous. It was not until 1808-17 that major improvements were carried out under the direction of John Rennie. These included ramped piers, to suit sailing boats at any state of the tide, that continued in use until the Forth Road Bridge was opened in 1964.

A temporary boat bridge at the Forth Bridge site may have been considered by the Romans A.D. c. 208. Later proposals included one in 1805-7 with tunnels for "comers" and "goers" passing 200 ft. under the river. This scheme was seriously considered but abandoned probably more for economic reasons than doubts about its practicability, although soft ground would have prevented its completion. *(2)*

In 1818 an over-bold suspension bridge proposal was made by James Anderson (c. 1790-1861). It was to have been of stay or catenarian form with spans of up to 610 m. (2000 ft.) and a sag to span ratio of 1:30, a bridge which Westhofen justifiably described as "so light that on a dull day it would hardly have been visible and after a heavy gale probably no longer to be seen on a clear day either". *(1)*

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With the development of steam locomotion towards the mid-19th century the railway system became the main means of transport in Britain and the need arose for a rail bridge across the Forth to achieve a more direct east coast route north from Edinburgh to Dundee other than via Stirling and Perth. In 1850 a bridge crossing at Queensferry was impracticable because of the deep water and the innovation then introduced was to cross the Forth via the relatively inefficient Granton to Burntisland floating railway ferry. This was installed by (Sir) Thomas Bouch (1822-80) and operated until the Forth Bridge was opened in 1890 at Queensferry (see Figure 1).

Bouch's bridges. In 1862 Bouch, now Engineer of the North British Railway, and the company's consulting engineers ruled out a suspension bridge at Queensferry as being impracticable for railway traffic, citing the 5 km (3 mph) speed limit on Niagara Bridge (J.A Roebling). From 1863-65 Bouch worked on a project for a multi-span wrought iron lattice girder bridge with spans up to 152 m. (500 ft.) at Charlestown west of Queensferry estimated to cost £476,000. His designs involved trains passing within 19.5 m. (64 ft.) tall girders but, after a site trial in 1866, the project was abandoned due to doubts about obtaining adequate pier foundations. *(2)*

Bouch's next design, in 1871-73, was for a double 488 m. (1600 ft.) span steel chain [u.t.s. 620 N/mm^2 (40 $tons/in^2$)] suspension bridge at the site of the present bridge, with a deck stiffened by substantial wrought iron lattice trusses. The design was checked and found satisfactory by leading engineers Barlow & Pole. The various approvals were obtained and construction began in 1878 with (Sir) William Arrol (1839-1913) as the contractor. The initial work was progressing satisfactorily until the fateful night of 28 December 1879 when the central part of the Tay Bridge, for which Bouch was also the Engineer, fell into the River Tay during a storm with the loss of 75 lives. Bouch's inelegant Forth bridge, which under Arrol's capable stewardship would probably have been successful, was abandoned. All that remains is a brick pier base on Inchgarvie now supporting a navigation light (see Figure 1).

Figure 1 – Forth Bridge Site

The Forth Bridge

Design. In 1881 leading engineers Sir John Fowler, (Sir) Benjamin Baker and Baker's chief assistant Allan Stewart set to work on the design of the present bridge. Considering a suspension bridge too flexible for railway traffic, they adopted the double cantilever girder system for the 521 m. spans on the 2.5 km (1½ mile) long crossing and decided to use steel with its improved qualities over wrought iron. The steelwork comprises tubular struts and lattice-girder ties in three double-cantilevers each connected by 105 m. [346 ft.] "suspended" girder spans resting on the cantilever ends (see Figure 2). The outside double-cantilever shoreward ends carry weights of

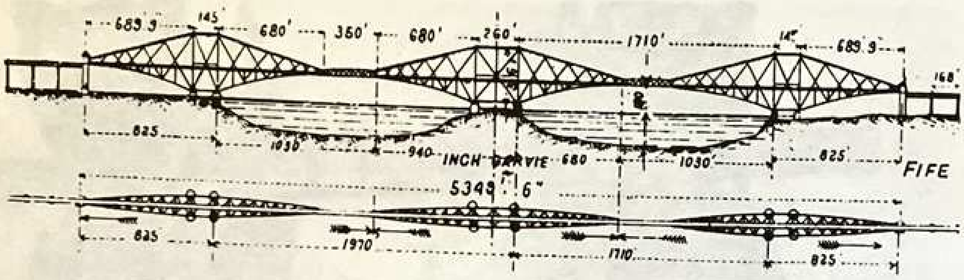

Figure 2 – Forth Bridge Elevation and Plan with Dimensions *(1)*

about 1000 tonnes to counter balance half the weight of the suspended span and live load. This concept is readily understood from Baker's 'human cantilever' model with his assistant Kaichi Watanabe representing the suspended span load. The ***pull*** in the men's arms indicates the ***tension*** in the ties and, the ***push*** in the lower struts, the ***compression*** in the tubes. From a sketch elevation in a letter from Fowler to Stewart (see top of Figure 3) the effective cross – bracing in each tower elevation suggested by consultant W. H. Barlow (1812 – 1902) had not been finalised by September 1, 1881. (ICE Library).

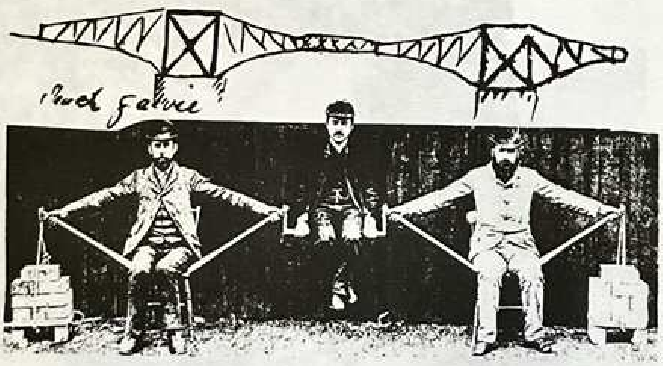

Figure 3 - Human cantilever model and Fowler's Sketch

In forming their designs, which were on an unprecedented scale, the engineers do not seem to have been particularly influenced by any of the many examples listed in Westhofen *(1)* but more by the basic traditional cantilever concept. The advantage of which was that it reduced the effective span and weight that would otherwise have been necessary for the central portion of the spans by concentrating the load on the piers. The construction of piers adequate to support the bridge's 110 m. high towers and span loadings was therefore a matter of great importance (see Figure 2).

Foundations. The Fife and North Inchgarvie piers were founded on rock, within cofferdams and the remainder within 21.3 m. (70 ft.) diameter by 27.4 m. (90 ft.) high pneumatic caissons, floated into position, and sunk to a solid foundation achieved by compressed air working (see Figures 4 & 5). The piers were filled with concrete, apart from the top section, which was Arbroath rubble surrounded by a granite facing built within a temporary caisson on top of the permanent one. A base plate was then fixed to the pier top for attaching the ten-element "skewbacks" of the tower base.

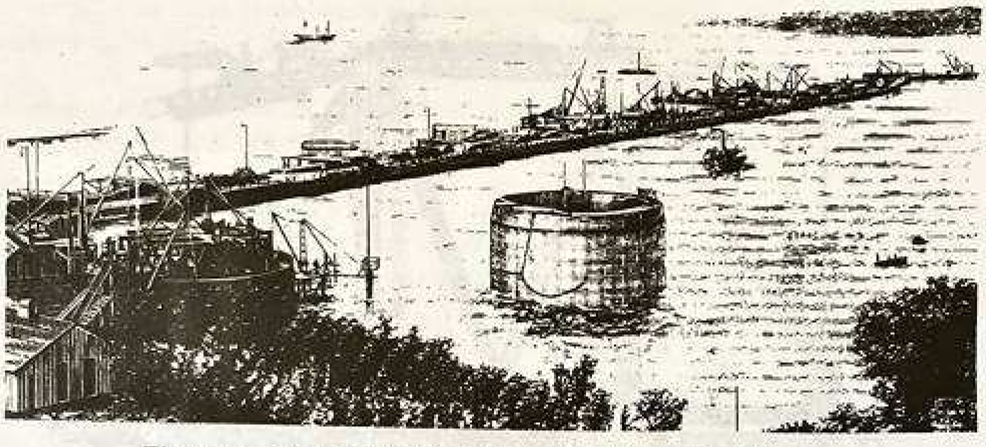

Figure 4 – Floating Out the Caisson for Queensferry Pier

Steelwork erection. The tubes were assembled in the work yards from bent plates, fabricated, pre-drilled, numbered, dismantled and shipped to site. The three towers were erected concurrently by means of climbing platforms bearing "Goliath" and derrick cranes which held the members in position until secured in position by climbing hydraulic tube riveting machines and cages (see Figure 6). The trusses for the approach viaducts were jacked up the granite towers into position (see Figure 7). Arrol's equipment and temporary works innovation were of outstanding quality.

When the towers were complete, work started on the cantilevers, great care always being taken to ensure that the weight on each side of the tower was equally balanced. The members were held in position by "Jubilee" and other cranes and then hydraulically riveted (see Figures 8 & 9). Each central girder was constructed from the cantilever ends, from which it was held by plate ties, and joined in the middle (see Figure 10). The connection was achieved by means of temporary sliding plates at mid span, a delicate temperature-dependent operation that in one case, to complete in cold weather, it was necessary to set fire to naptha-soaked waste to expand the steelwork. Roller bearings were installed at the shoreward cantilever ends with the approach viaducts.

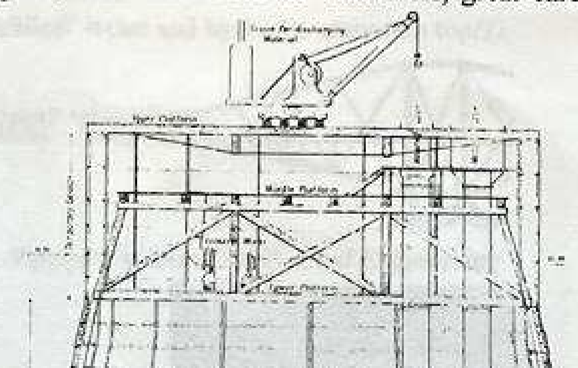

Figure 5 – Inchgarvie Caisson Under Construction (1)

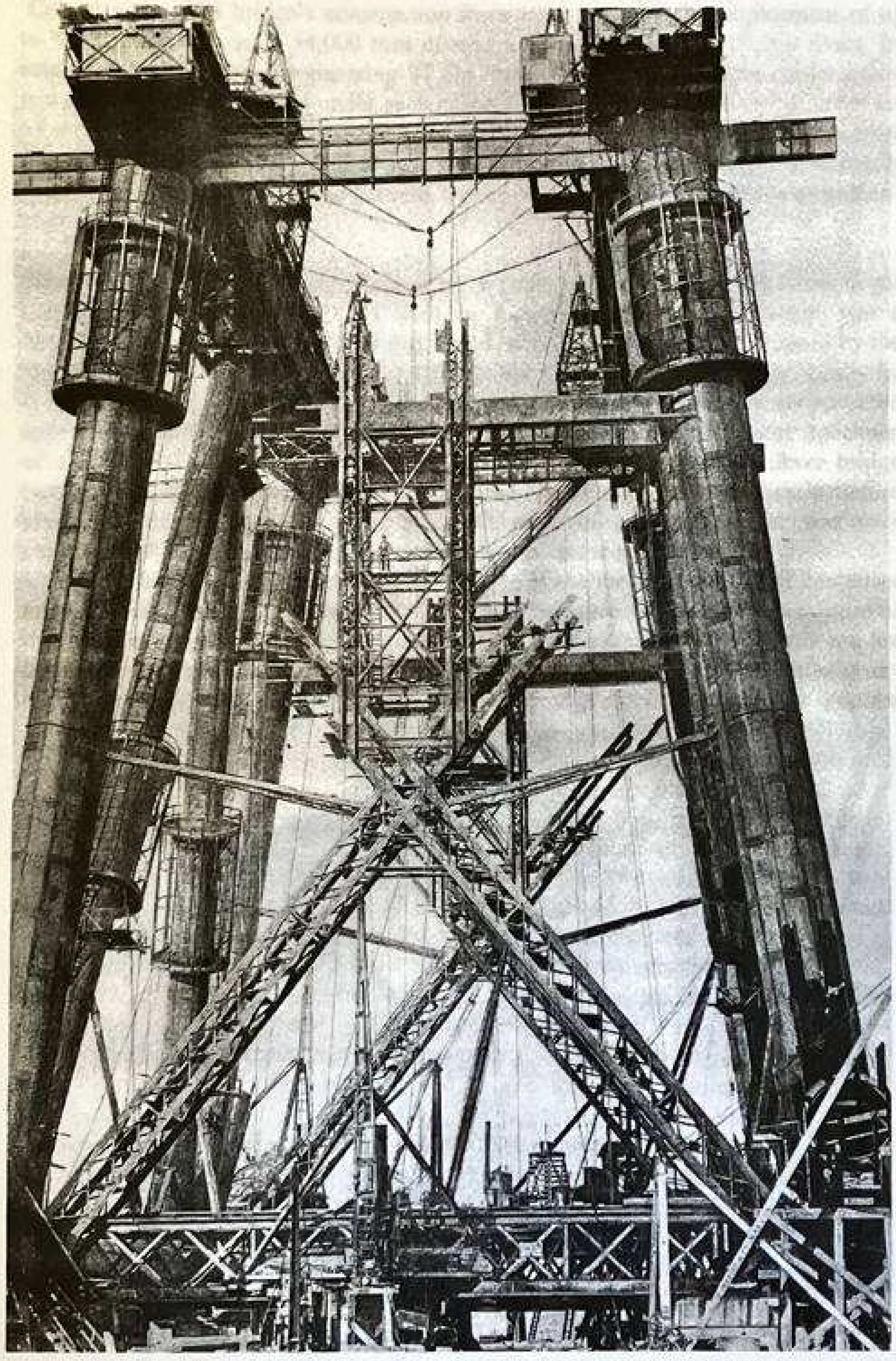

Figure 6 – Queensferry Pier – Lifting Platform Raised 58 m. Note Figure on Gantry *(1)*

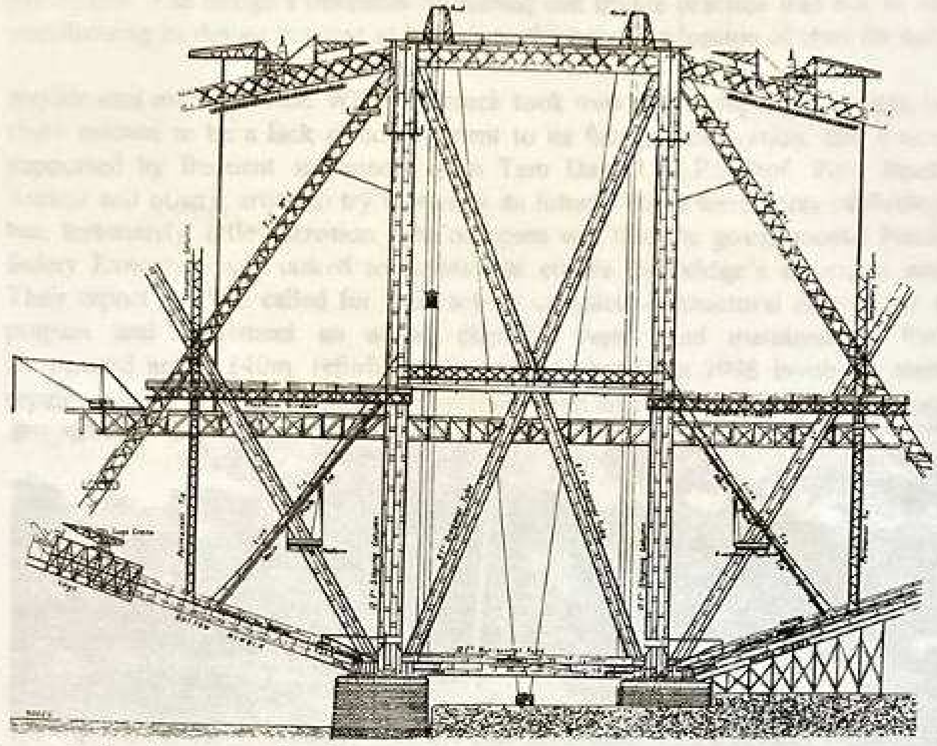

Figure 7. Cantilever erection. Note "Jubilee" steam and hydraulic cranes on top*(1)*.

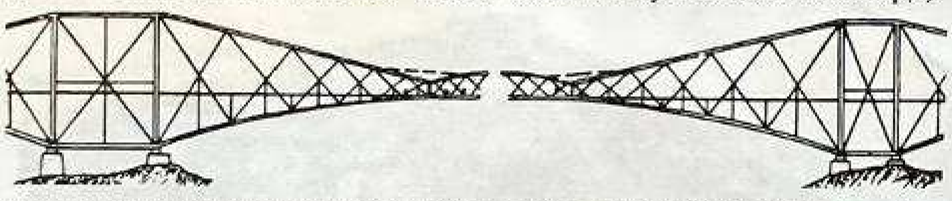

Figure 8. Completing a central girder. Vernon-Harcourt (1902). *Civil Engineering*.

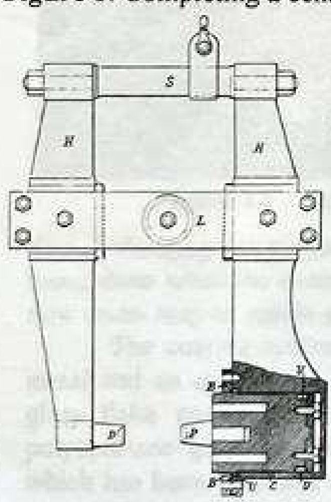

Figure 9. Hydraulic riveter*(1)*

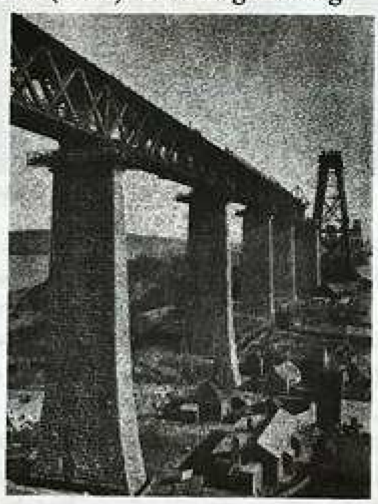

Figure 10. Approach Viaduct*(1)*

Completion. The bridge's construction from 1883 involved the employment of up to 4,600 men, the use of 54,000 tons of steel and driving about 6,500,000 rivets. Its total cost was £3.2m. (engineering £2.6m. net). During the bridge's construction, rescue boats were stationed under each cantilever saving at least 8 lives but, even so, 57 men died. The characteristic red paint applied to its 18 ha. (45 acre) surface from the outset until recently was supplied by Craig & Rose. The bridge was formally opened on 4 March 1890 when Edward, Prince of Wales tapped into place a "golden" rivet.

Significance. To achieve a rigid bridge, the world's largest in 1890, with spans larger than the Brooklyn Bridge (1883), then the longest span suspension bridge, was a remarkable achievement - a record that lasted until it was marginally surpassed by the Quebec Bridge 28 years later. The Forth Bridge was certainly costly by comparison with a stiffened suspension bridge. Its design has not always attracted approbation. For example, William Morris thought it " the supremest specimen of all ugliness". Theodore Cooper, engineer for the first Quebec cantilever bridge (writing before its collapse in 1907), thought the Forth Bridge "the clumsiest structure ever designed by man, the most awkward piece of engineering that was ever constructed" and that an American would have done it for half the cost.

In the Author's opinion the Forth Bridge is the most elegant of all cantilever bridges, with a slender appearance in elevation (see Figure 11). Also, the curvature of its lower booms and central girder tops, and the "Holbein straddle" of its towers, are particularly attractive and evocative features. Although there is an element of over-design influenced by the Tay Bridge disaster, this is much less than the popular

Figure 11 – Bridge Maintenance at the Time of Mr. Tony Blair P.M's Visit

perception. The bridge's influence on subsequent bridge practice was not so much in popularizing its design concept as leading to the general adoption of steel for bridges.

Repair and maintenance. When Railtrack took over ownership of the bridge in 1994 there seemed to be a lack of commitment to its future preservation, and a campaign supported by frequent statements from Tam Dalyell M.P., Prof. Paul Jowitt, the Author and others, arose to try to ensure its future. There were acres of flaking paint but, fortunately, little corrosion. The outcome was that the governmental Health and Safety Executive was tasked to assess and ensure the bridge's structural integrity. Their report in 1996 called for Railtrack to complete a structural assessment and to prepare and implement an action plan for repair and maintenance. Railtrack cooperated and a £40m. refurbishment package begun in 1998 involving steelwork repairs, surface coating, access improvements and new flood lighting (see Figure 12).

Figure 12 – Maintenance, September, 2000, with Rennie's Pier

The challenging work was consuming the funding at a greater rate than the work was being done when the contractor left the site permanently in 2000. Preparatory work is now under way to enable a 7-year maintenance programme to start in 2002.

The coating system adopted for the steelwork requires blast cleaning to bare metal and an application of zinc based primer to prevent corrosion (35 microns); a glass flake epoxy intermediate coat providing a barrier (400 microns); and, a polyurethane gloss top coat to give an attractive finish (35 microns). This system which has been tried and tested in an offshore environment is designed to give a 20-year life before any major overcoating. Railtrack placed emphasis on quality control to ensure that any different microclimates created, which could lead to "amine blooming", porosity and other defects, were identified and controlled. In scaffolding a global loading of 1500 t. / cantilever was not exceeded. The total final cost of the refurbishment is estimated at £70m., a large sum relative to potential user benefit, but this bridge is more than just a vital artery in Railtrack's east coast railway system, it is "Arrol's Masterpiece" and a national symbol of Scotland.

References

(1) Westhofen, W. (1890) *The Forth Bridge. Reprinted from "Engineering," February 28, 1890.* Offices of *"Engineering"*, London.

(2) Paxton, R. (Ed.) (1990) *100 years of the Forth Bridge.* Thomas Telford, London.