THE WONDER

OF THE

FORTH BRIDGE

WORLD HERITAGE SITE

Produced by Jim Dorward CEng MICE

jimdorward@ntlworld.com

THIRD EDITION JULY 2024

THE WONDER OF THE FORTH BRIDGE

World Heritage Site

This pdf is the result of a project I embarked on after my retirement as a railway civil engineer.

My interest in the bridge started when I was a school boy passing through the bridge's bewildering array of girders during the highlight of the annual train journey, with my parents, to Edinburgh.

The bridge's designers had to deal with many issues and problems that had never been tackled before. As their ingenious solutions are not obvious when viewing the bridge, I have endeavoured to explain them, using images and simplified diagrams.

I hope you find the information both useful and enlightening. I would welcome any comments you may wish to make.

Jim Dorward

jimdorward@ntlworld.com

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APPENDICIES

PREFACE

The Forth Bridge is the result of pioneering design work carried out over 130 years ago by two civil engineers who had to make many crucial design decisions without the benefit of existing tried and tested solutions. Also, they were aware that the bridge would have, at the time, the longest cantilever spans in the world, in addition to being Scotland’s first steel bridge.

The Forth Bridge is one of the few bridges designated as a World Heritage Site. It attracts many visitors from around the world, visitors whose interests range from the iconic aesthetics of the bridge, to the ingenious engineering that enables it to carry heavy trains across the exceptionally long gaps between supports.

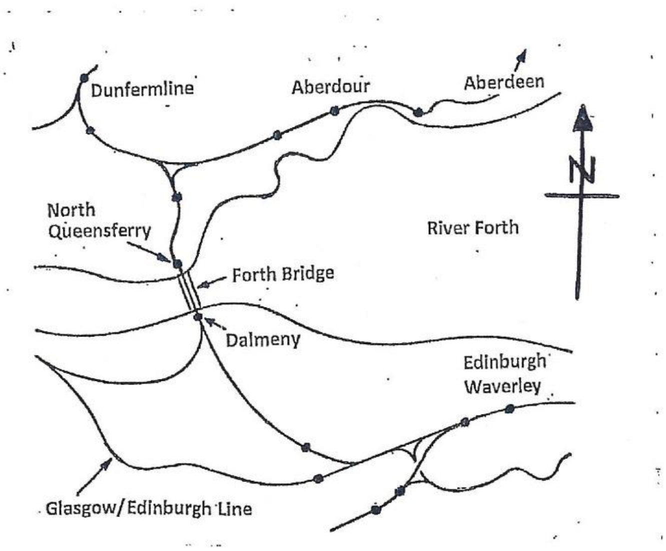
This pdf, apart from outlining the need for the bridge, explains the fundamental issues that had to be addressed by the designers, thereby encompassing an excellent area of study.

THIRD EDITION

(contains additional information)

JULY 2024

The Forth Bridge



Railways in the Forth Bridge area

The East Coast Main Line

1. INTRODUCTION

1.1 The railway company most associated with the need for a bridge across the River Forth was the North British Railway (NBR). After the Tay Bridge at Dundee was opened in 1878, the railway route between London King's Cross and Aberdeen still involved a break of journey north of Edinburgh, due to the absence of a bridge over the River Forth.

Figure 1.1 The gap across the River Forth

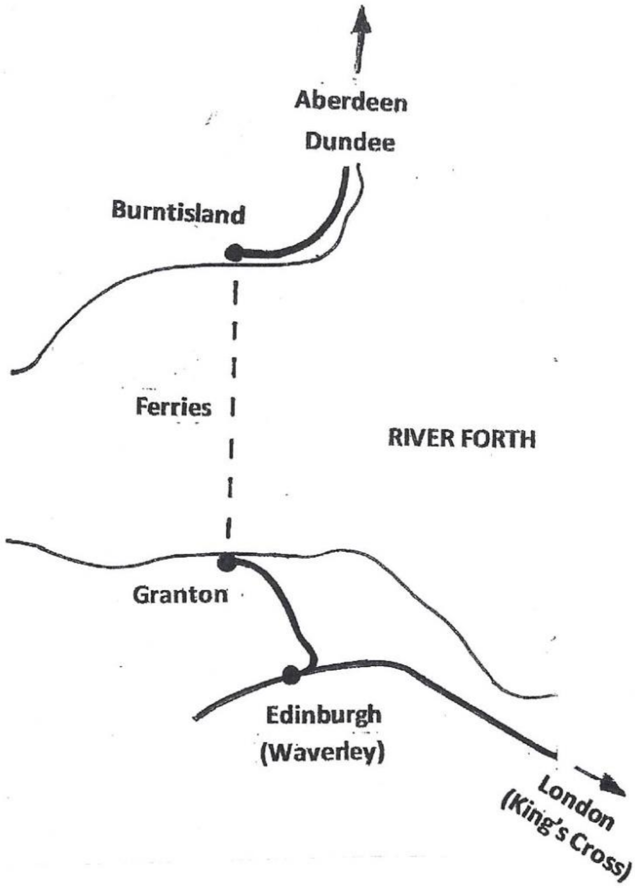


Figure 1.2 The Ferry services between Granton and Burntisland

1.2 Ferries criss-crossed the river. Goods wagons used a ***train ferry*** and the passengers used a separate walk-on walk-off service. The ferries operated between Granton in Edinburgh and Burntisland in Fife. However, the ferries were expensive to run and slow.

Several other railway companies that operated in that part of Scotland had amalgamated and decided to exclude the NBR from their routes forcing more NBR traffic on to the ferry services. The obvious solution for the NBR was a bridge over the River Forth, but it was one not easy to execute.

1.3 The NBR realised that building a bridge and the necessary links to existing lines, was going to be extremely expensive. Finding financial backers who could see the great commercial benefits to themselves, was essential.

1.4 The North Eastern Railway, the Great Northern Railway and the Midland Railway agreed to combine with the North British Railway in 1873 to form the Forth Bridge Railway Company. This financed and operated the bridge until the ***nationalisation*** of Britain's railways in 1948.

1.5 As the Forth Bridge was required to fill a gap in the East Coast Main Line, (London King's Cross – York – Newcastle – Edinburgh - Aberdeen), the Forth Bridge Railway Company's Specification for the railway track on the bridge, would have included:-

1.6

i) Standard Gauge ***Double Track*** to be provided (unlike the first Tay Bridge which only had one line; a ***'Single Line'***).

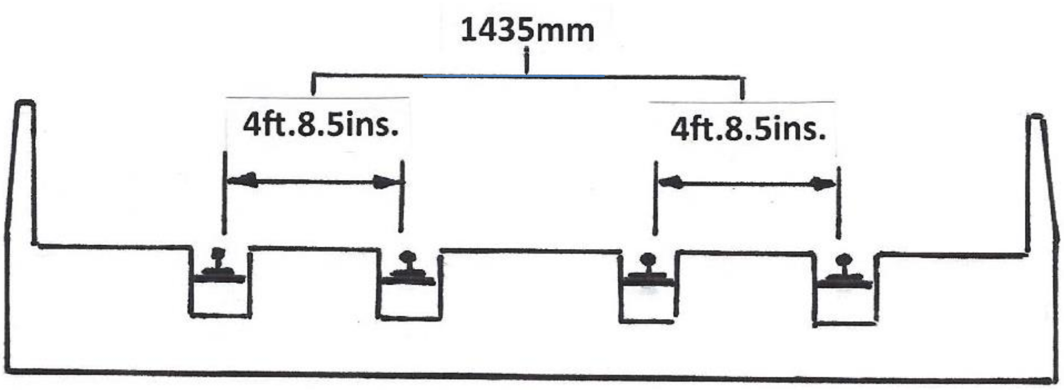


Figure 1.3 The two ***Standard Gauge tracks***

ii) Main Line ***Structure and Load Gauges*** to be complied with.

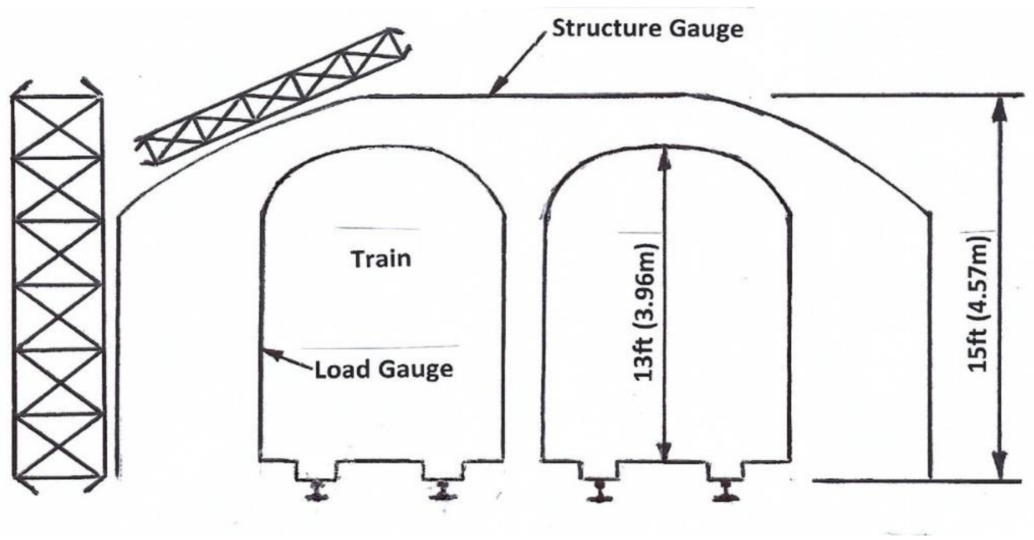


Figure 1.3A The Structure and Load Gauges likely to exist when the Forth Bridge was being designed. (The Ministry of Transport's 1950 Requirements have been used to produce Figures 1.3 and 1.3A given that there was little scope for changing gauges and profiles after railways were built).

iii) Main Line steam engines, coaches and wagons to be permitted. (The weight of the heaviest train would have been stated, along with the axle loads of the heaviest steam engine expected to haul the heaviest train. If ***double heading*** were to be permitted, the axle loads of both engines would have been quoted).

iv) Main Line ***train signalling*** system to be provided with signal boxes at Dalmeny and North Queensferry, to permit two trains, one on each line, to be on the bridge, at the same time, with each train at any location on the bridge.

v) The maximum speed of trains on the bridge to be that allowed by a cost affordable bridge design.

vi) All weather train operation to be possible.

vii) Access for railway maintenance work to be provided.

viii) Track level to be at a height above High Water Level that gives at least 150 ft (45.72m) headroom below the supporting girders, for ships using the River Forth's ***Navigation Channel***.

1.7 The requirement in the specification for two trains, one on each line, to be anywhere on the bridge at any given time, was to become a major design issue in relation to the Cantilever Section.

As the bridge was designed in the days of the Imperial system of units, it is such units that are quoted. However, the metric equivalent is shown in brackets.

1.8 It had been established that the least difficult site for a bridge was at Queensferry. However, it was also clear that unprecedented design challenges would be encountered.

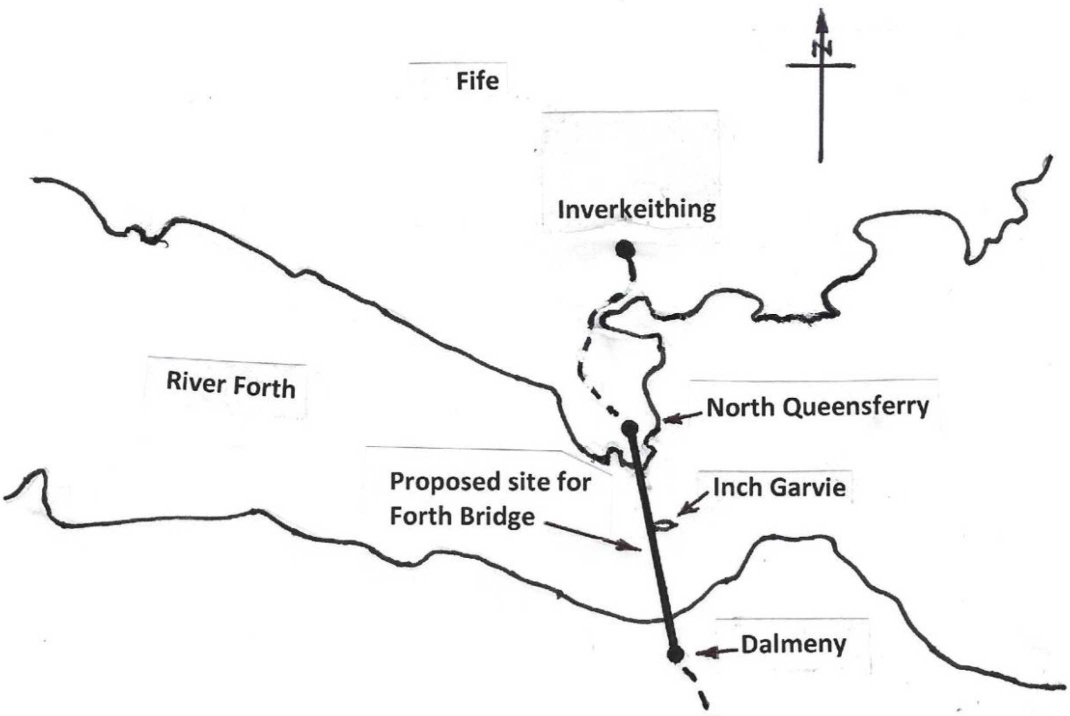


Figure 1.3B The site chosen for the Bridge

1.9 Sir Thomas Bouch, the English designer of the first Tay Bridge was commissioned to suggest and design a bridge that could cross the River Forth. He suggested a ***suspension bridge***.

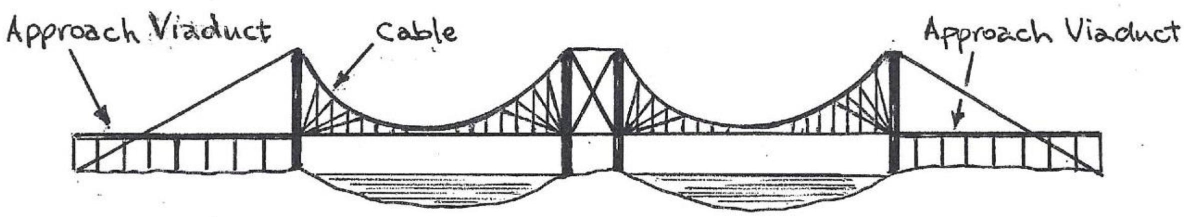


Figure 1.4 Sir Thomas Bouch's suspension bridge proposal

1.10 However, the ***Board of Trade*** considered suspension bridges to be much too flexible for heavy trains. Tragic events then intervened when the Tay Bridge Disaster occurred. Sir Thomas Bouch's bridge collapsed during a ferocious storm. A passenger train fell into the river, claiming the lives of 79 people. As the collapse was caused by several fundamental failures, including a flawed design, Sir Thomas was discharged as engineer for the Forth Bridge.

1.10 Sir John Fowler and Benjamin Baker, two English civil engineers, were then appointed as the new designers. They were confronted with major design challenges.

KEY TERMS

Train ferry - a ship with railway tracks on it's deck and access ramp.

Nationalisation – the 'Big Four' railway companies formed in 1923, the London and North Eastern Railway (LNER), London, Midland and Scottish Railway (LMS), Great Western Railway (GWR) and Southern Railway (SR), were brought under state control in 1948 to form British Railways (BR). In 1923, the Forth Bridge Railway Company was **NOT** incorporated in to the LNER.

Double track - a railway with two tracks, one for each direction of travel.

Single line - a railway with only one line, which is used by trains travelling in either direction.

Standard Gauge tracks - when railways were being built in the UK, the distance between the rails was set at 4 ft. 8.5 ins (1435 mm). This distance was then adopted by many other countries when building their railways, hence the term Standard Gauge.

Structure and Load Gauges – the Structure Gauge is the profile around a track that all structures, such as bridges and tunnels, must not be built within. Conversely, the Load Gauge is the profile around a track that all vehicle bodies and loads must not protrude out of. (The horizontal width of these gauges needs to be increased on curved track to compensate for the end and centre throw of coaches and wagons. However, the Forth Bridge has no curved track).

Double Heading – two engines needed to haul the train.

Train Signalling – the safety system which keeps trains a safe distance apart.

Navigation channel - the portion of a river used by shipping.

Suspension bridge - a bridge whose deck is suspended from overhead cables anchored at each end of the bridge.

Board of Trade - a government department of the time whose responsibilities included railway safety.

2. FINDING A SOLUTION

2.1 The design challenge was so great that there was not a 'ready-made' solution. The River Tay at Dundee is relatively shallow, which enabled both the first and present day Tay Bridges to have over 80 short ***spans*** between ***piers***, commonly the case with other long bridges.

Figure 2.0 The present day Tay Bridge looking south from Dundee.

2.2 However, in comparison, the depth of the River Forth at Queensferry is as much as 200 ft. (61 m) in places, thereby preventing the use of a ***multi-span*** bridge with many supporting piers founded on the river bed. Although there was the very small Inch Garvie island which could provide the location for one support, it was clear that the bridge would need to have exceptionally long spans, so long in fact that this was to become the most challenging aspect of the project, and the one that, 125 years after the opening of the bridge, would justify it being designated a ***World Heritage Site***.

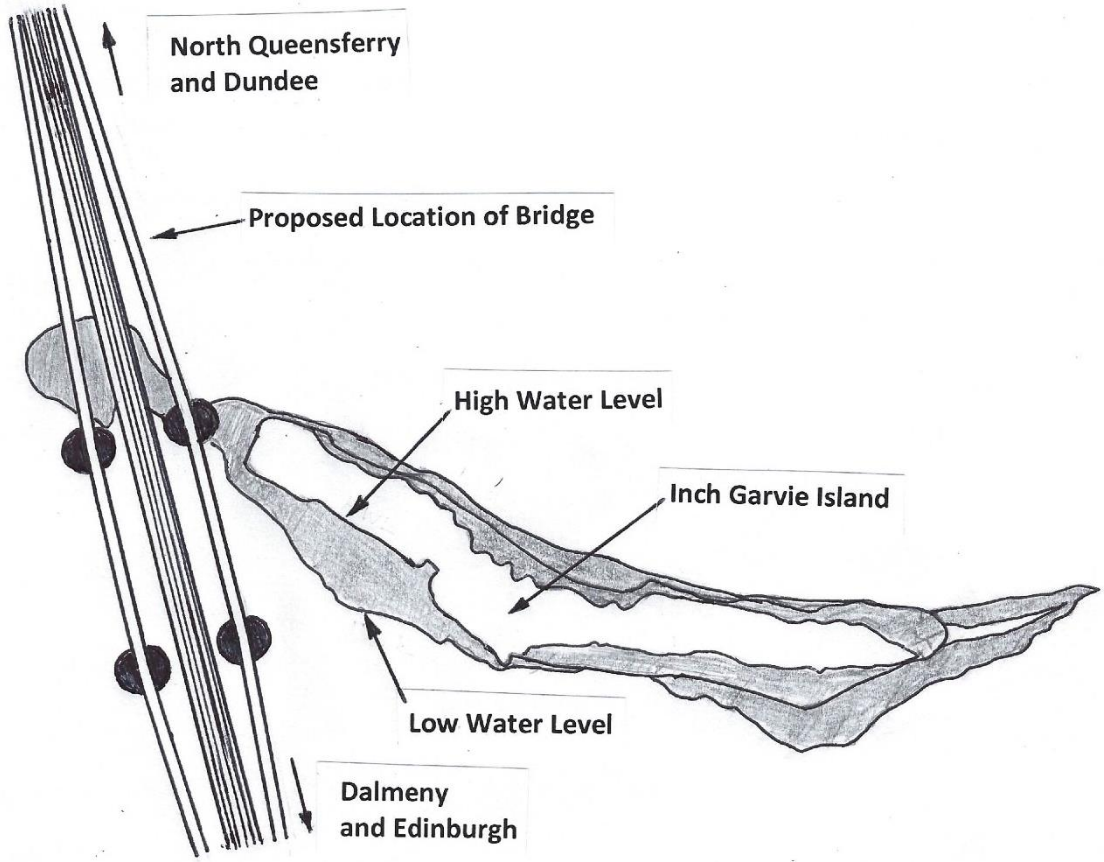


Figure 2.1 It was clear that the shallow water at the tiny Inch Garvie Island should be the location for one of the three giant towers, in fact the centre tower.

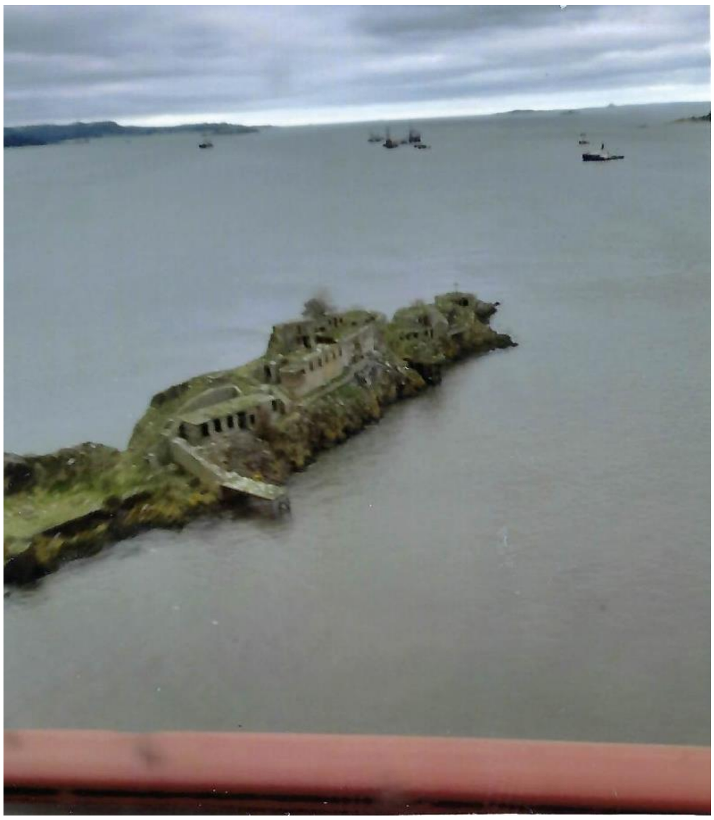


Figure 2.1A Inch Garvie Island as seen from an Edinburgh bound train.

2.3 Sir John Fowler and Benjamin Baker most likely rationalised the design challenges as follows:-

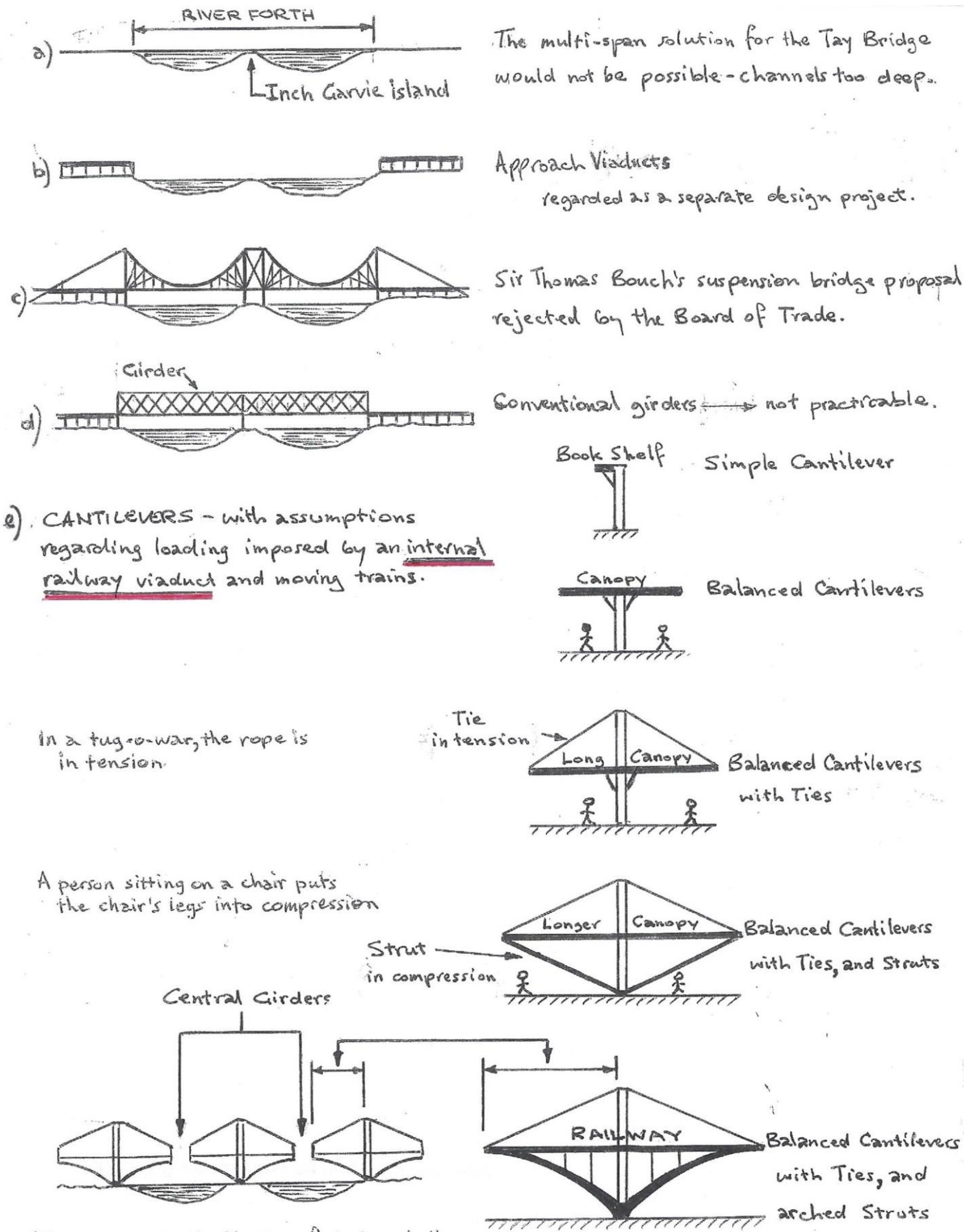


Figure 2.2 Rationalisation of design challenges

KEY TERMS

Spans - the level decks on which railway track is placed
Piers - vertical structures that support spans.
Multi – span - a bridge composed of several spans
World Heritage Site - a site of exceptional interest, as designated by UNESCO (United Nations Educational, Scientific and Cultural Organisation).
Internal railway viaduct - a viaduct within, and supported by, the Cantilevers, which carries the two railway tracks.

Figure 2.3 This photograph, taken from a train on the Fife approach viaduct, illustrates how high the bridge is above North Queensferry.

3. BALANCED CANTILEVERS SELECTED AS SOLUTION

Having established a solution in principle, detailed design proceeded.

3.1 The designers therefore decided that the only method for crossing such very long distances required the use of 3 sets of BALANCED CANTILEVERS with two CENTRAL GIRDERS.

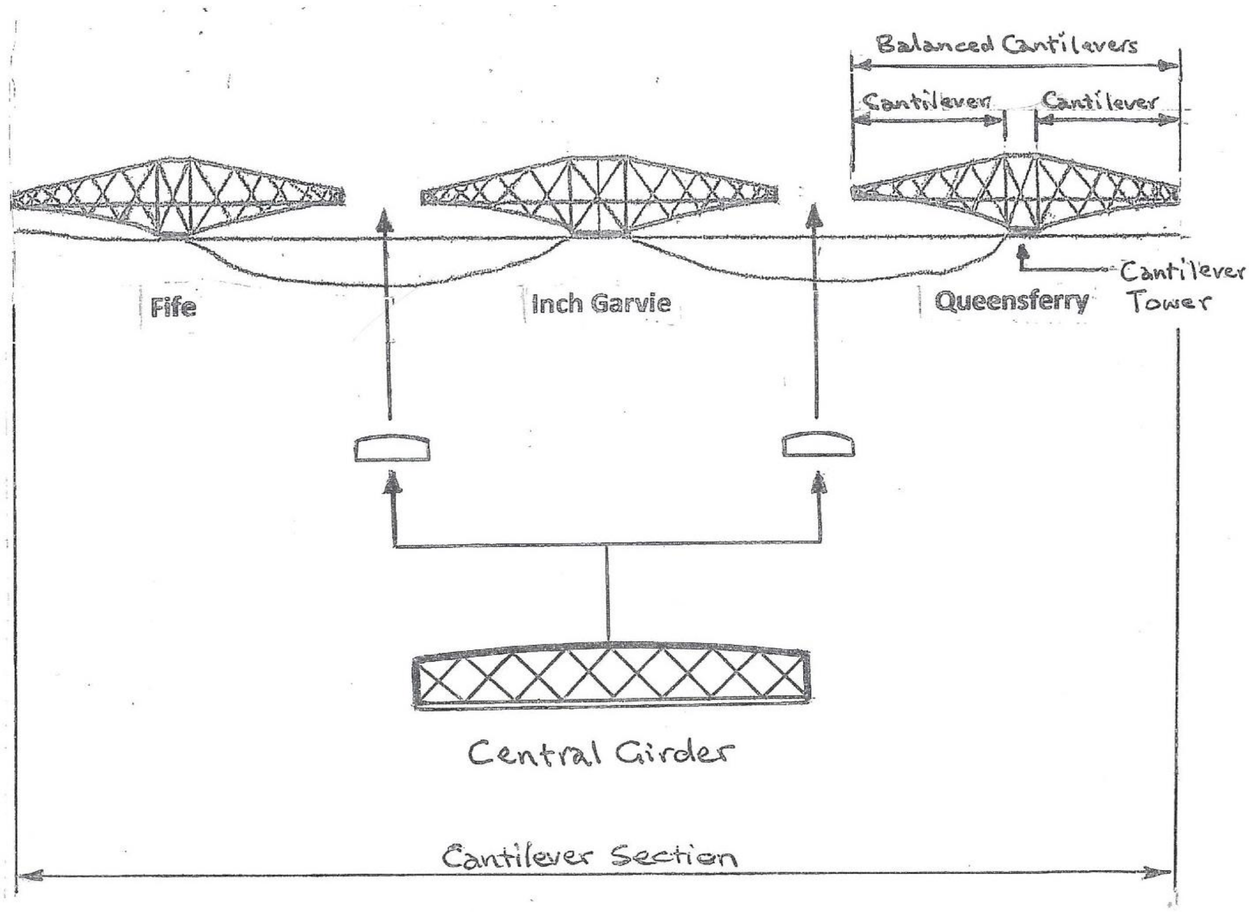


Figure 3.1 Three sets of Cantilevers and two Central Girders

3.2 The Central Girders between Cantilevers, enabled the amount of steel required to span the large distances involved, to be kept to the minimum. The Girders would almost be regarded as though they were for a bridge spanning a river that only needed girders of that length. At the Forth Bridge they would be supported at each end, by being connected to the adjacent Cantilevers.

3.3 The ratio, length of the Cantilever arm 681.75 ft. (208m) over length of Central Girder 346.5 ft (106m) is 1.96. Some engineers now believe that this ratio could have been lower, making the Central Girders longer. However, the length chosen enabled the Girders to be assembled by building out from the adjacent Cantilevers. This might not have been possible with longer and therefore heavier girders.

4. BALANCE ISSUE CAUSED BY THE CENTRAL GIRDERS

The use of Central Girders introduced issues that affected the balance of the Cantilevers.

4.1 The use of Central Girders required measures to overcome the ***eccentric loading*** they cause. The Queensferry and Fife Cantilevers each have to support the weight of half a Central Girder, loaded with two moving trains (one on each line).

The problem was solved by the provision of a 1,000 ton (1,016 tonnes) ***Counterpoise*** at the ***free end*** of these cantilevers.

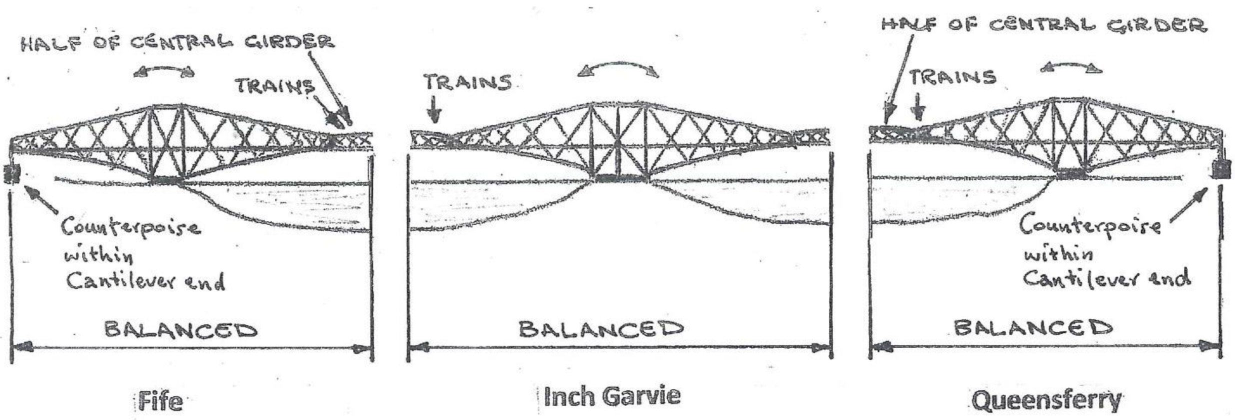


Figure 4.1 The distribution of the weight of the Central Girders and trains in three separate situations.

4.2 Although the loading caused by moving trains is highly variable, depending on their location on a Cantilever, the Cantilevers are stable at all times and therefore regarded as balanced. The cyclists below are also regarded as balanced despite one having tilted the cycle to counteract the weight of the bag on the handlebar.

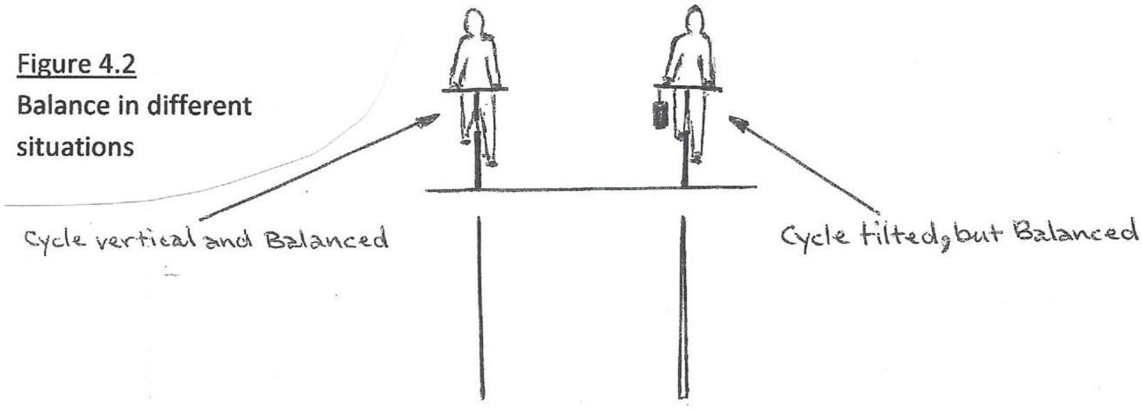


Figure 4.2
Balance in different situations

Figure 4.2A

Note:- The counterpoise box contains 1,000 tons (1,016 tonnes)of cast-iron bricks and scrap steel, made very secure by having had hot asphalt poured into the box after it was filled.

4.3 The three sets of Cantilevers would only be supported at three locations.

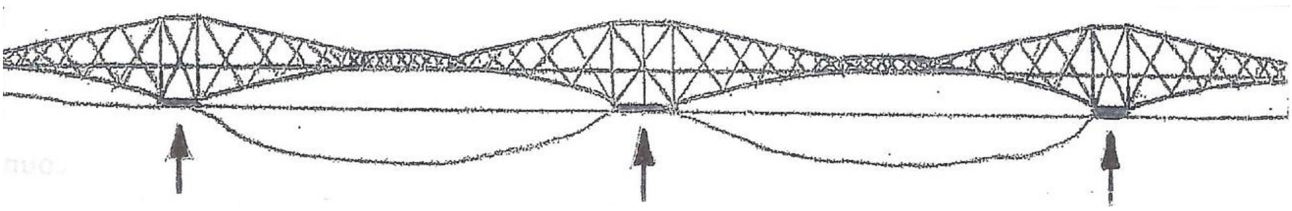


Figure 4.3 The masonry tower at each end of the Cantilever Section of the bridge would NOT take any load from the adjacent Cantilever.

4.4 If the bridge design had not involved Central Girders, the Counterpoises would not have been necessary. The three sets of Cantilevers could then have been of identical design, as below. However, the design would not have been so economical regarding the amount of steel required. For instance, the three towers would probably have had to be taller.

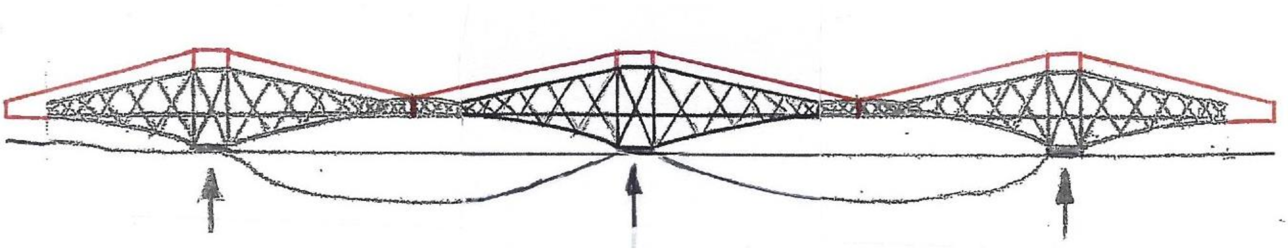


Figure 4.4

KEY TERMS

Eccentric loading - loads that cause imbalance.
Counterpoise – a weight specially provided at a specific location on a structure to counteract a weight at another part, or parts, of the structure, in order to maintain stability/balance.
Free ends - girder ends that are not supported.

5. CONVINCING DECISION MAKERS OF THE SOLUTION

The solution was so original that the Forth Bridge Railway Company had to be sure that they were funding a workable project. This was essential as confidence in the design of very long bridges had been considerably reduced by the collapse of the Tay Bridge a few years earlier in 1879.

5.1 To convince important opinion formers in 1887 of the practicality of their Cantilever design, the two designers, Sir John Fowler and Benjamin Baker, produced a photograph of themselves sitting on chairs, representing the towers, and supporting a person suspended between them, all as a result of the use of their arms (ties), wooden sticks (struts) and bricks (counterpoises or counter-balances). The following diagram is based on the photograph.

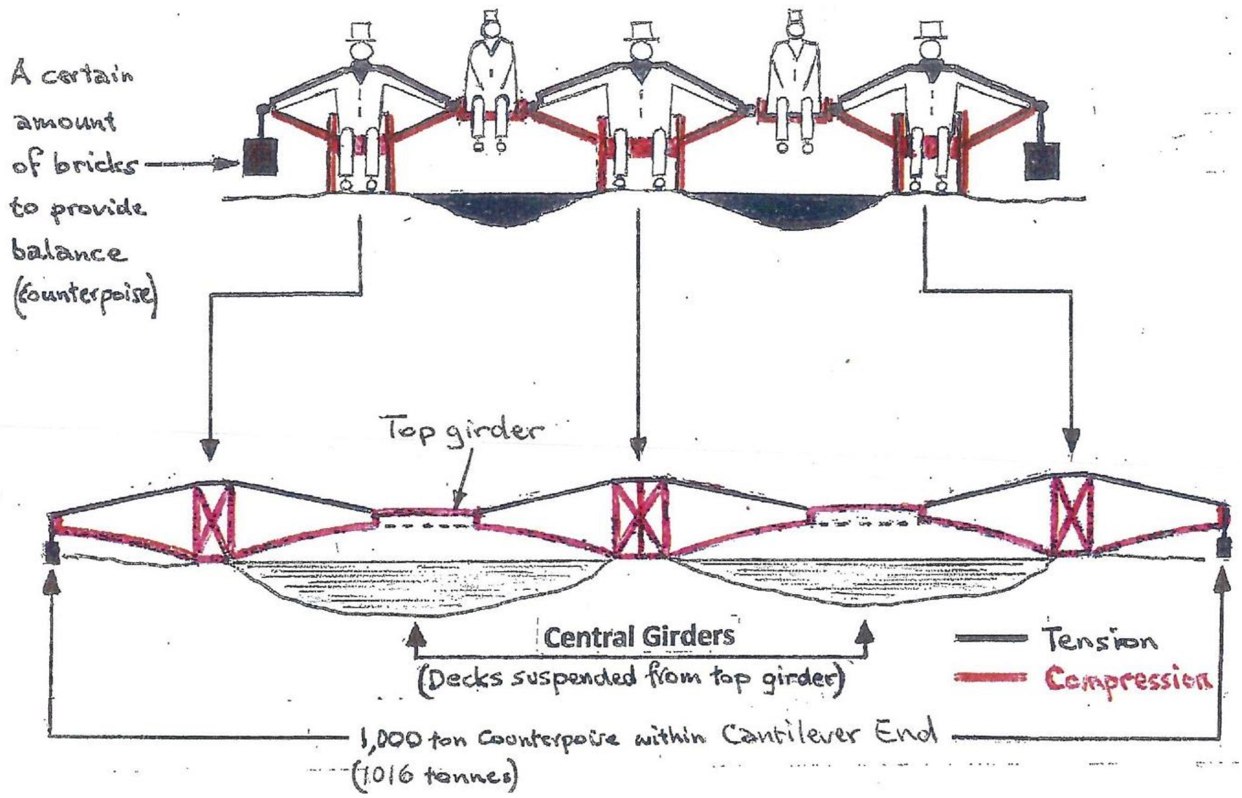
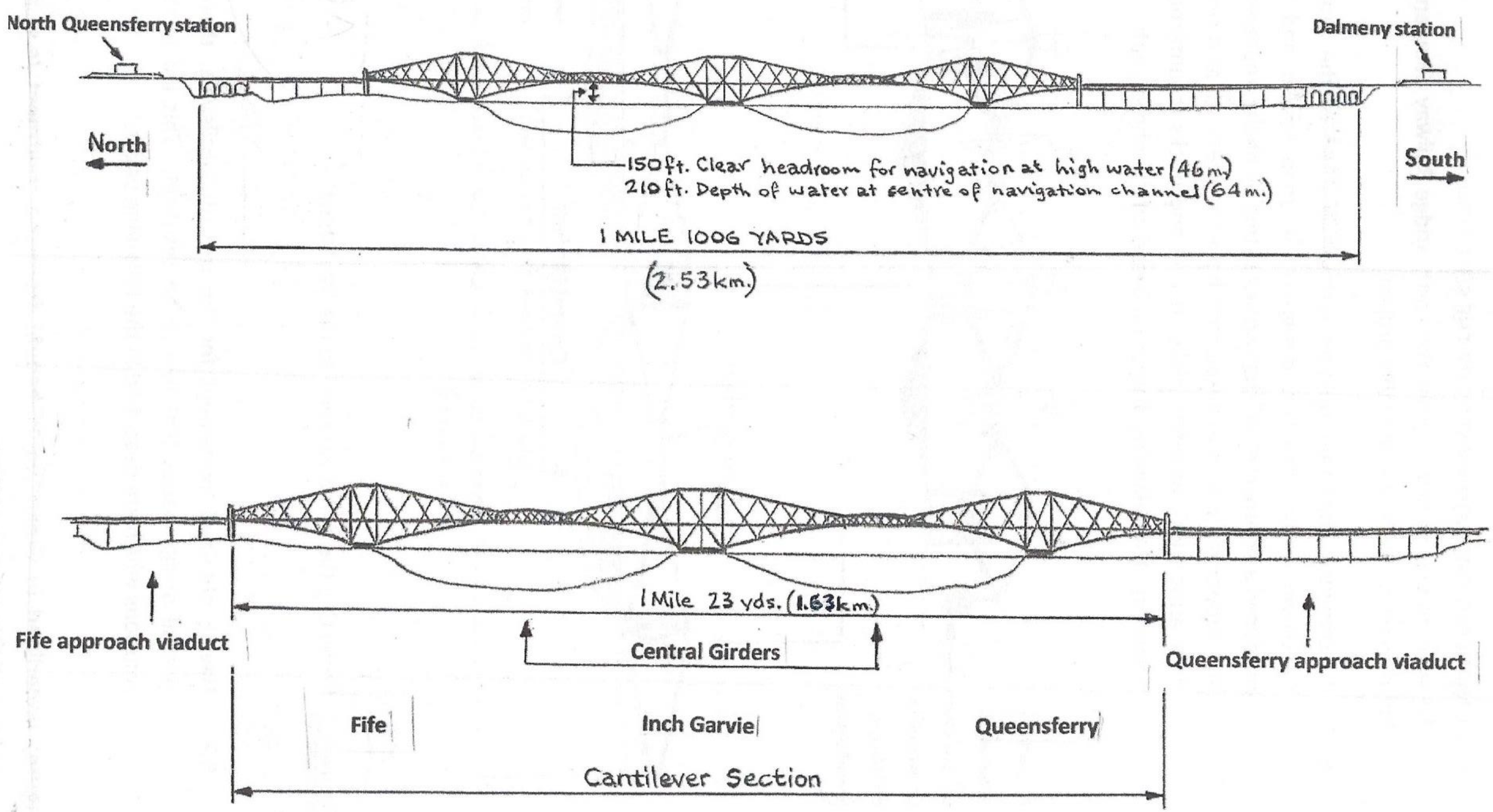


Figure 5.1 Projecting the demonstration to the 'real thing'

5.2 Having obtained agreement for the use of Cantilevers, there then followed several design issues that had to be resolved. This led to Sir John Fowler and Benjamin Baker taking major bridge design far beyond what was generally understood by civil engineers in the 1880s. The spans had to be exceptionally long and steel was to be used for the first time for a major UK bridge.

Figure 5.2. The final design of the entire bridge is shown here to aid the understanding of the various design challenges .



6. THE FORTH BRIDGE IS FOUR BRIDGES

6.1

- The Queensferry approach viaduct
- The Cantilevers including two Central Girders
- The Fife approach viaduct
- The internal railway viaduct, supported by the Cantilevers

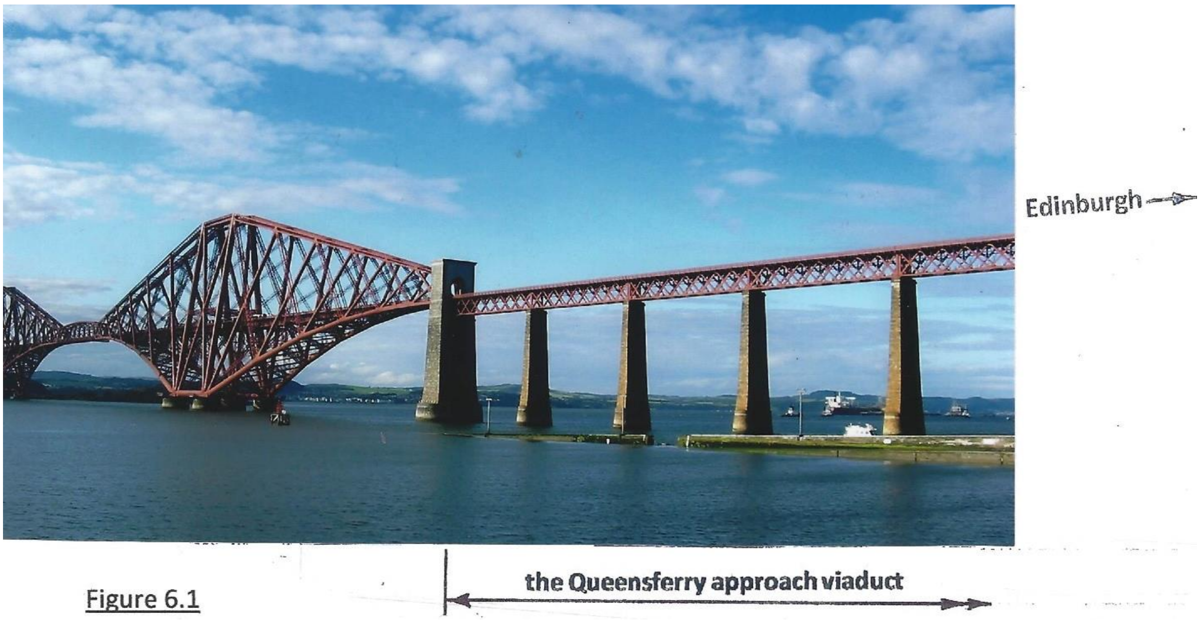


Figure 6.1

Figure 6.2 the Cantilevers including two Central Girders (the Cantilever Section)
(It is the Cantilever Section that makes the Forth Bridge such an unusual and interesting structure).

Figure 6.3 Fife approach viaduct

Figure 6.4 the internal railway viaduct highlighted in white (A ‘Bridge within a Bridge’).

Figure 6.5 The internal railway viaduct has two tracks and walkways for maintenance staff. The paint used on the Forth Bridge has always been red in colour.

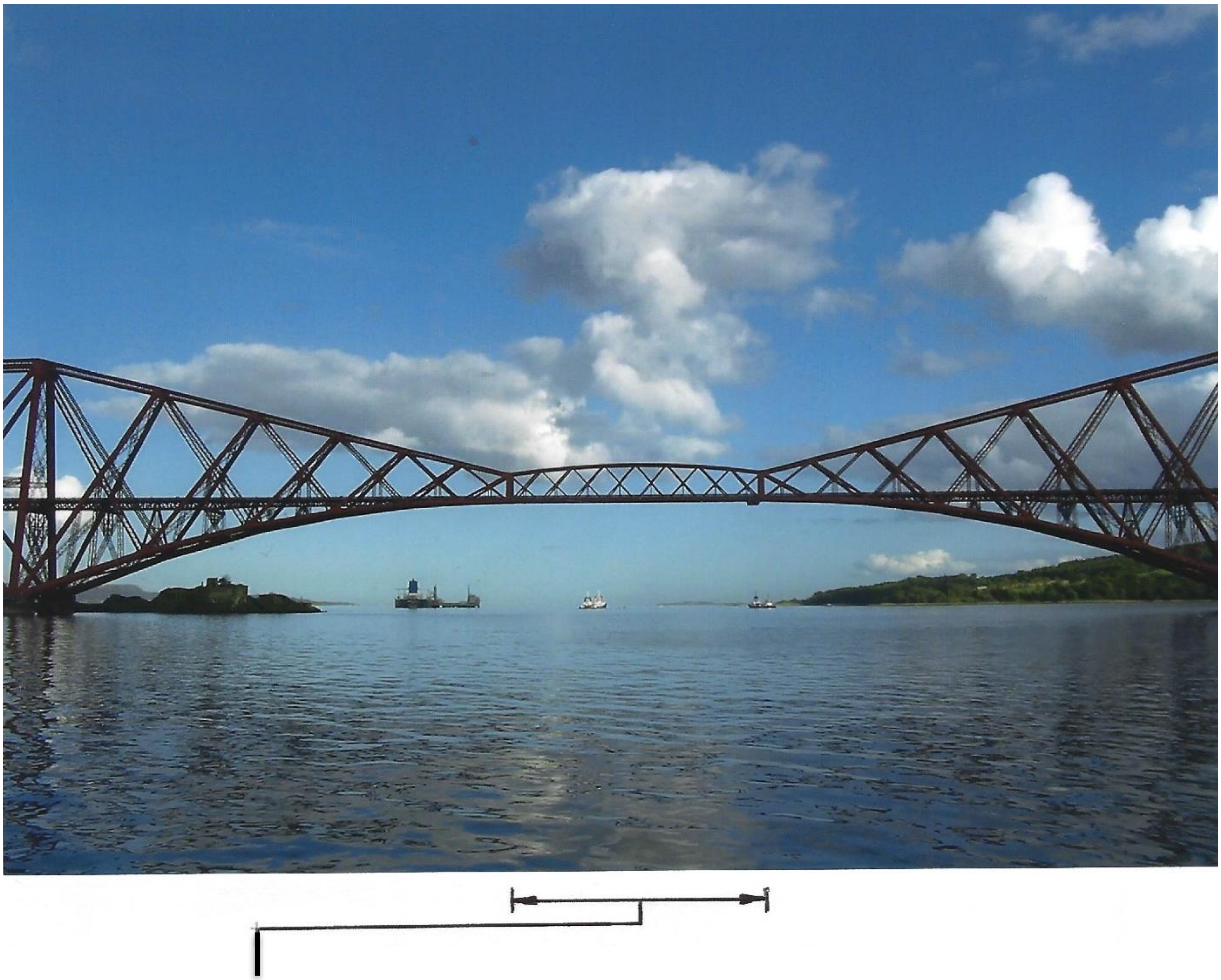


Figure 6.6 A Central Girder weighs 822 tons without any trains (835 tonnes)
Length = 346’6” (106 m)
Note:- The average length of a football pitch is 345 ft. (105m)

6.2 One of the Central Girders provides the 150 ft. (45.72 m) headroom navigation channel mentioned in paragraph 1.6.

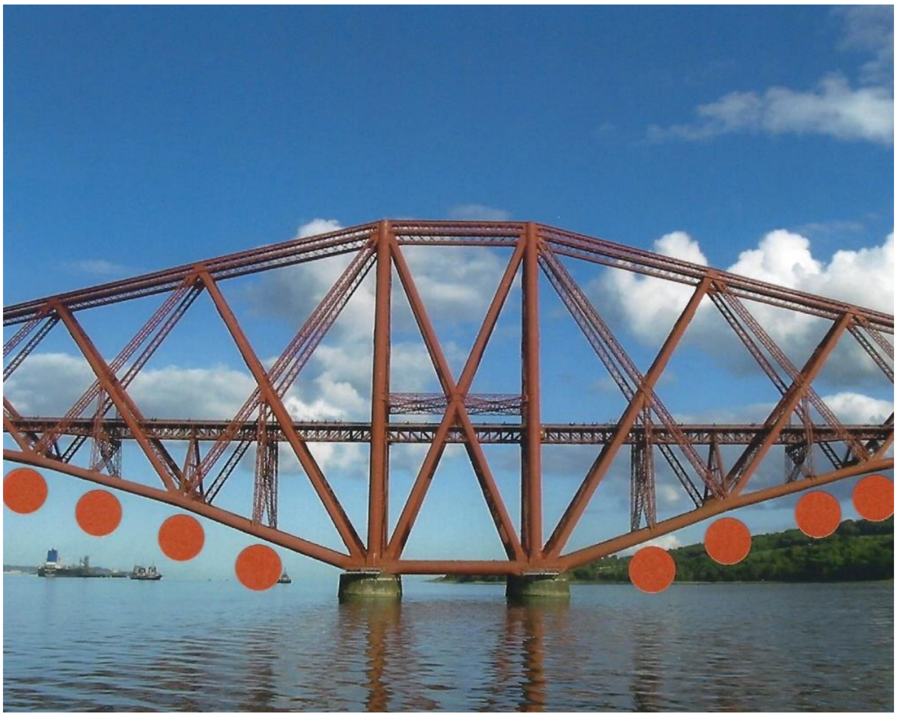


Figure 6.7 The Internal Railway Viaduct is supported by trestles resting on the bottom booms (struts) at the locations shown by a circle.

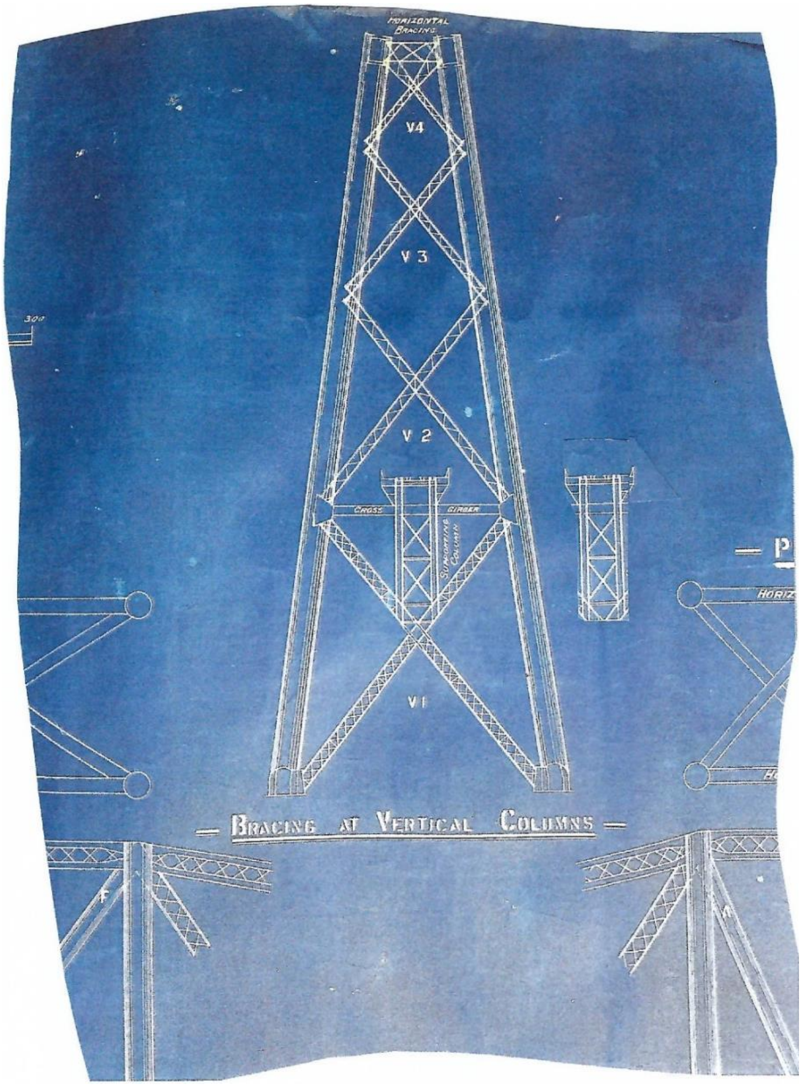


Figure 6.8 This cross-section, from one of the hundreds of original drawings, highlights the massive height of the three towers in comparison with the size of the Internal Railway Viaduct.

7. THE CANTILEVER SECTION IS A CONTINUOUS STRUCTURE
   not connected to the Approach Viaducts

7.1 The three Balanced Cantilevers, the Central Girders and the two Counterpoises form one 'stand-alone' 'continuous structure', continuous meaning that every part is essential all the time, irrespective of the bridge loading conditions at any given time; otherwise, the entire structure has the potential to fail (i.e. become permanently damaged).

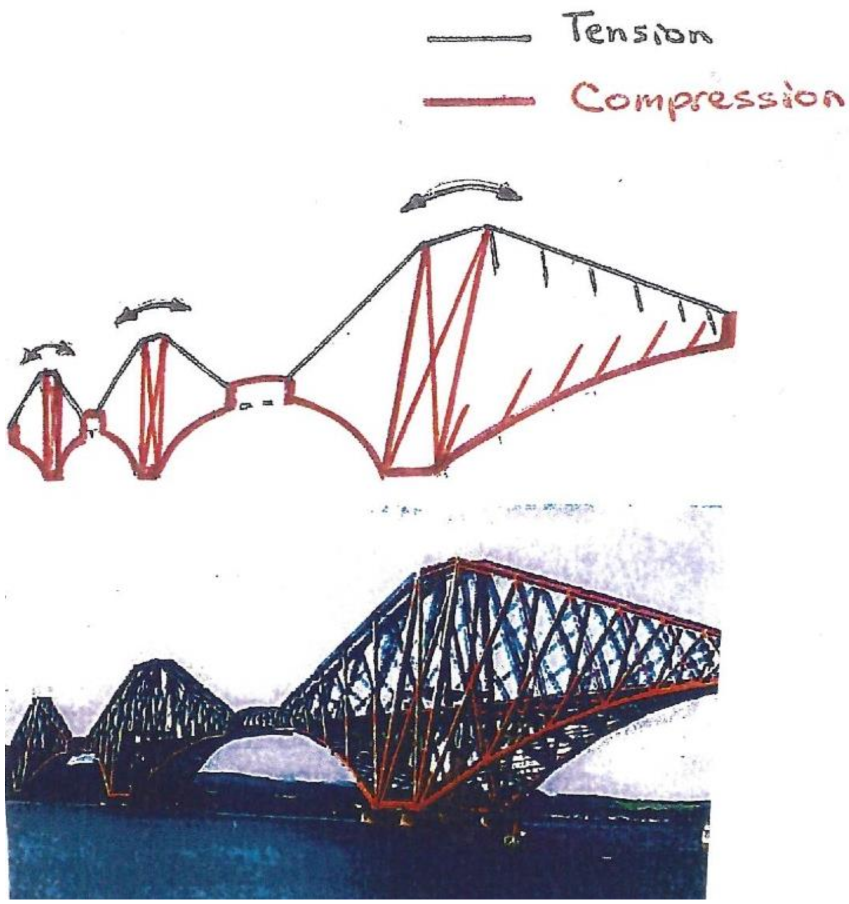


Figure 7.1 illustrates the continuous nature of the Cantilever Section

7.2 Balance is such a vital aspect of Balanced Cantilevers that the designers had to be sure it would be addressed when the Cantilevers were being constructed. Therefore, the work had to be closely controlled and staged to ensure balance at all times. (The three sets of Cantilevers, Queensferry, Inch Garvie and Fife were built concurrently, as shown in Figure 7.2).

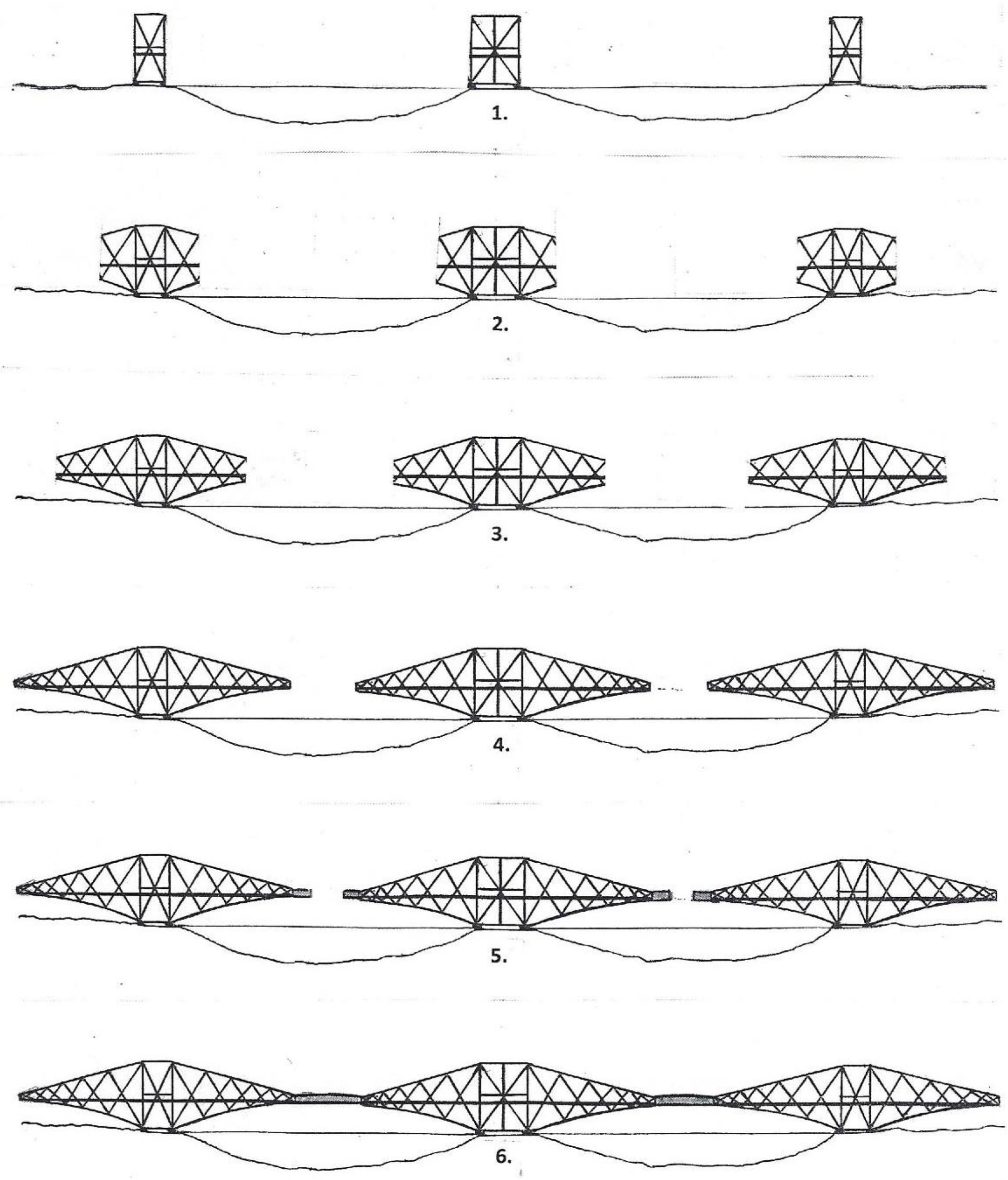


Figure 7.2

8. THE EXTRAORDINARY LENGTH OF THE CANTILEVER SECTION

It is remarkable that such a long length of bridge has only three supports.

8.1 The following scale diagrams compare the length of the Cantilever Section with the length of Edinburgh's famous Princes Street.

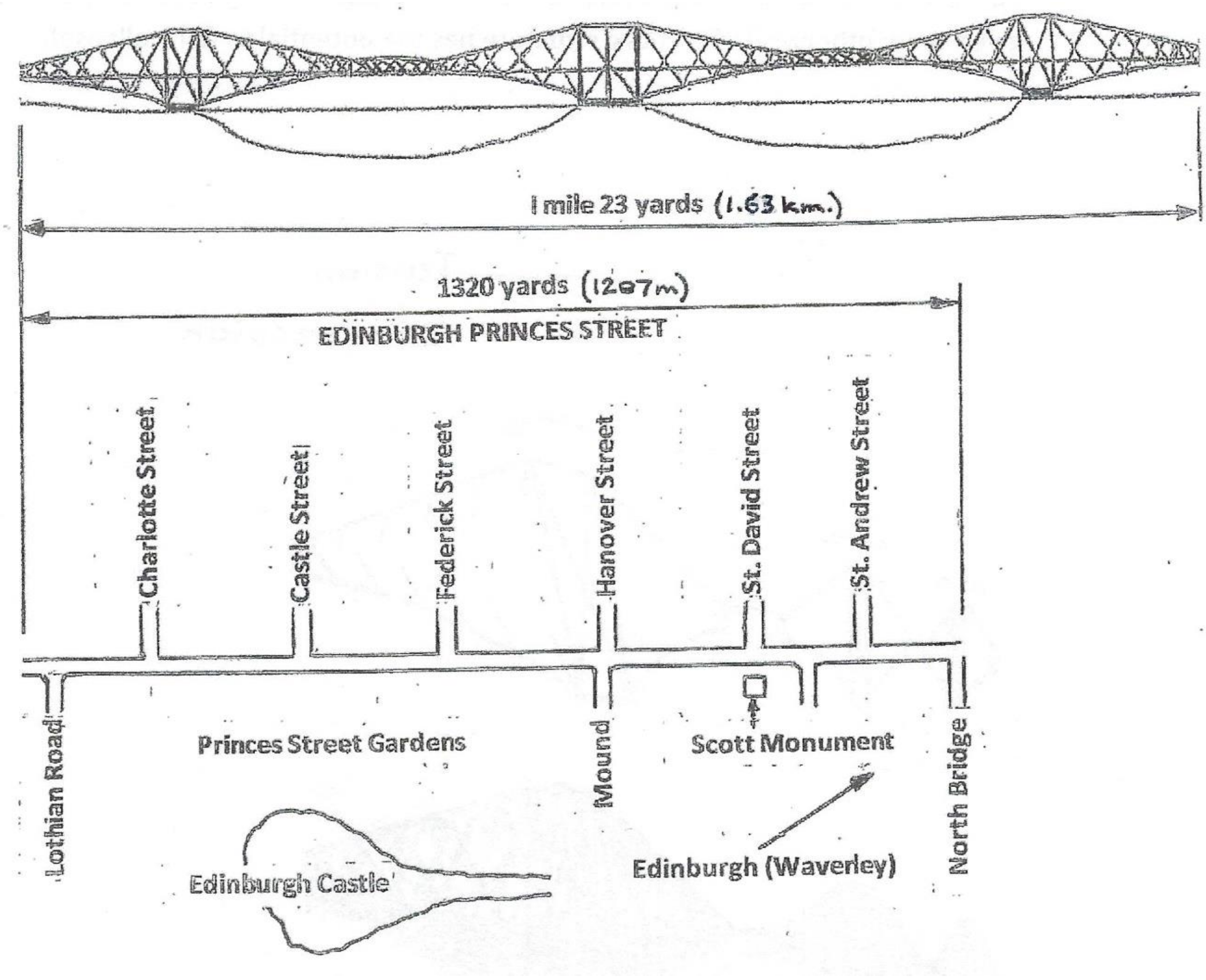


Figure 8.1

9. THE JUNCTIONS BETWEEN THE CANTILEVER SECTION AND THE APPROACH VIADUCTS

The arrangements for keeping unsupported Cantilever Ends in line and level with the Approach Viaducts.

9.1 Although the south end of the Queensferry Cantilevers and the north end of the Fife Cantilevers APPEAR to be supported by the very substantial ***masonry towers***, they are in fact not supported. As Cantilevers, they are supported by their own steel towers. The 1,000 ton (1,016 tonnes) Counterpoises are, of course, attached to the free end of the Queensferry and Fife Cantilevers.

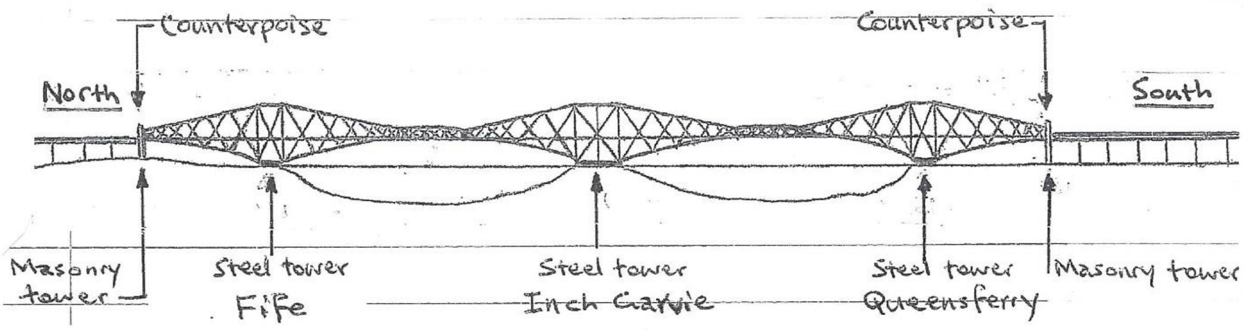


Figure 9.1

9.2 The opposite situation applies to the north end of the Queensferry Approach Viaduct (and the south end of the Fife Approach Viaduct) as it's girders rest on the tower and therefore ARE supported.

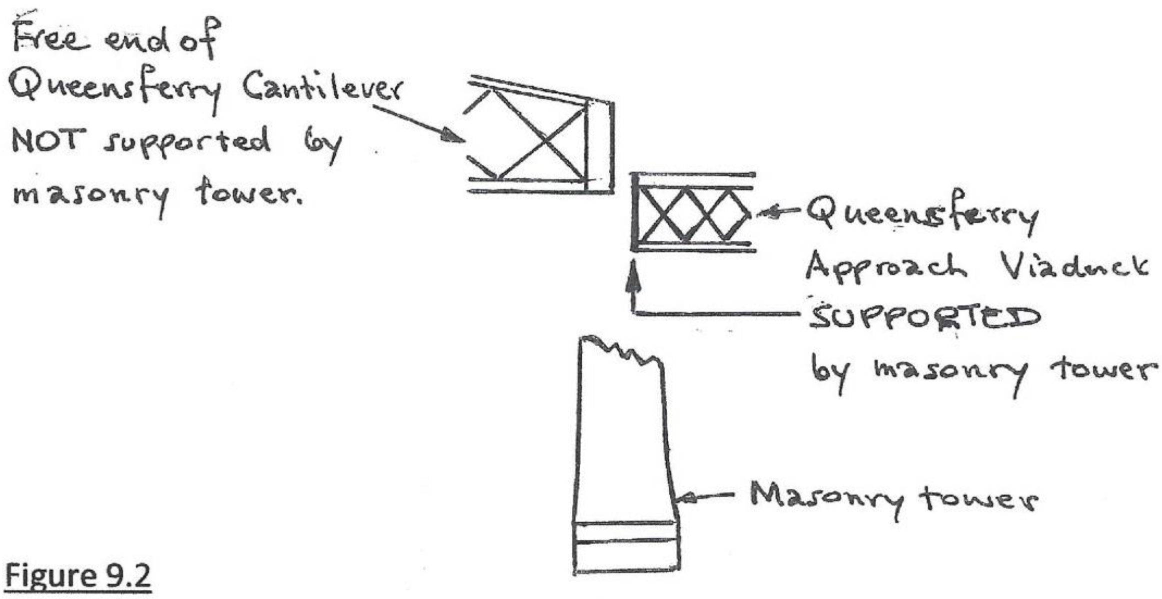


Figure 9.2

9.3 These different situations required the devising of arrangements that ensured that the free ends of the Cantilevers always remained in ***line and level*** with the restrained ends of the Approach Viaducts.

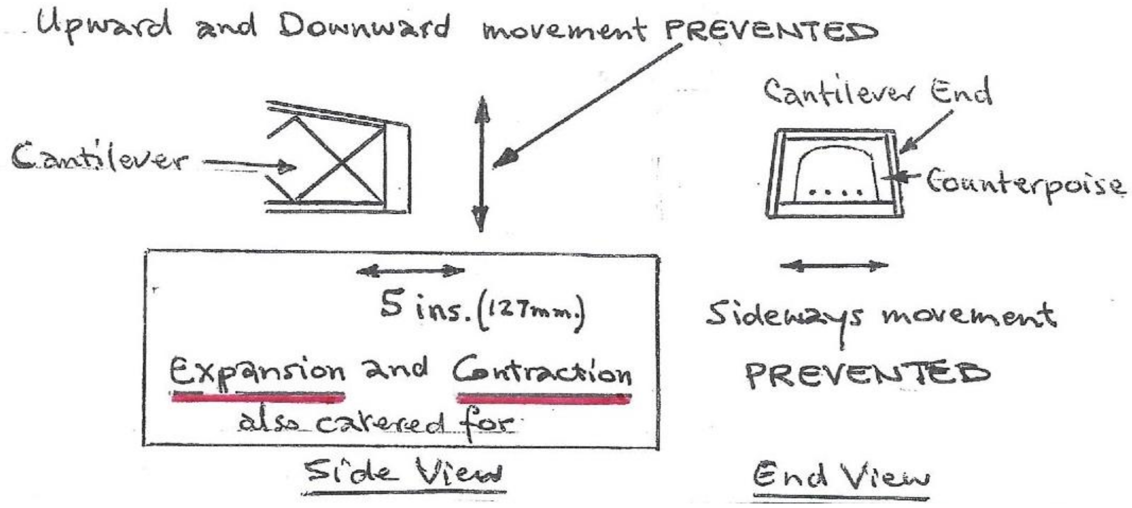


Figure 9.3 Illustrates the issues that had to be addressed regarding line and level

9.4 The passage of a train or trains along the Cantilever Section provides the potential for upward and downward movement at the free end of the Cantilevers, whereas wind provides the potential for sideways movement.

Concealed within the masonry tower at each end of the Cantilever Section is the 1,000 ton (1,016 tonnes) Counterpoise.

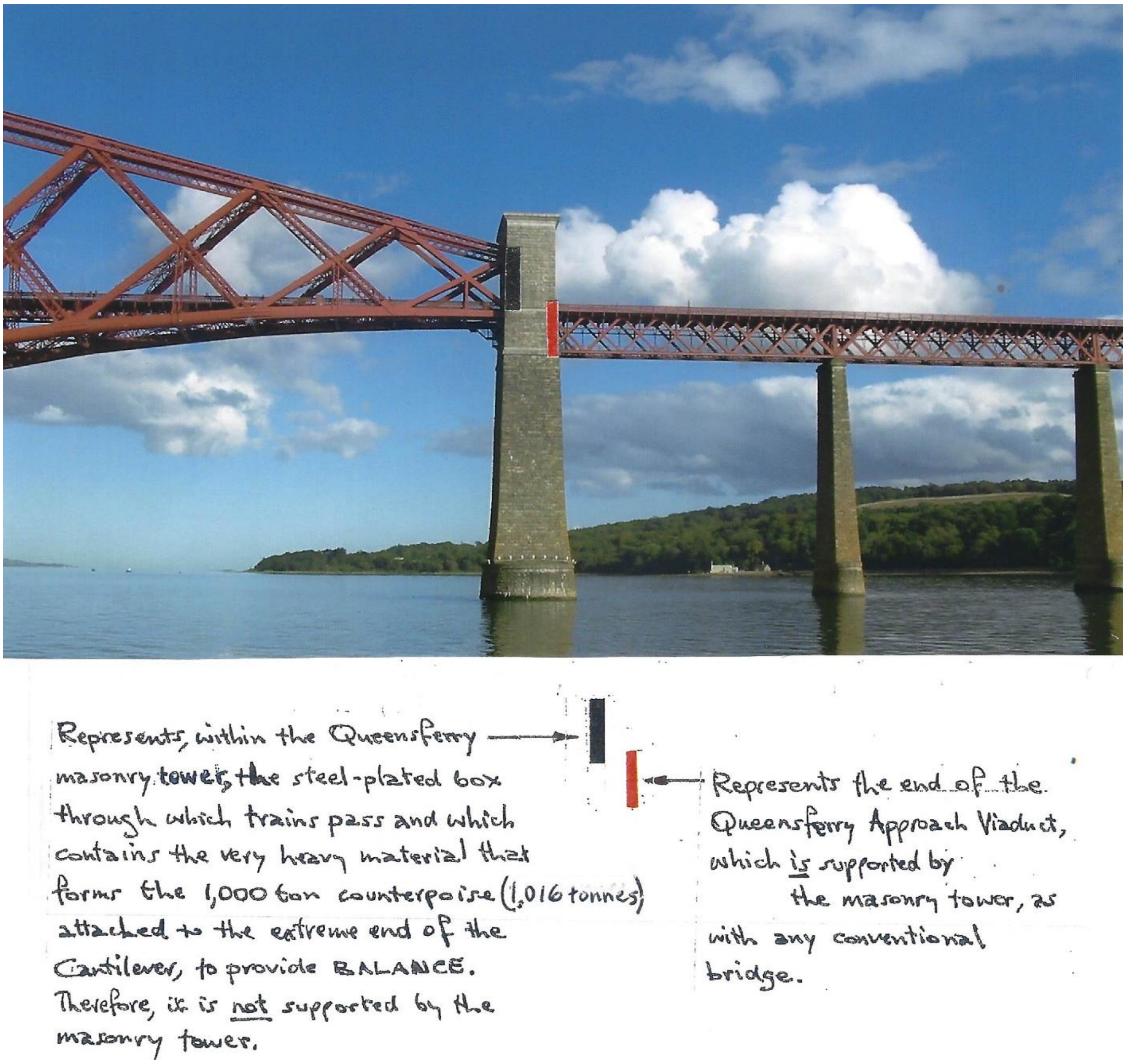


Figure 9.4 Shows the masonry tower that would 'appear' to support the extreme end of the Queensferry Cantilever, but does NOT.

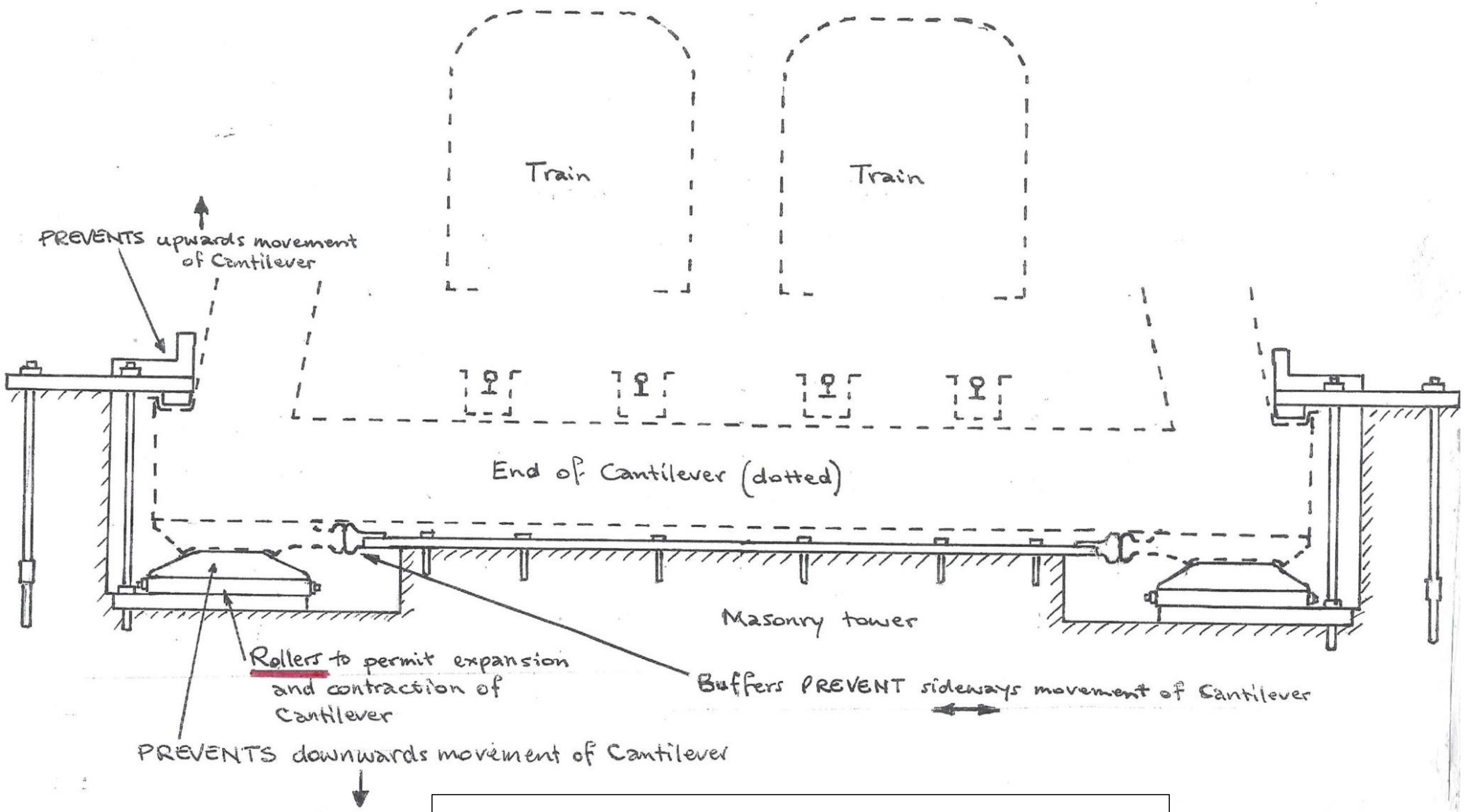


Figure 9.5 End view of free end of Queensferry and Fife Cantilevers

KEY TERMS

Masonry towers - vertical structures composed of very hard stone, such as granite, to support bridge spans.

Free end - the end of a girder that is unsupported.

Line and level - the relationship between two structures in terms of their horizontal and vertical positioning.

Expansion - the natural lengthening of a material such as steel as a result of an increase in temperature.

Contraction - the natural shortening of a material such as steel as a result of a decrease in temperature.

Rollers - a group of wheels or balls which enable a girder end to move as a result of expansion or contraction.

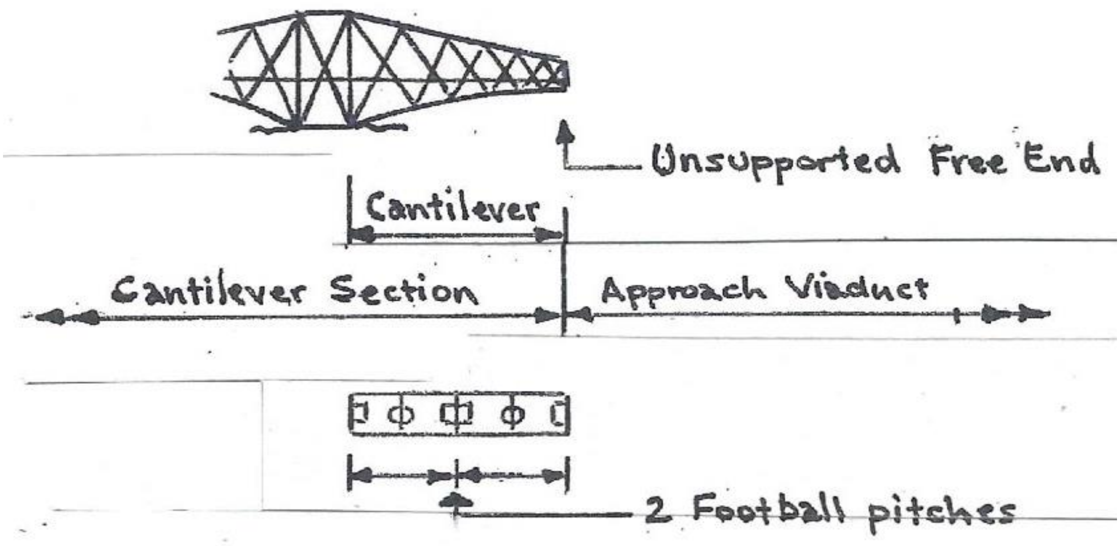


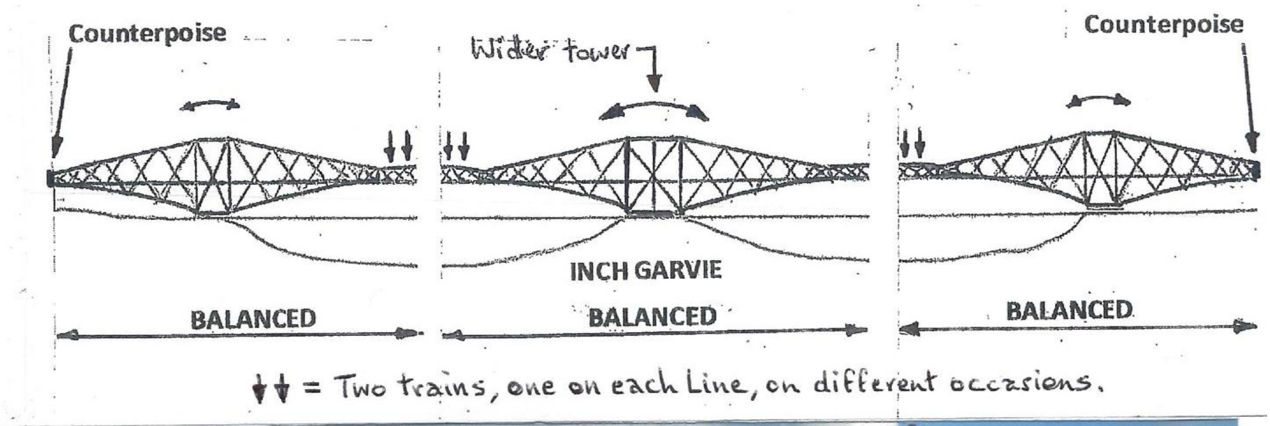
Figure 9.6 Unsupported Free End of Queensferry Cantilever in comparison with two Football Pitches

10 INCH GARVIE STABILITY

The Inch Garvie Cantilevers have their own balance issues.

10.1 The tower of the Inch Garvie Cantilever is wider than the other two towers. The Queensferry and Fife Cantilevers have their 1,000 ton (1,016 tonnes) Counterpoises at one end, and 'half' of one Central Girder at the other end. Consequently, they can withstand the weight of two trains, one on each line, on their respective 'half' Central Girder.

10.2 However, the Inch Garvie Cantilever and its tower in particular, have to withstand the out of balance weight of two trains on 'half' of one Central Girder without the benefit of a Counterpoise. Therefore, the Inch Garvie's wider tower provides the ***stability*** required.



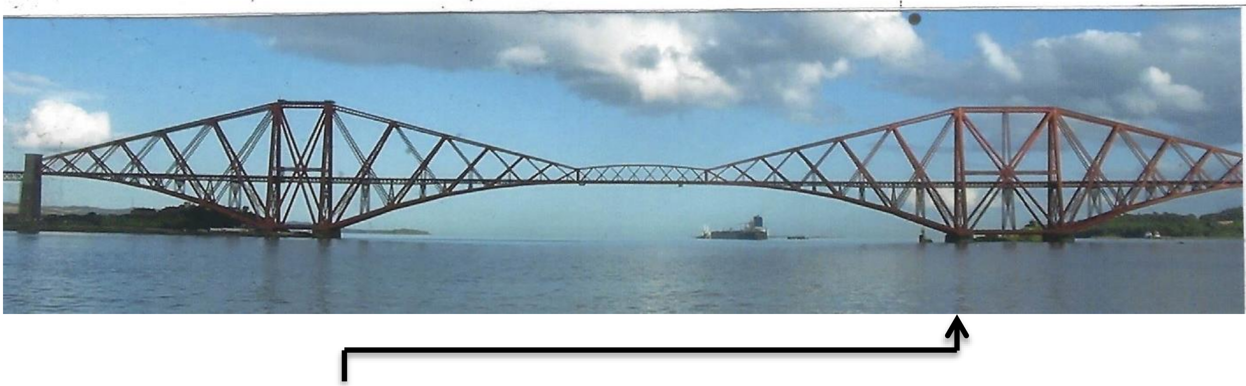


Figure 10.1 The Inch Garvie tower had to be wider

KEY TERMS

Stability - the steady state of a structure irrespective of the variable load imposed on it (e.g. wind loading).

11 ROCKING POSTS FOR TRANSFER OF LOAD

11.1 The north end of the Queensferry Cantilever is fixed to the south end of the adjacent Central Girder. Likewise, the south end of the Fife Cantilever is fixed to the north end of its adjacent Central Girder. However, the other end of each Central Girder is not ***fixed*** to the adjacent Inch Garvie Cantilever but instead is ***connected*** in a unique way, using ***Rocking Posts***, that enable:

- The loading on the Central Girders to be transferred from their top girders to the adjacent Cantilever's bottom girders.

F = Fixed RP = Rocking Posts South →

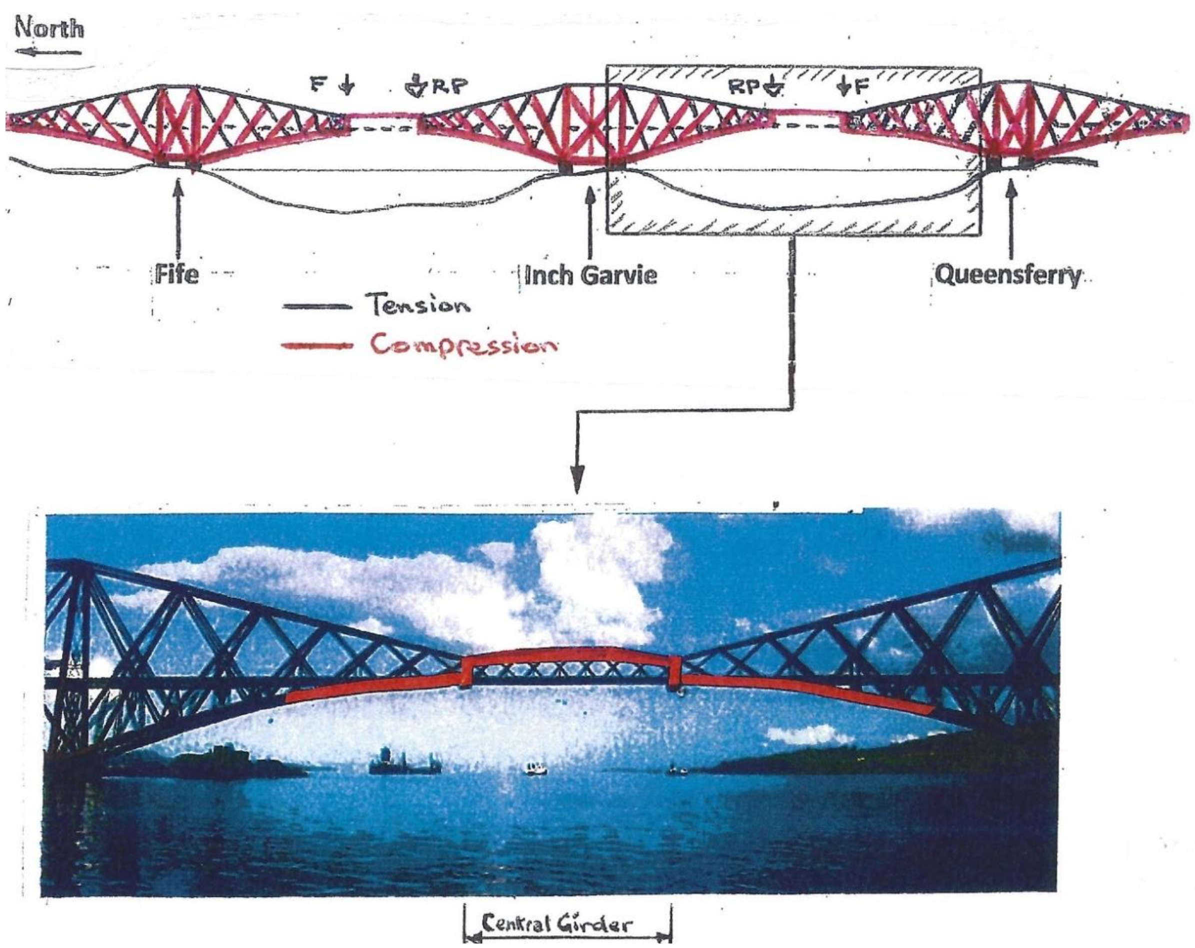


Figure 11.1 One end of each Central Girder is Fixed and the other end has Rocking Posts.

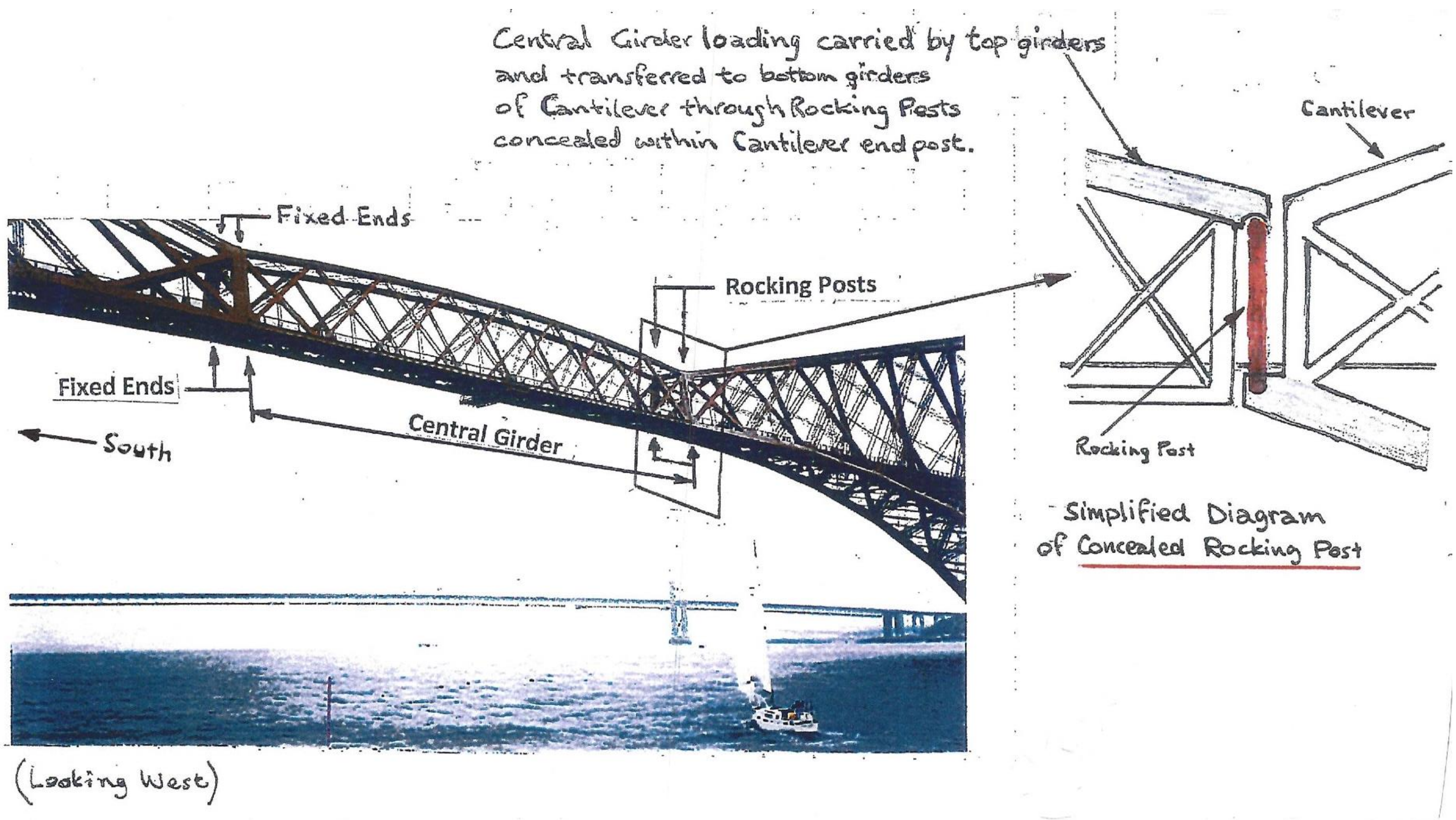


Figure 11.2 The transfer of load from Central Girder to Cantilever through Rocking Posts.

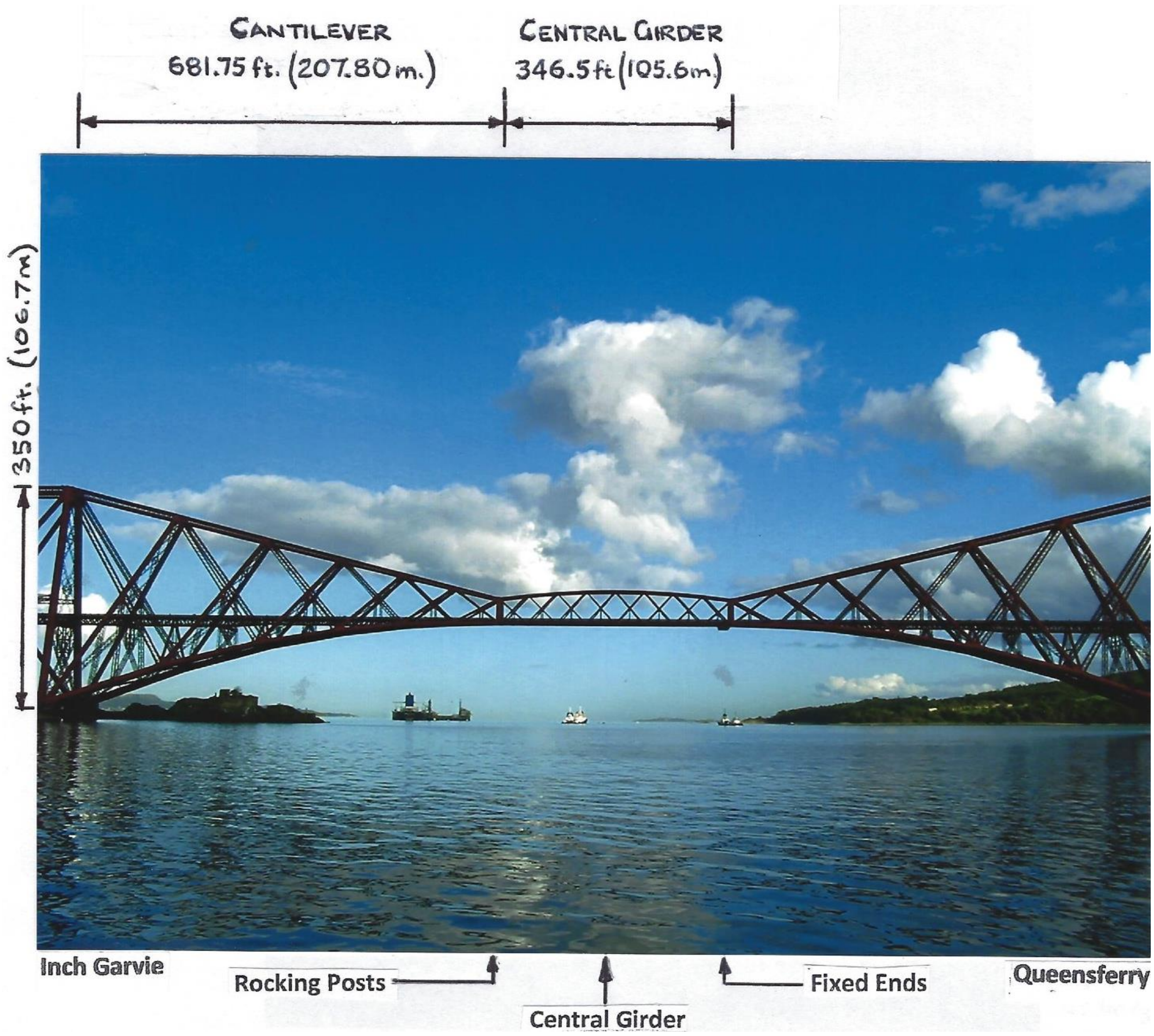


Figure 11.3 The Rocking Posts are concealed from view

KEY TERMS

Fixed - a structure is attached to another structure in a way that does not permit movement.

Connected - a structure has a relationship with another structure that may, or may not, permit movement.

Rocking posts - a vertical column or pin which can rock from side to side whilst permitting load transfer, and movement, between two structures.

Concealed Rocking Post - that cannot be seen from outside of the structure.

12 CANTILEVER EXPANSION AND CONTRACTION

12.1 The Cantilevers including their three supporting towers and the two Central Girders, comprise of 51,000 tons (51,818 tonnes) of steel which averages 28 tons (28 tonnes) of steel to support each yard of double track railway. Consequently, there is plenty of potential for steel expansion during the summer and contraction in winter, as a result of changes in temperature.

12.2 Essential provision for ***longitudinal expansion and contraction*** is made at the south end of the Queensferry Cantilever, the north end of the Fife Cantilever and at the rocking posts at each end of the Inch Garvie Cantilever. This is independent of the provision made for the expansion and contraction of the rails (***continuous welded rails – CWR***) on which the trains run. (See Section 14 regarding the short rails used on the Forth Bridge until CWR was installed in the 1990's).

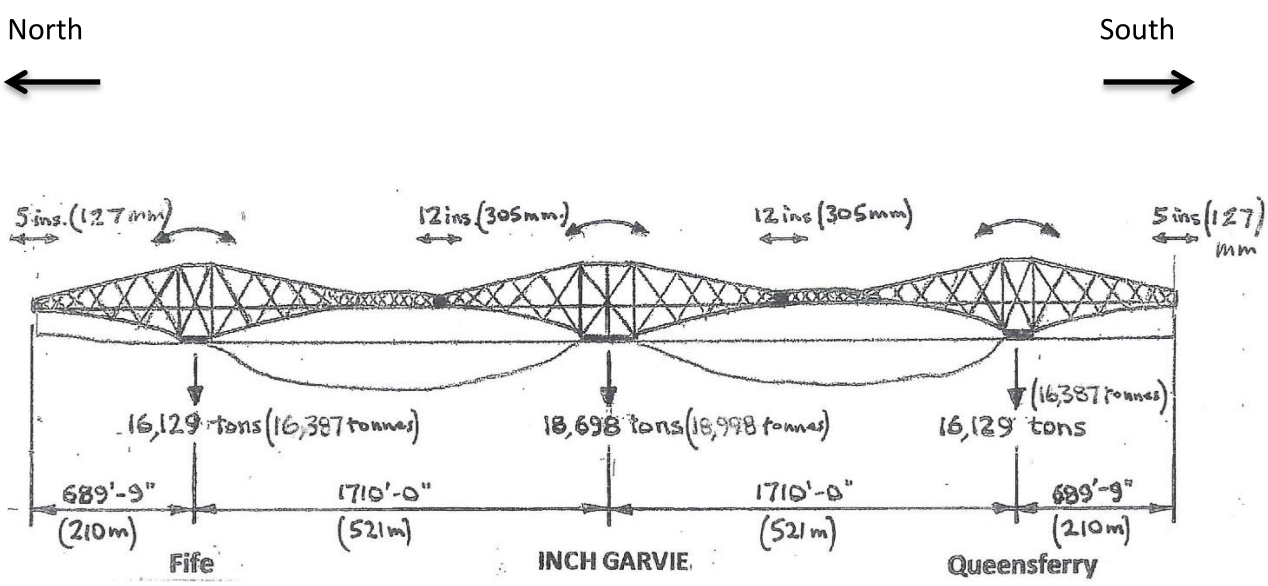


Figure 12.1

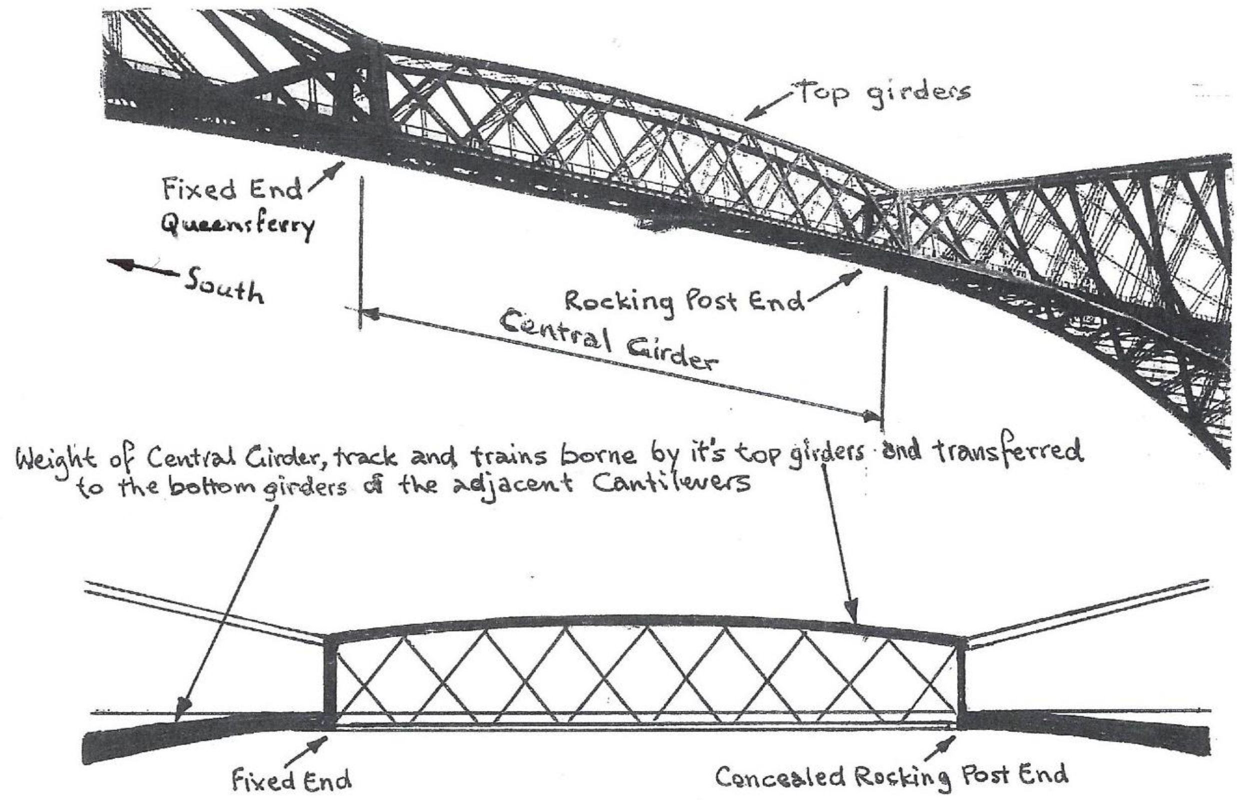


Figure 12.2 (Looking West)

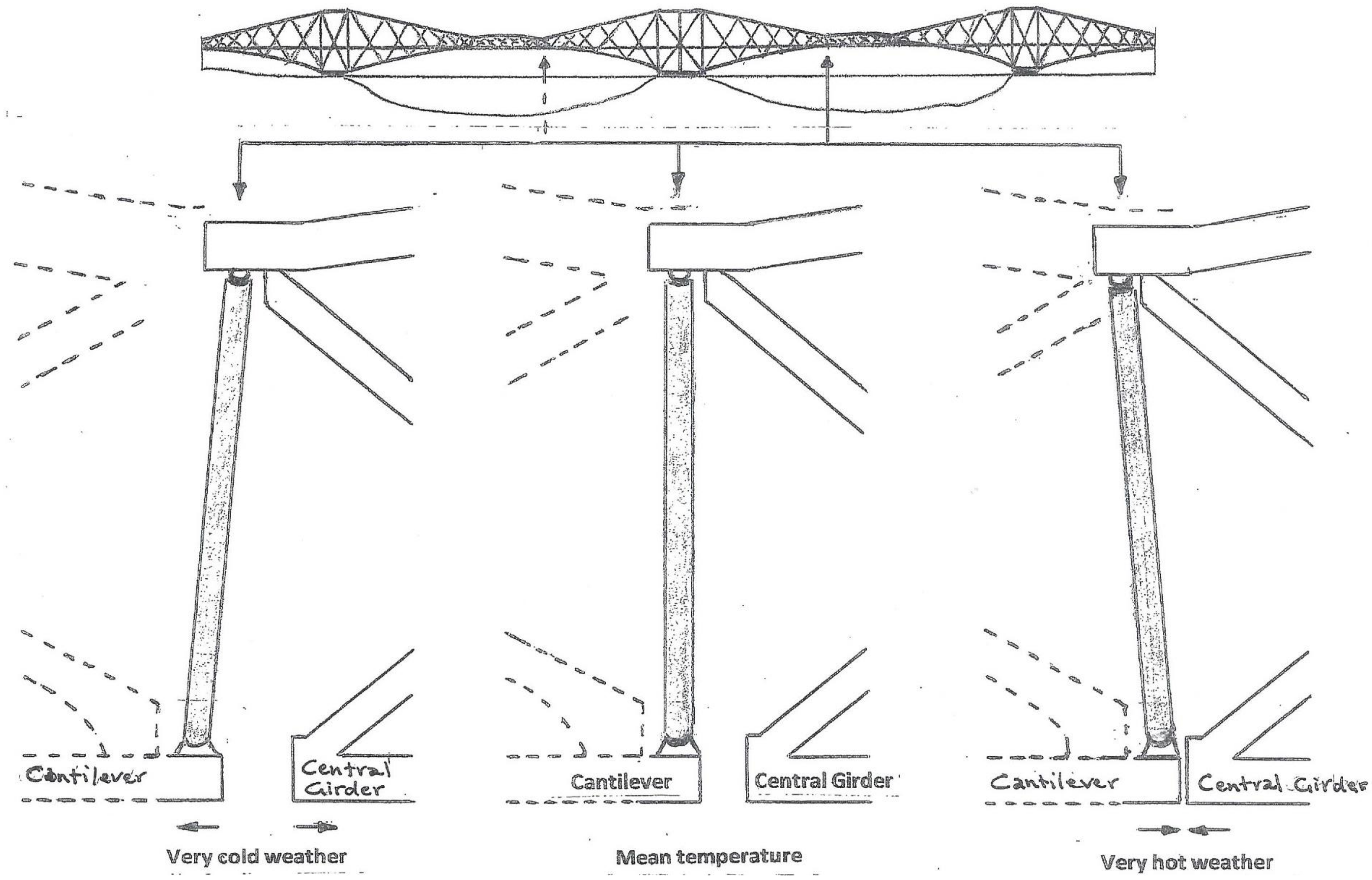


Figure 12.3 Simplified Diagram of Concealed Rocking Post for expansion, contraction and transfer of load.

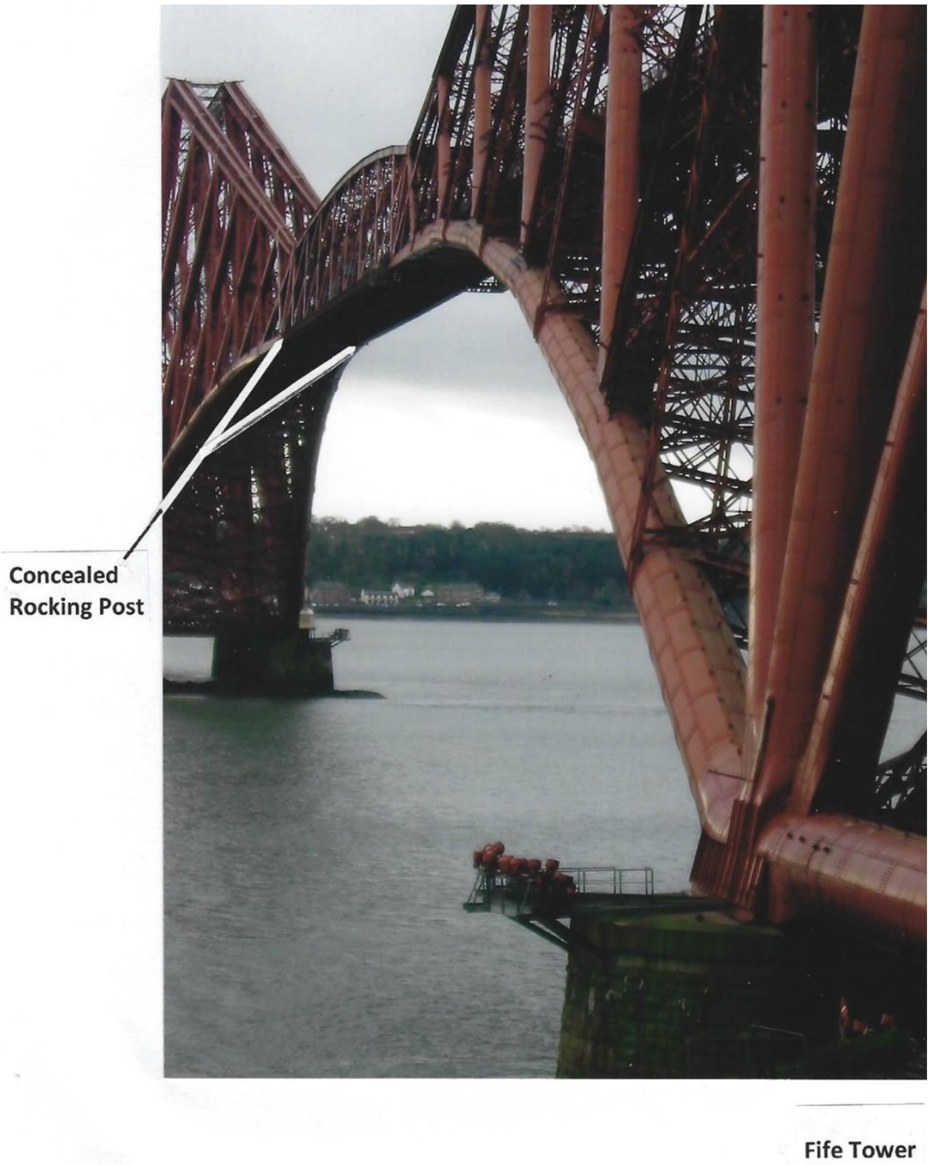


Figure 12.4 The Central Girder between Inch Garvie and Fife Cantilevers, looking towards South Queensferry.

KEY TERMS

Longitudinal expansion and contraction – movement in the direction of the Internal Railway Viaduct.

Continuous welded rails (CWR) - very long lengths of rail on which trains run and which have no gaps for expansion or contraction. They are neither in compression nor tension when at a temperature which is mid-way between the hottest and coldest temperatures that the rails are likely to experience. When being installed, the rails are stretched to the length that is commensurate with the 'midway' temperature.

13 VERTICAL PINS BETWEEN CENTRAL GIRDERS AND CANTILEVERS

13.1 ***Vertical pins*** between the Central Girders and the Cantilevers are part of the arrangements for connecting the two together.

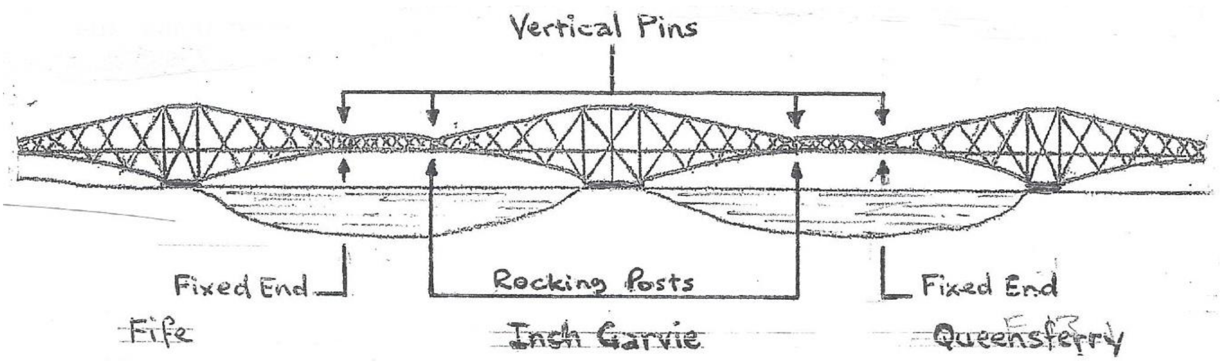


Figure 13.1

The pins at the Rocking Posts end of each Central Girder have three functions:-

1. Keep the Central Girders in line with the Cantilevers
2. Give some horizontal flexibility during gale force winds
3. Permit the same amount of expansion and contraction as the Rocking Posts (+/- 12ins) (305 mm)

The pins at the fixed ends of each Central Girder have functions 1. and 2. above but not, of course, function 3.

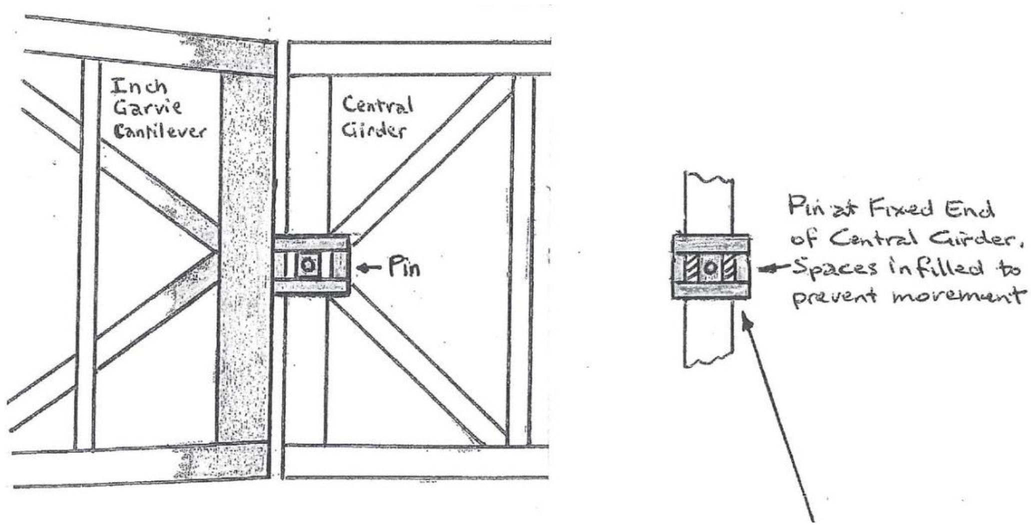


Figure 13.2 PLAN VIEW (Bird's eye view)
Showing space on each side of pin for 12 ins. of movement.
Pins at the fixed ends have spaces infilled to prevent movement.

KEY TERMS

Vertical pins - connect two structures whilst permitting rotational movement between them.

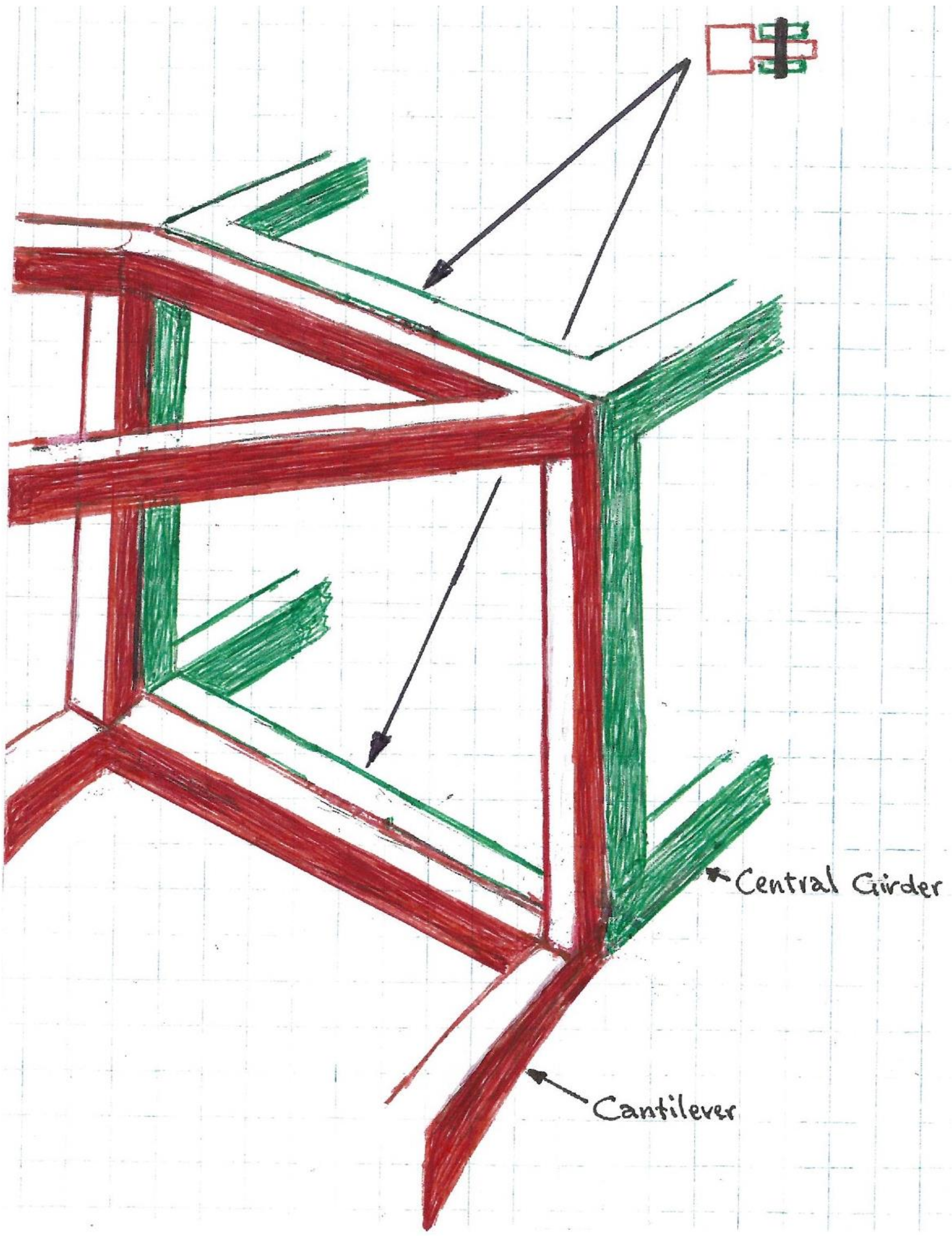


Figure 13.3 Simplified diagram showing location of the vertical pins.

14 RAIL EXPANSION AND CONTRACTION

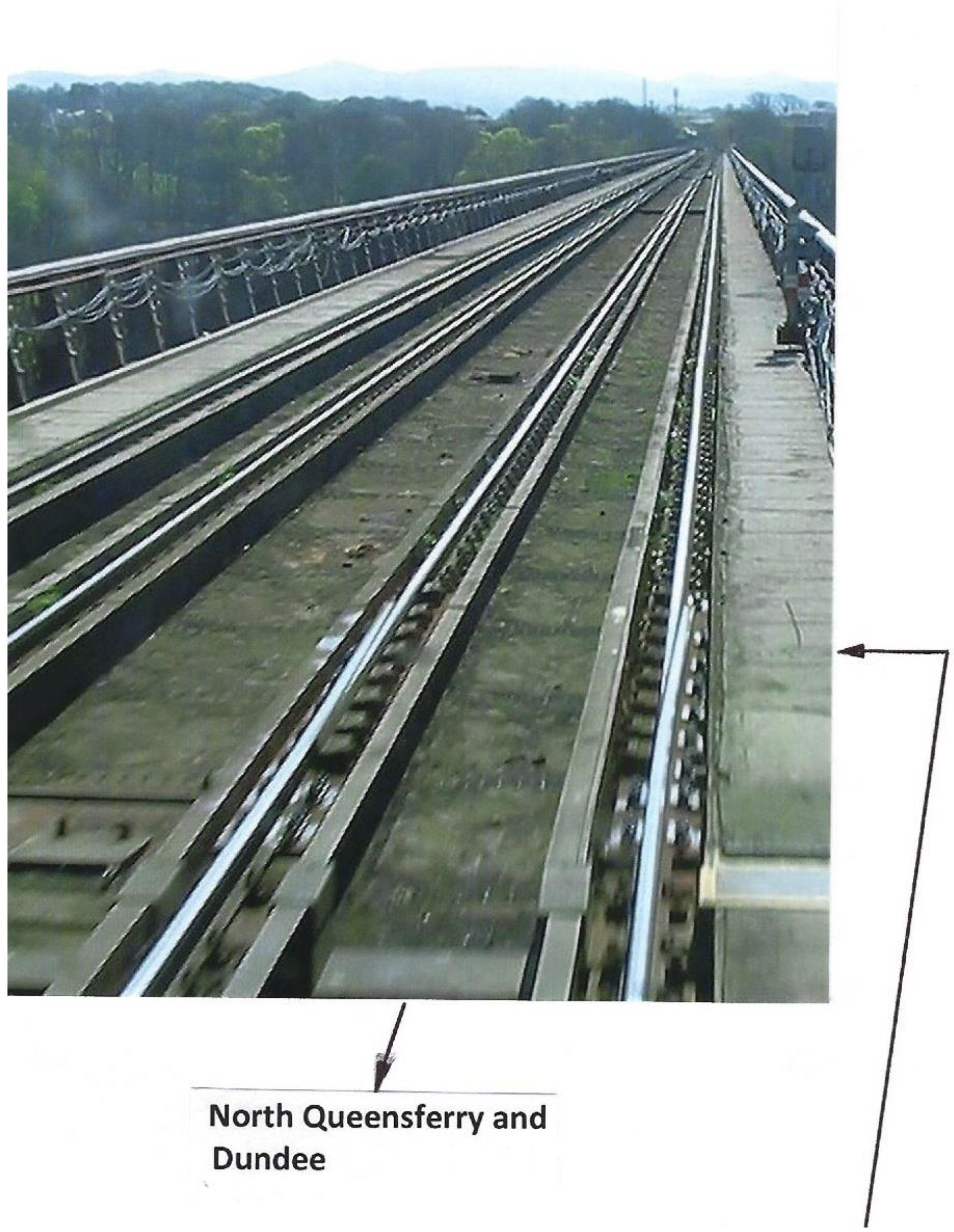
14.1 The already mentioned continuous welded rails (CWR) sit on baseplates which are fastened to timber waybeams that run parallel to the track. To ensure that train wheels have constant rail contact despite the total nature and extent of the expansion or contraction that may be taking place, expansion switches are incorporated in the rails at strategic locations. As a significant amount of movement occurs at the rocking posts at each end of the Inch Garvie Cantilever, specially designed ***'Forth Bridge' expansion switches*** are provided at these locations. Also, 'Forth Bridge' expansion switches are located at the end of the Queensferry and Fife Cantilevers. ***Standard expansion switches***, as used throughout the railway network, are provided much more than normal, at other locations on the Cantilevers and Approach Viaducts.

14.2 In total there are approximately 30 expansion switches between Dalmeny and North Queensferry stations. An equivalent stretch of 'normal' railway with CWR track would have no expansion switches within that distance.

14.3 The use of timber waybeams to support the rails, instead of the normal sleepers and stone ballast, minimises the weight of the track that the bridge has to carry. Stone ballast across the full width of the track bed would have produced a very heavy load.

Figure 14.1 'Forth Bridge' expansion switches.   At FB on Figure 14.3

Figure 14.2 Standard expansion switches. At S on Figure 14.3.



Forth Bridge type of expansion switch at end of Queensferry Approach Viaduct and start of Queensferry Cantilever.

Figure 14.2A The railway track has also to accommodate bridge expansion and contraction

As exists throughout the main line railway, continuous welded rails (CWR) are neither in compression or tension when their temperature is 27˚c. This is achieved by a procedure that uses powerful jacks when the rails are being installed, and are at a temperature of lower than 27˚c. The rails are stretched by the jacks to the length that is commensurate with 27˚c. This ensures that the rails will not be susceptible to buckling during very hot weather nor breakage during very cold weather.

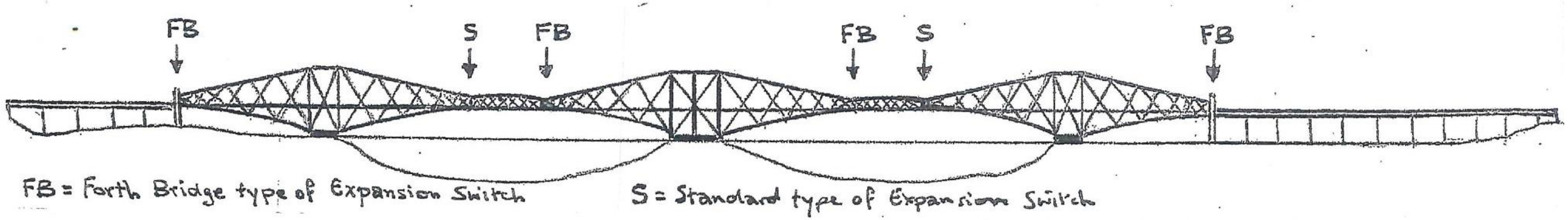
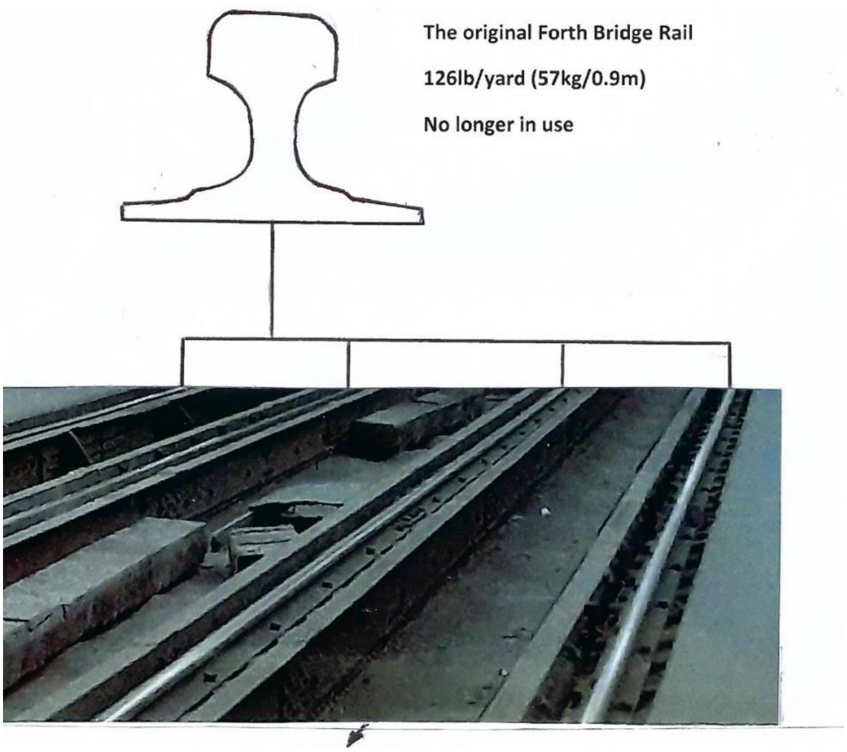


Figure 14.3



The original Forth Bridge rails sat horizontally, but as rails have to be slightly inclined towards each other, their shape was not symmetrical. Therefore, at any given place on the bridge, in the direction of travel, rails were either left hand or right hand.

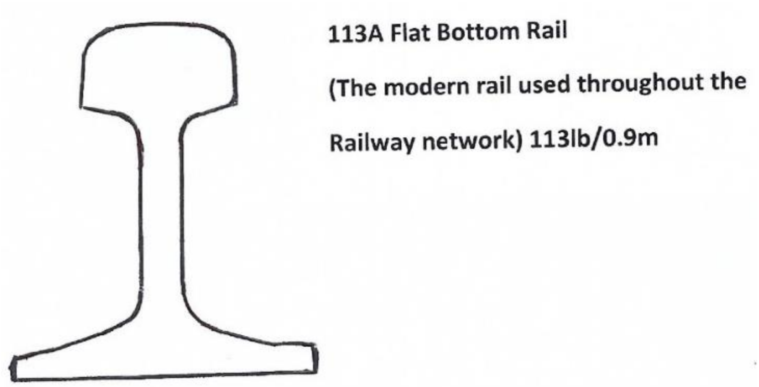


Figure 14.4

14.4 To illustrate the ability of steel to expand and contract it is worth considering the behaviour of the 60 ft. (18.3 m) long rails that were used on the railway network before the introduction of continuous welded rails (CWR), which started in the 1960s. When the 60 ft. (18.3 m) rails were installed in the track on a very cold day, the gap between each rail was set at approximately 6 mm. so that on a very hot day the gap would close. Had the gap not been provided, there would have been a very high risk of buckling occurring. The original Forth Bridge rails were approximately 40 ft. (12m) long.

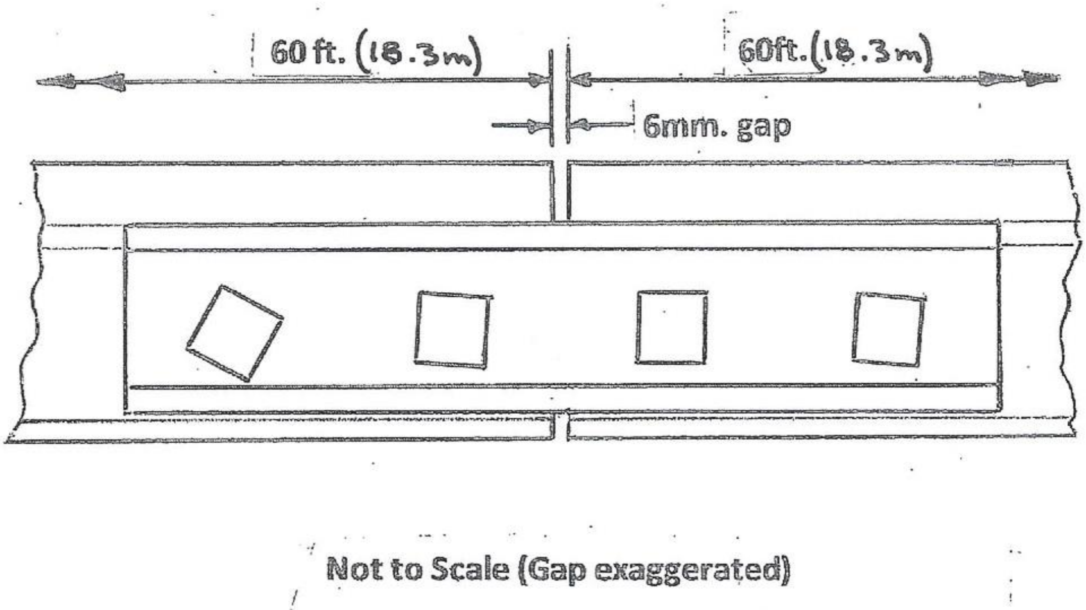


Figure 14.5 Four bolt Joint

14.5 An accident in Scotland, in unusually hot weather, near Abington on the West Coast Main Line on 8th August 1953, was caused by the compression in the 60 ft. (18.3 m) long rails being so high that they buckled under the London Euston to Glasgow Central 'Royal Scot'. Seven coaches were derailed. Fortunately there were no serious injuries, but considerable track damage was caused by the derailed coaches.

14.6 Although other factors were involved, the basic cause of the accident was the inability of the inadequate gaps at the rail joints to accommodate the expansion generated by the very high rail temperatures.

14.7 The track on the Queensferry and Fife Approach Viaducts is basically as shown in Figure 14.2. Standard expansion switches are provided to protect the rails when Approach Viaduct girders expand or contract out of step with the expansion or contraction forces experienced by the rails.

KEY TERMS

Forth Bridge expansion switches - an arrangement of rails which permits one rail to slide past another during expansion or contraction, without changing the gauge of the track and always giving support to train wheels. Forth Bridge expansion switches enable considerably more sliding than standard expansion switches.

Standard expansion switches - an arrangement of rails which permits one rail to move towards or away from another rail during expansion or contraction, without changing the gauge of the track and always giving support to train wheels. They are normally only necessary where long lengths of CWR meet jointed track, jointed track being a weaker structure.

Powerful jacks - equipment for stretching rails.

Buckling - the shape taken by a steel rail or bridge member when it cannot withstand an exceptionally high compressive load.

Breakages - the splitting into two parts of a steel rail when it cannot withstand an exceptionally high tensile load.

15. VERTICAL MOVEMENT (DEFLECTION) OF CANTILEVER SECTION BY TRAINS

15.1 The 200 trains that cross the bridge each day subject the Cantilever Section to constantly changing amounts of slight VERTICAL movement (***Deflection***), depending on where the moving train, or trains, happen to be and their particular weight and speed. The movement is accommodated by steel's natural elasticity. For instance, when redundant 60 ft. (18.3 m) long rails are being lifted on to a train by a crane, their flexibility makes them take the following shape:-

Figure 15.1

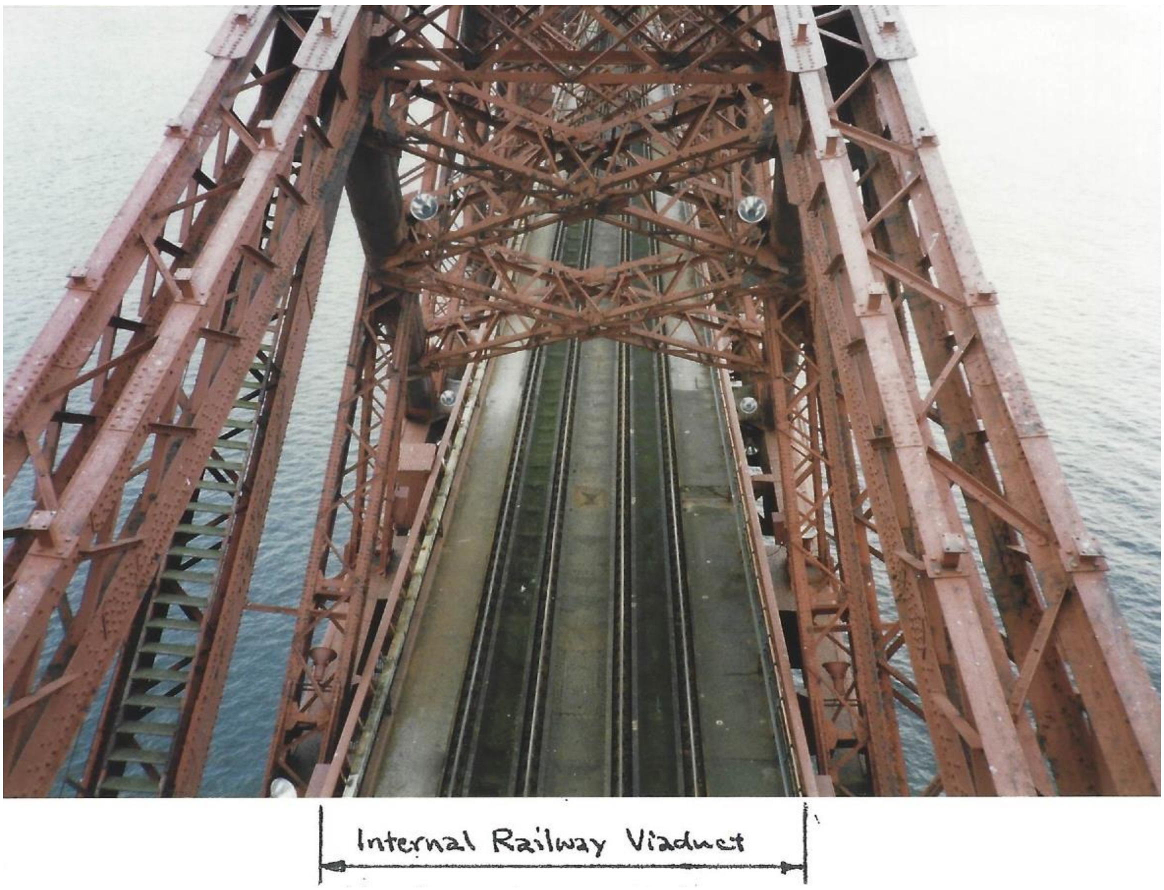


Figure 15.2 A bridge within a bridge!

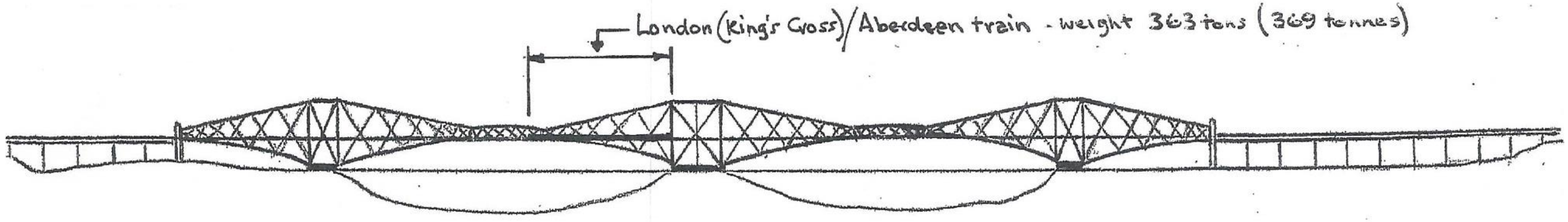


Figure 15.3

North Queensferry Station

Figure 15.4

20 mph - The maximum permitted speed for freight trains
50 mph - The maximum permitted speed for passenger trains

KEY TERMS

Deflection – the slight movement normally experienced by a steel girder when subjected to the load it was designed to carry. Maximum deflection normally occurs at the middle of a single span bridge.

16 GALE FORCE WINDS

16.1 As the River Forth at this location is often subjected to powerful winds and even gales, the designers made provision for high horizontal wind loads hitting large expanses of bridge surface. Given that gusting is often uneven, the bridge can contend with high wind loading on one Cantilever and not so high on the adjacent Cantilever. Such different loading conditions require flexibility. This is accommodated by the pins already mentioned at each end of the Inch Garvie Cantilever (See Section 13) and the inspired decision of the designers to fasten down only one of the four legs on each tower to its concrete foundation. The three not fastened down legs do not lift off their foundations during gales. However, at such times, they are free of unnecessary restraint stresses at the bottom of the legs.

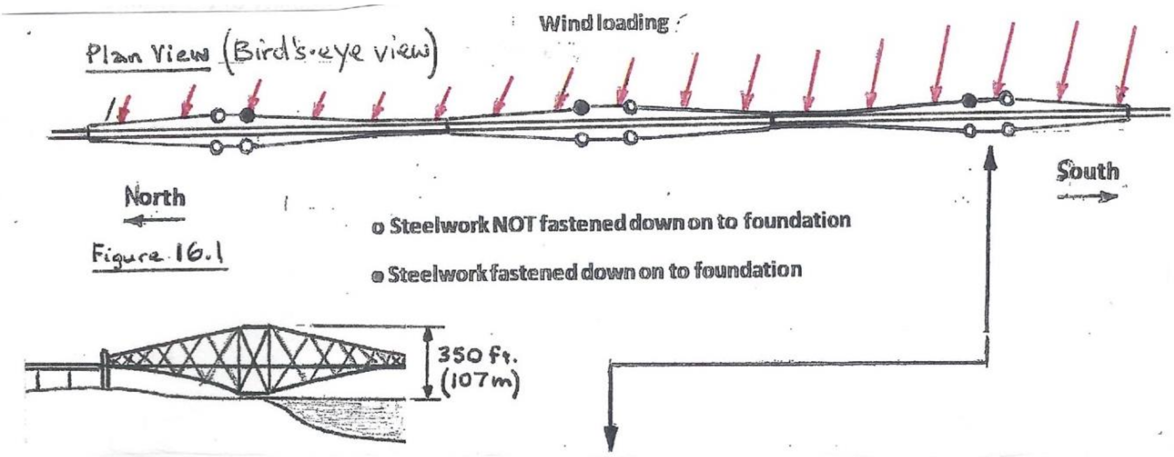


Figure 16.1

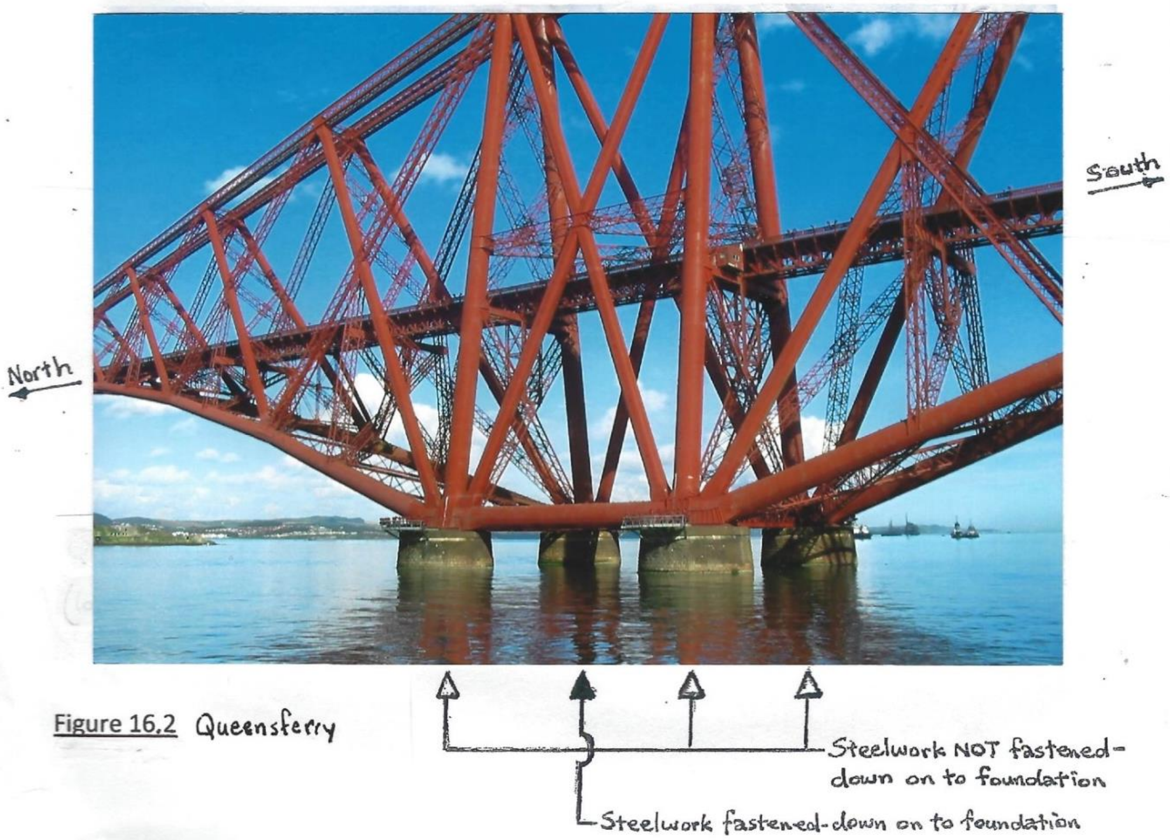
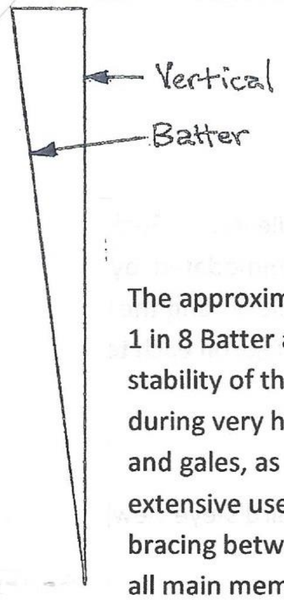


Figure 16.2 Queensferry



The approximately 1 in 8 Batter adds to the stability of the bridge during very high winds and gales, as does the extensive use of cross bracing between virtually all main members as is clear in the photograph below.

Figure 16.3

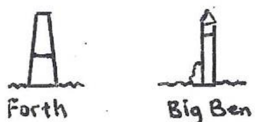


Figure 16.5

Figure 16.4

16.2 When establishing the horizontal wind load imposed on the Cantilever Section, Benjamin Baker had to calculate the total area of steel that the wind would strike. He believed it would be reasonable to assume that the streamlining effect of the circular struts would give an effective area in direct contact with the wind of 50% of the equivalent flat surface, as shown below.

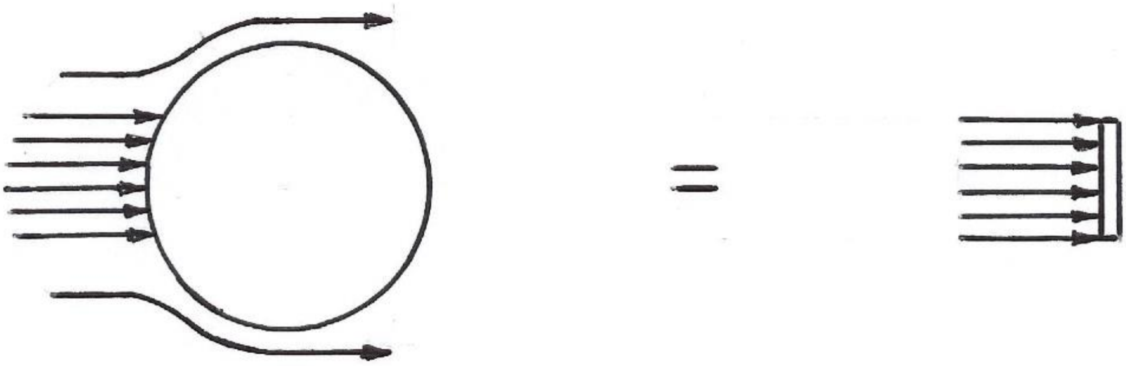


Figure 16.6

Figure 16.7 The array of cross-bracing as seen by train drivers.

17 TENSION, COMPRESSION AND FATIGUE

17.1 Those members of the bridge that are in compression and therefore called struts, appear to be solid but are in fact hollow cylinders up to 12 ft.(3.7m) in diameter.

Figure 17.1
A cylinder is the ideal shape for dealing with the buckling loads, produced by compression, which try to make the member shorter.

Figure 17.2 Internal Railway Viaduct

17.2 Those members that are mainly in tension and called ties are of a light appearance as they are dealing with loads that are trying to stretch them i.e. make them longer.

Figure 17.3

17.3 The ties that are also required for wind and gale loading are designed to withstand both tension and compression, as they are subject to wind direction reversals.

17.4 Between those members that have a ***partner*** and have to withstand very high COMPRESSION, a considerable amount of cross-bracing has been provided to ensure buckling cannot occur. See Figure 17.4.

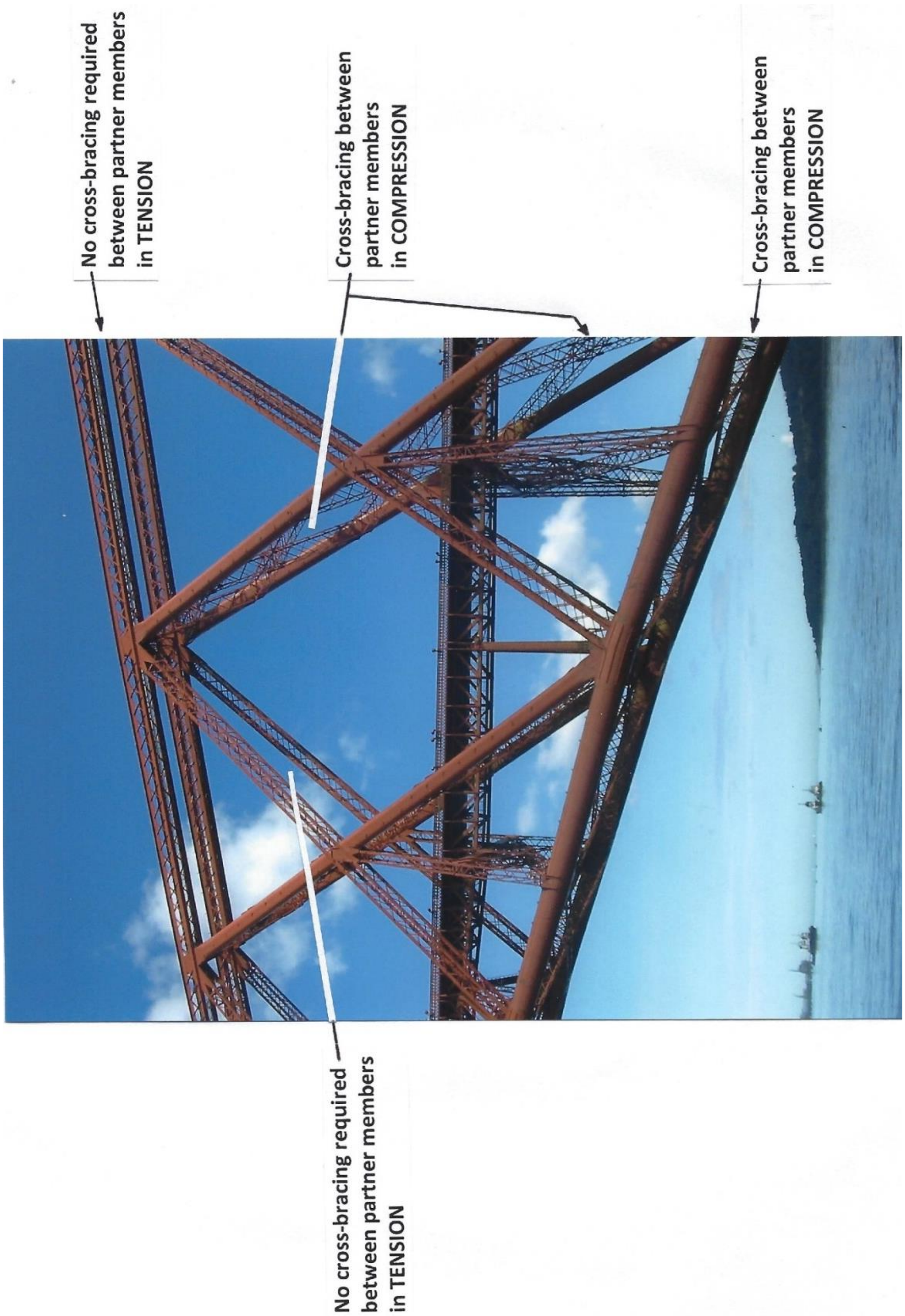


Figure 17.4 Cross-bracing provided between partner members in COMPRESSSION to prevent buckling.

Figure 17.4A Cross bracing between Compression members (struts) is clear in this view from North Queensferry of the Fife Cantilevers.

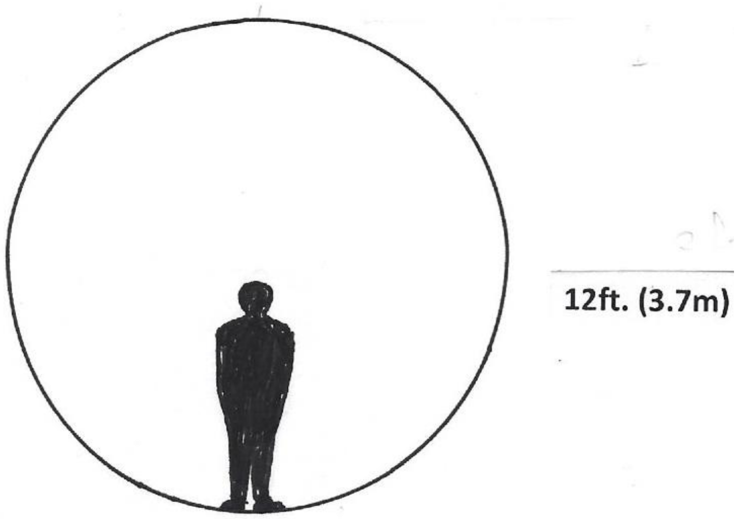
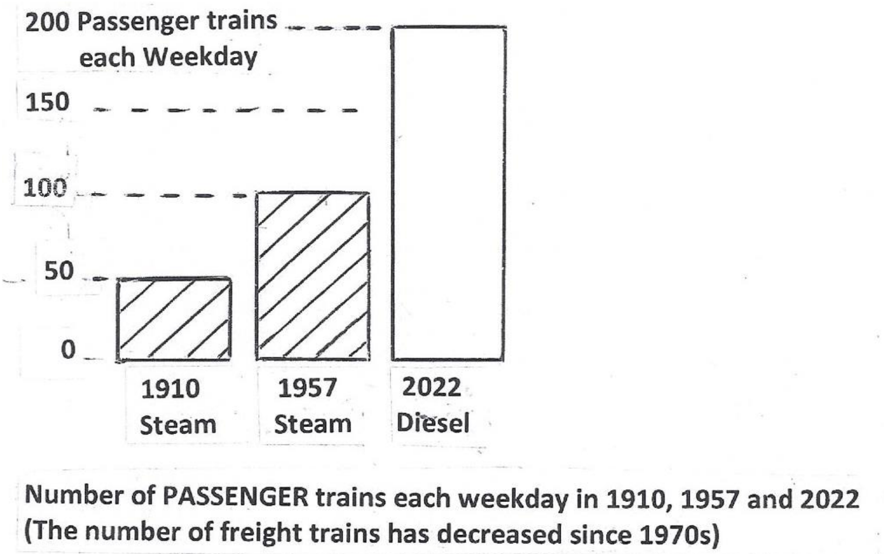
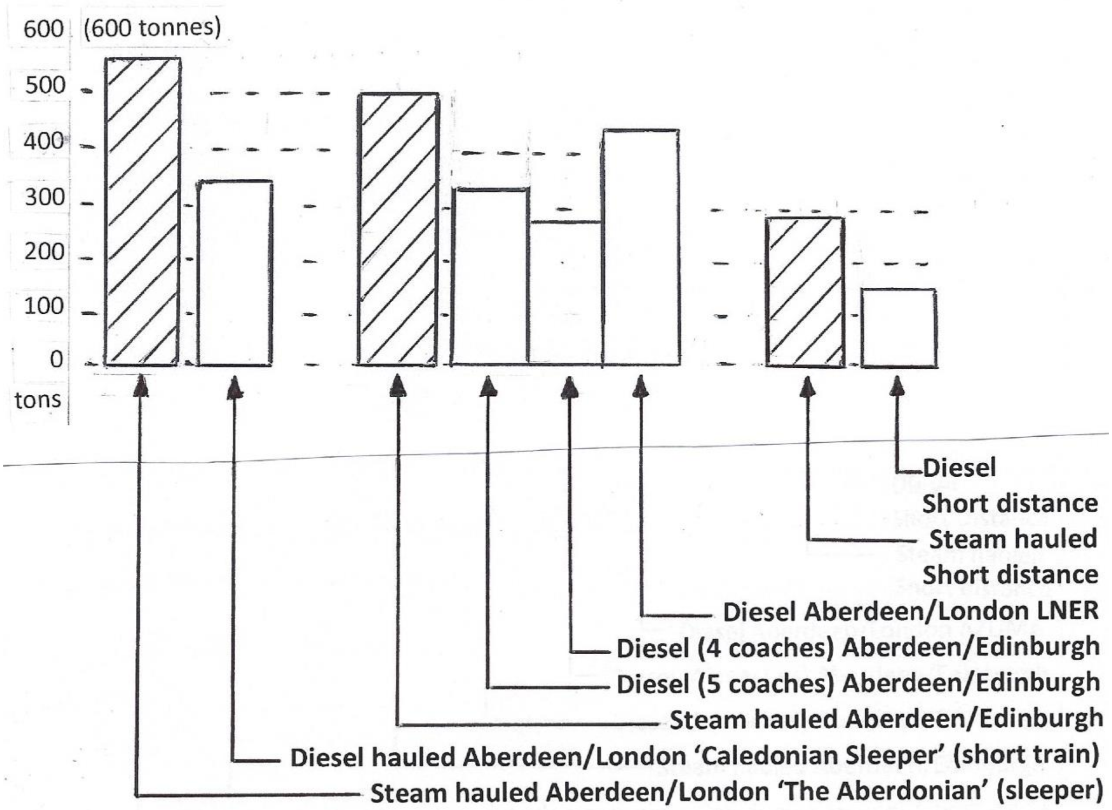


Figure 17.5 Illustrates the immense size of some of the hollow Compression members. (The stiffening around the internal periphery is not shown).

17.5 The ***fatigue*** experienced by the various members of a steel railway bridge depends on the weight and number of trains which use the bridge. Figure 17.6 shows that although the number of passenger trains each day using the Forth Bridge has INCREASED considerably over the years, their weight has DECREASED.

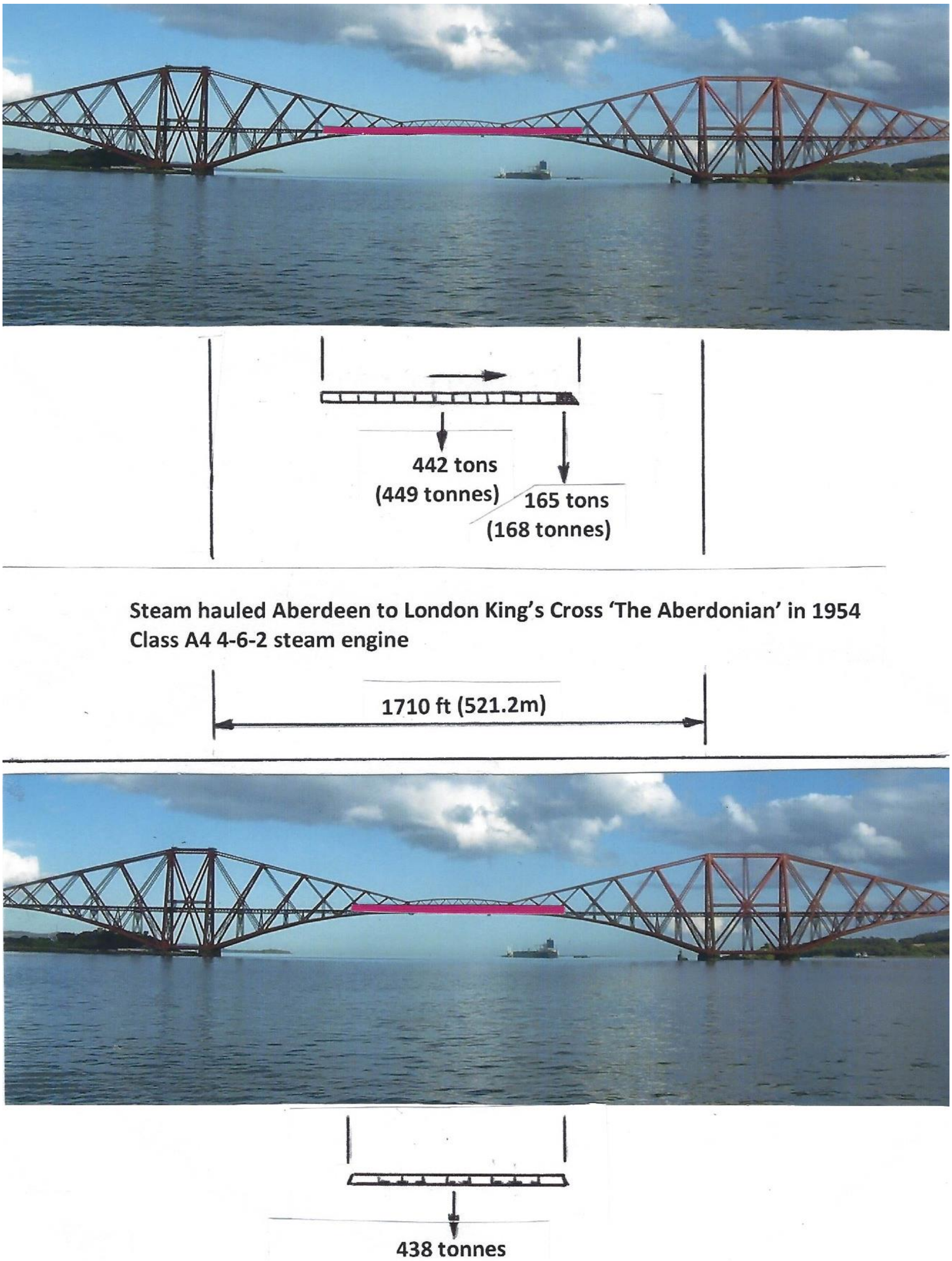


Number of PASSENGER trains each weekday in 1910, 1957 and 2022
(The number of freight trains has decreased since 1970s)



Weight of PASSENGER trains in 1957 (Steam) and 2022 (Diesel)

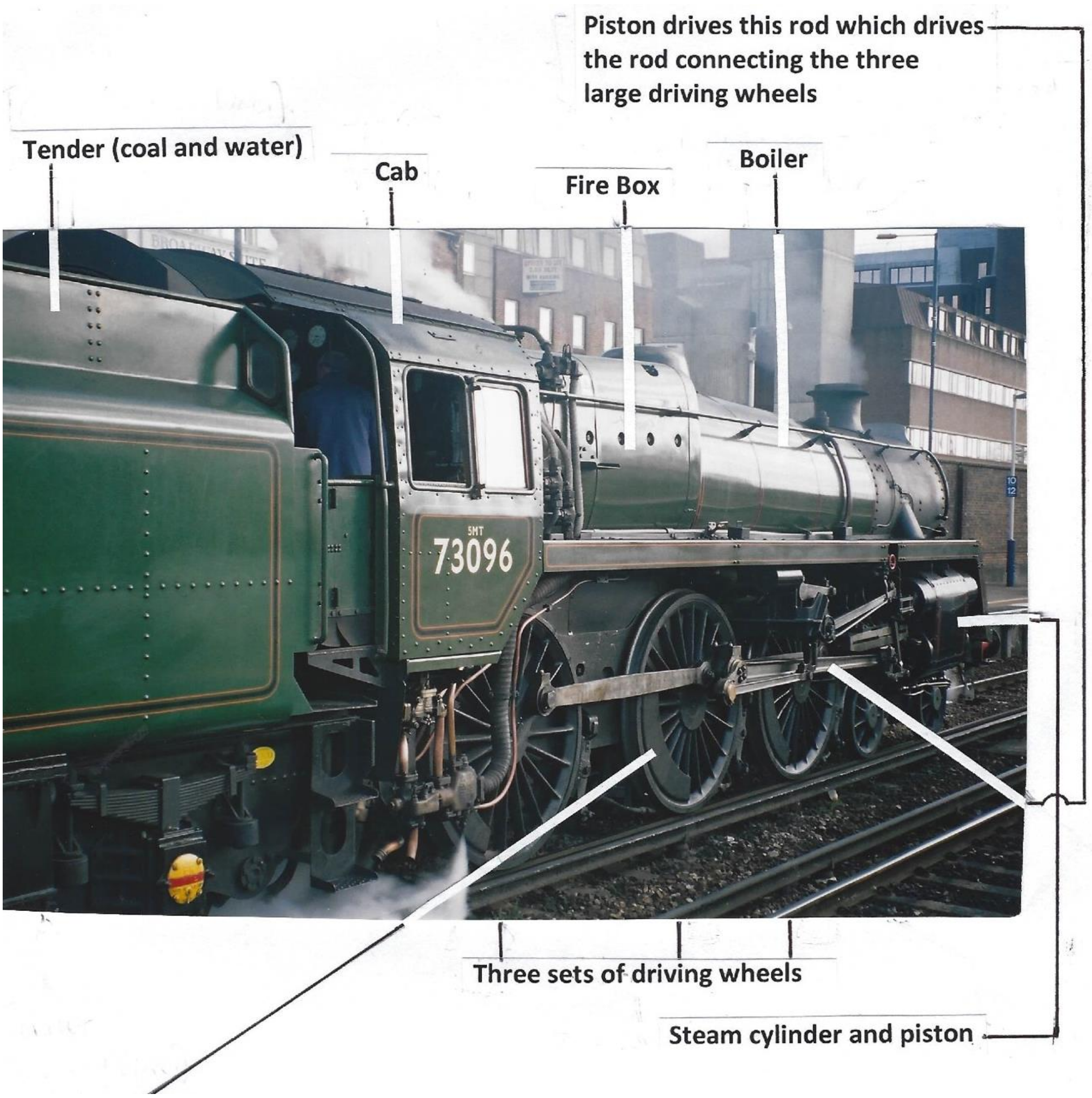
Figure 17.6 Although the number of passenger trains each day has increased, their weight has decreased.



Diesel Aberdeen to London King's Cross LNER AZUMA in 2022
(Traction power distributed from motors on certain vehicles

Figure 17.7 Long passenger trains in 1954 and 2022 on the very long span between two towers. A possible train on the northbound line is not shown.

17.6 Most importantly not only has the weight of each passenger train decreased, the change from steam to diesel traction has removed the detrimental effect of ***steam engine hammer blow***, caused by reciprocating parts.



Weight to counteract (balance) the reciprocating weight of the connecting rods

Figure 17.8 A Standard Class 5 4-6-0 steam engine used by British Railways in the 1950's and 1960's. Five engines of this Class were allocated to Perth Depot and occasionally worked trains across the Forth Bridge.

17.7 Figure 17.8 shows the key parts of a steam engine of the 1950's. The movement of the piston in the steam cylinder is transmitted to the driving wheels by connecting and coupling rods. This puts significant reciprocating loads on to the driving wheels, causing cyclic downwards and upwards forces. Although these very different forces are counteracted to a considerable extent by out of balance weights on each driving wheel, the residual downwards and upwards forces produce hammer blows to the track and therefore, bridges. (See Figure 17.8A)

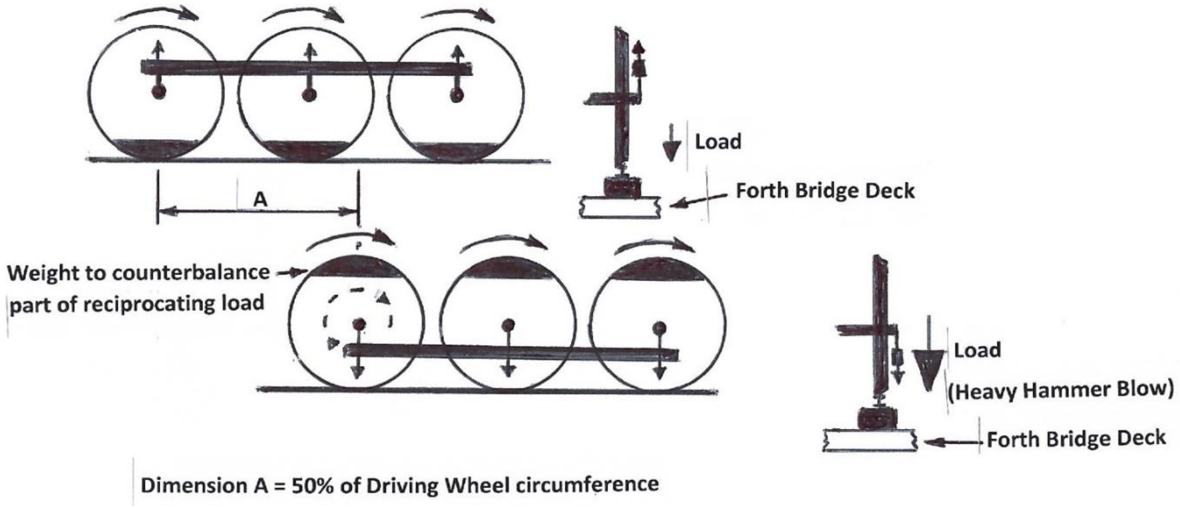


Figure 17.8A

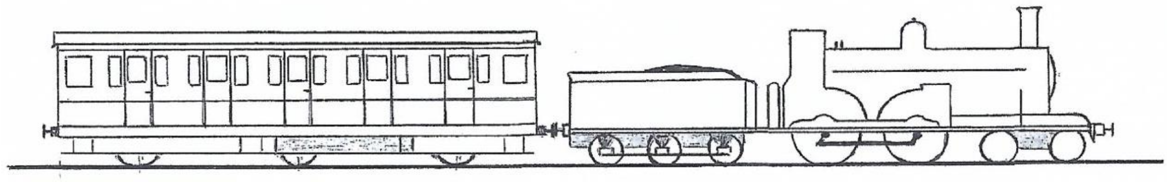


Figure 17.8B An approximate outline of the 4-4-0 steam engine and a passenger coach of the 1880's. The engine's large wheels are the driving wheels.

17.8 The bridge's designers would have welcomed, in relation to train weight and fatigue, the concept of 'distributed power,' which is now a feature of long distance passenger train design. Unlike the days of steam when all the tractive effort to move a train was produced by the heavy engine at the front, the bogies on five of the cars (coaches) of LNER's 9 car AZUMA trains have traction motors, thereby distributing the weight of the equipment needed to move the train along the length of the train. (See Figure 17.9)

Figure 17.9 The steam engine's power is in the 3 sets of large driving wheels (i.e. 6 wheels).
The LNER AZUMA'S power is in certain coaches. For instance, in the above photograph, the bogies on the left hand coach are powered, whereas those on the right hand coach are not powered (trailer coach).

Note:- Although without the status of a passenger train, the Aberdeen to London 'Fish' was given much attention by the railway authorities. In the 1950s, the steam hauled train crossed the Forth Bridge at approximately 4.30 pm each day with fish that had to be in the London fish market very early the following morning. Punctual arrival was essential.

KEY TERMS

Partner member – a girder that has a virtually identical partner that has an identical function. Most bridges have such members.

Fatigue - is caused by severe cyclic loading of a material (e.g. girder) which initiates and then propagates cracking. Overtime, this may result in failure (e.g. permanent deformation).

Steam engine hammer blow – The heavy downwards force produced by the reciprocating connecting and coupling rods during every revolution of the driving wheels, when the rods reach the bottom part of their revolving cycle.

18. STRESS, STRAIN AND FACTOR OF SAFETY

18.1 Stress = $\frac{\text{Force exerted on member}}{\text{Cross sectional area of member}}$

Strain = $\frac{\text{Change in length of member when under load}}{\text{Original length}}$

Shear Stress = $\frac{\text{Force exerted on (say) rivets}}{\text{Cross sectional area of (say) rivets}}$

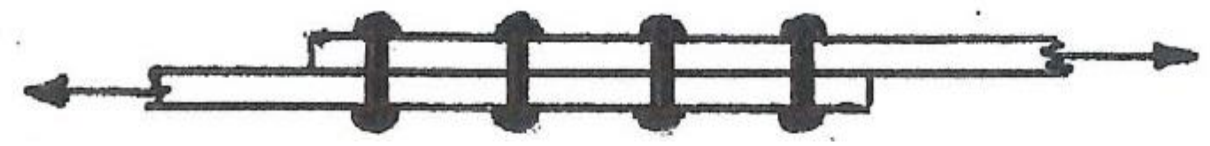


Figure 18.1

The Forth Bridge has approximately 6.5 million rivets. (Welding had not yet been invented).

Maximum Permissible Stress and Factor of Safety:-

The Board of Trade's Maximum Permissible Stress (***Allowable Working Stress***) for steel was 7.5 tons per square inch, which was 25% of the ultimate strength of steel, thereby giving a significant Factor of Safety. Bearing in mind that this was the first major bridge in Scotland to be made of steel, the Board of Trade's decision was very prudent and far-sighted.

KEY TERM

Rivet - - a steel pin which, when heated to a very high temperature and passed through holes in two pieces of steel, fastens the two pieces very firmly together as a result of the shrinking that takes place during the cooling process.

Allowable Working Stress – ensures for instance that a girder returns to its original (normal) unstressed condition after any permissible load has been removed.

Figure 18.2 A bridge with members connected by many rivets

Figure 18.3 Rivets on the Forth Bridge

19. APPROACH VIADUCTS, FORTH BRIDGE/INVERKEITHING CONNECTING LINE AND NAVIGATION CHANNEL

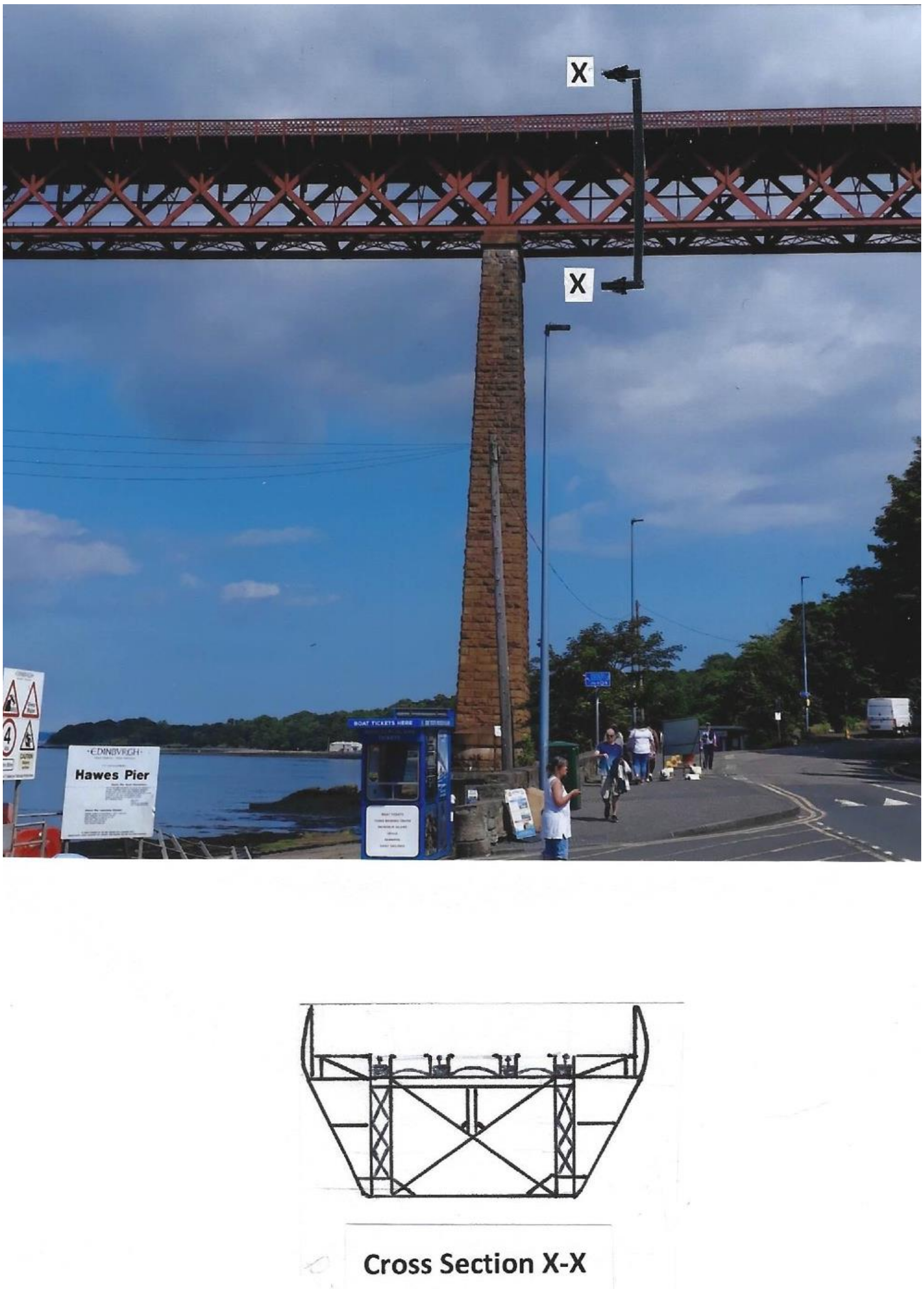


Figure 19.1 The Queensferry Approach Viaduct and a typical simplified Cross Section of the Queensferry Approach Viaduct. Both Approach Viaducts (Queensferry and Fife) have two main girders spanning between piers.

19.1 The Queensferry and Fife Approach Viaducts were designed by ***James Carswell***, a Scottish railway engineer, in close collaboration with Sir John Fowler and Benjamin Baker.

19.2 Although the Approach Viaducts have the appearance of multi-span railway bridges, the Forth Bridge viaducts have a significant difference. Whereas many multi-span bridges consist of several ***simply-supported spans***, the Forth Bridge's approach spans involve ***continuous girders***, each girder covering, not one but two spans. See Figures 19.2, 19.3 and 19.4.

A simply-supported span

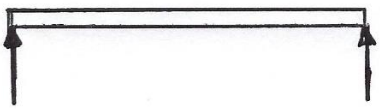
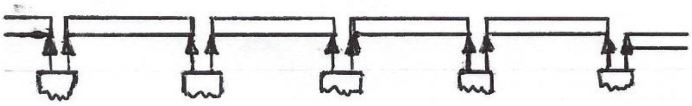


Figure 19.2

The Tay Bridge's 'High Girders' are simply-supported spans

Figure 19.3



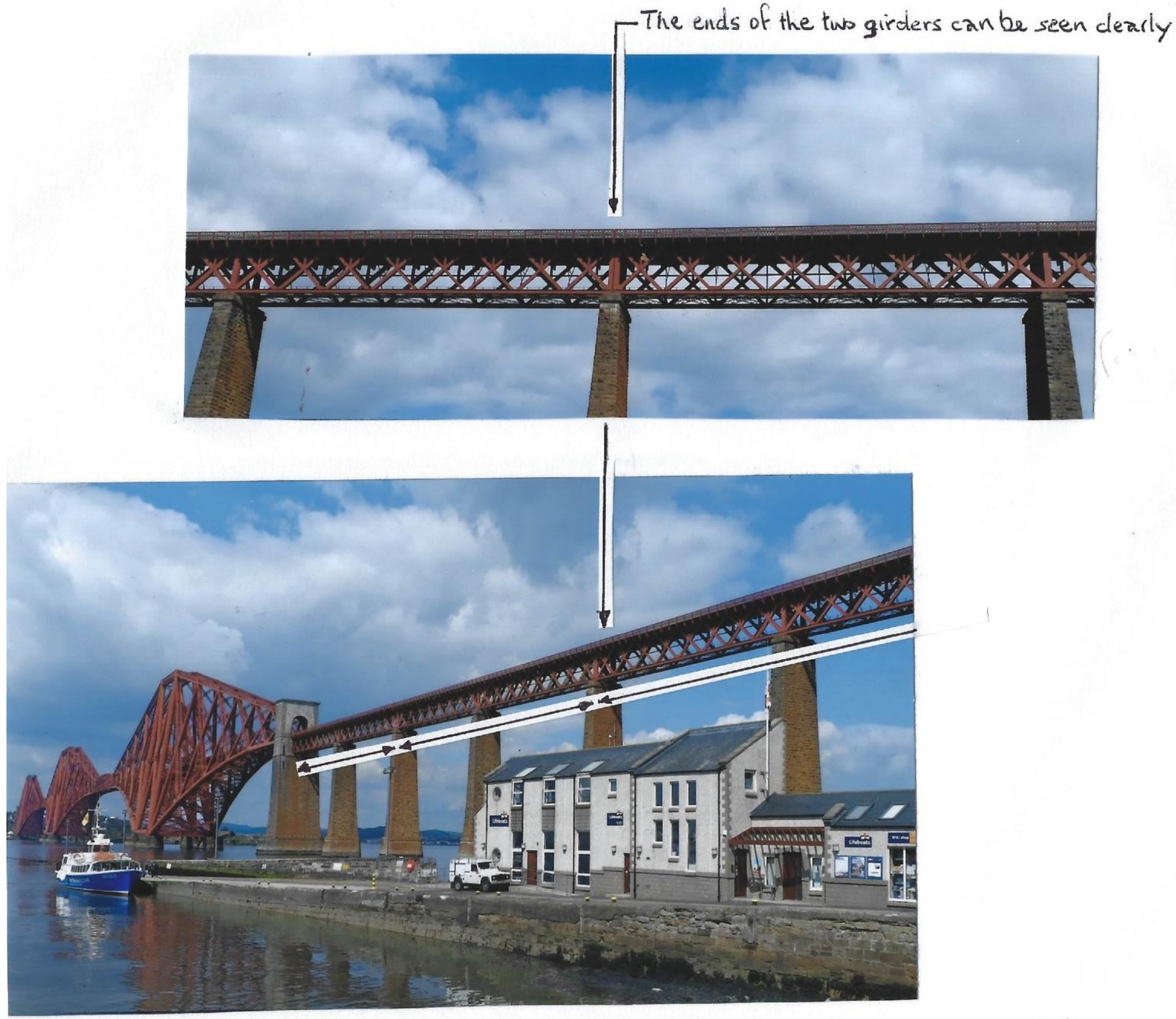


Figure 19.4 The arrows indicate the continuous spans - Queensferry Approach Viaduct

19.3 Each continuous girder is the length of two spans and therefore produces a significant amount of expansion or contraction, which is accommodated by the bearings that sit on the masonry piers.

19.4 Standard railway expansion switches are provided to accommodate the expansion and contraction of these girders. See Section 14.

19.5 The use of continuous girders covering two spans give the following benefits:-

- a reduced amount of deflection at mid span when loaded with one or two moving trains
- a reduced amount of vibration
- the girders are more able to withstand ***load reversals*** during strong squally winds
- provides additional strength

Figure 19.5 The connection between the Queensferry Approach Viaduct and the adjoining masonry arches. Several multi-span steel bridges have their extreme ends bearing on masonry or brick arches located on firm ground. The south end of the Tay Bridge at Wormit is another good example. (See also Figure 5.2)

19.6 Although it was necessary to make the Cantilever Section level to maintain balance it was decided to also make the Queensferry and Fife Approach Viaducts level. This, coupled with the 150 ft. (45.72m) headroom required for the Navigation Channel, determined the level of the north end of the Fife Approach Viaduct at North Queensferry.

19.7 This in turn determined the gradient required for the 2 miles (3.2 km) connecting line that had to be built between North Queensferry and Inverkeithing.

19.8 The civil engineers designing this stretch of railway quickly concluded that a severe rising gradient was needed all the way from Inverkeithing to the start of the Fife Approach Viaduct.

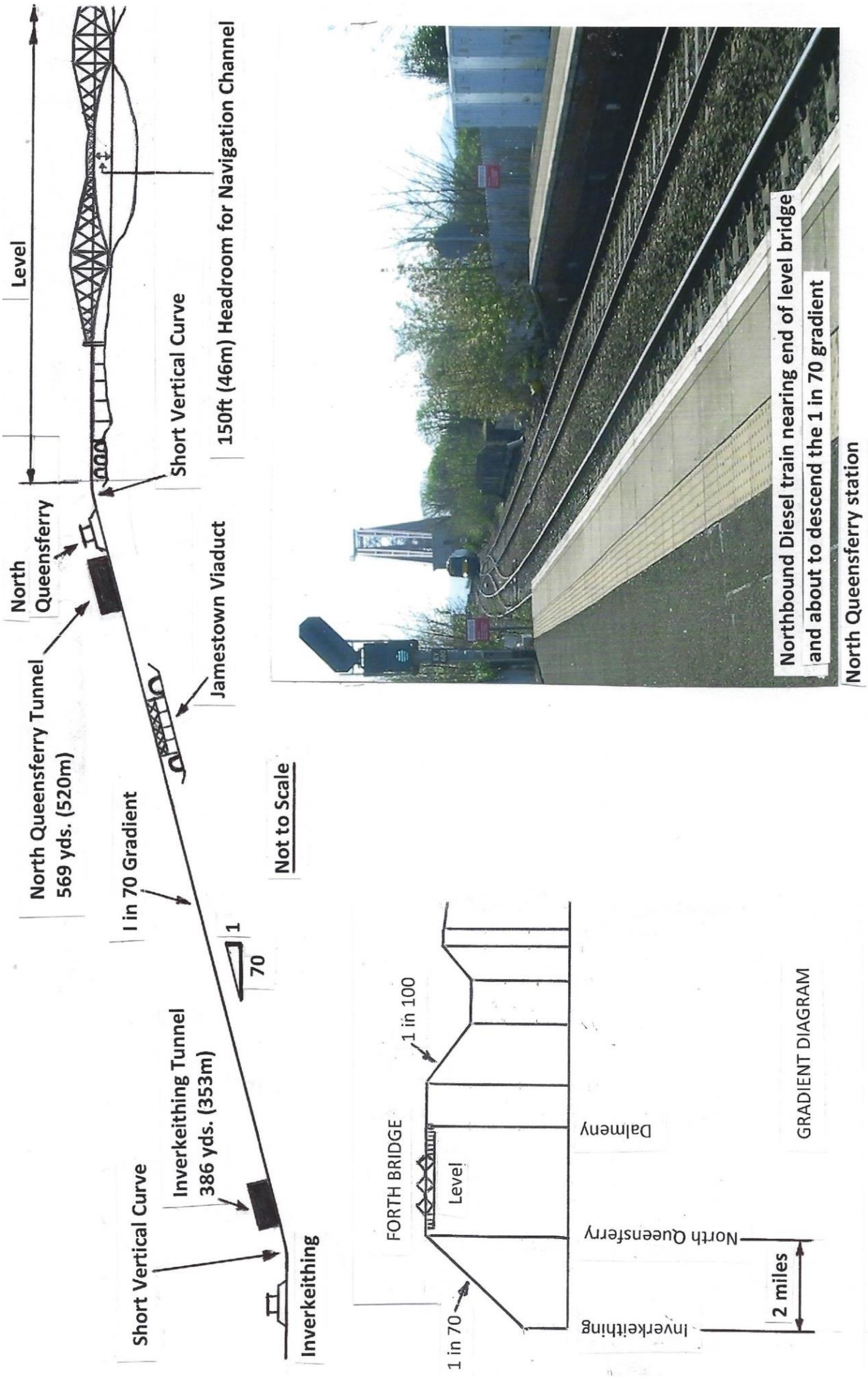


Figure 19.6 The connecting line between the Bridge and Inverkeithing

19.9 Perhaps they examined the two steep gradients that already existed on the other main line between England and Scotland, the West Coast Main Line. The incline at Shap in Cumbria and Beattock in Scotland, were both built with 1 in 75 gradients, rising south to north. It would appear that the engineers secured agreement from the railway operating officers and locomotive engineers that the rising gradient between Inverkeithing and North Queensferry would be 1 in 70. However, this required North Queensferry station to be on the gradient. As it was best practice to have stations on level track or only slight gradients (e.g. not steeper than 1 in 260), it was probably necessary for special permission to be obtained from the Board of Trade, the railway safety authority.

Figure 19.7 North Queensferry station and the south end of North Queensferry tunnel

19.10 This short stretch of railway was expensive to build given the need for two tunnels, Inverkeithing 386 yards (353 m) and North Queensferry 569 yards (520 m), plus Jamestown Viaduct. See figure 19.8

Figure 19.8 Jamestown Viaduct looking south.

19.11 As with the extreme ends of the Forth Bridge (See Figure 19.9), each end of the Jamestown Viaduct bears on a masonry arch (See Figure 19.8).

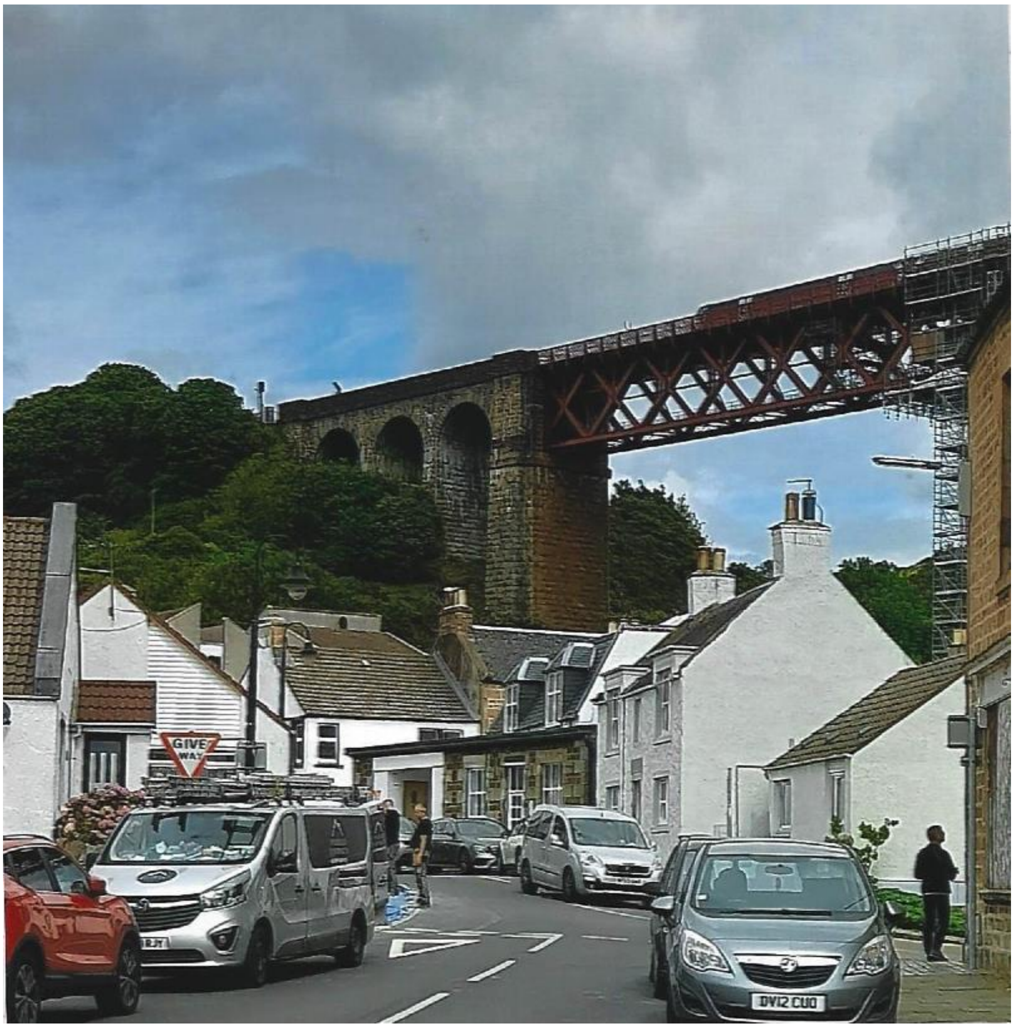
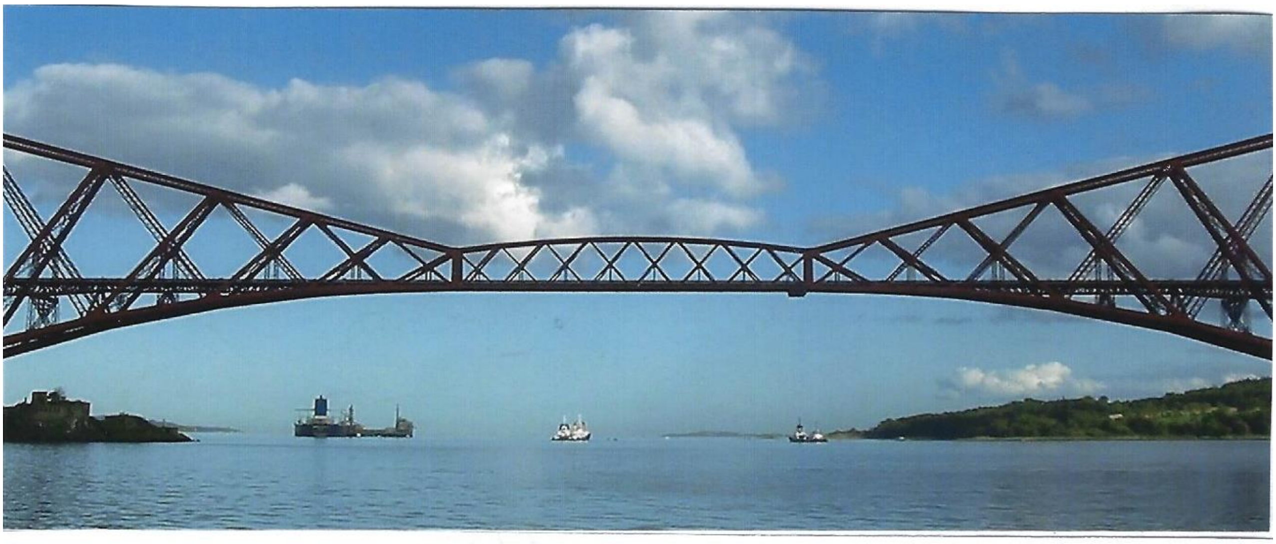
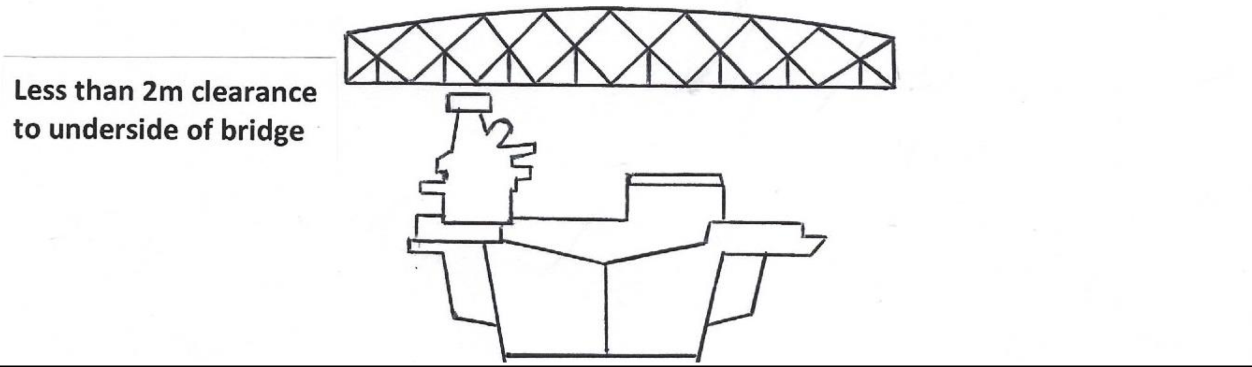


Figure 19.9 The three masonry arches at the North Queensferry end of the Bridge.

19.12 The Navigation Channel passes under the Central Girder between the Inch Garvie and Fife Cantilevers. It is interesting to note that when the Royal Navy's aircraft carriers HMS Queen Elizabeth and HMS Prince of Wales pass under the bridge for maintenance at Rosyth Dockyard, the clearance is less than 2 m., with pole mast lowered.





HMS QUEEN ELIZABETH (Aircraft Carrier)

Figure 19.10 HMS QUEEN ELIZABETH and HMS PRINCE OF WALES are a 'very tight fit' under a Central Girder. This photograph is of the Central Girder between Queensferry and Inch Garvie Cantilevers, whereas the Navigation Channel is under the identical Central Girder between Inch Garvie and Fife Cantilevers.

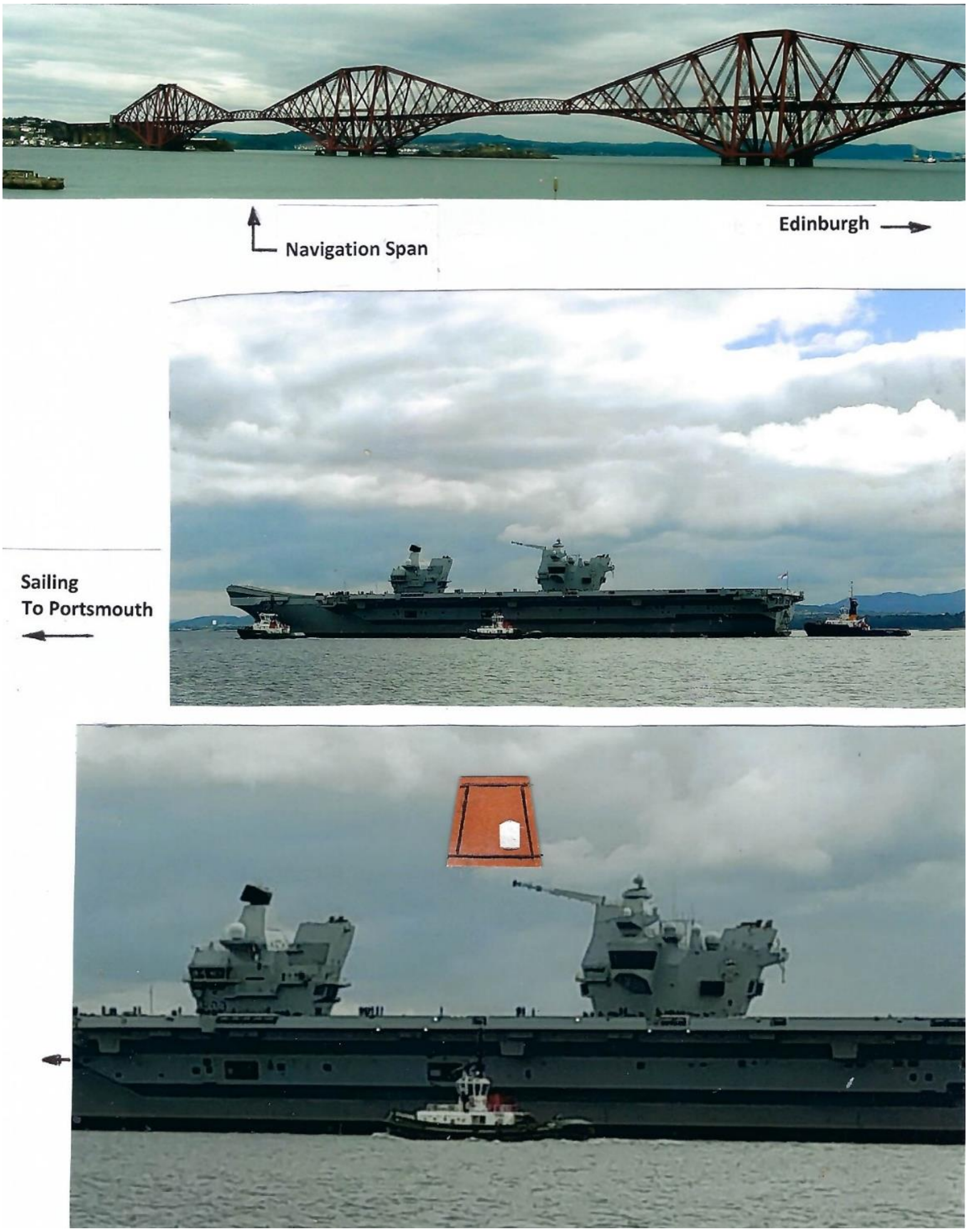


Figure 19.11 This is a SIMULATION of HMS PRINCE OF WALES passing under the Central Girder. (The photograph was taken on 25 July 2023 a few minutes after the compensate for them not being permitted to travel over the bridge at the ship passed under the Central Girder, under the control of ***tugs*** and with the pole mast LOWERED).

19.13 The new stretch of railway to connect with the south end of the Forth Bridge (i.e. Dalmeny end) did not require such a severe gradient.

19.14 It should be noted that severe rising gradients are much less of a problem for diesel (and electric) trains, a fact of course not known to designers in the 1880s.

19.15 It is interesting to note that North Queensferry Tunnel (also named Ferryhills Tunnel) is unusual, but not unique, in that it was built within a cutting that had been excavated in accordance with the original design for the Inverkeithing/Forth Bridge connecting railway. It is understood that the Forth Bridge Railway Company agreed to the tunnel being built to placate a local landowner who objected to the smoke and steam that would come from engines pounding up the steep gradient to the bridge.

19.16 It was sometimes necessary for a steam engine to be provided at the rear of particularly heavy trains to give assistance to the engine at the front of train for the journey up to the Bridge from Inverkeithing. The assisting engine was called a 'Banker'.

KEY TERMS

James Carswell – also designed the roof of Glasgow Queen Street station.

Simply-supported spans – A simply supported span is a girder that is supported at each end, with no attachment to a girder on an adjacent span.

Continuous girders – A continuous girder covers two or more spans, thereby causing its total length to influence how the load on any or all of the spans is carried.

Load reversal – occurs when the loading of a girder reverses thereby changing the forces it has to withstand from compression to tension, or vice versa.

Tugs – Powerful boats used to move very large ships at locations such as harbours, where manoeuvring is difficult due to lack of space.

20. COMPLETION OF BRIDGE

20.1 Before the completed bridge could take train services, the Board of Trade, which was responsible for railway safety, carried out tests starting on 18th February 1890. The tests were carried out over a three day period and involved the measuring of the deflections caused by two exceptionally heavy test trains when on the Cantilever Section. The two trains, one on each line, were very heavy to compensate for them not being permitted to travel over the bridge at the intended normal service speed of 40 mph.

Each train was formed as follows:-

2 steam engines	146 tons	(148 tonnes)
44 wagons loaded with ***pig iron***	682 tons	(693 tonnes)
1 steam engine at the rear	73 tons	(74 tonnes)
Total	901 tons	(915 tonnes)

Therefore, the bridge was subjected to test loads of 1802 tons (1830 tonnes). The tests produced satisfactory results enabling the bridge to be opened for traffic two weeks later on 4th March 1890, by the Duke of Rothesay, the future King Edward VII.

20.2 After the opening ceremony, Benjamin Baker was knighted.
The other designer, Sir John Fowler, was made a baronet.
William Arrol, the Glasgow contractor who built the bridge, was also knighted.
(Sir William Arrol & Co. also built the present day Tay Bridge).

20.3 Nearly 5,000 men were involved in the construction of the bridge but, tragically over 70 were killed. It took seven years to build the bridge.

Note:- It took seven years to build the Queensferry Crossing, the cable-stayed Bridge opened in 2017 to relieve the Forth Road Bridge.

20.4 The Forth Bridge Railway Company, which was formed to build, own and maintain the bridge, (see paragraphs 1.3 and 1.40) operated a Tolls System to generate on-going funds for the upkeep of the bridge. As railway tolls in general were based on mileage, the cost charged for each train that crossed the bridge, assumed the bridge to be 19 miles long. The exaggeration was necessary to take account of the unique nature of the 1.53 miles (2.5 km) of railway between Dalmeny and North Queensferry. It is likely, but not definite, that the cost per mile varied, depending on the type of train. For example, the cost for a London/Aberdeen passenger train may have been higher than that for a short local, if the value of the traffic was a factor.

KEY TERM

Pig iron – used in the making of steel and not normally suitable for use on it's own.

21 TRAIN SIGNALLING SYSTEM

21.1 The bridge design, and therefore the train signalling system, permit at any given time, two trains to be on the bridge, one on the Up Line (southbound line to Edinburgh) and one on the Down Line (the northbound line to Dundee and Aberdeen). (Throughout the railway network, the Up Line is generally the line which carries trains towards London).

Figure 21.1 Passenger train leaving north end of Cantilever Section at North Queensferry. (Scaffolding on bridge for maintenance work).

<u>Figure 21.2</u> One type of special Freight train is an Engineering train, which is a train for the conveyance of materials or equipment to locations where railway maintenance work is to be carried out. The train in <u>Figure 21.2</u> is conveying long rails to a location where they will be welded together to form Continuous Welded Rails (CWR) See Section 14.

Figure 21.3 When the train is on curved track, the long rails bend with the train, which is another example of steel's ability to be flexible within limits. (See Figure 15.1)

Figure 21.4 Illustrates the train with the long welded rails extending over the whole length of the train.

22 BRIDGE MAINTENANCE CROSSOVER TRACKS

22.1 To facilitate bridge maintenance, the two lines have bi-directional signalling which enables, using crossover tracks, northbound trains to use the southbound line and vice versa. This permits one line to be closed on a Sunday for instance, without seriously disrupting normal train services.

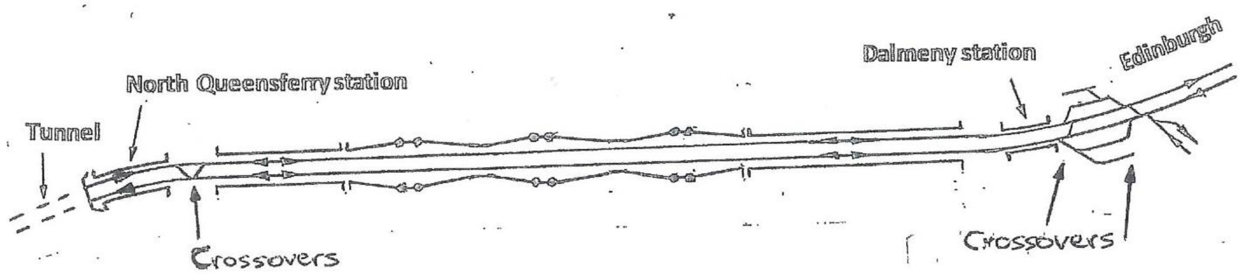


Figure 22.1

Figure 22.2 Crossovers ahead of North Queensferry station

22.2 Whereas two separate crossovers between the two tracks are shown at Dalmeny and North Queensferry in Figure 22.1, in 'Steam Days' a complex arrangement of points and crossings, termed 'Scissors Crossovers', placed one crossover on the other. The modern version of scissors crossovers is present at two locations within Edinburgh Waverley station, one between platforms 1/19 and 2/20 and the other at platforms 7/11. See Figure 22.3

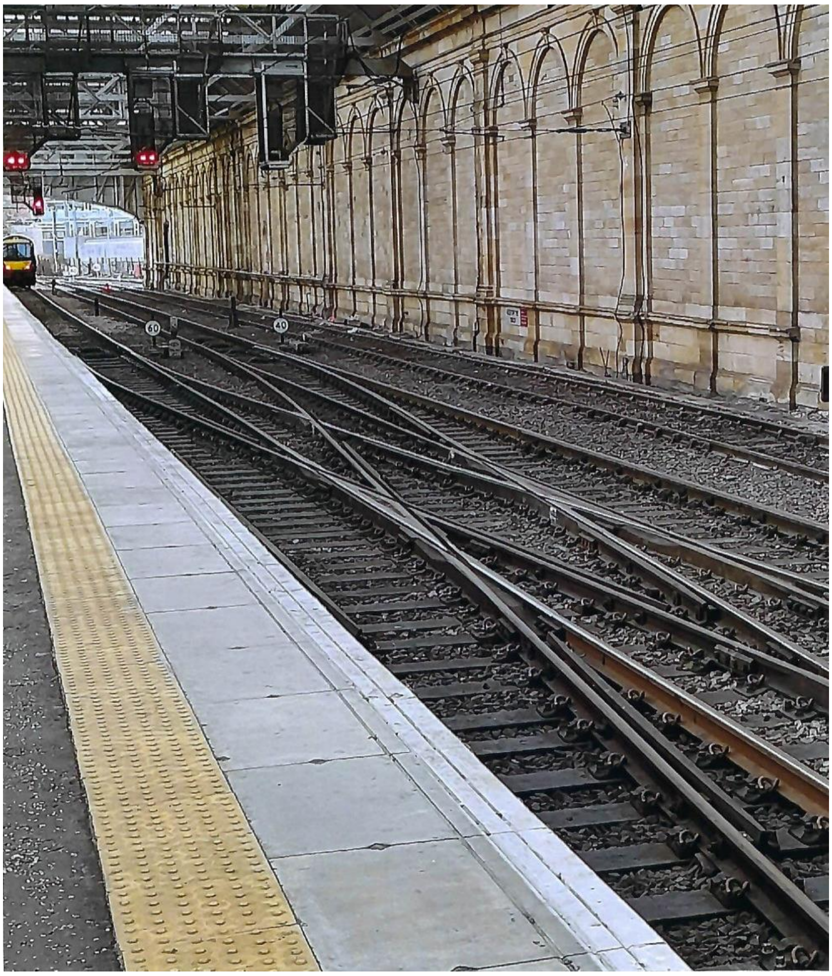


Figure 22.3 The scissors crossovers at Edinburgh Waverley station at platforms 7/11

23. QUICK ACCESS TO EXPLANATIONS

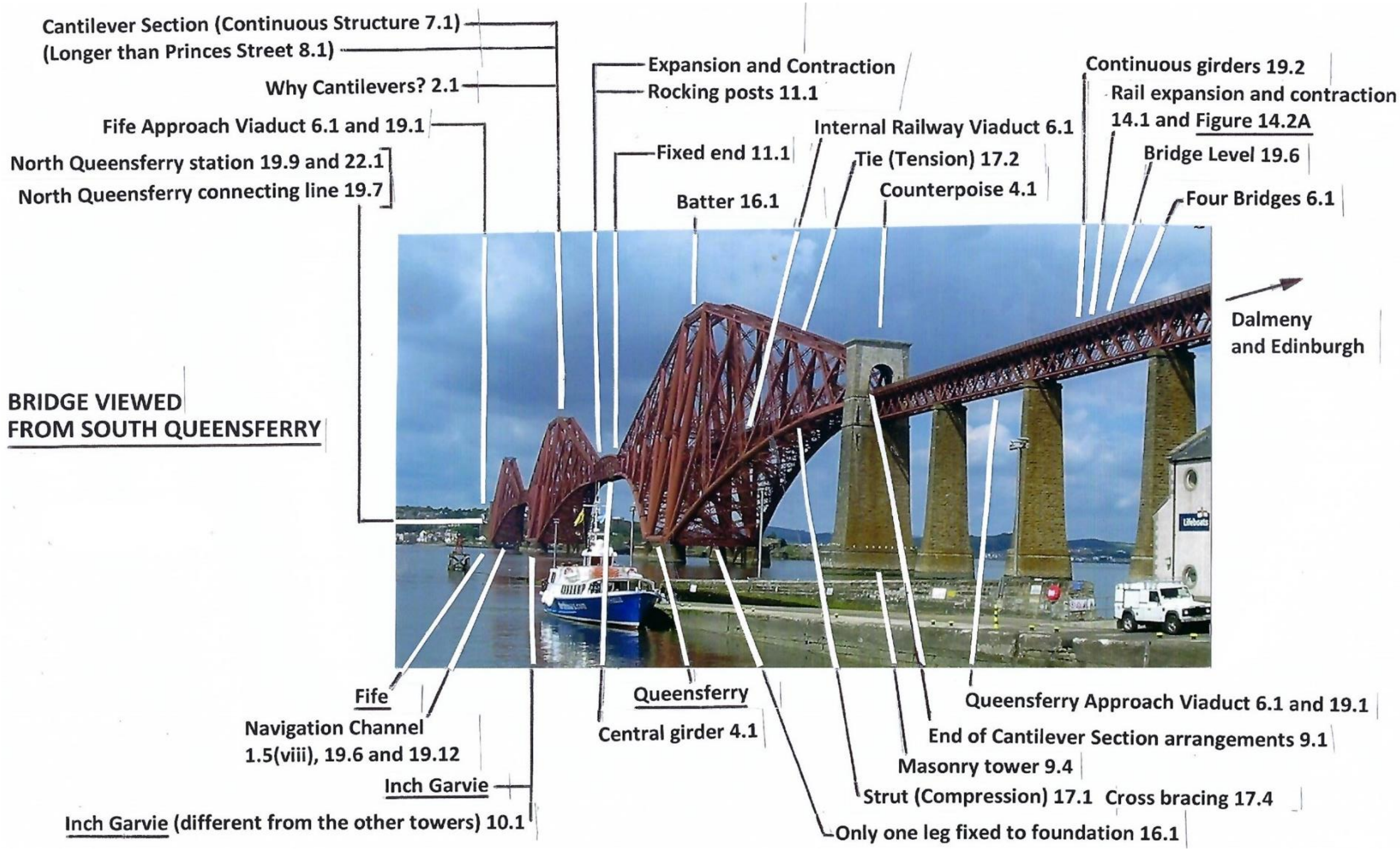
A view of the bridge from South Queensferry (Figure 23.1), and the corresponding view from North Queensferry (Figure 23.2), give a quick means of access to 20 typical points of interest, and obtaining the relevant paragraph number/s.

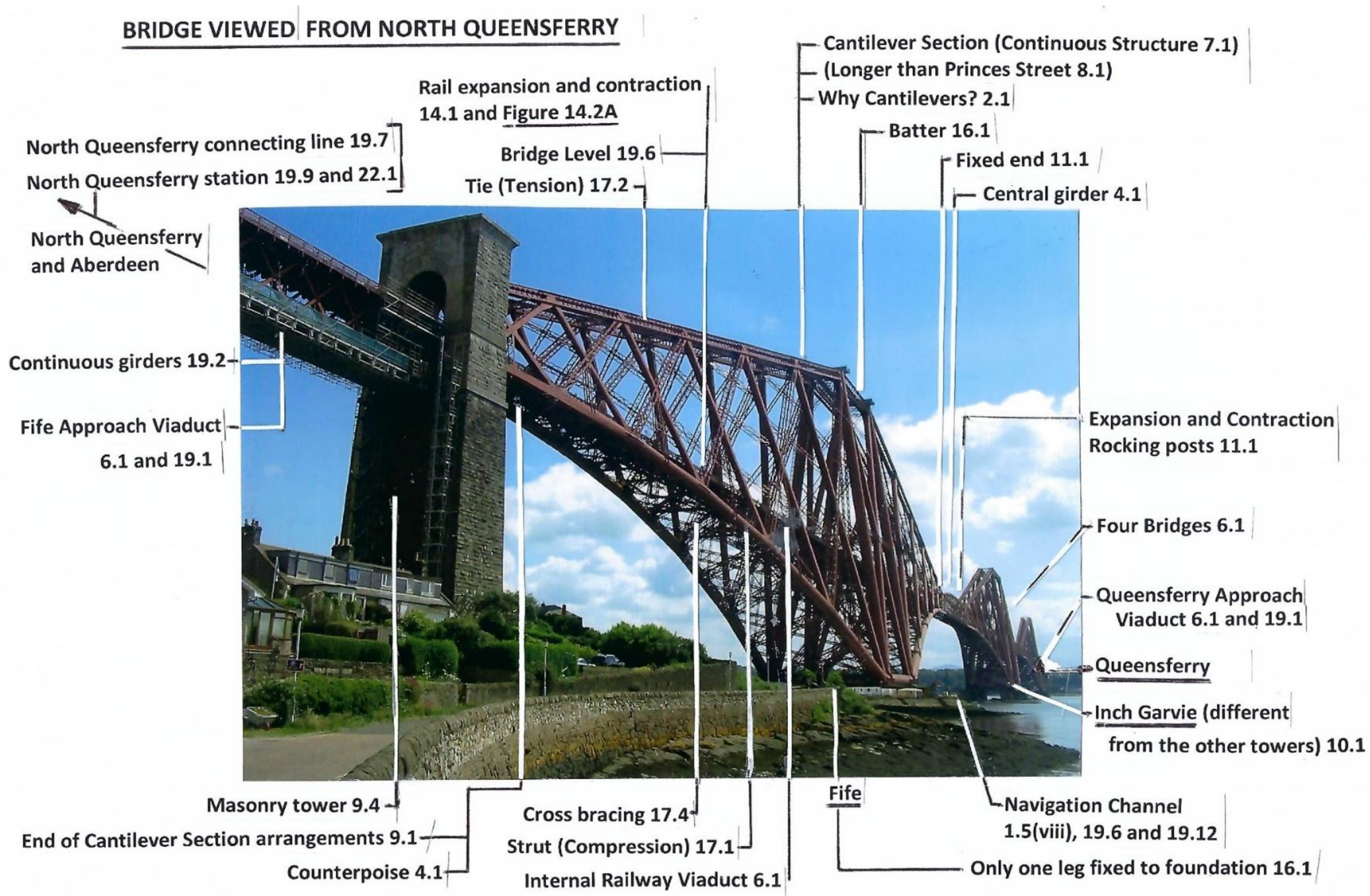
23.1 Standing beside the Forth Bridge at either South or North Queensferry gives an excellent appreciation of it's size, especially the enormity of the 51,000 tons (51,818 tonnes) of the Cantilever Section.

23.2 Figure 23.1 shows the bridge when viewed from it's west side at South Queensferry and Figure 23.2 shows the view from the same side at North Queensferry.

23.3 Superimposed on the Figures is reference information (clause numbers) to give quick access to explanations.

Figure 23.1


Cantilever Section (Continuous Structure 7.1)
(Longer than Princes Street 8.1)
Why Cantilevers? 2.1
Fife Approach Viaduct 6.1 and 19.1
North Queensferry station 19.9 and 22.1
North Queensferry connecting line 19.7
Expansion and Contraction
Rocking posts 11.1
Fixed end 11.1
Batter 16.1
Internal Railway Viaduct 6.1
Tie (Tension) 17.2
Counterpoise 4.1
Continuous girders 19.2
Rail expansion and contraction
14.1 and Figure 14.2A
Bridge Level 19.6
Four Bridges 6.1
Dalmeny
and Edinburgh
BRIDGE VIEWED
FROM SOUTH QUEENSFERRY
Fife
Navigation Channel
1.5(viii), 19.6 and 19.12
Inch Garvie
Inch Garvie (different from the other towers) 10.1
Queensferry
Central girder 4.1
Queensferry Approach Viaduct 6.1 and 19.1
End of Cantilever Section arrangements 9.1
Masonry tower 9.4
Strut (Compression) 17.1
Cross bracing 17.4
Only one leg fixed to foundation 16.1



BRIDGE VIEWED FROM NORTH QUEENSFERRY
Rail expansion and contraction 14.1 and Figure 14.2A
North Queensferry connecting line 19.7
North Queensferry station 19.9 and 22.1
Bridge Level 19.6
Tie (Tension) 17.2
North Queensferry and Aberdeen
Cantilever Section (Continuous Structure 7.1)
(Longer than Princes Street 8.1)
Why Cantilevers? 2.1
Batter 16.1
Fixed end 11.1
Central girder 4.1
Continuous girders 19.2
Fife Approach Viaduct 6.1 and 19.1
Expansion and Contraction Rocking posts 11.1
Four Bridges 6.1
Queensferry Approach Viaduct 6.1 and 19.1
Queensferry
Inch Garvie (different from the other towers) 10.1
Masonry tower 9.4
End of Cantilever Section arrangements 9.1
Counterpoise 4.1
Cross bracing 17.4
Strut (Compression) 17.1
Internal Railway Viaduct 6.1
Fife
Navigation Channel 1.5(viii), 19.6 and 19.12
Only one leg fixed to foundation 16.1

Figure 23.2

24. FORTH BRIDGE COMPARED WITH COLNE VALLEY VIADUCT AND HOW TO BECOME A CIVIL ENGINEER

MAIN DESIGN CHALLENGES

Forth Bridge (opened 1890) and Colne Valley Viaduct (under construction in 2023 for HS2, High Speed London/Birmingham Line)

Steel used for the first time for a major UK Bridge

Balanced Cantilevers with Central Girders between

Exceptional Expansion and Contraction (52,000 tonnes of steel)

High Winds (Gales)

Hammer Blow loads from steam engines

908 Precast Concrete units, each with unique dimensions, and steel tension bars.

320kph (200mph) trains on curved track causing Centrifugal Force

Retardation Forces from trains having to reduce speed from high speed

Expansion and Contraction

Substantial public concern about landscape intrusion

Asthetics capable of addressing public objection

Figure 24.1

HOW TO BECOME A CIVIL ENGINEER

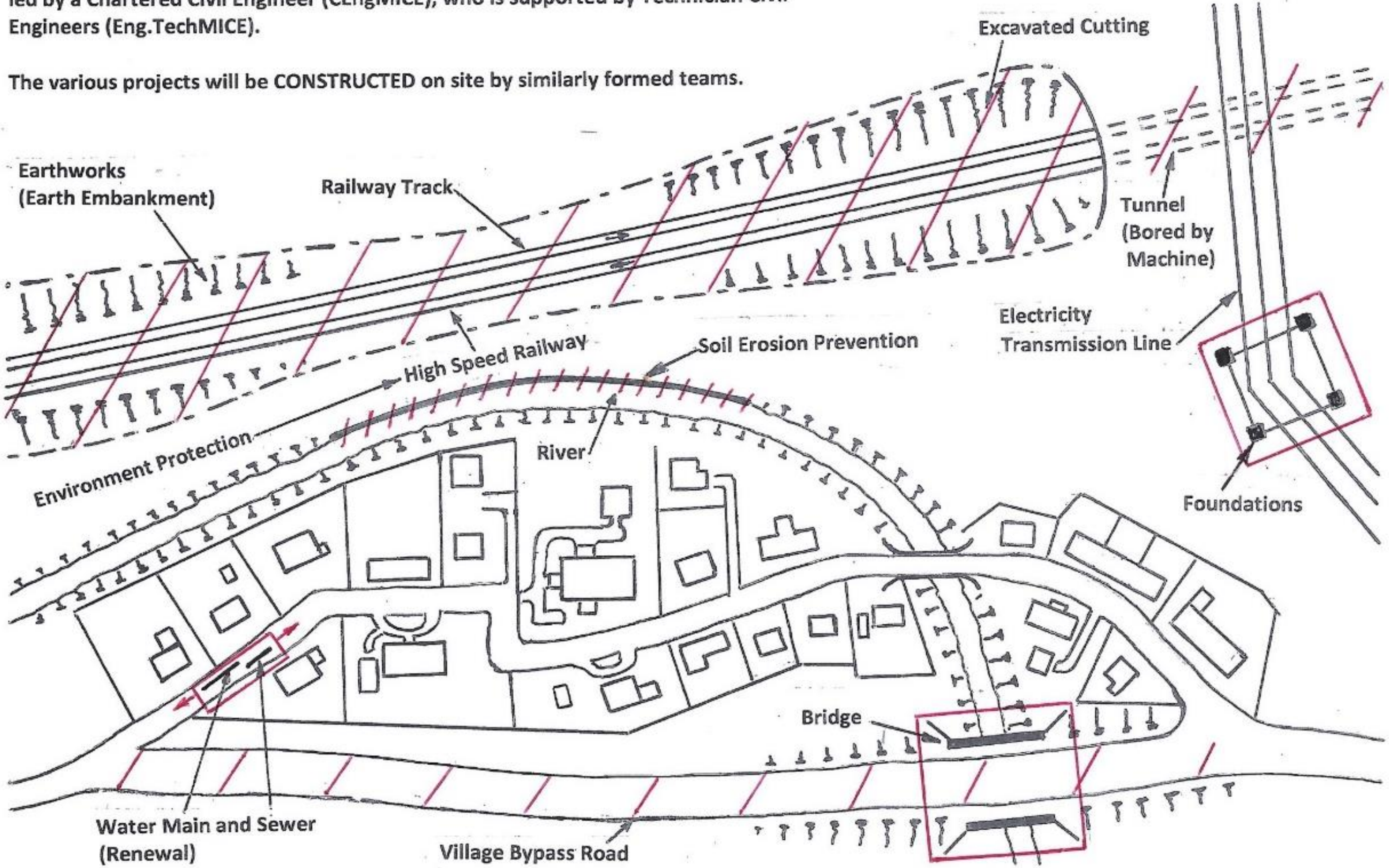
Civil Engineers design and construct many types of projects, only some of which are shown on page 91.

For information about the Institution of Civil Engineers and civil engineering careers, go to:-

ice.org.uk

Each of these civil engineering projects is being DESIGNED by a team of Civil Engineers, led by a Chartered Civil Engineer (CEngMICE), who is supported by Technician Civil Engineers (Eng.TechMICE).

The various projects will be CONSTRUCTED on site by similarly formed teams.



25. Acknowledgements

Ben Howe, Max Howe and Lorna Dorward for advice.
Gordon Pettitt OBE, former Managing Director, Regional Railways, for advice.
Christine Herne for production of several drafts.

26. References

‘The Forth Bridge’- Paper by W. Westhofen, reprinted in ‘Engineering’ 28 February 1890 and held in the Institution of Civil Engineers’ archive. Wilhelm Westhofen was born in 1842 in Mainz, Germany and moved to London in 1867. He became an Assistant Engineer on the building of the Forth Bridge, with responsibilities for the construction of the Inch Garvie Cantilevers. Fortunately, he produced the most authoritative and detailed account of the design and construction of the Bridge. In 1891, he moved to South Africa and worked on the building of the Gouritz River Bridge, which was designed by Sir Benjamin Baker, one of the principal Forth Bridge designers.

‘100 years of the Forth Bridge’- edited by Roland Paxton

‘The Forth Railway Bridge – A Celebration’ by Anthony Murray

‘Edinburgh’s Railways’ by W.A.C. Smith and Paul Anderson.

APPENDICIES

1. Miscellaneous
2. The Tay Bridge Disaster (1879) and the replacement bridge
3. The ‘Railway Races’
4. Bridge loading test in 1952 and exceptional trains in 1899
5. The next major development for the Forth Bridge?
6. Gradient Diagram, Saughton Junction/Inverkeithing
7. Bridge drawings
8. Access to the bridge from Dalmeny and North Queensferry stations
9. Forth Road Bridge and Queensferry Crossing

Appendix 1

Miscellaneous;

The bridge is subject to the following speed restrictions;

- 50 mph Passenger Trains
- 20 mph Freight Trains

These maximum permitted speeds were determined by the impact on the bridge of axle loads, the loads increasing as speed increases.

The bridge’s route availability index is RA8. RA10 is the maximum. RA8 means that a vehicle or locomotive of RA8 or less is permitted to use the bridge. RA relates to axle loading.

Number of trains each day is approximately 200 (mainly passenger trains).

Painting the Forth Bridge

As the bridge is now painted with the type of long-lasting paint used on North Sea oil rigs, the phrase ‘it is just like painting the Forth Bridge’ to describe a never ending activity, is no longer appropriate.

Dates;

First Tay Bridge collapsed (The Tay Bridge Disaster)	1879	
Present day Tay Bridge opened	1887	
Forth Bridge opened	1890	
Forth Bridge Railway Company nationalised	1948	(The present owner of the bridge is Network Rail)
Forth Bridge designated a World Heritage Site.	2015	
Forth Road Bridge opened (suspension bridge).	1964	
Queensferry Crossing opened (cable stayed bridge)	2017	

Appendix 2

The Tay Bridge Disaster (1879) and the Replacement Bridge

On the night of the Tay Bridge Disaster, eleven years before the Forth Bridge opened, the journey that ended so tragically started in Edinburgh with the 4.15pm train from Waverley station to Granton. The passengers transferred as usual to the passenger ferry for the crossing over the River Forth to Burntisland. They then boarded the 5.27pm train for Dundee, on the north side of the River Tay. However, the weather was atrocious with a fierce gale blowing. As the train, when only a short distance from Dundee, was passing through the 'High Girders' of the Tay Bridge, this portion of the bridge collapsed, plunging the train into the water and resulting in the death of 79 people.

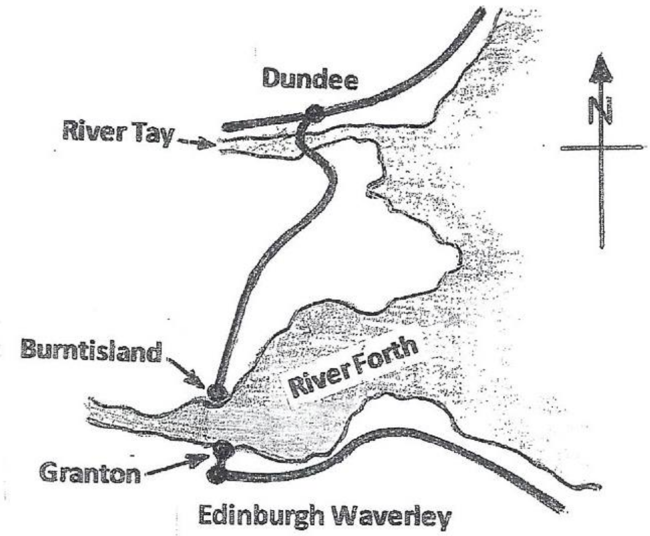


Figure A2.1

A replacement Tay Bridge (the one in operation today) was opened in 1887, eight years after the disaster. Sir Thomas Bouch, the designer of the first bridge, died in Moffat ten months after the disaster, aged 58.

Unlike the single line bridge that collapsed, today's bridge has double track and therefore able to handle the traffic of a main line railway, in this case the East Coast Main Line.

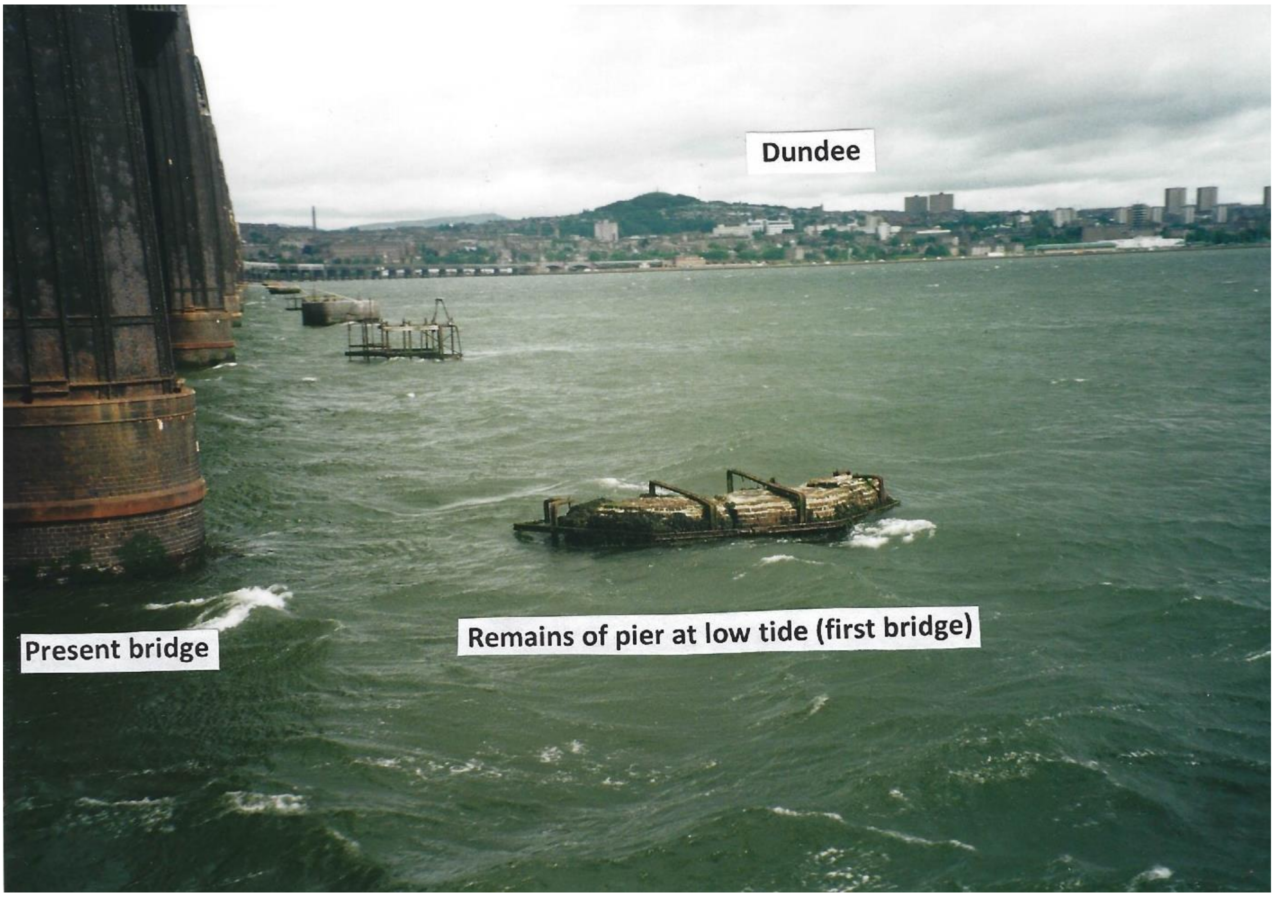


Figure A2.2 The lower part of the piers of the first Tay Bridge (Single Line) were not removed when the bridge was dismantled after the Disaster. They can be seen at low tide on the east side of the present double track bridge.

Appendix 3

The 'Railway Races'

The map below shows how the Tay Bridge, and then in 1890, the Forth Bridge, enabled the railway companies that ran the East Coast Main Line between London King's Cross and Aberdeen, to compete with those companies that ran the West Coast Main Line between London Euston and Aberdeen. The West Coast route did not need to cross any very wide rivers and certainly not one as challenging as the Forth.

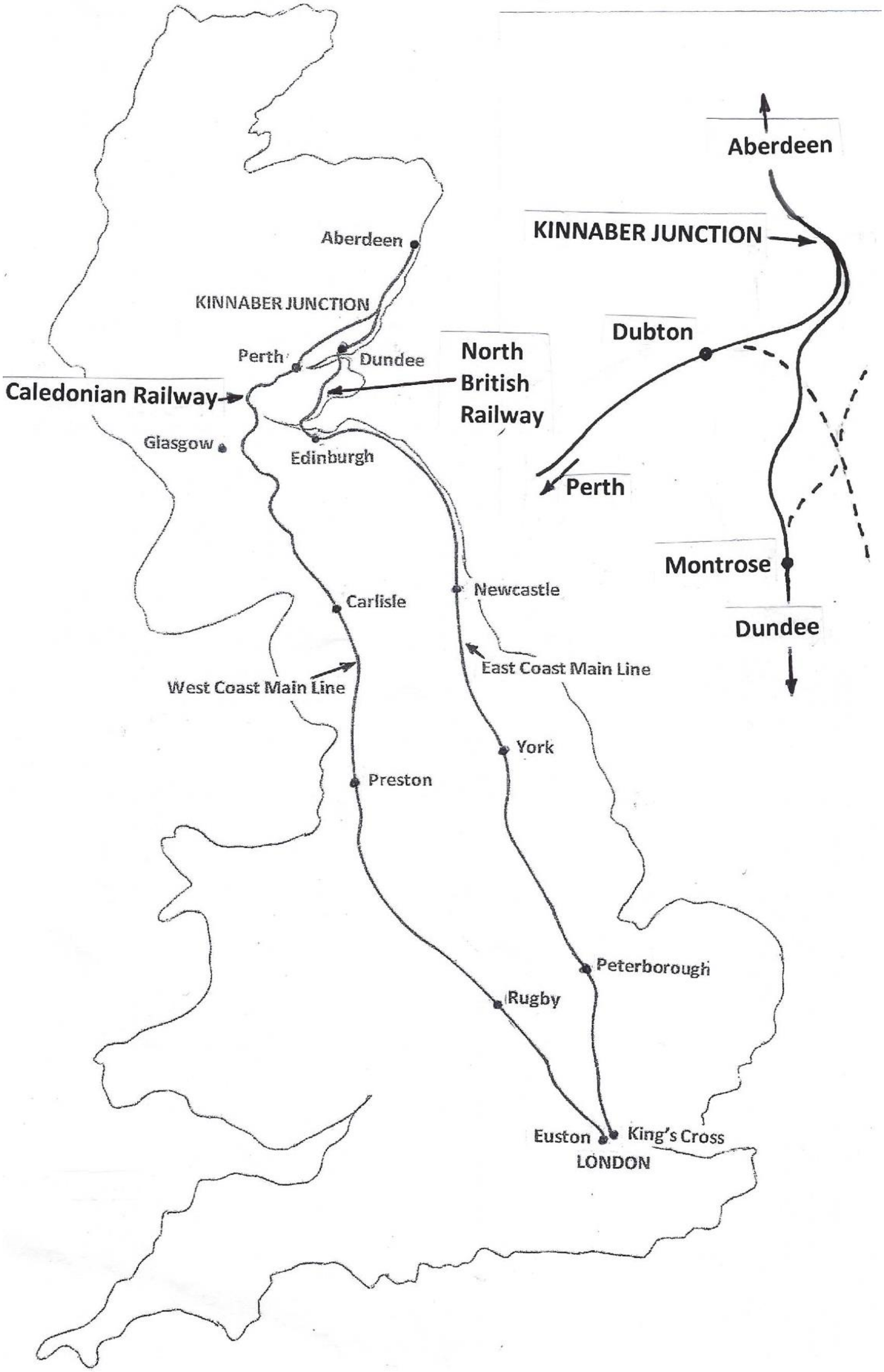

Aberdeen
KINNABER JUNCTION
Perth
Dundee
North British Railway
Caledonian Railway
Glasgow
Edinburgh
Newcastle
Carlisle
East Coast Main Line
West Coast Main Line
York
Preston
Peterborough
Rugby
Euston
King's Cross
LONDON
Aberdeen
KINNABER JUNCTION
Dubton
Perth
Montrose
Dundee

Figure A3.1

Within a few years of there being two continuous railways between London and Aberdeen, the "unofficial" "Great Railway Races to the North" started. The objective was to establish which route provided the quickest service between London and Aberdeen. In fact, the race was won each day by which ever train reached Kinnaber Junction, north of Montrose, first as the West Coast and East Coast routes merged there. The portion of the route between Kinnaber Junction and Aberdeen was operated by the Caledonian Railway, which ran the Scottish part of the West Coast Main Line.

'The Railway Magazine' of January 1952 had an article regarding the signalling of the two trains during the early hours of Monday 19th August 1895.

The East Coast train from London King's Cross was offered by the North British Railway Signalman at Montrose to the Signalman at Kinnaber Junction at the same time as the Kinnaber Junction Signalman was offered the West Coast train by the Caledonian Railway Signalman at Dubton. (See diagram)

The Kinnaber Junction Signalman, who was employed by the Caledonian Railway, had to decide very quickly which train to accept first, bearing in mind that that train would reach Aberdeen first and win that day's race.

He decided to accept the East Coast train from the North British Signalman at Montrose (the 'opposition') thereby creating a memorable piece of railway folklore. (The offering and acceptance of trains was done by the use of bell codes).

The West Coast Main Line between Stanley Junction, just north of Perth, and Kinnaber Junction, was closed in the 1960s. Trains now travel between Perth and Aberdeen via Dundee. The route between Perth and Dundee is along the north side of the River Tay.

Appendix 4

Bridge Loading Test in 1952 and exceptional trains in 1899

For many years, engineers limited the maximum permissible steam locomotive loading on the Cantilevers to an ex LNER Class A4, 4-6-2 such as 60009 'Union of South Africa', double-headed with an ex LNER Class D49, 4-4-0. Although the instances on which an A4 would require assistance were relatively few, in 1952 British Railways Operating Department in Edinburgh asked the Civil Engineering Department's engineers to determine if, instead of using a D49 locomotive, a more powerful, and thereby heavier, ex LNER Class B1 4-6-0 could be used to double-head a train on a journey that involved crossing the bridge with a Class A4 locomotive. The possibility of the more powerful engine increasing hammer blow would have been a concern to the engineers conducting the tests. (See Section 17).

So, on Sunday 20 April 1952 a special train composed of B1 61076 and an A4 travelled from Edinburgh to the bridge to carry out test runs at various speeds. Feredy Palmer Stress Recorders were used to measure the stresses imposed on the bridge by the passage of the heavier load.

The tests established that it was acceptable for a train on the bridge to be double headed by an A4 and B1.

The reason for the request may have been due to normally there being more B1s available in the area than D49s.

Today, it is mainly the high axle loads of modern freight wagons rather than the impact of diesel locomotives that concerns the engineers responsible for determining load restrictions for the bridge.

The permitted double heading of a Class A4 steam engine with a Class D49 engine seems to have been a standard maximum load restriction of the period. For instance, this combination of steam engines was used to test the temporary bridges built in record time in the Grantshouse area when several East Coast Main Line bridges were swept away during extreme flooding in 1948.

Figure A4.1 The engine types used in the test.
Note:- The Class A4 4-6-2, 60022 'Mallard' holds the World Speed Record for steam engines (126mph)

Barnum and Bailey's Circus trains use the Forth Bridge

Nine years after the Forth Bridge opened, the famous American circus, Barnum and Bailey *'The Greatest Show on Earth'* toured the UK, using four special constructed trains. During the visit to Scotland, the trains crossed the Forth Bridge overnight on three separate occasions:-

Thursday 31 August 1899/Friday 1 September (Falkirk to Dunfermline)
Saturday 2/ Sunday 3 September (Kirkcaldy to Edinburgh)
Saturday 9/Sunday 10 September (Edinburgh to Dundee)

Although it was not a bridge loading concern, the trains were exceptionally long, heavy and restricted at all times to 25 mph. The four trains ran 30 minutes apart. The following diagram shows their length in comparison with the main spans.

The journey from Kirkcaldy to Edinburgh (Gorgie) also involved the 1 in 70 rising gradient between Inverkeithing and the Forth Bridge. (See Figure 19.6). Consequently, an extra steam engine was probably attached to the rear of each train at Inverkeithing to assist the two engines at the front.

The trains conveyed circus personnel, many horses and elephants.

Figure A4.2 The white strip represents one of the circus trains
A typical long passenger train would probably be about 25% shorter

Appendix 5

The next major development for the Forth Bridge?

Although the East Coast Main Line is electrified between London King's Cross and Edinburgh, the portion between Edinburgh and Aberdeen, which of course includes the Forth and Tay Bridges, depends on diesel trains.

Bearing in mind the drive towards decarbonisation of rail services, it is foreseeable that the Forth and Tay Bridges will, at some time in the future, be carrying electric trains.

The Azuma trains used by LNER for their London King's Cross/ Aberdeen service operate as electric trains between London and Edinburgh and, 'at the flick of a switch', as diesels between Edinburgh and Aberdeen.

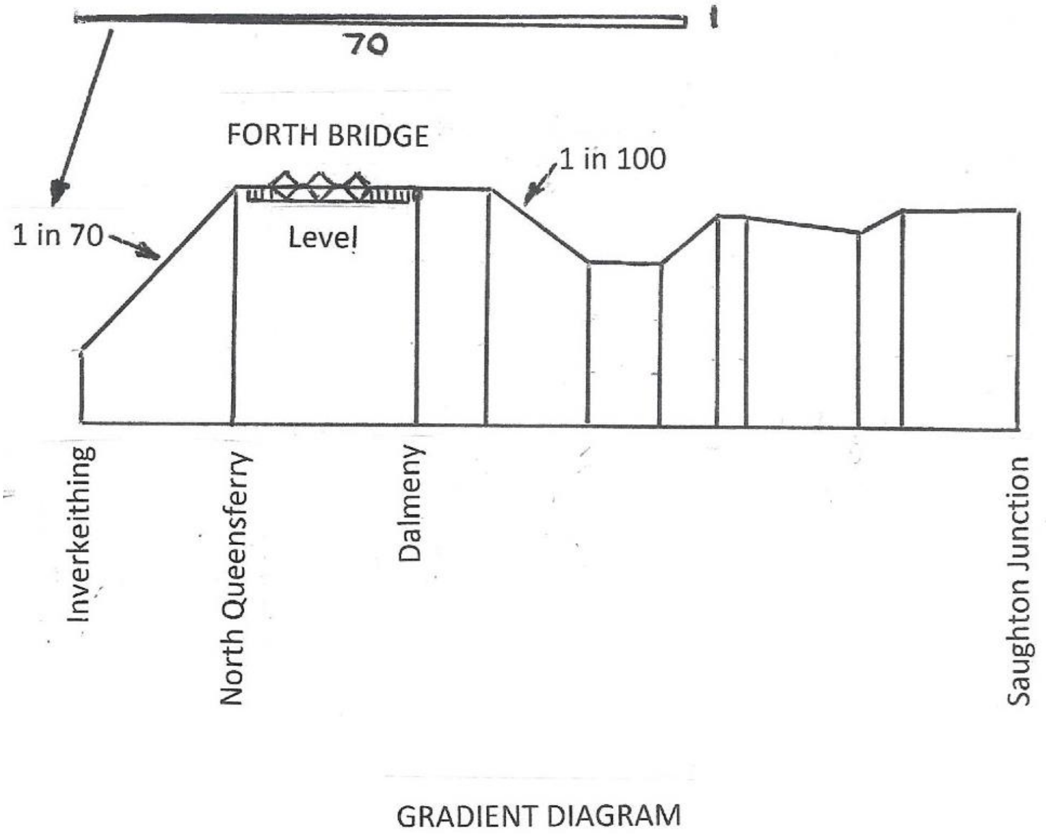
The provision of 25kV (25,000 volts) Overhead Line Equipment for electric trains on the Forth and Tay Bridges could be controversial regarding the visual impact that the necessary masts would have on aesthetics. Masts would not be needed within the Cantilever Section of the Forth Bridge nor within the High Girders Section of the Tay Bridge, as the Overhead Line Equipment could be suspended from the array of steelwork that already exists above the tracks. However, the Queensferry and Fife approach viaducts of the Forth Bridge and much of the Tay Bridge, would require masts for the Overhead Line Equipment, unless the trains could switch to battery operation, for their passage over the bridges, with pantographs in the lowered position.

Figure A5.1 LNER Azuma train at Edinburgh Waverley station
Note:- The present day LNER is ***not*** connected to the LNER formed as one of the 'big four' in 1923, and disbanded in 1948 when the railways were nationalised

Figure A5.2 Pantograph on an Azuma train in the raised position and in contact with the 25kV (25,000 volts) Overhead Line Equipment.

In November 2021, an experimental battery powered passenger train crossed the Forth Bridge. This demonstrated the possibility of having electrically powered trains on the bridge without the need for Overhead Line Equipment carrying high voltage electricity.

Appendix 6 GRADIENT DIAGRAM. SAUGHTON JUNCTION/INVERKEITHING



<u>Figure A6.1</u>

Appendix 7

Bridge Drawings

Some of the drawings produced by the contractor Sir William Arrol, for construction purposes, are lodged in the Mitchell Library in Glasgow. However, the library does not have any of the calculations produced by the bridge's designers. Also, there are no calculations shown in various papers produced by Benjamin Baker.

The paper by W. Westhofen mentioned in Section 26 contains many drawings.

Appendix 8

Access to the bridge from Dalmeny and North Queensferry stations

Dalmeny station is relatively near the south end of the bridge. A leisurely walk from the station to the bridge takes between 15 and 20 minutes. Much of the route involves a pathway which passes below the Queensferry Approach Viaduct and goes down a long flight of steps which lead to the main road that passes through South Queensferry.

The walk from North Queensferry station is downhill along streets which lead to the north end of the bridge and in particular, the part of the village that is directly under the bridge. It is this end of the bridge that can be viewed at reasonably close quarters.

A popular walk on a fine day starts at North Queensferry station, views the bridge at close quarters and then heads for the Forth Road Bridge, crossing the bridge as pedestrians and giving excellent views of the Forth Bridge, passes through the quaint part of South Queensferry and ends at Dalmeny station, which is reached using, in the reverse direction, the Dalmeny station route described above.

There is a good train service from Edinburgh Waverley and Haymarket to Dalmeny and North Queensferry.

Figure A8.1 Dalmeny station

Figure A8.2 The steps which lead to the main road at South Queensferry from Dalmeny station

A Shorter Visit

Alternatively, a very good shorter visit involves a train journey to Dalmeny station, the footpath to the bridge as already described and the steps already illustrated. The footpath enables a close view of the junction between the steelwork of the Queensferry Approach Viaduct and the four spans of masonry. On reaching the main road, excellent views of the bridge are possible by walking to the pier beside the bridge. Also , the harbour at the west end of the road that passes through the village gives a very good side view of the Cantilever Section.

There is a regular bus service (Route 43) to Princes Street in Edinburgh, from the nearby road called ‘The Loan’.

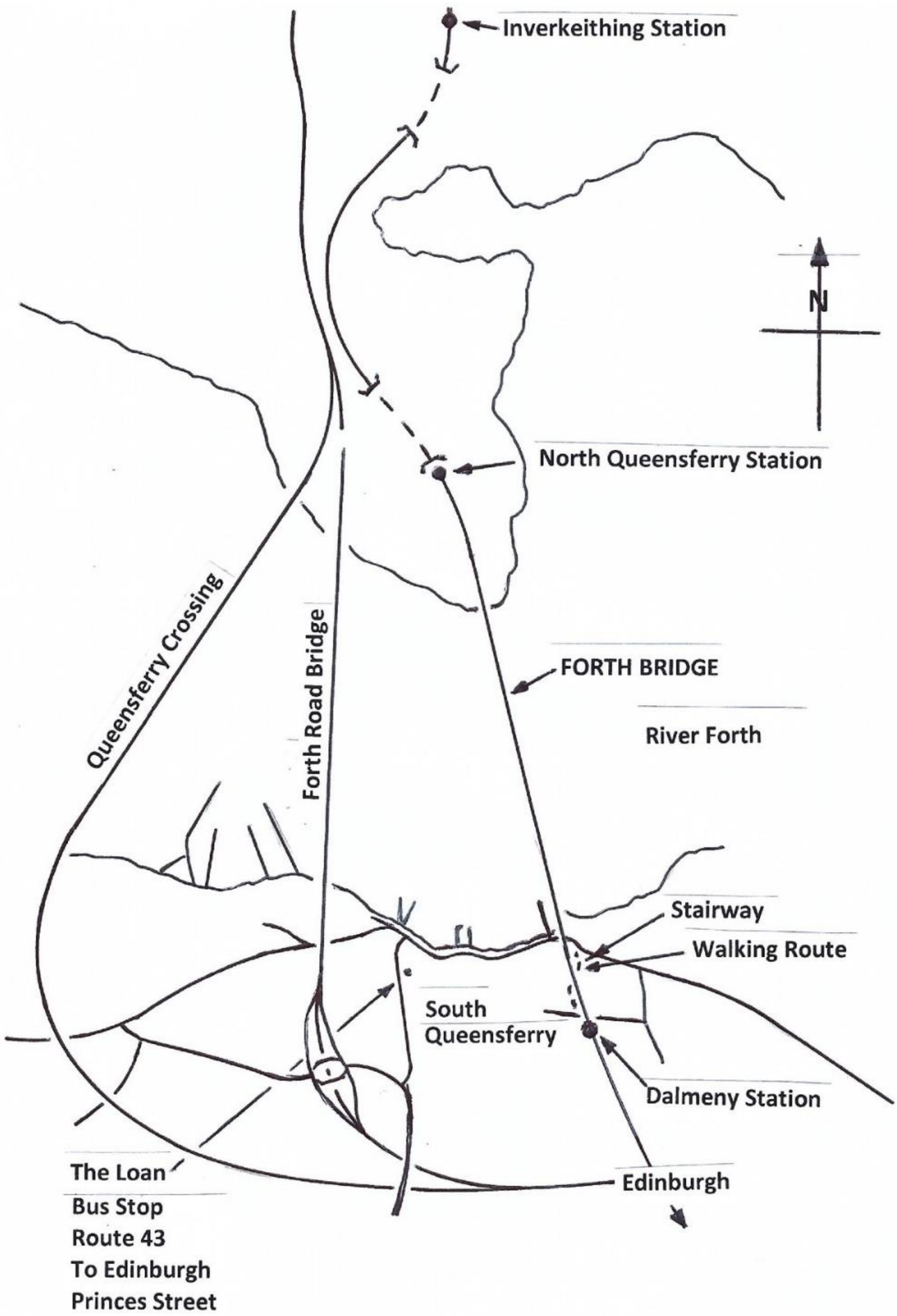

Inverkeithing Station
N
North Queensferry Station
Queensferry Crossing
Forth Road Bridge
FORTH BRIDGE
River Forth
Stairway
Walking Route
South
Queensferry
Dalmeny Station
Edinburgh
The Loan
Bus Stop
Route 43
To Edinburgh
Princes Street

Figure A8.3

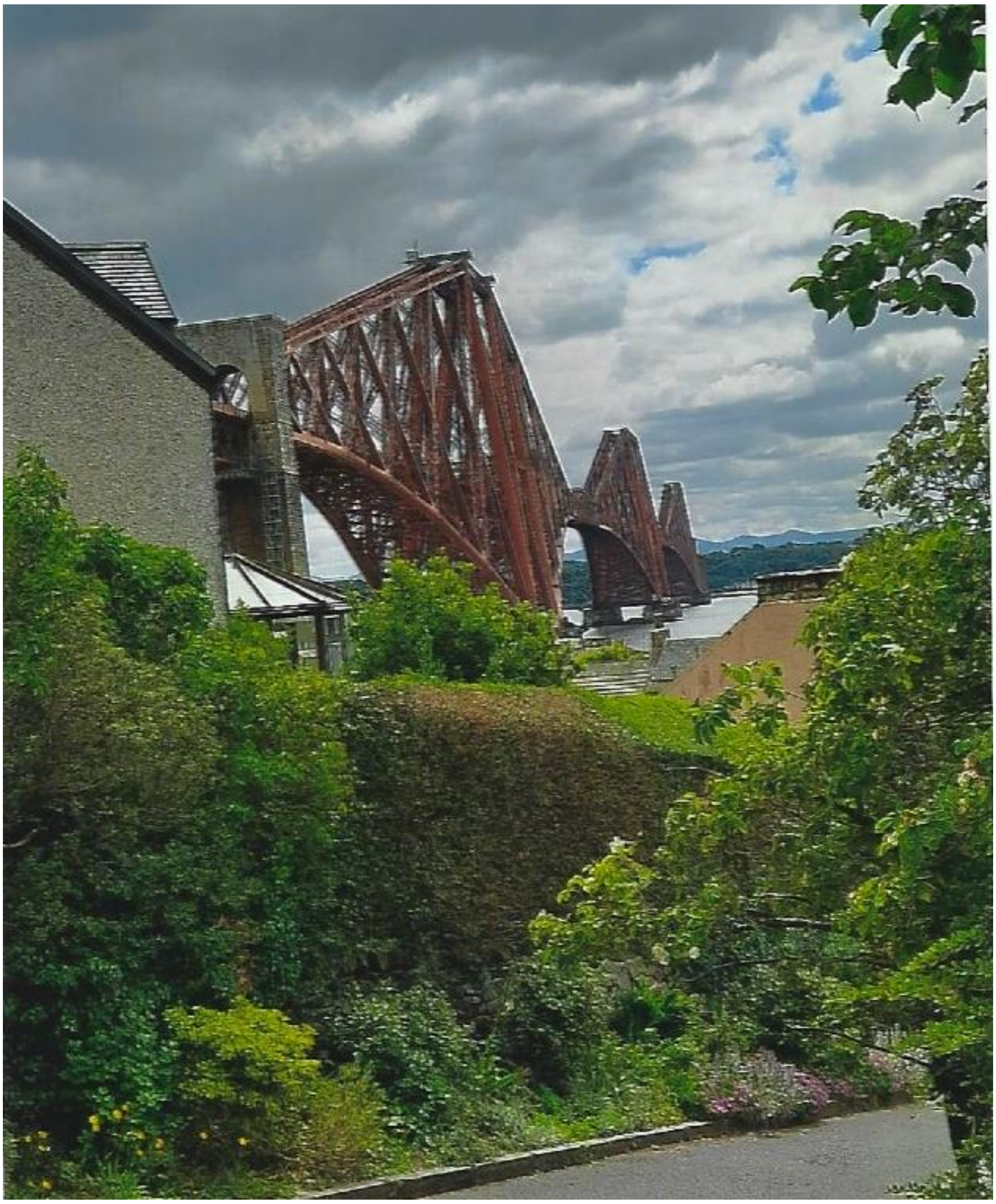
Figure A8.4 North Queensferry station

Appendix 9

The Forth Road Bridge and Queensferry Crossing

The Forth Bridge, opened in 1890, has two very important close neighbours, namely the Forth Road Bridge, opened in 1964 and the Queensferry Crossing opened in 2017, thereby making South Queensferry a location where three different types of long span bridges can be found. The Forth Bridge is of course an excellent example of Balanced Cantilevers, the Forth Road Bridge is a suspension bridge and the Queensferry Crossing is a cable stayed bridge with an interesting variation from the normal as a result of the need for interlacing of stays to give adequate stability. The use of the Forth Road Bridge is now restricted to buses, taxis, pedestrians and cyclists.

Queensferry Crossing Forth Road Bridge
Figure A8.5



Jim Dorward CEng MICE jimdorward@ntlworld.com

Jim Dorward, a retired railway civil engineer and a Member of the Institution of Civil Engineers, spent the first half of his career in the Civil Engineering Department of the Scottish Region of British Railways. This included work on the electrification of the West Coast Main Line between Gretna Junction and Glasgow (Central).

He was then very much involved in the management of major railway projects on the routes emanating from London's Waterloo and Victoria stations.

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