TEACHER GUIDANCE NOTES

THE WONDER

OF THE

FORTH BRIDGE

WORLD HERITAGE SITE

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‘And then this amazing Bridge came into view’

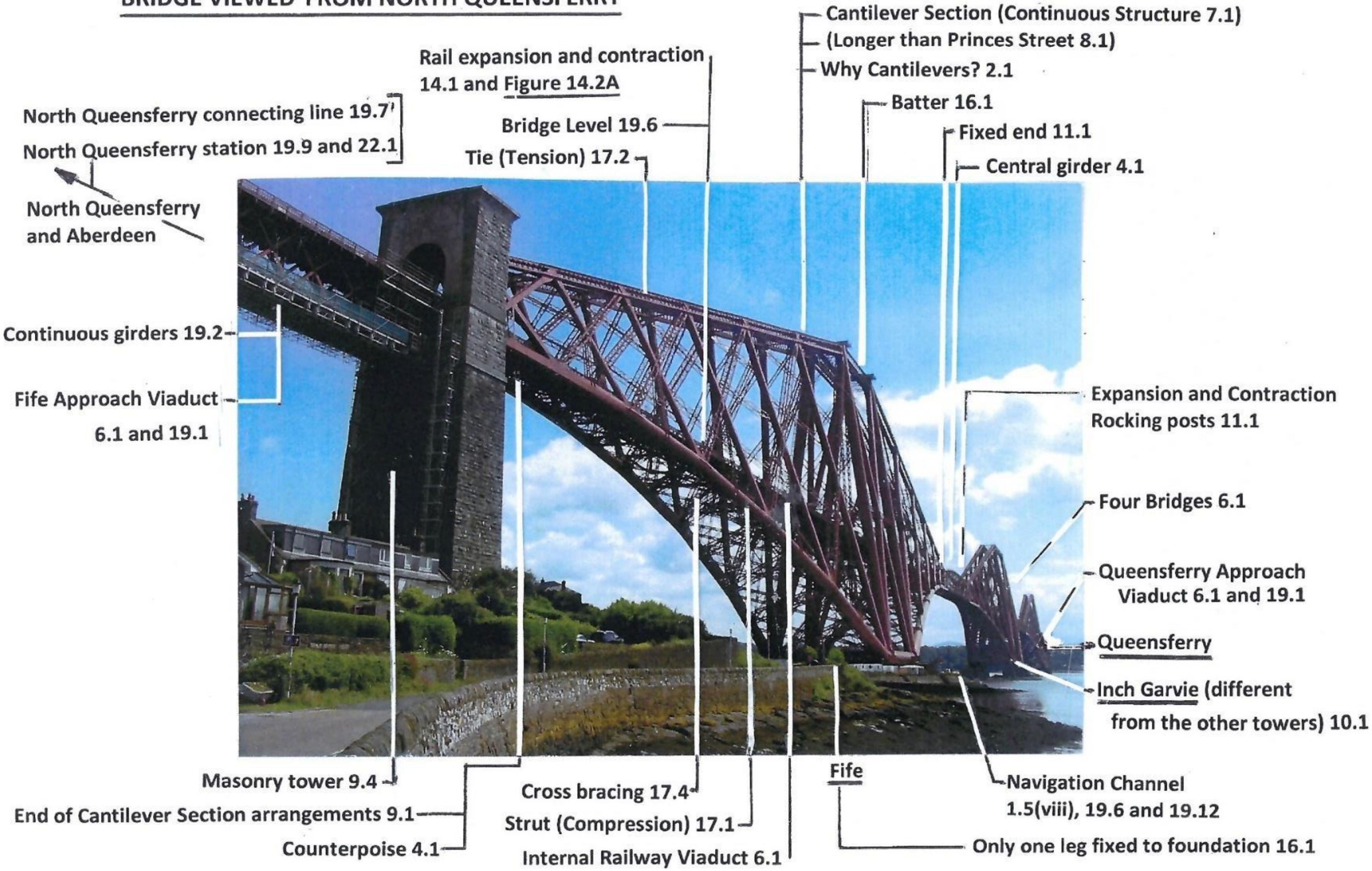
These Teacher Guidance Notes

- Refer to certain Sections, Paragraphs and Figures in the main pdf,
- Provide an easy way of finding the Section, Paragraph or Figure number for a particular item of interest in the main pdf,
- Provide, in connection with the main pdf’s Introduction (Section 1), additional information regarding the Bridge’s History and Geography,
- Provide Important Supplementary Information. (See CONTENTS),
- Provide information regarding ‘The Pioneers’ who designed, approved and financed the Bridge. (See CONTENTS).

CONTENTS Page

BRIDGE VIEWED FROM SOUTH QUEENSFERRY

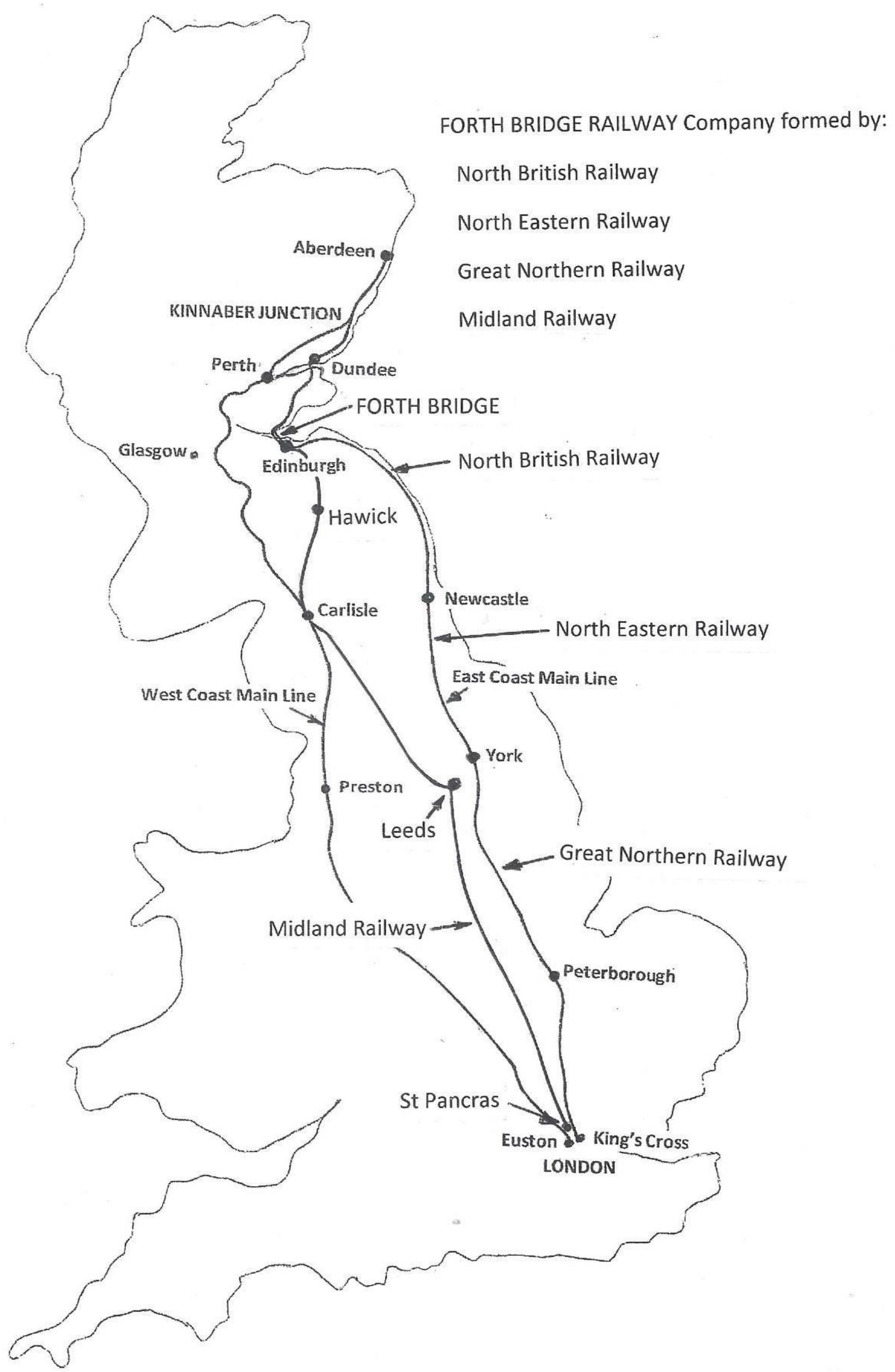
BRIDGE VIEWED FROM NORTH QUEENSFERRY



Section 1.

Additional information regarding the Bridge's History and Geography.

The Forth Bridge Railway Company (FBR) was formed by the three East Coast Main Line Companies, plus the Midland Railway.



The cost of the Bridge was split between the four companies as follows:

North British	35%	Berwick Upon Tweed/Kinnaber Jn. (North of Montrose) Carlisle/Edinburgh via Hawick
Midland	30%	London St Pancras/Carlisle via Leeds
North Eastern	17.5%	York/Berwick Upon Tweed
Great Northern	17.5%	London King's Cross/York

The Chair of the Forth Bridge Railway Company was held by the Chair of each of the four companies in rotation, the term of office being one year. The Secretary of the FBR was the Secretary of the North British Railway.

Before the Forth Bridge was built, the journey between Edinburgh and Dundee took about 2 hours 30 minutes given the need for a journey by ferry across the River Forth between Granton, in north Edinburgh, and Burntisland. (Edinburgh Waverley/Granton/Burntisland was approximately 8.75 miles, 14.1 km).

Part of Granton Harbour in 2024

After the Bridge was built, the railway mileage travelled was longer but the journey took just under 2 hours with awkward transfers between train and the 8 km. ferry trip no longer required. (Edinburgh Waverley/Forth Bridge /Burntisland is 20.25 miles, 32.6 km).

The North British Railway had Running Powers over the Caledonian Railway between Kinnaber Junction, north of Montrose, and Aberdeen, to enable the East Coast Main Line to reach Aberdeen.

The willingness of certain English railway companies (GNR, NER and MR) to make a substantial financial commitment towards the funding of the Bridge, reflected the expected volumes of new Anglo-Scottish passenger and freight traffic (e.g. Peterborough/Aberdeen) that the Bridge would generate. The total expected volumes of new Anglo-Scottish traffic probably exceeded the amount of new traffic that would be exclusively on the NBR (e.g. Edinburgh/Dundee).

The Railway Clearing House in London was the organisation responsible for attributing portions of revenue to railway companies in respect of journeys that involved more than one company (e.g. Peterborough/Aberdeen involved the GNR, NER and the NBR). However, there was a special financial arrangement, authorised by Act of Parliament, regarding trains using the Forth Bridge, to reflect the immense cost of building and maintaining it. Therefore, the Forth Bridge Railway's revenue was obtained from an unusual tolls system.
For instance, a journey from Edinburgh (Waverley) to Newtyle, a station on the Caledonian Railway (CR) between Dundee (West) and Alyth Junction on the West Coast Main Line, covered a distance of 76 miles (122 km) and involved travelling over the Forth Bridge, deemed by the toll system to be 19 miles (31 km) long (instead of 1.75 miles), a considerable, but necessary exaggeration. Therefore, the mileage revenues for the journey were:-

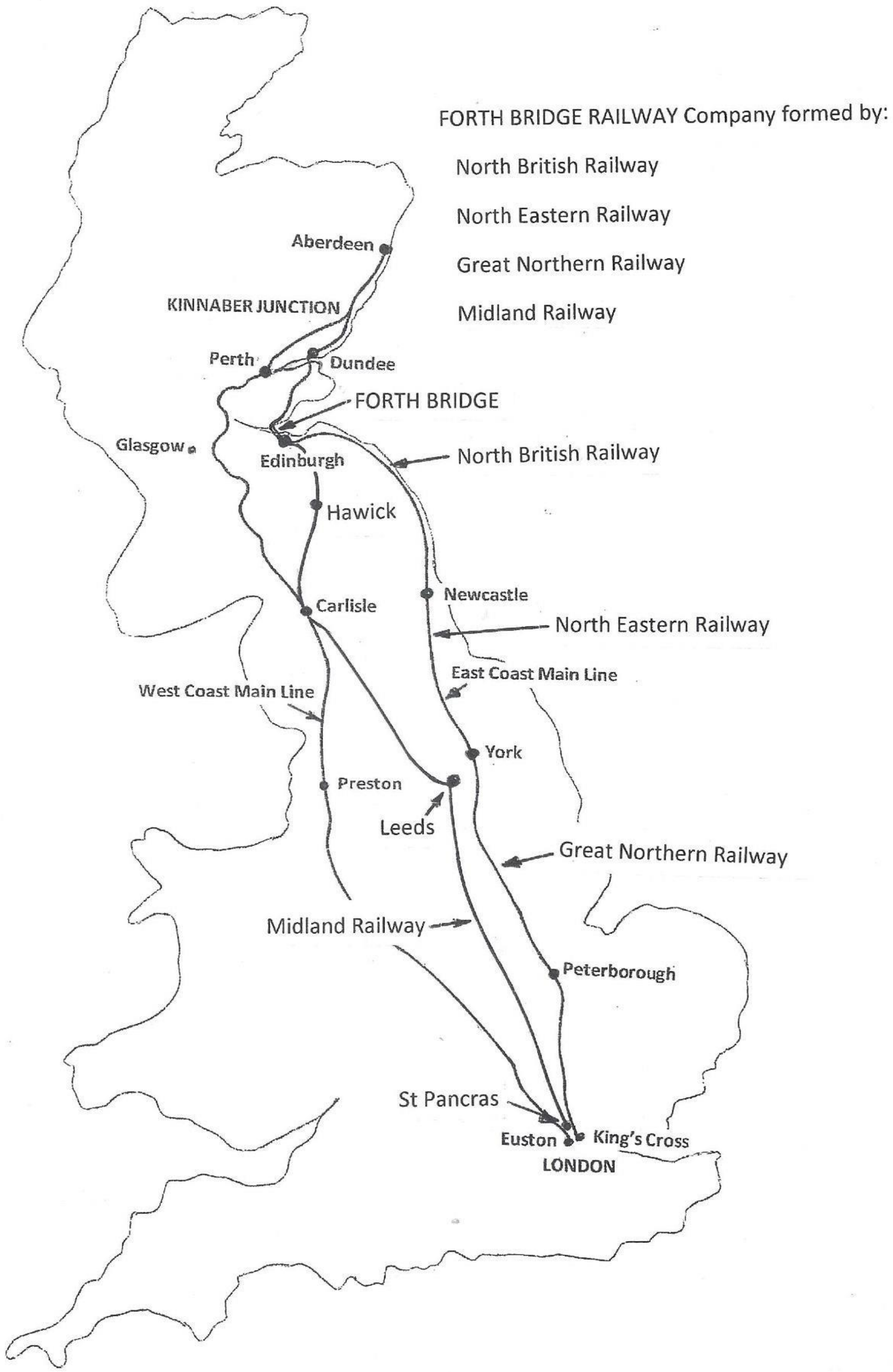
		Miles
NBR	Edinburgh (Waverley)/Dundee	9.5
FBR	Dalmeny/North Queensferry	19.00 (actually 1.75)
NBR	North Queensferry/Dundee(Tay Bridge)	48.00
CR	Dundee (West)/Newtyle	16.75
		93.25 (150 km)

Note A short walk was required between the two stations at Dundee.

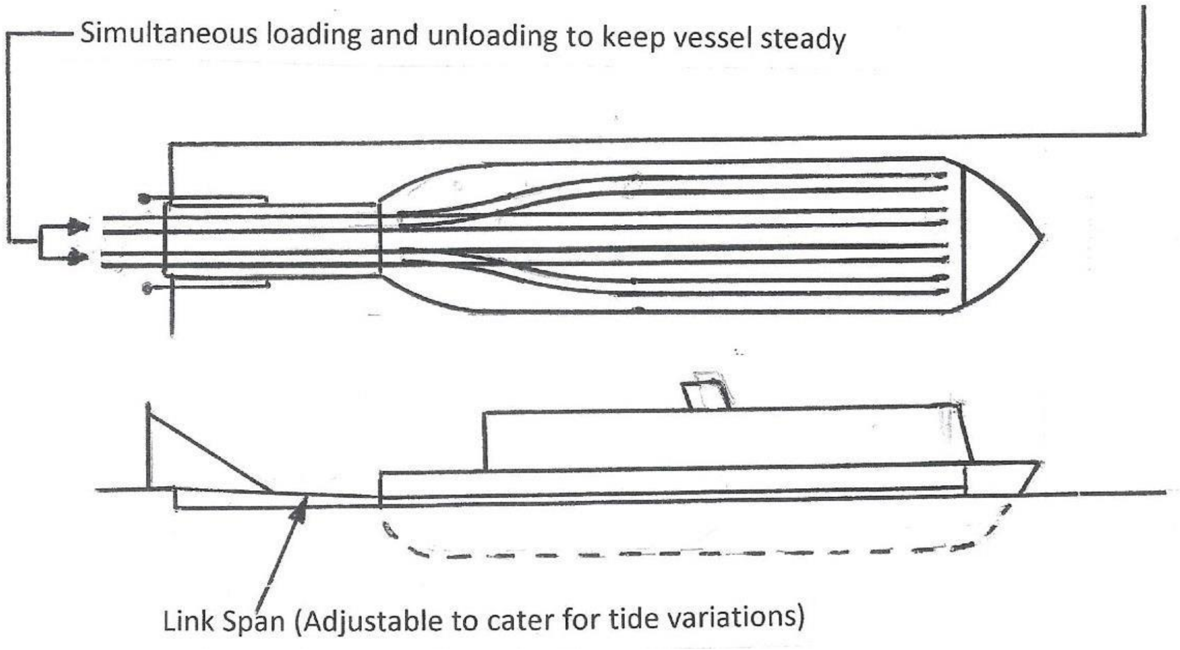
The opening of the Forth Bridge in 1890 and the already opened second (replacement) Tay Bridge considerably increased the overall economy of Fife, 'the County that needed a bridge to get into and another to get out of!'

In 1948 , the FBR was one of 25 unusual railway undertakings acquired by the newly formed British Transport Commission, under the 1947 Transport Act, which introduced Railway Nationalisation in 1948. (The FBR did not own any trains).

The FBR was jointly owned by the LNER (not the present day LNER) and the LMS between 1923, when the LNER and LMS were formed, and 1948, when British Railways (BR) absorbed the FBR, BR being part of the British Transport Commission.



Although railway passengers crossed the River Forth by a passenger ferry until the Bridge was built, goods wagons were transported across the river by a train ferry, a very clever concept that was used, for instance, between Dover and Dunkerque until the Channel Tunnel was opened in 1994.



MODERN TRAIN FERRY

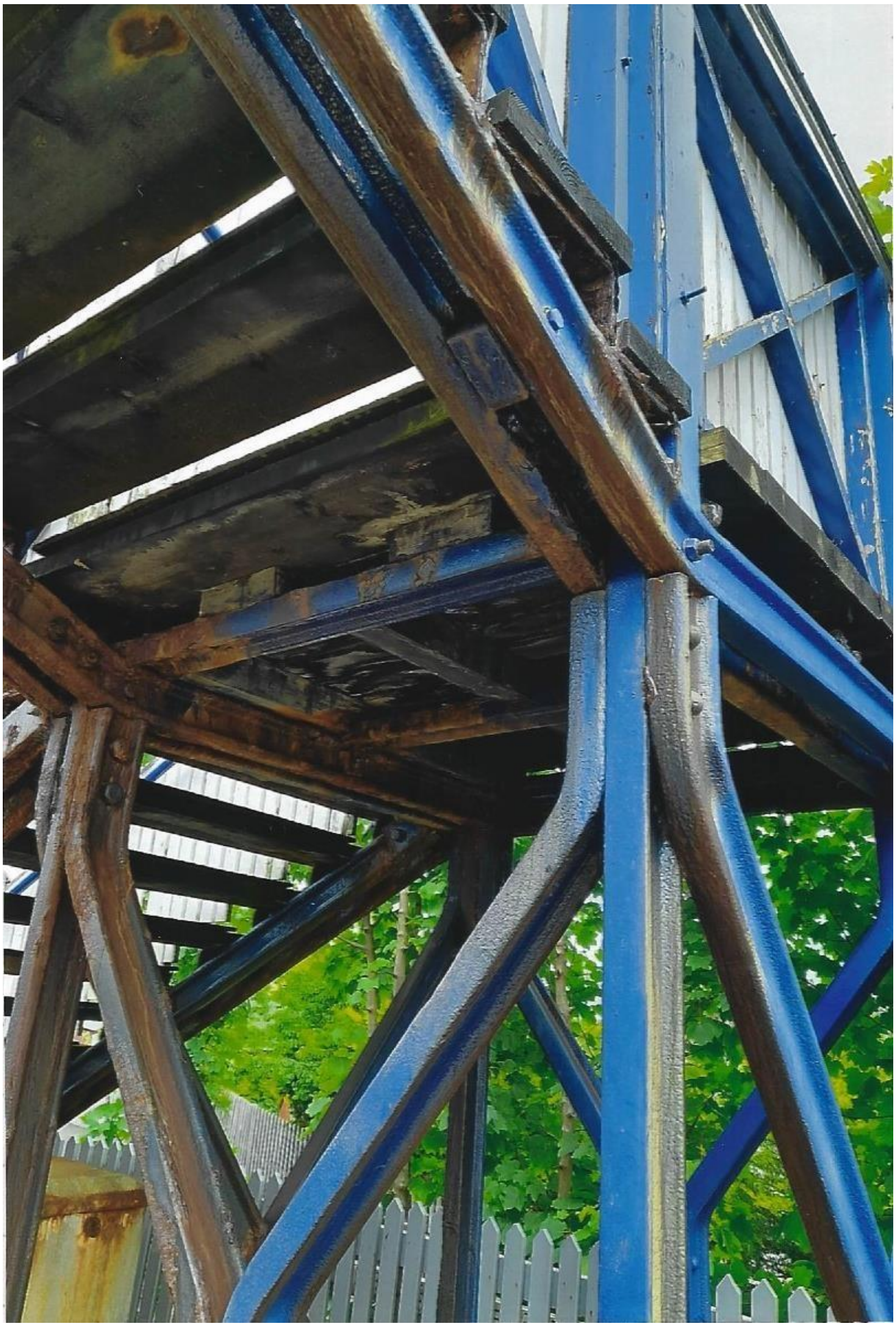
The above is a <u>modern</u> train ferry. However, the basic principles are as devised for the Granton/Burntisland train ferry by Thomas Bouch. (Designer of the first Tay Bridge, which collapsed in 1879. The concept demonstrated his inventive skills).

NORTH QUEENSFERRY STATION FOOTBRIDGE

The footbridge at North Queensferry station is interesting as it is made of railway rails. This was common practice for many years until the late 1940s. It can still be seen in 2024 that at least one of the rails was rolled in 1879. The rails were either removed from the track in worn condition, in say the mid-1880s, or were, for some other reason, never used to carry trains.

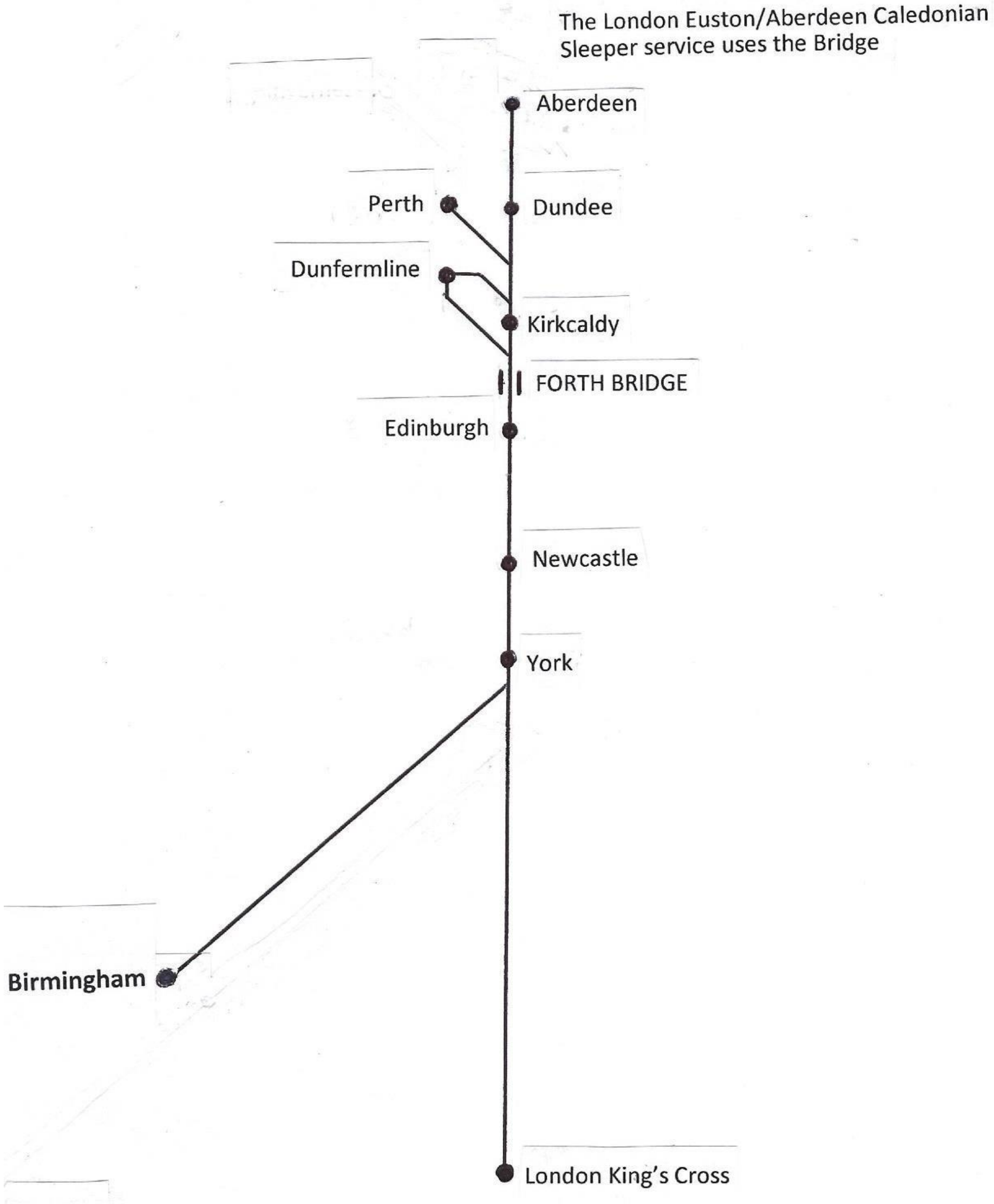
North Queensferry station footbridge.

STEEL 1879 NB on web of rail
(NB = North British)



Footbridge support on Edinburgh-bound platform

Note:- Old railway rails were also used, no doubt as a cost saving measure, to make for instance, railway fences, buffer stops and sign posts.

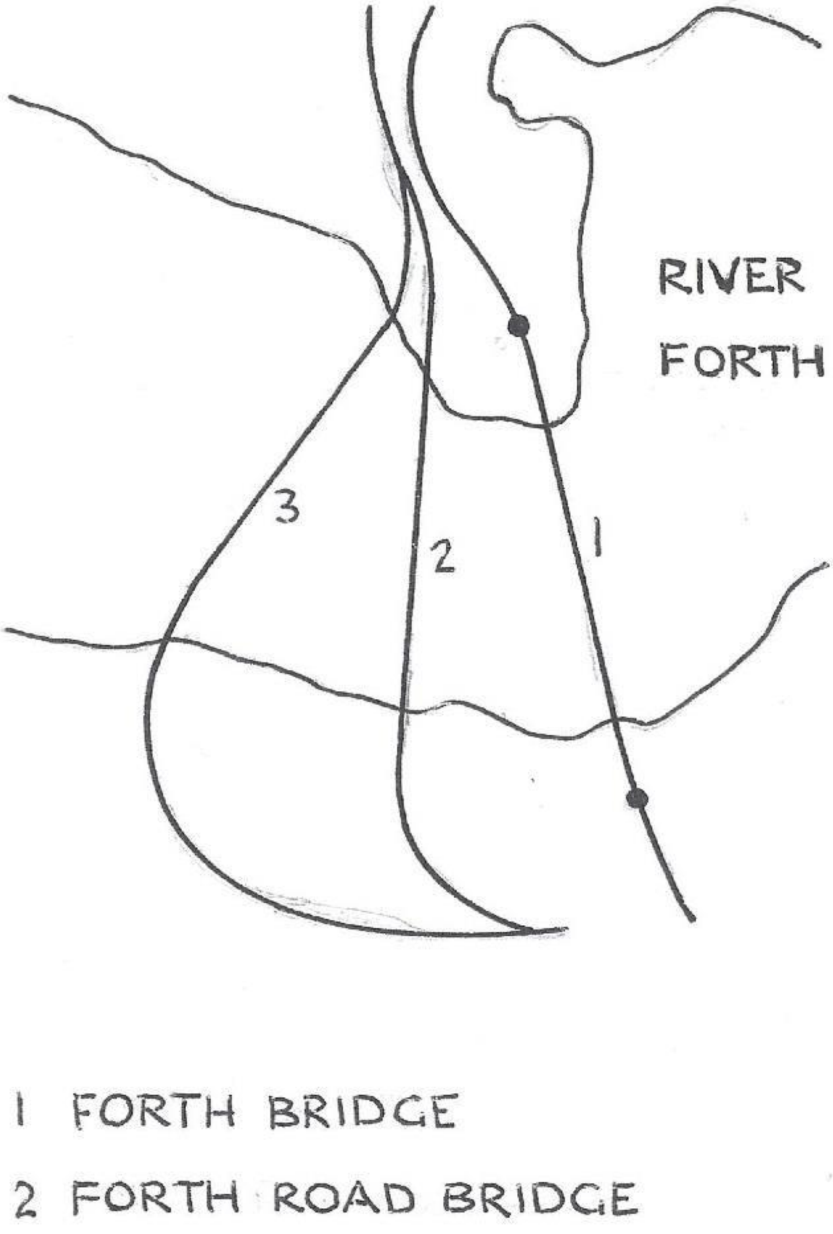


The passenger train services using the Bridge in 2024

Note: A branch line to Leven was opened in June 2024.

13.

THE THREE BRIDGES DIAGRAM



1 FORTH BRIDGE

2 FORTH ROAD BRIDGE

3 QUEENSFEERY CROSSING

14.

Queensferry Crossing Forth Road Bridge

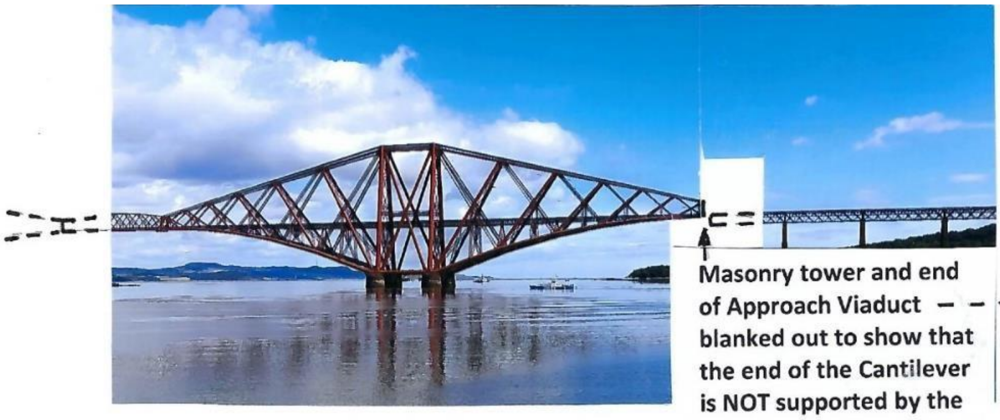
15.

The following pages give guidance and additional information concerning the Sections in the main pdf which cover the Design and Use of the Bridge.

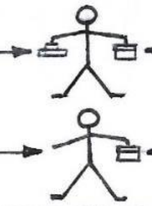
1. To achieve a certain amount of consistency, most but not all, of the Figures show the Bridge, looking towards the East. (Edinburgh towards the right).
2. The work involved in actually constructing the Forth Bridge, over a 7 year period, was a different engineering challenge, and has therefore been excluded from The Wonder of the Forth Bridge.

Section 4 and 9

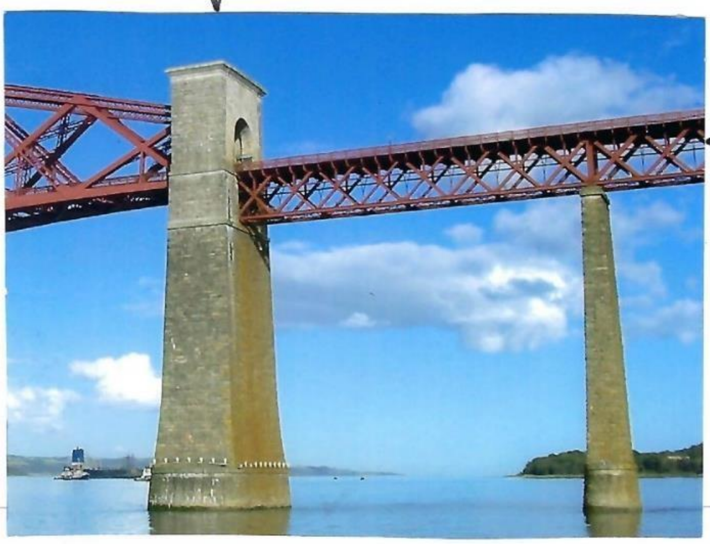
Balance issue caused by the Central Girders affecting Queensferry and Fife Cantilevers



Masonry tower and end of Approach Viaduct blanked out to show that the end of the Cantilever is NOT supported by the tower



Person, with legs apart, able to remain upright, whether there are two 'trains', or no 'trains', on the near half of the Central Girder



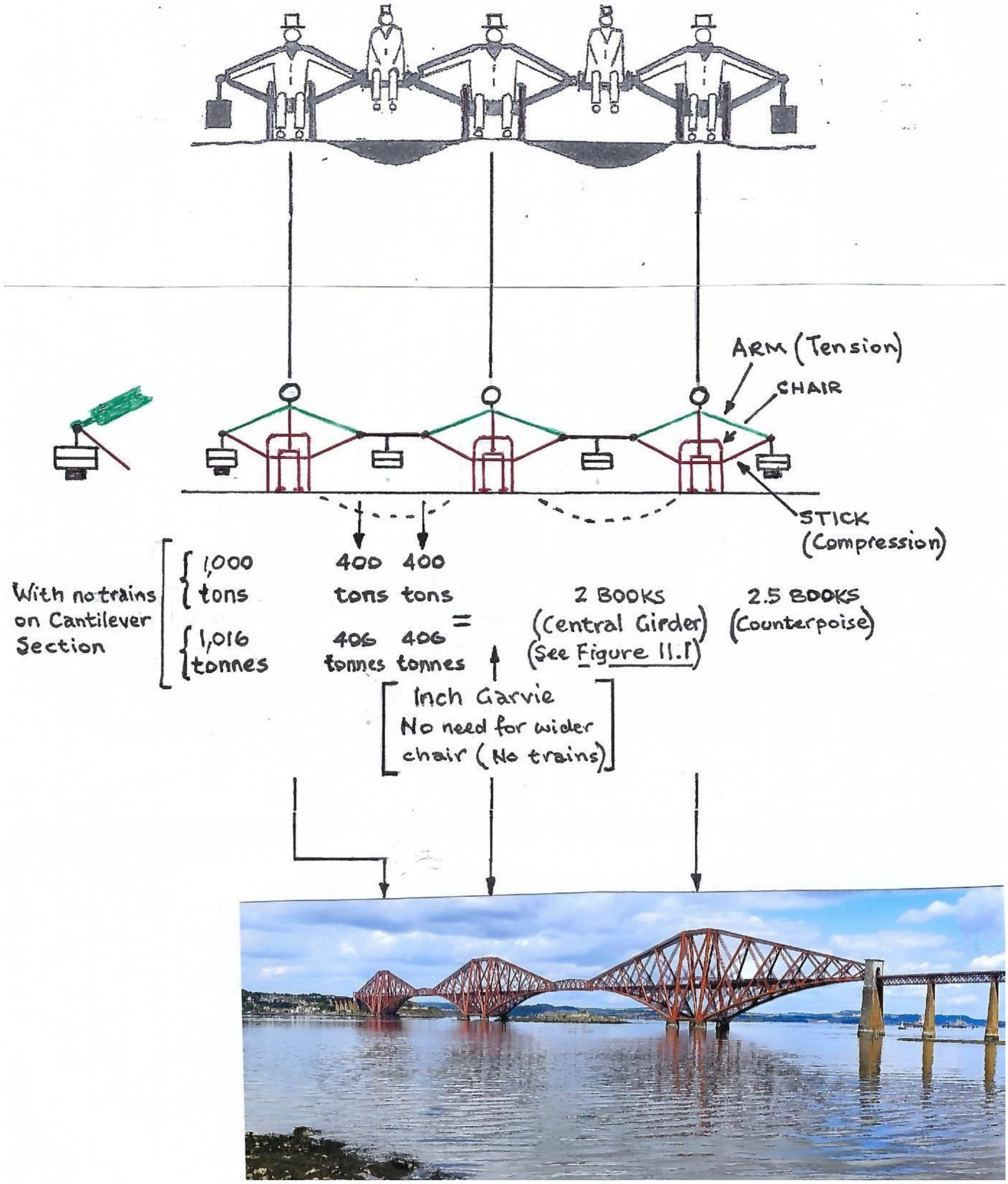
The Counterpoise is inside the tower, attached to the end of the Cantilever which does NOT transfer any weight to the tower. The end of the Approach Viaduct IS SUPPORTED by the tower

Sections 5 and 7

Convincing the decision makers of the solutions (Section 5) and
Continuous Structure (Section 7).

The very convincing demonstration produced by the Bridge's designers can be replicated by using 8 books of equal weight and two books that are about 50% the weight of the others. Three chairs and 6 sticks are also required (See diagram below).

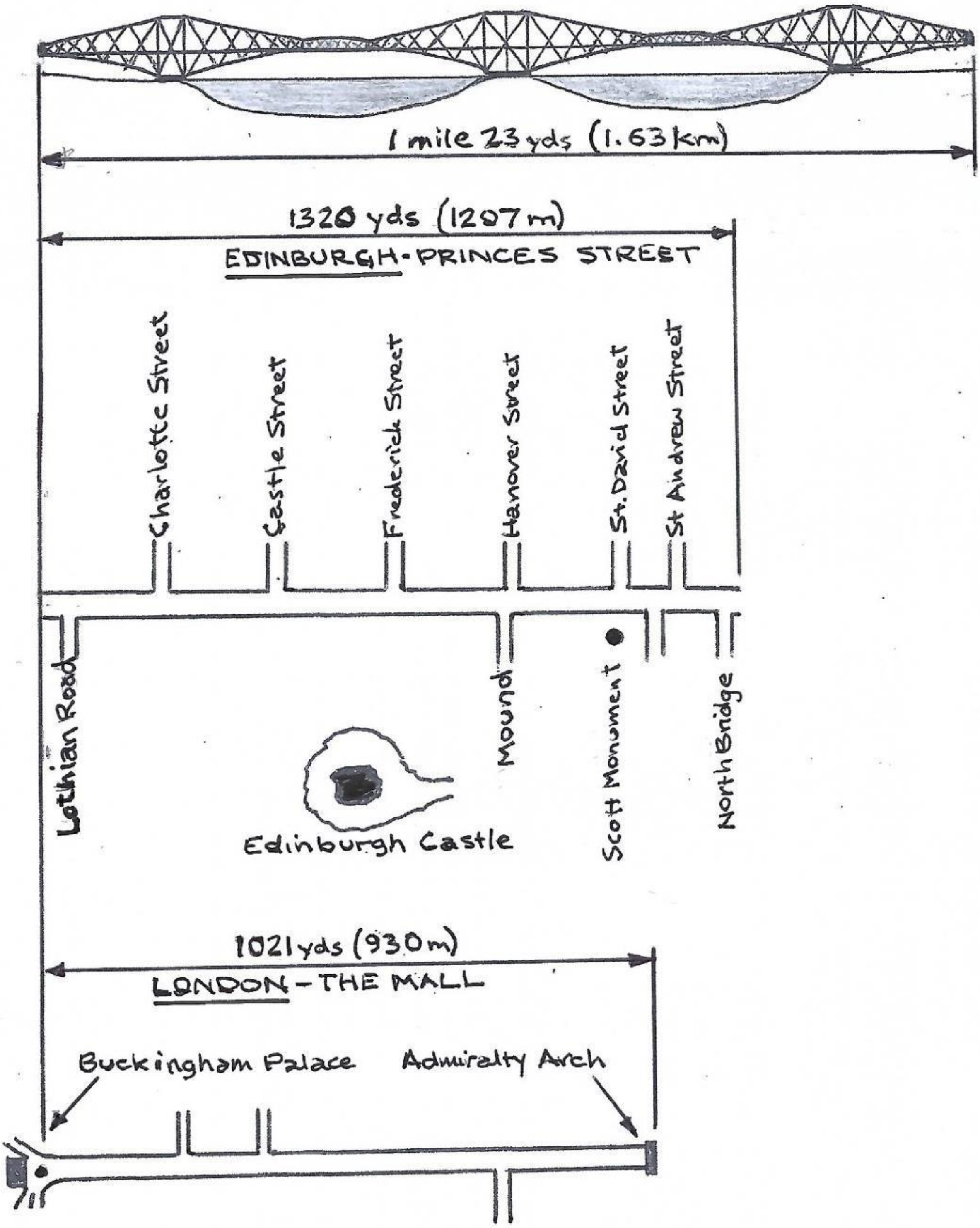
The demonstration represents the situation when there are no trains on the Cantilever Section.



The essential part played by every member of a Continuous Structure can be demonstrated by removing (carefully) any one of the principal parts.

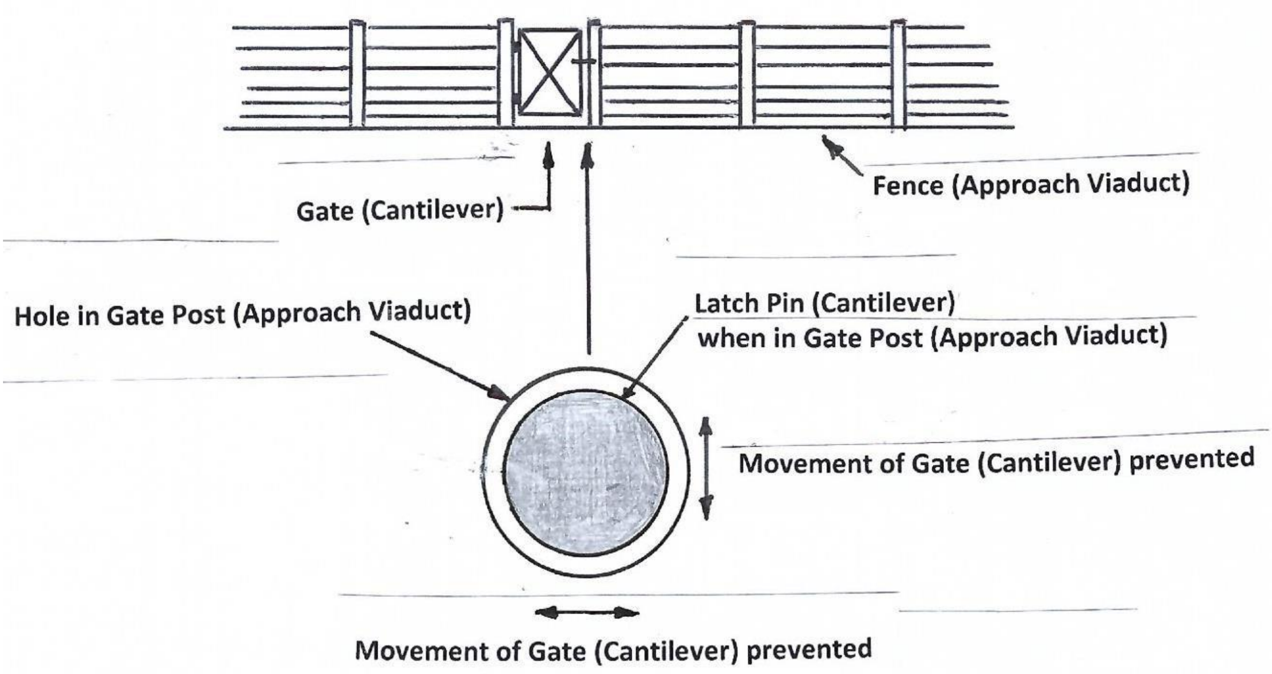
For instance, if one of the counterpoises were removed, the tower in question would tend to topple thereby initiating progressive failure along the entire length of the Cantilever Section, especially if trains were on the Cantilever Section.

The Cantilever Section is supported at only three locations (the three towers) and yet it is longer than Princes Street in Edinburgh and The Mall in London.


1 mile 23 yds (1.63 km)
1320 yds (1207 m)
EDINBURGH - PRINCES STREET
Charlotte Street
Castle Street
Frederick Street
Hanover Street
St. David Street
St Andrew Street
Lothian Road
Mound
Scott Monument
North Bridge
Edinburgh Castle
1021 yds (930 m)
LONDON - THE MALL
Buckingham Palace
Admiralty Arch

Section 9

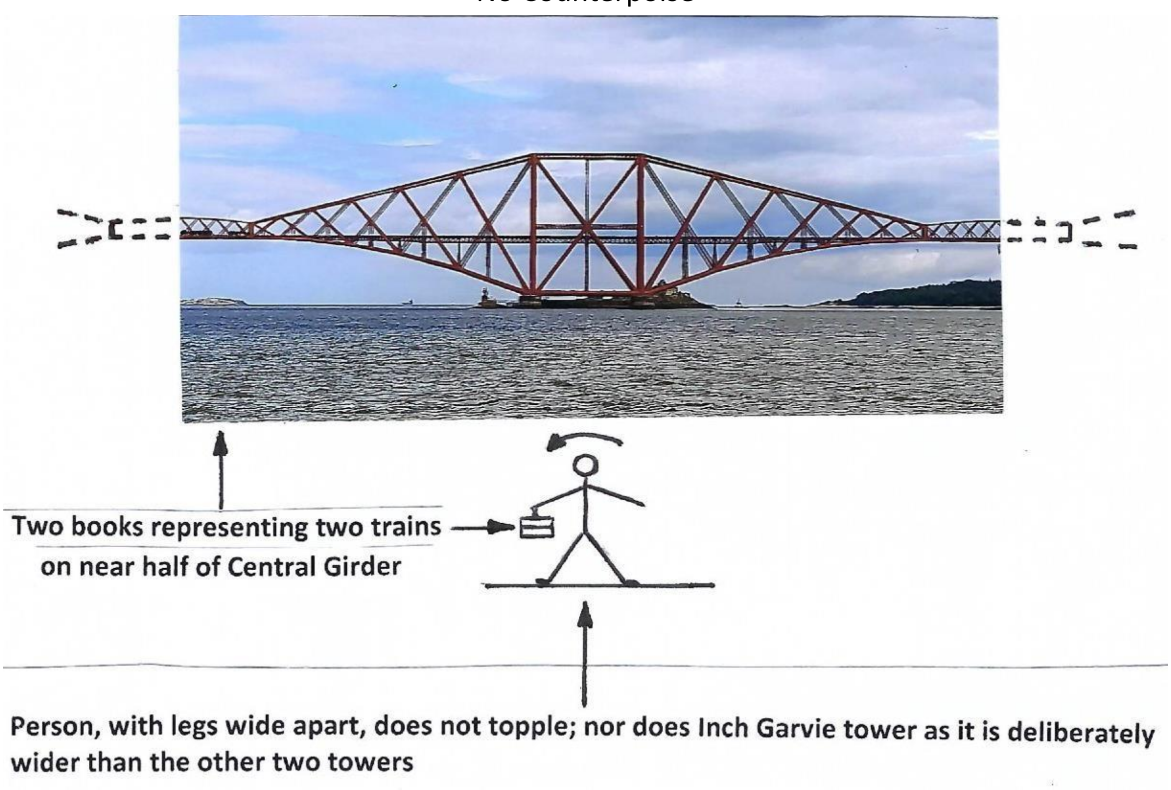
Arrangements for keeping each end of the Cantilever Section in Line and Level with adjacent Approach Viaduct.



Section 10

Inch Garvie Stability

Inch Garvie
No Counterpoise



See also Section 16 regarding the fixing of only one of the four tower legs to the foundation

Section 11

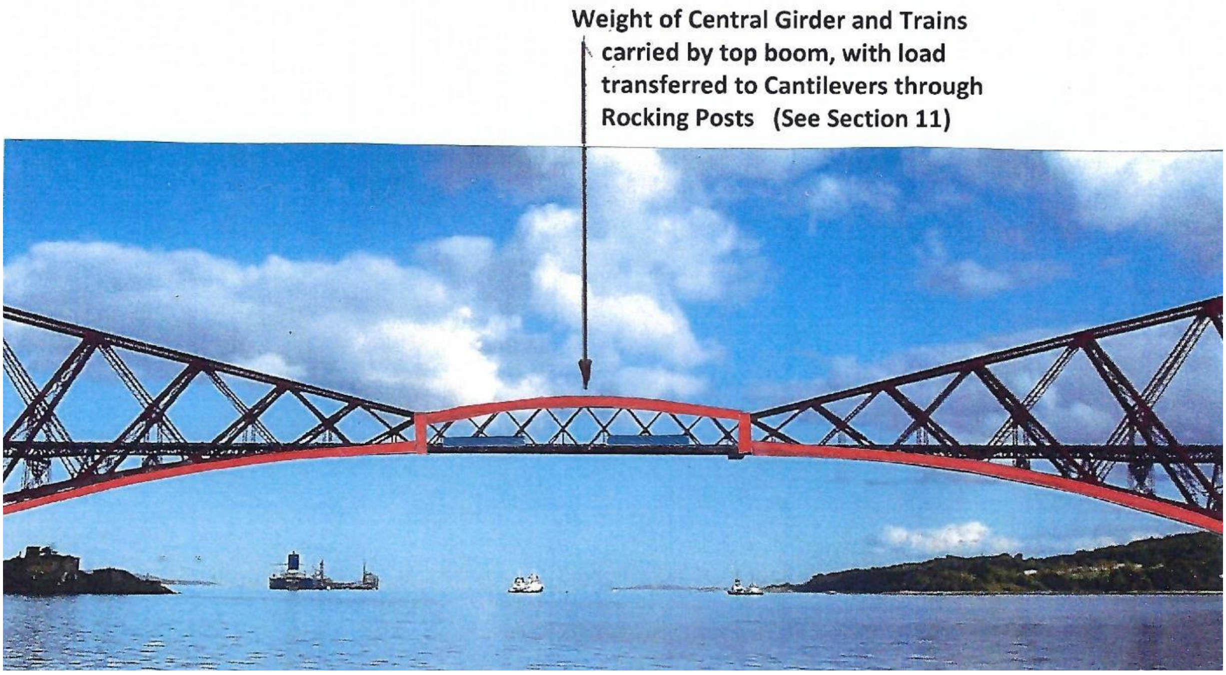
22.

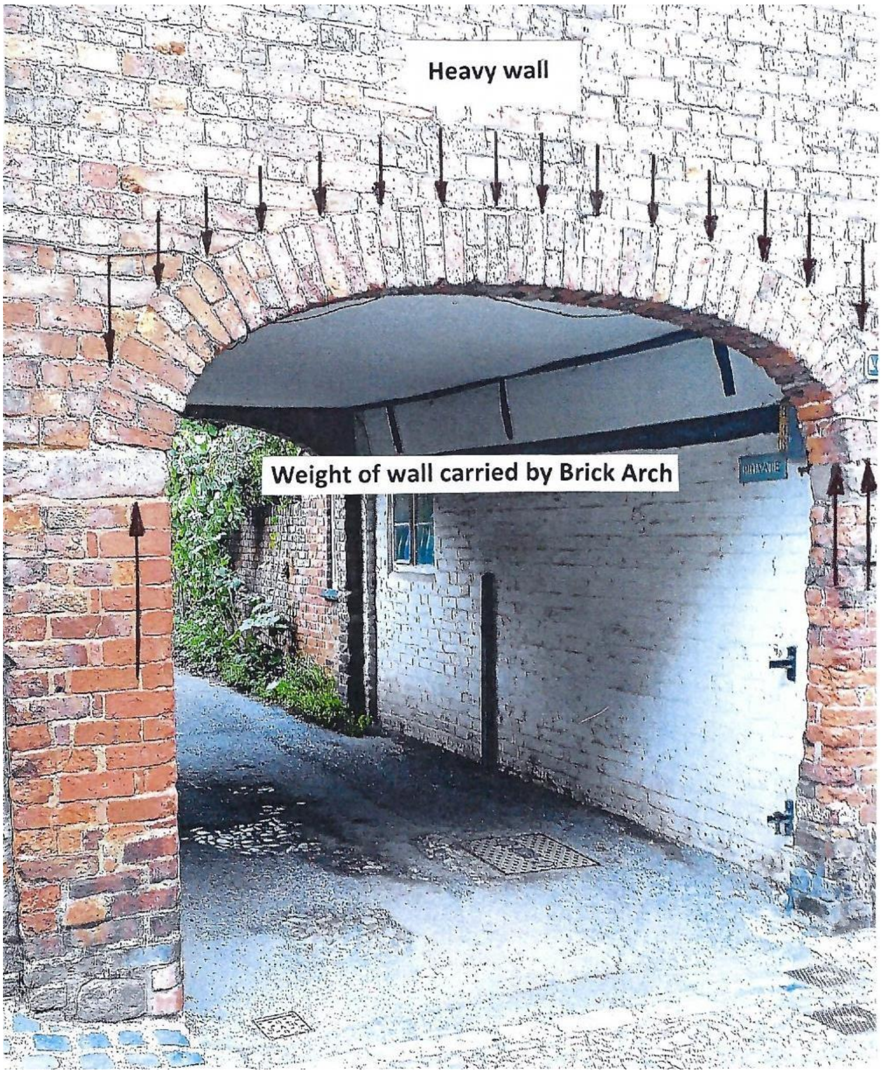
Central Girders

The top girder of each Central Girder is slightly curved (bowed) thereby giving it the strength of a shallow 'arch' capable of taking the full load of the Central Girder, plus trains. Transferring the load to the bottom girders of the Cantilevers get the load to the Bridge's foundations by the shortest route.

Section 12

23.


Weight of Central Girder and Trains
carried by top boom, with load
transferred to Cantilevers through
Rocking Posts (See Section 11)


Heavy wall
Weight of wall carried by Brick Arch

Sections 12 and 14

Steel, unlike concrete, is ductile (pliable) and consequently if a restrained steel girder is subjected to excessive compression during expansion, buckling could occur causing the girder to become crippled and therefore unable to return, after cooling, to its exact original shape.

Railway rails are also susceptible to buckling if inadequately restrained, both horizontally and vertically. The rails on the Forth Bridge are very well restrained by being fastened to longitudinal waybeams and being stress free at 27˚ C . See Section 14.

The expansion switches in the rails on the Approach Viaducts (See Figure 14.2) are mainly provided to compensate for the expansion and contraction that occurs in Approach Viaduct girders, at those masonry piers shared by adjacent continuous girders. See Section 19.

As on some other major railway bridges, such as the King Edward VII bridge at Newcastle, which carries the East Coast Main Line over the Rive Tyne, the deck used on the Forth Bridge precludes the use of 'normal' CWR (Continuous Welded Rail) track. See Figure 14.1 and 14.2. ('Normal' ballasted track would have been too heavy).

'Normal' track has the two rails located on pre-stressed concrete sleepers supported and surrounded by stone ballast. (See photograph below of North Queensferry station). The depth of ballast under the sleepers is approximately 300 mm. Also, extra ballast is provided at the sleeper ends to assist with the track's lateral stability when, in very hot weather, the rail temperature could be at least 40˚ C, which is considerably more than the stress free temperature of 27˚ C.

'Normal' track can be seen at Dalmeny and North Queensferry stations, but the 'unusual' Forth Bridge track can only be seen from a train.

North Queensferry Station
Note: The sleepers have become partially covered by ballast. The far line has timber sleepers and near line pre-stressed concrete sleepers.

To demonstrate the immense ability of steel to rapidly increase and decrease in temperature, place a spoon in a cup of hot water (hot enough for tea) for 5 seconds. On removal, the part of the spoon that has been in the water will be very hot, whereas the other end will still be cool.

Repeat the procedure with a wooden stick (as used in cafes) to show that wood is not a good conductor of heat.

Consequently, the 51,000 tons (51,818 tonnes) of steel in the Cantilever Section were known to be very susceptible to expansion and contraction. The issue was addressed by arrangements shown in Section 12. The arrangements concerning the rails on which the trains run, are shown in Section 14.

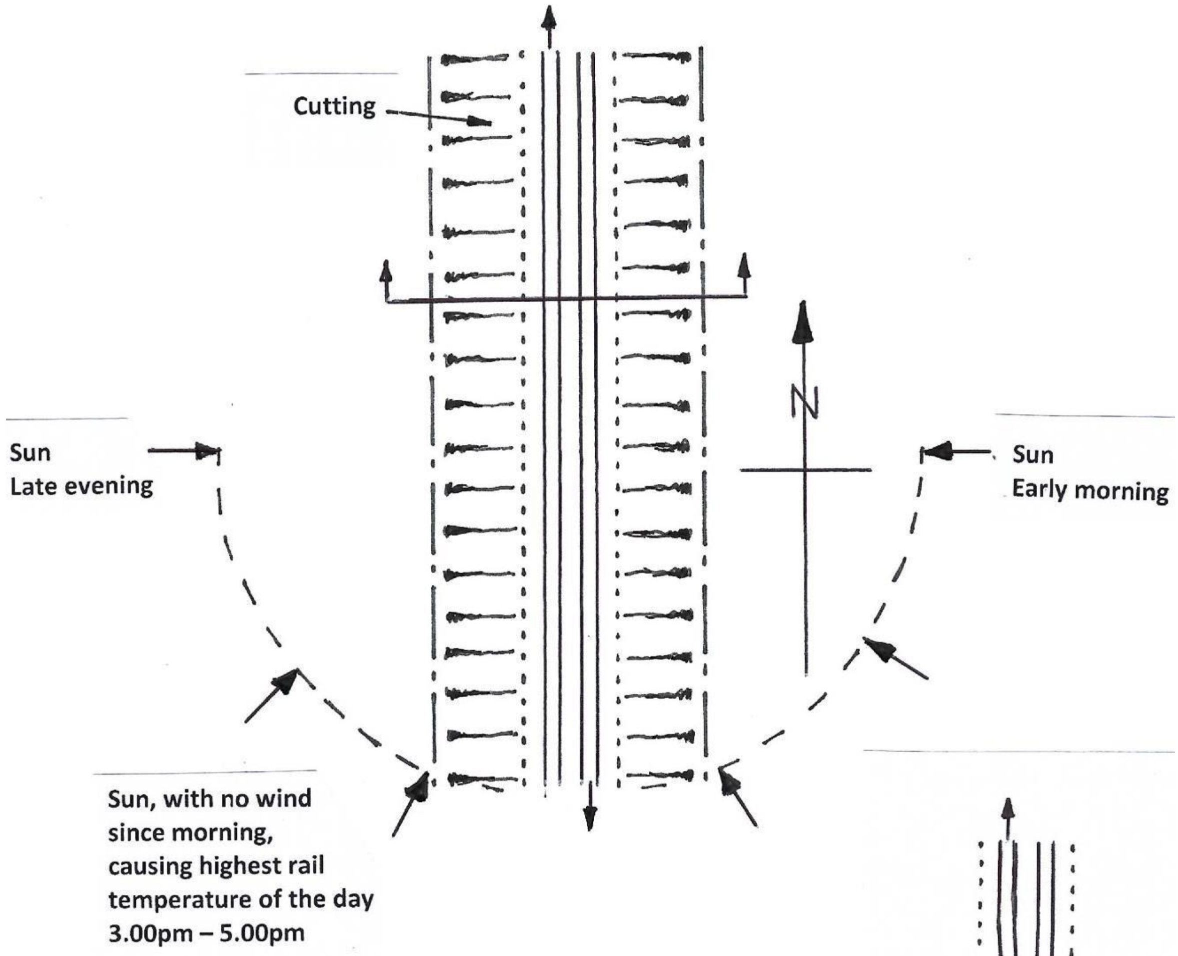
These two different arrangements were compatible, with those for the rails being dictated by the needs of the Cantilevers.

Regarding the derailment of the 'Royal Scot' at Abington in 1953 (See para. 14.5) the Accident Report states that buckling is most likely to occur between 3.00 pm and 5.00 pm in cuttings running North/South and sheltered from wind. This highlights steel's propensity to conduct heat and therefore expand. Although the Forth Bridge is not 'sheltered' it is located approximately on a North/South alignment.

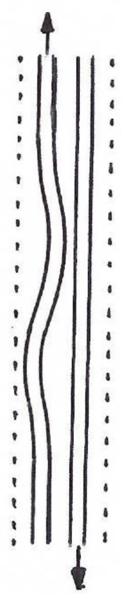
The principal cause of the Abington Accident was inadequate gaps between the 60 ft. (18.3m) long rails.

Section 14

Rail Expansion

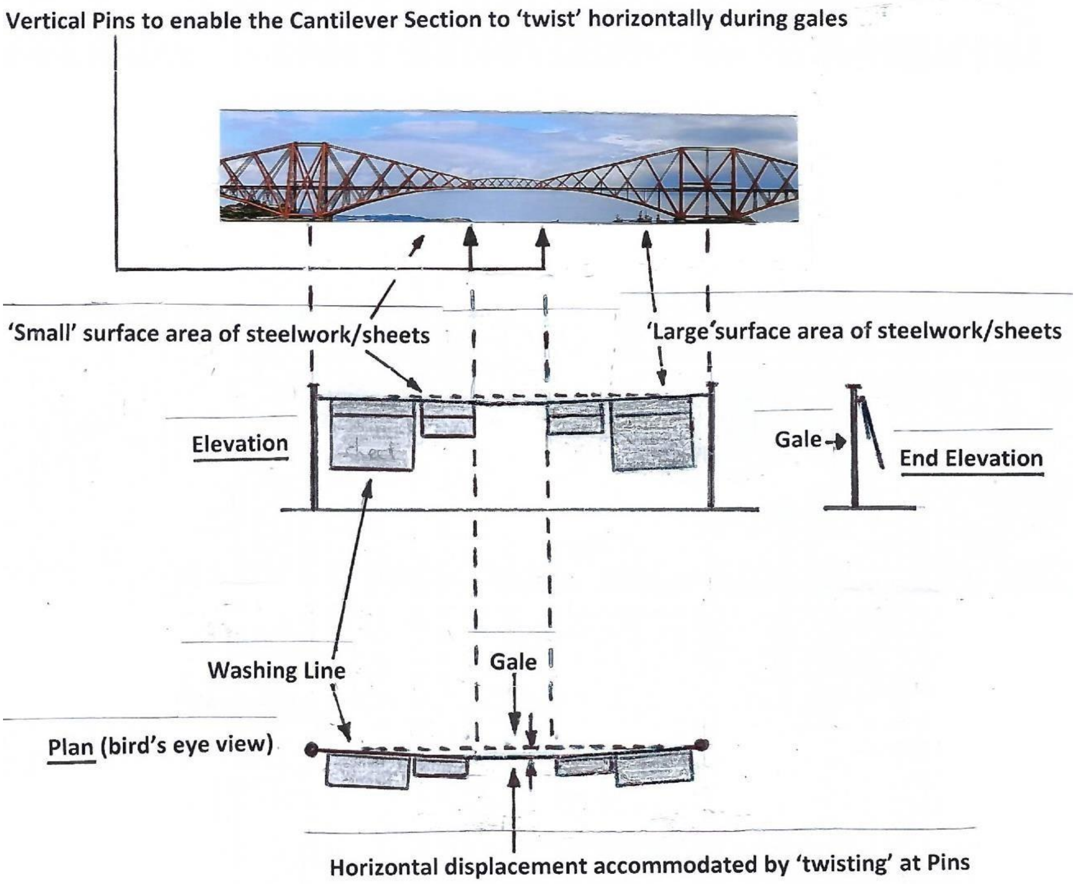


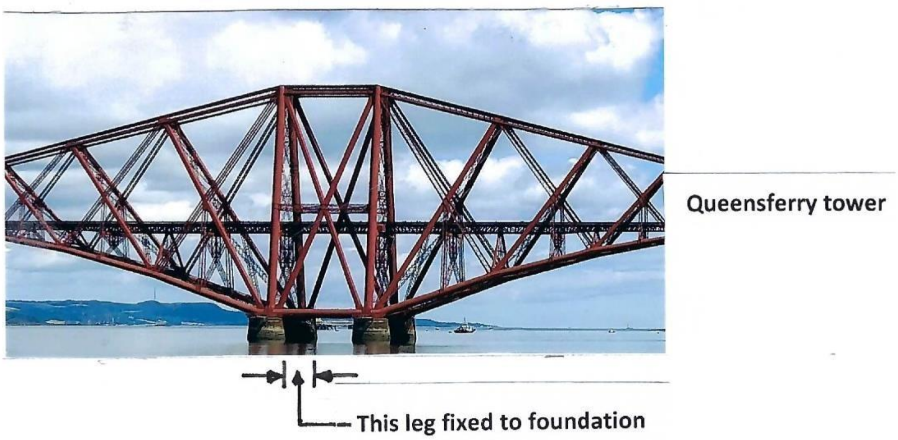
Cross Section



This photograph shows the type of track involved in the Accident; Bull-head 60 ft. (18.3 m) long rails. The photograph was taken when the joint was fully ‘open’.

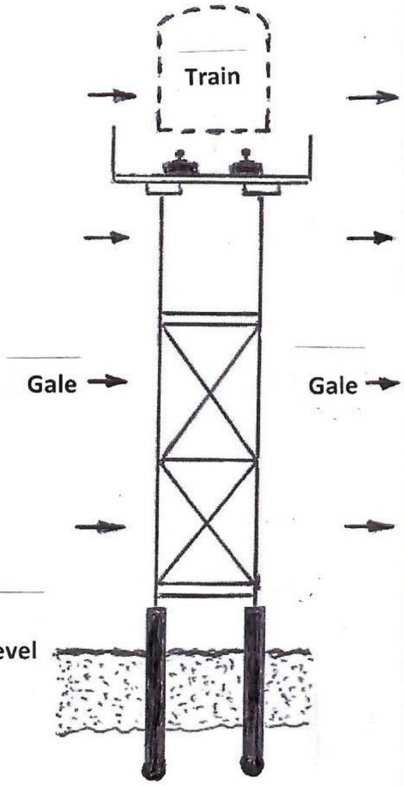
Section 13

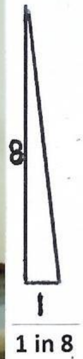

Vertical Pins to enable the Cantilever Section to 'twist' horizontally during gales
'Small' surface area of steelwork/sheets
'Large'surface area of steelwork/sheets
Elevation
Gale
End Elevation
Washing Line
Gale
Plan (bird's eye view)
Horizontal displacement accommodated by 'twisting' at Pins


Queensferry tower
This leg fixed to foundation

Section 16

The Stability of the Forth Bridge during Gales





The First Tay Bridge

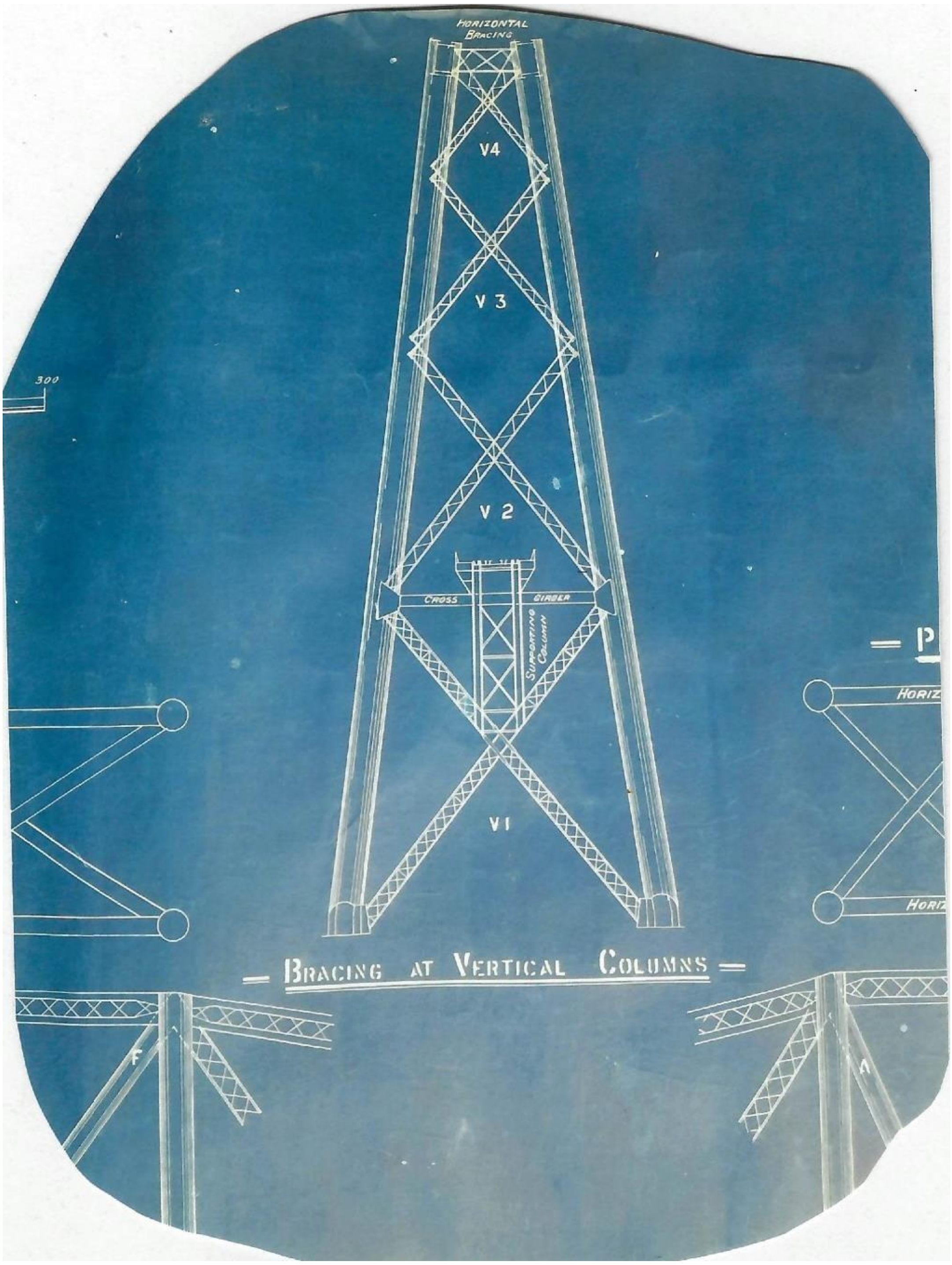
The Forth Bridge

The First Tay Bridge, which collapsed in a storm, was criticised in the Disaster Report for being too slender

The pressure on one foot decreases slightly, but the person, with legs apart, does not topple.

The 1 in 8 batter gives the Bridge considerable stability.
As only one of the four legs on each tower is fixed to the foundation, no unwelcome stresses are transferred horizontally between legs.

Only the leg indicated is fastened to the foundation. The other three legs ‘rest’ on the foundation, thereby preventing the generation of unwelcome stresses between the legs at foundation level, during gales.



This photocopy of a part of an original drawing shows some of the Cross Bracing provided within the three Towers, Queensferry, Inch Garvie and Fife. (Drawing kept in Institution of Civil Engineers' Archive).

An easy way of demonstrating the stability provided by the 1 in 8 batter of the Forth Bridge Cantilever towers is the ease with which a person who has both feet together can be pushed over, whereas this is much more difficult if the person has both feet far apart.

Section 17

Fatigue

Although the steel forming the Forth Bridge is over 130 years old, it's age is proof that the Bridge was well designed and has been properly maintained.

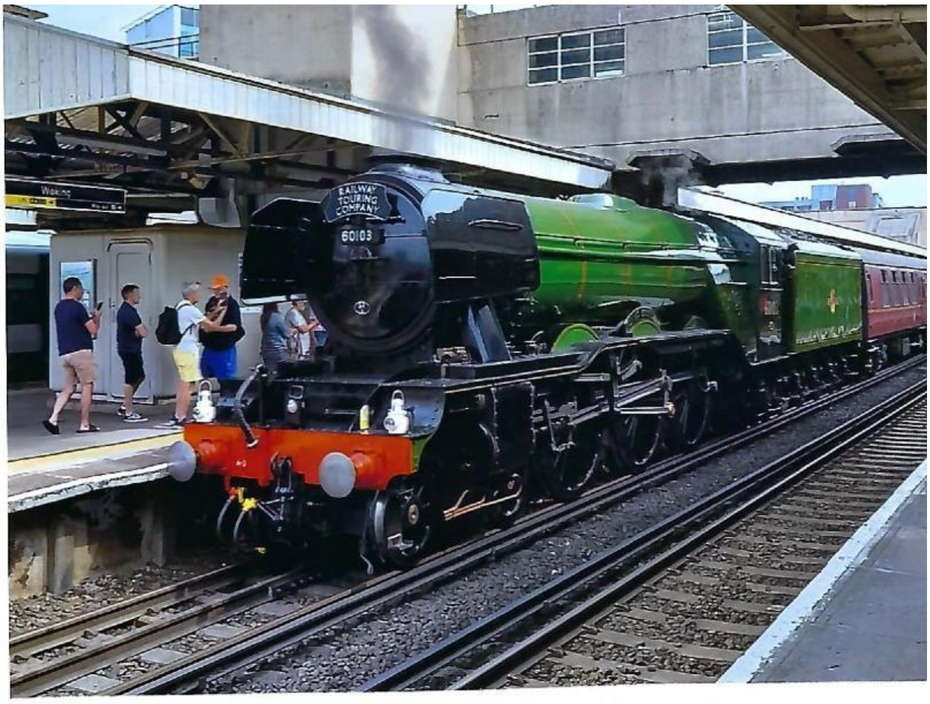
Fatigue is always a concern on major steel bridges due to the ever changing loading conditions. However, the compressive and tensile forces within the Forth Bridge girders are well within the safe working limits for steel. The ever changing loading conditions are referred to as 'live load'. Railway bridges have to withstand the high axle loads of locomotives, passenger coaches and heavy freight wagons.

Fortunately, there are now very few 'traditional' rail joints on the Forth Bridge (See Figure 14.5). Such joints had to withstand heavy hammer blows as wheels passed from one rail to the next, even when the gap had been closed by expansion during hot weather.

A useful demonstration of 'live load' and hammer blow involves hitting a peg into the ground with a hammer, ten light blows (slow speed train), then ten heavy blows (fast train).

The reciprocating connecting and coupling rods on steam engines produced exceptionally heavy hammer blows. (See the following photograph of the 'Flying Scotsman,' Class A3, 4-6-2, built in 1923, British Rail number 60103). The upwards and downwards reciprocating forces generated by the rods can be demonstrated by whirling fast a weight at the end of a 400 mm (approximately) piece of string.

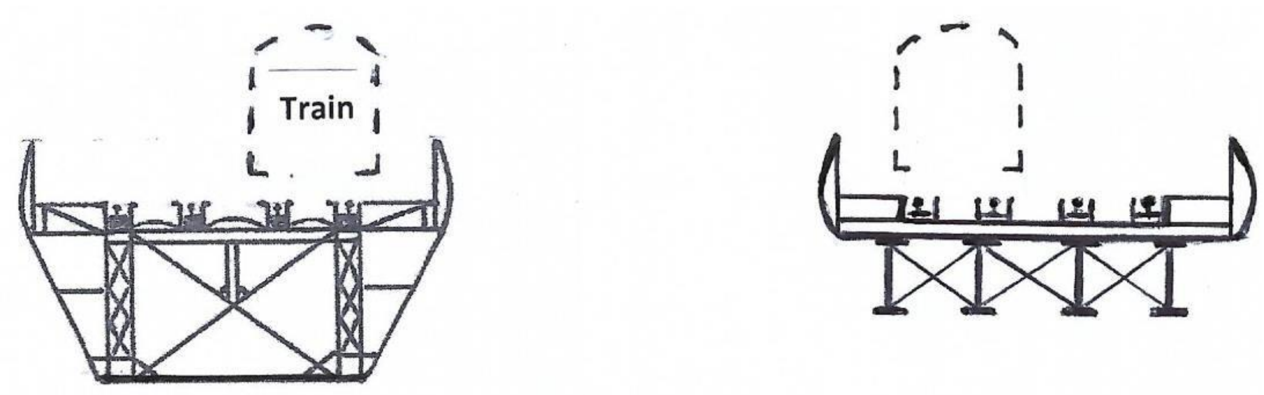
34.



The lower photograph shows the heavy connecting and coupling rods

Section 19

Approach Viaducts



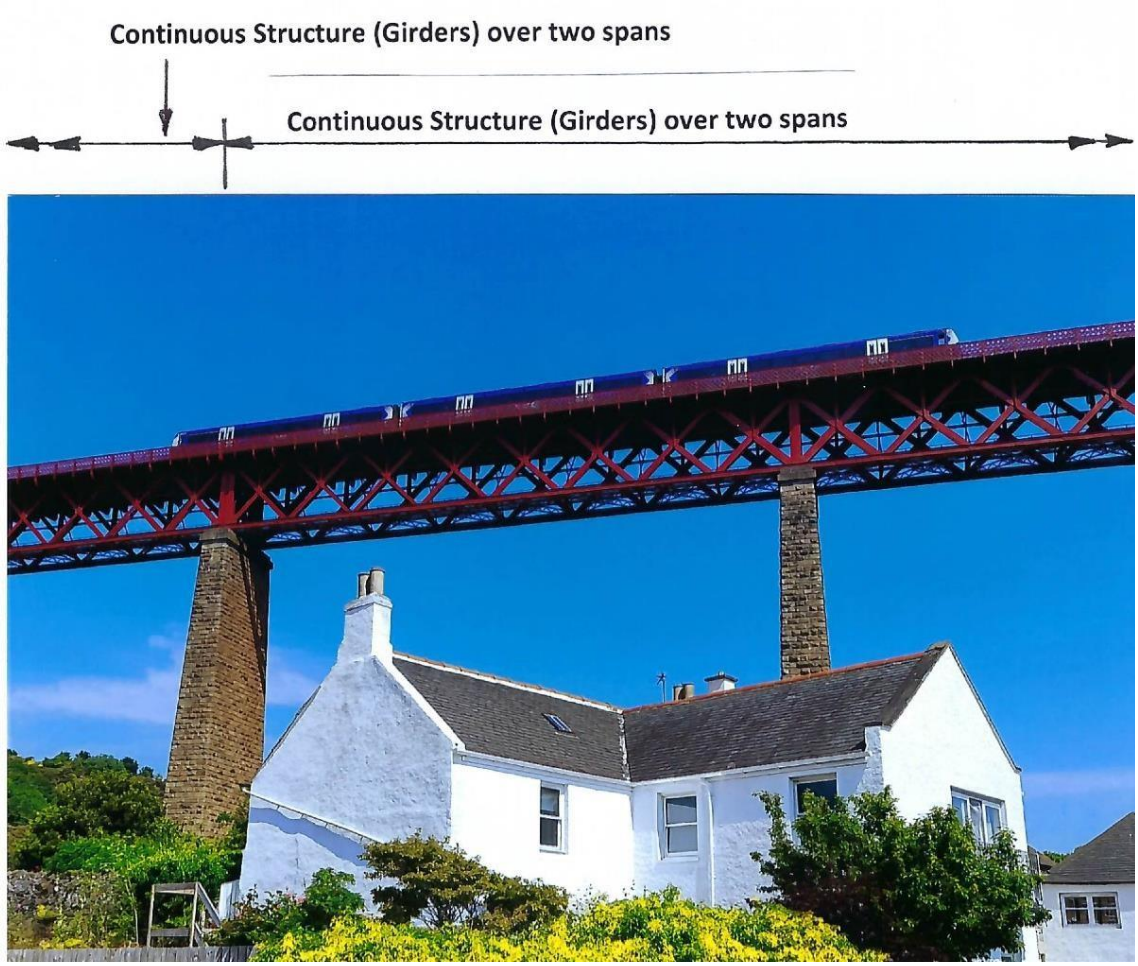
The Cross Section on the left shows the two girder design of the Forth Bridge Approach Viaducts, whereas the Cross Section on the right shows a typical four girder Viaduct as used at many other locations on the railway network.

Another difference regarding the Forth Bridge Approach Viaducts concerns the use of Continuous Girders, covering two spans as shown below.
See Section 19 and Figure 19.4.

36.

Section 19

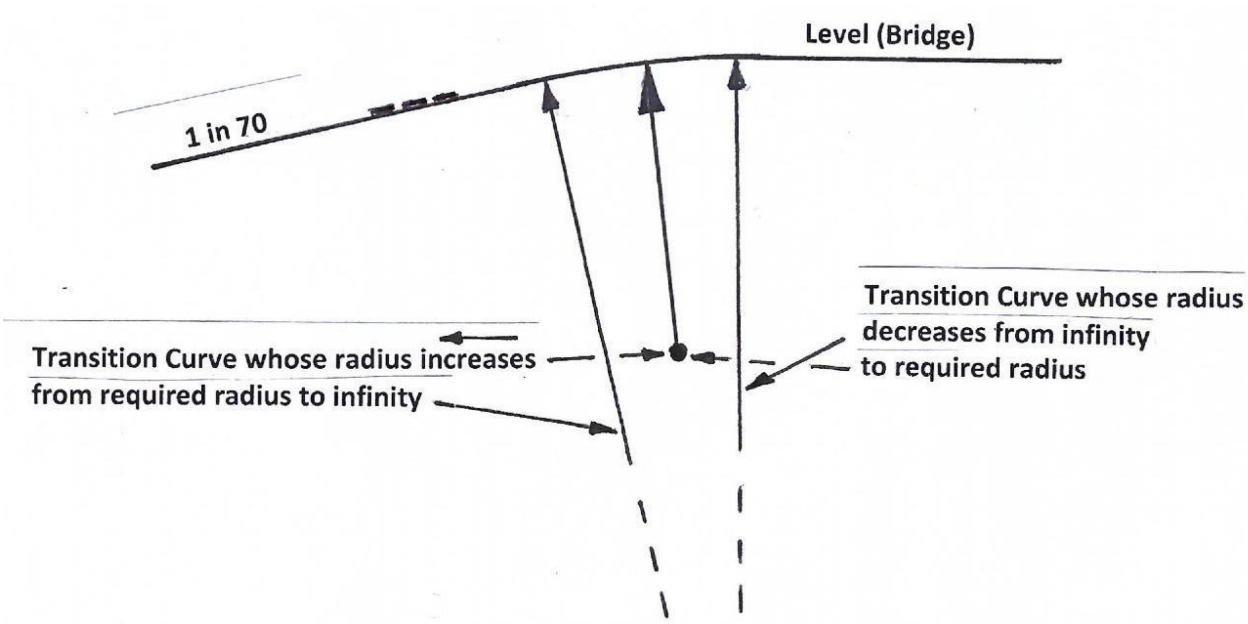
Approach Viaducts – Continuous Girders over Two Spans



Northbound 3 car diesel passenger train on Fife Approach Viaduct

Had the Forth Bridge Approach Viaduct girders been continuous over more than two spans, the provision for expansion and contraction would have had to be considerably increased. For instance, Forth Bridge type of rail expansion switches (See Figure 14.1) would probably have been necessary above piers with bearings that accommodated girder expansion and contraction.

Vertical railway transition curves between the Forth Bridge and the North Queensferry/Inverkeithing 1 in 70 falling gradient ….(Section 19)



The Gradient between the Forth Bridge and Inverkeithing

Railway Gradients are expressed as 1 (Vertical) in Whatever (Horizontal) (e.g. 1 in 240)

1 in 7 Gradient

1 2 3 4 5 6 7

The Gradient between the Forth Bridge and Inverkeithing is 1 in 70 (Falling)

Note: Road Gradients are expressed as % ages.

e.g. 1 in 70 Gradient $\frac{1.00}{70.00} \times 100 = 1.42\%$ **(say 1.4%)**

A ScotRail Aberdeen/Edinburgh High Speed Train (HST) reaches the top of the 1 in 70 rising gradient before moving onto the level Bridge.

Navigation Channel (See Figure 19.11)

Use a piece of string 2 m. long to emphasise how little clearance there is between the lowered pole mast of the aircraft carrier HMS Prince of Wales and the underside of the Bridge (Central Girder).

Section 20

Completion of Bridge

Present day testing and modelling techniques for establishing if a newly built structure is actually able to carry the loads envisaged during its design stage, had not been invented when the Forth Bridge was completed. However, in the 1880s, the Board of Trade, which was responsible for railway safety, was satisfied that the placing of as many trains as possible on a new bridge, was a very effective way of checking it’s structural integrity. Consequently, such a test was ordered for the Forth Bridge on completion.

Track level on the Forth Bridge in modern time (see cables)

It was reported that the trains used for the test were so heavy that three steam engines were needed at each end of each train.

For some bridges, the Board of Trade required as many steam engines as possible to be used for the test thereby maximising the total weight placed on the bridge. When possible, deflection of the various girders when under load would be measured to determine if the structure was behaving as expected.

Section 21

Train Signalling System

The train signalling system in use when the Forth Bridge was opened depended mainly on mechanical engineering with a relatively small amount of electrical engineering. The overall railway was split into Signalling Sections of lengths varying from 0.5 miles to about 10 miles (800 m to 16 km).

The system and it's operating rules were designed to ensure that there could only be one train in a Section at any one time. On a double track railway, each line was considered to be a separate railway. (An Up Line and a Down Line). The average Section was about 4 miles long.

Modern signalling systems are highly electronic and digital, with much of the equipment operating automatically, although under the supervision of Signallers in Signalling Centres, each Centre being responsible for very large parts of the railway network.

The design and operational integrity of railway signalling is very high.

Longforgan signal box, on the Dundee/Perth line, is a ‘traditional box’ with a Signaller who operates equipment in conjunction with neighbouring Signallers, to ensure that there is only one train in the Signalling Section at any one time. (One on each line). The Signaller at Longforgan also controls a level crossing, the barriers being interlocked with the Signalling equipment.

The train on this preserved railway, which has ‘traditional’ signalling, has just passed the semaphore signal which authorises passage into the next Signalling Section.

The tail lamp on the rear coach indicates to the Signaller that <u>all</u> of the train has been seen.

Modern signalling is now used on the Forth Bridge, using colour light signals, electronics, IT and equipment on the track which detects automatically the location of trains in relation to signals.

Section 21

The trains that use the Forth Bridge (in 2024)

A ScotRail train from Edinburgh (Waverley) to Perth

Approximately 200 passenger trains use the Bridge each day. (Slightly less on Sunday).

The train shown above is a 2 car Diesel Multiple Unit (DMU) which can be attached to another similar DMU. For instance, trains could be formed of two, 3 car DMUs, making 6 car trains.

The Edinburgh/Aberdeen trains operated by ScotRail are reduced length High Speed Trains (HSTs), which were used on London King's Cross/Aberdeen trains until replaced by LNER's AZUMA 9 car trains. (The AZUMAs operate as electric trains between London and Edinburgh and as diesels between Edinburgh and Aberdeen). (The information in these Notes regarding Section 19, includes a photograph of an HST).

The overnight Caledonian Sleeper train between Aberdeen and London (Euston) is hauled by a diesel locomotive between Aberdeen and Edinburgh (Waverley).

The ‘Highlander’ Section of the Caledonian Sleeper at London (Euston) awaiting departure to Aberdeen (via Forth Bridge), Inverness and Fort William.

Relatively few freight trains use the Bridge.

Passenger trains are restricted to 50 mph and freight trains to 20 mph. (Freight trains have heavier axle loads).

Diesel Multiple Units operated by Cross Country also use the Bridge.

The Bridge is owned and maintained by Network Rail, the organisation which ‘sells’ train paths to Train Operating Companies, such as LNER and ScotRail.

The following pages give IMPORTANT SUPPLEMENTARY INFORMATION of particular interest to Teachers.

(i) Which Drawing is Correct?

(ii) Cantilever/Central Girder Ratio.

(iii) Centrifugal Force AVOIDED.

(iv) Is the Bridge (Cantilever Section) over-designed?

(v) World Heritage Site.

(vi) The design of a modern Forth Bridge (Railway)?

(vii) Diagram showing present day typical civil engineering projects

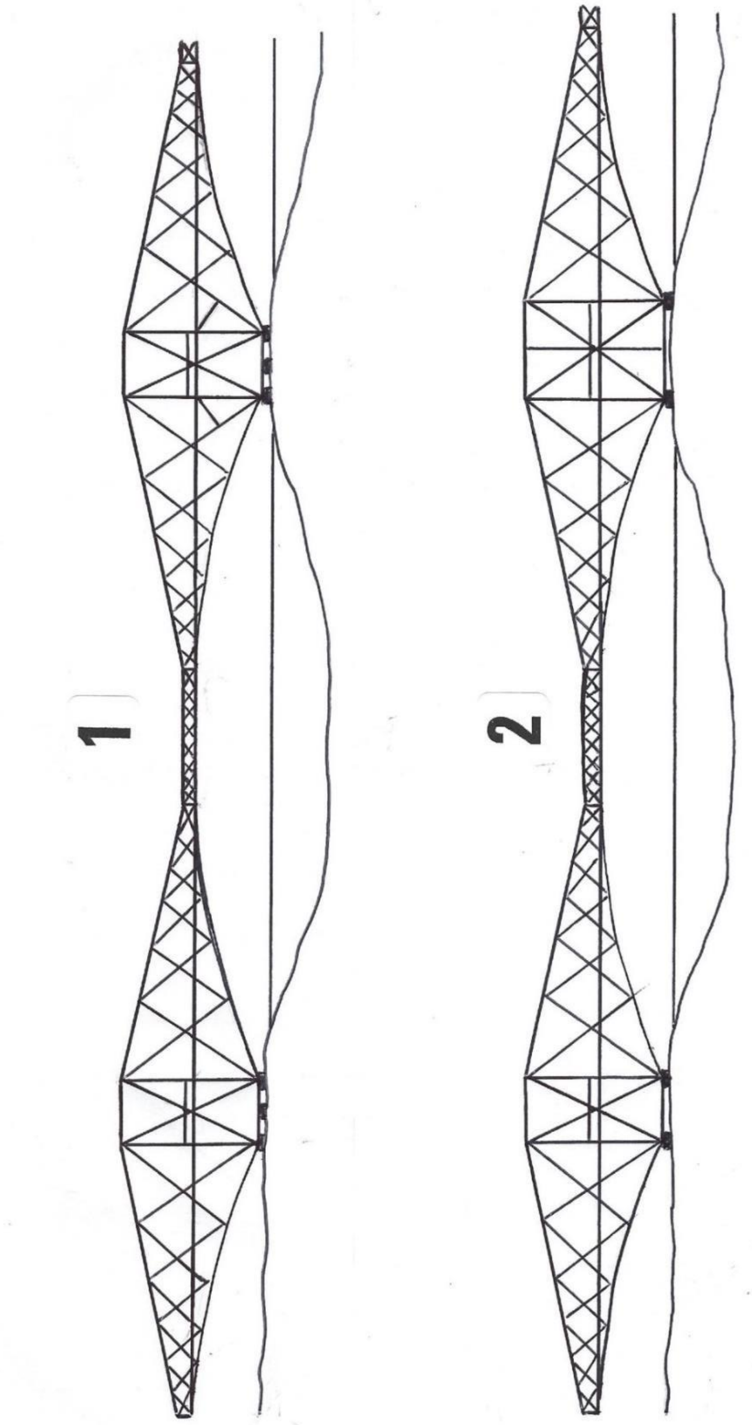
(viii) THE PIONEERS who designed, approved and financed the Forth Bridge.

(i) Which drawing is correct?

How many errors are there on the incorrect drawing?

See <u>Figures 4.3, 6.4, 6.6 and 16.2</u>

(No. 2 is the correct drawing)

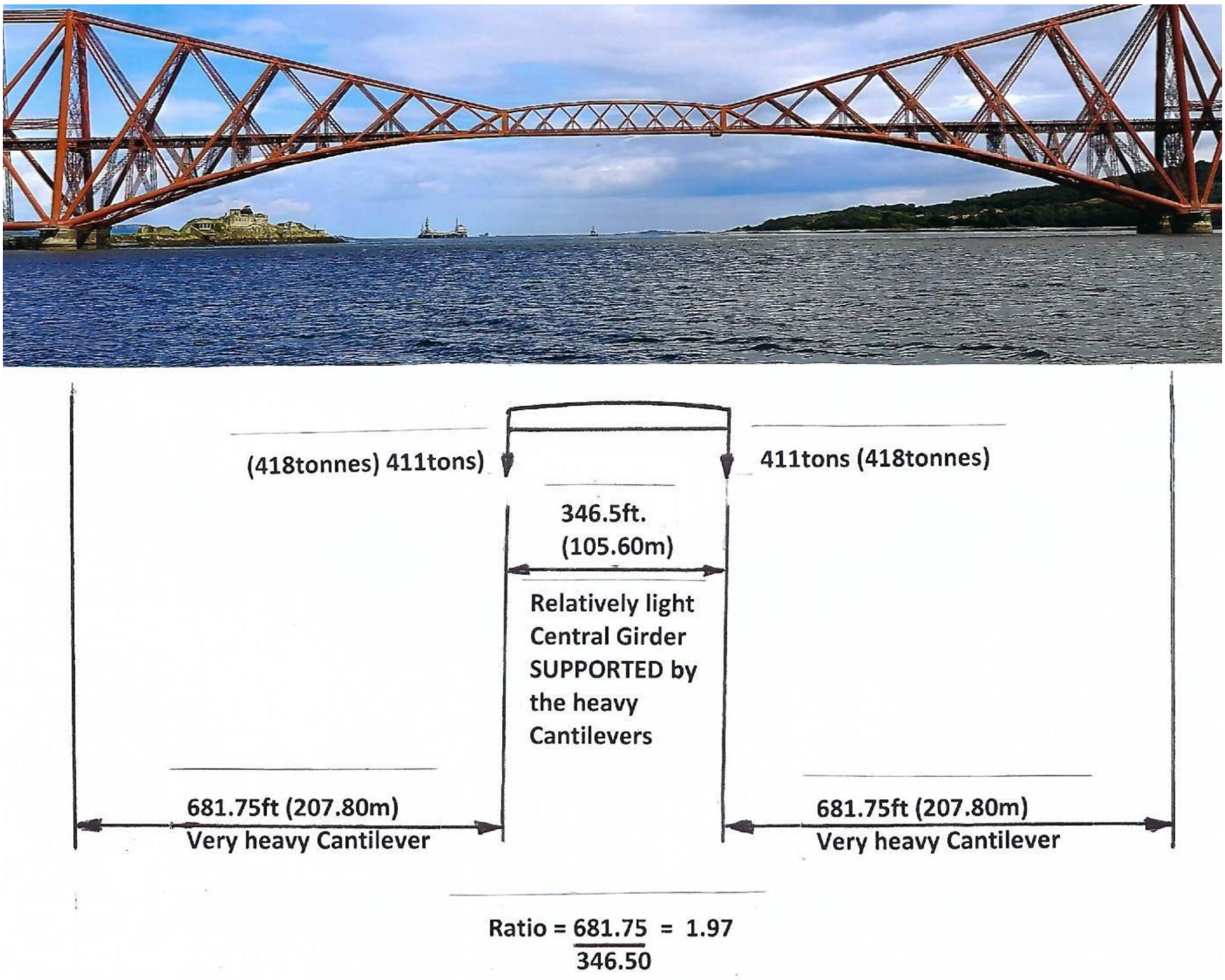


(ii) CANTILEVER/CENTRAL GIRDER RATIO

It will be seen from Figure 11.3 that a Cantilever arm is 681.75 ft. (207.80 m.) in length and a Central Girder 346.5 ft. (105.6 m) in length, giving a ratio of 681.75/346.5 = 1.97.

It was known to the designers that there was considerable economic benefit in using two Central Girders, especially in relation to the amount of steel required. In some respects half of a Central Girder is like strong slender fingers at the end of a long robust arm. The ratio was, and still is, a matter of debate. Also, the Central Girders gave the ability to provide an excellent arrangement for dealing with expansion and contraction. See Section 12.

Central/Central Girder Ratio



(iii) CENTRIFUGAL FORCES AVOIDED (by the Bridge being straight)

Many long railway bridges are curved, or partly curved, to accommodate the ideal alignment for the railway, the north end of the Tay Bridge being a good example (see Figure 2.1).

However, the Cantilever Section of the Forth Bridge is, and had to be, straight to eliminate the need for the design to cater for the significant Centrifugal forces that can be generated by trains whilst travelling over curved track. In fact the total length of the Forth Bridge is straight, thereby ensuring that Centrifugal Force also did not have to be catered for in the design of the Queensferry and Fife Approach Viaducts.

Centrifugal Force occurs when trains travel along a curve at a speed that is greater than Equilibrium Speed, thereby causing it's wheels to press against the higher rail. (Equilibrium Speed is the speed at which a train travels along a curve as though on straight track with no flanges touching the rails, as a result of the amount of Superelevation provided). (Superelevation is the amount the higher rail is above the lower rail).

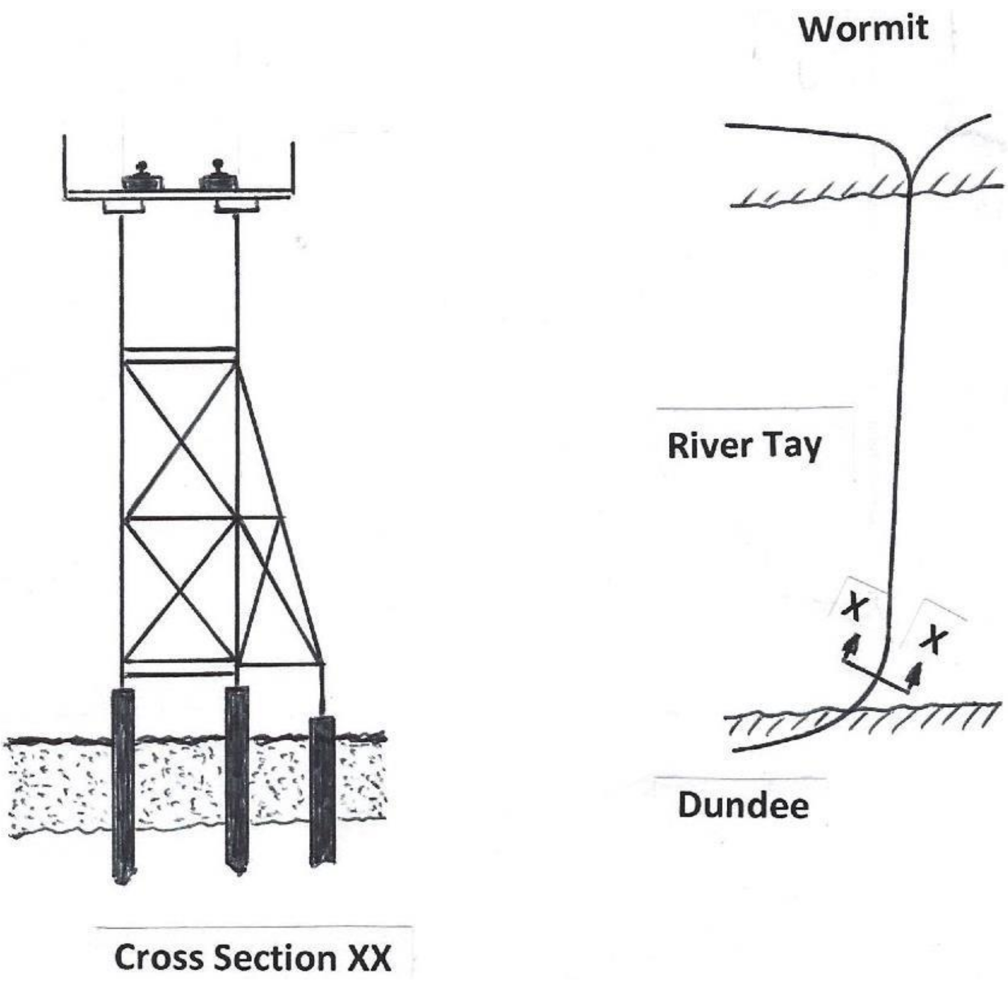
Figure (i) shows the relationship between wheel and rail on straight track, or at Equilibrium Speed on curved track.

Figure (ii) shows the relationship between wheel and higher rail at Maximum Permissible Speed on curved track. (Maximum Permissible Speed is usually higher than Equilibrium Speed). The wheel is pressing sideways against the higher rail, thereby producing Centrifugal Force. In general, passenger trains travel on curved track at Maximum Permissible Speed.

Note:- The gauge is sometimes quoted as 1432 mm, which is the gauge used on certain modern types of track to give a 'tighter' ride, whereas the 'well known' gauge for other track is 1435mm as quoted on Figure 1.3.

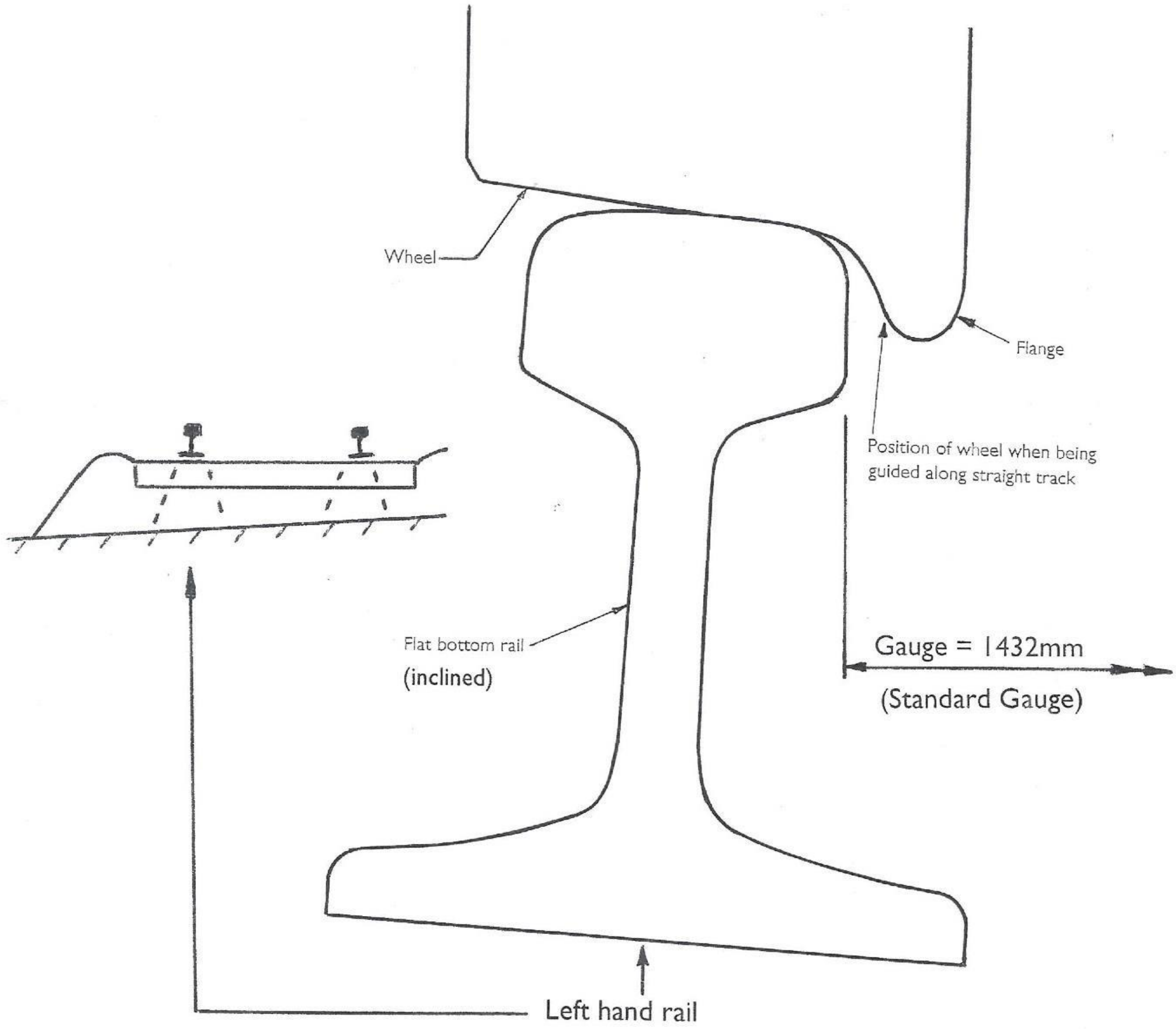
A sharply curved section had to be provided on the first and present day Tay Bridges, at the Dundee end.

The first bridge was of very slender design, so much so that the designer, Sir Thomas Bouch, added external strengthening to the curved section to counteract Centrifugal Force, as shown below.



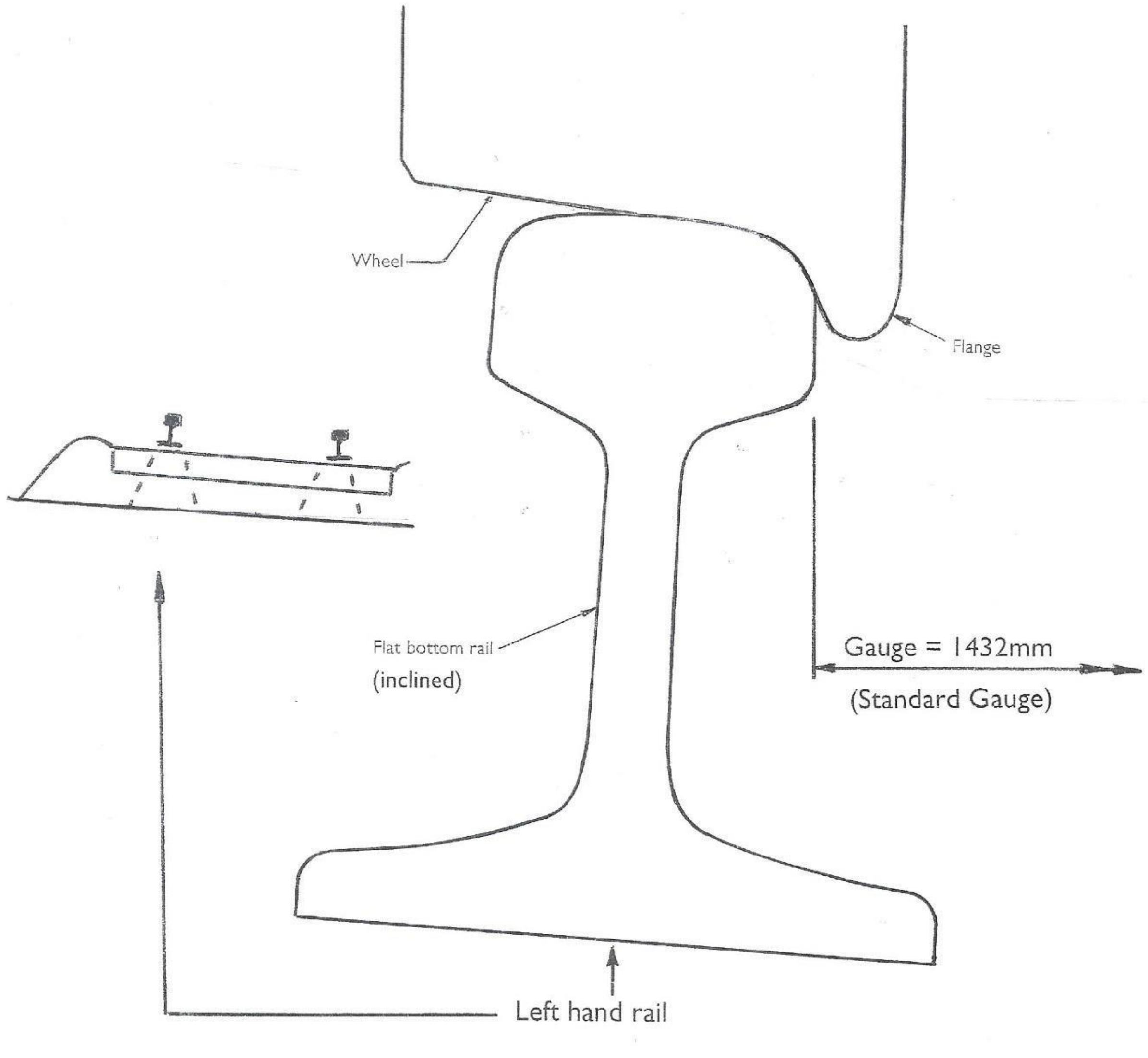
The curved section of the first Tay Bridge.

The above Cross Section XX also shows how slender the first Tay Bridge piers were, an issue criticised after the Bridge's collapse. They were made slender to minimise their width and thereby the cost of the foundations. Figures 16.2 and 16.3 clearly show that the Forth Bridge's stability was assured by the 1 in 8 batter of the vertical members.



Wheel
Flange
Position of wheel when being guided along straight track
Flat bottom rail
(inclined)
Gauge = 1432mm
(Standard Gauge)
Left hand rail

Figure (i)



Wheel
Flange
Flat bottom rail
(inclined)
Gauge = 1432mm
(Standard Gauge)
Left hand rail

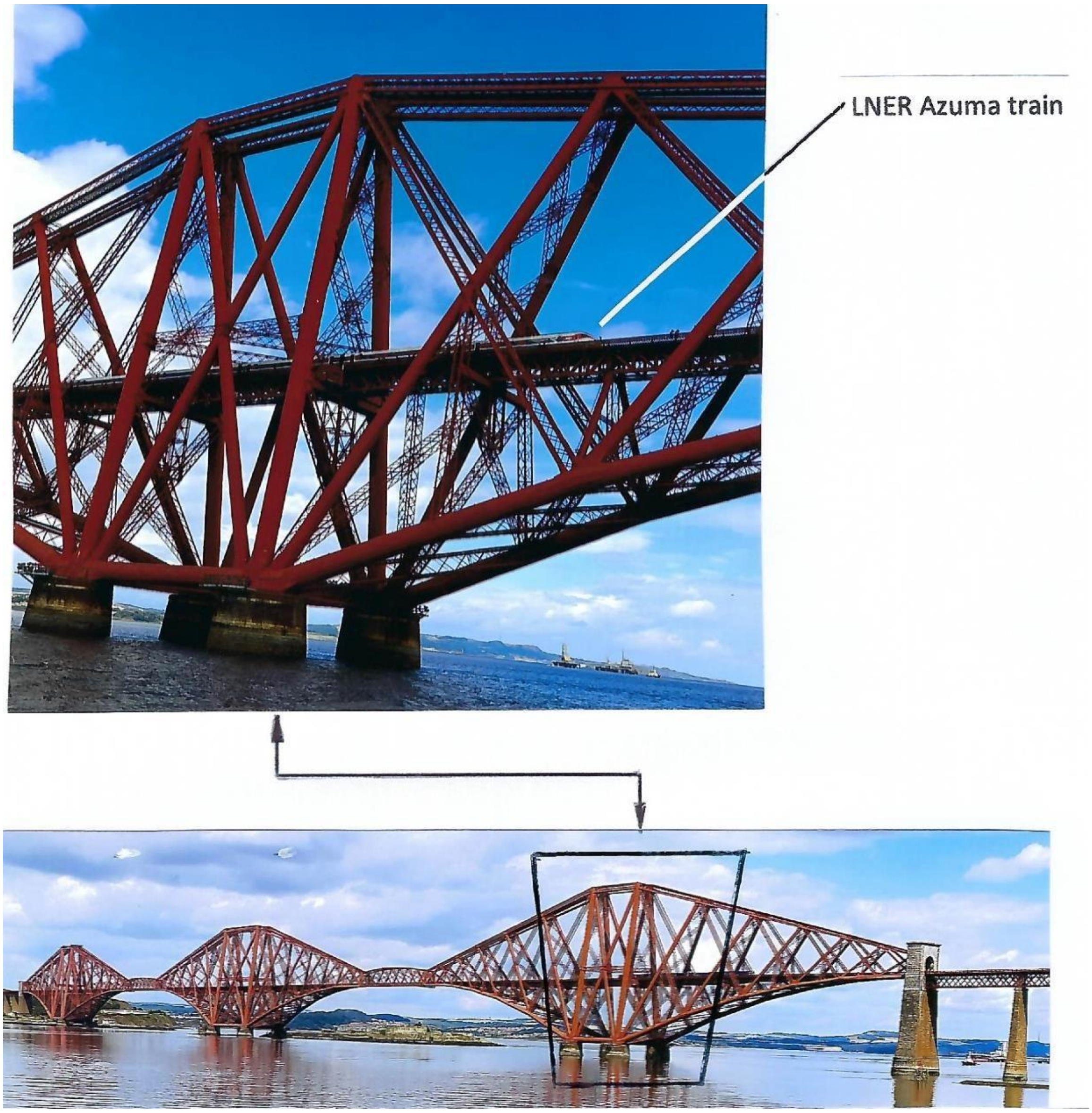
Figure (ii)

The present double track Tay Bridge (see below) withstands Centrifugal Force without the need for external strengthening.

A London to Aberdeen train, in the 1980s, on the curved section of the Tay Bridge. The train, which is travelling at the Maximum Permitted Speed for the curve, is producing some Centrifugal Force as it’s speed is slightly above the curve’s Equilibrium Speed.

(iv) Is the Bridge over-designed?

The massive size and weight (51,000 tons, 51,818 tonnes) of the Bridge’s Cantilever Section, tends to dwarf the trains it carries, which sometimes raises the question: was it overdesigned, possibly as a reaction to the collapse of the Tay Bridge?



The answer is ‘No’ for the following reasons.

Although some of the original drawings are held by the Institution of Civil Engineers, the original design calculations are assumed to be lost, or were destroyed many years ago (not by the Institution).

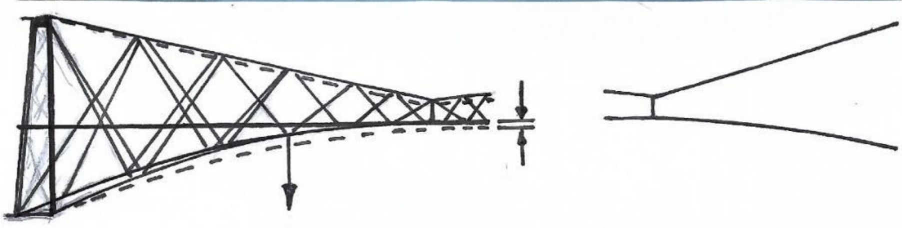
The book '100 Years of the Forth Bridge', edited by Rowland Paxton, indicates that the two main designers, Sir John Fowler and Benjamin Baker, devised the arrangement of the Bridge's principal structural features (three towers, each supporting two balanced cantilevers, with a counterpoise at the extreme ends of the Cantilever Section).

After being recruited by Fowler and Baker as their main Assistant, Allan Stewart, a civil engineer who was also a Cambridge mathematician, was given the important task of structural analysis, taking into account the need for two trains on the Bridge at any one time, each travelling at 40 mph (one on each line).

The book mentions that Stewart used what he called a 'Diagram of Forces' technique and the 'Principle of Elastic Forces' to determine the forces involved and therefore the size of the various girders. The Board of Trade Regulations for the use of steel stated that the working stress should not exceed 25% of the ultimate stress.

The book also states that Wilheim Westhofen, a German engineer who worked on the construction of the Bridge (and fortunately produced the most authoritative paper about the Bridge), stated that the final weight of the Cantilever Section was 51,000 tons (51,818 tonnes). Baker, in lectures up to 1885, however gave an estimated weight of 42,000 tons (42,675 tonnes), then revised for an 1887 lecture to 45,000 tons (45,720 tonnes).

Westhofen also mentions design alterations may have been necessary to carry erection equipment and cranes, leading to the increase in steel required. Also, it may have been necessary to strengthen certain parts to prevent excessive 'drooping' of the Cantilevers when about 95% formed but not yet able to benefit from the support about to be given by being part of a Continuous Structure (see Diagram below and Section 7). The high accuracy of Stewart's analysis was confirmed by the deflections measured when the Bridge was being tested using very heavy stationary trains. The deflections were within anticipated limits (see Section 20). This enabled the Board of Trade to issue the Certificate that confirmed satisfaction with the tests (and thereby permitted the opening of the Bridge for trains travelling up to 40 mph (65 kph).



As present day testing and evaluation procedures require passenger trains to be restricted to 50 mph (80 kph) and freight trains to 20 mph (32 kph) when on the Bridge, it would appear that the original design for a maximum speed of 40 mph in 1890 was not an ‘overdesign’, bearing in mind the hammer blow effect known to be produced by steam engines.

Another indication that the Cantilever Section is not over-designed is the test carried out in 1952, whose purpose was to establish if a Class A4 steam engine could be assisted on the Bridge by a Class B1 engine, instead of a Class D49 engine, the heaviest engine permitted on the Bridge at that time as an engine assisting an A4 (i.e. a ‘Double headed’ train). The difference in weight between a B1 and a D49 was not exceptional, but was sufficiently significant to require a successful test to be carried out, involving stress measuring devices, before the A4/B1 combination could be authorised by the civil engineers for standard use.

Note; Although Class A4 steam engines were very powerful (i.e. ‘Mallard’ held the world speed record for a steam engine at 126 mph (203 kph), the British Railways Operating Department must have had instances when the more readily available Class B1 engine would have been very useful on occasions when an A4 needed assistance (e.g. when in difficulty working the very heavy overnight Aberdeen/London sleeper train ‘The Aberdonian’).

(v) World Heritage Site

Why was the Forth Bridge selected?

Probably because of the exceptionally long Cantilever spans, which still attract engineers from around the world, plus tourists. (see Section 5).

Note: The official name of the Forth Bridge is simply 'Forth Bridge' and not 'Forth Railway Bridge'.

(vi) The design of a modern Forth Bridge.

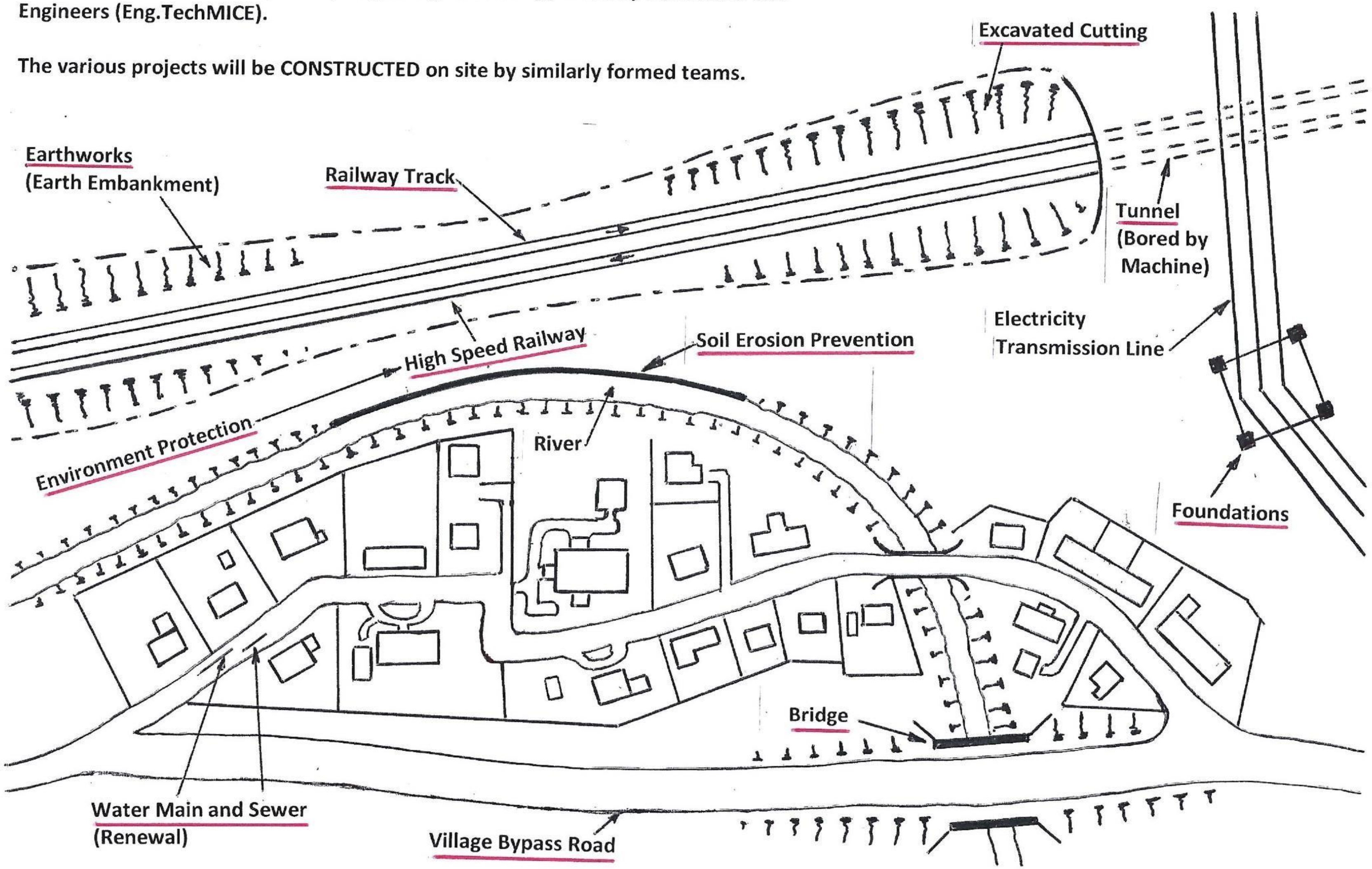
What might the appearance be of a Forth Bridge (railway) designed today, taking account of modern practices, materials and aesthetics?

Would a tunnel at a different location be a better solution?

(vii) Diagram which shows some present day Civil Engineering Projects.

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.



(viii) THE PIONEERS

The following pages give information covering the pioneering gentlemen who designed, authorised and financed the Bridge in the 1880s.

As previously stated, the construction of the Bridge was a different engineering challenge and therefore, the people involved are not covered.

How did the Bridge's Designers obtain the knowledge required for such a challenging Project?

Initially, the complex Cantilever Section had two main designers, Sir John Fowler and Benjamin Baker, whose combined skills produced the basic design concepts. Shortly afterwards, they recruited the third main designer, Alan Stewart.

Sir John Fowler	1817 ……………………………………………………………. 1898
Benjamin Baker	1840 ………………………………………………………… 1907
Alan Stewart	1831 …………………………………………………… 1894

BRIDGE OPENED IN 1890

The more conventional Queensferry and Fife Approach Viaducts were designed by James Carswell in conjunction with Sir John Fowler and Benjamin Baker.

Today, the civil engineering profession is regulated by the Institution of Civil Engineers. Members of the profession must comply with standards set by the Institution, and statutory requirements covering design, construction and maintenance.

When the Forth Bridge was being designed in the 1880s, the situation was completely different. Although the Institution of Civil Engineers was formed in 1818, little existed in the way of tried and tested examples of long cantilever structures, legally binding engineering standards, Codes of Practice, and compulsary qualifications. Consequently, those designing exceptional projects were working in 'unchartered waters.' However, they were usually of great tenacity and highly motivated to push the boundaries of current accepted practice to the limit, and then beyond.

Sir John Fowler, the Bridge's main designer, wrote the following in 1865 before becoming the youngest President of the Institution of Civil Engineers in 1866, 24 years before the opening of the Forth Bridge.

We of the passing generation have had to acquire our professional knowledge as best we could, often not until it was wanted for immediate use, generally in haste and precariously, and merely to fulfil the purpose of the hour; and therefore it is that we earnestly desire for the rising generation those better opportunities and that more systematic training for which in our time no provision had been made, because it was not so imperatively required.

Sir John Fowler had had a good general education up to the age of 17 and then became a pupil of a hyraulics engineer involved with water supplies for large towns in England. When only 26, he believed he had gained enough confidence and experience to start an independent career in civil engineering. This led to being heavily involved in the design of the Metropolitan Railway in London, a project many considered to be 'an impossible and stupid project,' but not Sir John.

Benjamin Baker, the second of the three designers had had a grammer school education in Cheltenham up to the age of 16 and then was apprenticed to work at an iron works. He joined John Fowler's practice in 1862 and by 1875 was Fowler's business partner. He worked with Fowler on the design of the Metropolitan Railway and had acquired considerable experience in the design of long-span bridges, including the use of cantilevers, but none as challenging as the Forth Bridge. Also, he described Fowler as a "born commander who formed opinions with instinctive guidiness and then held on to them furiously, never questioning their soundness, nor failing to convince others by his ingenuity of argument and charm of manner". (Baker was President of the Institution of Civil Engineers 1895/96).

Following the Tay Bridge Disaster, Baker was asked to assist with the Public Inquiry. His obituary stated "he well knew how to discard a computation if it led to results at variance with his practical experience."

Consequently, the first two designers were of the 'practical school.' The third designer, Alan Stewart, was mainly of the 'theoretical school' having been the 9th Wrangler in the 1853 Mathematics Tripos at Cambridge University. He became a civil engineer and set up business in Edinburgh. In view of his considerable mathematical expertise, Sir John Fowler and Benjamin Baker secured his appointment as their Chief Assistant, (1881 – 1899) mainly for the stress and dimensional analysis of the intricate girder configurations devised by Fowler and Baker. Stewart assisted Sir Thomas Bouch with his design of the illfated first Tay Bridge and was involved with the design of Edinburgh Waverley station roof.

Clearly, the most common way of becoming a civil engineer in those days was by the 'practical' route taken by Fowler and Baker. Stewart's route on the other hand involved the much less common, University based, 'theoretical' approach. This situation was to be the start of the never-ending debate as to the ideal balance between practice and theory when determining the attributes required by a Member of the Institution of Civil Engineers. The matter was highlighted in the following statement made some years later in 1895 by Sir Benjamin Baker.

……'If anything more needs to be said on the subject, it must therefore be of the nature of a warning, that technical education is of little value unless accompanied by the practical experience, sound judgement, and bold initiative which, rather than book knowledge, characterised the famous members of this Institution (ICE) in the past. Education will do much, but it will not endow a man (person) with common sense, nor will it make his (or her) opinion on a multitude of important subjects worth more than that of a naturally observant person' …..

These three gentlemen were pioneers. The arrival of protocols and Codes of Practice for the design of massive structures was trailing some years behind the work they were actually producing. Although the Tay Bridge Disaster of 1879 was a 'wake-up call' that forced the Government of the day to accelerate the introduction of regulated competence and materials quality, the Forth Bridge designers had to be highly confident about their judgement and ability to make decisions that would result in a safe and workable structure. Such people were truly exceptional.

The essential work done by the Designers could only be transformed into an actual Bridge by Officials of the Board of Trade believing the design to be safe, and the Directors of the Forth Bridge Railway (FBR) being willing to authorise the considerable expenditure involved.

This was a major project involving substantial technical and financial risks. Caution was required given the lessons that had to be learned from the very recent Tay Bridge Diaster. Although the Directors of the FBR had professional advisors, none could have had more bridge expertise than the three main Designers. Consequently, after receiving Board of Trade approval for the design, the FBR Directors, who carried prime responsibility for the safety of passengers, had to use their powers of judgement when deciding whether or not to confirm the funding and decide to proceed with the actual construction of the Bridge, a project that would take several years to complete.

The North British Railway actually obtained authority to provide 'a railway bridge across the River Forth' in 1873, but the 'Forth Bridge' was not completed, tested and opened to traffic until 1890, some 17 years later. As stated earlier, the NBR found it necessary to find other railway companies to support it in the forming of the Forth Bridge Railway, given the scale of the project.

References:-

'The Civil Engineers' published by the Institution of Civil Engineers.
'100 years of the Forth Bridge' published by Thomas Telford Limited.
'The Forth Railway Bridge – a Celebration' by Anthony Murray.

‘Time for a Coffee!’

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