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A CRITICAL ANALYSIS OF SCAMMONDEN BRIDGE, YORKSHIRE

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Abstract: This paper provides a detailed review and a critical analysis of the design, construction and aesthetics of Scammonden Bridge in Yorkshire. An assessment of the structure, both in terms of ultimate and serviceability limit state, was undertaken and calculations were provided to reinforce these assessments where necessary. Where specific data was not available, educated assumptions were made during the analyses. Any assumptions that have been made will be highlighted in the following text. This paper also highlights any problems that the bridge may have, as well as potential solutions and modifications that could be incorporated in the future.

Keywords: *Scammonden Bridge, Concrete Arch, Open-Spandrel, Motorway Underbridge*

1. Introduction

[1]Scammonden Bridge is a fine example of an open-spandrel concrete arch bridge [Fig. 1], situated in the rugged and inhospitable Pennine hills approximately 8km west of Huddersfield in Yorkshire, in the north of England. The bridge is named after the nearby village of Scammonden, which was flooded to make way for Scammonden Reservoir.

The design of the bridge was constructed as part of the overall M62 motorway contract, which was the first highway to traverse the Pennines and link the east and west coasts of England. The bridge, along with the M62 and neighbouring Scammonden Dam, was designed by Colonel Stuart Maynard Lovell, one of the most experienced motorway engineers of the time, with Sir Alfred McAlpine contracted to carry out the construction work. Both Lovell and McAlpine had successfully worked together on similar projects in the past, such as the M1; the first motorway to be constructed in the UK.

Site surveys of the motorway route and bridge location commenced in 1961. The bridge took four years to construct and was completed in 1970. To highlight the engineering achievement of the motorway and bridge, it was officially opened by HM Queen Elizabeth II, along with the motorway, on 14th October 1971.

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The main arch spans a distance of 125m with the deck spanning 200m. It carries the A6025 single-carriageway road 37m above the M62 motorway. Originally designed to be a simple flat arch bridge, it was redesigned, using computer design software, as an open-spandrel bridge to prevent a reduction in airflow through the cutting, as a reduction in airflow would cause snow-drifts to build up on the motorway.

Figure 1: Scammonden Bridge in elevation

When completed, the bridge was the longest single span non-suspension bridge in the world, and remains the longest concrete arch bridge in the UK today.

2. Aesthetics

Analysing the aesthetics of any bridge is often subjective to the individual and it can be difficult to conclude whether a bridge can be regarded as beautiful or not. The following analysis is based on the ten principles of aesthetics set out by Fritz Leonhardt in his book entitled ‘Bridges’; [2]. These principles should be regarded as guidelines rather than rules as a bridge that applies them can still be unattractive.

When viewing the bridge for the first time, it is easy to see that it feels right and well proportioned for its location. It integrates itself into the surrounding environment, but at the same time it does not fade into obscurity [Fig. 1]. Instead it stands out as a unique and interesting structure without detracting from the Pennine scenery.

Scammonden Bridge is unusual in that it is mostly viewed in elevation by motorists travelling under it. For many other landmark bridges, the main view is on top of the deck in the direction that the bridge is crossed. Therefore, the design of the bridge in elevation was very important.

The function of Scammonden Bridge is very clear to see. The open spandrel design exposes the main structural elements and the load paths are clearly defined in elevation. Differences between the member sizes further enhance the structure, highlighting which members are doing the work. This is emphasised by the spandrel columns, which are much less prominent and imposing than the arch, proving that the arch is fundamental to the bridge's stability. With its open spandrels, Scammonden appears almost skeletal, making the bridge seem lighter and less imposing, but at the same time doesn't reduce the appearance of stability and strength.

Straight away, the bridge appears to be well proportioned, with none of the members seeming oversized, undersized or redundant. With the bridge being mainly viewed in elevation, member sizes and spacings must be considered carefully. The spacing of the spandrel columns looks correct in relation to the length of the bridge and the depth of the deck gives the impression of stability without imposing on the form of the structure.

Although Scammonden Bridge appears to have good order from afar, it is evident that the order of the structure was not given enough detailed attention close-up. There are too many edges and lines within the structure, especially in the deck where the soffit is broken. The spandrel columns are also misaligned from the edge of the deck soffit. This is due to the fact the arch is narrower than the deck; however it makes the bridge to appear awkward when viewed closely [Fig. 2].

Figure 2: Close-up of the deck and spandrel columns

Unfortunately, the refinement detail has also been overlooked during the design, reducing the elegance of the bridge when viewed close-up. The main example of this is where the crown of the arch cuts into the deck, creating an excessive number of lines and edges [Fig. 2], ruining the fluidity of the deck. When viewing the bridge in elevation, the members look slender and lightweight; however when looking from an oblique view, the continuous spandrel columns make the bridge look heavy and cumbersome. The spandrel columns are also spaced equally and do not taper. Column tapering was a refinement introduced by the Greeks, which prevented the columns from looking top-heavy. Although Scammonden Bridge has ignored these refinements, it does not detract from the overall appearance as it will be seldom seen at close range.

The bridge is located high in the Pennines, which is noted for its rugged scenery and views. This was a very important consideration during the design process, both from an aesthetical and a practical point of view. The line of the deck follows the existing mountain ridge, making it continuous in elevation [Fig. 3]. The choice of an arch suits the deep valley and also means that none of the structure extends above this line, reducing the bridges impact to the skyline. The open spandrel arch is also practical as it enables the wind to pass through the cutting without reducing the wind speed. This prevents snow from drifting onto the motorway below [4].

Figure 3: Scammonden Bridge and surrounding scenery

The colours and textures of the bridge fit in well to the ruggedness of the surrounding moors. The bridge has never been painted, but rather been left in its original concrete finish. The colour and texture bode well with the natural mudstone outcrops in the neighbouring embankment. Unfortunately, the attention to detail has been overlooked in this aspect too, with visible construction joints between the precast arch sections and expansion joints between the spandrel columns and the deck and arch.

Maintenance of the bridge has also been neglected in this area. The bridge is regularly inspected in a structural capacity, however the concrete is heavily stained with algae and rust from the reinforcement steel, which can be seen in Figure 2.

The bridge has plenty of character, and it is easy to see how the bridge functions. It is also unusual for a motorway bridge to be so interesting when compared to standard highway bridges. Simplicity is often regarded as beautiful, and the design of Scammonden Bridge is very simplistic. From a distance, this makes the bridge attractive but from a close-up level, the complexity of the refinement makes the bridge look awkward.

Many successful designs have been influenced by nature, and although the design of Scammonden Bridge has not been directly influenced by natural forms, the spandrels give the bridge a skeletal appearance. The colour of the bridge is also similar to the local mudstone; giving the impression the bridge has always been an integral part of the local environment.

2.1. Summary of Aesthetics

Following Leonhardt's ten rules of aesthetics doesn't necessarily guarantee a beautiful bridge and Scammonden Bridge doesn't follow all ten of them implicitly. However, it successfully fulfils its purpose as a bridge while looking attractive and interesting. The only disappointment is the lack of attention to detail incorporated into the design.

3. Structural Design

For all calculations in this paper, the following key dimensions have been used. These dimensions have been taken from various sources and many have been converted from imperial measurements.

Table 1: Key dimensions

Scammonden Bridge	
Deck Length = 200m	Clear Arch Span = 125m
Clear Height = 37m	Carriageway Width = 7.3m
Footway Width = 1.8m*	Spandrel Width = 0.45m
Deck Depth = 1.5m	Spandrel Spacing = 15.4m
Spandrel Heights between 2.4m and 18.3m	Arch Depth between 1.5m at centre and 2.4m at spring points

* Deck width is carriageway width plus 2 footway widths

The bridge itself consists of a twin-box arch made from modular precast concrete sections. The deck is made up of inverted pre-tensioned precast concrete T beams with in-situ concrete infill [Fig. 4]. Finally, the spandrel columns are made from precast concrete units pinned top and bottom.

The spandrel columns are pin connected, with a continuous deck running over them. Each spandrel has an elastomeric bearing top and bottom to allow movement and expansion. These bearings can be seen in Figure 2.

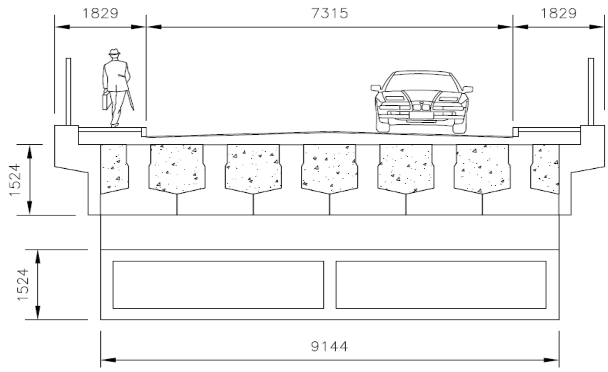


Figure 4: Cross section through the bridge; [4]

4. Loading

Just like any other structure, bridges must be able to withstand loads that are predicted to be exerted onto it. These loads may include dead, superimposed dead, live and wind loads. Typically, for a bridge such as Scammonden, the most onerous loads tend to be a combination of these.

As well as these traditional load cases, some bridges may also need to withstand other loads, such as creep, earthquake, impact and temperature. The load analysis in this paper follows BS 5400-2: 2006.

4.1. Dead Loading

As with all structures, the dead load can be described as the load that the structural elements exert due to dead weight. For this bridge, the dead weight can include the weight of the deck, columns and arch. For the following bridge analysis, it is assumed that all concrete elements have a bulk weight of $24kN/m^3$. Dead loads have a safety factor of 1.15 for ULS and 1.0 for SLS [5], and the estimated unfactored dead loads are as follows:

- Deck = 396kN/m
- Arch = 1813kN/m
- Spandrel columns = 100kN/m

4.2. Superimposed Dead Loading

Non-structural elements on the bridge are not classed as dead loads. This is because they can be added and removed at any time during the lifespan of the bridge, making it hard to quantify exactly. In most cases, it is assumed that items such as blacktop are replaced many times over the lifespan of a bridge, meaning large safety factors are used during calculations – 1.2 for SLS conditions and 1.75 or ULS [5]. Superimposed dead loads for this bridge are assumed to include blacktop, sub base, services and hand railings. The estimated unfactored superimposed dead loads for Scammonden Bridge are as follows:

- 300mm Sub base = 55kN/m
- 150mm Tarmac blacktop = 33kN/m
- Drainage, Services and railings = 9kN/m

4.3. Live Loading

The live loading on a bridge will vary greatly depending on the type of infrastructure using it. For instance, a highway bridge will experience different live loads to a railway or pedestrian bridge. For highway bridges, live loads will tend to include vehicle loads, braking forces, impact forces, accident forces and pedestrian loads. Bridges with cambers may also experience centrifugal loads. As there are many forms of loading, it can be difficult to select the most onerous load combination.

In the UK, highway bridge loadings used for analysis are found within BS-5400-2:2006 [5]. Under this standard, there are two types of traffic loading; HA and HB. This standard also sets the notional lanes upon the bridge, the loads applied and the position of them.

4.3.1. Notional Lanes

Notional lanes are identified to determine how the live loads will be placed during analysis. It is worth noting that these lanes are independent of the actual lanes marked on the highway [Fig. 6]. Clause 3.2.9 in BS 5400-2 states that two-lane single carriageways with widths between 5m and 7.5m (Scammonden Bridge is 7.315m wide) have 2 notional lanes in total.

Figure 6: Topside of bridge looking north

4.3.2. HA Loading

This load is formed up from both a uniformly distributed load acting over a set number of notional lanes (which represents traffic crossing the bridge) as well as a knife edge load (KEL), which is positioned in such a position as to give the worst loading case.

From BS-5400-2, the unfactored HA load (w) is found from clause 6.2.1 using the following equation:

$$w = 36\left(\frac{1}{L}\right)^{0.1} \qquad (1)$$

With the length, L measuring 200m, the total HA UDL is 21.2kN/m length of notional lane. This equates to 5.8kN/m^2 on the carriageway. This load is then multiplied by design factors γ_{fl} and γ_{f3} [Fig. 7]. The KEL is always taken as 120kN [5].

Load		Limit state	γ_{fL} to be considered in combination				
			1	2	3	4	5
Highway bridges live load:	HA alone	ULS	1.50	1.25	1.25		
		SLS	1.20	1.00	1.00		
	HA with HB or HB alone	ULS	1.30	1.10	1.10		
		SLS	1.10	1.00	1.00		
	footway and cycle track loading	ULS	1.50	1.25	1.25		
		SLS	1.00	1.00	1.00		
	accidental loading[c]	ULS	1.50				
		SLS	1.20				

Figure 7: Load Factors for γ_{fl}; [5]

BS-5400-2 states that the HA load and KEL are to be distributed over two of the notional lanes. If the bridge has any more notional lanes, the loads on these will be a third of the HA and KEL loads. As Scammonden Bridge has only two notional lanes, the following distribution is taken:

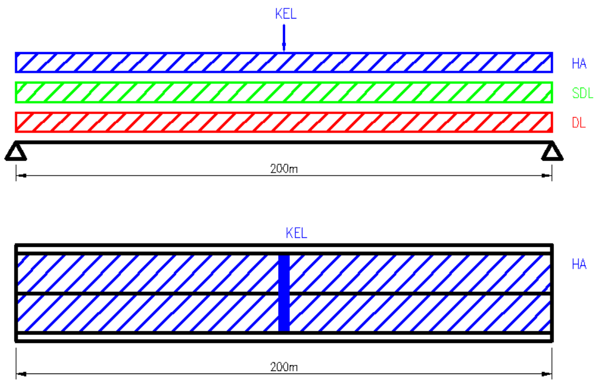


Figure 8: HA load position to give worst case load for the deck

This will be the worst case scenario for the deck, when the load is acting over the whole of the plan area. The deck can be assumed to have some fixity at the ends, meaning the maximum bending moment can be worked out simply as:

$$M = \frac{wL^2}{12} + \frac{PL}{4} \qquad (2)$$

$$M = 11.2\text{MNm}$$

Where P is the 120kN KEL, L is the spacing between the spandrels and w is the factored dead, superimposed dead and HA live load.

The worst case for the arch will be when the loads are acting over half of the deck, causing the maximum moment to occur at the quarter point of the arch.

4.3.3. HB Loading

HB loading under BS-5400-2 characterises extreme, abnormal vehicles such as heavy duty low-loaders. In the UK, these vehicles will only be mobile under police escort with designated road closures or traffic control.

Under BS-5400-2, these vehicles vary in length, with central axle spacings between 6m and 26m. The length of vehicle will be chosen to produce the most adverse loadings. The HB load can also be placed at any point along the bridge to give the worst case loading.

As the width of the HB vehicle is 3.5m, it is narrower than the notional lane width on Scammonden Bridge. Therefore, as a worse case, the HB load should be taken alongside a full HA loaded notional lane [Fig. 9]. If HB vehicles were to use Scammonden Bridge, it is likely that the bridge would be closed to other traffic. But however unlikely this scenario, it should still be taken as a worst case.

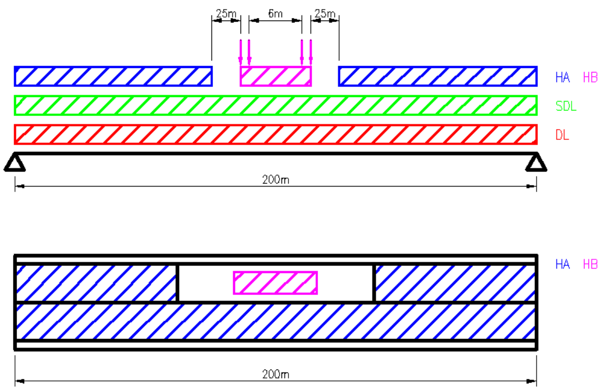


Figure 9: HA and HB load position and combinations

Using a 6m long HB truck gives the maximum sagging moment in the deck, which equates to 16.7MNm.

4.4. Wind Loads

Steep sided valleys have a tendency to direct the wind, causing a funnelling effect to occur. Scammonden is no exception, especially with the bridge being in the exposed location of the Pennines. However, unlike many other bridges, the valley sides have been engineered to reduce the wind-tunnelling effects.

The following wind calculations are undertaken in accordance with BS-5400-2. They determine the wind loads experienced on each structural element both in the horizontal and vertical uplift directions.

Firstly, the site hourly mean wind speed (v_s) is calculated using Equation 3 below.

$$v_s = V_b S_p S_a S_d \quad (3)$$
$$v_s = 24x1.05x1.305x0.99$$
$$v_s = 32.6m/s$$

This is then used to calculate the maximum wind gust [Eq. 4]. S_g has been calculated as 1.75.

$$v_d = S_g v_s \quad (4)$$
$$v_d = 57m/s$$

The dynamic pressure head (q) can be calculated from this [Eq. 5].

$$q = 0.613 v_d{}^2 \quad (5)$$
$$q = 2kN/m^2$$

Using the various Drag Coefficients listed in the British Standard, the following loads in Table 2 were calculated.

Table 2: Wind Loads

Scammonden Bridge	
Deck	2.2kN/m^2
Arch	2.4kN/m^2
Spandrels	2.0kN/m^2

Downward and upward pressures on all elements can also be calculated using the following equation.

$$P_v = qA_3C_L \quad (6)$$
$$P_v = 2x1826.6x0.525$$
$$P_v = 1.97kN/m^2$$

5. Strength

With simple analysis, checks can be made to the strength of the deck in compression and the prestressed tendons which prevent bending. In order to achieve this, assumptions have been made due to the absence of data. Therefore, the following assumptions have been made regarding the serviceability of the deck.

5.1. Deck

The force in the prestress tendons at serviceability can be calculated as seen in Equation 7. It is assumed that the neutral axis is located at 0.4d, the area of prestressed steel is 0.5% of the total area (69677mm^2), cover to the prestress tendons is 150mm, the prestress is 1700N/mm^2 and 70% prestress has been achieved.

$$F = 0.6 f_y A_{ps} \quad (7)$$
$$F = 71MN$$

From this, the compressive strength can be calculated from Eq. 8

$$\sigma_c = \frac{F}{A} \quad (8)$$
$$\sigma_c = \frac{71x10^6}{13935000}$$
$$\sigma_c = 5.1N/mm^2$$

The effect that the prestressing force has on the compression in the deck is calculated as:

$$\sigma_{c,t} = \frac{Pe\,y}{I} \tag{9}$$

Where P is the prestress force calculated in Eq. 7, e is the eccentricity of the prestress force and y is the distance to the neutral axis.

$$\sigma_c = 1.42N/mm^2$$

$$\sigma_t = 2.1N/mm^2$$

Using Equation 10 below, the overall tension and compression in the deck can be calculated.

$$\sigma_{c,t} = \frac{My}{I} \tag{10}$$

$$\sigma_c = 3.18N/mm^2$$

$$\sigma_t = 4.7N/mm^2$$

M is taken as 16.7MNm from the HB load case, resulting in an overall deck stress block of:

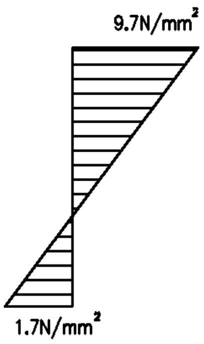


Figure 10: Deck stress block

The maximum allowable compressive strength is given as $0.33f_{cu}$ where f_{cu} is the compressive strength of concrete at 35N/mm^2. This results in the maximum compressive stress value of 11.55N/mm^2, which is greater than the stress calculated in this load case.

5.2. Arch

Calculations can also be undertaken to check the strength of the reinforced concrete arch section. For these calculation checks, a non-uniform loading was added to the arch, as this will cause bending to occur in the section. The dead loads were taken over the whole bridge as these will always be in place. Full HA and HB live loads were added to half of the arch along with the superimposed dead load. All loads on one half of the bridge were factored to ULS, while loads on the other half have been left unfactored. This scenario is unlikely as superimposed dead loads are likely to be acting on the bridge during operation; however this calculation gives the worst case situation.

This situation will cause the maximum bending moment to form at the quarter span point. This equates to 16.7MNm.

As with the deck, assumptions have been made due to absent information. Firstly, the reinforcement within the arch box section is located within the flange at half distance; the total area of steel equates to 5% of the total area and the thickness of the box section flange is 200mm. The arch is assumed to carry no axial force. In the following equations, F_{st} is the tension force in the steel, F_{sc} is the compressive force in the steel and F_c is the compressive force in the concrete.

$$F_{ST} = F_{SC} + F_C \tag{11}$$

$$F_{ST} = \frac{A_{ST} f_y}{1.15} \tag{12}$$

$$F_{SC} = \varepsilon_{SC} E_S A_{SC} \tag{13}$$

$$F_C = 0.45 f_C A_C \tag{14}$$

Where f_y is the yield stress of steel; 460N/mm^2, E is 200000N/mm^2, f_c is the compressive strength of concrete; 35N/mm^2, A_{sc} and A_{st} are the areas of steel in compression and tension respectively and the steel compressive strain was determined to be 0.00225.

Through iteration, the neutral axis was found to be approximately 280mm from the top flange edge. These calculations produced the following forces:

$$F_C = 36MN$$

$$F_{SC} = 47MN$$

$$F_{ST} = 84MN$$

Taking moments from the tension steel bars gives the ultimate bending capacity of the arch section, which is 107.8MNm. This is much higher than the 16.7MNm maximum moment calculated for the worst case HB load factor.

5.3. Deflections

A simple check can be carried out to determine the deflection of the bridge deck. In the deflection equation below [Eq. 15] w is the load per unit length (made up of dead, superimposed dead and live load) and l is the spacings between the spandrels. The calculation assumes that the deck is simply supported.

$$\delta = \frac{5wl^4}{384EI} \tag{15}$$

$$\delta = 4.3mm$$

Under British Standards, the maximum allowable deflection is determined by:

$$\delta = \frac{\text{Span}}{360} \tag{16}$$

$$\delta = 43mm$$

6. Foundations and Geotechnics

Both bridge design and location are heavily dictated by the geotechnical properties of the site. Due to the extreme dead and live loads, bridges must be constructed on suitable ground conditions. In some instances, it is cheaper and easier to reroute existing infrastructure to a site with good ground conditions than to construct extensive foundations to cope with poor soils.

The general location of Scammonden Bridge was initially dictated by the route of the existing A6025 and the proposed location of Scammonden Dam. The existing A6025 could have been rerouted, but ground surveys indicated that the bedrock was suitable in the area.

Although no geotechnical records are available for the bridge, located either side of the bridge are two quarries [Fig. 11], and the original quarry geotechnical report [6] found that the area around Scammonden Bridge mainly consists of grey Mudstone bedrock with some sandstone and siltstone outcrops. The bedrock is overlain with peat bogs and Midgley Grit.

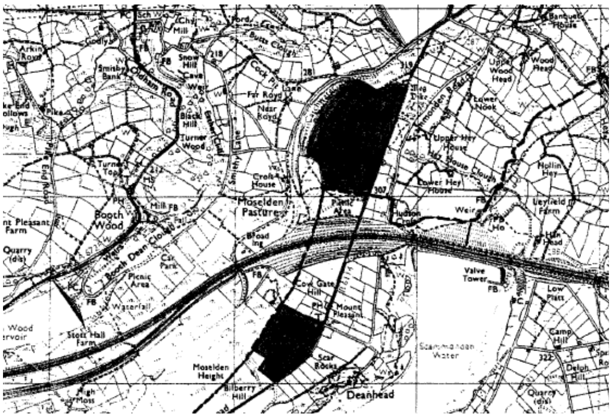


Figure 11: Location of the quarries either side of Scammonden Bridge; [6]

On-site tests proved the bedrock was capable of withstanding the bearing pressures caused by the dead and live loads of the bridge. This meant that the foundations for the bridge did not have to be specially designed to operate in poor ground. Excavations were made into the cutting and pads were constructed from in-situ reinforced concrete. These were made flush with the embankment in an attempt to hide them, thus preventing them from ruining the aesthetics of the bridge.

This scheme was unusual in that the cutting did not exist prior to the construction of the motorway. So unlike many other projects, the embankments were carefully engineered to both support the bridge and reduce problems caused by the harsh weather.

The cutting was initially designed on a scale model, which was subjected to wind tunnel testing [1]. Both tunnelling effects and snow drift depths were measured in the lab. It was discovered that snow drifting was a huge problem, so 4.5m steps were incorporated into the cutting banks to allow snow to settle [Fig. 12]. The ends of the cutting were profiled to prevent large vehicles from being blown over by side-winds.

Figure 12: Deanhead cutting being profiled in 1970

Blasting of the rock was required to create the cutting for the motorway. Due to the scale of the project and the innovative methods of blasting, an onsite geology laboratory was set up to monitor progress [7].

In total, 5.4million cubic metres of rock were blasted to create the cutting. In modern construction projects, this quantity of rock removal is extremely unsustainable; however in this case, the blasted rock was used to build nearby Scammonden Dam. This prevented the need for long distance transportation and subsequent land-fill disposal.

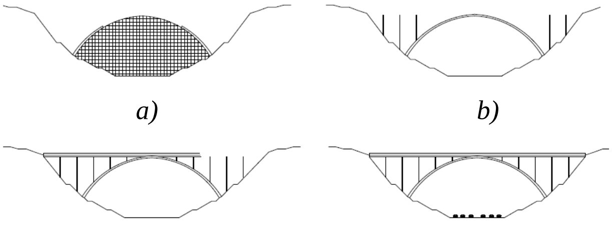
7. Construction

Although Scammonden Bridge is a relatively basic open-spandrel design, the construction of the bridge was by no means straightforward. The harsh weather coupled with the inhospitable Pennine terrain meant that construction work was often delayed and even postponed at one point. As well as environmental problems, anti-motorway protests also increased the overall construction time on site.

Due to the remoteness of the site, a major site compound needed to be set up to store plant and materials to use during the winter months. The half completed motorway allowed plant and materials to be transported to site without disrupting local road networks and villages.

Pre-stressed concrete was a common structural material in the 1960s with many highway bridges being manufactured from it at the time. It was selected for this project because of its cheapness, availability and because it was a tried and tested material.

With work for the motorway embankment already under way, construction started on the bridge in 1967. However, due to various delays to the motorway construction, the erection of the bridge began before the embankment was fully completed. This meant that blasting of the embankment rock was carried out while the arch was being concreted [4]. To ensure that the blasting wouldn't cause damage to the arch or centring framework, sample sections were mounted on temporary scaffolding and vibrations were monitored.



a) *b)* *c)* *d)*

Figure 13: Construction process: *a)* Arch sections attached. *b)* Spandrels cast. *c)* Deck added. *d)* Finished bridge.

The following construction methods used were common throughout concrete highway bridge design during the mid twentieth century. These tried and tested methods reduced the overall construction costs and timescale.

Once the foundations had been constructed, the scaffold centring framework for the arch was assembled. This framework was extensive in its own right, as it not only had to take the dead load of the concrete arch, but also immense wind and snow loads passing through the cutting. With the site being exposed, the temporary framework was constructed to withstand wind speeds of up to 110mph, and during one winter it was estimated to have an extra 1100 tonnes of ice and snow build-up [4]. In order to withstand these loads, approximately 70 miles of scaffold tubing made up the framework [Fig. 14].

Figure 14: Temporary arch centring framework with precast arch sections and spandrel joints; [4]

Arch centring of this scale is rarely used in modern day construction due to the quantity of material required and the timescale needed to erect the frame. Although not in this case, extensive framework can also prevent existing infrastructure passing underneath.

The arch itself is made up of precast reinforced concrete sections which were prefabricated off site. These were then lifted into position by two tower cranes, starting at the springing points. Finally, the key-stone piece was positioned, giving the arch rigidity, and the centring framework was removed.

Once the arch had been constructed, the spandrel columns could be erected. During the arch construction, spandrel joints were built into the prefabricated arch sections [Fig. 14]. The spandrels were cast in-situ using formwork. Once the reinforcement bars were linked into cages, formwork was set up around them [Fig. 15]. For the longer spandrel columns, the concrete was poured in stages to allow the concrete to cure properly. Due to the poor surface finish, thin joints can still be seen in these longer spandrels.

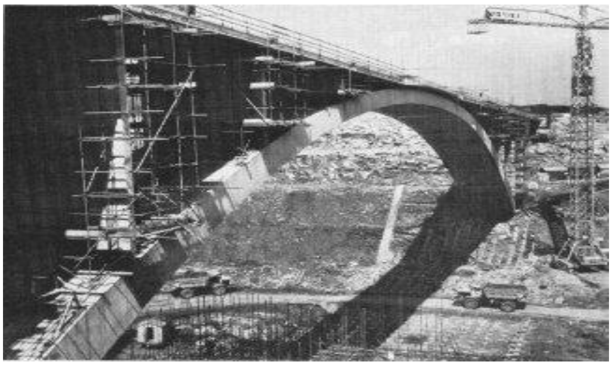


Figure 15: Spandrel scaffolding and formwork; [1]

Once cured, the formwork was removed from the spandrels, allowing them to effectively cantilever from the arch. The scaffolding was retained to aid the positioning of the precast deck beams.

The deck consists of prestressed, inverted T beams [4], which were positioned using the same tower cranes used during the construction of the arch [Fig. 16]. Each T beam spans 15.4m between the spandrel columns, which meant they were lightweight and easy to transport to site. Once the deck beams were positioned, in-situ concrete was used to fill the gaps between them and provide a level surface for the carriageway to be built upon.

The extensive temporary works, coupled with the tower cranes, meant that the loads the bridge was subjected to during construction were lower than the loads it has to withstand during operation. This prevented the need for over-sizing the bridge members, allowing the bridge to retain its slender appearance.

Figure 16: Ariel view of bridge taken when the deck was craned into position

As with any large-scale civil engineering project, Scammonden Bridge had its fair share of problems and issues during construction. By far the biggest problem during construction was the harsh weather coupled with the inhospitable Pennine terrain. During the winter months, snow and ice build-up was often encountered, causing delays to the site work. Indeed, on one occasion, the weather was so fierce it completely cut off access, electricity and communication to the site, causing construction to be halted for several weeks.

The worst hazard for construction workers was the freezing fog, which caused major ice build-up on the bridge and temporary works during construction [1]. This phenomenon meant that careful design had to be undertaken for the temporary formwork and framework used to construct the bridge.

Construction of the bridge, embankment and motorway section was completed in December 1970 at an overall cost of £14 million.

8. Serviceability

8.1. Temperature

Varying diurnal temperatures can have a significant impact in the overall stresses and strains within a bridge, which are generated by structural elements expanding or contracting when heated or cooled. These diurnal temperature fluctuations can cause overall increases in bridge temperature, causing the whole bridge to expand or contract, or can cause temperature differences between the topside and underside of the bridge. If expansion joints designed to allow this movement get blocked up, large stresses can occur.

Analysing these stresses can be very difficult due to the temperature differences being non-linear. However, for general simplified analysis, it can be assumed that the temperature fluctuation is linear across the bridge deck. The strain caused by the temperature difference is calculated using Eq. 17 below.

$$\varepsilon_T = \alpha \Delta T \tag{17}$$

Where α is the coefficient of thermal expansion; set at $12 \times 10^{-6}/^{o}C$ and ΔT is the temperature change; 20 ^{o}C.

$$\varepsilon_T = 240\mu\varepsilon$$

With the deck length being 200m, the increase in length can be calculated using Eq. 18.

$$\Delta L = \varepsilon_T L \qquad \Delta L = 48mm \tag{18}$$

These extensions will be catered for by the expansion joints in the deck, however in rare circumstances, these joints may get blocked up with debris, preventing movement. If this happens, the residual stresses would be as follows:

$$\sigma_c = E\varepsilon \qquad \sigma_c = 30000 x 240 x 10^{-6} \qquad \sigma_c = 7.2N/mm^2 \tag{19}$$

This is well under the maximum compressive stress value calculated in Section 5.1.

8.1. Creep

Concrete bridges are susceptible to creep during their lifetime. The majority of the creep deflection (approximately 80%) will occur during the first 30 months after completion [8]. A simple creep calculation is given below [Eq. 20].

$$\delta_{creep} = \frac{5w(0.6L)^4}{384EI} + \frac{w(0.2L)^4}{8EI} + \frac{(0.3wL)(0.2L)^3}{3EI} \tag{20}$$

Where L is the length of the bridge at 200m and the load is w at 545N/mm. This gives a total creep deflection value of 25mm, which is minimal over 200m of deck.

8.2. Natural Frequency

It is important to determine the natural frequency of a bridge as the tolerable frequency range is relatively small. Calculating the actual natural frequency of a bridge requires complex analysis, however a simplified Rayleigh-Ritz equation can be used [Eq. 21]. The suitable range for natural frequency is between 5 and 75Hz. High level frequencies above 75Hz may only cause physiological problems for users, however low level frequencies below 5Hz can cause collapse.

For Eq. 21, the mass includes superimposed dead loads and dead loads, but ignores live loading. The simplified natural frequency equation is as follows:

$$\omega_n = (\beta_n l)^2 \sqrt{\frac{EI}{ml^4}} \tag{21}$$

Where E is the Young's Modulus of concrete at 30×10^9, I is the second moment of area at $3.1m^4$, m is the mass of the deck at $64 \times 10^3 kg/m$ and l is the length between the spandrel columns at 15.4m. $(\beta_n l)^2$ is 22.37 for a clamped-clamped bridge system and is 15.42 for a clamped-pinned system.

Clamped-clamped = 114Hz
Clamped-pinned = 78Hz

The difference between the two is 36Hz. Scammonden Bridge is a pinned-pinned system, which means that, with extrapolation, the estimated natural frequency will equal **42Hz**. This result is well within the 5-75Hz range.

9. Durability and Vandalism

Naturally, as with all structures, the condition of the structural elements will deteriorate over time. In most cases, long term fatigue will need monitoring and maintaining as well as less predictable events such as vandalism and accidental damage.

The reduction or loss of prestress is one of the biggest problems with concrete bridges such as this one. The steel prestress cables running in the deck section weaken due to either shrinkage of concrete or creep of the bridge.

The other major issue with reinforced concrete road bridges is the problem of chemical attack. Chemicals such as chlorides, contained within de-icing salts can soak into pores and attack the concrete, reducing its strength [9]. This is a severe problem with Scammonden as, located in the Pennines, the weather is often below 0^{o}C in the winter.

Moisture, along with the chemicals, can also soak into the pores and attack the reinforcement. This causes the steelwork to expand and rust, which can cause spalling if the concrete cover was not adequate. Unlike the prestress steel, it is extremely difficult and disruptive to replace reinforcement.

Vandalism is not a serious threat as the bridge is located in an isolated area of Yorkshire; indeed there have never been any reported cases of vandalism in the bridge's history.

10. Future Modifications and Improvements

Since the bridge was opened, there have been no major modifications made to the structure. At the present there are no load restrictions on the bridge; however local residents have been concerned in recent months that quarry trucks using the bridge have caused its condition to deteriorate. On May 20th 2008, a news article in the Huddersfield Examiner stated that a local warden had: "…*never felt it shake like it does now. You can feel it move as lorries go across it and it's quite frightening*" [3]. This may lead to the bridge being strengthened or a weight restriction being imposed in the future.

Other recent modifications include a meshing retrofitted to the parapet hand railing on the top of the deck. This has been added to prevent rock and aggregate from quarry trucks falling onto the motorway below.

Apart from general maintenance such as painting and resurfacing, it is unlikely that any further structural or superficial changes are going to take place in the future.

11. Conclusion

Scammonden Bridge is unique as it was built in a time when motorways in the UK were in their infancy and were being built quickly and economically. Many other bridges constructed on highways at this time were nondescript and dull; however Scammonden is spectacular to view both architecturally and structurally.

Even today, almost 40 years after construction finished, the bridge still looks modern and impressive. It also remains the largest single span non-suspension bridge in Europe; a testament to the scale of the project back in 1970.

The analysis has focused on the loads, strength and construction of the bridge as well as aesthetics and durability. All calculations conducted in this paper follow the latest British Standard 5400-2:2006 for steel, concrete and composite bridges. It is worth noting that the latest British Standards have been revised and will be different to the standards used during construction.

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