Hammersmith Bridge

Review of Recent Documents and Summary of Existing Condition

Prepared for:

Department for Transport

Prepared by:
AECOM UK
Sunley House
4 Bedford Park,
Croydon,
Surrey,
CR0 2AP

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Executive Summary

Following a heatwave in August 2020, acoustic monitoring alerts led to closer inspection of the suspension chain pedestals on Hammersmith Bridge. It was found that a crack (ref. NE10) in the north-east pedestal had extended since April 2020. The bridge was already closed to road traffic and the decision was made to also close it to pedestrians and cyclists. In addition, river traffic was prevented from passing underneath the bridge and the river towpaths under the bridge were also closed and diverted.

Mott MacDonald (MM) published an initial assessment report in January 2019 and reported a theoretical overstress in the pedestals. Subsequent surveys found several significant defects in the pedestals (two cracks in the south-west pedestal, one crack on the north-west pedestal and six cracks on the north-east pedestal) which lead to the closure of the bridge in April 2019 by the London Borough of Hammersmith and Fulham (LBHF), with access given to pedestrians and cyclists only.

The cause of the cracks was related to the rollers between the pedestal tops and the underside of the chain saddles being seized. In the original design of the bridge, the roller bearings accommodate temperature changes by movement along the top of the pedestals. The pedestals were designed to withstand a force normal to the top surface applied via the rollers from the saddle. However, as the roller bearings have seized, this results in a restraining force being applied to the top of the pedestal, leading to high shear and bending stresses in the pedestal castings for which they were not designed.

Further assessment work was carried out by MM on the pedestals in line with developments on site. In summary, in April 2019, after the bridge was closed to traffic MM produced the document: "CI Pedestals – Investigation into Restricting Vehicular traffic". In this report, MM developed and refined the original assessment concentrating on the pedestals and were able to reduce the theoretical overstress in the pedestals, but not enough to comply with code requirements. Then, in January 2020, MM carried out further analysis, specifically of the south-west pedestal in advance of the Thames Tideway Tunnel works and produced a report titled "Revised CI Pedestal Analysis for Ground Movements induced by Thames Tideway Tunnel". In this report, MM further refined the analysis by correlating monitoring results with theoretical modelling results. To help justify maintaining the partial opening to pedestrians and cyclists LBHF commissioned Xanta (via TfL) to produce a "Case for Continued Safe Operation after Closure to Motorised Traffic" (CCSO). The CCSO refers to work carried out by MM in following the procedures from BD79 (now renamed as CS470): Management of Sub-standard Highway Bridges. This work and subsequent studies including setting up of monitoring have been carried out methodically by MM.

In April 2020, the north-east and south-east pedestals were blast cleaned and were inspected by MM, and an additional 7 cracks in the north-east pedestal were found, taking the total up to 13. No cracks were found in the south-east pedestal. In November 2020, the north-west and south-west pedestals have not yet been blast cleaned and inspected for further cracks. AECOM recommends that this is carried out as soon as possible and a strategy developed in advance to anticipate possible outcomes of the inspection.

Weekly inspections were undertaken from the end of October 2019 until April 2020 when they were halted due to the Covid-19 restrictions. Monitoring systems have been added, including an acoustic emission (AE) system to detect crack growth and strain gauging on each of the chain links on either side of the pedestals.

In August 2020 during a period of extreme hot weather, the AE system detected an event on the east web of the north-east pedestal. A follow-up visual inspection showed the largest crack (NE10) had propagated in length from approximately 160mm to 240mm and LBHF decided to completely close the bridge to all users and river traffic on safety grounds. It was assumed by LBHF that the AE event was related to the growth of the crack. However, AECOM has noted that crack NE10, whose growth has been associated with this acoustic event, is actually located on the central web and not the east web.

Therefore, the growth of crack NE10 between April and August 2020 may not necessarily be connected with the high temperatures seen in August 2020. AECOM recommends that the exact source of the AE event, and the depth of this crack should be investigated as it seems likely that the crack is quite shallow.

Heating and cooling systems have been installed in the north-east chain tunnel to limit the temperature change of the chains and hence potential loads on the pedestal. Temperature control systems are also being installed in the other 3 pedestals, with the aim to complete this activity in November 2020.

AECOM has carried out a high-level order of magnitude analysis of the intact north-east pedestal using a 3D finite element (FE) model, and then introduced the known cracks to the model in order to gain an understanding of the behaviour. Our views are similar to Professor Fleck's and we note that there is a possibility of uplift on the back end of the pedestal as well as on the rollers. But this is subject to various assumptions on the boundary conditions. Our analysis of the intact pedestal shows that the pedestal can sustain a maximum peak load greater than 2MN with a small reduction for the cracked analysis. But with deformations of 3-5mm, the restraining load will tend to dissipate and reduce the stresses due to the shear force.

AECOM has carried out a high-level review of the potential global failure mechanism of the bridge, whilst assuming that the pedestal could potentially fail either by shearing horizontally or diagonally, or by crushing vertically. We have carried out high level analysis to investigate the possibility of the pedestal crushing vertically. Broad risk factors have been assigned to each primary element, with the tower bearings, towers and main span at highest risk.

AECOM has reviewed the original CCSO after Closure to Motorised Traffic (Issue 5, 30 March 2020). Significant amounts of additional information have been gathered and knowledge extended since the CCSO after Closure to Motorised Traffic was written. Since April 2020, it has been used as a vital report documenting all the various issues relating to the continued closure of the bridge, but it needs to be updated and reviewed to include for subsequent events. More refined analysis has been carried out on the south-west pedestal which shows that the utilisation factor is significantly lower than previously understood, albeit it still does not comply with design codes. Mitigation in the form of temperature control of the anchor chains and monitoring are in place together with the recommendation for more frequent visual inspections. AECOM recommends that the CCSO should be updated and developed with input from all interested parties.

During the course of AECOM's study, the CCSO for limited river traffic was received. This appears to be a pragmatic step forward and it permits limited river traffic to pass under the bridge. However, we understand that agreement has not yet been reached on its implementation. The CCSO also refers to a further CCSO developed to permit workers on site. Further discussion should be made to develop the potential use of the CCSO to permit limited pedestrian use of the bridge.

Acoustic events and weekly inspection reports have been reviewed by AECOM. It has been established that the acoustic events to the beginning of August 2020 have been investigated and shown not to indicate any crack growth.

AECOM has reviewed the various proposals to free up the roller bearings as well as collating evidence from other bridges across the UK and the rest of the world, which have experienced seized roller bearings. We have found that it is potentially feasible to remove rust and debris, depending on the overall condition. For example, Dorothea Restorations are a company who worked on freeing up the roller bearings on Clifton Suspension Bridge.

Strengthening options for the Pedestals have been developed by Pell Frischmann. The preferred solution includes the installation of props and filling the voids within the pedestals with fibre-reinforced concrete. AECOM has raised a few observations on the design which need to be resolved. It is important to state that preparation of the design of the strengthening works must continue and be prioritised whilst other studies into the condition of the bridge are being carried out.

Executive Summary – Recommendations

1. Complete the removal of the ornamental casing and carry out blast-cleaning and inspection of the NW and SW Pedestals – this is imperative as it will quantify the unknown risks associated with these pedestals. When the north east pedestal was blast cleaned and inspected, further cracks were discovered including NE10. A view was taken at the time of discovery that these additional cracks were historical as they were not visible through the paint. This work must be carried out with due attention to Health and Safety matters.
2. Prepare a strategy for responding to the inspection results of the NW and SW pedestals in advance of blast cleaning – a strategy is needed such that a quick reaction can be initiated. For example, it is possible that further cracks will be detected, and a review must be made to determine if these are historical cracks or develop an action plan if there is a large number of cracks, or if any of the cracks are long or wide. Or, it may be possible that no further cracks are detected.
3. Ensure that temperature control is operational on all 4 pedestals – it is imperative that this action is implemented as soon as possible. AECOM understands that it was the aim to complete installation by the end of November 2020 before the colder winter months set in.
4. Increase frequency of visual inspections – weekly visual inspections were stopped in April 2020, due to Covid restrictions. However, inspections were not increased in frequency after the discovery of the propagated crack NE10 in August 2020. It is recommended that weekly visual inspections are reinstated to augment the strain gauging, acoustic emission monitoring and temperature monitoring already installed on the bridge. Monitoring cannot be solely relied on and it must be backed up by regular visual inspections.
5. Determine depth of crack at NE10 – AECOM recommends that the depth of crack NE10 is established by using, for example, a pencil grinder. This will help to determine if the crack has gone through the full depth or if it is just a surface crack. This action will also be helpful to establish if the crack has terminated as it moves from the web outstand to the base plate.
6. MM to complete the analysis of cracked pedestals – AECOM understands that MM are currently modelling the effects of the cracks on north East pedestal. This will be useful to determine to what extent the failure load of the pedestal has been reduced. When the extent of the cracks in the west pedestals has been determined following blast cleaning, the other pedestals should also be analysed with the cracks incorporated in the model, if they are more widely cracked than the NE pedestal. (To be read in conjunction with recommendation 8 below).
7. MM to review the assumptions for the SW pedestal UF calculations. The temperature at which it has been assumed that the roller bearings seized as 20°C appears to be high. This assumption needs to be reviewed by MM. In addition, the maximum temperature of 47°C appears to be very high as approximately two-thirds of the anchorage chain is underground and the temperature range will be much reduced. We recommend that both these sets of assumptions are reviewed by MM and checked by Atkins.
8. MM have carried out a refined analysis of the SW pedestal and AECOM recommends that a similar analysis is carried out for the other three pedestals. We noted that the accompanying displacement at the peak total load is about 4mm and, consequently, the applied shear will dissipate due to this displacement and is unlikely, therefore, to reach this value. We recommend that MM review these issues for all four pedestals, if sufficient differences exist.

9. Carry out independent Category 3 check of all critical issues including all four cracked pedestals – AECOM understands that the refined analysis of the SW pedestal has been checked internally within MM, but not independently. This should be completed by Atkins.
10. Strain gauging of pedestals (as recommended by Professor Fleck) – this will be important to gain confidence and correlation with the results from the MM model and the independent checker.
11. PF to continue design of jacking frame and strengthening design of pedestals – AECOM understands that the jacking frame is currently being designed to incorporate provision for dealing with a sudden release of energy resulting from any longitudinal movement of the saddle when the roller bearings are released. AECOM has raised a few high-level observations on the design of the pedestal strengthening which need to be addressed, and these should be agreed by the checker.
12. The CCSO after Closure to Motorised Traffic was last revised in March 2020. Since then the Thames Tideway Tunnel has passed under the bridge, the NE and SE pedestals have been blast cleaned and inspected and much analysis and investigation work has been undertaken. As this CCSO is a pivotal document, it should be updated.
13. Prepare a CCSO to permit limited (or greater) access for pedestrians – this issue needs to be studied in more depth, but it should be pointed out that a significant amount of additional information has been gathered and knowledge has been extended since the CCSO after Closure to Motorised Traffic was written. More refined analysis has been carried out on the SW pedestal which shows that the utilisation factor is significantly lower than previously understood, albeit it is still above the code acceptable limits. Mitigation in the form of temperature control of the anchor chains (on the basis that it is fully operational) and monitoring are in place together with the recommendation for more frequent visual inspections. This needs to be developed with input from all interested parties.
14. AECOM understand that ground investigation has been carried out on or near the site on behalf of Pell Frischmann and we recommend that MM review their assumptions against this GI and amend their models if necessary.
15. We note that crack NE10, whose growth has been associated with an acoustic event on the east web, is actually located on the central web of the NE pedestal. Therefore, the growth of crack NE10 between April and August 2020 may not necessarily be connected with the high temperatures seen in August 2020. AECOM recommends that this is investigated further.
16. AECOM has provided high level considerations of how gross failure may occur. These considerations have been developed through our experience and through carrying out limited simplified analysis. AECOM recommends that MM and Atkins study how gross failure will occur. It is further recommended that this work is fed back into the CCSO.

1. Introduction

1.1 Introduction

Following a heatwave in August 2020, acoustic emission monitoring alerts led to closer inspection of the suspension chain pedestals on Hammersmith Bridge. It was found that a crack in the north-east pedestal had extended since April 2020 and the decision was made to close the bridge to pedestrians and cyclists as well as road traffic which had already been removed; in addition, river traffic was prevented from passing underneath the bridge and the river towpaths under the bridge were also closed and diverted.

The closure has become a focus of local, national and international attention. A Ministerial Task Force has been set up to expedite the safe reopening of the bridge to pedestrians, cyclists and river traffic, and ultimately to road traffic.

AECOM were approached by DfT in early September 2020 to provide technical assistance in understanding why the bridge was closed, and to assist in forming a strategy to re-open the bridge to pedestrians, cyclists and river traffic as soon as possible.

It is acknowledged that a huge amount of complex technical work has been undertaken by others. AECOM has not carried out any detailed calculations but have relied on their experience to scrutinise the results to identify anything unexpected or for gaps or steps not undertaken.

During the course of our work we are aware that others continue to carry out studies and develop their analyses which could change their viewpoints.

This Report summarises our work carried out to date and includes our current thoughts for the possible re-opening of the bridge.

Section 1.2 sets out more background information behind the original construction of the bridge and subsequent structural modifications, plus the more recent history of the various stages in the development of the refurbishment design.

Section 2 covers the description of the pedestals and the recent history of investigations into the pedestals.

Section 3 presents AECOM's views on the processes in CS470 (formerly BD79; Management of Sub-Standard Highway Structures) and how this has been applied to the bridge.

Section 4 covers AECOM's review of the documents relevant to the events which led to the closure of the bridge and potential means of re-opening the bridge.

Section 5 presents AECOM's comments on issues relating to de-rusting and freeing up the roller bearings.

Section 6 presents a summary of AECOM's outline analysis of the pedestal subjected to the restraining forces arising from the seized rollers. This section provides analysis of an undamaged pedestal and also the cracked North East pedestal. This Section also provides commentary on the potential collapse mode of the bridge, should one or more of the pedestals fail.

Section 7 provides a short summary of AECOM's comments on the paper produced by Professor Fleck[1].

Section 8 provides a log of high-level queries which have not been responded to.

Section 9 provides a summary of the main Risks and Opportunities.

Section 10 presents our conclusions.

[1] Considerations on cracking of the Hammersmith Bridge pedestals, 6 November 2020

Section 11 presents our recommendations.

Appendix A contains a list of documents received.

Appendix B contains a log of the detailed comments raised by AECOM in our review of the various documents. It also contains responses where available.

Appendix C contains a detailed analysis of the CCSO for limited river traffic.

1.2 Background

The current Hammersmith Bridge was opened in 1887 and was constructed over the foundations of an earlier suspension bridge. It has a main span of 422 ft (129m) and two equal side spans. Figure 1.1 below shows an elevation of part of the bridge and is annotated to show the names of the parts that are mentioned in this report.

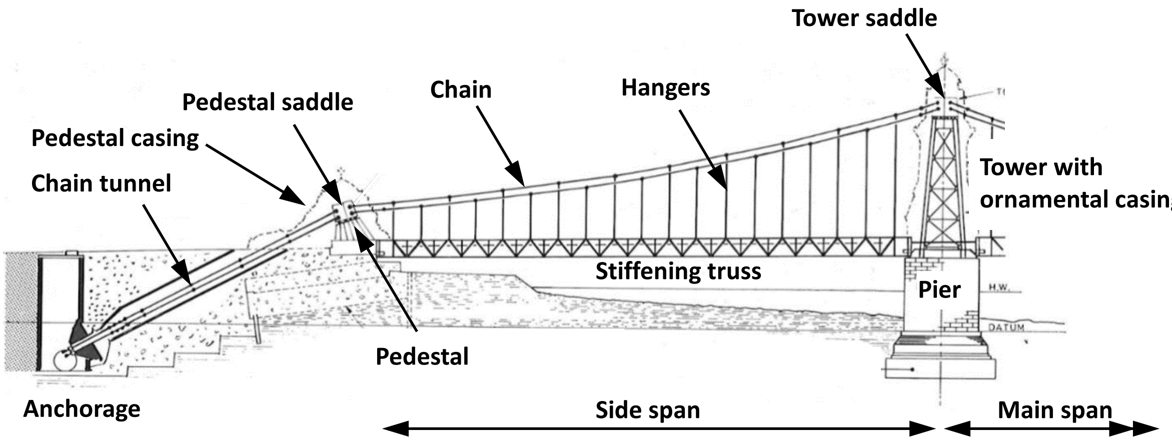


Figure 1.1: Annotated part elevation of Hammersmith Bridge

An unusual feature of the bridge is the height of the chains at the end of the side spans. This is a consequence of building around the anchorage of the old bridge. This results in the need for a tall pedestal for the chains to turn down towards the anchorages, as shown in Figure 1.2.

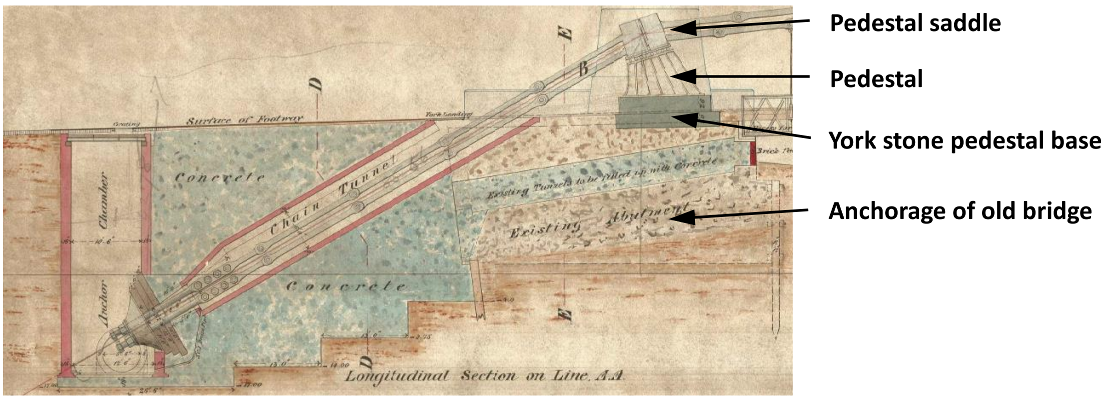


Figure 1.2: Section through anchorage showing relationship with previous bridge foundations (source: LBHF)

Concerns over the bridge's condition and behaviour in 1960 eventually led to a major refurbishment in the mid-1970s involving the replacement of the stiffening trusses, some hangers, the tower roller bearings and the roadway deck.

In 1996, an assessment of the bridge strength highlighted a major issue with the chain saddle rollers on top of the Hammersmith tower being seized. The bridge was immediately closed to general traffic, but a load test showed it was possible to permit single buses to continue to cross the bridge. The Barnes tower rollers had previously failed when an errant heavy truck had crossed the bridge in February 1984 and had been replaced with elastomeric bearings. It is understood that the failure occurred because the roller bearings under the tower saddle had been forced against their keep plates under the combination of excessive load and cold weather.

Strengthening and refurbishment contracts were carried out in the late 1990s and the bridge was reopened to 7.5 tonne traffic and single deck buses.

In 2016 LBHF & TfL commenced work to study and ultimately refurbish and strengthen the bridge to accommodate 18 tonne double deck buses. This was planned to be carried out in a number of phases:

- Stage 1 – A desk study to review previous work and existing documentation to determine whether increasing the bridge weight limit to 18t GVW is possible based on available information. The study was carried out by BAM Nuttall with Arup.
- Stage 2 – A Feasibility Design comprising survey, study and analytical work to establish the extent of work required and how this could be achieved. The report was carried out by Mott MacDonald (MM) with Atkins as Category 3 Checker.
- Stage 3 – Preliminary Design of bridge refurbishment including design of pedestal strengthening, currently carried out by Pell Frischmann (PF) with Atkins as Category 3 Checker.
- Stage 4 – Design and Build Contract for stabilisation and strengthening works. Future contract, not let.

This process was disrupted towards the end of Stage 2 when cracks were found in the pedestals and the decision was taken to close the bridge to vehicular traffic in April 2019. Pedestrian, cycle and river traffic were not affected. The cause of the cracks was believed to be related to the rollers between the pedestal top and the underside of the chain saddle being seized, leading to high stresses in the pedestal castings that they were not designed for.

Further assessment work was carried out by MM on the pedestals in line with developments on site. (Refer to Section 4.2 of this document which provides more details of the assessments made by MM). In summary, in April 2019, after the bridge was closed to traffic MM produced the document: "CI Pedestals – Investigation into Restricting Vehicular traffic." In this report, MM developed and refined their original assessment concentrating on the pedestals and were able to reduce the theoretical overstress in the pedestals. Then, in January 2020, MM carried out further analysis, specifically of the SW pedestal in advance of the Thames Tideway Tunnel construction and produced a report "Revised CI Pedestal Analysis for Ground Movements induced by Thames Tideway Tunnel. In this report, MM further refined the analysis by correlating monitoring results with theoretical modelling results. To help LBHF justify maintaining the partial opening to pedestrians and cyclists they commissioned (via TfL) Xanta to produce a document "Case for Continued Safe Operation after Closure to Motorised Traffic" (CCSO).

Weekly inspections were undertaken from the end of October 2019 until April 2020 when they were halted due to Covid-19 restrictions. Monitoring systems have been added – an acoustic emission (AE) system to detect crack growth and strain gauging on each of the chain links on either side of the pedestals.

In August 2020 during a period of extreme heat the AE system detected an event on the NE pedestal. A follow-up visual inspection showed the largest crack, NE10, had propagated in length from approximately 160mm to 240mm and LBHF determined to completely close the bridge to all users and river traffic on safety grounds. (Refer to Section 2.3 below for a history of the investigations into the propagation of crack NE10).

Heating and cooling systems have been installed in the NE chain tunnel to limit the temperature change of the chains and hence potential loads on the pedestal. Temperature control systems are also being installed in the other three pedestals with the aim to complete this activity in November 2020.

1.3 Other Current Activities

Whilst AECOM was carrying out this review, several other activities have been taking place forming part of the overall Task Force to augment existing studies. The findings of these studies may influence some of the issues raised in this report, which will be updated on receipt of further information.

- MM are currently undertaking an analysis of the NE pedestal incorporating the existing cracks. This analysis will form part of an overall study into the anticipated failure mode of the pedestal.
- Freyssinet are carrying out a cost estimate of the bearing replacement scheme
- PF are refining the design of the jacking frame for replacing the roller bearings
- A fracture mechanics expert (Professor Fleck from Cambridge University) was appointed to review the behaviour of the pedestal including his views on crack growth and possible failure modes.

2. Pedestals and their defects

2.1 Pedestal Description

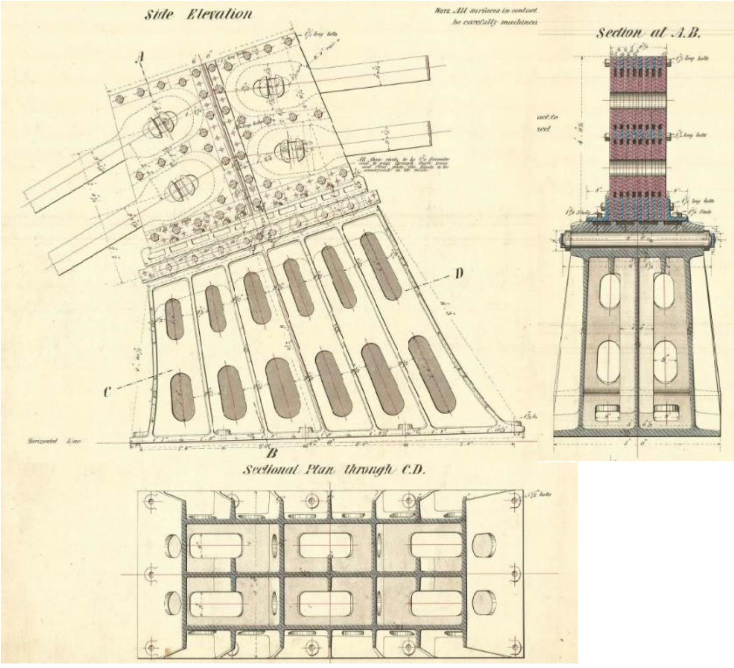


Figure 2.1: Original drawing of pedestal, saddle and roller assembly (source: LBHF)

The pedestals are cast iron castings forming a hollow cellular box. (Refer to Figure 2.1 above.) Each comprises three longitudinal webs with linking end plates and two intermediate diaphragms. The webs have full-height stiffeners. The upper plate has a machined top surface for the rollers and the bottom plate is fixed to foundation stones via 12 vertical bolts. There are elongated openings in each of the faces (except the upper plate), largely to facilitate the casting process and permit the sand mould to be removed after casting. The pedestals are believed to be made from flake grey cast iron using sand moulds. These would have been large complex castings for the time, and it is evident that defects and discontinuities were formed in the material during the casting process.

Cast iron has very good characteristics in compression and, having been manufactured in the late 1880s, MM have reasonably taken a permissible stress value of 154 MPa in compression taken from the standard BD21/01. However, cast iron tends to be very brittle and is much weaker in tension and MM have used a permissible stress value of 46MPa in tension, again based on BD21/01. MM have made comparisons with cast iron elements from the High-Level Bridge in Newcastle which gives an ultimate tensile stress (UTS) of 80MPa. However, the UTS must be used with a principal tensile stress approach, compared to a permissible stress approach and, due to the difference in approaches to the assessment, this did not lead to an increase in the strength of the cast iron. (Refer to Section 4.2.3)

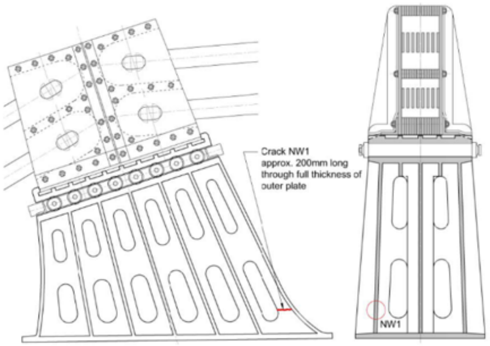
2.2 History of Pedestal Investigations

Figure 2.2 summaries the findings from inspections carried out in 2019 and 2020. The information has been extracted from the various inspection reports provided.

Figure 2.2: Pedestal Investigation History & Findings

North West

April 2019 – Over paint – 1 crack 200mm long



Post April 2019 – Over paint (Eddy current) – 3 cracks

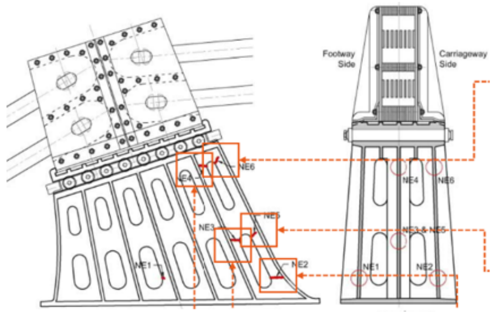
Current (Nov 2020) – Casing removal and blast cleaning not started

Current (Nov 2020– Chain tunnel temperature control system being installed

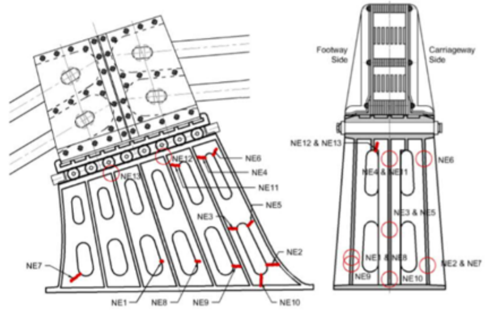
North East

Post April 2019 – Over paint (Eddy current)

– 6 cracks



April 2020 – Post blast clean – 13 cracks 30 to 205mm long. Crack NE10 160mm long.

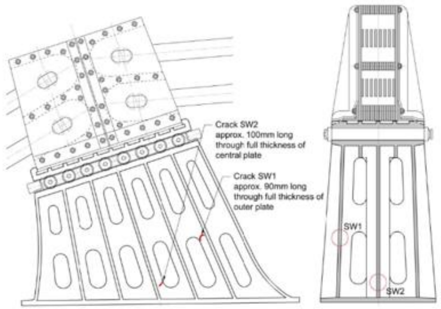


August 2020 – Crack NE10 now 240mm long

August 2020 – Chain tunnel temperature control system installed

South West

April 2019 – Over paint – 2 cracks 90 & 100mm



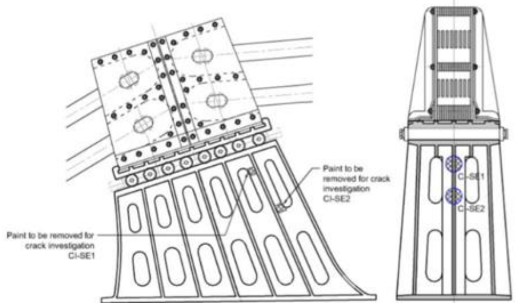
Current (Nov 2020)– Casing removal and blast cleaning not started

Current (Nov 2020) – Chain tunnel temperature control system being installed

South East

April 2020 – Post blast clean – No cracks

Current (Nov 2020) – Chain tunnel temperature control system being installed



2.3 History of Crack NE10 (North East Pedestal)

An initial inspection for crack-like defects using eddy current techniques over the paint was used in the period after April 2019 and six cracks were identified. Crack NE10 was not identified at that time (although it may have been present).

In April 2020 the ornamental casings were removed and the NE pedestal was stripped of paint by grit blasting. A detailed visual inspection was undertaken and magnetic particle inspection (MPI) was used in selected areas. The number of cracks increased from six to thirteen.

Crack NE10 was identified in the web and was evidenced as being through-thickness and terminating in the fillet region, with a length of about 160mm, as shown below in Figures 2.3 and 2.4.

Figure 2.3 – Crack NE10 April 2020 Outside Face

Figure 2.4 – Crack NE10 April 2020 Inside Face

Figure 2.5 – Crack NE10 August 2020 Outside Face (source all pictures: MM)

Following an acoustic emission alarm on 7 August 2020, an inspection found that crack NE10 had grown on the east side from about 160mm to about 240mm and had reached the edge of the opening in the base plate (Figure 2.5). There was no propagation on the west side. However, it is clear from the photograph that, at the edge of the opening in the base plate, the crack has shallow depth. This strongly suggests that the crack is in fact shallow from the opening edge to the fillet. As the growth of this crack resulted in the complete bridge closure, it is crucial to understand its depth and hence risk it presents. Clearly a shallow crack presents much less risk than a full depth crack.

The crack depth could easily be determined at several locations by either taking core samples or carefully using a pencil grinder, which is a recommended course of action. If this crack were full depth, then we would have expected evidence of propagation on the other side of the web.

3. Review of CS470 (formerly BD 79) Processes

3.1 Relationship of CS470 to Case for Continued Safe Operation (CCSO)

The various reports which have been prepared by MM and Xanta used in the management of the bridge refer to the use of Highways England's standard CS470 (formerly BD 79/13): Management of Sub-Standard Highway Structures.

Xanta was contracted by TfL on behalf of LBHF to prepare a reasoned case for the continued safe operation (CCSO) of the bridge following the discovery of cracks in the pedestals in April 2019.

The Xanta CCSO report was used to justify that the bridge be kept partially open to pedestrians and cyclists from April 2019. But since August 2020, when the bridge was closed to pedestrians and river traffic, it has been a vital report to document all the various issues relating to the continued closure of the bridge.

It is important to review and discuss if a CCSO is the most relevant reporting system to continue with the management of the bridge. As a minimum, the CCSO should be judged against the procedures laid down in CS470 to ensure that the actions taken have been reasonable and safe, yet at the same time not overly conservative.

The CCSO "CCSO after Closure to Motorised Traffic, Issue 5, dated 30 March 2020" is qualitative and it is important to introduce some measurable parameters by which management decisions about the bridge can be made.

If a case is to be put forward to re-open the bridge in some format, it is necessary to review the actions taken systematically against the provisions in CS470.

It is noted that a new CCSO for limited river traffic was developed by Xanta in October 2020 and this is discussed in more detail in Section 4 and Appendix C.

3.2 Review of Processes carried out using CS470 (BD79)

It is evident that MM followed the BD79 processes during their work on the bridge. The extract below (Figure 3.1) is Appendix 1 taken from the latest CCSO for Limited River Traffic and summarises the activities taken by MM after the results from their original assessment were published. AECOM has requested a copy of the BD79-related documents produced by MM but these have not been received.

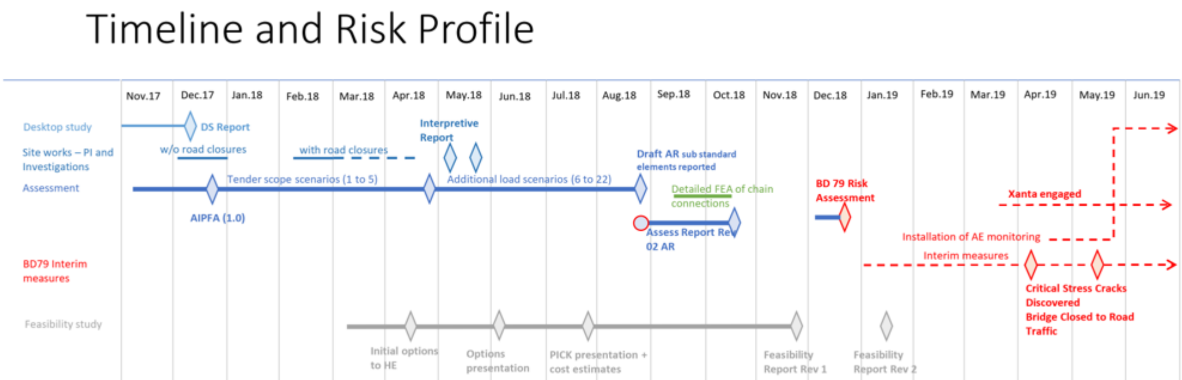


Figure 3.1: Extract from CCSO for Limited River Traffic

Figure 3.2 below is an extract from BD 79 (now CS 470) illustrating the management process for a sub-standard bridge.

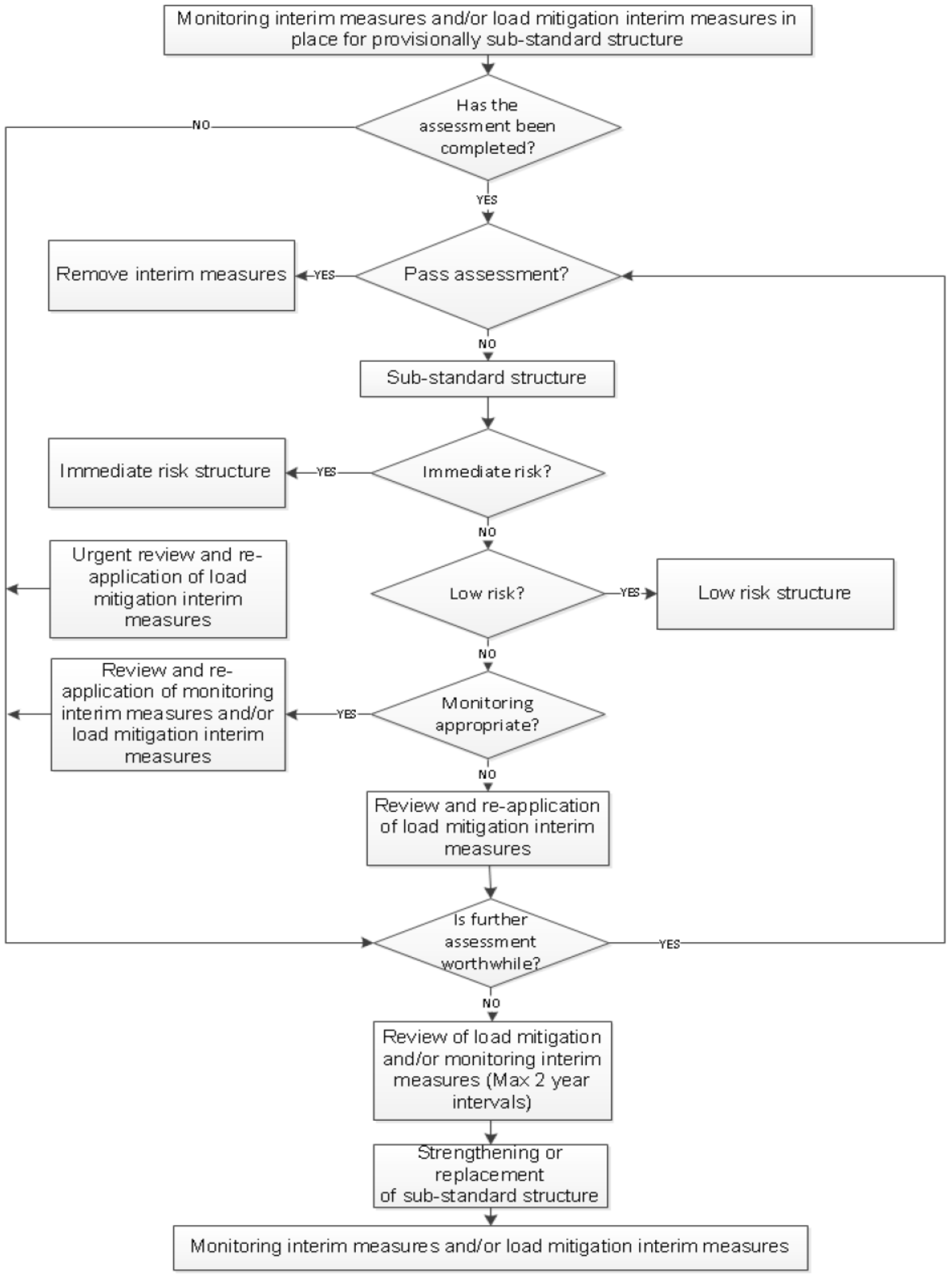


Figure 3.2: CS470 Figure 5.1N1 Management process for sub-standard structures

In the absence of the documented BD79 processes, AECOM has carried out an independent review of the processes carried out as set out in the Table 3.1 below. It is concluded that MM has reasonably followed the procedures in BD79.

CS470 Item	Comment
Monitoring interim measures and/ or load mitigation interim measures in place for provisionally sub-standard structure	This starting position relates to the time after April 2019 when cracks were first discovered in the pedestals. Load mitigation measures were achieved by removing traffic in April, and at this time, monitoring was implemented
Has the Assessment been completed?	Original assessment completed in April 2019
Pass Assessment?	No – pedestals grossly overstressed according to MM's initial assessment
Sub-standard structure	Yes
Immediate risk?	No – MM would have considered that, as traffic had been removed, the risk had been significantly reduced
Low risk	Yes – MM would have considered that, as traffic had been removed, the risk had been significantly reduced MM would have taken into account the monitoring on the bridge but traffic still needed to be kept off the bridge
Monitoring appropriate	Load mitigation measures and monitoring continued
Review and re-application of load mitigation interim measures	Further reviews were carried out by MM including more refined analysis of the SW pedestal prior to the Thames Tideway Tunnel construction.
Is further assessment worthwhile?	Further assessment is being carried out including the cracked pedestal analysis
Review of Load and/ or monitoring interim measures (max 2 year intervals)	Load and monitoring measures have been reviewed on a regular basis – but it is noted that weekly inspections were terminated in April 2020 due to Covid-19.
Strengthening or replacement of sub-standard structure	The design of stabilisation works has progressed including jacking and replacement of the roller bearings, and strengthening of the pedestals

Table 3.1: AECOM review of CS470 (BD79) processes

4. Review of Existing Documents

A full list of documents supplied is given in Appendix A.

4.1 Review of Case for Continued Safe Operation After Closure to Motorised Traffic dated 30th March 2020 (CCSO Report)

This report was produced by Xanta Limited, who were contracted by TfL to prepare a reasoned case for the continued, limited safe operation of the bridge following the discovery of cracks in the pedestals in April 2019.

The Xanta CCSO report was used to justify that the bridge is kept partially open to pedestrians and cyclists from April 2019. But since August 2020, when the bridge was closed to pedestrians, cyclists and river traffic, it has been a vital report to address all the various issues relating to the continued closure of the bridge.

The latest revision of the report is revision 5 dated 30 March 2020. The report does not include for the additional assessment work on the South pedestals prior to the Thames Tideway Tunnel passing through the area. The report also does not include the events in August 2020 which led to the full closure of the bridge. The report needs to be revised to include these issues if it is intended to continue to use the document.

The CCSO discusses the processes followed including BD 79 and CS470 and its original purpose was to provide justification for keeping the bridge open in 2019. It discusses the measures that have taken place including instrumentation and monitoring as well as acoustic monitoring.

The report recorded that the removal of vehicular traffic resulted in an 18% reduction in utilisation factor of the pedestals in certain conditions.

Section 6.12 of the CCSO includes a long list of tasks which must be undertaken to maintain safety risk as low as reasonably practicable. These included the following issues, many of which have been completed. (For a more detailed summary of completed work, refer to Section 4.5 of this report.)

- Additional crack and stress monitoring
- Further visual inspection and non-destructive testing (NDT) after stripping off paint from the NE and SE pedestals
- Assessment of the acoustic emission monitoring
- Explore the possibility of releasing the saddles and freeing the bearings
- Review the chain knuckle defect in the NW chain tunnel. MM have stated that any stabilisation work associated with the chain knuckle must also be prioritised at the same time as work on the pedestal. AECOM is not aware of any developments in the design of this issue.

The CCSO refers to BD79/13 and its successor CS470, The Management of Sub-Standard Highway Structures. However, it does not explicitly follow the procedures contained in these documents which were written specifically for Highway Structures.

A new report has been produced by Xanta Limited which relates to the Case for Continued Safe Operation for Limited River Traffic. This latter CCSO uses information from the original CCSO report but it does not replace the original CCSO as it is intended for a different purpose. (The review of the CCSO for Limited River Traffic is covered in Section 4.8 of this report.)

Detailed comments and responses are included in Appendix B1.

4.2 Review of Assessment Reports

The following reports record the development of MM's structural understanding of the pedestals and the refinement of the analysis of the issue.

As discussed in Section 1.2 above, the original assessment was carried out by Motts as part of the LBH&F Stage 2 phase, and was published in January 2019 (Refer to Section 4.2.1 below).

In April 2019, after the bridge was closed to traffic MM produced the document: "CI Pedestals – Investigation into Restricting Vehicular traffic". In this report, MM developed and refined the original assessment concentrating on the pedestals and were able to reduce the theoretical overstress in the pedestals. (Refer to Section 4.2.2 below.)

Then, in January 2020, MM carried out further analysis, specifically of the SW pedestal in advance of the Thames Tideway Tunnel (TTT) and produced "Revised CI Pedestal Analysis for Ground Movements induced by Thames Tideway Tunnel". In this report, MM further refined the analysis by correlating monitoring results with theoretical modelling results. (Refer to section 4.2.3 below.)

Section 4.2.1 summarises the initial assessment carried out in January 2019.

Section 4.2.2 summaries further assessment in April 2019 following the discovery of cracks in the north west and south west pedestals. This report was produced before the effects of the Thames Tideway Tunnel (TTT) were considered.

Section 4.2.3 summarises further refinement of the analysis to take into account the effects of ground movement from TTT.

4.2.1 Assessment Report (Report 383488-MMD-HSB-SE-ASR-000001 dated 25 January 2019 including Appendix B11)

This assessment report produced by MM covers their assessment of the full bridge, subject to numerous live load cases relating to different bus types and weight restrictions. This is a relatively early report and, for the cast iron pedestals, it has largely been superseded by more recent reports. However, it indicates that at this point in time it was known that the roller bearings could be seized.

The more detailed calculations from Appendix B11 have also been reviewed and we have raised a few detailed queries.

In this report, MM evaluated the utilisation factors for the pedestals based on 3 scenarios:

- Free rolling
- Partially seized
- Fully seized

The following utilisations were recorded as shown in the extract from the report below in Table 4.2.

Table 30: Cast iron pedestal utilisation factors (envelope on combination 1 - 4)

Verification	Articulation	Sc1	Sc2	Sc3	Sc4	Sc5	Sc5a
CI Principal stress (Total)	Free rolling	0.29	0.29	0.29	0.29	0.36	0.36
	Partially seized	0.97	0.97	0.97	0.97	2.13	2.13
	Fully Seized	4.43	4.43	4.43	4.43	5.52	5.52
CI Principal stress (LL)	Free rolling	0.1	0.1	0.1	0.1	0.35	0.35
	Partially seized	1.74	1.74	1.74	1.74	4.32	4.32
	Fully Seized	9.18	9.18	9.18	9.18	11.52	11.52
CI Contact stress at rollers	Free rolling	2.18	2.18	2.18	2.18	2.49	2.49
	Partially seized	2.75	2.75	2.75	2.75	3.24	3.24
	Fully Seized	3.25	3.25	3.25	3.25	3.57	3.57
Pad stone pressure	Free rolling	0.1	0.1	0.1	0.1	0.13	0.13
	Partially seized	0.18	0.18	0.18	0.18	0.35	0.35
	Fully Seized	1.59	1.59	1.59	1.59	2.34	2.34

Source: Derived in assessment calculation

Table 4.2: Pedestal Utilisation Factors (Sc1 etc refer to various live load cases considered) (Source: MM)

It can be seen that the utilisation factors (UF) for all live load cases for the fully seized condition are well in excess of 1.0 (the permissible limit).

This assessment report includes Appendix B11 which provides more detail behind the calculations. The report does not appear to provide the utilisation factor for self-weight of the bridge plus temperature, excluding traffic and pedestrian loading. The utilisation factor for the self-weight only is based on the free roller bearing condition, as MM assume that this condition was in place at the end of construction; AECOM recognises that much of the detailed assessment of the pedestals has been superseded by later assessments as described in section 4.2.2 and 4.2.3 below.

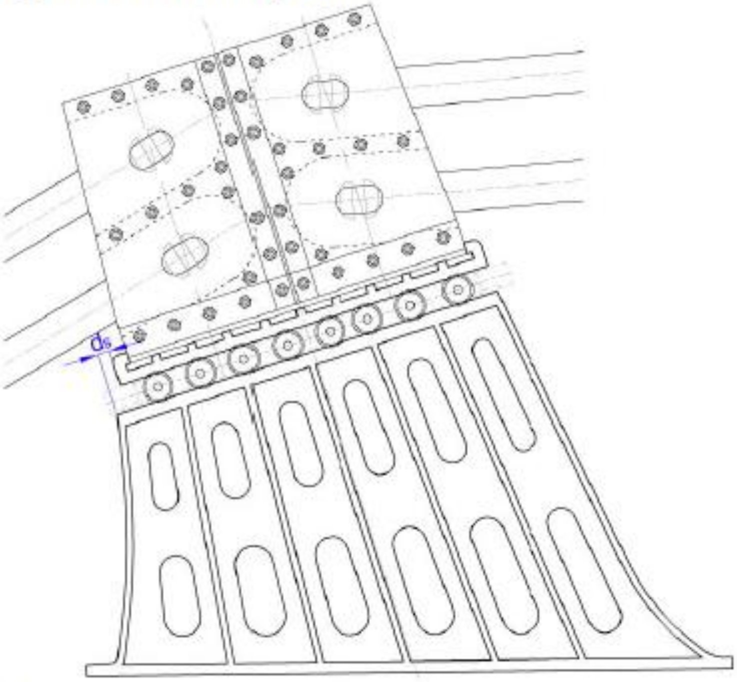
Detailed comments and responses are included in Appendix B2.

4.2.2 Investigation into Restricting Vehicular Traffic Report (Document Ref: 383488-MMD-HSB-SE-RA-000004)

This report was produced by MM in April 2019 following the discovery of cracks in the north west and south west pedestals. This report was produced before the effects of the TTT were considered.

The report summarises the results of the site investigations and NDT findings in the NW and SW pedestals. The report includes a section on the relative position of the saddle to the pedestal and from this analysis, and based on this, various conclusions are drawn relating to the direction of the restraining force at each pedestal as shown in the extract below in Figure 4.1 below, with a definition of d_s. Table 4.3 below is an extract from the report showing the measured value of d_s which gives the relative position of the saddle.

Figure 4: Relative saddle position



The position of the saddle at time of construction is not known but for the saddle positioned centrally with respect to the pedestal, d_s = 38mm. Refer to Table 1 for a summary of measured relative saddle positions.

Figure 4.1: Extract from MM report showing definition of d_s

Table 1: Relative saddle position

Pedestal	d_s [mm]	d_s – 38mm [mm]
South West	68	30
North West	-16	-54
South East	34	-4
North East	18	-20

Table 4.3: Extract from MM report showing assumed saddle position.

From this analysis, MM conclude that the direction of the restrained force is as shown below in Table 4.4 below.

Pedestal	**Direction of Restraining Force**
South West	Towards Anchorage
North West	Towards Main Span
South East	Towards Main Span
North East	Towards Main Span

Table 4.4: Direction of Restraining Force (Source: MM)

The report describes the approach used for modelling. A 2D model was used to derive the loads on the pedestal and modelled the ground, anchorage chain and the rollers. The loads were than applied to a 3D shell model of the pedestal and the utilisation factor (UF) was obtained for various load conditions as shown in the two tables extracted from the report, shown in Table 4.5 below:

Table 3: Cut 1 utilisations (restrained force towards span); central plate

Case	N [kN]	M [kNm]	σ_t [MPa]	σ_b [MPa]	UF
PRM	-227	6	-21	7	0.16
PRM + Ped	-436	12	-40	16	0.34
PRM + Ped + Temp	-1396	58	-153	117	2.55
PRM + Ped + Temp + LL	-1727	71	-189	143	3.10

Table 5: Cut 3 utilisations (restrained force towards anchorage); central plate

Case	N [kN]	M [kNm]	σ_t [MPa]	σ_b [MPa]	UF
PRM	-173	3	-11	-4	0.07
PRM + Temp	-1807	-149	-195	173	3.76
PRM + Temp + Sett	-1853	-154	-201	179	3.90

Table 4.5: Utilisations for pedestal (Source: MM)

Key terms in Table 4.5 above:

PRM - Permanent Loads

Ped - Pedestrian Loading –

Temp – Load affects from temperature changes

LL – Vehicular (Live) Load

Sett – Load affects arising from Ground Settlement

For the NW, SE and NE pedestals, where the restraining force is towards the main span, the report summarises the fact that removing vehicular traffic leads to a reduction in the utilisation factor of 18%. This can be seen in Table 4.5 above where the UF reduces from 3.10 to 2.55. From the same table, it can be calculated that the contribution to the UF from pedestrian loading is 0.18 which is the difference between 0.34 (PRM + Ped) and 0.16 (PRM).

For the SW pedestal, where the restraining force is towards the anchorage, the maximum UF is 3.90, and the addition of pedestrian loading does not increase that figure as it is a relieving effect.

The report concludes that the magnitude of the assessed utilisations is highly dependent on a number of assumed parameters which can only be reliably confirmed through structural monitoring of the pedestals. This point is developed in the next report, and so this report is an interim report in the history of the development of the understanding of the pedestals.

Detailed comments and responses are included in Appendix B3.

4.2.3 Revised CI Pedestal Analysis for Ground Movements Induced by Thames Tideway Tunnel (Document Reference: 383488-MMD-HSB-REP-SE-RA-000008)

This report was produced by MM in January 2020 with the intention of providing a more refined analysis of the south pedestals subject to ground movements induced by Thames Tideway Tunnel construction. The tunnel passes through the area south of the bridge under parts of Barnes. The report consequently concentrates on the SW pedestal. Although the tunnel passes closer to the SE pedestal, as this pedestal did not have any known cracks at the time, the SW was chosen for the study. This report was carried out in advance of the tunnel which was programmed to pass through the area in March 2020, in order that any mitigation measure could be identified in advance.

In Figure 4.2, which is an extract from the MM report, it shows the UF for the SW pedestal much lower as 1.10, increasing to 1.24 after the effects of TTT are included. Adding 0.18 from pedestrian loading takes the UF up to 1.42.

Figure 6.10: Plot of SW pedestal utilisation factors

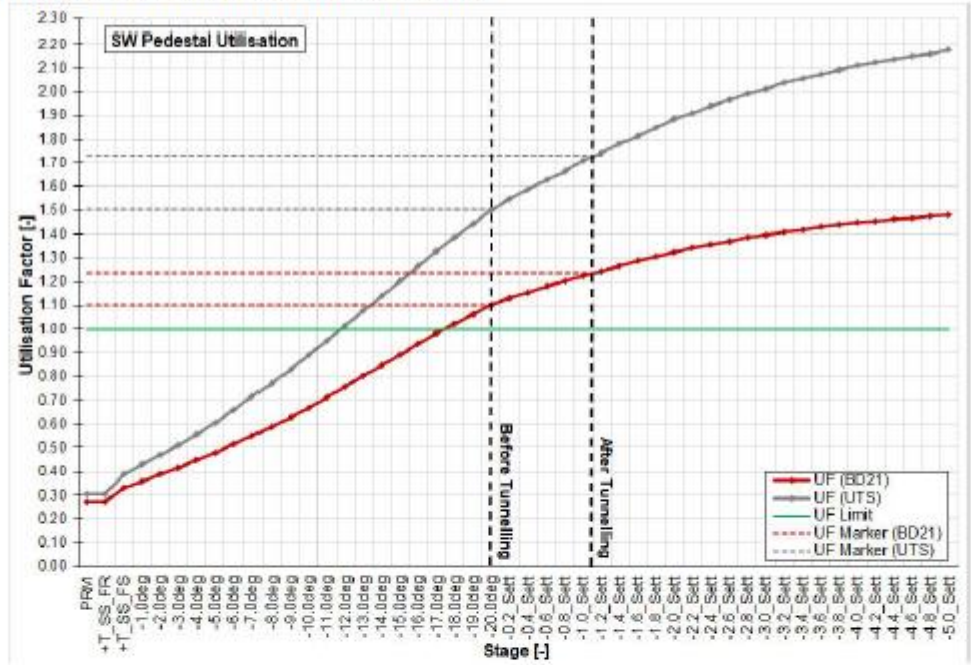


Table 6.3: Summary of utilisation factors before and after tunnelling

Stage	UF (BD21)	UF (UTS)
Before tunnelling	1.10	1.50
After tunnelling	1.24	1.73
Impact from tunnelling works	**+12.4%**	**+14.7%**

Figure 4.2: Extracts from MM report showing Utilisation Factors

The report represents the most recent and most refined analysis of one of the pedestals and hence provides the best available background information to the criticality of the pedestals.

The main points in the report are as follows:

- The following work and conclusions were reached in the report:
- The initial assessment found that the pedestal was significantly overstressed and BD 79: Management of Sub-standard Structures was implemented; the first action was to carry out Non-Destructive Testing of the pedestals.
- Strain and temperature gauges were added each side of the SW and SE saddles. As the chain loads measured in the SW were higher than in the SE, it was concluded that there was more movement in the roller bearings in the SE, or there was a soft spot in the ground under the SE pedestal.
- It has been established through discussion and comments sheets AECOM understands that the presence of the previous chain tunnel has been included in the analysis of the ground conditions. It is likely that the softer ground may help to dissipate the restraining force. The extracts in Figure 4.3 below show the geometry and the subsequent model used for the 2D analysis of the anchorage and ground.

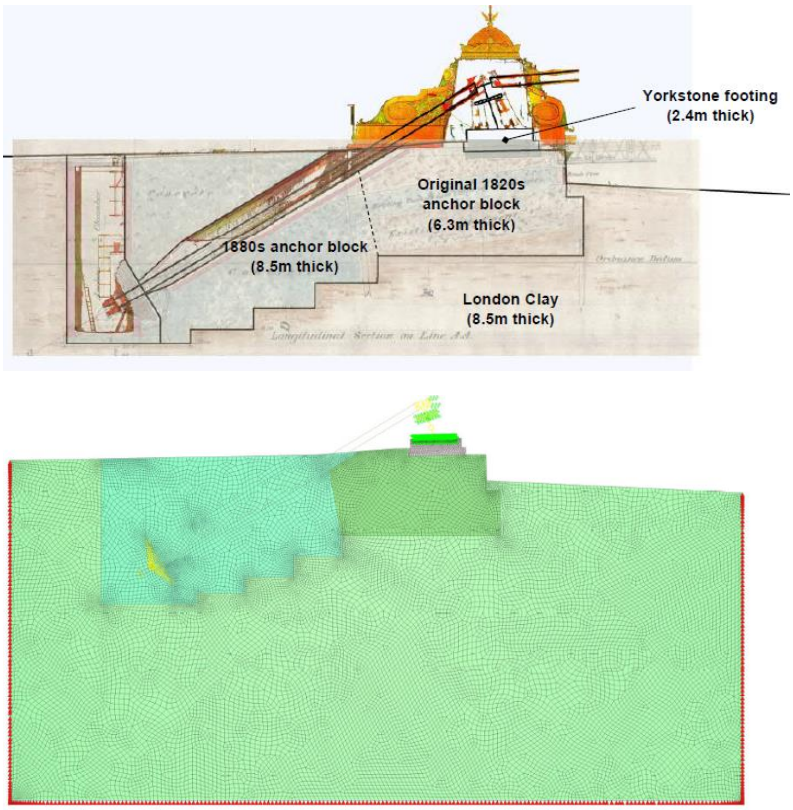


Figure 4.3: MM Soil-structure interaction model

- ICHD testing was carried out, which measure stresses in elements by drilling a small surface hole. These results predicted much higher chain loads but they are less reliable due to the challenging working environment coupled with an uneven and sometimes pitted chain link surface. These results were not taken forward by Motts within the scope of the report, but recommendations were made to carry out more tests to obtain improved repeatability.
- As the cast iron dates from the late 1880s it was perceived that the quality of the iron could be better quality than that used in BD21. As it was not possible to cut coupons for testing out of the pedestals, MM referenced back to a similar but older bridge – the High-Level Bridge in Newcastle. From this, MM derived an increased Ultimate Tensile Stress (ULS) of 80 MPa. But whilst this appears to be an improvement it cannot be compared directly to the permissible tensile stress limit of 46 MPa used in accordance with BD21. Having compared the two approaches, the use of the 80MPa ULS in combination with the compatible applied stress regime, did not lead to a reduction in the utilisation factor and was not used further. But it did serve to validate that the use of BD21 permissible stresses is appropriate.
- The report assumed that the roller bearings were functioning at the start of the bridge's life and so all permanent loads are modelled assuming the bearings are free.
- For permanent loads, the chain load was taken as 3900 kN in combination with a bending moment of 60 kNm.
- The report concludes that the bearing seized in the summer months at a temperature of 20°C, however, we are not clear how this can be justified. We recommend that MM review this assumption in more detail.
- Maximum temperature range in Winter was taken as 20°C based on temperature monitoring records.

- Maximum temperature range in Summer was taken as 27°C (using maximum effective bridge temp of 47°C taken from BD37/01). However, much of the anchor chain length is underground in the tunnels and is unlikely to experience such a high temperature range. We recommend that MM review this assumption in more detail.
- The restraining forces at the pedestals for the seized roller condition and assuming the above temperature ranges are 1980kN and 1988 kN respectively.
- The effects of the ground movements provided by TTT were modelled by MM as an increase in the chain length.
- The utilisation Factor of the uncracked pedestal reduced to 1.10 for permanent and temperature load combination only. The main reason for the reduction in UF from the original assessment was through the accumulation of monitoring data which allowed MM to relax some of their original assumptions.
- With the addition of predicted settlement effects after TTT, the new combined UF increased to 1.24.
- The report refers back to the CCSO and concludes that the impact from TTT is not small. This resulted in the recommendation to install an anchorage chain temperature control system before tunnelling. (See Section 4.6 below) The report also recommends separate calibration of the SE saddle. Finally, the report recommends that repeat tests using ICHD are carried out as the original ICHD tests did predict high loads in the chains which cannot be ignored.

Detailed comments and responses are included in Appendix B4.

4.3 Review of Mott MacDonald's Report "Hammersmith Bridge - Cast Iron Pedestals - Post-blast inspection report NE & SE (06-Apr-20 to 09-Apr-20)", 20 April 2020

This report first describes the method of casting the pedestals. It is suggested that each pedestal was manufactured as a single large casting using sand moulds. The report describes how defects and discontinuities are likely to have been created, especially for such a complex item. The report states: "*It is important to note that these defects have been part of the structure since manufacture and their discovery does not necessarily constitute a "change in condition".*

This report then describes the results from the non-destructive testing (NDT) of two of the four pedestals following complete paint removal. The process was to carry out a full visual inspection first, followed up by magnetic particle inspection (MPI) with reveals surface-breaking cracks. Visual inspection was carried out by MM staff and the MPI by qualified staff from Intertek.

At the NE pedestal a further 7 cracks were identified beyond the 6 previously found (before removal of paint). Of these, 2 were classified as original casting defects and 5 were believed to be stress related (overstress or fatigue). The lengths of the original cracks as first found is not given. A summary of the cracks found as given in Table 4.6 below.

Defect	Location	Detail	Type	Stressed state	Restrained force direction	Likely cause
NE1	East Web	Approx. 30mm long	Surface break	Tension[1]	Towards span	Manufacturing defect
NE2	West Web	Approx. 200mm long	Through thickness crack	Tension	Towards span	Tensile rupture
NE3	Centre Web	Approx. 100mm long	Through thickness crack	Tension	Towards span	Tensile rupture
NE4	Centre Web	Approx. 100mm long	Through thickness crack	Tension	Towards span	Tensile rupture
NE5	Centre Web	Approx. 80mm long	Through thickness crack	Compression	Towards span	Fatigue crack
NE6	West Web	Approx. 80mm long	Through thickness crack	Compression	Towards span	Fatigue crack
NE7	West Web	Approx. 205mm long	Through thickness crack	Tension	Towards anchorage	Tensile rupture
NE8	East Web	Approx. 50mm long	Surface break	Tension[1]	Towards span	Manufacturing defect
NE9	East Web	Approx. 70mm long	Surface break	Tension	Towards span	Manufacturing defect
NE10	Centre Web	Approx. 160mm long	Through thickness crack	Compression	Towards span	Fatigue crack
NE11	Centre Web	Approx. 95mm long	Through thickness crack	Tension	Towards span	Tensile rupture
NE12	Diaphragm 5	Approx. 140mm long	Through thickness crack	Tension	Towards span/ anchorage	Tensile rupture
NE13	Diaphragm 3	Approx. 125mm long	Through thickness crack	Tension	Towards span/ anchorage	Tensile rupture

Table 4.6: Summary of cracks found in NE pedestal (Source: MM)

The acoustic emission system has detected one event on the NE pedestal, this could not be associated with any of the newly discovered cracks.

No cracks were found on the SE pedestal which was believed to be associated with a better quality casting.

The report concludes that none of the defects discovered following post blast inspection had occurred or propagated since the acoustic emission system was installed and it was highly probable that these defects had been stable since the bridge was closed to vehicular traffic in April 2019.

A further conclusion was that the ‘no-change’ criterion set out in the Case for Continued Safe Operation (CCSO) continues to be maintained.

AECOM comments

A number of significant through-thickness cracks have been identified in the NE pedestal, two being about 200mm in length. Over half have been associated with a tensile rupture, but this always coincides with a tension stressed state. Those with a supposedly compression stressed state have been associated with a fatigue mechanism. The mechanism for the propagation of these cracks is considered by AECOM to be conjecture.

The conclusions drawn deserve comment. The statement that the cracks have been stable since closure to traffic has been shown to be inaccurate with the growth of NE10 during the August 2020 heat wave. Without traffic the main driver for crack propagation will be temperature variations – for any fatigue this would be high stress/very low number of cycles.

The other conclusion regarding the maintenance of the ‘no-change’ criterion is questionable as it neglects the discovery of seven further cracks, five of which are significant. It is presumed that the ‘no-change’ criterion was maintained because all the newly discovered cracks are considered to be stable and non-propagating.

Detailed comments and responses are included in Appendix B5.

4.4 Review of Mistras Reports

4.4.1 Review of Mistras Report "Hammersmith Bridge AE Monitoring System Performance Review", 03 August 2020

This report describes the design, installation, commissioning and operation of the acoustic emission system installed on all four pedestals in May 2019.

Each pedestal is fitted with 15 sensors with five on each web. These are located in the four "corners" of the web with one placed centrally. This enables an event to be located through analysis of the precise timings of the hits at the five sensors.

The report covers the period from commissioning up to 03 August 2020, i.e. it does not include the events on 07 August 2020 which led to the complete closure of the bridge. A total of 163 events are listed of which 4 were originally thought to be confirmed crack growth. 105 of the events were discarded as being either work related or due to rain. The confirmed events are: NE – 1, NW – 0, SE – 1, SW – 2. However, all these locations were inspected (see Section 4.6 below) and no evidence of cracks or crack growth were found.

AECOM COMMENTARY

Acoustic emission monitoring has been used for 25+ years and Mistras are one of the leaders in this technology. AECOM have used this application to monitor fatigue cracks in the Midlands Links structures and to monitor wire breaks in the major UK suspension bridge cables and Hammersmith Flyover post-tensioning.

However, it is by no means perfect and we have seen other systems both under and over record events. Deliberate blind wire cutting tests have produced both positive and negative results.

Nevertheless, it is a very useful tool primarily as an indicator to show activity is taking place and provide a focus for reactive visual inspection.

Detailed comments and responses are included in Appendix B6.

4.4.2 Review of Mistras Report NE Saddle Alarm Report 07/08/20

This is a reactive report arising from a high energy emission which triggered one of the system alarms. This was associated with a period of activity lasting about an hour and corresponded to a period of high temperature. (Temperature is measured under the deck at the NW corner of the bridge.)

The location of the event that triggered the alarm was in the lower front (facing river) corner on the east web. Note that crack NE10, whose growth has been associated with this acoustic event, is actually located on the central web and not the east web. Therefore, the growth of crack NE10 between April and August 2020 may not necessarily be connected with the high temperatures seen in August 2020. We recommend that the origin of this AE event is investigated further.

4.5 Review of Weekly Reports

Between 29th October 2019 and 3rd April 2020 Mott McDonald undertook weekly inspections of the bridge pedestals as part of the BD79 and CCSO interim measures for the bridge. The inspections used visual examination initially which was supplemented by NDT in the following order:

a. Eddy current testing will be undertaken around the perimeter of all openings (within approx. 50mm from the inside face of opening) where stress induced cracking is most likely to occur.
b. If indications of surface breaks are picked up with eddy current, then the paint will be cleaned back to base metal before undertaking MPI testing, to confirm any cracking.
c. In areas with a rough or lumpy surface, skip eddy current and jump straight to MPI testing.

The number of cracks found at each pedestal are listed in Table 4.9 below.

Date	NE	SE	NW	SW
29/10/2019	1	-	1	2
4/11-19/11/2019	6	-	1	2
26/11/19-10/3/20	6	-	4	2
17/03-30/03/20	6	-	4	7

Table 4.9: Cracks found at each Pedestal

The crack lengths were found to vary slightly depending on the MPI equipment used.

The report also picked up any Acoustic Emission events over the 7 day period and addressed whether they related to real events. There were typically several AE events recorded every week although the majority were not related to defects that were found. At the end of the weekly inspections the summary shown in Table 4.10 below, of what were believed to be actual events, was produced.

Timestamp	Pedestal	Event	Investigation & Findings
23-Jul-19	SE	Cluster alarm	Paint cleaned back locally around the openings within the zone of the located emission. Detailed visual examination did not find any evidence of a fracture event.
17-Oct-19	NE	High energy alarm	Paint cleaned back locally around the openings within the zone of the located emission. Detailed visual examination supplemented with magnetic particle inspection (MPI) confirmed a defect although it was concluded that this was likely due to the manufacturing process rather than a stress fracture.
26-Jan-20	SW	Cluster alarm	Paint cleaned back locally around the openings within the zone of the located emission. Detailed visual examination did not find any evidence of a fracture event.
09-Feb-20	SW	High energy alarm	Contractor cleaned back paint within the zone of the located emission. Detailed visual examination did not find any evidence of a fracture event.

Table 4.10: MM inspections carried out after acoustic monitoring confirmed events

The weekly reports also contain a table showing progress against the CCSO requirements as shown in Table 4.11 below:

Task	CCSO requirement	Due	Review
1	Additional crack sensor NE		Complete - W/e 18/10/2019
2	Chain link sensors & alarm system (Stage 2 instruments)	14/10/2019	Complete - 06/08/2019
3	All paint work stripped Suspected cracks in central plates	15/11/2019	On-going TfL to instruct Taziker to remove paint locally as soon as possible
4	Thames Tideway impact assessment	Urgently	Completed – 7/02/20
5	Targeted Eddy Current testing		Completed – 09/12/2019
6	Assess acoustic signals to inform trigger levels		Complete - 13/12/2019

7	Tarpaulin SE pedestal	08/11/2019	Complete - 13/12/2019
8	Explore possible release of saddles	25/11/2019	Completed 21/2/20
9	Material Testing	15/11/2019	Complete
10	Temporary new alternative load paths		Options investigated - presented on 28/11/2019. Mitigation measures required, see 10a
10a	Temperature control of chain tunnels		System installed w/c 2nd March 20 and commissioning is ongoing.
11	Establish a solution for chain knuckle defect (NW)	Urgent	Action by others. Inspection by others has yet to take place.

Table 4.11: Summary of CCSO requirements (compared to Section 6.12 of CCSO Report)

The inspections were stopped as a result of restrictions caused by Covid-19. The final report includes a justification technical note giving contingency measures. These include AE monitoring and a permissible temperature range and strain monitoring. This section states that:

'for an average anchorage chain temperature within the range observed from monitoring records, the pedestals can safely resist the load demand'

The permissible temperature range was 3- 24°C. Alarms were to be set for temperature and strain measurements.

The final report also sets out recommended additional measures including additional AE sensors, Temperature Control System, Refined Pedestal Assessment and Release of Rollers.

Detailed comments and response are included in Appendix B7.

4.6 Impact from Thames Tideway Tunnelling (Document Reference: 417593-MMD-HSB-REP-SE-TTT-00001)

Following the passage of the tunnel boring machine (TBM) through the zone of influence for the bridge MM produced a supplementary report reviewing the actual measured settlement of the bridge compared to the predicted values and corresponding impact on the pedestals. The report also reviews the performance of the heating systems that were installed on the southern anchorages.

The heating system was installed over 3 days starting Monday 2nd March and was commissioned fully on Monday 16th March. The system was a water based one with pipes installed down the anchorage chamber with a boiler on the ground intended to achieve an average temperature of 13.5^{o}C over the length of the anchorage. An extract showing the schematic of the heating system is shown in Figure 4.4 below:

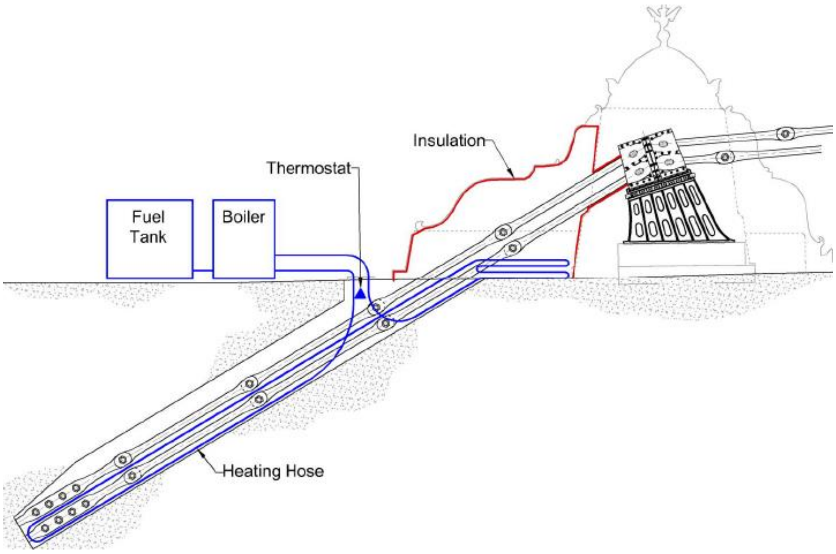


Figure 4.4 – Schematic of Heating System (Source: MM)

The system managed to maintain a temperature between 11^{o}C and 16^{o}C during the passage of the tunnel.

The pedestals were also extensively monitored during the tunnel passage. As well as the established AE and strain gauge monitoring discussed elsewhere, there was an array of levelling points monitored for displacement along Castelnau on the southern approach to the bridge extending to the actual line of the tunnel to the south of the bridge. The results of these showed a volume loss in the tunnel of approximately 0.6%, which was better than the 1% that had been the conservative estimate used to predict the effects. The effect of this was that the settlements experienced by the bridge were 40% less than the anticipated values (measured settlements were 0.22mm and 0.41mm at the SW and SE anchorages respectively).

There were a number of AE events during the passage of the tunnel; however, investigations showed these all to be false alarms.

The strain gauge readings showed no change between values before and after the passage of the tunnel once some spurious results, thought to have been caused by blast cleaning being carried out at the time, were ruled out.

The overall conclusion of the report was that there was no effect to the anchorages as a result of the tunnelling. The increase in utilisation of between 12.4% and 14.7% estimated in MM report 383488-MMD-HSB-REP-SE-RA-000008 was not realised.

4.7 Review of Pell Frischmann Approval in Principle for Advance Works: Cast Iron Pedestals, Pedestal Bearings and Tower Bearings July 2020 (Report Ref: 102963-BAS-ZZZ-AIP-S-00002)

This report was produced by Pell Frischmann and is the Approval in Principle for the design of the refurbishment and strengthening of the pedestals and the tower bearings.

In Appendix 7, The document describes that three options were considered for remedying the Pedestals and Bearings at the abutments, and the bearings at the Towers. The three options were

1. Repair
2. Strengthen
3. Replace

For the **pedestals**, the option chosen to develop was Option 2: strengthen by installing 12 props within the voids in the pedestal to transfer load directly from the top bearing plate to the base plate. The voids would then be infilled with steel fibre reinforced concrete which would also encase the props. The design is such that, if the pedestal starts to fail, the loads normal to the bearing plate will be transferred via the concrete and props. If the pedestal does not fail the load will be shared between the pedestal, concrete and props acting compositely.

For the refurbishment of the **roller bearings**, three options were considered:

1. Repair,
2. Replace with new steel roller bearings,
3. Replace with new mechanical bearings.

Option 3 was chosen primarily because this would provide a reliable design life of 60 years, but with the assumption that the bearing pads will need to be replaced after about 30 years as their life expires. It was not possible to provide a bearing design fully compliant with current codes due to the available vertical space. Further space could be improved by the removal of the top bearing plate on the pedestals.

In order to replace the bearings, two further sub-options were considered. In the first sub option, the pedestal would be temporarily strengthened by steel frames at the front and back of the pedestal clamped together by external steel bars. These frames would provide support to the jacks. This option was rejected due to concerns for the integrity of the pedestal.

The second preferred sub-option would employ an independent jacking frame which would be supported on the base slab. AECOM understands that the frame design is currently being refined. AECOM notes that, in the original assessment by MM, the base slab was overstressed but we are unaware if any further analysis has been undertaken. The base slab will need to be checked that it is not overstressed by the temporary jacking frame. The analysis of the slab must also consider the existing chain tunnel beneath.

Details of comments raised are included in Appendix B8.

4.8 Review of CCSO for Limited River Traffic Movements

Introduction

As reported in Section 4.1 of this report, the original CCSO was produced by Xanta Limited, who were contracted by TfL to prepare a reasoned case for the continued safe operation of the bridge following the discovery of cracking in the pedestals in April 2019.

The Xanta CCSO report was used to justify that the bridge is kept partially open to pedestrians from April 2019. But since August 2020, when the bridge was closed to pedestrians and river traffic, it has been a vital report to document all the various issues relating to the continued closure of the bridge.

A new report has been produced by Xanta Limited in October 2020 which relates to the Case for Continued Safe Operation for Limited River Traffic. This CCSO updates in part the original CCSO report but it does not appear to replace the original CCSO. A review has been made of draft 4, dated 25 October 2020. A summary of the main report is included below whilst a detailed review is included in Appendix C.

Summary Review

The CCSO for Limited River Traffic is a positive step forward to enable river traffic to pass under the bridge under controlled circumstances. However, at the time of writing AECOM understands that this document is being reviewed by others before implementation. Some of the limitations on movement are provided but more guidance is required on the times and conditions when boats can pass under the bridge. Priority should be given to any emergency boats. The CCSO mentions that boats may take 2 to 3 minutes to pass under the bridge; in reality, most boats will take significantly less than this time.

This CCSO refers to the relative risks of pedestrians using the bridge to that of allowing limited river traffic. It also refers to a separate CCSO for workforce on the bridge. AECOM has not seen this document, but it would be useful to review it when made available and would encourage duty holders to review to see if this can be extended to include limited (or greater) pedestrian and cyclist use of the bridge.

This CCSO has moved on from the previous CCSO. It accepts that cracks identified before April 2020 are historical, but the cracks should be monitored for stability. On this basis, AECOM notes that weekly visual inspections stopped in March 2020 because of Covid-19, but it has not been confirmed if the visual inspections have been re-instated since August 2020. AECOM recommends that the frequency of inspections is increased as this is one of the mitigation points raised in the CCSO.

The CCSO accepts that there are mitigation measures in place including monitoring and temperature control. AECOM understands that temperature control was installed on the NE pedestal in September 2020, and that temperature controls will be installed on the remaining pedestals in November 2020.

In a number of places, the CCSO states that there are many unknowns, whilst at the same time it recognises that MM have gained a good understanding of the bridge behaviour. AECOM agrees that MM have a good understanding and have carried out their work in a logical way. It is possible to calculate, within good accuracy, the loads in the chain as there is detailed information on the weight of the bridge deck and on the catenary geometry of the chain. Combined with correlation of the theoretical models and monitoring information, MM have been able to make a reasonable calculation of the restraining force applied at the seized rollers. Having reviewed MM's assessment reports it can be seen that MM have carried out sufficient sensitivity checks on the models. AECOM recommends that this work is checked independently, whilst we understand that the work has been peer-reviewed by MM.

The CCSO states a number of times that full reliance on monitoring and temperature control needs to be backed up with further technical measures. In response to this, it is well documented that there is a wide ranging task force which is looking at this bridge in detail. Pell Frischmann are undertaking the design of the frames for jacking the saddle off the pedestal and removing the seized roller bearings. PF are also designing the strengthening of the pedestals. MM are continuing to develop their understanding of the behaviour of the pedestal and are looking at the failure mode and load of the cracked NE pedestal. AECOM recommends that MM also carry out analysis of the other pedestals. AECOM recommends that all critical items are independently checked by Atkins. AECOM agrees that it is difficult to quantify the magnitude of residual stresses.

The CCSO recognises that the combination of monitoring and modelling has provided information to establish a temperature range where stable conditions will occur, but it must be backed up with real-time monitoring. The CCSO further recognises that since August 2020, the NE10 crack has not propagated further, but this should not be relied on.

The CCSO mentions that there must be a sufficient management regime in place and that duty holders develop the management arrangements, and associated resourcing to deliver the matters detailed herein, as well as a rapid deployment strategy should an event happens. AECOM agrees with these statements. In terms of rapid deployment of staff, we do not know what arrangements have been made. But we would assume that that this will include include:

- Immediate notification of AE events to competent personnel including weekend and holidays
- Emergency action procedure in place
- Training for emergency procedure involving emergency services, etc

The CCSO states that it must be reviewed after six months and that it should be revised or renewed after 12 months.

Detailed comments on the CCSO are included in Appendix C.

4.9 Review of Interim Release of the Seized Saddle Rollers (Report Ref: 383488-MMD-HSB-TN-SE-00016)

This is a good background information and includes very useful photos. The report provides a useful section on the manufacturing process likely to have been used in the original casting of the pedestal. The report is inconclusive regarding the material used for the rollers themselves. In a paper produced by Hailstone in 1987, it is suggested that the rollers are steel. However, when a chisel was used to investigate the material, the material appeared to be softer and more ductile, similar to wrought iron.

Several issues were identified as contributing reasons for preventing movement of the rollers. These included:

- Rust and debris accumulation
- Inaccurate original manufacture and
- Distortion since manufacture and original construction.

The report includes several photographs which illustrate these items. AECOM has also noted a photograph of one of the pedestals in which there is a visible dip in the top bearing plate which would require rollers to move “uphill” if they reached this point.

Dorothea provide an outline methodology to free up the roller bearings, which involves a de-rusting process similar to that used on Clifton Suspension Bridge. The methodology involves the installation of temporary folding wedges and restraining bars which enables rollers to be de-rusted three at a time. After de-rusting the wedges and restraining bars are removed.

Dorothea provide a quotation to carry out the work but exclude temporary works and cleaning. The most significant issue to be resolved is the temporary works required to control movement when the rollers are freed. The design of the temporary works is subject to design development by Pell Frischmann.

4.10 Reports not reviewed

The following reports shown in Table 4.12 below have not been reviewed in depth but used for general understanding.

Title	Ref.	Author	Reason for no review
Global Analysis Methodology, September 2018	383488-MMD-HSB-TN-AN-00001	MM	Covers global analysis of bridge
Hammersmith Bridge - Refurbishment Inspections and Investigations: Interpretive Report 02 November 2018	383488-MMD-HSB-REP-SE-ITR-000001	MM	Report precedes discovery of pedestal cracks
Hammersmith Bridge - Strengthening and Refurbishment Feasibility Study 10 May 2019	383488-MMD-HSB-REP-SE-FSR-00001	MM	Report precedes discovery of pedestal cracks
TfL comments on Beckett Rankin proposal for a Temporary Traffic Bridge, March 2020		TfL	Not relevant to scope of Stage 1 report
Hammersmith Temporary Pedestrian and Cycle Bridge AIP July 2020	0013-01-002 N001	Costain	Not relevant to scope of Stage 1 report

Table 4.12: Reports not reviewed in depth

5. Review of issues relating to freeing up roller bearings

Introduction

This section of the report covers issues relating to freeing up of the roller bearings. This was discussed during a meeting held on 8 October 2020 with DfT and NR.

Discussion Items

Materials

It is not clear if the rollers are made from wrought iron or steel. The majority of the bridge is made from wrought iron which was the most common structural material at time of construction. A notable exception is the chain links which are known to be made from steel. Nevertheless, there is little consequence between the use of wrought iron or steel as they would have had similar yield and ultimate strengths. Both these would be considered as "soft" in comparison with modern high tensile structural steels.

The surfaces of the saddle and the pedestal, on which the rollers bear, are both cast iron.

Bearing stresses

A simple calculation has been carried out following the roller design rules in BS5400 Part 9.1. This gives a maximum bearing stress per unit length of roller of 18 x roller radius x UTS^2 / E. (Note check is carried out at SLS with γ_m = 1.0.) Taking a UTS for cast/wrought iron/steel as 300N/mm^2, gives a maximum bearing stress per length of about 600 N/mm.

There are 8 rollers four feet long and taking a dead load force normal to the rollers of 400 tonnes, this gives an actual bearing stress per length of about 400 N/mm. Obviously any live load would increase this.

It does suggest that contact stresses are quite high.

Sources of roller friction

There are other potential sources of friction other than simple rolling friction. These include the roller flanges bearing against the upper and lower castings, and shouldered-down pins in the link plates.

The saddles, pedestals and bearings were painted with an epoxy paint system in the mid-1990s and this will also contribute to the friction in the system.

Other bridges with roller bearings

Similar roller bearings are known on the following historic bridges, as shown in Table 5.1 below:

Bridge	Knowledge of roller condition
Royal Albert, Saltash	Rollers support the tube & chains at the outer piers only (centre pier is fixed). Rollers are known to have seized many years ago, however, as the piers are very tall, they are able to flex to accommodate any thermal movement.
Brooklyn, New York	It was reported in 1945 that the 3½ inch tower rollers were seized. However, the situation is complicated by the presence of an extensive cable stay system that tries to restrain roller movement.
Clifton, Bristol	It has been mentioned that Dorothea Restorations "freed the seized Clifton rollers". We have spoken to the Trustee's consultants, and obtained a technical account. As part of an overall review of risk of the bridge, measurement transducers were installed at all four tower tops. Three were moving as expected but

	one “was dragging its heels” (i.e. not seized). Dorothea were engaged to clear out the debris, oil them and install Perspex covers. The monitoring is still present and all bearings are moving OK. There are further saddles just underground at the bottom of the backstay chains to turn the chains into the anchorages (i.e. like the Hammersmith pedestals). These do not have rollers and are fixed in position. These have been inspected in the past and it was concluded that given their underground location the ambient temperature is fairly constant, coupled with no signs of distress, there was no concern.

Table 5.1 – Other Bridges with Roller Bearings

Some modern suspension bridges have employed rollers, but these are not complete cylinders but bars on edge with radiused top and bottom surfaces (large radius) so as to pivot rather than roll.

Other bridges with seized up bearings

Alexander Bridge, Rockhampton is a 5-span steel truss bridge in Australia constructed in 1899. The roller bearings were found to have seized up and were also surrounded by debris. These rollers were successful de-rusted and freed up in 2018.

Detailed Comments are included in Appendix B9.

6. Review of Potential Failures Modes of Bridge

6.1 Introduction

The likely failure mode (ranging from damage, but no collapse, to full collapse) of the bridge as a result of the failure of one of the pedestals is difficult to predict as it is dependent on many factors and how they sequentially interact. The global failure mode will depend on what happens to the pedestal, e.g. whether it fractures or the holding down bolts fail etc. It should be noted that these are high level comments based on our experience and need to be developed by MM and checked independently.

6.2 Loading

As-Designed Condition: Roller Bearings Free

The pedestals were designed to withstand a force normal to the top surface applied via the rollers from the saddle. This force is the resultant due to the change in angle of the chains as they pass from the side spans into the chain tunnels. If the rollers are able to move freely (as it was originally designed) the magnitude of the chain force is balanced on either side of the saddle, and the resultant force from change in direction is directed through the rollers into the pedestal as a simple thrust, as shown in Figure 6.1.

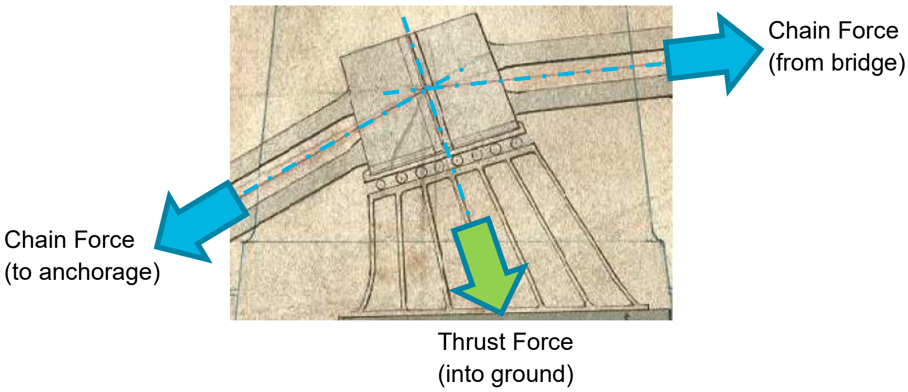


Fig 6.1: Pedestal force diagram (rollers free)

The magnitude of the chain force from the dead load of the bridge is a function of its weight and geometry and so can be readily calculated and is therefore knowable. It increases if there is live load (vehicles, pedestrians etc.) on the bridge, but it is little affected by changes in temperature (if the bridge behaves as it was originally designed with the roller bearings working).

The chains run from the pedestal down to the anchorages, partly inside the ornamental casing and partly in small diameter tunnels. As can be seen in Figure 6.2, approximately two-thirds of the chain is contained inside the tunnels and one-third above ground (but inside the casing). The temperature of the length of chain that is underground is likely to be fairly static with a small change between summer and winter. The chain temperature inside the casing is likely to vary more due to solar gain on the casing and there may be some limited conduction of heat down the chain.

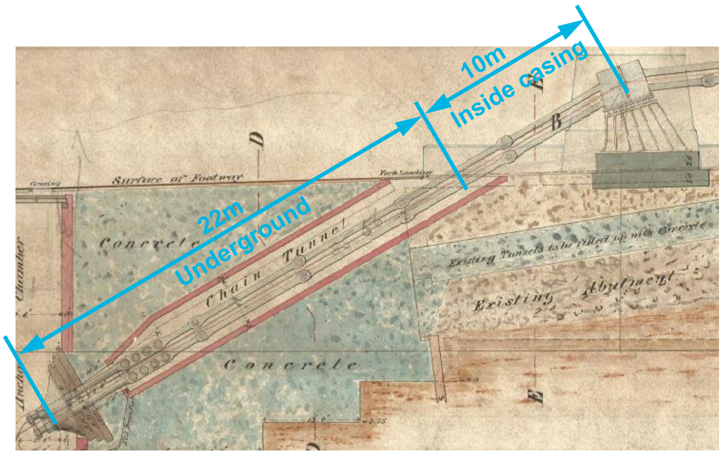


Fig 6.2: Anchorage chain lengths (Source: LBHF)

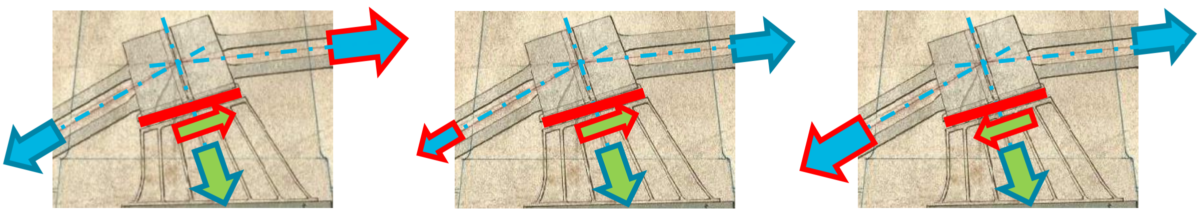
The rate of thermal expansion of the 32m anchorage chain length is about 0.4mm per degree, and this reduces to about 0.12mm per degree when just the upper 10m is affected. So even on very hot days or cold nights it is unlikely that the roller movement would be more than, say, 2 to 3mm. Live load would also cause movement of about the same order but it is transient (and for many years after opening would have been small compared with modern traffic). Assuming this to be the case then, with the rollers properly functioning, they would have seen very little movement and there is a strong likelihood that they hardly moved.

Current Situation: Roller Bearings seized

As discussed throughout this report, the roller bearings have seized.

A paper presented in 1990 (Hammersmith Bridge: 160 years of Road Traffic) indicates that the pedestal rollers were known then to be seized, although there is no indication as to how long this had been the case.

Given that the rollers have seized, there is now an additional tangential (shear) force applied to the top surface. With the bridge in normal operation carrying traffic and pedestrians the resultant shear force will always be towards the river. Now that the bridge is closed to the public the dominant effect will be due to temperature changes to the length of chain between the pedestal and the anchorage, which can produce shear loads either towards or away from the river, as shown in Figure 6.3.



Increased live load on bridge
Shear towards river

Anchorage chain "warmer", reducing its load
Shear towards river

Anchorage chain "cooler", increasing its load
Shear towards anchorage

Fig 6.3: Seized rollers – shear forces from differential chain loads

Forces due to temperature changes can be large but they are associated with very small strains of a few millimetres, so if there is any "give" anywhere the forces can dissipate rapidly. The flexibility of the soil below the pedestals is particularly significant and is something that MM has included in their analyses. However, using standard properties of London clay rather than from test samples at the bridge. AECOM understand that ground investigation (GI) has been carried out on or near the site on behalf of Pell Frischmann and we recommend that MM review their assumptions against this GI and amend their models if necessary.

6.3 Pedestal Model

6.3.1 Introduction

To gain a better understanding of the structural behaviour of the pedestals, AECOM has prepared a simplified finite element model to develop an order of magnitude understanding of the pedestal behaviour which will enable us to direct more detailed responses to MM.

All four pedestals are dimensionally the same but have differing numbers of cracks. At present the NE pedestal has the greatest number of cracks and so has been modelled. Two versions have been developed, one uncracked to benchmark against MM's analysis and a second including all known cracks in the NE pedestal.

We have not seen the results of MM's analysis of the cracked NE pedestal; a review can be carried out in the future using the modelling described below.

6.3.2 Description of the Model

A three-dimensional shell finite element model of the NE pedestal was created in LUSAS. The model is visualised in Figure 6.4 below:

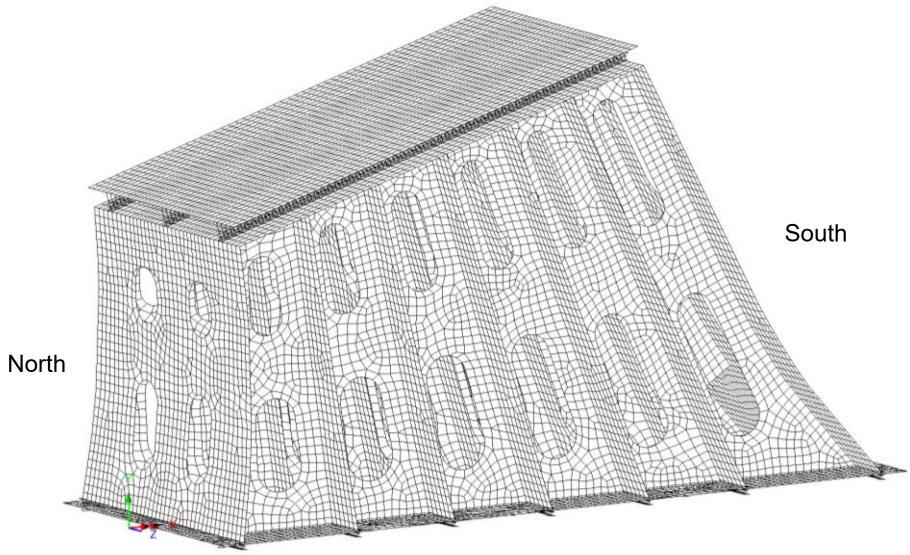


Fig 6.4: 3-D model of NE Pedestal by AECOM

The mesh comprised thick shell elements, located on the mid-planes of the plates represented. The geometry was taken from the record drawings from the original construction and all plates, stiffeners diaphragms and openings therein shown on the drawings were represented in the model. A non-linear material model approximating the brittle behaviour of cast-iron was assigned to all elements of the pedestal. The elastic modulus was assumed to be 114GPa – the value in Network Rail assessment standard NR/GN/CIV/025 and middle of the range given in BD 21/01. The non-linear material model allowed for rapid strain-softening of the cast-iron at tensile strains greater than that at which the maximum tensile stress is reached but did not model the formation of individual cracks.

Loads on the pedestal were taken from MM reports and rounded as the purpose of the analysis was to obtain rough order of magnitude. The permanent load was applied to the pedestal in the first load increment; this comprised a normal force on the upper surface of the pedestal of 3.7MN. The shear force across the upper surface of the pedestal of 2.0MN, plus the moment effect from the eccentricity of the centroid of the chains to the top of the pedestal together with the accompanying reduction in normal force of 0.46MN was applied incrementally until a peak total load factor was reached. The suspension chains were not modelled; the analysis is therefore conservative in that it does not account for the reduction in the applied shear force as longitudinal movements occur at the top of the pedestal resulting from overall shear deformation of the pedestal and rotation about the toe. Lift-off at the rear rollers was accounted for in the analysis by applying the loads to a dummy surface of shell elements above the roof of the pedestal and connecting this surface to the roof of the pedestal with a line of compression only joint elements above each of the three longitudinal webs.

Joint elements were used to model a compression-only, frictional interface between the base of the pedestal and the stone substrate. The assumed coefficient of friction between the cast-iron and the York stone was 0.5. The holding-down bolts were each represented by a spring; the axial stiffness of the bolt was calculated assuming elongation over the full length of the bolt from the centre of the nut to the base. The longitudinal stiffnesses of the bolts was calculated assuming the bolt to be a cantilever with effective depth to fixity at three diameters below the top of the stone.

The pedestal was modelled initially as uncracked, with no pre-existing cracks. The analysis was then repeated with the cracks recorded in the NE pedestal included in the analysis. The crack position was estimated from the sketches in Figure 2.12 and the data in Table 2.1 of the "Post-blast inspection report" (Document Reference 417457 MMD-HSB-REP-PBI-000001 01) by MM.

6.3.3 Results

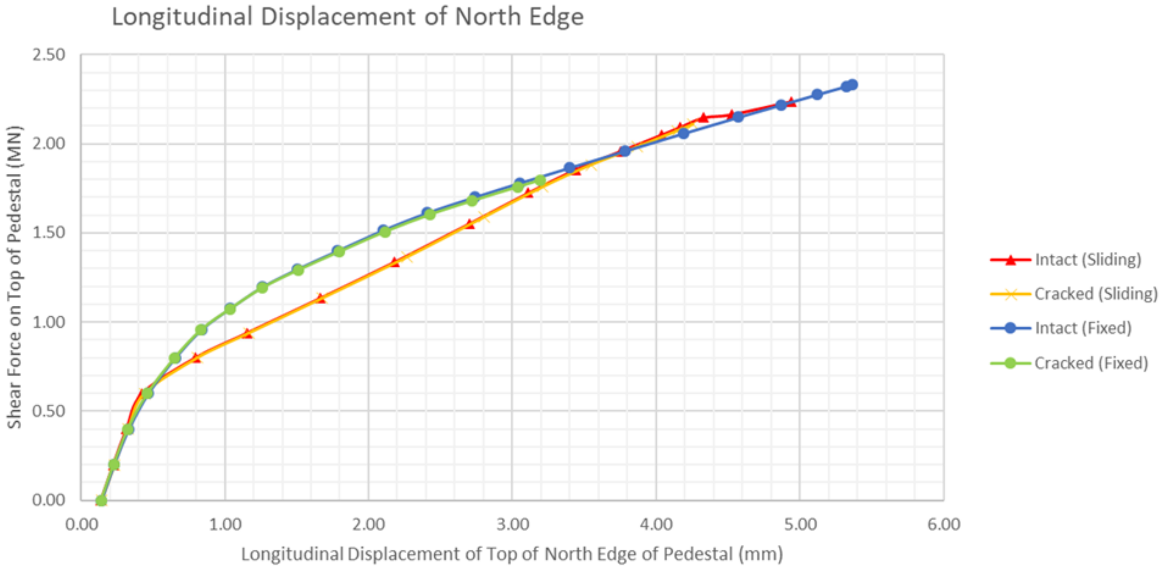


Figure 6.5: Longitudinal displacement against shear force for NE pedestal

The longitudinal displacement against shear force for the NE pedestal is shown in Figure 6.5 above.

The increase in the rate of deflection with load between 0.6MN and 0.8MN corresponds to the onset of slip on the base as the limiting friction force is reached. A zero gap between the base plate and the bolts is assumed – therefore the real displacement may be higher, with the consequence that the applied shear force, which arises from restraint of thermal movements, will be shed more effectively.

The principal stress trajectories with shear load of 0.80MN (uncracked model) is shown in Figure 6.6 below and the principal stress trajectories at final increment (Shear Load = 2.33MN) (uncracked model) is shown in Figure 6.7 below:

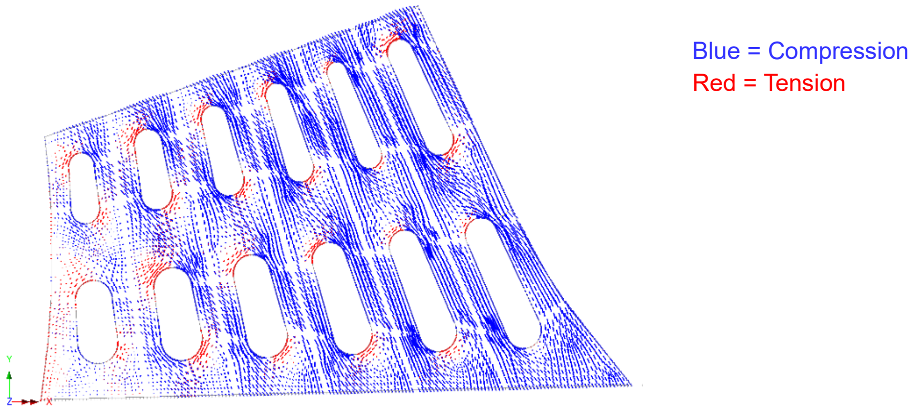


Figure 6.6: Principal Stress Trajectories with Shear Load of 0.80MN (uncracked model)

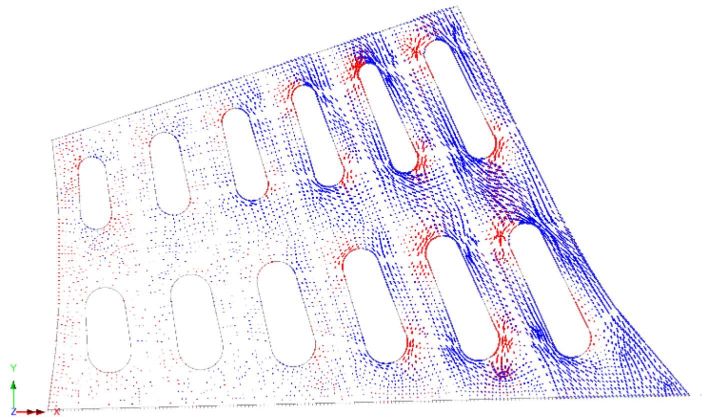


Figure 6.7: Principal Stress Trajectories at Final Increment (Shear Load = 2.33MN) (uncracked Model)

6.3.4 Discussion

As noted by Mott Macdonald and by Professor Fleck, the initial boundary conditions of the model are subject to some uncertainty. Non-uniform seating of the pedestal on the component stones of the pedestal and gaps between the anchor bolts and the pedestal base are possible. However, as the longitudinal shear force increased, the pedestal tended to rotate such that only the front surface of the pedestal was in contact with the ground, with restraint against over-turning provided by tensile forces in the anchor bolts at the back of the pedestal. It is possible that the anchor bolts were installed with a pre-load but, as this is not recorded on the drawings, this has been conservatively ignored.

Application of the shear force at the top of the model of the uncracked pedestal causes Vierendeel frame type bending of the longitudinal webs. As the shear force increased, the base of the pedestal tends to lift off at the north end (for the NE pedestal), restrained elastically by the holding-down bolts. Also the northernmost rollers will also lose contact with the top of the pedestal. These lift-off phenomena at the north end tends to further increase the stresses at the south end of the pedestal. These regions of high stress correlate with the pattern of some of the cracks observed in the north east pedestal – cracks NE1 to NE9 & crack NE11 all exist in the regions which are highly stressed due to Vierendeel bending of the webs, in the direction roughly perpendicular to the cracks. These cracks are larger and greatest in number toward the south end of the pedestal. However, the uncracked pedestal model is not highly stressed adjacent to crack NE10 in the direction perpendicular to the crack. These stresses do not increase significantly when the cracks in the pedestal are modelled.

6.3.5 Conclusions

The conclusions are to a large extent a function of the boundary conditions applied to the model. It can be seen from the various MM reports that MM faced similar challenges. It is likely that the actual behaviour of the pedestal lies between the various assumed boundary conditions.

Based on the uncracked pedestal model, it can be seen that the shear force across the upper surface of the pedestal of 2.0MN, plus the moment effect from the eccentricity of the centroid of the chains to the top of the pedestal together with the accompanying reduction in normal force of 0.46MN was applied incrementally until a peak total load factor in excess of 2MN was reached. The accompanying displacement at this peak total load is more than 5mm and, in reality, the applied shear will tend to dissipate due to these longitudinal movements resulting from shear deformation and rotation about the toe of the pedestal.

When the cracks were modelled, there was a reduction in the peak total load factor and the deformation, but as described above, the applied shear load will tend to dissipate due to the longitudinal movements.

These regions of high stress correlate with the pattern of some of the cracks observed in the north east pedestal – cracks NE1 to NE9 & crack NE11 all exist in the regions which are highly stressed due to Vierendeel bending of the webs, in the direction roughly perpendicular to the cracks. These cracks are larger and greatest in number toward the south end of the pedestal. However, the uncracked pedestal is not highly stressed adjacent to crack NE10 in the direction perpendicular to the crack. These stresses do not increase significantly when the cracks in the pedestal are modelled.

It should be pointed out that these conclusions are high level comments based on a preliminary model to provide an order of magnitude overview. These conclusions must be developed further by MM and checked independently.

6.4 Potential Pedestal Failure Modes

6.4.1 Introduction

The above modelling shows the complexity of the behaviour of an isolated pedestal and suggests there is to some degree a reserve of strength. However, it does not include how the pedestal interacts with the remainder of the bridge and the supporting ground. Both of these will contribute in different ways. The anchorage chains are tied into the anchorages which cannot move, and with seized rollers the pedestals are being effectively restrained. The supporting ground is not rigid and will provide for some dissipation of the shear forces through small movements.

Further discussion of this and other potential failure modes are presented in this section.

6.4.2 Crack Growth

The patterns of cracks discovered are mostly located in the webs towards the river side, consistent with shear forces toward the river, i.e. from traffic and temperature increase in the anchor chains. These cracks have initiated at the top and bottom of the elongated openings in the web and correspond to areas to maximum stress, although this is not always a tensile stress as might be expected.

An important point to note is that if any crack was to propagate fully it would only locally fracture the pedestal as the perforations effectively divide it into 21 sections (either "T" or "+" shapes), see Figure 6.8 below:

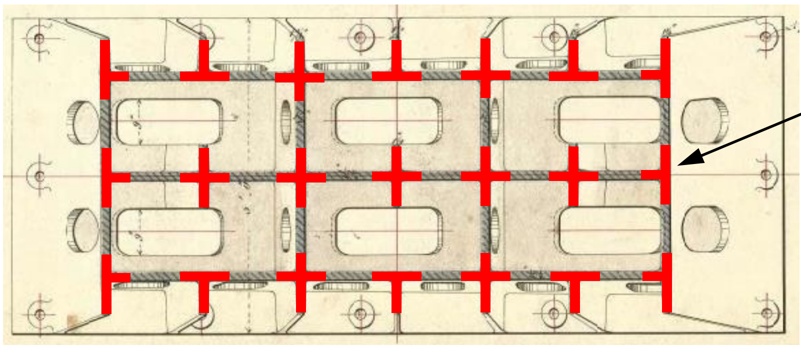


Figure 6.8: Plan on typical pedestal showing net section through openings

Further, the stress on any of these sections will comprise a small compression from the normal component of chain force plus local bending from Vierendeel-type frame effect. So the stress variation (for an uncracked and cracked cruciform) will be approximately as shown in Figure 6.9 below:

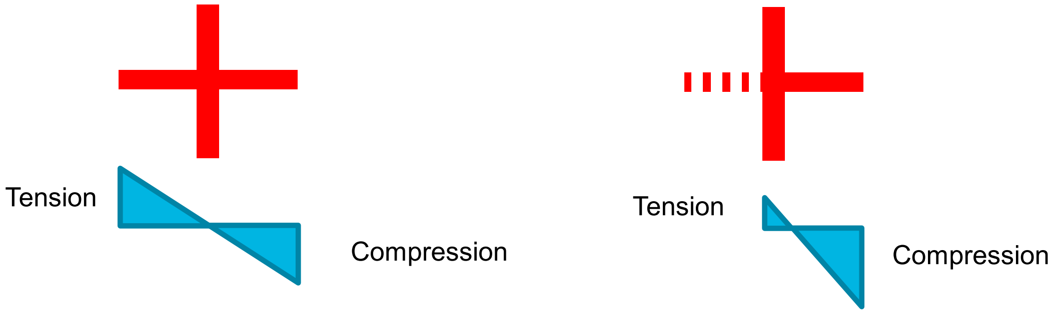


Figure 6.9: Illustrated difference in stress distribution between an uncracked and cracked section

For the uncracked section, the tensile and compressive stresses will be equal and opposite, but for the cracked section, the remaining "T" will have lower stresses (as it is less stiff) with the tensile stresses lower than the compressive stresses as the section is no longer symmetrical.

Cast iron performs well in compression but poorly in tension and can be prone to brittle cracking. Potential initiation sites will be those with high tensile stresses but will also be influenced by stress-raising factors like poor surface condition. If the local applied tensile stress is sufficiently high, then a crack could initiate at the outer fibre and then propagate towards the centre. However, the further the crack grows, the tensile stress reduces thus slowing the ability to grow. As it reaches the centre the crack front would need to transform from the narrow outstand into a broad front in order to grow further, which requires significant energy and stress levels. Therefore, it can be seen why none of the observed cracks have propagated beyond the outstand, with the exception of NE10. In this case it is strongly believed that, having turned the corner, the crack is very shallow as evidenced where it appears at the plate edge (Figure 2.5).

Another source of crack growth could be fatigue. However, this is not believed to be a significant issue at present as there is no traffic on the bridge and the main stress variations arise from chain temperature differences with low cycle numbers. However, as noted by Professor Fleck in his report," *Cast iron is a brittle material, with a low resistance to crack growth under monotonic loading. It is also relatively insensitive to fatigue loading once a crack has initiated: the level of load required to grow a crack by fatigue is close to that required to drive a crack under monotonic loading."*

The finite element model presented above suggests that a peak total load in excess of 2MN can be achieved. The accompanying displacement at this peak total load is about 4mm and, consequently, the applied shear will dissipate due to this displacement.

From the above it is reasoned that the progression of cracks is highly unlikely to proceed beyond the outstand of the cruciform or tee section.

Even if somehow a series of horizontal cracks in the same plane managed to cleave the pedestal into two pieces it is hard to visualise anything beyond a small longitudinal slip to balance up the chain forces on either side. The length of anchor chain is firmly attached to the anchorage and restrains movement; there is no component of force to try to displace the saddle laterally.

6.4.2 Holding down bolt failure

Each pedestal is held down by 12 Lewis bolts 1½ inches in diameter with an embedment of 8 inches into the upper layer of stone blocks. These would be adequate with functioning roller bearings, but are now subject to the longitudinal shear forces, which are shared between the bolts and friction of the pedestal on the stone blocks. The finite element analysis also suggests an overturning effect which places the anchorage-end bolts into tension.

These bolts may be working quite hard, but if they were to fail under a shear load then it is likely that the pedestal would only slip slightly before equilibrium is regained.

6.4.3 Crushing or shear failure

Under dead load the uniform compressive stress is low at about 15N/mm^2 compared to a maximum permissible stress of 154N/mm^2. Although it is modified by the Vierendeel bending action, it is considered that the crushing failure mode is highly unlikely.

A further potential failure mode could be a diagonal crack between the openings in the web across the full length of the pedestal. This would be analogous to a diagonal shear crack in concrete. This is considered unlikely due to the low shear stresses.

6.5 Effect of pedestal failure on remainder of bridge

If a pedestal were to somehow fail, there would be major ramifications for the bridge. The actual consequences are complex (and of course depend on what happens to the pedestal), but it is possible to apply broad risk ratings to parts of the bridge as shown in Figure 6.10 and Table 6.1 below.

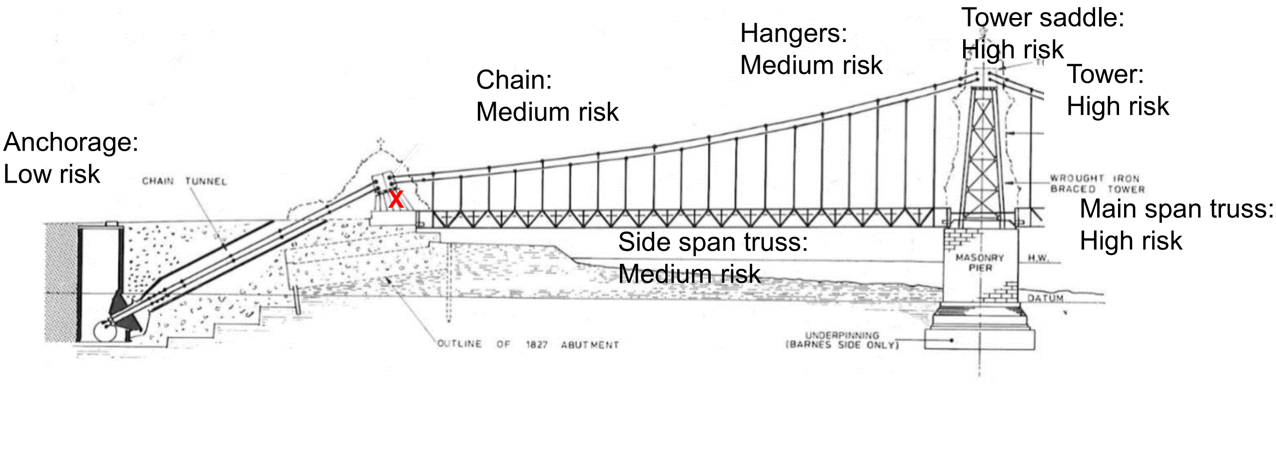


Figure 6.10 – Illustration showing relative risk rating for bridge elements if pedestal fails

Item	Risk rating	Comments
Anchorage	Low	Unlikely to be affected
Chain	Medium	Has good ductility and redundancy (2 chains)
Hangers	Medium	Likely to sustain damage if placed in compression but has redundancy
Side span truss	Medium	May span without hangers under dead load
Tower saddle	High	Vulnerable to excessive longitudinal movements
Tower	High	Displaced saddle could overload tower legs
Main span truss	High	Unable to span without hangers under dead load

Table 6.1: List of relative risk rating for bridge elements if pedestal fails

The tower saddles are a particular concern as they have limited longitudinal movement capacity. The original rollers were removed and replaced by elastomeric bearings in the 1980s and 1990s, as shown in Figure 6.11 below (picture taken after installation of elastomeric bearings when casing had been removed). With the increased eccentricity of application of load arising from the displaced bearings, there will tend to be an increased moment acting on the towers framed legs, leading to potential overstress.

Figure 6.11: Tower top saddle showing replacement elastomeric bearings (Source: AECOM)

As described above, the failure mode of the pedestal is complex and the analysis is highly dependent on the assumed boundary conditions. The potential failure modes are summarised below:

In Section 6.4.1 above, we discuss the potential failure mode of the pedestal through propagation of cracks in the 21 individual cruciform sections of the pedestal. However, the compression stresses are low in comparison with the permissible stresses stated in BD21.

In Section 6.4.2 above, we highlight the manner by which the pedestal could potentially fail through failure of the holding down bolts and consequently slip. However, any movement will tend to dissipate the restraining force.

In Section 6.4.3 above, we highlight that failure by pure crushing or shearing of the pedestal is unlikely. But for the purposes of illustrating possible failure modes for the bridge, we have considered the failure mode arising from crushing of the pedestal. Although it is not seen as a logical failure mode, a simple 2-D analysis has been carried out to assess the effect of a pedestal and chain saddle dropping. As the bridge deck has a low torsional stiffness there is little load redistribution from one chain plane to the other. Two aspects have been noted – the longitudinal displacement of the tower saddle and the drop of the deck at mid main span as shown in Figure 6.12 below.

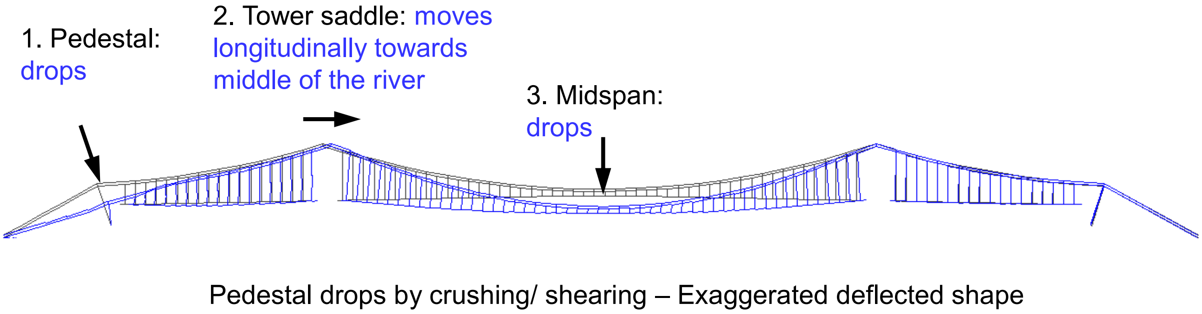


Figure 6.12: Illustration showing potential displacement of bridge if pedestal fails by crushing/ shearing

7. Review of Professor Fleck's Report

AECOM has reviewed the report by Professor Fleck and is in general agreement.

AECOM has carried out an approximate analysis of the NE pedestal which is different to Professor Fleck's high level approach. However, both approaches yielded similar observations that there is a potential for uplift of the pedestal. It must be pointed out that this analysis is highly sensitive to the boundary conditions used and small changes to these conditions may result in changes to the detail but not to the overall conclusion.

Professor Fleck made the following observations, with which we concur.

- *It is recognised that the stress state within the pedestal is sensitive to the precise choice of boundary conditions on the bottom face of the pedestal. The difference in chain force either side of the deviation saddle (due to temperature changes associated with summer peak temperatures) gives rise to a resultant force with a line of action that runs close to the toe of the pedestal – see Fig. 1. A small rotation of the pedestal about the toe will alleviate the force imbalance in the chains: this is beneficial as it leads to a reduced level of stress concentration in the pedestal. Likewise, any small displacement of the pedestal towards the river will relax the chain force imbalance.*
- *It is difficult to envisage that a large shear restraining force from the foundation onto the tip of the pedestal can develop (not least as the pedestal is close to the embankment wall of the river – see Fig. 2). If a large shear force were to develop at the toe of the pedestal, then there is no clear reason why tension will develop in the vicinity of crack NE10. An alternative scenario is that a small degree of rotation and/or slip of the pedestal takes up any gaps between the foundation anchor bolts and the pedestal, and the shear force from these anchor bolts leads to tension in the vicinity of crack NE10. This explanation is sketched in Fig.* 1.

We agree in principle with the calculation for the out of balance chain force. We generally agree with the recommendations. See Section 11 for our recommendations.

8. Log of Further Queries raised during review of documents

The following queries were raised by AECOM during the course of our study and have not yet been answered.

Ref	Information Requested	Date	Date	Status
A1	It has come to AECOM's attention that the inspections on site stopped completely in April and prior to that they were weekly. There is no indication that there have been any inspections, apart from any triggered by AE alarms since. Please confirm how often are the pedestals inspected. How often has an Acoustic Emission activity brought about a site visit? If it is true that the inspections are happening less frequently this is surprising as the CCSO requires more frequent inspections.	29/10/20		
A2	Please confirm if there has been a change in the length or depth of the NE10 crack since August 2020	29/10/20		
A3	As raised in previous discussions, it would be very useful to determine the depth of NE10 crack – possibly by using a pencil grinder or similar.	29/10/20		
A4	The process in the flow chart from the Hammersmith Bridge Interim Measures Management and Communication Plan 383488-MMD-HSB-REP-RA-000003 Rev 6 6th August 2020 (slide presented by Motts on 10 Sept) has not been followed. This stated that if the defect could be safely monitored, the bridge could potentially be re-opened. Clarification is required.	29/10/20		
A5	Most or all of the check items in section 6.12 of CCSO Report have been actioned. The CCSO should be revised as several of the key items have progressed since the report was written.	29/10/20		
A6	In MM report 383488-MMD-HSB-REP-SE-RA-000008, section 4.2.1, reference is made to 2-D model. Please confirm the ground movements obtained from the model.	29/10/20		
A7	In MM report383488-MMD-HSB-REP-SE-RA-000008, Table 6.3 gives the summary of utilisation factors before and after tunnelling. What is the UF using the actual recorded ground movements? The response covers the case for restrained force towards the anchorage. What does the UF increase to for restraining force towards the main span? It would be useful to carry out a similar refined analysis for the SE, NE and NW pedestals – is this due to be carried out?	29/10/20		
A8	What is the programme for blast-cleaning the remaining pedestals?	29/10/20		
A9	In MM report 383488-MMD-HSB-REP-SE-RA-000008, section 4.2.3.2, it is taken that the rollers seized in the summer at an average temperature of 20 degrees. This seems to be based on a broad set of assumptions. Has a sensitivity analysis been carried out to check these assumptions? This seems a high temperature	29/10/20		

	to consider if considering temperature range up to the maximum temperature.			
A10	In the CCSO for Limited River Traffic Movements Draft 4 (Oct 2020), Appendix 1 Timeline and Risk Profile – why is there no reduction in the risk in March/ April after the more refined analysis of the pedestal had reduced the UF for the SW pedestal to 1.24.	02/11/20		
A11	In the CCSO for Limited River Traffic Movements Draft 4 (Oct 2020), Appendix 1 Timeline and Risk Profile, there is a combined change in risk from the installation of additional AE sensors (in dotted line) but mitigated by the reduction in frequency of inspections. What is the overall net change in risk?	02/11/20		
A12	In the CCSO for Limited River Traffic Movements Draft 4 (Oct 2020), Appendix 1 Timeline and Risk Profile – there is a reference to carbon fibre plate bonding study – is this available for review?	02/11/20		

9. Summary of Main Risks and Opportunities

Main Risks
West pedestals have not been blast cleaned and no MPI – risk of discovering further significant cracks, although it could be argued that cracks hidden by paint are likely to be historical cracks
Cast Iron is weak in tension and is brittle – failure will be difficult to predict and will be sudden rather than yielding giving rise to visible deterioration. Residual stresses will have been created during casting of the pedestal, and these stresses are difficult to calculate
All assessments of the pedestals by MM to date have not included the presence of any cracks – risk that the pedestals are weaker than currently thought
CCSO has not followed normal practice for management of sub-standard bridges – risk that something has been missed

Main Opportunities
CCSO may be overly conservative. For example, when seven further cracks were discovered in NE pedestal in April 2020 following blast cleaning it was considered that this was not enough to close the bridge. Whereas the extension of one crack was used to close the bridge and being used to keep the bridge closed.
NE10 crack appears to have propagated into the base plate and it is not possible to propagate any further. Furthermore, it is recommended that further investigations are carried out to determine if the crack is just on the surface or through thickness. Therefore this crack may not be as serious as previously thought.
In the CCSO, it is stated that the loads in the chain links are unknown. However It is possible to make a reasonably accurate assessment of the loads in the chain links as they are a function of the chain geometry and permanent loads which are quantifiable, as well as making a judgement of the likely temp when the roller bearings seized and modelling the elastic behaviour of the pedestals and foundations.
The failure load and mode for the pedestal should be given more consideration, based on alternative forms of analysis. A better understanding of the failure load and mechanism may potentially over-ride more conventional and conservative stress analysis. Even though there may be peak stresses which are theoretically over-utilised, a large part of the pedestal is not overstressed and load re-distribution can take place. The highest stresses in the pedestal lie along the planes through the openings where it separates into 21 cruciform/tee sections – these provide redundancy.

10. Conclusions

Over recent years, a wealth of information on Hammersmith Bridge has been produced by many Consultants including Mott MacDonald, Pell Frischmann, Atkins, Arup and Xanta. In this report by AECOM, we have reviewed the numerous documents produced and we acknowledge that a huge amount of complex, competent technical work has been undertaken by others. AECOM has not carried out any detailed check calculations but have relied on our experience to scrutinise the results to identify anything unexpected or for gaps or steps not undertaken.

AECOM acknowledges that the planning for the strengthening and stabilisation of the bridge must continue as a priority, whilst other investigations, studies and discussions are being undertaken.

Hammersmith Bridge was closed to vehicular traffic in April 2019 due to the discovery of cracks in the SE, NE and NW pedestals, after an early assessment by MM had indicated very high utilisation factors for the cast iron pedestals. Following an Acoustic Emission event in August 2020, one of the cracks in the NE pedestal had been found to have grown from about 160mm to 240mm. As a result the bridge was closed to pedestrians and cyclists crossing over the bridge and walking under the bridge, whilst river traffic was prevented from passing underneath. Following this event, the reasons for keeping the bridge closed have been scrutinised by a task force including AECOM.

It should be noted that a paper presented in 1990 (Hammersmith Bridge: 160 years of Road Traffic) indicated that the pedestal rollers were known then to be seized, although there is no indication as to how long this had been the case. This clearly suggests that the bridge has operated with seized pedestal roller bearings for at least 30 years.

Cast Iron

The pedestals are made of cast iron which is weak in tension and is brittle. In principle, failure will be difficult to predict and will potentially be sudden rather than yielding giving rise to visible deterioration. MM has carried out hardness tests on the pedestals and have proved that it is of a similar, if not higher quality of material used in another bridge, where physical samples were taken.

The manufacturing process for large cast iron elements results in residual stresses locked into the casting. AECOM agrees that the magnitude of these stresses is difficult to calculate, and due to the brittle nature of the material, may have resulted in some cracks caused during the cooling process. It appears from the MM reports that the SE pedestal is of higher quality and no cracks have been found.

Cast iron performs well in compression but poorly in tension and can be prone to brittle cracking. Potential initiation sites will be those with high tensile stresses but will also be influenced by stress-raising factors like poor surface condition. If the local applied tensile stress is sufficiently high, then a crack could initiate at the outer fibre and then propagate. The highest stresses are found adjacent to the openings where the pedestal divides into the 21 cruciform/tee sections. Here, as a crack grows, the tensile stress reduces thus slowing the ability to grow further. As it reaches the base of the outstand the crack front would need to transform from the narrow outstand into a broad front in order to grow further, which requires significant energy and stress levels. Therefore, it can be seen why none of the observed cracks have propagated beyond the outstand, with the exception of NE10. In this case it is strongly believed that, having turned the corner, the crack is very shallow as evidenced where it appears at the plate edge.

Crack NE10

The bridge was completely closed in August 2020 due to the fact that one single crack, NE10, had increased in length from about 160mm to 240mm. This crack has not propagated any further since this event. An acoustic emission alarm was triggered during a spell of hot weather and it was concluded at the time that this crack was caused by the hot weather. Whilst this seems logical, AECOM have picked up on the fact that the location of the event that triggered the alarm was in the lower front (facing river) corner on the east web. Note that crack NE10, whose growth has been associated with this acoustic event, is actually located on the central web and not the east web. Therefore the growth of crack NE10 between April and August 2020 may not necessarily be connected with the high temperatures seen in August 2020 and this needs to be investigated further. On inspection, it could be seen that crack NE10 had grown on the east leg and had reached the edge of the opening in the base plate. There was no propagation on the west leg and it is strongly suggested that the crack is in fact shallow from the hole edge to the fillet. As the growth of this crack resulted in the complete bridge closure, it seems crucial to understand its depth and hence risk it presents. Clearly a shallow crack presents much less risk than a full depth crack.

The crack depth could easily be determined at several locations by either taking core samples or carefully using a pencil grinder, which is a recommended course of action. If this crack were full depth then we would have expected evidence of propagation on the other side of the web.

Blast Cleaning and Inspection of the West Pedestals

The NE and SE pedestals have already been blast cleaned and inspected. This led to the discovery of further cracks on the NE but none on the SE pedestal. The NW and SW are planned to be blast cleaned and inspected and this work must start soon. AECOM recommends that a plan is prepared in advance on how to deal with the various scenarios arising from the inspection.

Utilisation Factors

Mott MacDonald (MM) published an initial assessment report in January 2019 and reported on a theoretical overstress in the pedestals. The utilisation factor for the pedestals, as calculated by MM, has reduced significantly with each successive refinement of the analysis. In January 2020, MM carried out further analysis, specifically of the SW pedestal in advance of the Thames Tideway Tunnel (TTT) construction. In this report, MM further refined the analysis by correlating monitoring results with theoretical modelling results. The refinement was also achieved by making assumptions about the temperature at which the roller bearings seized and about the temperature range. Following the passage of the TTT through the area, it was shown that the actual ground movements were significantly less than the predicted values and as a result the ground movements mostly affecting the SW and SE pedestals will have minimal impact on the utilisation factor (UF). AECOM notes that MM followed the procedures for Highways England standard BD79: Management of Sub-standard Highway Structures when the original assessment results were published and the subsequent inspection for cracking in the pedestals.

The current theoretical UF still remains above the code requirement of 1.0 and will increase if pedestrians are permitted. The analysis carried out by MM is for an uncracked pedestal and the UF will increase when cracks are taken into account in the model. However, AECOM has queried some of the assumptions made by MM in obtaining the most recent UFs. MM has assumed, for the SW pedestal, that the roller bearings seized at a temperature of 20°C, whereas it is more likely to be a lower temperature closer to the average temperatures experienced at the bridge. In addition, the maximum temperature for the chain has been taken as 47°C which is the maximum effective bridge temperature under UK bridge assessment codes. The section of chain between the pedestal and the anchorage is mostly underground and the maximum temperature of the chain will be significantly less than 47°C and hence it is conservative. Monitoring results from the hottest days in August indicate that the temperature of the chain showed a small variation between 18 and 21°C. AECOM appreciates that the temperature of the chain used for modelling temperature loads will be based on several readings along the length of the chain, but we recommend that this assumption about the maximum temperature is reviewed by MM.

In summary, the utilisation factors for all four pedestals need to be updated to take into account the dissipation of the shear force arising from displacement of the pedestal, any cracks present and the comments raised on the temperature range adopted.

Mitigation Measures

As MM had identified that temperature has a significant effect on the utilisation of the pedestals, temperature control of the pedestals and adjacent chain section has been under consideration for since March 2020. It is understood that temperature control will be completed by end November 2020, by which the effects of extreme cold and hot weather on the utilisation factor will be mitigated. It is also pointed out that the utilisation factors which have been calculated by MM are based on the maximum and minimum temperatures such that, in more ambient temperatures, the utilisation factor reduces.

In addition, monitoring instruments including strain gauges as well as acoustic emission monitoring equipment have been installed on the bridge. This is monitored on a continual basis. It has been noted that the weekly visual inspections which were stopped in March 2020 were not restarted in August 2020 following the AE event. It is strongly recommended that the frequency of visual inspections is increased as also recommended by the CCSO.

CCSO

The CCSO after Closure to Motorised Traffic has provided a vital role in addressing and focussing the various issues relating to the status of the bridge. It was originally used to justify the continued opening of the bridge after cracks were first found in the pedestals. Since August 2020, it has been used to justify the closure of the bridge. However, it is now out of date and needs to be modified to incorporate all the new information which has come to light since March 2020. The CCSO refers to BD79; Management of Highway Structures but it does not follow it. There is a risk that the document may be too conservative and it is recommended that it is reviewed and revised. It is noted that the majority of the requirements set out in the CCSO section 6.12 relating to mitigation measures have been completed.

A further CCSO has recently been received in October 2020 relating to the limited use of river traffic. This is a positive step and does include updated information. However, it cannot replace the original CCSO.

Potential Failure Modes of the Pedestal

In order to gain a better understanding of the utilisation factors obtained by MM, AECOM produced a simplified 3D FE model of the NE pedestal, first with no cracks and then cracks were introduced for comparison. The model showed that the theoretical peak shear force applied at the top of the pedestal exceeded the value of approximately 2.0 MN calculated by MM. However, the accompanying displacement at this peak total load is about 4mm and, consequently, the applied shear will dissipate due to this displacement and is unlikely, therefore, to reach this value.

Our modelling shows the complexity of the behaviour of an isolated pedestal and suggests there is to some degree a reserve of strength. However, it does not include how the pedestal interacts with the remainder of the bridge and the supporting ground. Both of these will contribute in different ways. The anchorage chains are tied into the anchorages which cannot move, and with seized rollers the pedestals are being effectively restrained. The supporting ground is not rigid and will provide for some dissipation of the shear forces through small movements.

Holding down bolt failure

Each pedestal is held down by 12 bolts into the upper layer of stone blocks. These would be adequate with functioning roller bearings, but are now subject to the longitudinal shear forces, which are shared between the bolts and friction of the pedestal on the stone blocks. The finite element analysis also suggests an overturning effect which places the anchorage-end bolts into tension.

These bolts may be working quite hard, but if they were to fail under a shear load then it is thought likely that the pedestal would only slip slightly before equilibrium is regained. The result will be that the chain loads each side of the pedestal will tend to balance, reducing the shear force.

Crushing or shear failure

Under dead load the uniform compressive stress is low at about 15N/mm^2 compared to a maximum permissible stress of 154N/mm^2. Although it is modified by the Vierendeel bending action, it is considered that the crushing failure mode is highly unlikely.

A further potential failure mode could be a diagonal crack between the openings in the web across the full length of the pedestal. This would be analogous to a diagonal shear crack in concrete. This is considered unlikely due to the low shear stresses.

Effect of pedestal failure on remainder of bridge

If a pedestal were to somehow fail, there would be major ramifications for the bridge. The actual consequences are complex (and of course depend on what happens to the pedestal), but it is possible to apply broad risk ratings to parts of the bridge

Item	Risk rating	Comments
Anchorage	Low	Unlikely to be affected
Chain	Medium	Has good ductility and redundancy (2 chains)
Hangers	Medium	Likely to sustain damage if placed in compression but has redundancy
Side span truss	Medium	May span without hangers under dead load
Tower saddle	High	Vulnerable to excessive longitudinal movements
Tower	High	Displaced saddle could overload tower legs
Main span truss	High	Unable to span without hangers under dead load

11. Recommendations

The following recommendations need to be read in conjunction with the recommendations made by Professor Fleck.

1. Complete the removal of the ornamental casing and carry out blast-cleaning and inspection of the NW and SW Pedestals – this is imperative as it will quantify the unknown risks associated with these pedestals. When the North East pedestal was blast cleaned and inspected, further cracks were discovered including NE10. A view was taken at the time of discovery that these additional cracks were historical as they were not visible through the paint. This work must be carried out with due attention to Health and Safety matters.
2. Prepare a strategy for responding to the inspection results of the NW and SW pedestals in advance of blast cleaning – a strategy is needed such that a quick reaction can be initiated. For example, it is possible that further cracks will be detected, and a review must be made to determine if these are historical cracks or develop an action plan if there is a large number of cracks, or if any of the cracks are long or wide. Or, it may be possible that no further cracks are detected.
3. Ensure that temperature control is operational on all 4 pedestals – it is imperative that this action is implemented as soon as possible. AECOM understands that it was the aim to complete installation by the end of November 2020 before the colder winter months set in.
4. Increase frequency of visual inspections – weekly visual inspections were stopped in April 2020, due to Covid restrictions. However, inspections were not increased in frequency after the discovery of the propagated crack NE10 in August 2020. It is recommended that weekly visual inspections are reinstated to augment the strain gauging, acoustic emission monitoring and temperature monitoring already installed on the bridge. Monitoring cannot be solely relied on and it must be backed up by regular visual inspections.
5. Determine depth of crack at NE10 – AECOM recommends that the depth of crack NE10 is established by using, for example, a pencil grinder. This will help to determine if the crack has gone through the full depth or if it is just a surface crack. This action will also be helpful to establish if the crack has terminated as it moves from the web outstand to the base plate.
6. MM to complete the analysis of cracked pedestals – AECOM understands that MM are currently modelling the effects of the cracks on North East pedestal. This will be useful to determine to what extent the failure load of the pedestal has been reduced. When the extent of the cracks in the west pedestals has been determined following blast cleaning, the other pedestals should also be analysed with the cracks incorporated in the model, if they are more widely cracked than the NE pedestal. (To be read in conjunction with recommendation 8 below).
7. MM to review the assumptions for the SW pedestal UF calculations. The temperature at which it has been assumed that the roller bearings seized as 20°C appears to be high. This assumption needs to be reviewed by MM. In addition, the maximum temperature of 47°C appears to be very high as approximately two-thirds of the anchorage chain is underground and the temperature range will be much reduced. We recommend that both these sets of assumptions are reviewed by MM and checked by Atkins.
8. MM have carried out a refined analysis of the SW pedestal and AECOM recommends that a similar analysis is carried out for the other three pedestals. We noted that the accompanying displacement at the peak total load is about 4mm and, consequently, the applied shear will dissipate due to this displacement and is unlikely, therefore, to reach this value. We recommend that MM review these issues for all four pedestals, if sufficient differences exist.

9. Carry out independent Category 3 check of all critical issues including all four cracked pedestals – AECOM understands that the refined analysis of the SW pedestal has been checked internally within MM, but not independently. This should be completed by Atkins.
10. Strain gauging of pedestals (as recommended by Professor Fleck) – this will be important to gain confidence and correlation with the results from the MM model and the independent checker.
11. PF to continue design of jacking frame and strengthening design of pedestals – AECOM understands that the jacking frame is currently being designed to incorporate provision for dealing with a sudden release of energy resulting from any longitudinal movement of the saddle when the roller bearings are released. AECOM has raised a few high-level observations on the design of the pedestal strengthening which need to be addressed, and these should be agreed by the checker.
12. The CCSO after Closure to Motorised Traffic was last revised in March 2020. Since then the Thames Tideway Tunnel has passed under the bridge, the NE and SE pedestals have been blast cleaned and inspected and much analysis and investigation work has been undertaken. As this CCSO is a pivotal document, it should be updated.
13. Prepare a CCSO to permit limited (or greater) access for pedestrians – this issue needs to be studied in more depth, but it should be pointed out that a significant amount of additional information has been gathered and knowledge has been extended since the CCSO after Closure to Motorised Traffic was written. More refined analysis has been carried out on the SW pedestal which shows that the utilisation factor is significantly lower than previously understood, albeit it is still above the code acceptable limits. Mitigation in the form of temperature control of the anchor chains (on the basis that it is fully operational) and monitoring are in place together with the recommendation for more frequent visual inspections. This needs to be developed with input from all interested parties.
14. AECOM understand that ground investigation has been carried out on or near the site on behalf of Pell Frischmann and we recommend that MM review their assumptions against this GI and amend their models if necessary.
15. We note that crack NE10, whose growth has been associated with an acoustic event on the east web, is actually located on the central web of the NE pedestal. Therefore, the growth of crack NE10 between April and August 2020 may not necessarily be connected with the high temperatures seen in August 2020. AECOM recommends that this is investigated further.
16. AECOM has provided high level considerations of how gross failure may occur. These considerations have been developed through our experience and through carrying out limited simplified analysis. AECOM recommends that MM and Atkins study how gross failure will occur. It is further recommended that this work is fed back into the CCSO.

Appendix A – Drawings and Documents Received

Title	Doc Ref	Originator	Date rec'd	Reviewed?
BRIEFING NOTE: HAMMERSMITH BRIDGE - Summary of Engineers' Reports and Early Conclusions	V1.0dc	DfT	09/09/20	Background only
Crack NE10 Propagation			09/09/20	Background only
Hammersmith Bridge Emergency Meeting 13 August 2020 - Minutes		LBHF	09/09/20	Background only
Case for Continued Safe Operation – Hammersmith Bridge SUMMARY		Xanta	09/09/20	Background only
Hammersmith Bridge - Case for Continued Safe Operation After Closure to Motorised Traffic	Issue 5	Xanta	10/09/20	✓
Hammersmith Bridge - Cast Iron Pedestals - Post-blast inspection report NE & SE (06-Apr-20 to 09-Apr-20) 20 April 2020	417457-MMD-HSB-REP-PBI-000001-01	MM	10/09/20 & 23/09/20	✓
Hammersmith Bridge – Assessment CI Pedestals - Investigation into Restricting Vehicular Traffic 16 April 2019	383488-MMD-HSB-SE-RA-000004	MM	10/09/20 & 23/09/20	✓
Hammersmith Historic Drawings (from Pell Frischmann AIP)		PF	10/09/20	Background only
Hammersmith Bridge Historic Drawings – Anchor Details (from Pell Frischmann AIP)		PF	11/09/20	Background only
Hammersmith Temporary Pedestrian and Cycle Bridge AIP July 2020	0013-01-002 N001	Costain	14/09/20	×
Hammersmith Bridge Refurbishment Approval in Principle for Advanced Works July 2020	102963-PEF-BAS-ZZZ-AIP-S-00002	PF	14/09/20	×
TfL comments on Beckett Rankin proposal for a Temporary Traffic Bridge March 2020		TfL	14/09/20	×
Hammersmith Bridge - Strengthening and Refurbishment Feasibility Study 10 May 2019	383488-MMD-HSB-REP-SE-FSR-00001	MM	14/09/20	×
Hammersmith Bridge Report Summaries		DfT	14/09/20	N/A
Hammersmith Bridge - DfT Meeting 10th September 2020 (Powerpoint slides)		MM	14/09/20	Background only
Hammersmith Bridge AE Monitoring System Performance Review August 2020	FT9833 - 3	Mistras	14/09/20	✓
Hammersmith Bridge – Request for Information Log		NR	14/09/20	N/A
Hammersmith Bridge - Refurbishment Assessment Report 25 January 2019	383488-MMD-HSB-REP-SE-ASR-000001	MM	23/09/20	✓
Hammersmith Bridge - Refurbishment Inspections and Investigations: Interpretive Report 02 November 2018	383488-MMD-HSB-REP-SE-ITR-000001	MM	23/09/20	×
Hammersmith Bridge Refurbishment - Revised CI Pedestal Analysis for Ground Movements Induced by Thames Tideway Tunnel 29 January 2020	383488-MMD-HSB-REP-SE-RA-000008	MM	23/09/20	✓

Global Analysis Methodology, September 2018	383488-MMD-HSB-TN-AN-00001	MM	23/09/20	×
Calculations for Seized Splay Saddle, 01/08/18	383488-MMD-HSB-SC-CAL - Splay Saddle Pedestal	MM	23/09/20	✓
BD79 - Cast Iron Pedestals - Weekly Report 23-29/10/19	383488-MMD-HSB-MON-WR-00001	MM	23/09/20	✓
BD79 - Cast Iron Pedestals - Weekly Report 30/10-05/11/19	383488-MMD-HSB-MON-WR-00002	MM	23/09/20	✓
BD79 - Cast Iron Pedestals - Weekly Report 06-12/11/19	383488-MMD-HSB-MON-WR-00003	MM	23/09/20	✓
BD79 - Cast Iron Pedestals - Weekly Report 13-19/11/19	383488-MMD-HSB-MON-WR-00004	MM	23/09/20	✓
BD79 - Cast Iron Pedestals - Weekly Report 20-26/11/19	383488-MMD-HSB-MON-WR-00005	MM	23/09/20	✓
BD79 - Cast Iron Pedestals - Weekly Report 27/11-03/12/19	383488-MMD-HSB-MON-WR-00006	MM	23/09/20	✓
BD79 - Cast Iron Pedestals - Weekly Report 04-10/12/19	383488-MMD-HSB-MON-WR-00007	MM	23/09/20	✓
BD79 - Cast Iron Pedestals - Weekly Report 11-17/12/19	383488-MMD-HSB-MON-WR-00008	MM	23/09/20	✓
BD79 - Cast Iron Pedestals - Weekly Report 18-24/12/19	383488-MMD-HSB-MON-WR-00009	MM	23/09/20	✓
BD79 - Cast Iron Pedestals - Weekly Report 25/12/19-07/01/20	383488-MMD-HSB-MON-WR-00010	MM	23/09/20	✓
BD79 - Cast Iron Pedestals - Weekly Report 08-14/01/20	383488-MMD-HSB-MON-WR-00011	MM	23/09/20	✓
BD79 - Cast Iron Pedestals - Weekly Report 15-21/01/20	383488-MMD-HSB-MON-WR-00012	MM	23/09/20	✓
BD79 - Cast Iron Pedestals - Weekly Report 22-28/01/20	383488-MMD-HSB-MON-WR-00013	MM	23/09/20	✓
BD79 - Cast Iron Pedestals - Weekly Report 29/01-04/02/20	383488-MMD-HSB-MON-WR-00014	MM	23/09/20	✓
BD79 - Cast Iron Pedestals - Weekly Report 05-11/02/20	383488-MMD-HSB-MON-WR-00015	MM	23/09/20	✓
BD79 - Cast Iron Pedestals - Weekly Report 12-19/02/20	383488-MMD-HSB-MON-WR-00016	MM	23/09/20	✓
BD79 - Cast Iron Pedestals - Weekly Report 20-25/02/20	383488-MMD-HSB-MON-WR-00017	MM	23/09/20	✓
BD79 - Cast Iron Pedestals - Weekly Report 26/02-03/03/20	383488-MMD-HSB-MON-WR-00018	MM	23/09/20	✓
BD79 - Cast Iron Pedestals - Weekly Report 04-10/03/20	383488-MMD-HSB-MON-WR-00019	MM	23/09/20	✓
BD79 - Cast Iron Pedestals - Weekly Report 11-17/03/20	383488-MMD-HSB-MON-WR-00020	MM	23/09/20	✓
BD79 - Cast Iron Pedestals - Weekly Report 18-24/03/20	383488-MMD-HSB-MON-WR-00021	MM	23/09/20	✓
BD79 - Cast Iron Pedestals - Weekly Report 25/03-03/04/20	383488-MMD-HSB-MON-WR-00022	MM	23/09/20	✓
Cat 3 Check Comment Log (MM & Atkins)	383488-CAT-AR-RE-0004-MM Rev C	MM	15/10/20	✓
Interim Release of Seized Saddle Rollers	383488-MMD-HSB-TN-SE-00016	MM	15/10/20	✓

Impact from Thames Tideway Tunnelling	417539-MMD-HSB-REP-SE-TTT-000001	MM	15/10/20	✓
NE Saddle Alarm Report 12-08-20	FT10060-8-A1	Mistras	15/10/20	Not relevant
NE Saddle Alarm Report 07-08-20	FT10060-6-A1	Mistras	19/10/20	✓

Appendix B – Detailed Comments on Reports reviewed by AECOM

This appendix contains the detailed comments on reports raised by AECOM during the course of the study. Where responses have been received from the original document author, these have been included. Some of the comments (marked by asterisk) were observational comments and were not issued to the document authors.

B1 Detailed Comments on Case for Continued Safe Operation After Closure to Motorised Traffic (CCSO Report)

AECOM DETAIL COMMENTARY:

Ref	Clause No.	Comment	Response Received	Response Received
1	2.3	What test loading has taken place (2.3)	An instrumented load test was undertaken as part of the global model calibration process prior to undertaking the structural assessment. Refer to Appendix L within the interpretive report 383488-MMD-HSB-REP-SE-ITR-000001 (already provided).	Closed
2	3.2 1st bullet	"The bridge is sensibly at the end of its life in terms of estimated fatigue damage." Is this really true for the whole structure? Might be true for some hangers where end bending is taking place but wonder if this is right for 1960s trusses and tower structures. If this statement was true it would not be worth repairing the bridge.		Comment only – not issued to wider team
3	3.4	"the pedestals remain theoretically overstressed". It must be pointed out that the pedestals are only overstressed in some local areas, the majority is not overstressed. Depending on the results of the cracked pedestals, it should be verified if the pedestal can remain functioning if cracked portions are discounted in the load assessment		Comment only – not issued to wider team
4	3.5	"where utilisation factors are quoted which are significantly in excess of unity; this is, in theory, not possible." Note that utilisation factors are based on permissible stresses and not ultimate stresses. BD21 suggests max tensile stresses of 54 N/mm2, but UTS likely to be at least 6 tons/sq.in. (93 N/mm2). [BCSA Historical Structural Steelwork Handbook]. The use of higher UTS could lead to reduction in utilisation, but it is noted that MM looked into using a		Comment only – not issued to wider team

		principal stress approach to the assessment.		
5	3.7	"A trigger level has been set by the provider of the acoustic monitoring equipment which is notional and based on two energy levels: 500dB and 1,000dB". Two points – use of <u>notional</u> trigger level is concerning (are we missing or over-recording?), and energy levels seem huge.		Comment only – not issued to wider team
6	3.9	"To date, there has been no visible evidence of any propagation of the known cracks on the SW and NW pedestals." Very important statement.		Comment only – not issued to wider team
7	3.9	"The NE pedestal has newly discovered evidence of damage that is expected to be stable." Another important statement. Has this statement been checked since August 2020?		Comment only – not issued to wider team
8	3.11	"The second monitoring regime is still being commissioned and consists of load monitoring in the suspension chains on either side of the deviation saddles. … and may effectively form a true alarm function…" It is difficult to believe that it could form a true alarm function but it can form a first approach		Comment only – not issued to wider team
9	4.4	"The planned load monitoring in the chain elements is not yet reliably operational and so no benefit may be taken from its existence." – Is it now operational and what results are we getting?		Comment only – not issued to wider team
10	6.5	*"...as no change to the stable condition of the principal bridge components was seen in that time, resumption of more frequent inspection will allow risk to be reduced further from that which currently applies and which has been found to be acceptable…."* Are we not carrying out more frequent inspections? More frequent inspections should reduce the risks.	.	Comment only – not issued to wider team
11	6.12	*"Material Testing has now been completed"* The testing indicated a potentially higher tensile capacity, but this was not adopted. Has this approach been checked by Cat 3 Checker, or has only the most conservative result been checked?		Response received elsewhere – Cat 3 check does not include the latest April 20 report on TT

12	6.13	*"This redundancy provides some relief from the effects of cracking in any one load path. The benefit remains unquantifiable in the absence of knowledge of the absolute levels of loading."* Do we not have a reasonable understanding of the cable load through combination of theoretical analysis and strain gauging? However, we do not know how much of the load is being transferred through friction and possibly small movements of the roller bearings, or by some rotation of the pedestal (since it does not sit on an infinitely stiff foundation). But it is possible to model the pedestal (as done by Motts) and also incorporate the existing cracking.		Comment only – not issued to wider team
13	6.18	*Differential Settlement due to Thames Tideway* - what was the actual measure outcome of the actual tunnel passing under the bridge? Further studies have been carried out by Motts – should the CCSO be updated? In reality, it increased the utilisation under permanent loads plus temperature from 1.10 to 1.24	The impact from Thames Tideway tunnelling activity is documented within report 417593-MMD-HSB-REP-SE-TTT- 000001 which was issued to LBHF on 11-May-20. A copy of this report has been emailed to LBHF today for ease of reference.	Closed – but it is recommended that the CCSO is updated.

Table B1: AECOM detail comments on Xanta CCSO report

B2 Detailed Comments on Assessment Report (Report 383488-MMD-HSB-SE-ASR-000001 dated 25 January 2019 including Appendix B11)

AECOM DETAIL COMMENTARY

Ref	Comment	Response Received	Further Comment
1	It is unclear if the ground model includes the presence of the previous chain tunnels and the sea wall. The previous chain tunnel and sea wall will tend to provide a soft spot and lead to a decrease in the ground stiffness. With a decreased ground stiffness, this may potentially lead to a reduction in the restraining force at the top of the pedestal	The thickness of the plane stress elements is adjusted at the current chain tunnels to account for the reduction in stiffness. The adjustment of the support stiffness in general is based on calibration with the measured change in the chain force from thermal effects. The analytical modelling methodology, the stiffness parameters and calibration process used within the 2D plane stress model are summarised within report 383488-MMD-HSB-REP-SE-RA-000008.	Closed. This response was provided for a similar earlier comment.

<table>
<tr><td></td><td></td><td>The river wall is not explicitly modelled as it was not deemed to significantly influence the findings.</td><td></td></tr>
<tr><td>2</td><td>AECOM has not undertaken any sophisticated analysis but consider that the UF for the self-weight only under the free roller condition will be low</td><td></td><td>Comment only</td></tr>
<tr><td>3</td><td>We could not find a definition for “UF.tot” and “UF.LL” but we assume that they mean utilisation factor for the Total condition and for Live Load respectively. If this is the case, we would expect the “UF.tot” to be greater than “UF.LL”.

$MAT_{UF.ENV}$ =
<table>
<tr><td>"Scenario"</td><td>"Articulation"</td><td>"UF.tot"</td><td>"UF.LL"</td></tr>
<tr><td>"[-]"</td><td>"[-]"</td><td>"[-]"</td><td>"[-]"</td></tr>
<tr><td>"Sc1"</td><td>"Red_kT_1"</td><td>0.97</td><td>1.74</td></tr>
<tr><td>"Sc1"</td><td>"Free"</td><td>0.29</td><td>0.1</td></tr>
<tr><td>"Sc1"</td><td>"Seized"</td><td>4.43</td><td>9.18</td></tr>
<tr><td>"Sc5a"</td><td>"Red_kT_1"</td><td>2.13</td><td>4.32</td></tr>
<tr><td>"Sc5a"</td><td>"Free"</td><td>0.36</td><td>0.35</td></tr>
<tr><td>"Sc5a"</td><td>"Seized"</td><td>5.52</td><td>11.52</td></tr>
</table></td><td></td><td>Open. Response not received</td></tr>
</table>

Table B2: AECOM detail comments on MM Assessment report

B3 Detailed Comments on Investigation into Restricting Vehicular Traffic Report (Document Ref: 383488-MMD-HSB-SE-RA-000004)

AECOM DETAIL COMMENTARY

Ref	Comment	Response Received	Response Received
1	2D model does not appear to include the previous cable tunnel. This could introduce a soft spot in the ground conditions which potentially allows a small amount of movement which will tend to dissipate the restraining force.	See response 1 to comments on Report 383488-MMD-HSB-SE-ASR-000001	Closed
2	NW pedestal - cracks from force towards main span		Comment only – not issued to wider team
3	SW pedestal - cracks from force opposing main span		Comment only – not issued to wider team
4	Restraining force towards span, no traffic - utilisation 2.55. UF significantly above 1.0 but now superseded by later report		Comment only – not issued to wider team
5	Restraining force towards anchorage, no traffic - utilisation 3.90. UF significantly above 1.0 but now superseded by later report		Comment only – not issued to wider team

6	Direction of restraining force depends on relative position of the saddle on the pedestal? Have the eccentricities of the saddle (as described in Table 1 in the report) in relation to the pedestal been included in the analysis?	This offset was not captured by the analysis within the referenced report although all subsequent analysis (specific to individual pedestals) has captured this eccentricity. Other than stresses local to the top of the pedestals, the eccentricity has been found to make little difference to the outcome of the assessment.	Yes - closed
7	It was mentioned in Section 3 that the ground conditions were varied - how did this affect the UF?	Please clarify as to what variation in ground conditions you are referencing. Please note that no site specific GI has been carried out although this was recommended during stage 2.	Original comment withdrawn as this is not mentioned in Section 3 – but was a sensitivity analysis carried out in which the ground conditions were varied?
8	Page 14 mentions stiffness of CI - how sensitive is this, bearing in mind the difference between compression and tension?	With reference to the 3D shell model, a sensitivity study was performed considering an upper and lower bound modulus for cast iron and this made negligible difference to the results	Yes - closed

Table B3: AECOM detail comments on MM Restricting Vehicular Traffic report

B4 Detailed Comments on Revised CI Pedestal Analysis for Ground Movements Induced by Thames Tideway Tunnel (Document Reference: 383488-MMD-HSB-REP-SE-RA-000008)

AECOM DETAIL COMMENTS

Ref	Comment	Response Received	Further Comment
1	Has the Cat 3 Checker checked the conclusions from this report.	Atkins were the independent Cat 3 checker for the structural assessment and there was agreement that the pedestals are overstressed. As the TTT analysis work was time critical, there was not time available for LBHF to engage a Cat 3 checker so instead, it was agreed to undertake an internal challenge/peer review of this work. It should also be noted that the calibrated model showed a very good agreement with the measured response of the bridge to change in temperature. Therefore, an independent check was less important for this particular study, at least in terms of deriving the pedestal load demand.	Response received – checked internally/ peer reviewed. It is suggested that a Cat 3 check is carried out

2	What do the UFs of 1.1 and 1.24 increase to, if pedestrian loading is included?	This particular assessment work was undertaken specifically for a restrained force towards the anchorage and as such, pedestrian loading has very little influence on the referenced UFs. However, for a restrained force towards the river, pedestrian loading does contribute to the overall pedestal load demand.	Closed
3	Has the SE saddle been calibrated in a similar way to the SW?	In the context of the TTT analysis works, this follow on study was never instructed. However, this work will now be undertaken under a separate instruction, and work will commence on the SE following completion of analysis and assessment at the NE pedestal.	Closed
4	Have further tests using ICHD been carried out?	This work was never instructed.	Closed
5	It is unclear if the ground model includes the presence of the previous chain tunnels and the sea wall.	Refer to response to comment 14	Closed
6	Restraining forces of 1980 and 1988 kN – these forces need to be checked and verified. Has the Cat 3 Checker verified these results?	Refer to response to comment 1 above	Closed

Table B4: AECOM detail comments on MM Thames Tideway report

B5 Detailed Comments on Mott MacDonald's Report "Hammersmith Bridge - Cast Iron Pedestals - Post-blast inspection report NE & SE (06-Apr-20 to 09-Apr-20)", 20 April 2020

AECOM DETAIL COMMENTARY

Ref	**Comment**	Response Received	Further Comment
1	Crack NE10 was found to be about 160mm long when inspected in April 2020. Following the August 2020 heat wave the crack grew to about 240mm long.		Comment only – not issued to wider team
2	Crack NE10 has reached the edge of the casting and so cannot propagate further.		Comment only – not issued to wider team
3	The other two pedestals should be blast cleaned and receive the same inspection. Without this the extent and number of the existing cracks is unknown and presents a high risk.		Comment only – not issued to wider team
4	What overall condition factor has been adopted for the assessment and was it revised after the post blasting inspection?	Since we are explicitly accounting for the observed defects within the ongoing analysis and previous studies (refer to Table 4.9 in 383488-	Closed

		MMD-HSB-REP-SE-RA-000008), the use of a condition factor is not deemed necessary. This is confirmed in cl. 8.2.1 from CS 454.	
5	Has any thought been given to why NE10 runs vertically whereas all other cracks run approximately in a longitudinal direction. (It is noted that NE10 appears to run towards an opening in the base plate)	Refer to response to comment F3 and F15 (responses to Norman Fleck comments)	Closed – but subject to further investigation of crack depth

Table B5: AECOM detail comments on MM Post-Blast Inspection report

B6 Review of Mistras Report "Hammersmith Bridge AE Monitoring System Performance Review", 03 August 2020

AECOM DETAIL COMMENTARY

Ref	Comment	Response Received	Further Comment
1	We wish to see Mistras' latest report which includes their analysis of the events on 07 August 2020.	Performance reviews are undertaken and reported once or twice a year. However, the event on 7th August is covered in alarm report FT10060-8-A1. A copy of this report has been emailed to LBHF today for ease of reference.	Closed
2	Is there any evidence that some of the acoustic signals could be the rollers moving?	The acoustic emission was located towards the bottom (front) of the pedestal and the signature of the emission (reviewed in detail by the specialist supplier) is consistent with a real fracture event. Alarm report FT10060-8-A1 states 'Signature does not correlate to fretting noise and is considered of interest'.	Closed

Table B6: AECOM detail comments on Mistras Acoustic Emission report

B7 Detailed comments on Weekly Reports

AECOM DETAIL COMMENTARY

Ref	**Comment**	**Response** (To be added on receipt from the original document author)
1	The reports refer to a report by Dorothea 383488-MMD-HSB-TN-SE-00016 Interim Release of the Seized Saddle Rollers. Has this been progressed?	
2	NE10 was not discovered during the weekly inspections. Have any AE events been traced to its discovery?	
3	Were the alarms installed for temperature?	

Table B7: AECOM detail comments on MM Weekly reports

B8 Detailed comments on Hammersmith Bridge Refurbishment Approval in Principle for Advanced Works July 2020 (Ref 102963-PEF-BAS-ZZZ-AIP-S-00002)

AECOM Commentary

Ref	Comment	**Response** (To be added on receipt from the original document author)
1	Has the AiP been accepted and approved by TfL/ LBHF?	
2	Has the Cat 3 Checker reviewed and checked the document	
3	How will longitudinal and transverse loads be transferred in the strengthened pedestal – the props will be capable of transferring loads normal to the bearing plate. If as described this load transfer is achieved by composite action, how will the composite action be assured? In accordance with design codes, the supporting structures to a bearing need to be designed for up to 8% friction loads, so there will still be a reasonably large shear force on the pedestal.	
4	The report states that shear studs will be attached to the top of the props – why not the full height?	
5	The report states in section 3.12 that should the top spreader plate have cracks, this plate will be removed. If so, how will the loads from the new bearings be spread into the pedestal?	
6	AECOM understands that the frame design is currently being refined. AECOM notes that, in the original assessment by MM, the base slab was overstressed but we are unaware if any further analysis has been undertaken. The base slab will need to be checked that it is not overstressed by the temporary jacking frame. The analysis of the slab must also consider the existing cable tunnel beneath.	
7	Has a survey for gas ducts under the base slab been undertaken?	
8	The early design of the frame indicated that the jacks would load the frame by bending of beams. AECOM suggests that the frame is reconfigured so that the jacks are located at nodes	
9	Section 3.13.2 – needs to be updated as it still contains reference to pedestrians and cyclists and river traffic	
10	Section 4.1.2 – this refers to a friction coefficient of 30%. MM reports refer to much higher coefficients – need to coordinate between reports and ensure that an upper value is used.	

11	Section 4.1.9 – it is noted that 8% friction is to be used. The pedestal strengthening must be designed for this value of longitudinal load.	
12	Section 6.1 – include the existing cable tunnels and river walls in ground models	
13	Section 6.3 – include settlement of TTT	

B9 Detailed Comments on Interim Release of the Seized Saddle Rollers (Ref 383488-MMD-HSB-TN-SE-00016)

AECOM Commentary

Ref	Comment	
1	Is it possible to carry out a first stage clean without removing the retaining bars and without reliance on temporary works to provide a small (1-2mm, say) amount of movement which will assist in dissipating the restraining force?	

Appendix C – Detailed review of CCSO for Limited River Traffic

Clause No	CCSO	AECOM Comment
1.0	Preface	
1.1	This Case for Continued Safe Operation (CCSO) is provided by Xanta Limited (Xanta) to the duty holder, the London Borough of Hammersmith and Fulham (H&F) and its officers. Xanta is contracted by H&F to undertake that task. All responsibility for action rests with the duty holder. Xanta provides here a reasoned case for the continued safe operation of limited river traffic under Hammersmith Bridge based on evidence provided to it by the duty holder and the appointed agents of the duty holder. No attempt has been made to verify any of that evidence and it is for the duty holder to decide on acceptance of this Case for Continued Safe Operation, or otherwise. Acceptance of the case implies acceptance of all actions arising, which, if not delivered, must cause the case to be withdrawn.	This new CCSO is a positive step forward, recognising that there is scope to allow limited river traffic movements. The previous CCSO was contracted by TfL – is this still the case or has there been a change in emphasis or responsibility? It is assumed that LBH&F has accepted this document Has PLA been involved in any discussions in developing this CCSO document? Have the limitations on the safe passage of river traffic been defined and agreed?
2.0	Introduction	
2.1	The purpose of this Case for Continued Safe Operation is to set out the circumstances that represent managing safety risk for limited river traffic under Hammersmith Bridge As Low As Reasonably Practicable (ALARP) following closure of the bridge to motorised traffic in April 2019 and subsequent closure of the bridge to all traffic in August 2020	Comments as 1.1 above
2.2	This statement is intended to be read alongside briefings and other CCSOs (now expired) already produced on the matter and those details, and details of construction of the bridge, are not reproduced here as they have been provided exhaustively elsewhere. References are stated where they are used.	No comments
3.0	How to use this Case for Continued Safe Operation	
3.1	This CCSO is provided to duty holders so that they can have confidence that the use of their assets is consistent with legislated requirements for safe use and is consistent with societal expectations for use. The case for this is set out explicitly so that it can be subjected to independent scrutiny from time to time, should that be required (notwithstanding any peer review undertaken for issue of this document). It is good practice to revisit such cases from time to time.	Has the document been subject to independent review? What timescale has been placed to revisit this report?

3.2	The responsibilities for action by duty holders are set out clearly. The validity of this CCSO is predicated on competent and timely action by duty holders in responding to those actions. This CCSO sets requirements for outcomes to be achieved in order to establish and maintain safety risk ALARP. It is for duty holders to put in place operational plans and procedures which meet those requirements. Such plans, where they already exist, are referenced in this CCSO.	No Comments
3.3	Actions required of H&F are indicated throughout this document as shown here: Specification of the action required It is for H&F to confirm that the detailed arrangements, plans and processes created are consistent with the requirements set out in this CCSO.	No Comments
3.4	This CCSO is valid from opening of the bridge to limited river traffic until the point at which further progression of damage, or new damage, may be observed. Any such event invalidates this CCSO and re-opening in any form from that point is subject to re-evaluation of the safety risk and issue of another CCSO.	It would be useful to provide a flow chart with the decision-making process
4.0	Summary of Bridge Condition and Monitoring	
4.1	The bridge is sensibly at the end of its life in terms of estimated fatigue damage and general deterioration through age and use.	"The bridge is sensibly at the end of its life in terms of estimated fatigue damage." Is this really true for the whole structure? This might be true for some hangers where end bending is taking place but wonder if this is right for 1970s trusses and tower structures. If this statement was true it would not be worth repairing the bridge.
4.2	Analysis of the bridge structure indicates that cracking might be expected in some components. Cracking in the pedestals was discovered on 10th April 2019 after inspections specifically organised to confirm the modelling. There was clear indication that the cracking had been there for some time and that no recent movement had taken place	MM's original assessment was in the absence of any monitoring results and has been shown to be conservative by more refined analysis which uses calibrated results from the monitoring. In MM's revised analysis including the effects of the Thames Tideway tunnel, the utilisation has reduced to 1.1 (increasing to 1.24 after TTT has passed through) for the SW pedestal for permanent loads plus temperature. It is likely that the utilisation for the NE pedestal will reduce if a similar revised analysis is carried out. The CCSO accepts the presence of existing cracks.
4.3	At an emergency meeting on 11th April 2019 attended by Mott Macdonald (MMD) and H&F, the decision was taken by H&F to close the bridge to vehicular traffic. This had the effect of a significant reduction in utilisation for the case of a restrained force towards the river.	As noted in 4.2, above, MM's revised analysis due to Thames Tideway tunnel showed that the utilisation has reduced to 1.1 for the SW pedestal for permanent loads plus temperature. It is likely that the utilisation for the NE pedestal will reduce if a similar revised analysis is

		carried out. This information has not been provided but it would be useful to understand the current utilisation including pedestrian loading. Further, it must be pointed out that the pedestals are only overstressed in some very local areas. Depending on the results of the cracked pedestals, it should be verified if the pedestal can remain functioning if cracked portions are discounted in the load assessment
4.4	This relates to the total loading rather than to a quantification of reduction in fatigue loading, although such a beneficial effect undoubtedly also exists. This action reduced the safety risk by some unknown increment, but against a position of apparently stable operation.	See comment on 4.3 above
4.5	At the point of initial assessment, the bridge was not considered to be a structure at 'Immediate Risk' (Section 3, BD79/13), although that view was revised as the results of the intrusive inspection became available. This position has now effectively been reached following the discovery of cracks in the deviation saddle support pedestals. BD79 has now been superseded by CS 470 which is predicated on the same principles. The term, 'Structure at Immediate Risk' (the CS 470 term is 'Immediate risk structures') accurately describes the circumstances without further explanation being required, but does not necessarily refer to a structure that must be taken out of use immediately, although that is the most likely outcome unless it can be shown that there are interventions that can be taken to reduce the safety risk to acceptable levels immediately. This was done through the application of monitoring and selective chain heating with plans now to fit chain cooling being well advanced. The chain temperature control allows the effects of seizure of the rollers to be mitigated to avoid a dangerous build-up of residual loading. So far, it has only been proven effective with defined limits of anchorage chain temperature.	In the flow chart in the Interim Measures Management and Communication Plan 383488-MMD-HSB-REP-RA-000003 Rev 6 6th August 2020, it shows a potential path to re-open the bridge if the defect can be safely monitored. A decision must have been made in April 2019 that it was possible to safely monitor the defect and so the bridge was kept open to pedestrians. The same flow chart shows that an emergency meeting be convened to discuss the defect – are there any minutes from the meeting which reflect the decisions made? As stated: *"The term 'Structure at Immediate Risk' accurately describes the circumstances without further explanation being required, but does not necessarily refer to a structure which must be taken out of use immediately"* As the CCSO points out, interventions have been carried out to reduce the safety risk to acceptable levels – and this includes monitoring and temperature control of the anchorage chains.
4.6	Monitoring regimes exist in three principal forms, (1) temperature monitoring, (2) strain gauges on the chain links which allow knowledge of changes in link loading, but not absolute loading as they were applied with unknown residual loading present, (3) Acoustic Emission (AE) monitoring which, through analysis of the frequency content of the signals, allows fracture events to be noted and confirmed, or otherwise, through line-of-site inspection and manual non-destructive inspection techniques. AE events do not distinguish easily between micro and macro cracking. Responses allow for immediate closure without inspection if there are repeated 'clusters' of AE events and/or rapid strain change events. Line of sight and manual non-destructive inspection, typically using Magnetic Particle Imaging (MPI) then follows.	As the CCSO states, monitoring exists in three forms which helps to reduce the safety risk. It is also noted that, after AE events, detailed visual examination did not find any evidence of a fracture event. It should be pointed out that visual inspections have reduced significantly since March/ April 2020 and do not appear to have been increased in frequency since August 2020.

4.7	The full extent of fracture damage is unknown. Not all pedestals have had their paint removed which is a necessary precursor to being able to examine them to have confidence that any fractures present will be found.	Agreed that all pedestals should be examined as soon as possible
4.8	There can be no doubt that the pedestals and chain links contain residual loading in consequence of the seizure of the saddles at some unknown time, in some unknown condition. The loading on the pedestals would ordinarily be normal to the surface on which the saddle rollers bear. Seized rollers lead to forces which are normal and parallel to this surface, which is clearly not the original design intent. All this leads to unquantifiable risks. High residual stresses in any component increase its sensitivity non-linearly to cracks or defects and to the risk of unstable crack growth in response to further loading applied through temperature changes or usage	MM have carried out a correlation between site measurements and theoretical analysis to calibrate the loading in the chain and have achieved a reasonable agreement. (This has been internally checked by MM but should be checked by the Cat 3 Checker). By using these loads, the risks are not "unquantifiable" and it should be possible to derive a reasonable estimate of the restraining force. The chain load can be calculated with reasonable accuracy, knowing the permanent loads and chain catenary geometry. Agreed that it is difficult to quantify residual stresses.
4.9	Since 11th April 2019, with monitoring in place, no new cracking, or extensions to existing cracking, had been noted until the latest event leading to complete bridge closure on 13th August 2020. However, a number of alarms that could not be ruled out as due to other innocuous causes (eg rain, electro-magnetic interference, etc) were received but on investigation, including the use of manual non-destructive inspection, no new cracking or crack extension was found.	As noted above, it is also noted that, after AE events, detailed visual examination did not find any evidence of a fracture event.
4.10	MMD has produced a comprehensive and accessible summary of the history of events on the bridge which is included in Appendix 1. Importantly, it makes reference to a qualitative, but well supported, assessment of safety risk. This summary documents continuous degradation punctuated by the effect of the various events.	In the CCSO for Limited River Traffic Movements Appendix 1 Timeline and Risk Profile – why is there no reduction in the risk in March/ April after the more refined analysis of the pedestal had reduced the UF for the SW pedestal to 1.24? Also in the Appendix 1, Timeline and Risk Profile, there is a combined change in risk from the installation of additional AE sensors (in dotted line) but mitigated by the reduction in frequency of inspections. What is the overall net change in risk?
5	Current Status - summary.	
5.1	The closure of the bridge to all traffic on 13th August 2020 left the bridge unavailable for any use by the public, with precautions taken against unauthorised access so that H&F could exercise its duty of care to the public by preventing such use. These arrangements are the subject of separate documentation by H&F. These arrangements must be kept under regular review by H&F to confirm their continued suitability.	No comment

5.2	The bridge remains available for critical inspections and work to be undertaken on its structure subject to suitable arrangements for protection of the workforce. This is the subject of a separate CCSO.	Has the separate CCSO been distributed? AECOM has this CCSO for Limited River Traffic, and CCSO version 5 dated 30 March 2020.
5.3	The bridge remains available for limited river traffic beneath it subject to arrangements set out in this CCSO. In the case of 5.2 and 5.3 it is necessary to demonstrate that safety risk is ALARP. The case for 5.3 having safety risk ALARP is provided below.	What are the limitations to river traffic? Have these been agreed with PLA?
6	Safety Risk As Low As Reasonably Practicable	
6.1	Establishment and maintenance of safety risk ALARP requires the following: Reducing safety risk to a 'tolerable' level; and Continuously reducing risk further over time where this is practicable; and Continuously monitoring management arrangements to confirm that any assumptions remain valid.	The list should include maintaining, or preferably increasing the frequency of visual inspection
6.2	There is no longer any safety risk to the public as the bridge is closed to all traffic and all use by the public. There remains safety risk to workers on the bridge, which is the subject of a separate CCSO, and to river users, which is the subject of this CCSO. There remains also a potential safety risk to neighbours and river users distant from the bridge in the event of complete collapse. That issue is outside of the scope of this work to address but reduction of the risk of such an event is naturally delivered by the use of this CCSO which provides for net anchorage chain load reduction through temperature controls.	No comment
6.3	This CCSO must be seen as a temporary measure to enable use of the bridge in limited circumstances which are tightly controlled. Ultimately, continuously reducing risk must require physical stabilisation of the bridge before public access is possible. This CCSO is predicated on such works for its validity. If such works are not planned to take place, then this CCSO will cease to be valid as it is contrary to all established practice knowingly to allow temporary measures to be used unaccompanied by a clear permanent solution.	It is reasonable to say that there is an holistic view of all the work being carried out – including various plans for temporary footbridges, stabilisation of the bridge by freeing up the bearings, and for overall refurbishment of the bridge Pell Frischmann has developed a strengthening scheme and continues to refine the design The Cat 3 Checker has checked the design of the strengthening Costing of the strengthening has been developed and is being reviewed. Methods of freeing up the roller bearings, including de-rusting are being discussed.
7	The role of monitoring and chain temperature control in maintaining safety risk ALARP	

7.1	Monitoring (AE and strain gauge data) and chain temperature controls must be considered to be elements of a management regime designed to reduce safety risk. They are made useful by the management regime in which they are deployed which provides for the necessary responses to the information provided.	Monitoring is part of the holistic view of all the work being carried out. All AE events are reviewed on site The effects of chain temperature controls are being monitored by Motts and checked against their analysis of the chain load and restraining forces.
7.2	The ability of monitoring to perform a useful and valid function means that its contribution must be capable of providing timely relevant information which is integrated into the management regime for a response. If a response to the information provided by monitoring is not possible, or insufficiently timely, then it is not possible to have any reliance on it as a means of reducing safety risk. This is dealt with further below.	
7.3	The ability of the chain temperature controls to perform a useful and valid function means that the effect of ambient temperature on incremental chain loading must be understood adequately to use that information effectively. MMD has modelled the conditions of: Saddle seizing at extreme low temperature (restrained force towards river); and Saddle seizing at extreme high temperature (restrained force towards anchorage) The actual conditions under which the saddles seized are unknowable, but almost certainly lie between these two points, the quantification of which allows some conservative, but reasonable assumptions to be made. MMD has also demonstrated a good degree of correlation between modelled incremental chain loading caused by temperature loading and measured incremental chain loading from strain gauge data. Use of the monitoring instrumentation across a range of anchorage chain temperatures, coupled with the understanding provided by modelling described above, has provided a position in which a range of anchorage chain temperatures when the bridge appears to exhibit stable operation has been identified. This information is used as detailed below as part of the management regime. That is something that cannot be relied upon absolutely and must be coupled with real-time monitoring to provide adequately safe operation. It is notable that once this range was exceeded in August 2020, some crack growth then took place. That the growth stopped and did not progress further is something to be noted, but not relied upon	It is more likely that the rollers seized at a more ambient temperature as this is the relative position that the rollers occupy for the majority of the time with the result that corrosion and rust debris will build up, and hence more likely to seize in this position. The extreme temperatures last only a few days (as they did in Aug 2020) and, in the days when the rollers were operating, the saddle would have moved back to a more ambient position. Although it is noted that:" It is notable that once this range was exceeded in August 2020, some crack growth then took place. That the growth stopped and did not progress further is something to be noted, but not relied upon" – the extreme high temperatures have now passed. It is assumed that the temperature control for the winter of 2020/21 is now in place (i.e. warming the anchorage chains)
8	Case for Continued Safe Operation for limited river traffic movements	
8.1	There must be continued reliance on 'no change' being constantly confirmed by monitoring and controlled by chain temperature management to support the position that safety risk is	The CCSO should, however, include for review of the reasons why the bridge was closed, and include quantifiable mechanism to re-open the bridge.

	ALARP. When a change was detected it led to bridge closure on 13th August 2020. This is a demonstration that the arrangements in place were fit for purpose. That event changed the position from what was a demonstrably stable platform with the potential for change, to one in which change had taken place but which was adequately detectable and for which adequate response was available.	Since the bridge was closed in Aug 2020, it can be said that more is known about the bridge, and further work is ongoing, including the analysis of the cracked pedestal The work carried out on the refined analysis of the pedestal should be developed further for all pedestals and independently checked
8.2	The net safety risk must now be seen as higher than that which applied before the events of 13th August 2020 because a potential change became an actual change. Absolute quantification of the safety risk is not possible because of the number of unknowns that apply to the bridge, which include: The absolute magnitude of restrained force on the pedestals; and The mechanical properties of the cast iron used in the pedestals; and The residual stresses and imperfections from the manufacturing process; and The details of bedding at the rollers and pedestal base; and The confirmed condition of the pedestals on the west side of the river; and The precise absolute stress distribution (static and dynamic and accounting for residual loading from all sources) on each pedestal correlated with an understanding of how the crack distribution seen is explained by that stress distribution. This lack of understanding extends to initiation, propagation and arrest of the cracking.	Restrained Force – as this CCSO discusses earlier, "MMD has also demonstrated a good degree of correlation between modelled incremental chain loading caused by temperature loading and measured incremental chain loading from strain gauge data" MMD has established a set of assumptions from which a range of restraining forces have been calculated. Mechanical properties – MMD has carried out hardness tests and compared with a slightly older structure. Residual stresses and imperfections – agreed difficult to assess Bedding at the rollers and pedestal base – can these not be determined from visual inspection? Condition of west side pedestals – this needs to be completed as soon as possible Absolute stress distribution – MMD has carried out a refined analysis of the SW pedestal. This needs to be repeated for the other pedestals.
8.3	The monitoring arrangements for AE and strain gauge data supplemented by support chain temperature management provide some mitigations from the effects of these unknowns. Whereas the effect of these unknowns, and associated mitigations, has been the subject of competent estimation, those estimations cannot support reliance upon them to the degree necessary to enable confident use of the bridge by the public, either because of the assumptions that have had to be made, or because evidenced quantification of governing parameters is not available. That must remain the case until stabilisation works, which enable limited use by the public, and restoration, which enables full use by the public, have taken place.	Acoustic monitoring and strain gauging of the bridge has continued, along with temperature control. Apart from the propagation of one crack at NE10 on the NE pedestal, no further new cracks or propagation of existing cracks have been observed since April 2019. Further analysis of the pedestal must be developed as it has been pointed out that the pedestals are only overstressed in some local areas, the majority is not overstressed. Depending on the results of the cracked pedestals, it should be verified if the pedestal can remain functioning if loads are redistributed away from cracked portions. The failure load and mode of the pedestal must be calculated by MMD and independently checked.
8.4	This is also the position espoused by the HSE in its 2001 document 'R2P2'[2] in which it is clear that an unquantifiable risk of an unacceptable outcome requires the focus to be on the prevention of the unacceptable outcome. This intuitively meets societal expectations. Further	No comment

[2] https://www.hse.gov.uk/managing/theory/r2p2.pdf Aimed at explaining the decision-making process in HSE rather than providing guidance to individual duty-holders on what they need to do. It contains the principles used to inform any competent decision-making process for the management of safety risk and is an indicator of the approach the HSE would take in investigating any apparent breach of requirements or duties.

	analysis that does not reduce the risk of the unacceptable outcome, and the application of additional monitoring to enable enhanced response to ongoing degradation, are not appropriate. This is also the situation which emerges through the use of CS 470. The bridge is not a 'monitoring-appropriate structure' for public use as it fails to meet the criteria set out for such structures in CS 470 section 6.9.	
8.5	That position does not prevent the use of the bridge for limited river traffic or for work and inspection on the bridge as the numbers of people then affected by safety risk, and the ability of those people to respond in managed operational environments that can be provided, support the basis for maintaining safety risk ALARP as shown below. Such a position could not apply if members of the public were allowed to use the bridge without very significant additional controls that would make the bridge practically unusable.	Can a set of controls be developed to permit limited numbers of pedestrians to use the bridge? This could concentrate usage in the morning and evenings within a pre-determined temperature range – although this will require strict policing and may prove to be unworkable
8.6	Safety risk for limited river traffic movements would be ALARP if, among other things: River traffic could be halted at no notice if monitoring arrangements indicated an adverse change in status of the bridge. Were this to happen and the cause found to be due to progression of damage, or new damage, then the provisions of section 3.4 apply; and The number of occupants of each vessel were to be minimised; and The time each vessel spends in transit under the bridge were to be minimised; and A management system is in place which integrates these items with the chain temperature controls and the fact of increased risk following the last progression of damage noted on 13th August 2020 is accommodated. The first provision removes all risk at source and the other provisions contribute to minimisation of risk as far as is reasonably practicable. However, it is still necessary to show that absolute safety risk is tolerable. This must be done by deduction as absolute quantification is not possible as detailed above.	Has a set of rules been developed and agreed with the PLA? The bullet points listed are a sensible preliminary list of risk-mitigating measures Emergency river traffic must be given priority
8.7	Prior to 13th August 2020 the combination of a demonstrably stable structure, maintained in a stable condition by temperature controls (a proxy for load control) and monitoring, provided safety risk that was tolerable by inspection; sudden growth of cracks catastrophically was both very unlikely and likely to be signalled by monitoring before any significant growth took place based on recent and historical behaviour. The cracks appeared to be long standing, at least to the degree that such an inspection could draw that conclusion. This applied between 11th April 2019 and 13th August 2020, a period of proven and expected stability which only ended when anchorage chain temperatures approached, and briefly exceeded, the upper limit of what had previously been demonstrated as being related to stable behaviour. The	. Visual inspections had reduced since March 2020. As stated before, this should be increased. It is assumed that heating is now in place as winter 2020/21 approaches.

	Management and Communication Plan also specifies low temperature thresholds; 3ºC to 5ºC – Amber, Less than 3ºC – Red. This position represents a baseline for tolerable risk from which deduction can be made.	
8.8	Although the crack growth which triggered closure of the bridge did not extend catastrophically, that is a situation that cannot be relied upon. It does provide notional indication of a potentially continuing stable position, but without an accompanying complete understanding of all the governing influences. It represents an unquantified increase in safety risk beyond that which applied before 13th August 2020 even if it correlates to increased anchorage chain temperature beyond previously established 'safe' limits. Correlation must not be assumed to be causation, although there is no obvious additional factor in play.	Crack NE10 should be investigated further to determine the depth Agree with this CCSO that the current situation does indicate a potentially continuing stable position Now, mitigation in the form of temperature control is in place which will keep the anchorage chain temperature within "safe" limits
8.9	If the safety risk exposure to anyone on or under the bridge (of a catastrophic adverse event per unit time) just before the event of 13th August 2020 (R-) and the safety risk exposure just after the same event (R+) are examined, then some insights can be gained. Risks R- and R+ are those inherent in the structure of the bridge with the mitigating effects of management, monitoring and temperature control arrangements. The absolute magnitude of these risks is unknowable. Risk R+ must be assumed to be greater than R- in some degree without further mitigation being applied. Risk R+ can be reduced below, or at most equal to, R- by ensuring that no risk exposure takes place near to the extremes of temperature which have been experienced previously.	The safety risk exposure since August can be reduced by the following measures: Temperature control Further analysis of the pedestals including calculation of the failure load and mode Increase the frequency of visual inspections The safety risk exposure has already been reduced by the following: The extreme heat has been replaced by cooler temperature but will soon be replaced by winter temps. According to MMD, the NE pedestal is the only one which is more susceptible to summer heat due to the relative position of the saddle in its seized position There is a greater knowledge of the bridge and across a wider group of technical people
8.10	Temperatures of 23ºC at the NE pedestal chain have been observed, and it is known that limiting this to 18ºC will result in a significant reduction in maximum temperature loading. This could be as high as 20% but because of the non-linear behaviour at the saddles, a reduction of 20% of the temperature loading may result in a reduction of stress of less than 20%.This provides some protection against unstable structural behaviour and is based on the observed stability over a wide range of temperature loading between 11th April 2019 and 13th August 2020, albeit without the recent extension in cracking latterly observed. This does mean that the supposed 'safe' temperature range may now be less than applied before the latest crack extension and a clear margin away from the previous maximum temperature of 23ºC must be provided. Because the temperature controls are now working well this margin can probably be achieved with temperatures lower still than the notional 18ºC discussed here.	The temperature control was installed on the NE pedestal in September 2020. It appears that temperature control will be installed on all 4 pedestals by 13 Nov 2020.

8.11	There is further context that aids understanding. With of the order of 10^4 bridge users each day (before 13th August 2020) this could conservatively be considered to represent a continuous exposure of, say, four hours with the order of 10^2 people on the bridge continuously (each person takes 2.4 minutes to cross at 1.4 m/s walking speed). With river passages limited to very small numbers of people exposed (of the order of 10^0) for small fractions of that time (a vessel takes about two to three minutes to travel under the bridge, according to the PLA – this accommodates close proximity as well as positioning under the bridge, but still seems large) that represents a time exposure ratio of minutes to hours (a reduction of the order of 10^1). This gives a total reduction in risk exposure of the order of $10^2/10^0$ (people) x 10^1 (time) = 10^3. It must be noted that this reduction in risk is only available and enabled if R+ ≤ R- which is achieved by choosing to operate in a limited temperature range (as in 8.10). If R+ > R- this may give rise directly to a catastrophic failure.	A vessel will take far less than 2-3 minutes and will be less than say 30 seconds See comments on 8.9 regarding the safety risk exposure
8.12	All this leaves a position in which safe operation is predicated on being able to maintain reliably an acceptable temperature range for the anchorage chain, noting that the choice of that range following cracking found on 13th August 2020 is not directly indicated because of the increased risk caused by that cracking. The choice of 18ºC, or lower, represents an arbitrary and achievable clear margin from the previous maximum. This does mean that temperature controls must be accompanied by real-time monitoring of any progression of damage leading to immediate cessation of operations if it were to occur. The accompanying management arrangements must include provisions to cause that cessation safely and reliably.	Agreed
8.13	Based on the above, limited river traffic movements under the bridge are acceptable, and with safety risk ALARP, provided that: H&F establishes a regime in which: River traffic can be halted safely at no notice if monitoring arrangements indicate a change in status of the bridge; and The number of occupants of each vessel is minimised; and The time each vessel spends in transit under the bridge is minimised; and The average anchorage chain temperature is predicted to be no more than 18ºC and no less than 8ºC at any location. This further assumes that: A regime of bridge operation based on temperature controls with associated anchorage chain temperature ranges has been developed linked with observed stable behaviour of the structure. Until implementation of the full temperature	Agree in principle for limiting river traffic How will communications be made immediately to river users? Has the PLA accepted these arrangements?

	control system any expedient temporary measure may be used, such as hosing, which has already proved to be effective. The number of vessels involved in any movements is such that an unexpected bridge closure for an extended period will not leave vessels without the means of reaching a position of safety; and Monitoring arrangements have been developed that can provide a signal from AE that indicates a potential adverse change in status of the bridge and that can be communicated immediately and effectively to river users; and The Port of London Authority confirms the acceptability of these arrangements and can provide management arrangements for the controlled passage of vessels under the bridge. It is implicit that any monitoring signals indicating a potential adverse change in status of the bridge must lead to its immediate closure and evacuation before any other examination takes place.	
8.14	H&F has a procedure in place for river traffic movements detailed in Reference [1]. It is for H&F to confirm that its details comply with the requirements of this CCSO.	This reference 1 seems to be general HSE guidance and is not a specific procedure
9		
9.1	It is implicit in maintaining safety risk ALARP that continuous effort is made to reduce safety risk further. In this case that may be achieved by improving understanding of the behaviour of the structure of the bridge and the effectiveness of operation of the management arrangements. Testing management arrangements through unannounced interventions to demonstrate the degree to which events develop as expected is invaluable in safety critical situations; such tests often provide outcomes or insights which it is impossible to foresee.	There is much evidence of ongoing improvement of the understanding. This includes: More detailed analysis of the pedestals Discussion between wider range of consultants including DfT, NR, AECOM and the wider task force
9.2	In respect of understanding of the behaviour of the structure: Effort must continue to be made to reduce the number of unknowns listed in section 8.2.	It is understood that all these actions are all being implemented

	The AE signals should continue to be correlated with 'real-world' events which include actual fracture extensions, but also include other events such as rain ingress, works on the bridge, or electromagnetic interference to build a library of correlations to aid rapid understanding and to identify emergent true adverse conditions better. The modelling of the bridge should continue to be the subject of correlation with real-world experiences to aid the understanding of the behaviour of the structure.	
9.3	In respect of the management arrangements: The management arrangements must be monitored to confirm their effectiveness. Key parameters are: Time of response to adverse monitoring signals Effectiveness of response Practical testing of the management arrangements through unannounced interventions must be undertaken.	What are the arrangements for responding rapidly to an event? It is assumed this will include: Immediate notification of AE events to competent personnel including weekend and holidays Emergency action procedure in place Training for emergency procedure involving emergency services, etc
9.4	In respect of ongoing works: The installation of the full temperature control system must be completed at the earliest opportunity. Temporary measures, such as hosing, may continue to be used until then as they have already proved to be effective.	Agreed
10	Practical Operation of this CCSO	
10.1	Practical operation of this CCSO requires that duty holders develop the management arrangements, and associated resourcing to deliver the matters detailed herein.	Agreed
10.2	If the matters for action by H&F are not delivered, then this CCSO must be withdrawn.	Agreed
10.3	This CCSO is predicated on the underlying assumption that a currently stable situation will continue to be stable in the absence of undetected changes. That assumption carries less credibility with the passage of time unless better monitoring can be used to reduce the risk	Agreed

	further by gaining the ability to detect currently undetected but still present or emerging changes.	
10.4	This CCSO must be reviewed for its continued effectiveness six months after its implementation. A natural expiration of this CCSO must occur after 12 months. It may be reinstated after review if the ability to maintain continuous improvements is confirmed and there is confirmation of an achievable date for physical stabilisation works.	Agreed