MOTT MACDONALD

Document - Hammersmith Bridge Fleck Report No1 draft final 061120

Ref	Comment
MM1	Throughout these review comments, comment references refer to the originator followed by the comment number (where MM refers to Mott MacDonald, WSP refers to Williams Sale Partnership, X refers to Xanta and LBHF refers to the London Borough of Hammersmith and Fulham).
MM2	NF states *'the crack growth direction is along the direction of maximum tensile stress'* *It is assumed that this should read perpendicular to the direction of the maximum tensile stress.*
MM3	NF states *'A small rotation of the pedestal about the toe will alleviate the tension imbalance in the chains'* Whilst it is agreed that this rotation is beneficial in terms of reducing the overall demand on the pedestal, the Mott MacDonald analysis shows that the movements accommodated are not enough to fully alleviate the problem and a significant restrained force remains.
MM4	NF states *'It is difficult to envisage that a large shear component of 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'* Refer to report 417457-MMD-HSB-REP-SE-RA-000001 Section 5.7 for discussion on this topic. Generally, for the lower-bound estimate of ground and foundation stiffness parameters, stresses within the foundations beneath the pedestal are found to be similar to (or less than) typical characteristic strengths assumed for those materials. The analysis performed (which assumes linear elastic behaviour of the foundations) is therefore considered representative. For the upper-bound estimate of ground and foundations stiffness parameters, the stresses within the foundations beneath the pedestal are found to exceed the typical characteristic strengths assumed for those materials and some softening may occur due to localised crushing and splitting of concrete, which will tend to alleviate the restrained force on the pedestal. However, there is no experimental confirmation for the strengths and condition of the material below the pedestal, nor the condition of the interface and as such, localised damage of the foundation should not be relied upon since it cannot be ensured. In either case, a favourable set of conclusions are drawn from the refined analysis, regardless of whether movements are accommodated by localised damage of the foundation for the case of upper-bound stiffness parameters.
MM5	NF states *'An alternative scenario is that a small rotation and/or slip of the pedestal takes up any clearance gap between the foundation anchor bolts and the pedestal base plate; this shear force induces tension in the pedestal the vicinity of crack NE10'* The proposed hypothesis could be considered with an additional simulation as an addendum to the refined analysis report. It is unlikely for this case to change the overall conclusions of report although it may offer an alternative hypothesis for propagation of cracking at NE10. It should however be noted that a significant reduction in friction beneath

Ref	Comment
	the base will be required in order to mobilise the full shear strength of these bolts and that the limiting shear resistance of these bolts may not be sufficient to generate a stress associated with cracking at NE10. Furthermore, due to the behaviour of the discrete blocks below the pedestal, the majority of the load taken by the bolts will be within the first two rows thus minimising any potential tension at NE10.
MM6	NF states *'Instrument each pedestal at salient highly stressed points by strain gauges, and rotation gauges, to help monitor it as a function of temperature fluctuations and to validate the MMD stress analysis'* Instrumenting the pedestals with strain gauges is a possibility (in combination with a controlled load test using the temperature control system). Mott MacDonald proposed strain gauging of the pedestals in in 2019 (with the intention of monitoring the variation in strain to understand the profile of base reactions) although this study is not without its challenges and if instructed, it should be noted by all parties that interpretation of the monitoring data may not reliably yield useful conclusions for the following reasons: 1) Unlike for the steel chain links, the elastic modulus of the cast iron material is not known and there is a wide range of potential stiffnesses from literature. Furthermore, due to the nature of the casting process, this stiffness may vary across the component. This makes it difficult to reliably interpret stresses from the strain data. Rather than investigation of explicit stress, it may be possible to instrument the pedestals with a larger number of strain gauges which targets achieving an understanding of the pattern of relative changes in strain. 2) It is not uncommon for strain gauges to give spurious results, particularly for field applied bonded gauges; especially if installed on the central plating where access is poor. It is common practice to undertake an initial process of filtering out gauges with a response that is substantially different to the response of the accompanying gauges or analytical predictions of the structural behaviour. Such work is clearly more straight forward for the chains where a large number of in-line gauges could be compared against each other, and the direction of principal stress is clearly understood. It can reasonably be expected that the response from any pedestal gauges will be far more difficult to interpret than for the chains and overall, there will be less confidence in the measured data. This interpretation will be additionally complicated by the influence of the observed defects. 3) Given the non-linear contact behaviour at the pedestal, it is challenging to perform a calibration/ validation based on strain gauge results. Monitoring data and analytical results must first be referenced back to a seizing temperature which is unknown (rather than simply investigating a linear change in response regardless of absolute position). This was overcome within the refined analysis by iterating seizing temperature until a best fit is achieved with the measured chain force. However, the measured chain force is less sensitive (to exact bedding conditions etc.) than explicit stresses (magnitude and direction) at various locations across the pedestal. For a greater chance of success in performing a representative calibration, the range of anchorage chain temperatures investigated within the controlled load test must be maximised such that calibration can be performed over a wider band of the non-linear response curve. However, it should be noted that an acceptable test range must first be agreed with LBHF and their TAA. 4) Consideration must also be given to the achieved accuracy/resolution of a field applied strain gauge compared with the recorded fluctuation in strain expected for the controlled load test. Again, maximising the tested thermal range will improve confidence in the findings.
MM7	NF states *'Ideally, the above 3 steps should be conducted without delay, on a timeframe of weeks'* A timeframe of weeks is optimistic - Mott MacDonald suggested pedestal stabilisation/strengthening options in November 2019. Pedestal strengthening solutions must take due account of the cracked and stressed state as well as the risks associated with inducing further undesirable stress concentrations whilst implementation any such solution.
MM8	The line of thrust (Figure 2) towards the very tip of the pedestal base appears extreme and

Ref	Comment
	differs from the detailed FE findings undertaken by Mott MacDonald. This is attributed to differences in the applied loads and boundary conditions that have been considered within the high-level Norman Fleck review.
WSP1	First page, second paragraph – The statement is made that, once a crack in cast iron has initiated, it grows easily. It would be good to know Prof. Fleck's view on the level of stress that could be deemed capable of driving crack tip propagation as it could inform the recent Mott MacDonald work or future work if crack tips are found to terminate in areas of low tensile stresses, given residual stresses are currently unknown and unaccounted for in the analysis. A later comment in the report (page 4 – short term solution) advises the level of load required to grow a crack by fatigue in cast iron is close to that required to drive a crack under monotonic load, but similarly does not state it.
WSP2	First page, fifth paragraph – According to AECOM, a report dating from 1990 advises that the bearings were seized then, suggesting "decades" (at least three of them) is correct.
WSP3	Second page, bullet (ii) – Note that cracks may have initiated in a zone of tension if the full Live Loading is considered. The assessment report would need to be reviewed to this effect. There has also been events that may have resulted in loading "anomalies" in the life of the bridge, eg explosions, etc., that may have reversed loading over a short period.
WSP4	Page 3, first paragraph – a 10 degree C drop is considered as an example; however, the monitoring has shown a greater range of temperature being experienced by the bridge and the bearings didn't necessarily seize at the mid-range temperature, so a range greater than ten degrees is likely.
WSP5	Page 3 second paragraph – This states the release of the roller bearings will not move the saddle or the pedestal by more than a few millimetres and that the stored energy is negligible. It is agreed that the movement upon release will be small. However, in the scenario of this taking place in hot temperatures, could this sudden release not result in the slightly relaxed chain being extended with a dynamic impact applied when the chain reaches its limit (and potentially stretching slightly), which could potentially overload any weak point in the chain. There is concern about the NW anchor chain knuckle joint in particular and there may be other instances of part bearing links, etc.
WSP6	Page 3, point 2 (third paragraph). Agreed that the stabilisation should be in place prior to release if the pedestal is to be used to continue to resist the loads. However, the current stabilisation design does not accommodate the out-of-balance chain loads. The pedestal itself would continue to resist those, but the stabilisation works may impede/prevent continued AE monitoring of the pedestals, so monitoring as required for the bridge to remain open to workforce and for vessel passage may not be possible. A different stabilisation scheme, or the assumptions made in its design, would be needed, or, alternatively, as is currently proposed, an alternative load path could be used instead, eg the external frame.
WSP7	Page 3, fifth paragraph – The comment is made that one or more cruciform sections can crack without failure of the whole pedestal. Is this substantiated/demonstrated? How/where?
WSP8	Page 3, sixth paragraph – Agree that it is important to develop an understanding for, and confidence in, the reason for advance of crack NE10. At present, hypotheses from Mott MacDonald and Prof Fleck appear plausible, but both are based on assumptions and it is not possible to confirm either way.
WSP9	Page 4, top paragraph – The principle of slight displacement or rotation of the pedestal reducing the out-of-balance load is agreed between and has been examined by MM previously in calibrating the results for the SW pedestal and more recently for the NE pedestal with bounding assumptions for temperatures. However, the resulting "reduced" load is still significant.
WSP10	Page 4, second paragraph – This states "It is difficult to envisage that a large shear component of restraining force from the foundation onto the tip of the pedestal can develop

Ref	Comment
	[…]. However, this is what the results from the analysis by MM are suggesting, and this appears corroborated by the strain gauge measurements on the chains.
WSP11	Page 4, second paragraph. Prof Fleck presents an alternative scenario to that presented by MM to explain the propagation of crack NE10. This is "if a large shear force were to develop". What order of shear force would be required for this to happen?
WSP12	Page 4, 3rd paragraph. Agreed that the placement of strain gauges and tilt gauges will give information on the behaviour of the pedestal and that this information would be useful before any change to the current status of the bridge. If this is the case, how long a period of monitoring would be required, or would it be proposed to undertake this work for a short period only whilst manipulating the heat input into the chain using the temperature control system? If a long period of monitoring is proposed, which then requires processing and interpretation prior to further action, there may be little to be gained as the external frame may be in place by then. If manipulating the temperature using the control system, it may be that the limits within which the temperature can be varied (we would not wish to vary the temperature beyond the "safe" range) do not permit the tilting behaviour of the pedestal to be observed if the problem is not linear.
WSP13	Page 4, first paragraph under "Recommendations". This state a small sum of money would allow for immediate remedial action. However, the works then recommended as a "short term solution" are similar to those currently being pursued, the cost of which is still significant. Similarly, item 1 in "Short term solution" states it would be possible to reopen the bridge "quickly and cheaply" for pedestrian traffic provided a number of steps are followed. These steps are similar to the approach currently being progressed, but the estimates of cost and time advised by others for this work suggest the work is not "quick and cheap" and would take considerably longer than "a timeframe of weeks". In particular, note the following: - In relation to (i), blast cleaning of the remaining 2 pedestals, which requires the casings to be dismantled and removed, is due to commence shortly and the programme is understood to extend into April or May 2021 when the full visual inspection could be completed. - In relation to (ii), note the final note of comment 12 above. - In relation to (iii), this was one of the aspirations for the stabilisation scheme. However, see comment 6 earlier; the current stabilisation design is not able to resist the large out-of-balance loads and therefore the pedestal itself would continue to carry these and would therefore need to continue to be monitored, but the stabilisation scheme would make AE monitoring difficult/impossible. Hence, it has been proposed to bring forward the installation of the external frame, which would be required later for bearing replacement in any case. This has been reviewed by Pell Frischmann and an ECI Contractor and deemed to be the preferred solution.

Hammersmith Bridge – Review of Recent Documents and Summary of Existing Condition

Ref	Comment
MM9	Executive Summary – AECOM states '*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*' Mott MacDonald made the recommendation to remove paint to all four pedestals in April 2019 and this task was included within the first issue of the CCSO. The eastern pedestals were exposed and inspected in early April 2020. In late May 2020 concerns were raised over the suspension of works to expose the western pedestals. The contractor has recently been remobilised to complete activities to expose and remove paint from the western pedestals.

Ref	Comment
MM10	Executive Summary – AECOM states *'But with deformations of 3-5mm, the restraining load will tend to dissipate and reduce the stresses due to the shear force.'* It would appear that AECOM have only considered a single local FE model of the pedestal and *'loads on the pedestals were taken from MM reports'* including the normal force from permanent loads before incrementing the restrained tangential force (with accompanying normal force reduction). The calculated movements are then summarised as a function of the tangential load magnitude. The calculated overall movement is approx. 4mm and AECOM state that this will be sufficient to relieve the loads. However, AECOM appear to have misunderstood that the loads they have applied to their model are based on an analysis that has already captured the movement experienced by the system including the ground structure interaction and the non-linearity at the roller and base/padstone interfaces. In summary, the AECOM analysis has demonstrated, in a simpler format, that some movement is accommodated by the system. This cannot be used as a justification for load dissipation. The response of the 2D plane stress analysis (which is the source of the loading) has been calibrated against the measured chain forces and in that context the loads already account for the movement and thus cannot be assumed to have dissipated. There are numerous instances throughout the report where this statement is made. This should be reviewed and amended accordingly. From the Mott MacDonald analysis, considering functional roller bearings (i.e. free chain extension) and heating of the anchorage chain by 24ºC, the saddle is found to move approximately 8mm. For that same load case but with seized rollers, Mott MacDonald's analysis finds approximately 6mm of movement is accommodated by tipping of the pedestal and deformation of the pedestal, foundation and ground, with a significant restrained force remaining.
MM11	Executive Summary – AECOM states, *'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.'* Mott MacDonald are aware of this and highlighted this to the project team in May 2019. The task of exploring the possibility and practicality of releasing the seized saddles was included within the first issue of the CCSO. Geffrey Wallis of GW Conservation and previously of Dorothea Restorations was engaged by Mott MacDonald to inspect the roller bearings at the deviation saddles of Hammersmith Bridge and deliver a report on the feasibility of freeing the seized roller bearings. An inspection took place with Mott MacDonald present on 11th February 2020 and the report was issued soon thereafter. Indeed, the Feasibility Report produced has been reviewed and commented upon by AECOM.
MM12	Executive Summary Recommendations – AECOM states, *'The temperature at which it has been assumed that the roller bearings seized as 20°C appears to be high'* Whilst this seizing temperature may be considered conservative, it is within the range of anchorage chain temperatures (average along the length of the anchorage chain) recorded by the monitoring system. With the actual seizing temperature being unknowable, there is no reliable basis on which the thermal loading can be relaxed. However, even with an analysis bounded by extreme seizing temperatures, favourable conclusions can be reliably drawn (refer to report 417457-MMD-HSB-REP-SE-RA-000001)

Ref	Comment
MM13	Executive Summary Recommendations – AECOM states *'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'* It would appear that this figure has been incorrectly interpreted. 47ºC relates to the maximum bridge temperature, not that of the anchorage chain. Reference should be made to Table 4.5 in report 383488-MMD-HSB-REP-SE-RA-000008 which clearly sets out the assumed temperatures for both the bridge and the anchorage chain. It should be noted that the monitoring records show the suspension chains (span side) have reached a maximum temperature of 46ºC over the past year hence validating the code recommendation. For further commentary and discussion on temperature loading, refer to Section 3.2.4.3 of report 417457-MMD-HSB-REP-SE-RA-000001.
MM14	Executive Summary Recommendations – AECOM states, *'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'* See comment MM6
MM15	Executive Summary Recommendations – AECOM States, *'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.'* Findings from the GI which were not available at the time of undertaking the previous analysis. However, these have already been incorporated into the latest analysis, as documented in report 417457-MMD-HSB-REP-SE-RA-000001.
MM16	Executive Summary Recommendations – AECOM States, *'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'* Mott MacDonald has already undertaken a more comprehensive study into failure modes and presented the findings back in September 2020.
MM17	Section 3.2 – AECOM States, *'AECOM has requested a copy of the BD79-related documents produced by MM but these have not been received'* At no point has Mott MacDonald been asked to provide this document.
MM18	Table 3.1 A BD79 assessment was undertaken by Mott MacDonald soon after the original structural assessment (issued December 2018) and covered a number of sub-standard components including the pedestals. Recommendations included targeted NDT of the pedestal to investigate for any signs of distress. When cracks were found, the bridge was closed to motorised traffic and at this point the CCSO was drawn up by Xanta rather than revising the BD79 (in order to take advantage of evidence that BD79 ignores). Therefore, the statements made in Table 3.1 are not correct
MM19	Section 4.2.3

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	Similar to comment MM13, there appears to be some confusion over the temperature loading actually applied within the Mott MacDonald analysis.
MM20	Section 4.3 – AECOM states *'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'* The post blast inspection report was written in April 2020 (before the events of August 2020) and as such, the statement was an accurate representation of the facts at the time of writing the report.
MM21	Section 4.3 – AECOM states *'The other conclusion regarding the maintenance of the 'no-change' criterion is questionable as it neglects the discovery of seven further cracks'* No change relates to maintaining the steady state condition (as per the requirements of the CCSO) and does not refer to a change in understanding of newly discovered historic defects. Refer to comment MM34.
MM22	Section 6.1 – AECOM states *'It should be noted that these are high level comments based on our experience and need to be developed by MM and checked independently'* Mott MacDonald has already developed a far more comprehensive refined analysis, as detailed in report 417457-MMD-HSB-REP-SE-RA-000001.
MM23	Section 6.2 – AECOM states *'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'* The temperatures (and therefore actual thermal behaviour) along the length of each anchorage chain has been monitored for more than a year with a series of thermocouples. This has enabled the range of representative average anchorage chain temperatures to be evaluated, that already account for the aspects raised in this statement.
MM24	Section 6.3.2 – AECOM states *'A non-linear material model approximating the brittle behaviour of cast-iron was assigned to all elements of the pedestal.'* Presumably this would lead to cracking of the pedestal where no cracks have been recorded? What material model is considered within the analysis and how does the analysis deal with propagation following initiation of cracking? Considering the coarse mesh presented in Figure 6.4, it would be informative to see what material model has been used and what are the results of the non-linear material analysis, and how well this correlates with the observed damage.
MM25	Section 6.3.2 – AECOM states *'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.'* This approach is quite simplified and does not capture the distribution of discrete roller forces, nor the local load transfer through the top plate stiffeners and transverse rib plates (diaphragms and vertical stiffeners). Given that the peak stresses in the pedestal are a function of both the Vierendeel effect and localised splitting stresses beneath the first/last roller, this simplified approach will underestimate stresses in zones of importance.
MM26	Section 6.3.2 – AECOM states *'The analysis was then repeated with the cracks recorded in the NE pedestal included in the analysis.'*

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	There is no explanation on the methodology of crack modelling, nor a summary of the findings.
MM27	Section 6.3.3 - Results Principal stress vector plots are presented for the uncracked analysis, but no results are shown for the cracked analysis. These should be provided along with plots showing the behaviour at cracks and stress redistribution.
MM28	Section 6.3.4 – AECOM states *'with restraint against over-turning provided by tensile forces in the anchor bolts at the back of the pedestal'* It should be noted that the Lewis bolts are anchored into a discrete set of Yorkstone blocks. The restoring tensile force generated in these bolts is dependent on the mass of the discrete blocks (which is mobilised following separation) and is very small compared with the overall demand. This behaviour is captured within the refined analysis report – refer to report 417457-MMD-HSB-REP-SE-RA-000001
MM29	Section 6.3.5 – AECOM states *'applied incrementally until a peak total load factor in excess of 2MN was reached'* Presumably this result is for the case of the non-linear material model for the cast iron? It is not clear what stress limits were used within the material model to derive the 2MN tangential force resistance. Also refer to comment MM36.
MM30	Section 6.3.5 – AECOM states *'When the cracks were modelled, there was a reduction in the peak total load factor and the deformation'* The reduction factor is not stated. The deformation should slightly increase (rather than reduce) when cracking is introduced.
MM31	Section 6.4.2 – AECOM states *'it is reasoned that the progression of cracks is highly unlikely to proceed beyond the outstand of the cruciform or tee section'* The Mott MacDonald refined analysis explicitly investigates this behaviour and substantiates a similar conclusion, although also finds that some cracks are arrested in compression before reaching the transverse rib plates because of modification of the stress flow.
MM32	Section 6.5 – Effect of pedestal failure on remainder of bridge. The findings of this section are broadly in agreement with a more comprehensive MM study into failure modes (undertaken in September 2020 based on the calibrated 3D global model, rather than a 2D simulation) which relates potential progressive damage to the magnitude of movement experienced at the deviation saddle. The study also considered the potential for development of bending effects in the chains and the hangers which might accelerate the onset of damage.
MM33	Section 8 – AECOM states *'The following queries were raised by AECOM during the course of our study and have not yet been answered'* At no point have these questions been put to Mott MacDonald.
MM34	Section 9 – AECOM states *'CCSO may be overly conservative. For example, when seven further cracks were discovered in NE pedestal in April 2020 following blast cleaning it was*

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	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. The CCSO is largely predicted on no change to the steady state (i.e. the observed ability of the pedestal to resist the applied loads without further deterioration) rather than the assessed utilisation or evaluation of absolute stressed state. As described in Section 4.2 of the Post Blast Inspection report, each of the newly discovery defects were considered against acoustic emission events. As none of the newly found defects could be associated with acoustic events, they were defined as being historic i.e. occurred prior to closure of the bridge to vehicular traffic. The newly discovered cracks therefore did not threaten the basis of the CCSO. Conversely, the recorded propagation at NE10 marked a deterioration of the structure which invalidated the key principle upon which the CCSO is based and a potential change became an actual change. Also, refer to comment X4.
MM35	Section 9 – AECOM States, *'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.'* As explained in detail in the MM assessment report and associated appendices, the relationship between shape and force in the chains was used in conjunction with the findings from the point cloud survey. The results from the form matching analysis were corroborated with onsite ICHD testing. The locked in forces in the pedestals are unknowable as we do not know at what temperature the saddles seized. However, this is bounded within the analysis by considering either a high or low seizing temperature.
MM36	Section 9 – AECOM States, *'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'* This suggestion implies that justification of introduction of higher loads will be predicated on allowing significant further damage to occur within the pedestal which is a rather extreme course of action. Performing an analysis that is representative of the actual failure mode would require a greater understanding of the mechanical properties and potential variation thereof within the pedestal. Furthermore, the visual inspection has recorded a number of imperfections and manufacturing defects such as cold shuts and non-metallic inclusions/ areas where the sand mould has collapsed. The above combined with the likelihood for other hidden defects and the unknown level and distribution of residual stresses would affect the formation and propagation of cracks, thus making representative predictions hardly possible. The large number of caveats that would inevitably accompany such an analysis would result in conclusions that the duty holder would struggle to rely upon. However, the latest MM refined analysis offers an approach where favourable conclusions are drawn, based upon relative changes in stress and overall behaviour at cracks. The aforementioned unknowns in mechanical properties, manufacturing defects and bedding recede in importance, thus providing far more reliable findings.
MM37	Section 10 – Crack NE10, AECOM States, *'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.'*

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	It is noted that there is not a perfect correlation with the located source of the emission although an AE event was located at the front lower quadrant of the pedestal and upon inspection, propagation of NE10 was confirmed with NDT within this vicinity. There could be some debate over how much reliance should be placed on monitoring data, particularly for locating the source of an AE event within a cellular, cracked component with relatively complex geometry. Regardless of this, the fact is that a crack has been confirmed to have propagated between April and August 2020. It is more probable than not that this defect occurred when the pedestal was most highly stressed, which we know to be during the period of sustained hot weather in August. This is supported by either the MM hypothesis for a localised hard spot or the Norman Fleck hypothesis for tension generated by shear in the holding down anchors. If AECOM have an alternative hypothesis, then this should be shared so it can be investigated.
MM38	Section 10 – Crack NE10, AECOM States, *'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.'* Whilst this would be possible, there may be issues with insurance (for intrusive investigation) which need to be reviewed by LBHF before this work could be undertaken. It should also be noted that the refined MM analysis investigates a propagation through the full thickness on one side which is conservative. Refer to report 417457-MMD-HSB-REP-SE-RA-000001.
MM39	Section 10 – Utilisation Factors, AECOM States, *'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.'* As per comment MM10, AECOM should review this statement.
MM40	Section 10 – Mitigation Measures, AECOM States, *'temperature control of the pedestals and adjacent chain section has been under consideration for since March 2020'* MM first proposed the temperature control system in November 2019 and produced a performance specification in December 2019.
X1	Section 3.1 - AECOM questions, *"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"* It is self-evident that the CCSO is less conservative than CS 470. Use of CS 470 would condemn the bridge as not a "monitoring-appropriate structure" (section 6.9) leading to permanent closure whereas the CCSO extracts the most benefit from available evidence that CS 470 ignores.
X2	Section 4.1 - AECOM states, *"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."* In fact the 'original CCSO has been withdrawn as it no longer applied since 13th August 2020 when the bridge was closed. It has not been 'replaced'. The latest CCSOs deal with river traffic and working on the bridge for the bridge in its current state.
X3	Section 4.8 - AECOM states, *"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"*. The issued CCSO was dated 29th October 2020 and does have some differences to that reviewed. However, the essence of the AECOM commentary is that

Ref	Comment
	loading in the "chains" is known. AECOM states, *"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."* The MM analysis is based on assumed upper and lower limits of temperature at which the rollers are assumed to have seized. It is possible to say that the applied loads remain unknowable but that through the analysis the unknowability recedes in importance. The ultimate stressed state is certainly not known because the residual stresses are not known. This leaves a position in which net 'unknowability' still applies. That does mean that caution must be applied in making decisions about exposing the public to associated safety risk (R2P2, Appendix 1, item 12).
X4	Section 8.1 - AECOM states, *"The CCSO should, however, include for review of the reasons why the bridge was closed, and include quantifiable mechanism to re-open the bridge."* Provision of criteria for re-opening is not the intended function of the CCSO. The intended function is provided by its name – Case for Continued Safe Operation, not Case for Future Safe Operation. Such thinking is provided for elsewhere via emergent and ongoing understanding from the various analyses and tests. It is the function of the CCSO to reflect that thinking once complete if it changes the criteria for ongoing continued safe operation. Once criteria set for that cannot be achieved the bridge is closed and the CCSO withdrawn as it is no longer required. The reason for closure of the bridge is that the bridge could no longer comply with the no-change criterion for acceptably safe continued operation set by the previous CCSO (because existing cracks extended) which was withdrawn on 13th August 2020. The matter is also discussed in section 8 of the current CCSO.
X5	Section 9, Main Risks - AECOM states, *"CCSO has not followed normal practice for management of sub-standard bridges – risk that something has been missed."* The choice of a CCSO over CS 470 was deliberate as CS 470 would lead to permanent withdrawal of the bridge without being able to take advantage of the evidence that CS 470 ignores. A CCSO is based on the principles of safety risk ALARP (assessed by any means, include a Code such as CS 470, by first principles, or, as here, by deduction) but recognising that R2P2 issues specific warnings against the use of Codes because they are *"likely to be regarded as insufficient if the hazard requires an absolute and/or prescribed duty to deal with it."*. That situation applies here where there is an absolute requirement to be met. This is consistent with the general principle that compliance with a standard cannot, of itself, provide adequately low safety risk other than within its own narrow constraints of use, or otherwise by happenstance.
X6	Recommendation 12 - AECOM states, *"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"* No, it shouldn't. The purpose of the CCSO was to explain the rationale, and to provide controls, for safe operation while the bridge was at that stage of its life. The bridge is closed so the document has served its purpose.
X7	Recommendation 13 - AECOM states, *"Prepare a CCSO to permit limited (or greater) access for pedestrians"* That is not possible until the remedial works have been carried out as the CCSO makes clear. AECOM has provided no case or evidence, other than notional assertion in this recommendation, that it may be possible. If AECOM wishes to prepare such a case and is willing to take on duty holder risk in applying it, it can be considered. In Appendix C of its document, at item 8.5, that issue is discussed in respect of which AECOM states, *"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"*. We agree, it is unworkable, so this recommendation appears to be at variance with AECOM's own comments.

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X8	Appendix C – The version reviewed is not the issued version which was dated 29th October 2020. Some paragraph numbering has been changed and a number of detailed issues in AECOM's commentary are no longer relevant due to the updated content. AECOM's commentary also ignores the fact that the CCSO is not a procedure – those have been developed by duty holders (Hammersmith and Fulham, its contractors, and PLA). One issue which appears in the commentary, and elsewhere, directly or indirectly, is the question of why it was possible to have pedestrians on the bridge between 11th April 2019 and 13th August 2020, and not after that latter date. The matter is dealt with in the CCSO (29th October 2020) items 8.2 to 8.12, the essence of which is, "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." Whereas some of the items leading to uncertainty have now been reduced in uncertainty, that does not apply to all and enough uncertainty remains to continue to follow the principles in R2P2, Appendix 1.
WSP14	Note: Page numbering for the following comments corresponds to the page number within the pdf file rather than the page of the document. Page 17, 3.1, 3rd paragraph. This states that the CCSO has been used to the various issues relating to the continued closure of the bridge. Since August 2020, this CCSO has been withdrawn. It is not being used to keep the bridge closed; rather, there is no document currently in place to keep the bridge open other than to limited vessel movement and for the workforce
WSP15	Page 27, section 4.2.3, 4th bullet on the page. This states the main reason for the reduction in UF from the original assessment was through the accumulation of data, which allowed MM to relax some of their original assumptions. This should be confirmed by MM, but it is understood that the data allowed MM to calibrate some of their assumptions, particularly in terms of the soil stiffness parameters and rotation of the pedestal, to obtain better agreement of chain force variations between the model and strain gauge measurements.
WSP16	Page 28, second paragraph below "AECOM comments". The report discussed here is the post-blast inspection report from April 2020. We agree with AECOM's view that the cracks have been shown to not necessarily be stable given the growth of NE10 in August 2020, hence the CCSO being withdrawn following that event. However, at the date of the report, indications were that the cracks were stable.
WSP17	Page: 38, 6.1 Introduction – AECOM recommend MM develops the potential failure mode of the bridge and that this is checked independently. MM have looked at collapse scenarios and presented this in the past to the Taskforce. For the same reasons as given by AECOM, have advised it is only possible to offer a high-level "what-if" scenario rather than a more detailed analysis
WSP18	Page: 38, 6.2 Loading, bottom paragraph. There is a comment that 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. MM can confirm, but it is understood this phenomenon was observed by the temperature gauges on the chains, with evidence of heat conduction down the buried portion of the chain.
WSP19	Page: 39, 6.2 Loading, paragraph below Fig 6.2. Assuming a similar chain temperature range as was experienced last year (albeit that appeared to be a relatively mild year) from -2 degrees C to 24 degrees C, and an initial fixing temperature of 15 degrees, there would have been at least 3-4mm of movement towards the river and at least 6-7mm towards the anchor from this fixed position. MM can confirm what diurnal variation has been observed, and whether this is in line with the 2-3mm stated in the text. Over the course of a year, the chain would have moved by 10-11mm within that range. However, again, indications are that last year was relatively mild so greater movement would have taken place during more extreme temperatures.

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WSP20	Page: 40 6.2 Loading, sentence at the top of the page. This has been done and incorporated into the latest MM analysis and used to derive upper/lower bound soil parameters (eg springs) and this was calibrated against strain gauge measurements.
WSP21	Page: 41 6.3.2 Description of the model, second paragraph. AECOM have assumed a CoF of 0.5 between the cast-iron and the York stone. MM have carried out model calibration to test the coefficient of friction against observations and this suggests a higher CoF gives a better comparison with the measured response.
WSP22	Page: 41 6.3.2 Description of the model, third paragraph. AECOM describe having applied a normal force of 3.7MN and a shear force of 2.0MN on the pedestal. The analysis described shows that, with rotation/ displacement of the pedestal, the shear force reduces. This behaviour is accepted. However, the 2.0MN shear load applied, which is taken from MM's refined analysis of the SW from Jan 2020, already takes this behaviour into account as it is the result of the calibration exercise done earlier. The force in question compared well with the strain gauge measurements. Prior to this, the shear force applied was much greater.
WSP23	Page: 43 6.3.4 Discussion, paragraph at top of page. This states the uncracked pedestal model is not highly stressed adjacent to crack NE10 in the direction perpendicular to the crack, and that the stresses do not increase significantly when the cracks in the pedestal are modelled. The refined analysis from MM also finds that the zone surrounding crack NE10 does not have tension. Yet, crack NE10 extended and there must therefore be a cause for this. MM and Prof Fleck have provided hypotheses that may explain why NE10 has propagated; MM suggesting a potential hard spot beneath the pedestal, and if this hypothesis was true, modelling confirms a zone of tension would result at the location of NE10, and Prof Fleck presenting a simplified solid-body diagram that shows how tension could develop in this region. We still don't know with confidence why the crack has extended, but there is high confidence that it has extended.
WSP24	Page: 43 6.3.5 Conclusions, first paragraph. The text states that modelling is very sensitive to boundary conditions and recognises that MM faced similar challenges. This is also the view of Prof Fleck and therefore this can be considered a matter of agreement. It is therefore difficult to explain with certainty what is observed on site. Some assumptions can be bounded or calibrated to provide confidence that the real situation is captured, but there are certain aspects, for example, non-uniform bedding, which will be very difficult to confirm and yet have a significant impact on analysis results.
WSP25	Page: 43 6.3.5 Conclusions, second paragraph. See earlier comment WSP22. Our understanding of the work my MM is that the 2MN load was obtained from an exercise to calibrate the boundary conditions such that the resulting variation of chain forces with temperature would compare well with strain gauge measurements against temperature. This is therefore not a hypothetical load that will not be able to be reached in reality because the pedestal rotates; pedestal rotation is accounted for in deriving the 2MN load.
WSP26	Page: 43 6.3.5 Conclusions, last paragraph. This recommends that MM should develop the conclusions further. MM have recently carried out refined FE analysis, with and without the measured cracks, and applied UB / LB parameters to boundary conditions, and there are some similarities in the findings, but one key difference is in the magnitude of the applied shear load. AECOM also recommends that this is independently checked and this has not been done yet.
WSP27	Page: 44 6.4.2 Crack Growth, second paragraph beneath Fig 6.9. This hypothesises that none of the cracks, with exception of NE10, have propagated beyond the outstand because it would need to transform from a narrow outstand into a broad front in order to grow further and that this would require significant energy and stress levels. However, this is a hypothesis only and no validation/analysis has been carried out to support this hypothesis. Furthermore, this doesn't explain why crack NE10 has propagated.

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WSP28	Page: 45 6.4.2 Crack Growth, last paragraph before 6.4.2 (which should be 6.4.3) Holding down bolt failure. The text suggests that even if the pedestal was cleaved into an upper and lower part it would only slip a little longitudinally to balance up the chain forces. Does this consider that the normal reaction from the saddle is not vertical but inclined. If the pedestal is cleaved, would the longitudinal component of this load not move the pedestal even further unless there was sufficient friction restraint? Furthermore, it the cruciform ribs are not aligned, will the pedestal still be able to carry the normal force?
WSP29	Page: 49 8. Log of Further Queries, A1. The CCSO in question here was withdrawn as the conditions for it were not met. It also appears that the document reviewed was not the latest as, due to the practicalities of carrying out the inspection during the lockdown restrictions, the need for ongoing routine visual inspections was reviewed and it was deemed that more reliance should be put on the AE system, with visual inspections reduced to reactive inspections only.
WSP30	Page: 49 8. Log of Further Queries, A3. This may be possible; however, this may require discussion with regards the bridge insurance, which a number of activities could potentially invalidate.
WSP31	Page: 49 8. Log of Further Queries, A4. Based on CS470, the bridge did not meet the conditions for a monitoring-appropriate structure, hence why it was not felt that the defect could be safely monitored to the point of allowing public on the bridge.
WSP32	Page: 50 8. Log of Further Queries, A9. The basis of the assumption is that this was a temperature within the range that was measured during the monitoring period. This is itself a departure from the values recommended in the code. As the analysis strips out factors of safety, etc, there must remain some allowance for uncertainty such that the analysis remains robust, and too narrow a range of temperature would not provide this. Assumptions with regards temperature have been reviewed as part of the latest refined analysis by MM.
WSP33	Page: 50 8. Log of Further Queries, A10. There is no reduction in the risk after the more refined analysis of the pedestal had reduced the UF because: a) it was only for one of 3 pedestals; b) it was not independently checked and c) it was deemed to have mitigated what would otherwise have been an increase in risk due to TTT works.
WSP34	Page: 51 9. Summary of main risks and opportunities. Second main risk. We agree, which is why these have not been included in the analysis models. Their inclusion could alter the conclusions, hence one reason why results must be treated with caution.
WSP35	Page: 51 9. Summary of main risks and opportunities. Fourth main risk. The CCSO goes beyond CS470 as, if following CS470, the bridge would have had to be closed to all indefinitely. Depart from it, on the basis on R2P2, was necessary to allow a managed limited reopening of the bridge after April 2019 in the first instance and since Aug 2020 to vessels and workforce in a controlled manner. But this is a risk, particularly given the unknowns, hence why the bridge is not open to pedestrians and cyclists
WSP36	Page: 51 9. Summary of main risks and opportunities. First opportunity. There is query as to why the discovery of additional cracks in April 2020 was not enough to close the bridge but the extension of one crack in August 2020 was used to close the bridge and is being used to keep it closed. The additional cracks discovered in April 2020 were investigated and deemed to have been historical cracks and therefore not a result of "live" deterioration. There were indications to this effect, and an absence of AE signal emanating from their locations. Therefore, the condition of “no change” to pedestal, upon which the CCSO was predicated, remained valid. The extension of a new crack was a sign that something had happened / was happening, and a clear "change". As the CCSO was predicated on "no change", this was no longer the case and the CCSO was withdrawn. A case for reopening the bridge to pedestrians/cyclists has not been made as it was not possible to state that the bridge, in its condition post the August event, was stable (see comment 3 earlier) or that it had safely resisted the applied loads in that condition for some time previously. CCSOs have been implemented for limited controlled operation only where it is deemed possible to

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	demonstrate that the risk is ALARP. It was not thought that this was possible for pedestrian movements on the structure.
WSP37	Page: 51 9. Summary of main risks and opportunities. Second opportunity. Comment that extension of crack NE10 may not be as serious as previously thought and that it is not possible for it to propagate any further. If we do not understand with confidence why the crack grew in August, how can the statement that "it is not possible to propagate further" be substantiated?
WSP38	Page: 51 9. Summary of main risks and opportunities. Third opportunity. Bounding scenarios combined with modelling assumptions have been used in the more recent analysis, but, as concurred in this report, this is very sensitive to the applied boundaries, which are themselves assumptions. The assumptions need to consider a wide enough range of temperature, given the unknowns, such that the analysis remains robust.
WSP39	Page: 53 10 Conclusions. Crack NE10, top of the page. This comments that the growth of crack NE10 between April and August 2020 may not necessarily be connected with the high temperatures seen in August 2020. However, the growth of a crack to this extent without accompanying AE signal is unlikely. Crack NE10 was inspected in detail after the pedestal was blasted so there is confidence that it has grown, and given the above, the likelihood is that this was associated with the event that led to the AE signal in August.
WSP40	Page: 54 10 Conclusions, CCSO. The text comments that the CCSO has been used to justify closure of the bridge and may be too conservative. The CCSO was withdrawn, so it is not used to keep the bridge closed. It was predicated on "no change" in the condition of the bridge and as a change has happened, this basis is no longer true. CCSO to reopen the bridge partially to vessels and workforce are in place. A CCSO to reopen to pedestrians and cyclists has not been developed due to unknowns and uncertainty and, whilst it may be true that additional knowledge has been gained since, it is not certain that a case could be made to demonstrate the risk is ALARP in this case. It would need to be demonstrated that the current situation is safe/stable, that the risk is ALARP and that there is no change from that condition. There are practical issues in implementing this whilst keeping the risk ALARP, and as recognised later in AECOM’s report, these may be unworkable.
WSP41	Page: 56 11 Recommendations. Recommendation 1 states it is imperative to complete the removal of the casings and blast-clean and inspect the western pedestals. This is being mobilised on site now. The view with regards the additional cracks discovered in the pedestal is not only that they were historical due to not being visible through the paint but also that there had been no corresponding AE signal.
WSP42	Page: 56 11 Recommendations. Recommendation 2 regards a strategy for responding to the inspection results following the post-blast inspection. The strategy would remain as it has been for any defect identified since the original CCSO has been in place, ie determine if the defect appears historical and whether there has been any AE indications of cracking in the locations in question, and take an holistic view of the pedestal at that time (eg if there is a large number newly identified cracks or any of the cracks are long or wide then perhaps operation of the bridge needs to be restricted further). Currently, there is little that can be done as the bridge is closed at most times so the worst outcome would be that the bridge remains closed to navigation and potentially with stricter controls on workforce. The action plan if the condition of the pedestal is alarming remains to stabilise the pedestals as soon as possible, for which a design is near completion and an independent check is under way.
WSP43	Page: 57 Recommendations. Recommendations 12 and 13. I believe further revision to the CCSO was made later than March 2020. However, with the “change” in August 2020, that CCSO has been withdrawn. New CCSO have been prepared for limited vessel passage and for the workforce. A new CCSO would need to be prepared to allow use of the bridge by pedestrians, and this would need to demonstrate that the risk is ALARP. The recommendation for more frequent visual inspections was removed in a later version of the CCSO.

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WSP44	Page: 72 Detailed review of CCSO for Limited River Traffic, 4.5. CS470 leads to the conclusion that this is no longer a "monitoring-appropriate" structure, whereas a case could be made for it prior to Aug 2020.
WSP45	Page: 72 Detailed review of CCSO for Limited River Traffic, 4.5. The safety risk may be reduced to an acceptable levels for vessels, which can be readily controlled and are only exposed for very short amount of time with very few people on board. Similarly for the workforce, who may be exposed for longer, but will have a defined evacuation procedure and rapid alert measures. This isn't the case for pedestrians.
LBHF1	Section 5 – Materials, AECOM States, *'It is not clear if the rollers are made from wrought iron or steel.'* It is known that the rollers are made of steel. Inspections as far back as 1959 by others have highlighted the roller bearings at the deviation saddles to be seized. A principal inspection for assessment in 2014 by Hyder similarly highlighted the roller bearings to be seized at both the tower saddles and deviation saddles. The bearings to the tower tops were replaced during the 1990's strengthening work (by Hyder/AECOM) as a result but the detrimental effects of seized roller bearings at the deviation saddles does not appear to have been considered and no remedial works were specified at that time. What was the reason for not addressing the seized roller bearings of the abutments during 1990's strengthening works? Despite seizure of the roller bearings being reported on numerous occasions in the past, the 2018 assessment appears to be the first time that this has been considered within a structural assessment.