MOTT MACDONALD

Hammersmith Bridge Refurbishment

Refined CI Pedestal Analysis at NE

November 2020

Confidential

EXECUTIVE SUMMARY ONLY

Executive Summary

Following a sustained period of hot weather in August 2020, propagation of cracking was detected and confirmed at the NE cast iron pedestal. This invalidated the Case for Continued Safe Operation (CCSO) for non-motorised traffic which is predicated on a steady state condition, hence resulting in the immediate full closure of the bridge to pedestrians, cyclists and navigation channels beneath. However, since the previous analysis for the pedestals was undertaken in January 2020, site investigations, monitoring and further refined analysis have enabled a much better understanding of the behaviour of the pedestal including the recorded defects. Furthermore, a temperature control system, capable of actively moderating the load demand on the pedestals (instructed in August 2020 and commissioned in September 2020), provides some mitigation. This report summarises the latest field gathered data and presents the findings from the recent analytical study into the behaviour of the damaged NE pedestal, including the impact from the recent crack propagation and the stabilising effect from the temperature control system.

The key objectives of this study are listed as follows:

- Incorporate the latest field-gathered data into the analysis of the NE pedestal, including calibration of the model against records from the enhanced monitoring system and consideration of the full cracked condition at the NE pedestal.
- Investigate the stressed state of the pedestal, including the uncracked condition and any stress redistribution associated with cracking.
- Investigate the behaviour at the recorded defects and the potential for uncontrolled propagation of cracking leading to catastrophic failure of the pedestal.
- Provide a hypothesis for the recent crack propagation at NE10 and review the impact on the rest of the pedestal.
- Investigate the influence of the temperature control system and its impact on stressed state in addition to the behaviour at cracks.

The analysis and assessment documented within this report has been undertaken with due skill and care and has been the subject of a thorough Mott MacDonald technical peer and challenge review. However, it should be noted that the information presented herein has not been subject to an independent check.

The 2D Plane Stress model has been updated to incorporate the as surveyed arrangement of padstone blocks beneath the pedestals and to include refined estimates of stiffness for the various materials (incorporating the findings from ground investigations). The refined analysis of the NE pedestal has considered the scenario of extreme temperature, including the effects of pedestrians and cyclists but excluding the effects of motorised traffic. The pedestrian/cyclists loading is considered along the footways only and with the magnitude defined at the overall bridge assessment phase. No account is taken of any other loading whether associated with refurbishment or other activities on the bridge.

Comparison of the analytical results with records from the enhanced structural monitoring system (commissioned in July 2020) indicate that movement is generally accommodated by tipping of the pedestal rather than sliding at the base (i.e. friction is not overcome between the padstone blocks). The lower-bound (LB) estimate of foundation and ground stiffness parameters provides the best correlation with the measured response although considering a reduced seizing temperature for the saddle, a similar correlation can be achieved with the upper-bound

(UB) estimate of stiffness parameters. It is not possible to reliably calibrate intermediate stiffness parameters between the UB and LB estimate, over the available window of monitoring data. Therefore, both the UB and LB stiffness estimate are considered throughout all analyses undertaken. The reality will be somewhere between these two cases although the above approach enables a robust envelope to be evaluated for assessment purposes.

The two key assumptions considered within previous analytical studies for the pedestals have been addressed and removed within the refined analysis:

- The absolute magnitude of restrained force on the pedestal is unknowable as there is no way of determining the temperature at which the saddles seized. This unknown is addressed by considering an upper bound design range on temperature and considering two cases; first the saddle seizing at a minimum low temperature (maximising a restrained force towards the river [+T]) and second, the saddle seizing at a maximum high temperature (maximising a restrained force towards the anchorage [-T]). The reality will be somewhere between these two cases although the above approach is robust and enables an envelope to be evaluated for assessment purposes.
- Following blast cleaning of the NE pedestal back to base metal, a 100% visual inspection supplemented by MPI has been undertaken to identify all cracks (of any significance) within the casting. With the exception of superficial surface breaking defect NE1, all 12no. discovered cracks are explicitly incorporated within the 3D shell model analysis.

Extensive sensitivity analysis has been undertaken to minimise other previous assumptions although some residual assumptions remain around manufacturing defects and uneven bedding (refer to Section 3.4) and hence the absolute stress magnitude should be treated with caution. However, as the conclusions drawn within this report are based upon relative changes in stressed state and overall behaviour, these residual assumptions recede in importance.

For a restrained force either towards the river or towards the anchorage, and for either UB or LB stiffness parameters, the zones where the UTS of 80MPa or the permissible compressive stress of 154MPa are exceeded are very localised at the openings in the web plates. Following the introduction of cracking, there is a slight increase in peak stress (<3MPa increase) as stresses redistribute. Following the introduction of temperature control however, there is a significant decrease in peak stress for all cases, with the reduction ranging from approximately 11% (UB) to 40% (LB). For the case of LB stiffness parameters, following the introduction of temperature control, the peak tensile and compressive stress for a restrained force both towards the river and towards the anchorage drop below the UTS and permissible compressive stress limit. However, this result should be treated with caution due to the presence of any residual tensile stresses from the manufacturing process. The conclusion that can be drawn however, is that the temperature control system is effective in maintaining a stressed state that is significantly less onerous compared to the one that has been experienced by the pedestal previously.

When even bedding is assumed beneath the pedestal, the top face of the base plate at the location of defect NE10 remains in compression. This contradicts the recent propagation of NE10 into the top face of the base plate during the August heatwave. One hypothesis for this is that there is a localised hard spot beneath NE10 (e.g. presence of a metallic shim within the mortar bed during construction). Therefore, a comparative analysis has been performed incorporating a local hard spot. This analysis shows significant tensile stresses are generated in the top face of the base plate due to local flexure at the location of NE10, hence validating this hypothesis as a possible explanation for propagation. Following the introduction of NE10 propagation, tensile stresses at the top face of the base plate are largely relieved and there is little redistribution of stress to the surrounding areas. Excluding some very localised zones, the change in the overall stressed state of the pedestal as a result of NE10 propagation is insignificant (< 1MPa change). Even if it is conservatively assumed that the crack at NE10 has propagated through the full thickness of the base plate on one side, the impact on the overall stressed state is negligible. The analytical investigation presented herein indicates that the inclusion of the recorded defects and the recent propagation of NE10 have very little effect on the overall stressed state of the pedestal and, the ability of the pedestal to resist loading (as observed prior August 2020) is effectively maintained.

The behaviour at each of the 12no. investigated cracks has been individually examined to understand whether there is a risk of uncontrolled propagation leading to catastrophic failure of the pedestal. The analysed stresses at the tips of the modelled cracks are highly influenced by modelling features and relative mesh density and are therefore not representative although the stress field within which the cracks are situated is adequately captured. The modelling philosophy adopted is not intended to explicitly investigate stresses at the tips of the cracks but to provide a conservative estimate on the likelihood of unacceptable propagation, at least by the time they reach the vertical rib plates. There are a few instances where the tips of the cracks reach large sections of such lightly stressed material that there is no cause for continued propagation. The introduction of the temperature control system tends to close the cracks further and introduce additional clamping, improving the situation in all instances. The investigations into the behaviour of the recorded and potentially extended cracks, indicate that the application of an active temperature control system minimises the potential for further deterioration of the casting and significantly reduces the risk of uncontrolled crack propagation; thus minimising the risk of progressive failure.

The temperature control system is currently set at a target temperature of 13.5^{o}C. This should be adjusted at the NE pedestal in-line with the analysis to match the average of the newly derived maximum (high) and minimum (low) seizing temperature of 24^{o}C and -2^{o}C, respectively (i.e. 11^{o}C target temperature).

This report documents the refined analysis for the NE pedestal but there are another 3no. pedestals with different defects pattern and ground conditions. Whilst there are clearly similarities in behaviour at each of these pedestals, conclusions cannot be reliably drawn on these remaining pedestals until blast cleaning and 100% visual and MPI examination are complete. It will be prudent to undertake a study to calibrate the response at the remaining pedestals in advance of the findings from the post blast inspections.

mottmac.com