Considerations on cracking of the Hammersmith Bridge pedestals

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6 November 2020

Brief

Prof. Norman Fleck (NF) was approached by David Coles of Dept. for Transport to perform a technical review on the state of health of the Hammersmith Bridge pedestals. NF has extensive practical and theoretical expertise on the fatigue and fracture of engineering materials. The brief is to consider the various technical reports by consultants (such as Mott MacDonald (MMD)) and to provide independent advice on the structural integrity of the pedestals.

The current state of health of the North-East (NE) pedestal

The state of cracking in the North-East deviation-saddle pedestal has been investigated by Mott MacDonald (MMD) and associated consultants. Cracks have been observed in the grey cast iron pedestals emanating from stress raising voids within the webs (and transverse diaphragms) of the pedestal casting. The position of these cracks in the NE pedestal are summarised in Fig. 1. These cracks may have formed as a result of residual tension during differential shrinkage when the pedestals were cast, in combination with subsequent loading on the pedestals from the deviation saddles. Grey cast iron has a low tensile strength and low fracture toughness: once a crack has initiated, it grows easily.

Crack NE10 in the NE pedestal underwent detectible crack advance in August 2020, as indicated by Acoustic Emission monitors; this cracking event was associated with a period of high temperature. Consequently, on 13 August 2020, the bridge was closed to all road traffic (including pedestrians and cyclists) and to river traffic.

A thorough investigation has been conducted by MMD and by associated consultants into the state of cracking in the bridge, including blast-cleaning to remove all paint from two of the four pedestals and subsequent non-destructive testing. It revealed the presence of additional cracks in the NE cast iron pedestal of the bridge. Since grey cast iron has a low fracture toughness, the residual strength of the pedestals is reduced by the presence of cracks.

The precise magnitude of the loading on these pedestals is unclear as the roller bearings between the deviation saddle and the underlying pedestal have seized at some historical date (perhaps decades ago). Seizure of the bearings allows for the presence of differential tension between the suspension chains and the anchor chains, and this differential, out-of-balance tension provides additional loading on the pedestals via the deviation saddle. The working hypothesis is that this out-of-balance force led to the extension of crack NE10 in August 2020.

13 distinct cracks exist in the NE pedestal, with none found in the SE pedestal. (MMD have suggested that "the condition and quality of the casting appeared to be better that that of the NE pedestal."[1]).

[1] MMD Report "Hammersmith Bridge Cast Iron Pedestals Post-blast inspection report NE & SE (06-Apr-20 to 09-Apr-20)" 20 April 2020. Document Reference 417457 | MMD-HSB-REP-PBI-000001 | 01

The cracks can be summarised as follows:

(i) Cracks initiated in a zone of local tension due to loading *towards span*: NE1, NE2, NE3, NE 4, NE8, NE9, NE11

(ii) Cracks initiated in a zone of local ***compression*** due to loading *towards span*: NE5, NE6, NE10

(iii) Cracks initiated in a zone of local tension due to loading *towards anchorage*: NE7

(iv) Cracks in the transverse diaphragms in a zone of tension due to loading towards span or anchorage: NE12, NE13.

Loading of the pedestals

Prior to seizure of the deviation saddle bearings, the pedestals were subjected to normal 'permanent dead loads' but zero net tangential loads and zero bending loads. After bearing seizure, the pedestals were also subjected to:

(i) Live traffic loads and pedestrian loads via tension in the suspension chains.

(ii) Thermal expansion and contraction of the anchor chains. This leads to a corresponding drop or increase in tension in the anchor chains. Note that thermal expansion and contraction of the suspension chains (river-side) leads to only a small change in the tension of the suspension chain; this expansion/contraction merely changes the height of the bridge deck (via the vertical hangers).

MMD have conducted a thorough stress analysis of the North-East (NE) pedestal, and have highlighted the relative sensitivity of the stress state within the pedestal to the thermal loads in the anchor chains and in the suspension (river-side) chains. They have calibrated the finite element model using the available data of chain force versus chain temperature. MMD have also highlighted the sensitivity of the stress-state within the pedestal to the assumed boundary conditions along the bottom face of the pedestal. For example, a non-uniform support condition along the bottom of the pedestal (due to uneven foundations) can induce local bending of the bottom plate of the pedestal in the vicinity of the NE10 crack.

The suspension chain load is known to acceptable accuracy (from MMD's non-linear global model of the suspension bridge, or from a catenary analysis and a knowledge of the sag of the suspension chains). It is much more difficult to determine the magnitude of any residual thermal load within the anchor chains following seizure of the roller bearings because the temperature at which the bearings seized is currently unknown.

Findings

1. The chains, pedestal, pedestal-foundation and anchor foundation each have a high stiffness, and consequently the stored elastic energy in the system is very small due to a temperature change. The stiffness of each component can be deduced from the MMD reports, and for the sake of simplicity, we neglect here the additional non-linear compliance associated with rotation of the base of the pedestal.

Consider, as an example, a 10°C temperature drop of the anchor chains, and an anchor chain length of L=27m. The thermal expansion coefficient of steel is on the order of 1.3 x 10^{-5} /°C, and consequently the thermal shortening is 27m x (10 °C) x (1.3 x 10^{-5} /°C) = 3.5 mm. The induced axial force in the sum of the top and bottom chains is on the order of F=600kN (from Figure 5.14 and Table 5.6 of the MMD calculations[2] of stiffness of chains, pedestal, pedestal-foundation and anchor foundation, but no rotation of pedestal). If pedestal rotation occurs (due to a sufficiently large temperature excursion) then the axial force is reduced by the presence of rotation. Thus, the stored elastic energy is very small: it is of order 0.5 x 600kN x 3.5mm = 1kJ per chain. For comparison, a 100kg object has a potential energy of 1kJ by lifting it by 1m.

These small displacements imply that the sudden release of the roller bearings will not move the saddle or the pedestal by more than a few millimetres. The stored energy is negligible due to temperature excursions.

2. The sudden release (by freeing) of the anchor chains can release them and send a stress wave through the pedestal. (Think of the sudden tapping a cracked wine glass.) The dispersion of elastic waves throughout the complex geometry of the pedestal may lead to some additional cracking. Thus, it is important to stabilise the pedestals prior to release of the roller bearings.

3. *Conjecture on the reason for advance of the crack NE10 within the pedestal.* The cracks in the pedestals are either casting defects (such as hot tears) or tensile fractures at some stage over the lifetime of the bridge. It is very difficult to distinguish between fatigue crack advance by cyclic loading (traffic loads and thermal loads) and by a tensile overload. (The visual appearance of a fatigue crack is very similar to that of crack advance under monotonic loading). For both types of loading, the crack growth direction is along the direction of maximum tensile stress.

It is noted that the cracks in the NE pedestal are isolated from each other, and there has been no observed case of a crack penetrating beyond the central web of a cruciform section. The many large voids within the faces of the pedestal endow it with a 'wine-box' construction and provide some redundancy: one or more cruciform sections can crack without failure of the whole pedestal.

Crack NE10 advanced in August 2020 (an acoustic event recorded this), and it is important to develop an understanding for, and confidence in, the reason for this crack advance. The crack advance indicates the presence of local tension in this zone of the pedestal. The generally accepted working hypothesis is that local tension within the cracked region of the pedestal is associated with the development of a net suspension chain force (towards the river) due to a thermal relaxation of the anchor-chain tension associated with its thermal expansion. The net chain force develops because the rollers between deviation saddle and underlying pedestal are seized (by corrosion).

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 tension on

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[2] MMD report: Hammersmith Bridge Refurbishment Revised CI Pedestal Analysis for Ground Movements Induced by Thames Tideway Tunnel 38388-MMD-HSB-RE-SE-RA-000008 29 January 2020

each 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. 2. A small rotation of the pedestal about the toe will alleviate the tension imbalance in the chains: this is beneficial as it leads to a reduced level of stress in the pedestal. Likewise, any small displacement of the pedestal towards the river will relax the imbalance in chain tension.

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 – see Fig. 3). If a large shear force were to develop at the toe of the pedestal, then there is no clear reason why tension would develop in the vicinity of crack NE10. 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. This explanation is sketched in Fig. 2.

The placement of strain gauges and tilt gauges at judicious locations within the pedestal will give useful information on the stressing of the pedestal by temperature changes. Such instrumentation would also serve as a high-fidelity check of the MMD finite element model of pedestal behaviour as a function of chain temperature.

Recommendations

The immediate provision of a small sum of money would allow for immediate remedial action to be taken, regardless of longer-term plans for the repair and strengthening the bridge.

Short term solution

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.

1. In the short term, it would be possible to reopen the bridge quickly and cheaply for pedestrian traffic provided measures are taken to stabilise the cast iron pedestals by the following steps:

(i) Blast cleaning of the remaining 2 pedestals, and a visual inspection of the pedestals for cracks.

(ii) 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. By monitoring both the stress state within the pedestal, and the chain tension (river-side and anchor-side) as a function of daily temperature, an improved understanding of the relationship between stress state in the pedestal, chain tension and temperature can be established by direct measurement. The recent provision of temperature control of the anchor chains will allow for a series of simple tests to be performed whereby small temperature fluctuations (of a few degrees Celsius) can be applied in a controlled manner, and the resulting change in stress state of the pedestal measured.

(iii) Internally reinforce the pedestals by a selected means, such as the use of adjustable bracing props (or adding rebar and high-grade concrete) to strengthen it. If the pedestal has adequate stabilisation prior to roller release, then the action of roller release is unlikely to cause additional damage to the pedestal. The change in stress state due to roller release can be monitored by the strain gauges adhered to the pedestal.

Ideally, the above 3 steps should be conducted without delay, on a timeframe of weeks, and at modest cost. Pell Frischmann are in a strong position to comment upon the competing options for stabilisation of the pedestal, and upon the consequences of roller release on pedestal health.

Mid-term solution

Replacement of the roller bearings will require the erection of a substantial support structure to:

(i) carry the normal (compressive) dead load from deviation saddle onto the top of the roller assembly), and

(ii) carry the transient out-of-balance chain force during release of the roller bearings. Note that there will be no out-of-balance chain force if the temperature equals that for which the bearings have been previously released.

The external support structure of the pedestals could be temporary (for example RMD struts), provided internal reinforcement of the pedestal is also conducted. There is merit in probing Pell Frischmann for competing cost-effective solutions. Much of the decision on a preferred option is likely to depend on what works can be delivered quickest – the cost difference is likely to be relatively small.

Annex A: Figures 1 to 3

Figure 2.12: NE pedestal surface breaking defect and crack locations

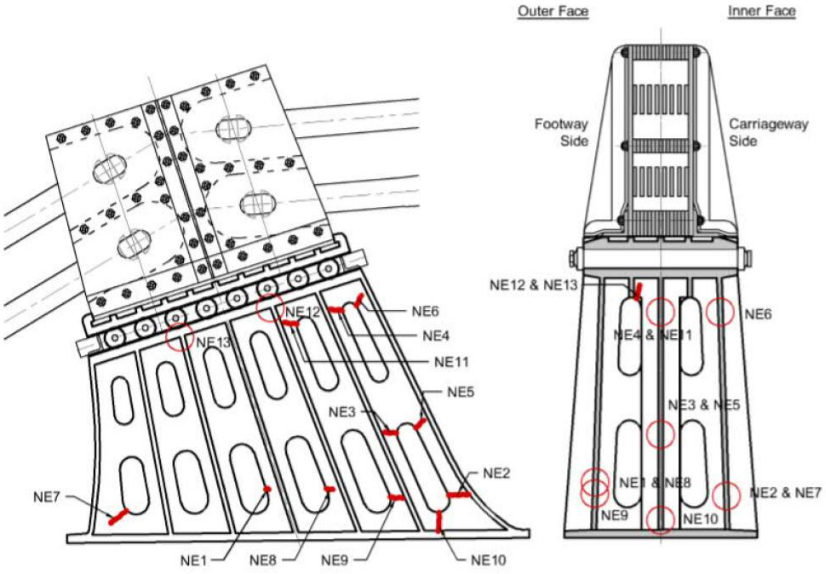

Table 2.1: Summary of NE pedestal surface breaking defect and crack locations

Defect	Location	Detail
NE1	East Web	Approx. 30mm long
NE2	West Web	Approx. 200mm long
NE3	Centre Web	Approx. 100mm long
NE4	Centre Web	Approx. 100mm long
NE5	Centre Web	Approx. 80mm long
NE6	West Web	Approx. 80mm long
NE7	West Web	Approx. 205mm long
NE8	East Web	Approx. 50mm long
NE9	East Web	Approx. 70mm long
NE10	Centre Web	Approx. 160mm long
NE11	Centre Web	Approx. 95mm long
NE12	Diaphragm 5	Approx. 140mm long
NE13	Diaphragm 3	Approx. 125mm long

Table 4.1: Summary of stressed state at crack locations and likely cause of each defect

Defect	Type	Stressed state	Restrained force direction	Likely cause
NE1	Surface break	Tension[1]	Towards span	Manufacturing defect
NE2	Through thickness crack	Tension	Towards span	Tensile rupture
NE3	Through thickness crack	Tension	Towards span	Tensile rupture
NE4	Through thickness crack	Tension	Towards span	Tensile rupture
NE5	Through thickness crack	Compression	Towards span	Fatigue crack
NE6	Through thickness crack	Compression	Towards span	Fatigue crack
NE7	Through thickness crack	Tension	Towards anchorage	Tensile rupture
NE8	Surface break	Tension[1]	Towards span	Manufacturing defect
NE9	Surface break	Tension	Towards span	Manufacturing defect
NE10	Through thickness crack	Compression	Towards span	Fatigue crack
NE11	Through thickness crack	Tension	Towards span	Tensile rupture
NE12	Through thickness crack	Tension	Towards span/ anchorage	Tensile rupture
NE13	Through thickness crack	Tension	Towards span/ anchorage	Tensile rupture

[1] – Stress of low magnitude

Fig. 1: The 13 cracks in the North East (NE) pedestal. Taken from MMD report 417457 MMD-HSB-REP-PBI-000001 01 20 April 2020.

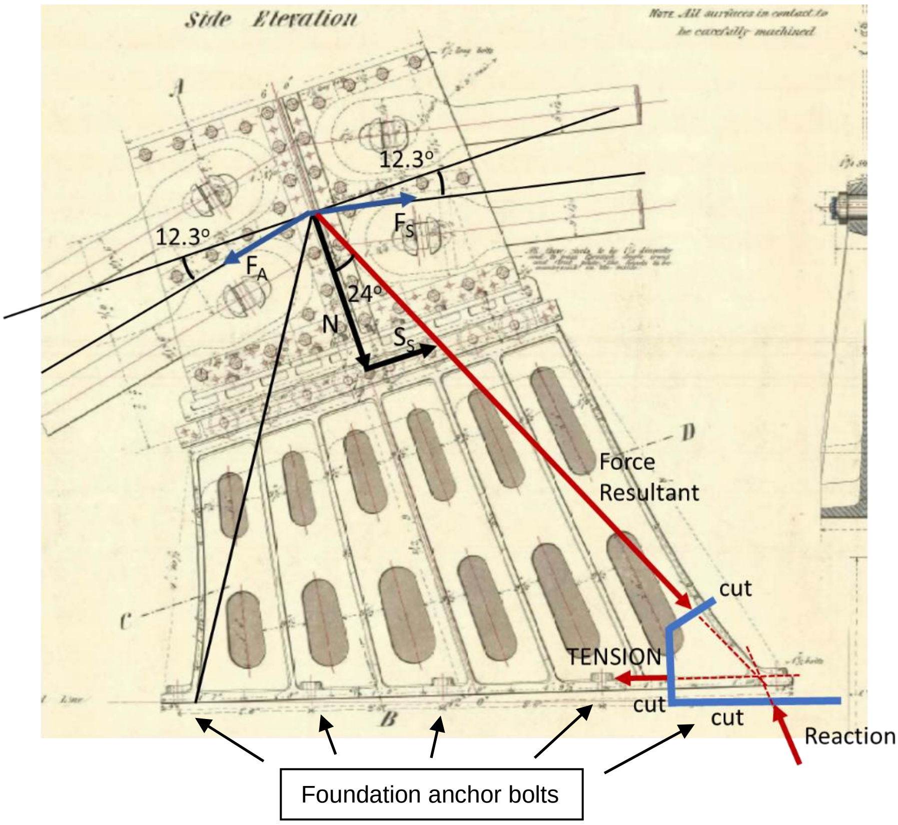

Fig. 2. The direction of the reaction force from foundation to pedestal dictates the level of tension at the location of the crack NE10 near the right-hand (river-side) toe of the pedestal. A free-body diagram of the forces on the right-hand toe of the pedestal due to a net chain force towards the river at high temperature (summer).

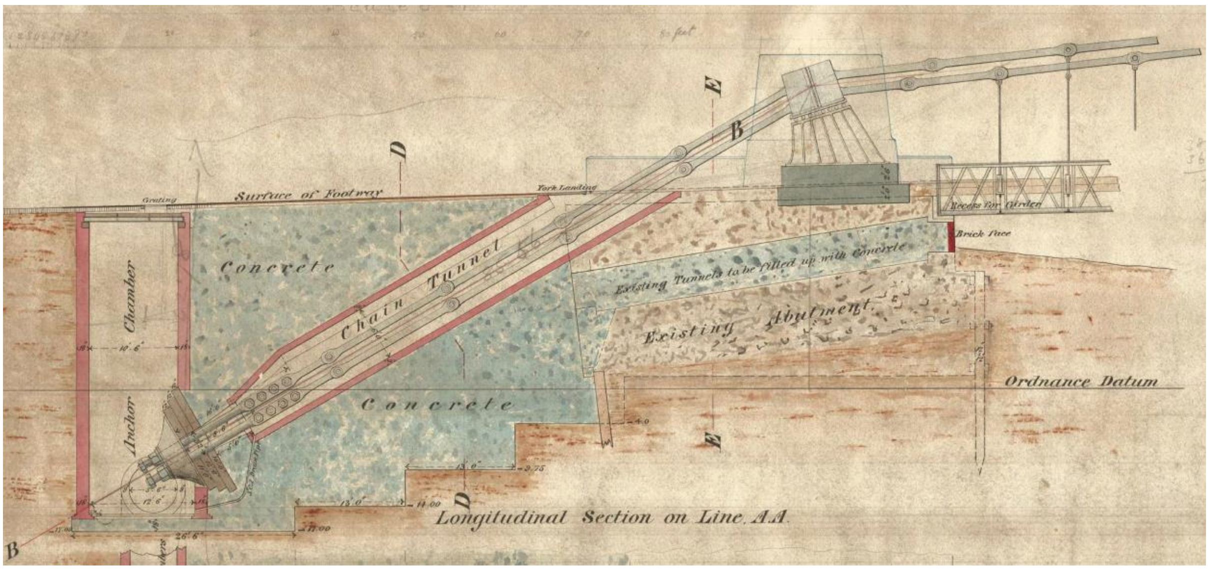

Fig. 3. An extract from the historic drawings showing the abutment arrangement. It shows the anchor chain arrangement and proximity of the pedestal foundation to the embankment wall / bridge deck girder seats.