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THE MODELLING, ANALYSIS AND ASSESSMENT OF THE IRON BRIDGE, SHROPSHIRE, UNITED KINGDOM

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Abstract. *The Iron Bridge in Shropshire, UK is the world's first iron bridge. Dating from 1779, it is a Grade I listed structure – the highest national category - and lies in a UNESCO World Heritage site in the Severn Valley at the heart of the Industrial Revolution.*

Custodian of the fabric English Heritage was concerned about the long-term stability of the structure given, amongst other factors, the extent of cracking in the cast iron and an increase in the depth of seasonal flood waters engulfing the bridge abutments. Detailed archive research on the nature and development of structural defects was undertaken. The findings were used to inform a detailed analysis of the structure to assess strength. The latter was based on geometry created from a 3D laser survey and, unusually, a 3D solid formulation so that stresses in the cast iron members and joints could be calculated directly, saving time and increasing accuracy.

The archive research, geometry modelling, structural analysis and strength assessment is described. The research provided information about earlier bridge movement and pre-existing cracks that was fed into the modelling process. The assessment led to recommendations that, amongst other matters, commented on permitted loading on the structure and the risk of failure from flood events.

1 INTRODUCTION

At the end of 2012, the UK's government body English Heritage commissioned a study for the modelling, analysis and assessment of load capacity of the Iron Bridge, in Shropshire, England. The structure was the world's first iron bridge and is widely regarded as an icon of the Industrial Revolution.

The main span was completed in 1779. The structure is a Scheduled Monument (UK National No. 27558) and Grade I listed and is located within the UNESCO World Heritage site in the Severn gorge in Shropshire. The study was to include an assessment of both the main span and the two later southern approach spans.

Figure 1: General view of the Iron Bridge

2 ARCHIVE RESEARCH

A desk study was conducted to research the history of defects in the principal structural fabric, to inform the work. This examined previous surveys and investigations, repairs to the ironwork and their efficacy. The desk study relied on available interpretation, inspections and reports and did not necessarily return to the primary sources.

As a pioneering and unique historic structure, the Iron Bridge has been the subject of extensive research, recording and archiving. The primary sources are all held in the UK: at the Shropshire Record Office, Ironbridge Gorge Museum and the National Monument Record in Swindon. These sources have been thoroughly researched, amongst others by David de Haan, author of the 2011 Conservation Management Plan[1], and by Neil Cossons and Barrie Trinder in their book 'The Iron Bridge, Symbol of the Industrial Revolution', revised 2002[2].

For the purposes of the study, visits were made to the archives at National Monument Record in Swindon and the Ironbridge Gorge Museum Archive. During the latter visit, detailed discussion was held with David de Haan and other references located. [3 4 5]

Almost all key interventions can be dated. The principal action on the bridge over its life has been the movement of the abutments, caused almost certainly by general instability of ground along the Severn gorge near the bridge. This has almost certainly given rise to many of the defects visible today, such as the deformation of the main arch; cracking in radial members and in other cast elements; movement and cracking in the stone abutments; apparent compression in one of the southern span deck beams; upward flexure of the main span deck causing cracking of the longitudinal deck bearer beams and the cracking of handrails. The development of cracking in the radial and other castings of the main span is recorded in a series of marked-up drawings held at the National Monument Record. This shows the extent of iron fractures present when the bridge was inspected in 1948, 1961 and 1980, and shows a general trend for the development of further cracks over that period.

The damage has resulted in the installation of various remedial structural brackets and plates, in particular the cast iron saddles on top of each of the ten inner verticals. The ground movement has been substantially stabilized by the installation in 1973-1974 of a reinforced concrete slab at river bed level forming a strut between the two banks at the location of the bridge. Monitoring of movement to show the effectiveness of this is on-going, but subsequent movements have been small.

The desk study revealed several attempts to measure the span of the bridge and monitor the inward movement of the feet of the main arch ribs. These are useful but not as conclusive as they might have been, as the datum point for measurement is in some cases not clear and cannot be correlated between studies.

Numerous surveys have been undertaken of the bridge. However, little engineering analysis appears to have been carried undertaken. An analysis was recorded in the text of the 1923 report by Basil Mott of consultants Mott Hay and Anderson, but calculations were not included in the archive record. This report led to the reduction in the road width.

3 GEOMETRY MODELLING

The recent commission required a full analysis and assessment of the bridge, to prove a load capacity and identify necessary repairs. As noted above, this was to be the first full strength assessment ever to be carried out on the bridge, and it was based on a very detailed model of the fabric.

The geometry was taken from a laser scan of the bridge structure, commissioned by English Heritage in 2012[6]. The bridge was scanned from 162 positions using a Faro Focus scanner and the bridge surroundings from 47 locations using a Riegl VZ400 scanner. For the bridge work the Faro scanner was mounted on a boom to achieve better sight lines. The survey was made available as a fully registered point cloud and contained approximately 1.1 billion xyz measurement points.

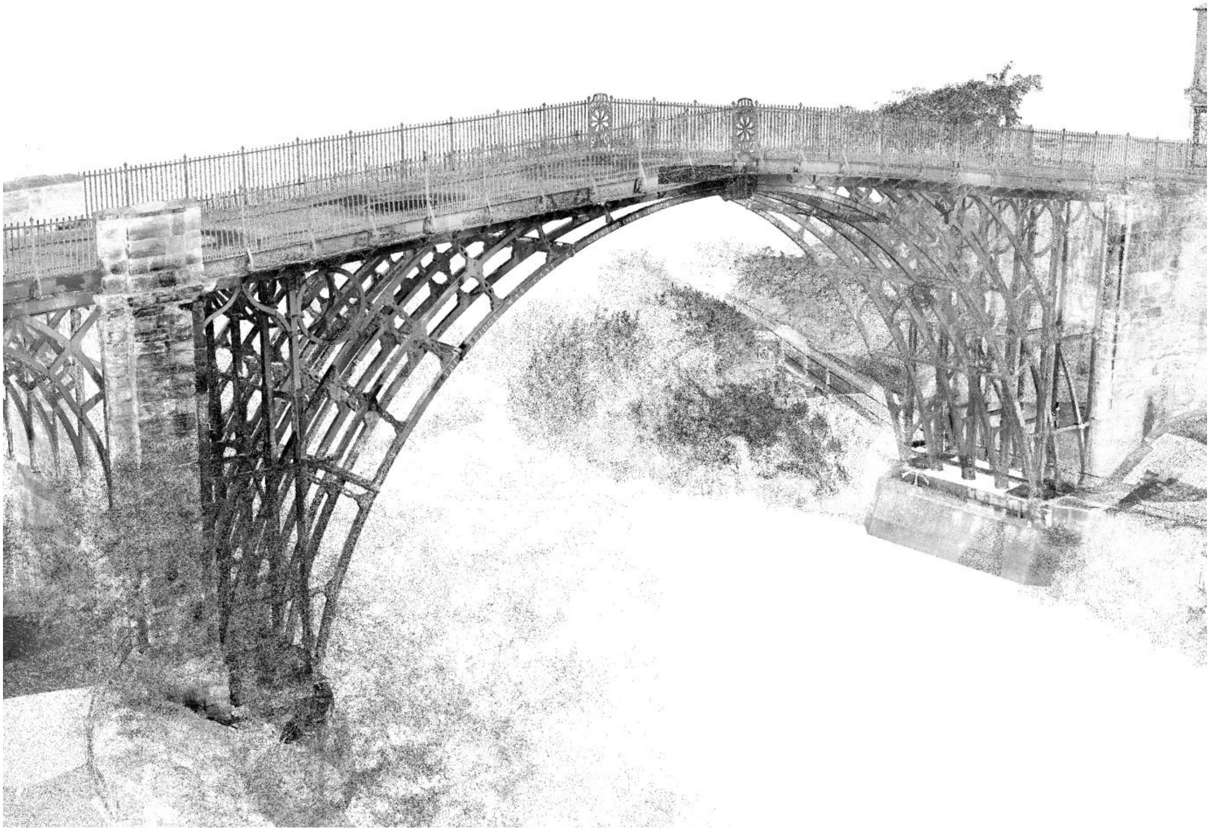

Figure 2: General view of the Point Cloud

A detailed surface model was then generated for the main span using a variety of modelling tools based around the product Rhinoceros. The iron castings are modelled as unique elements, according to the sizes and shapes recorded in the scanner's point cloud, and are not copied between elements or frames. No mirror or axis symmetry was assumed.

The surface model was converted into a solid model and with the exception of the deck all elements represented in a solid finite-element analysis. The extensive cracking in the structure is modelled. The analysis was undertaken with both as a linear and non-linear material behaviour in separate cases.

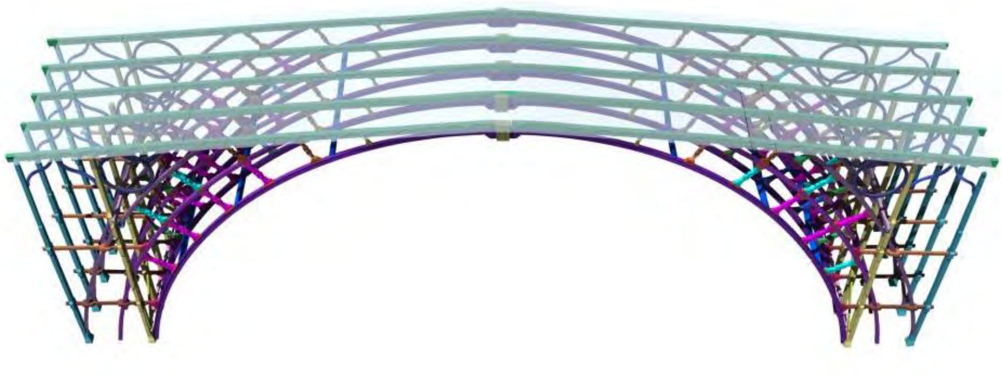

Figure 3: Image of the Surface Model

During the process of developing surface and solid modelling some aberration in the point cloud was identified where bridge member surfaces where measured several times in slightly different places. This appears as shadowing in the cloud and is best illustrated by taking sections through the cloud as illustrated in Figure 4. It is appreciated that the laser survey was particularly challenging and generally measurement appears to be in accordance with the specification; the main bridge structure scanned with a 2 mm resolution and attempting to get 95% coverage.

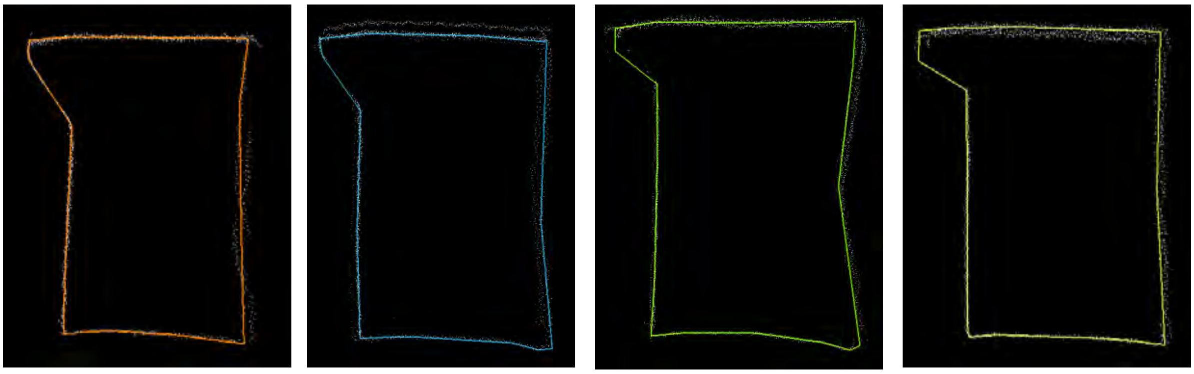

Figure 4: Typical Sections taken through the point cloud along one of the inner ribs.

The deck constructed from individual plates 40 mm thick, 0.914 metres wide and which span over the deck bearers for the full width of the bridge has been modelled with 3D thin shell elements with each plate individually represented. The wedges and packing plates/pads which locate and support the deck plates have each been modelled by using constraint equations. The accurate representation of the deck plates and their linkage with the underlying deck bearers is an important aspect of overall bridge behaviour as the whole system of plates working compositely is essential to provide bridge lateral stability.

One by-product of the modelling exercise was the creation of highly detailed surface geometry. This permitted precise measurement of the castings. It showed that they were not necessarily replicates, but often cast to fit, as they vary in size.

4 MODELLING OF DEFECTS

Defects include cracks, breaks and parts of connections that are obviously loose. Defects in the geometry, for instance where parts are distorted or bent, are captured in the overall modelled geometry as this has been precisely measured. The defects have been introduced by either deleting elements to introduce a physical break, or by softening parts of the modelled cast iron so that very little load is carried. In this way load is distributed through the bridge frames, bracings and deck in a realistic way.

The way in which defects are introduced into the model is shown in Figure 5. About one hundred defects were modelled in this way.

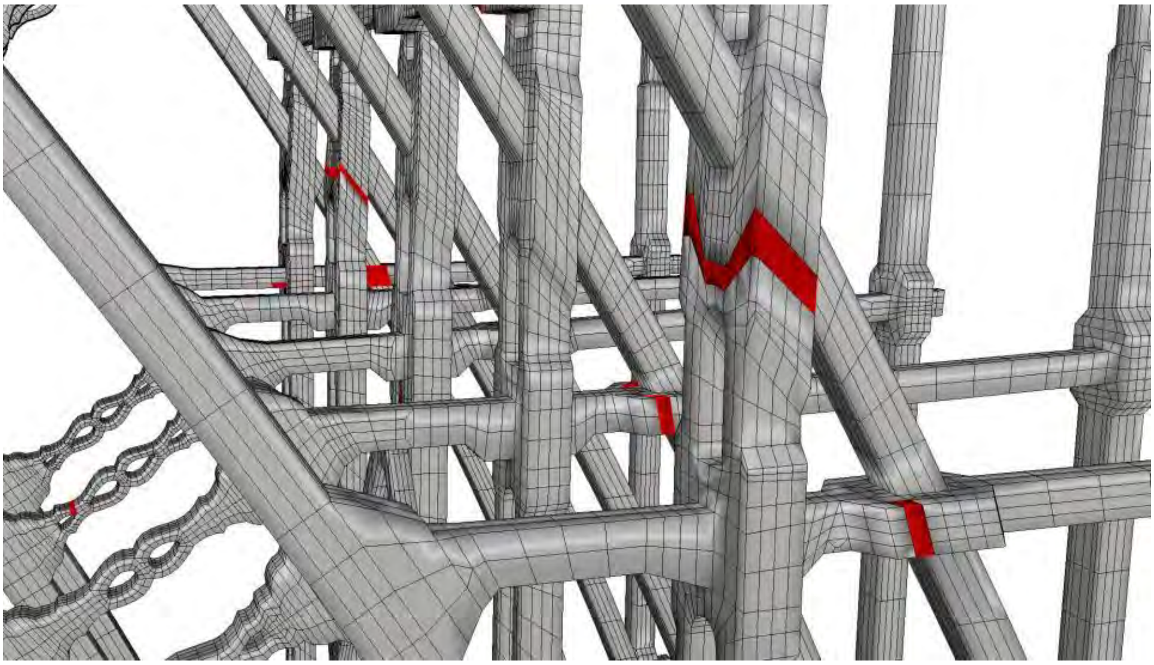

Figure 5: Modelling of the defects.

5 STRUCTURAL MODELLING

The Finite Element (FE) method has been used for structural analysis, which provides good flexibility for different types of calculation, but instead of using a 3D line beam formulation, which would be normal to investigate an open frame, a solid element formulation has been used.

A 3D beam approach would require thousands of geometric property calculations to represent the different shaped cross-sections, additional point cloud processing to define each different cross-section, and would not have sufficient resolution to predict behaviour close to important local features. It would also be time consuming to adapt materials to look at material variation within the cross-section to investigate factors such as porosity. Figure 4 also shows how the cross-section of a typical edge rib varies along its length.

6 MATERIAL PROPERTIES

The material properties of the cast iron were considered in some depth. Little is known about the mechanical properties of the iron used in the bridge. However, limited tests were carried out in August 1969 on a single, original bracket that had fallen from the parapet[7]. Figure 6 shows photographs of this bracket. In the absence of a large sample of data, the material properties proposed in Highways Agency document BD21 have been used in conjunction with these test results[8 9]. This is expected to give a conservative assessment.

The following were the test results obtained from a cantilever bracket that fell from the bridge. Due to the nature of the cantilever bracket the tests were carried out on fairly small samples.

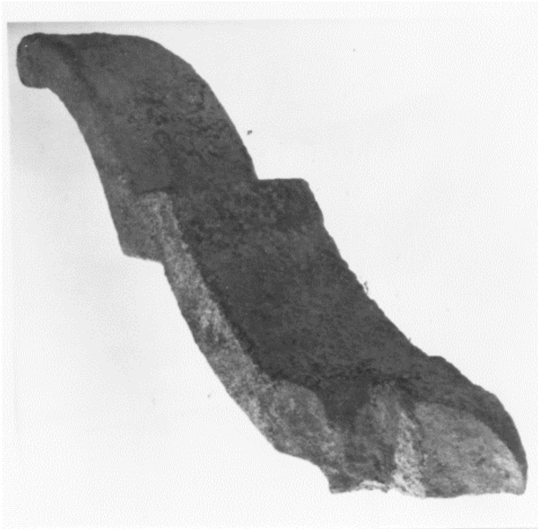

Figure 6: Photographs of fallen Cantilever Brackets used for material testing.

Figure 6 Cantilever Bracket (from Report 1)

The test results obtained were:

- Tensile strength 8.5 ton f/in2 (131 N/mm2) based on three results.
- Compressive strength 13.5 ton f/in2 (208 N/mm2) based on one result on a 1” diameter x 1” long cylinder.
- Bending strength 10.0 ton f/in2 (154 N/mm2) based on one result.
- Impact 1.25 ft lb based on one result using notched specimen.
- Hardness 149 using 10 mm ball with a 3000 kg load.

7 LOADING CRITERIA

The bridge has been analysed and assessed in its current cracked condition, which is considered the primary purpose of this study. Dead loads and imposed loads are applied to the main bridge span. The bridge has been checked for a notional 7.5 tonne lorry-mounted underbridge inspection platform.

Other load criteria considered include both a major strike on the bridge by a river craft that has broken its moorings in flood and lateral water pressure from a large obstruction trapped against the southern upstream springing.

During flood events when the river can break its banks, flood adjacent land, can pick up debris which may include trees, small outbuildings, caravans or vehicles. It is possible for this debris to become entrapped in the structure of the bridge forming a blockage to the flow of water. This will have the effect of transmitting the force of the river over the full area of the blockage into the structure.

Although the River Severn is navigable the only river traffic is now pleasure boats. An example of one is shown in Figure 7.

Figure 7: Example of a pleasure boat considered for Accidental Impact Load.

Loads from thermal expansion and contraction due to temperature change and lateral wind loading are also considered.

8 STRUCTURAL ANALYSIS

By using a 3D solid FE approach the structural geometry can be based on the surface geometry developed from the point cloud and directly used for solid FE meshing. This saves time and increases the resolution of the stress analysis, especially at local features and adjacent to joints and connections. FE meshing was carried out using the FE pre-processor DISPLAY3 working firstly on each frame and then building these parts together with cross bracing and the deck, and finally exporting the data to the FE system ANSYS. ANSYS Mechanical was used as the FE solver for assessing the current condition and for calculating all results. Linear elastic static analysis was carried for all basic load cases and load combinations, and linear buckling analysis undertaken for selected boundary conditions and load cases.

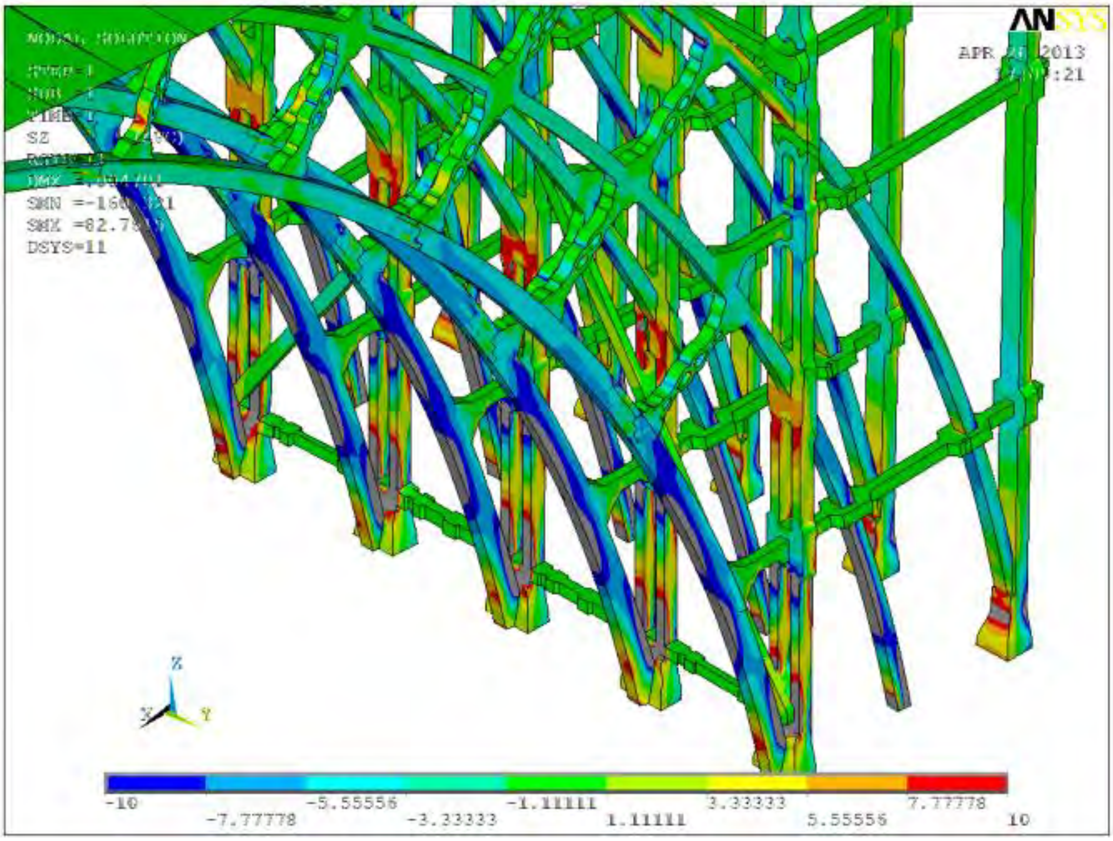

Figure 8: Typical graphical output from the analysis.

NISA2, which is a simpler FE solver, was also used to investigate individual frames in their as-built condition. The development of the NISA2 frame models formed an intermediate stage in the analysis where the behaviour of the model could be more easily verified. In addition to linear analysis a simplified materially non-linear analysis was also carried out based on Von Mises plasticity with a somewhat hypothetical yield strength to predict where damage might be expected to occur due to ground movement.

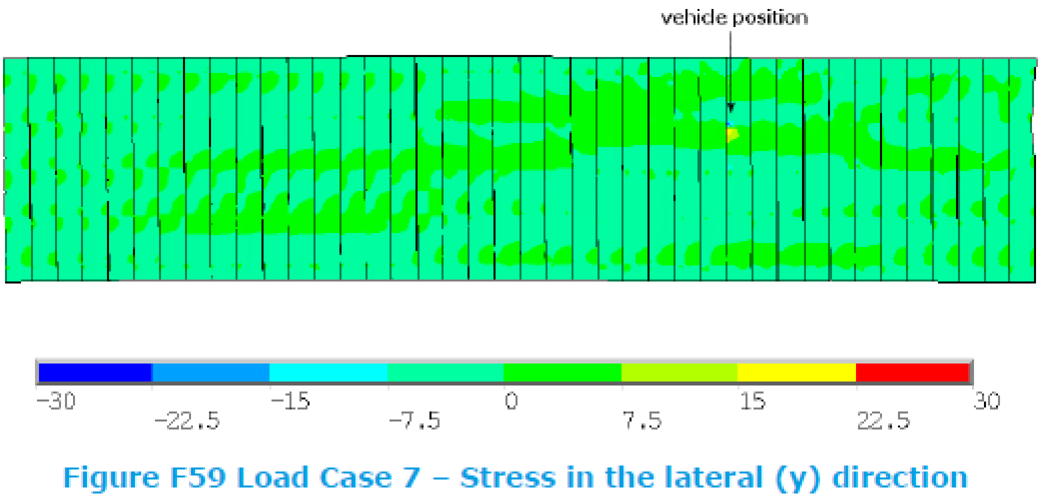

Figure 9: In-plane stresses within the deck plates

9 CONCLUSIONS

The assessment showed that:

The skeletal bridge structure of main span has good capacity, able to take a pedestrian load of 3 kN/m² or a 7.5 tonne double-axle inspection access vehicle.

The cast iron deck plates, found across all spans, are able to take the load of pedestrians at 3 kN/m² and inspection vehicle. However, some plates are cracked and so outrigger loads should always be spread across the deck.

The bridge would suffer irreversible damage to the main upstream rib if struck by a craft, having broken its mooring, or from a large obstruction lodging on the ironwork and applying very significant pressure from floodwater. Subsequent to this conclusion, English Heritage instructed a stakeholder group to be convened to consider the risk of these events. The likelihood of these events occurring was considered sufficiently remote to warrant no further action be taken to mitigate the risks. Nevertheless, given a background of climate change, it was recommended that the situation should be monitored and any events of this nature reported.

There was concern over the level of cracking in the radial elements. Generally, it was not necessary to repair cracks in the radials. However, it was recommended that radials cracked at both ends should be repaired at one end only to avoid risk of injury and loss of fabric from the fall of the component.

10 REFERENCES

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