Recent structural interventions to the eighteenth-century Greatham Bridge, UK.

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ABSTRACT

This paper describes interventions carried out on Greatham Bridge, a road traffic bridge spanning the River Arun in the county of West Sussex (UK) which is also a scheduled ancient historic monument. It carries a B road used by traffic traversing to or from the A29 and A283 and for traffic exploring the local countryside. The first intervention described in this paper occurred in 2002 and the second in 2018. Although a listed monument it is also a live part of the road traffic infrastructure network in the region. The paper details the challenges involved in working on an ancient protected structure in an area of restricted access and of ecological importance. The differences and improvements in processes and procedures between 2002 and 2018 are highlighted.

1. Introduction

West Sussex County Council (WSCC) is the local government authority tasked with the duty of the maintenance and upkeep of all road traffic bridges within its area (excluding Motorways). This includes old and ancient bridges. Within the area are approximately 720 highway bridges and 90 footbridges. Of this bridge stock 3-400 are older than circa 1900 and this includes 10 bridges designated as ancient monuments. Any works carried out on these monuments must meet the exacting requirements of Historic England (a public body which was previously part of English Heritage). This means that any works carried out must not significantly alter the appearance and, furthermore, all works must be scrupulously recorded in great detail.

WSCC's bridge inspection regime is currently the same for all bridges regardless of age or usage. It consists of an inspection every 22 months. There are two general inspections followed by a more detailed principal inspection (i.e. every 66 months).

2. History and Construction

Greatham Bridge is a medieval bridge commissioned by Sir Henry Tregoz (of the Manor of Greatham) most probably completed in 1294 (see http://www.westsussex.info/greatham-bridge.shtml). The bridge is located in the Horsham District of the county of West Sussex, England (at OS grid reference TQ043159).

The bridge is a multiple span masonry arch causeway leading to a two span wrought iron lattice girder supported bridge. The western end masonry arch causeway comprises 8 low elliptical stone arches and 2 higher arches, all interspaced with cutwaters. The higher arches adjoin the more modern part of the bridge. To the east is a solid ramp. The wrought iron lattice girders support transverse iron plates on which a concrete deck is seated. The girders are supported on a central steel trestle pier at mid-span. The bridge carries a single carriageway with a permitted traffic speed of 60mph over the River Arun with a weight restriction of 7.5 tonnes. The bridge was originally built in 1294 and completely reconstructed in 1795-99 in stone arches. In 1838 part of the bridge was destroyed by a flood and a wooden bridge was constructed over the main part of the river. The wooden bridge lasted 30 years and was replaced by the lattice girder bridge in 1869. The information available concerning the technical specifications and history of the bridge are held in the county's bridge records. However, the details become increasingly less complete as they stretch back in time. There is very little detailed information from before circa 1900. The central pier was added circa 1912. Additional steel stiffeners and the concrete deck were added in 1942 to enable Class 40 military vehicles to use the crossing. The structural type of the bridge is a continuous two span lattice through girder with stiffeners providing U frame restraint. The central piers are column piles embedded in concrete. The span arrangement is two equal spans of 9.92m (19.8m total span) and the lattice girders also act as parapets (together with high upstand kerbs). Photographs of the bridge as it appeared in 2002 (prior to the strengthening works to be described) are shown in figures 1-3. The addition of the central supporting pier meant the introduction of a stress reversal because the bridge had been originally designed as a simply supported single span structure.

Fig 1 View of Greatham Bridge from South West prior to works being carried out.

Fig 2 View of Greatham Bridge from South East prior to works being carried out. Showing central temporary stiffeners added.

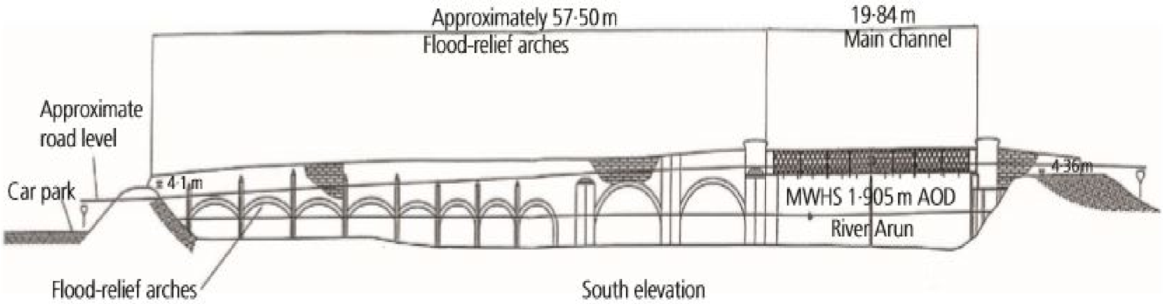

Fig 3 Drawing of South elevation of Greatham Bridge

3. <u>Structure Condition (2002)</u>

The bridge was inspected and assessed in 1995. The masonry arches passed the 40 tonnes assessment live loading, as did the central trestle pier. The transverse girders, lateral support, deck plate and connections (rivets) were all found to be adequate only for 7.5 tonnes assessment live loading. However, the lattice trusses were considered to have zero assessment live loading. The bridge was originally designed with a single span (the lattice members having larger cross section at each end to resist shear forces at the original support points). The addition of the central trestle pier transformed the bridge into a two span structure, continuous over the centre pier (thereby altering the bending moment profile, inducing hogging at the centre of the bridge as opposed to sagging etc.). The installation of the centre pier resulted in an increase in the load taken by these central web members. The failure mode was found to be buckling of the lattice web members in the vicinity of the intermediate pier.

4. <u>Intervention</u>

After the assessment, the Client, West Sussex County Council (WSCC) was obliged to act. The choices available were to strengthen the existing bridge or to demolish and rebuild anew. The option of demolition and replacement was discounted due to cost and probable English Heritage objection. Several alternative strengthening schemes were discussed with English Heritage and the Client most of which were discounted on the basis of visual appearance and cost of works which left the final selected scheme. The strengthening works proposed were to the superstructure of the lattice girder and to the concrete deck. Essentially the scheme consisted of replacing many of the lattice members with larger (in cross-sectional area), stronger members to increase the overall strength of the girder. In the centre of each girder (directly above the central supporting pier) new central stiffener plates would be designed and placed, see figure 4. This increase in girder strength would be supplemented by the replacement of the original concrete deck with a lighter, "voided" reinforced concrete deck. The deck would be formed with void spaces between it and the deck plate such that the concrete's weight would be supported by the transverse beams close to the points at which they joined the main longitudinal girders, see figure 5. Due to the demands of the local water company, it was also necessary to include in the design a new larger diameter water duct. In the existing bridge, there was a 100mm diameter water main. This was to be replaced with a 125mm water main within a 220mm water duct

Fig 4 New design of central stiffening plate

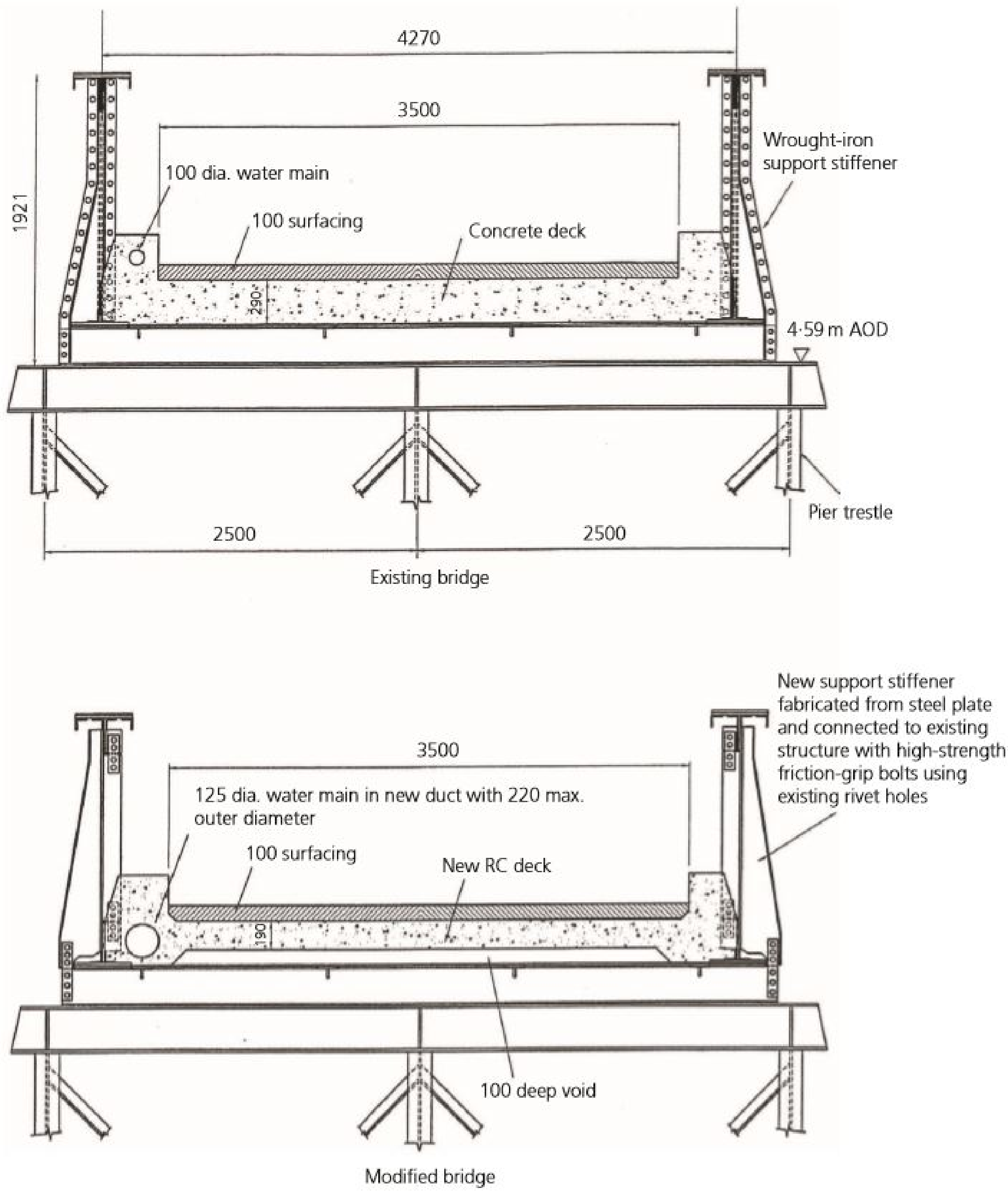

Fig 5   Drawing of previous deck profile and new voided deck slab profile

5. <u>Strengthening Design</u>

The wrought iron lattice girder was analysed as a two-span plane truss using LEAP 5 (Linear Elastic Analysis Program) Version 6.1. The concrete deck slab was analysed as a finite element slab with elastic supports modelling the support from the main girders and cross girders. For analysis and design, the articulation arrangements of the bridge were assumed to be freedom of rotation at all support locations. The deck was assumed to accommodate thermal movements about the centre support with end supports being free to slide over padstone bearings.

The design criteria used were for HA loading to 7.5 tonnes as per BD 21/01 assuming Lg conditions (Low HGV flow and good surface state) and for footbridge live loading to BD

37/01. BD 21/01 was the UK standard for the "Assessment of Highways Bridges and Structures" and was written by the Bridges Engineering Division of the UK's Department for Transport. BD 37/01 "Loads for Highway Bridges" was the standard that specifies the loading to use for the design of highway bridges and associated structures. This standard specifies HA loading as that design loading which adequately covers the effects of all permitted normal vehicles (i.e. not abnormal indivisible loads) found on roads in the UK. It consists of a uniformly distributed load and a knife-edge load (across the carriageway). Both BD 21/01 and 37/01 were volumes within the UK "Design Manual for Roads and Bridges". The category two check of the deck calculations was carried out by analysing the deck as a grillage (again using LEAP 5). Reinforced concrete (RC) detailing was carried out with the SAM (Sections and Moments) software package, based on the analysis of a finite width strip of transverse spanning slab. This was fed back into the grillage model using the worst transverse and longitudinal bending moments to check the longitudinal and transverse "beam" section reinforcement designs. The deck and RC edge beam were assessed for accidental wheel load (AWL), moment and shear resistance. AWL is another loading arrangement (from BD 37/01), which represents the possibility of vehicular loading passing off the nominal carriageway and onto outer verges or footways. It was not necessary to check for HB loading (exceptional industrial loads such as generators, transformers, machine presses and so on) because of the narrow breadth of the bridge and because it is a plated structure. Checks were completed for early thermal cracking, as per BD 28/87 (another standard within the "Design Manual for Roads and Bridges"). Checks were also carried out to ensure the standard requirements for minimum areas of main and secondary reinforcement were satisfied.

6. Strengthening Works

This project presented the designers, based at the (then) local Halcrow Group offices, several challenges over and above the normal design requirements. The bridge is in a designated Site of Special Scientific Interest (SSSI), it is also listed as a Scheduled Monument (County Monument No. 140) and is immediately adjacent to the grounds of a private angling club on one bank and a wildlife reserve on the other. Further to these issues, the river directly downstream of the bridge is home to one of (at the time) only three colonies of Depressed River Mussels in the UK. These creatures are very rare and very sensitive to environmental changes. This fauna was protected under the UK's Habitat's Directive and their wellbeing was considered, by the Environment Agency (EA), to be of prime importance.

A selection of contractors from the council's select list were contacted (to determine their interest in carrying out the works) and documents were issued for tender to 4 of them. The best tender was for the value of £98,000 by Dean & Dyball Construction Ltd, who were duly selected. After consultation with English heritage, the Environment Agency and the Contractor, the agreed start date for the works was the 25th February 2002 and the planned duration of the Works was 11 weeks.

6.1 Deck

The removal of the concrete deck took longer than anticipated by the Contractor. The concrete was stronger than expected and the transverse girders within the concrete were very effectively welded in place, see figure 6.

Fig 6 Original concrete deck being broken out

Once the concrete deck had been completely removed, it was noticed that the abutment support was not as stiff as originally assumed. Standing on the bare plate deck, midway between the corners of the deck at each end it was possible to feel the movement quite easily. The end beam design was checked with this new knowledge in mind and a redesign was necessary while the works were in progress, resulting in extra steel being added to each end beam to increase their strength.

Once the old deck slab had been broken out, the wrought iron deck plate was inspected for signs of corrosion and there were very little. The plate was remarkably clean and intact. Before placing the polystyrene deck void former panels, 6 drainage holes were drilled through the 13mm plate and fitted with 50mm long 20mm diameter drainage pipes which were epoxied into place, flush with the top of the plate (see figure 7). The later 2018 refurbishment was only to the masonry arch elements of the bridge after inspections revealed their poor condition. During these works, no inspection was made of the iron deck plate. However, the deck plate has been inspected in other regular inspections and has not suffered any great deterioration.

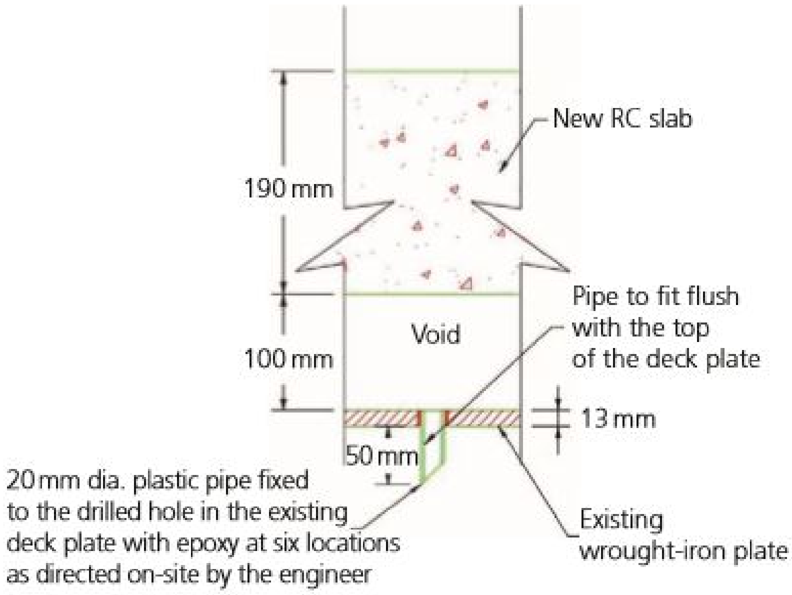

Fig 7 Deck plate drainage details

It was decided to locate the new water main duct within the new southern edge beam/kerb. The duct was rather large (as per the requirements of the water company) and this did cause an element of congestion with the steel in the edge beam, see figure 8. Before each pour checks had to be carried out for adequate clearance between the steel and the duct.

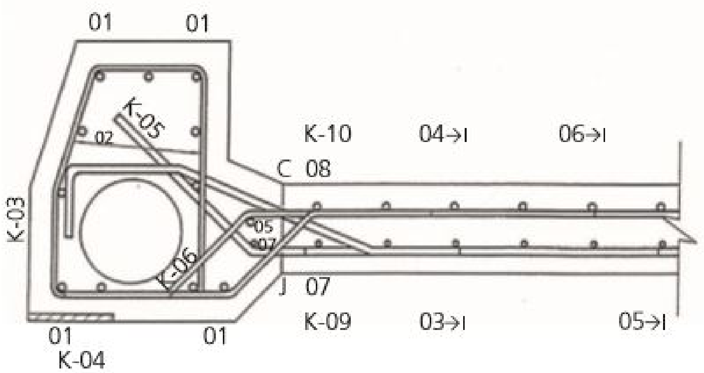

Fig 8 Southern edge beam showing replacement water duct

The new concrete deck was grade 50N/mm^2 concrete with Grade 460N/mm^2 steel, type 2 deformed bars to BS 4449. The concrete deck was constructed in two pours. One pour to form the edge beams, and the subsequent pour to form the deck itself. The deck void was created by pouring over the top of polystyrene former panels. Once any concrete had been cast, no further work was permitted on the deck during the first 24 hours of the cure that could have vibrated the placed concrete.

The formwork itself was the cause of a delay in the program as the Contractor had underestimated the complexity of it. The outside formed face of each of the edge beams partially covered the foot of the lattice members. The formwork had to be cut to accommodate this irregular pattern of bars. The operation took several days longer than the Contractor had programmed for. It was impossible to "chute" the concrete due to the weight restriction of the bridge and the Contractor decided that it would be cheaper to pump than to use a crane and skip. After sufficient setting time the deck was waterproofed. The road surfacing operation was done by hand with no heavy plant on the bridge at all

Originally it had been assumed that after the works had been substantially completed there would be a fairly small amount of painting required, to protect any scratched or damaged steel/iron surfaces. These defects would be where scaffolding supports had been pressing against original ironwork for instance. However, after a short while, it became clear that there would be much more re-painting required than originally thought. It was decided that, as the access scaffolding was already in place and the Contractor on site, to re-paint the entire bridge immediately after the strengthening works. For EA approval for these re-painting operations it was necessary to provide details of the existing paint system, its composition etc. and to specify exactly how the existing paintwork would be prepared for re-painting. Fortuitously, the "original" paint specifications were found in the county bridge records. This would have been the colour and specification from 1942 when the bridge was strengthened to Class 40 military standards. The works were carried out by a local coating contracting company, which had worked for the council before and had knowledge of environmental requirements in the area. Despite that working knowledge, the contractor was, of course, briefed thoroughly in the requirements of the works to be conducted. All steel was provided with a full paint protection system with a grey finishing coat. Thinner replacement lattice members (less than 6mm thick) had a galvanised metal coating under the paint system.

Existing paint was cleaned off back to the bare metal, then a primer layer and undercoat layer was applied. The top layer was a two-component, aliphatic polyurethane with a gloss "Natural Grey" finish (Tikkurila 168 Temathane PLV). This is an extremely tough and durable system with exceptional weathering characteristics. It can be applied an infinite number of times over itself, and is suitable in marine environments. It was also an approved item by the UK Highways Agency (Item 168) for use on steel highways bridges. The pot life of this two-pack system is 4 hours (after the parts are mixed). Onsite the painting contractors mixed one litre at a time and applied by hand (brush).

As for the preparation, high-pressure water washing as opposed to grit blasting, was suggested and agreed upon. This required an increased environmental protection in the form of extra (double) sheeting (see figure 9) and the wet vacuuming of all arisings. Meetings between EA representatives, Fisheries Officers, Pollution Control Officers and the Contractor to discuss the matter resulted in the requirement (amongst others) that the washing operations be carried out on an outward tide. It took several (extra) weeks to gain approval for these operations.

Fig 9 Extra (double) Sheeting During Repainting Operations

6.2 <u>Lattice Girder</u>

As the lattice members were to be removed and replaced, there was a need to consider, in detail, the construction sequence (as each time a member is removed the strength of the girder is reduced). The analysis of the construction sequence had to take into account the effects of the removal and replacement of pairs of lattice truss members, one at a time. It was found that the critical phase of the strengthening would be the replacement of the central lattice members with the new central stiffener plate (and adjacent members). It was necessary to apply temporary bracing to the structure during this phase. The loading due to temporary works (to be suspended from the bridge) during the construction phase also had to be considered during the design phase. In fact, the loading restrictions varied throughout the stages of the works. These temporary works involved the placement of access scaffolding, and environmentally protective double sheeting, completely around and suspended from the bridge, see figure 9. The access scaffolding was slung around and under the bridge so that access was available to both sides of each girder.

The replacement lattice members, stiffeners and strengthening plates were fabricated by a local steel fabrication company and were specified to be Grade Fe 430 Steel (tensile strength 430 N/mm^2 to 530 N/mm^2). The specification was to to BS EN 10025. This British Standard sets out specifications for flat and long products of hot rolled structural steels. The steels covered are normally used in welded, bolted and riveted structures. According to the structural analysis/design it was necessary to replace 40% (in number) of the lattice members. The members replaced were of cross sectional dimensions 63.5mm by 12.5 mm and 63.5mm by

9.5mm. They were replaced with members of dimensions 90mm by 30mm and 90mm by 25mm.

The mass of the new central support stiffener was 164kg and required a small crane to lift into position.

A potential problem was found in the attachment of the new steel work to the existing truss where there were splices along the girder. The original truss was joined together using rivets. The fishplate's rivet heads protruded from the face of the plate and would have obstructed the flush attachment of the new steel members. It would have been possible to either reduce the section size of the new members near their ends or to pack out the new members (to bring the ends away from the splices at the point of attachment. For ease of fabrication, it was decided to choose the latter option and to also neck the ends of the new members (see figure 10).

Fig 10 Splice plates and lattice member attachments to top flange

As stated above, the original bridge connections were rivets. To maintain the appearance of the bridge, the use of Tension Control Bolts (TCBs) was specified in the strengthening works. These high strength friction grip bolts have rounded, rivet-like heads and are tightened using special proprietary tools such that, at the correct tension, a spandrel on the end of the bolt shears off. The nut can then have a plastic cap fitted over it, which also gives a rivet-head like appearance (particularly when over painted).

7. <u>Results of 2002 Strengthening Works</u>

The original estimate for the Works was £98,000. The tender for the works was £98,300. The final cost of the Works was £102,700 and the time to completion was 19 weeks compared to the 11 weeks agreed at the outset. However substantial completion took 14 weeks. Some of the increase in cost and time can be attributed to the fact that the contract was varied to allow for the complete re-painting of the bridge after the strengthening works. This incurred a two week wait for an EA decision (regarding re-painting) and then another 3 weeks carrying out the painting.. Some of the delay/budget overrun was due to the fact that the removal of the original concrete deck took longer than expected, the manufacturer of extra stiffeners (some had been fabricated incorrectly "handed") and other minor unforeseen factors. However, despite these challenges, the bridge was strengthened as planned, the environment was unaffected and the immediately surrounding area retains all its original beauty and status as a Site of Special Scientific interest, see figure 11.

The bridge was strengthened and upgraded sympathetically enough to be awarded a commendation at the ICE Historic Bridge and Infrastructure Awards (HBIA) in 2003. Judges commented that it was "a very good repair, carried out extremely well" (NCE, 2003).

Fig 11 Greatham Bridge in 2003 after strengthening works completed

8. 2018 Arch Refurbishment Works

The 2018 masonry arch refurbishment followed the observation of significant areas of failing (eroded) stone work. Some of this is shown in figs 12 - 14. The refurbishment gave the council the opportunity to excavate into the top of the arches and make a true measurement of the ring depth. This was necessary because an earlier analysis had suggested that the ring depth of these arches was critical to the weight limit of the bridge. The measurement was carried out by taking levels from above the top of the ring (after excavation of the road surface) and from below. It was found that the ring depth was 310mm rather than the initial assessment estimate of 300mm. Anything greater than 300mm gave the arches a 7.5 tonne rating. However, if the depth had been below 300mm while the arch refurbishment work was going on it would have been possible to strengthen the arches at the same time. This would probably have been accomplished by excavating from above and constructing a lightweight concrete slab above the ring and then pinning the arch from below to the slab.

Fig 12 Eroded stone work prior to 2018 refurbishment

Fig 13 Eroded stone work prior to 2018 refurbishment

Fig 14 Eroded stone work prior to 2018 refurbishment

The analysis of the arch strength was carried out by Parsons Brinckerhoff for WSCC and the Consultants for the refurbishment work were WSP, with Contractors Balfour Beatty.

The original budget for the works was £300,000 but the final cost was only £200,742.17. The main reason for this big difference was the eventual non-use of a temporary dam (see figure

15). Where work at, or below, the water line was necessary, the work was planned to be completed while the river was held back by the hire of a temporary dam (at a cost of £90,000). It was originally planned to use the temporary dam system (to provide a dry work zone) to restrict flow through one or two arches at a time in order to minimise water flow restriction under the bridge i.e. staged work. In reality, the dam failed after 3 weeks and was then abandoned as the contractor (rightly) refused to allow operatives to work behind it after its failure. This meant that the work was carried out only during low-water conditions. The River Arun is still tidal at Greatham Bridge (in fact it is tidal for a length of 41km upstream from the sea at Littlehampton). Figure 16 shows the scaffolding arrangements required to give access to the faces of the arches.

Fig 15 Temporary dam used in the early stages of the refurbishment

Fig 16 Refurbishment temporary works for access to arch faces

Many masonry arch blocks had to be replaced to restore the integrity of this section of the bridge and figures 17-19 show some of the affected areas. These figures can be compared with figures 9-11, prior to the refurbishment.

Prior to the refurbishment the existing arches were constructed using Salterwath Limestone below the waterline and Midhurst Sandstone above the water line. Local stone from a quarry very close to the site (Fittleworth, Pulborough) was identified. The replacement stone closely matched that of the existing structure in type, colour and texture. Sample stones were provided for and approved by Historic England during early site meetings.

The scope of the works involved the removal and replacement of severely deteriorated stonework and the repointing of eroded mortar joints. Previously eroded cementitious mortar joints were repointed with a lime mortar/grout (for increased durability). Lime mortar mixes were selected to match as closely as possible the original mortar. However, lime is highly alkaline and can cause pollution to waterways. To minimise the risk of run-off entering the watercourse, the lime mortar mixing area was sited away from the surface water gullies and within designated washout areas provided. This washout water was transported and disposed of away from the site.

Hydraulic lime is a traditional; construction material and was the primary hydraulic binder used in mortars prior to the development of Ordinary Portland Cement (OPC) in 1824. The term "hydraulic" describes material that will set and harden under water. Natural Hydraulic Lime (NHL) is produced from a naturally occurring raw material rather than by blending Calcium Lime with a pozzolanic material as used in the production of Hydraulic Limes. Other forms of lime mortar were not permitted in these works (such as high calcium quicklime, hydrated lime and cement mortars). In addition, work was only permitted when shade air temperatures were 5°C and rising. If overnight frosts were anticipated after laying green mortar, the mortar was protected with fleeces, hessian and frost blankets etc. and also, an extension of curing time was considered prior to the application of waterproofing

During the refurbishment works, DEMEC mechanical strain gauges were placed in order to monitor possible future crack growth.

After all refurbishment works were completed a new rock armour defensive barrier was placed around the arch footings, shown in figure 20.

Fig 17 New masonry work

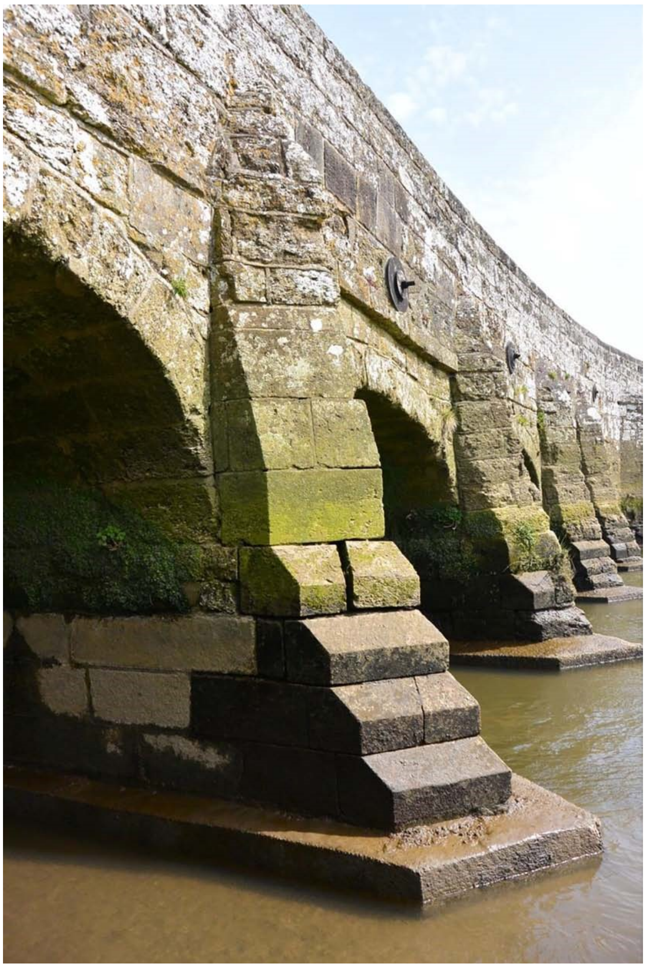

Fig 18 Refurbished pier

Fig 19 New masonry work

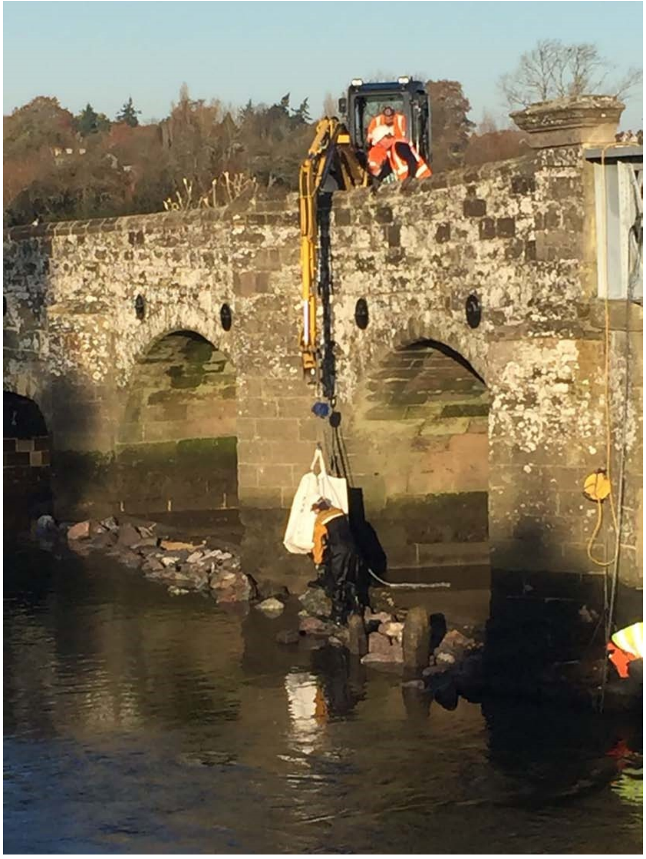

Fig 20 Rock armour installation

9. Conclusions

As explained above, in 2002 (in WSCC) the inspection regime for bridges was the same for all bridges. Currently, WSCC is coming to the end of a two-year transition period to a new inspection regime which will be fully implemented by the end of 2018. The new inspection regime will be on an integrated, risk-based, approach (for the first time). This approach is documented in the Code of Practice "Well-managed Highway Infrastructure", commissioned by the United Kingdom Department for Transport (DfT). When fully adopted this will include setting levels of service, inspections and responses and will specifically recognise the different requirements of listed structures and ancient monuments (Recommendation 34 –Heritage Assets). This new Code of Practice, authored by the UK Road Liaison Group in 2016, is the result of extensive consultation with multiple interested parties. The biggest change in this new code is its emphasis on a risk-based approach. It was decided to give local authorities a two-year period from the date of publication in which to implement the new code and after which the old standards were to be withdrawn. "The advice is simple: local authorities should consider the risks of all decisions associated with the highway service, understand the potential consequences, consider affordability and adapt their policies accordingly to reflect local needs. In turn, the highway service will become more targeted, flexible and responsive to local communities. This helps to avoid 'gold plateing,' create budget efficiencies and protect against legal challenge through an evidence based approach" (Tachtsi L 2017).

It remains to be seen how the new methodology of an integrated risk-based approach to maintaining highway infrastructure will perform in comparison to the previous approach.

However, it can be seen that ancient monuments and listed structures (such as Greatham Bridge) do require special considerations if they are to be preserved as important structures, and also, as still operational, functioning structures. In the case of Greatham Bridge the old approach and the new have resulted in successful strengthening and refurbishment operations that have extended the life and the functionality of this challenging structure. Both schemes can be considered as successful in terms of budget, project delivery time and final outcome.

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