Arch Bridges
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EVALUATION OF ARCH BRIDGE DEFECTS

A HANDBOOK FOR NETWORK RAIL

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Abstract. *Network Rail, the owners of Britain's railway infrastructure, is conscious of the erosion of a considerable body of uncodified knowledge of arch bridges. Network Rail has asked the authors to develop a handbook with material designed both to illustrate particular problems, and to use those illustrations as a basis for developing a systematic approach to thinking about faults and evaluating their significance as they are found on site.*

The volume produced reflects the knowledge of a number of senior engineers from within Network Rail and from the broader community of arch bridge engineers in Britain. It is based on photographs gathered from across the network from Network Rail and its contractors. The volume remains far from comprehensive, and it is intended to provide supplementary information on a web site.

The paper describes the need for the volume and the process which led to the particular format and design. A selection of faults illustrating the systematic evaluation technique is presented for discussion.

The authors welcome further examples submitted as digital photographs. Commentary will be provided on every photograph submitted.

1 INTRODUCTION

Arches, like all bridges deteriorate with time. It is perhaps unfortunate that most engineers live in brick houses and, while they are used to painting the woodwork, expect the brick walls to be maintenance free.

Bridges are faced with a much more arduous environment. The loads they carry are typically twice as big, three times as fast and many times as frequent as when they were designed. Because other bridges deteriorate much faster than arches, There is a potential risk of arches receiving less care. They suffer the ravages of weather, vegetation and traffic, and may only receive treatment when it is long overdue.

The main proactive structures management activity to ensure the safety and longevity of arches is structural examination and the evaluation of the reported defects to determine any necessary actions including physical works if appropriate. Arch bridges usually perform well but just like other structures require engineers with the requisite knowledge and experience to ensure they perform satisfactorily with appropriate interventions. The ability to identify the true severity of a defect is a skill which is not readily enough available. There is a risk that bridges might be condemned with relatively minor faults while others having more serious defects are not identified.

2 A HANDBOOK OF DIAGNOSTIC EVALUATION

The aim of producing a guide to the evaluation of arch bridge defects is to help less experienced engineers to interpret what they see in a bridge inspection. From the start, it was the intention to cultivate a way of thinking about bridges rather than providing specific examples which could be used in pattern matching.

The key steps in the diagnostic approach are:

- Fault prognosis: identification of the initial defects observed and more importantly identification of further clues to the behaviour. Is the visible symptom primary or secondary?
- Fault diagnosis: interpretation of the initially observed defects and further clues to identify possible underlying causes for the defects and rate of development.
- Evaluation of the significance of the defects with respect to the load carrying capacity of the structure and its longevity,
- Identification of remedial actions including monitoring or no further action if appropriate or physical works that are sympathetic to the material behaviour and load carrying mechanisms in arch bridges.

It is essential for the engineer to have a good working knowledge of the load carrying behaviour of arch structures when interpreting the causes and significance of arch bridge defects. To assist in ensuring adequate knowledge the handbook provides an introduction to the load carrying behaviour of arch bridges and viaducts. A series of diagrams describing the load paths through the structure and associated deformations are given leading the engineer through a series of qualitative explanations covering:

- the 2D behaviour of a strip of the barrel,
- the influence of abutments, fill and original construction techniques,

- 3D effects in the barrel,
- the influence of other arch bridge members such as spandrels and piers in resisting and distributing load effects in the barrel.

The core of the volume is a set of two page spreads encompassing photographs, sketches and text to introduce the engineer to the problem and describe the above key steps of diagnosis. A particular feature of the handbook is the use of sketches to highlight the significant features in corresponding photographs.

The remainder of this paper consists of a presentation of four of the pages of the Defects Handbook and a detailed description of the faults present and their significance. The defects, or Damages in EU parlance, have been chosen particularly to generate discussion.

3 EXAMPLES OF APPLICATION OF SYSTEMATIC DIAGNOSTIC APPROACH

3.1 Dropped Stones due to articulation

On many railway arches carrying two tracks, a crack is generated down the centre line as a result of the opposing effects of traffic in opposite directions. Occasionally, when the arch is constructed from very strong stone, the forces break up the mortar without cracking the stone as illustrated in the first example.

The sketch in Figure 1 shows stones which have dropped as a result of mortar loss and flexing of the arch. In this case, there is only heavy traffic on one half of the bridge and the damage shows a directional component. The bridge has a 3.6m span, 0.9m rise and is 9m wide. There is a modest covering of fill and ballast at the crown.

3.2 Dropped stones due to water penetration

The second example is on the same line and built from the same stone (Figure 2). When dropped stones are seen on the centre line of this bridge, there is therefore a risk of concluding that the cause is the same as for the bridge described in section 3.1 above. In fact, there are a number of differences.

Here, the dropped stones are in a group close to the crown. Detailed inspection shows that they are associated with two water stains. Water runs in each direction from the end of the damaged area towards the springing. It is clear that the water and the damage are connected. The questions are:

Is there a causal relationship? And

Which is cause and which effect?

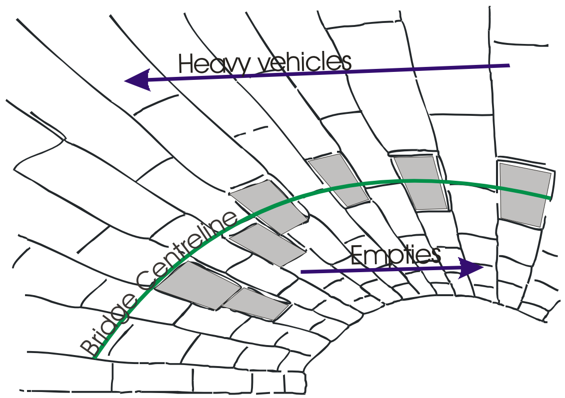
This arch has an 8.6m span and is semicircular. It is part of a viaduct with seven identical spans. There are internal spandrel walls probably capped with slabs and stabilized with cross walls over the pier and at fifth points of the span.

It seems likely that the capping slabs form an effective waterproof barrier. The arch will have dropped when the centres were struck, and may have crept since. The spandrels would follow down and leave the slabs with a slight fall towards mid span. This would concentrate all the water falling over a 12mx8m area of track into the centre of the span.

Suggestions of alternative diagnoses would be particularly welcome.

13 Dropped Stones in Small Arches

In this 4m span arch, the dropped stones are associated with the centre line, but deviate from it at one side



Observed Defects
Dropped stones are obvious; the reasons are less so. The picture shows a 12ft (3656mm) span, 3ft (914mm) rise bridge with a collection of dropped stones.

Further Investigation and observations
The dropped stones are largely in alternate courses. The joints around and between them are all open and largely devoid of mortar.
Is there evidence of excessive live load movement?
Is this likely to increase rapidly?

Underlying Causes
"Non-causes": These stones were not pushed down by load from above. If the bridge were otherwise sound (including secure mortar joints) that couldn't happen because the friction would always be too great. Stones drop (and bricks too) because they are freed to do so. In this case, the freedom is a transient event, brought about by movement as loads pass over.

Heavy loads travel down one half of the bridge so it wants to sway and the unloaded half doesn't (see page on live load movement). The stones at the joint are levered apart. Sometimes the action leaves a stone briefly unsupported and it drops a little. The movement of the stones destroys the mortar and makes room for them to drop.

The drops extend from the crown towards the down stream springing on a diagonal working away from the load. This is because the joints open on this diagonal more easily than by levering stones apart locally.

Significance of defects
Because these stones are strong and fit well together, there is no immediate danger of failure of the arch. It is clear that wear and tear, if left to continue, would eventually lead to serious damage.

Remedial Measures
Once the dropped stones have progressed so far treatment becomes difficult. Replacing mortar with hard material may give temporary respite but exacerbate problems later. There is often evidence of water penetration where drops are present. The importance of maintaining the waterproofing cannot be over emphasised.

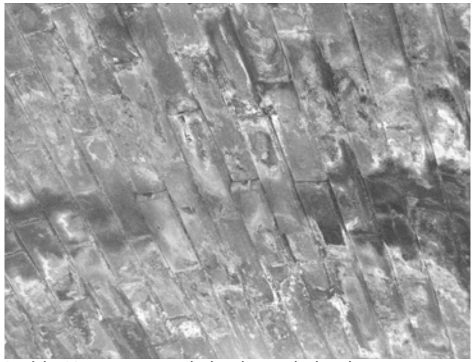
Where access is possible, lifting dropped stones and injecting a lime based mortar to refill the joint is likely to provide medium term respite.

Saddling is a great help, especially if the joints can be restored in the same operation.

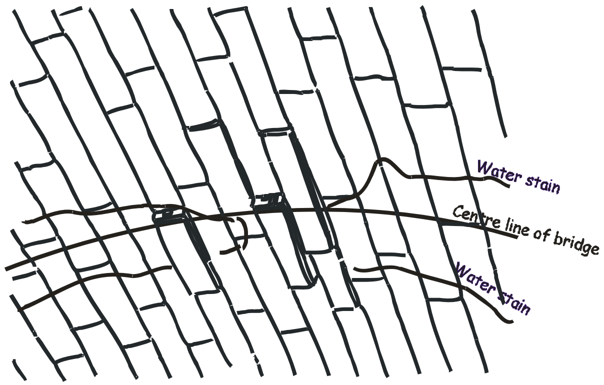
Under-lining has been used in bridges where masonry units are moving under load. In this circumstance it is unclear whether the movement is stopped or the underlining is merely containing the loose stones. This process is not reversible or repeatable, since the underlining cannot safely be removed once it has been in place for some time.

Figure 1: Application of diagnostic methodology to "Dropped stones in small arches"

14 Dropped Stones in Large Arches



In this 11m span, semi-circular arch the drops are concentrated at the centre



Observed Defects
A 35ft (10668mm)span semi-circular arch with a patch stones dropped at the crown.
The stones are large, approximately 1500x300mm in plan. The drops are similarly large, up to 100mm.

Further clues to behaviour
The drops are concentrated at mid width and close to the crown. There is a substantial water stain running away from the drops towards each abutment. The dropped stones themselves are largely dry.

Underlying Causes
Stones can only drop if the wedging action which supports them breaks down. This is nearly always a result of loss of mortar. The cause of the mortar loss is then the difficult question.

Larger viaducts on this line were built with hollow spandrels. These are made by building internal spandrel walls on top of solid haunching. The hollows were capped with large sandstone slabs with their upper surface level with the extrados at the crown.

These slabs presumably create a largely impervious layer which gathers water off the whole span towards the crown where it eventually finds a way through the joints.

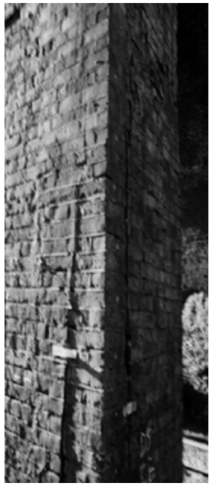
Significance of defects
Damage of this type is likely to progress unless treated. Access for further investigation and remedial works is a significant consideration for arches of this size.

Remedial Measures
The first requirement is to create deliberate drainage paths to replace the accidentally created ones. This might require the installation or restoration of a waterproofing layer. It might, though, be sufficient to create a free drain close to the top of the wet patch each side of the crown. Coring a hole through a voussoir would possibly be sufficient, though creating a free draining volume above it would also be useful.

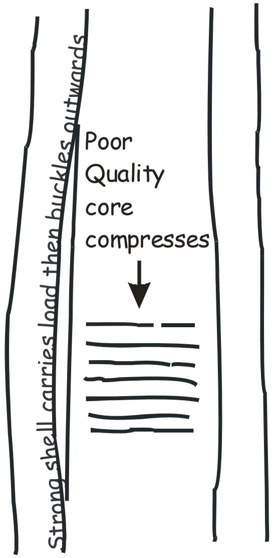
It is desirable that the stones be lifted back into place and the joints repointed. Lifting is possible in such a relatively modest area, using a centre floated underneath and jacked up into position using ties supported from above the bridge.

Figure 2: Application of diagnostic methodology to "Dropped stones in a large arch"

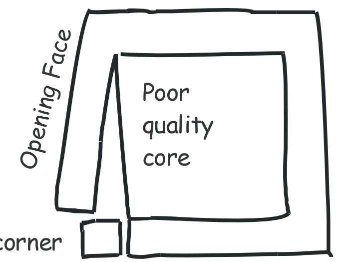
29 Bulge in Pier



Shadow shows panel bulging



Empty perpends in core



Observed defects - Pier
The pier has a bulge in the whole face which has caused the face to break away from the corner restraint.

Further clues to behaviour
Checking the opposite face reveals that the pier as a whole is not bowing. From this superficial view, it seems almost certain that the face of the pier has broken away and is buckling outwards. That, in turn, suggests that the core is not carrying its full share of the load. Other parts of the pier were crushing under the additional stress imposed as this face shed load.

Possible underlying causes
Further investigation revealed that the core was indeed a separate entity and much less well built, with no mortar at all in the perpend joints. Perhaps more importantly, there was a string course on the spandrel at road level and this had a dip of nearly 200mm in the span to the left of this photograph and only on the near side. Levelling confirmed that the abutment had tilted. This would have transferred additional load to this leg of the pier.

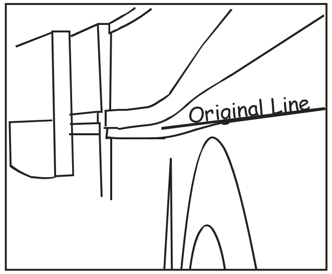
Significance of defects
With masonry buckling or crushing the life of the structure is difficult to predict. Action is required immediately.

Remedial action to consider
Remove live load immediately, followed by as much dead load as possible. A steel frame clamped round the pier will maintain sufficient strength while the work is done. If the pier is not to be replaced, stitching and grouting is the only workable solution.

Figure 3: Application of diagnostic methodology to "Bulge in pier face"

12 Dropped String Course

The drop in the string course is clearly visible. Note also the tilted rebuilt wall and the concrete blockwork round the new drain. The inset shows the drain and kerb with settlement.



The sketch indicates the continuing line of the string course.

This crack in the parapet is at the point where the drop begins.

Observed defects
The string course runs straight in the foreground, then drops about mid span and runs straight again over the abutment.

Further clues to behaviour
There were no cracks in the arch and no matching drop on the other side. It cannot have been built like this so the abutment has tilted to one side. A quick check with a level confirmed this. There were no cracks in the barrel related to this twist.

Possible underlying causes
Partly hidden behind the stairway is the outflow from a road drain, simply cut through the wingwall and on to the cutting. The inset photo shows the drain in question. The large settlement around it shows that water has also been penetrating the fill behind the wing wall.

Significance of defects
Provided the movement has stopped and the water flow is removed, there is no reason for concern unless other parts of the bridge are showing distress. In this case, the pier at the camera location was crushing (example 6).

Remedial action to consider
The drain must be repaired as a matter of urgency. While water continues to penetrate the structure, the foundation will continue to settle. Once that has been done, the bridge should be carefully observed for further distress and the position of the abutment should be recorded and remeasured regularly, perhaps every three months initially.

Figure 4: Application of diagnostic methodology to "Dropped string course"

3.3 Crushing Pier due to abutment movement

Figure 3 shows the pier of a brick built bridge over a railway. There are three semi-circular spans of 9.14m of which the central one crosses the tracks. The two side spans spring from shallow abutments at the top of a cutting. The piers are divided with two legs 1200x1200mm and a central gap of 1200x1200mm. There is an arch above and below the opening to transform the two legs into a solid pier at the main arch springing and at foundation level.

Cracking of the shell of one pier leg triggered a more thorough assessment. Other significant indicators were crushing of brickwork and a dropped string course. The string course (shown in Figure 4) has dropped about 160mm between mid span and the abutment. There is no corresponding settlement on the other face. This large twist has produced no cracks in the arch, but seems likely to have delivered excessive force to the pier leg which then began to fail.

Because each leg of the pier was a sound shell filled with coarse brickwork, the shell carried most of the weight and failed by a combination of buckling and crushing. The buckling of the faces of the leg was only possible once the corners had cracked free. The shadow evident in Figure 3 shows the buckle. (The greyscale illustration limits the clarity of the visual signs of crushing)

3.4 Dropped String Course

Figure 4 shows the dropped string course of the same bridge discussed in the above section. The distortion is matched in the parapet above the dipped stringer course and is thus unlikely to have occurred during the construction of the bridge. The absence of cracking in the arch, differential settlement across an abutment and settlement in the vicinity of a road water drain on the bridge indicate the damage has been caused by water. The dropped string course defect is less significant than the other consequences of the water ingress described in section 3.3 above.

4 CONCLUDING REMARKS

Arch bridges, like all structures, deteriorate with time. The main influences on that deterioration are usually environmental, but other effects can also be important. The diagnosis of faults is often difficult. The records of behaviour over time may be incomplete or inaccurate. Some of the most conspicuous evidence may not point directly to the primary cause. Even when it does, it may be hard to believe the evidence presented. It is vital, therefore that engineers inspecting arch bridges approach the task with an open but prepared mind and a willingness to take time to explore the significance of what is visible.

Our aim in compiling this volume was not to provide a detailed catalogue of faults, but rather to show, by example, how diagnosis might be approached and how serious and expensive miss-diagnosis might be avoided. A systematic technique of interpreting defects rather than relying on “unquestioning experience” is essential. Such a suitable process of:

- considering the initially observed defects,
- looking for further clues to behaviour,
- interpreting the observed defects and clues to establish possible underlying causes of the defects and rates of development,
- evaluating the significance of the defects,
- evaluating the requirement for and identifying possible remedial actions including monitoring, “do nothing” or physical works as appropriate

is described in this paper.

It is intended that a web site will be used to periodically add further material, thus reinforcing the fact that this is not a complete catalogue. Some cases may also be revised as new evidence arises.

In the mean time the authors will be happy to review photographs and notes of any faults which readers might care to submit by email to the first author.

5 ACKNOWLEDGEMENTS

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