DETERIORATION AND REPAIR OF MASONRY ARCH BRIDGES

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ABSTRACT

The masonry arch bridge is a vital part of the United Kingdom road network. The paper describes a condition survey of 98 arch bridges in Scotland and England. It examines water leakage through the arch soffit, spandrel wall defects, and arch ring defects and repairs. The Scottish bridges were found to be in poorer condition than the English bridges; the harsher climate may be responsible. A survey of the cost and effectiveness of repair and strengthening techniques has also been made. It was found that there are a variety of inexpensive techniques which can be used to restore or enhance load capacity of the structure, often with no change to its external appearance.

1 Introduction

There are about forty thousand brick or stone masonry arch bridges in the United Kingdom, representing about forty percent of the bridge stock. Very few have been built since the first world war and most of them are at least a hundred years old. They have therefore reached the end of the present nominal design life for UK bridges of 120 years. It would not however be either practicable or desirable to replace them. The cost would be enormous and many make a positive contribution to the landscape.

Many of them have deteriorated due to the effects of weathering and traffic and they may need to be repaired to maintain their function or strengthened to increase their load carrying capacity. This paper discusses the common types of deterioration and the effectiveness and cost of some repair and strengthening techniques.

Typical construction of masonry arch bridges is shown in figure 1.

Figure 1 Typical masonry arch bridge construction
2 Survey of 98 bridges

The main purpose of the survey, carried out in 1989, was to examine the effect of different weather conditions on the condition of spandrel walls. Outward movement of spandrel walls is a common problem. They may either bulge locally, move outwards as a whole, or tilt (or a combination of these). There are two likely mechanisms. One is the horizontal force produced in the fill by wheel loads and transmitted to the spandrel wall. The second is an outward force produced on the spandrel wall by freezing of water in the fill in cold weather, causing it to expand. Forty one bridges were examined in the north of Scotland which has a severe winter climate, eleven in south east England and forty six in south west England where the climates are milder. The survey also produced useful general information about arch bridges. As far as possible the bridges were chosen at random and the results of the survey are summarised in the next sections.

2.1 General description of the bridges

i) The spans varied from 1.5m to 31.4m. Ninety one of the bridges were in the span range 2-16m.

ii) Sixty seven of the bridges were single span.

iii) Seventy eight crossed a river, three a canal, and seventeen a railway (none crossed a road).

iv) Twenty three of the arch rings were of brick, twenty seven of cut stone, forty two of random stone, one of concrete, and five of brick and stone. Twelve of the spandrel walls and parapets were of brick, twenty eight of cut stone, fifty six of random stone, one of brick and stone, and one of random and cut stone. The construction materials reflected the readily available building materials in the three areas.

v) Ninety of the bridges had arch rings whose shape was a segment of a circle. Two appeared to be parabolic and six were semi-elliptical.

vi) Seventy six of the bridges had no skew. The remainder were fairly evenly distributed over the range up to the maximum angle of 45 degrees.

2.2 Condition

2.2.1 Water leakage through the soffit

Table 1 lists the severity of water leakage through the arch ring. A severity marking (SM) of 0 denotes no leakage or local staining, a marking of 5 denotes water dripping readily from the arch and heavy deposits of limescale or algae (the amount of water seen leaking from the arch will of course depend on the rainfall prior to the survey, and this was not recorded). (Note: SC = Scotland, SW = south west England, SE = south east England).

Leakage of water into an arch bridge is undesirable because it is likely to wash out fine particles in the fill, and if the water is acidic it will dissolve the lime in the mortar which was used in many of these bridges. The effect of freezing is likely to be more severe with saturated fill. Only Scotland had bridges where the leakage was classified as severe.
The bridges were examined for a variety of defects which indicate outward movement of spandrel walls - leaning and bulging walls, outward movement relative to the arch ring, and longitudinal cracks in the arch beneath the inside edge of the spandrel wall. The presence of tie bars was also noted.

Each defect was given a severity marking (SM) from 1 to 5 (0 = no defect). The marking is arbitrary but all the bridges were surveyed and marked by the same person so the marking should be consistent. Table 2 summarises the defects and their markings.

<table>
<thead>
<tr>
<th></th>
<th>SC</th>
<th>SW</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>% with leaning spandrel walls</td>
<td>29.3</td>
<td>30.4</td>
<td>9.1</td>
</tr>
<tr>
<td>Mean defect severity marking</td>
<td>1.7</td>
<td>1.6</td>
<td>2.0</td>
</tr>
<tr>
<td>% with bulging spandrel walls</td>
<td>53.7</td>
<td>47.8</td>
<td>45.5</td>
</tr>
<tr>
<td>Mean defect severity marking</td>
<td>2.4</td>
<td>2.1</td>
<td>1.8</td>
</tr>
<tr>
<td>% with outward movement relative to arch ring</td>
<td>63.4</td>
<td>43.5</td>
<td>27.3</td>
</tr>
<tr>
<td>Mean defect severity marking</td>
<td>2.1</td>
<td>2.4</td>
<td>2.3</td>
</tr>
<tr>
<td>% with crack in arch ring beneath inside edge of spandrel wall</td>
<td>29.3</td>
<td>17.4</td>
<td>27.3</td>
</tr>
<tr>
<td>Mean defect severity marking</td>
<td>2.3</td>
<td>3.0</td>
<td>3.3</td>
</tr>
<tr>
<td>% with any of the above defects</td>
<td>80.5</td>
<td>65.2</td>
<td>54.5</td>
</tr>
</tbody>
</table>

The bridges in England had fewer defects than the Scottish bridges, except for leaning spandrel walls. None of the bridges in SW England had tie bars, though a larger proportion (of a small sample) of bridges in SE England had them than in Scotland. The mean severity markings for the three areas appear to be quite similar.

The evidence therefore suggests that the Scottish bridges have suffered more outward movement of spandrel walls than the English bridges. There are
possible explanations for the difference other than climate, such as differences in building materials or more heavy goods vehicles (HGVs) on the Scottish bridges.

An estimate was made of traffic flow during the inspection, but only a short period was spent at each bridge so the reliability of the estimate cannot be assured (most bridges were also listed as having little HGV traffic).

The closeness of traffic to the spandrel walls may affect the amount of damage. To examine this, the width of the footpath or verge has been compared with the total severity marking for the spandrel walls of each bridge. No correlation was found. This should not however be taken to mean that allowing vehicles to travel closer to a spandrel wall will not have an adverse effect, only that any such effect could not be isolated from the data.

2.2.3 Arch ring defects and repairs

The arch ring soffits were examined for local bulges, cracks and missing mortar. The defects were given a severity marking of from 1 to 5. Repairs were also noted and a similar marking system was adopted, with a value of 1 for minor repairs and 5 for major repairs affecting virtually the whole arch. Table 3 summarises the results.

<table>
<thead>
<tr>
<th></th>
<th>SC</th>
<th>SW</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage with bulges</td>
<td>26.3</td>
<td>8.7</td>
<td>40.0</td>
</tr>
<tr>
<td>Mean defect severity marking</td>
<td>1.8</td>
<td>1.5</td>
<td>2.2</td>
</tr>
<tr>
<td>Percentage with cracks</td>
<td>23.7</td>
<td>10.9</td>
<td>40.0</td>
</tr>
<tr>
<td>Mean defect severity marking</td>
<td>2.9</td>
<td>1.4</td>
<td>2.0</td>
</tr>
<tr>
<td>Percentage with missing mortar</td>
<td>36.8</td>
<td>15.2</td>
<td>20.0</td>
</tr>
<tr>
<td>Mean defect severity marking</td>
<td>1.5</td>
<td>1.6</td>
<td>1.0</td>
</tr>
<tr>
<td>Percentage with any of above defects</td>
<td>57.9</td>
<td>23.9</td>
<td>50.0</td>
</tr>
<tr>
<td>Percentage with repairs</td>
<td>81.6</td>
<td>84.8</td>
<td>100.0</td>
</tr>
<tr>
<td>Mean repair severity marking</td>
<td>3.4</td>
<td>3.2</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Note: mean severity markings do not include bridges without the defect or repair.

Table 3 Arch ring defects and repairs

The Scottish arch rings were in a poorer condition than those in SW England, with a higher proportion having one or more defects. This is despite a similar proportion having had repairs, and about the same level of repairs. The bridges in SE England also had a high proportion of defects and all had been repaired but the small size of the sample should be borne in mind.

3 Repair and strengthening techniques

Table 4 identifies the common faults of arch bridges and the repair and strengthening techniques which may be applied (some of the techniques will be described in more detail later in the section).
<table>
<thead>
<tr>
<th>FAULT</th>
<th>REPAIR/STRENGTHENING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arch ring thickness assessed to be inadequate to carry required traffic loads</td>
<td>Saddle Sprayed concrete to soffit Prefabricated liner to soffit</td>
</tr>
<tr>
<td>Deterioration of arch ring material</td>
<td>Saddle Sprayed concrete to soffit Prefabricated liner to soffit Grout arch ring</td>
</tr>
<tr>
<td>Deteriorated pointing</td>
<td>Repoint</td>
</tr>
<tr>
<td>Internal deterioration of mortar — eg separation between rings of a multi-ring brick arch</td>
<td>Grout arch ring</td>
</tr>
<tr>
<td>Foundation movement</td>
<td>Mini-pile Grout piers &amp; abutments Underpin</td>
</tr>
<tr>
<td>Scour of foundations</td>
<td>Underpin Invert slab</td>
</tr>
<tr>
<td>Outward movement of spandrel walls</td>
<td>Tie bars Replace fill with concrete Take down &amp; rebuild Grout fill if it is suitable</td>
</tr>
<tr>
<td>Separation of arch ring beneath spandrel wall from rest of arch ring</td>
<td>Stitch (short tie bars spanning the crack)</td>
</tr>
<tr>
<td>Weak fill</td>
<td>Replace fill with concrete Grout fill if it is suitable</td>
</tr>
<tr>
<td>Water leakage through arch ring</td>
<td>Waterproof road surface Waterproof arch ring extras + improve drainage</td>
</tr>
</tbody>
</table>

Table 4  Arch bridge faults and repair techniques

An examination of these techniques was carried out in 1990 for TRRL by consultants Ove Arup & Partners. Details were obtained of work done and costs for about 180 bridges and then about 50 were selected for a more detailed examination to identify the advantages and disadvantages of the various repair and strengthening techniques and their relative costs. An assessment of the effectiveness of the techniques was made by inspection; however the repairs had all been done relatively recently so it was not possible to assess their long term effectiveness. Frequently more than one technique is applied to a particular bridge. The costs identified were initial costs, the data were not available to attempt to identify whole life costs.

3.1 Saddling

Saddling involves removal of the fill and casting an in-situ concrete arch on top of the existing arch. The new arch may be designed to act compositely with the existing arch or to structurally replace the existing arch, in effect
using it as permanent formwork. Its advantage is that the work is invisible once completed but it requires a major construction operation to install.

The only defects observed in the surveyed bridges strengthened using this technique were signs of weathering, discoloration and leachate encrustation on the arch soffit associated with water seepage which is common on masonry arches.

3.2 Repointing

Routine maintenance repointing is widely regarded as essential and may improve significantly arch load capacity by restoring the structurally effective arch ring thickness to its full depth. If properly done when it is needed, it may prevent the bridge from deteriorating to the point where it needs more expensive repair work. If incorrectly done it can accelerate deterioration of the structure (the mortar should not for instance be stronger than the brick or stone). Repointing can enhance the appearance of the bridge and need not disrupt traffic while being done.

3.3 Arch grouting

Arch grouting is used to fill voids in the arch ring to ensure that the full depth of section is available for load carrying. It is often used to fill voids caused by ring separation in multi-ring brick arches. It does not affect the appearance of the bridge unless grout extrudes from cracks and is not removed (it may be necessary to repoint the arch ring first). The grout needs to be carefully designed to avoid premature setting before it has completely filled the voids and to ensure that its properties are compatible with the existing arch material. High pressure grouting may damage weak structures. It will always take a line of least resistance which may be into fill, service ducts and drain pipes.

The cases examined suggest that when properly applied it is an effective strengthening technique.

3.4 Sprayed concrete

Sprayed concrete is widely used as a means of increasing arch ring thickness to increase load capacity, and of stabilising badly weathered masonry. Premixed concrete is sprayed at high velocity and it adheres on impact, filling crevices and compacting material already sprayed. A layer up to 300mm thick may be applied; it is usually reinforced with at least nominal steel. It is quick to apply and does not involve disruption to traffic or services. It reduces the size of the arch opening and it does not enhance the appearance of the bridge although careful design can reduce its visual impact.

All the cases investigated showed signs of cracking, made visible by seepage of water and the associated leaching of mineral salts. The lining may separate from the original arch by shrinkage of the concrete or by further deterioration of the arch material at the interface, which would mean that it would not increase the load capacity as much as if it were fully attached. It was not possible to check this on the cases surveyed.

3.5 Prefabricated liners

Arch ring thickness is increased by attaching a corrugated metal or glass
reinforced cement lining to the soffit as permanent formwork, and filling the space between it and the arch ring with concrete or grout. As with sprayed concrete, it is quick to apply and involves no disruption to traffic or services, but it reduces the size of the arch opening and does not enhance the appearance of the bridge. Care needs to be taken to ensure that the space between the arch and the formwork is fully filled with concrete or grout.

No evidence of serious problems were found in the cases studied. However, rusting corrugated steel and fixing bolts were found, and grout loss at sheet joints due to poor fit.

3.6 Underpinning

Underpinning involves excavating material from beneath the foundations and replacing with mass concrete. A sequence of work is followed to ensure that the stability of the existing structure is not compromised. The work is labour intensive. The cases studied appeared to have been successful.

3.7 Invert slabs

An invert slab (see figure 1) is a slab of concrete placed between the abutment walls or piers with its top surface at or below river bed level (older versions may be built of masonry). It helps to prevent scour. If incorrectly installed however, there is a risk of scour beneath the slab, particularly at its downstream end, and this was found in one of the cases studied.

3.8 Tie bars

Tie bars are used to restrain further outward movement of spandrel walls (see section 2.2.2). They consist of a bar passing through the full width of the bridge, with pattress plates at each end, generally secured by a nut and washer, to provide the restraint to the wall. If the arch ring requires strengthening at the same time a more common solution is to use a concrete saddle which will also relieve the spandrel wall of outward forces.

In one of the cases studied there appeared to have been further movement of a spandrel wall since installation of the tie bars. Rusting of the exposed parts, in one case severe, was also found.

3.9 Replacing some or all of the spandrel fill with concrete

This technique is used to stabilise outward movement of spandrel walls. When the whole of the fill is replaced, the technique is akin to saddling and is likely to be used to deal with arch and wall problems at the same time. The work is invisible once completed. Traffic and services are likely to be disrupted during installation. Few defects were seen in the cases studied, except for the appearance of leachate.

4 Relative cost of repair methods

From the cost data collected during the survey it is possible to estimate the cost of various methods of repairing or strengthening an arch ring. As an example a bridge with a semicircular arch of span 4.5m, headroom 3.5m (rise of arch plus height of abutment), total length at road surface 15m, and width 6m has been examined. The costs (at 1990 prices) are given in figure 2.
Figure 2 Cost of various repair methods for example bridge

The cost/m² of grouting was significantly different for the two examples examined in the survey, so two costings are included in the figure.

5 Conclusions

The condition survey showed that the Scottish bridges examined were generally in poorer condition than the English bridges but the cause or causes could not be isolated from the data available.

The survey of repair and strengthening techniques showed no serious defects with any of the techniques examined, although in some cases attention to detail is necessary. The costings suggest that if repointing is adequate to repair the deterioration present or if it gives an acceptable increase in load capacity then it should be used. If this is not sufficient and if the appearance of the bridge is unimportant then sprayed concrete is the cheapest option. Grouting of voids in the arch ring has advantages when appearance is important and when disruption to traffic would be unacceptable. If disruption to traffic is acceptable then saddling may be a more reliable option than grouting.

6 Acknowledgements

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