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Repair and Strengthening of Arch Bridges

Réparation et renforcement des ponts en arc

Ausbesserung und Verstärkung von Bogenbrücken

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SUMMARY

Masonry arch bridges form an important part on the highway network of the United Kingdom. It is essential to enable them to continue to play their part; the cost of replacing them would be enormous and many make a positive contribution to the landscape. This paper describes the common types of deterioration from which they suffer, including the results of a condition survey. Repair and strengthening methods are then examined, based on a survey of their cost and effectiveness. The importance of timely maintenance is demonstrated.

RÉSUMÉ

Les ponts en arc en maçonnerie constituent une partie importante du réseau routier de la Grande-Bretagne. Il est essentiel de leur permettre de continuer à jouer leur rôle; le coût de leur remplacement serait énorme et un grand nombre de ces ponts contribue d'une manière positive au paysage. Cet article décrit les types courants de détérioration qui affectent ces ponts et présente les résultats d'une enquête sur les coûts et l'efficacité de ces méthodes. L'importance d'effectuer l'entretien à temps est soulignée.

ZUSAMMENFASSUNG

Gemauerte Bogenbrücken bilden einen bedeutenden Teil des britischen Hauptstrassennetzes. Die Fortsetzung ihrer Rolle in der Zukunft ist wesentlich. Die Kosten für ihren Ersatz wären enorm. Viele leisten einen positiven Beitrag zum Landschaftsbild. Dieses Referat beschreibt die üblichen Schadensmechanismen an denen sie leiden, und enthält Ergebnisse einer Zustandsüberprüfung. Dann werden Ausbesserungs- und Verstärkungsverfahren im Hinblicke auf Kosten und Wirksamkeit untersucht. Die Bedeutung eines rechtzeitigen Unterhalts wird aufgezeigt.

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 many have reached the end of the present nominal design life for UK bridges of 120 years. It is not however either practicable or desirable to replace them. The cost would be enormous and many make a positive contribution to the landscape or are of historical or architectural importance.

Many of them have deteriorated due to the effects of weathering and traffic: some of the traffic they are now required to carry is much heavier than was envisaged when they were built. There are a variety of commonly used repair and strengthening methods used to maintain their function or to increase their load carrying capacity. This paper discusses the common types of deterioration and the effectiveness and cost of some repair and strengthening methods. Typical construction of masonry arch bridges is shown in figure 1.

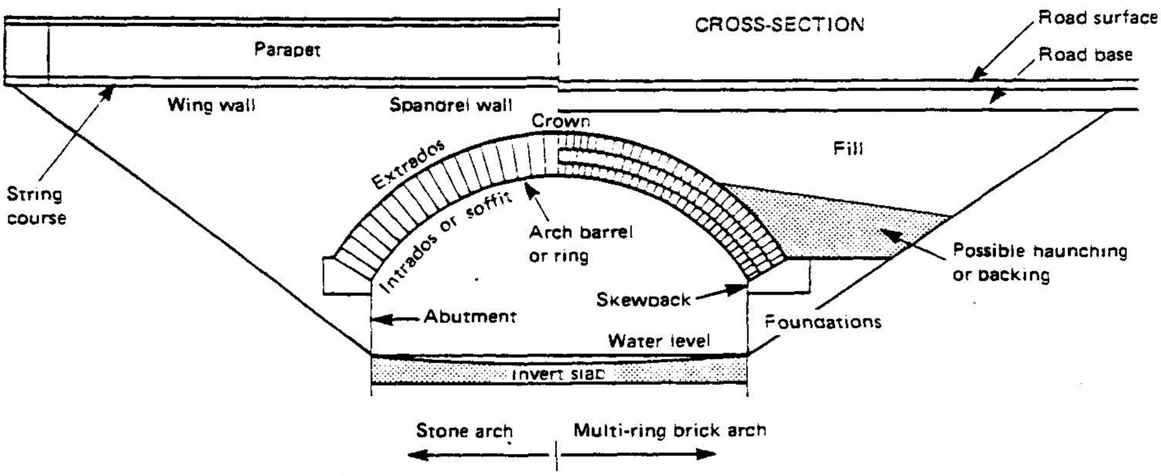

Fig 1 Typical masonry arch bridge construction

2. COMMON DEFECTS

2.1 Scour of river foundations

Scour is probably the most common cause of collapse of masonry arch bridges, because foundations are generally shallow. For example, severe rainfall in Southern Ireland in August 1986 resulted in considerable flood damage to many bridges; nine in County Wicklow alone. In all but one case failure was due to scour of the upstream side. River bed levels were lowered by up to 600mm, whereas foundations only extended to about 300mm below bed level.

Scour is difficult to detect because it is likely to be at its worst when the river is in flood and access is impossible. It may be made worse by fallen trees and other debris catching in the arch when the river is in flood. Scour holes may refill as floods subside and conceal undercutting of foundations.

2.2 Arch ring defects

2.2.1 Problems due to movement of abutments

Arch rings generate outward pressure on their abutments and may lead to outward movement. The fill behind abutments will resist the outward movement and may cause inward movement. The effect on the arch ring will depend on whether the movement is outwards or inwards and whether it is accompanied by rotation of the abutments. It is likely to manifest itself as transverse cracks in the arch ring.

Most arches would settle when the centring was removed during construction but would be expected to stabilise so recent cracks are a cause for concern as they indicate fresh movement.

2.2.2 Splitting beneath the spandrel walls

Fig 2 Crack in arch ring

Spandrel walls stiffen the arch ring at its edges. Flexing of the arch ring due to traffic loads will produce shear stresses in the ring where the relatively flexible part with only fill above it is stiffened by the spandrel wall, and these stresses may result in a crack. A severe example of such a crack is shown in figure 2. This type of failure may be assisted by rainwater getting into the structure at the parapet/surface joint and causing particular damage to the arch ring mortar where the spandrel wall meets the ring.

2.2.3 Ring separation

Ring separation is a common problem with multi-ring brick arches and may be due to deterioration of the mortar or may be load induced. Research [1] has shown that the load capacity is likely to be significantly affected. Tapping with a hammer is the technique commonly used to detect separation.

2.3 Spandrel walls

Spandrel walls probably represent the biggest single problem with masonry arch bridges. They suffer from the normal problems associated with exposed masonry such as weathering and loss of pointing. They are also frequently affected by dead and live load lateral forces generated through the fill or as a result of vehicle impact on the parapet or by freezing of the fill. The effect may be (see figure 3) outward rotation, sliding on the arch ring, cracking of the arch ring, or bulging.

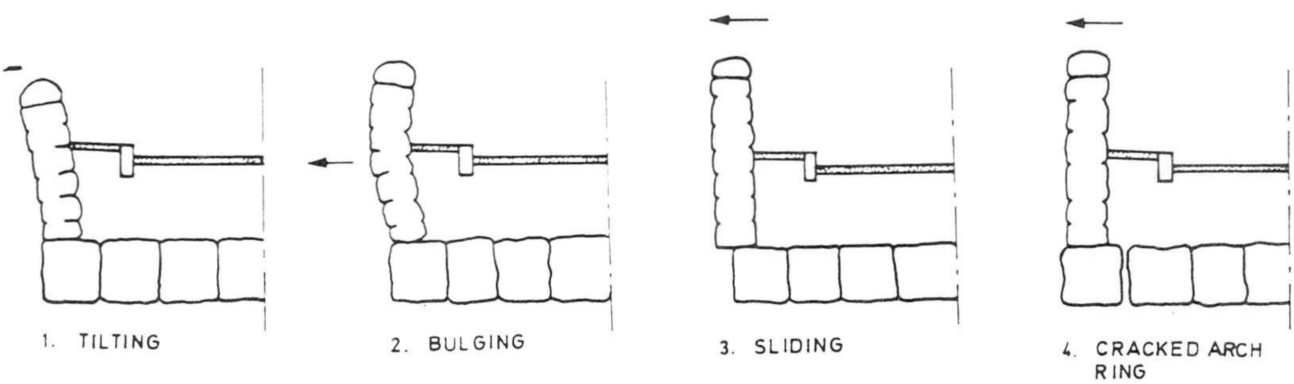

Fig 3 Spandrel wall failures

2.4 Fill

The major problem likely to affect fill is that the road surface or the drainage breaks down and the fill becomes saturated. This is unlikely to affect load capacity of the bridge immediately, indeed the increased weight may increase it. Longer term effects are that fines may be washed out of the fill leading to voids. Water percolating through the arch ring is likely to lead to deterioration of the mortar. Saturated fill will substantially increase the lateral pressures on spandrel walls particularly if the fill freezes in winter, perhaps leading to outward displacement of the wall.

3. FREQUENCY OF OCCURRENCE OF DEFECTS

A survey of 98 masonry arch bridges chosen at random was undertaken by the Transport Research Laboratory (TRL) in 1989. Forty one were in the north of Scotland, forty six in south west England and eleven in south east England. The main conclusions about the condition of the bridges were as follows:

- Only three bridges had no sign of water leakage through the arch ring. Severity of leakage was higher in Scotland.
- Sixty nine of the bridges had some spandrel wall defect, either leaning, bulging, outward movement, or a crack in the arch ring beneath the inside edge of the spandrel wall. Only seven of the bridges had tie bars.
- Forty of the bridges had some arch ring defect, either local bulges, cracks or missing mortar. Eighty four of the arches had been repaired at some time in the past.

Deterioration is therefore the rule rather than the exception.

4. MAINTENANCE

Routine maintenance consists of keeping the road surface in a sound condition to reduce ingress of water into the fill and to minimise dynamic loading from traffic due to potholes etc; removing vegetation growing on the structure; and making good small areas of deteriorated mortar. Maintenance involves modest expense compared with that which may result from neglect.

5. REPAIR AND MAINTENANCE TECHNIQUES

Damage will be caused by chemical, physical or biological sources. Examples are acidic rainwater reacting with lime mortar, water in fill freezing and expanding, and tree roots. These effects are discussed in some detail in reference [2].

It is essential that the cause of deterioration is understood before the most effective repair or strengthening method can be decided upon. For instance there is no point in repairing a deteriorated arch by saddling if the cause of the deterioration is movement of the abutments. The effect of any repair on the behaviour of the existing structure must also be considered. If the inherent articulation of the stonework or brickwork is lost as a result of the repair, it may have a long term detrimental effect on the fabric of the structure, the very thing the repair was trying to save.

The assessment of the structure will include an assessment of its load carrying capacity. There is not space here to discuss the techniques available; the reader is referred to reference [3]. The history of the structure should be checked, although records may be sketchy. Trial pits or cores should be considered to provide more detail of the internal structure.

Repair materials should be compatible with existing materials. For instance it is unwise to use hard engineering bricks to repair a structure built of much softer bricks. New material inserted into a structure, eg brick patching will not at least initially carry dead load stresses, only live load stresses. Care should be taken that the repair technique used does not itself cause further damage to the structure. For example, care needs to be taken with the use of rotary percussive drills.

Table 1 identifies the common faults of arch bridges and the repair and strengthening methods which may be applied: some of the methods will be described in more detail later in the section.

Table 1 Arch bridge faults and repair/strengthening methods

FAULT	REPAIR/STRENGTHENING
Deteriorated pointing	Repoint
Deterioration of arch ring material	Saddle Reinforced sprayed concrete to soffit Prefabricated liner to soffit Grout arch ring
Arch ring thickness assessed to be inadequate to carry required traffic loads	Saddle Reinforced sprayed concrete to soffit Prefabricated liner to soffit
Internal deterioration of mortar - eg ring separation	Grout arch ring
Foundation movement	Mini-pile Grout piers & abutments Underpin
Scour of foundations	Underpin Invert slab
Outward movement of spandrel walls	Tie bars Replace fill with concrete Take down & rebuild Grout fill if it is suitable
Separation of arch ring beneath spandrel wall from rest of ring	Stitch (short tie bars spanning the crack)
Weak fill	Replace fill with concrete Grout fill if it is suitable
Water leakage through arch ring	Seal road surface Waterproof arch ring extrados + improve drainage

An examination of these methods was carried out in 1990 for TRL [4]. Fifty bridges were examined to identify the advantages and disadvantages of the various repair and strengthening methods which had been applied to them, and their relative costs. An assessment of the effectiveness of the methods was made by inspection; however the repairs had all been done quite recently so it was not possible to assess their long term effectiveness. Frequently more than one method is applied to a particular bridge. Initial costs only were identified, data were not available to attempt to identify whole life costs.

No research is known which examines the structural effectiveness of the various methods; at the time of writing, TRL has just begun such a research programme.

5.1 Repointing

Routine maintenance repointing is widely regarded as essential and may improve 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 harder than the brick or stone. Repointing can enhance the appearance of the bridge and need not disrupt traffic while being done.

5.2 Saddling

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

Before choosing saddling as a strengthening method, it is important to ascertain the reasons for the arch deterioration. A common reason is signs of distress in the barrel; these may be caused by movements of the abutments. The addition of a saddle will lift the line of thrust which may increase abutment movement and make the problem worse.

The defects observed in the surveyed bridges strengthened using this method were signs of weathering, discolouration and leachate encrustation on the arch soffit associated with water seepage.

5.3 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 should 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.

Cementitious or resin grouts may be used. Cost considerations will normally dictate cementitious grout.

5.4 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. Pre-mixed 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 in the cases surveyed. Rusting of the reinforcement must be a serious concern and every effort should be made to exclude water from the structure.

Most processes rely on the nozzle operative to control the water content of the sprayed concrete which has led to variable quality. British Rail has carried out trials of a Hungarian system in which the water content is controlled at the mixing stage, and this has produced a more reliable product with reduced rebound.

5.5 Prefabricated liners

Arch ring thickness is increased by attaching a metal or glass reinforced cement lining (usually corrugated) 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.

In the cases studied, rusting corrugated steel and fixing bolts were found, and grout loss at sheet joints due to poor fit.

5.6 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.

5.7 Invert slabs

An invert slab (see figure 1) is a slab of concrete or masonry placed between the abutment walls or piers with its top surface at or below river bed level. 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.

5.8 Tie bars

Tie bars are used to restrain further outward movement of spandrel walls. 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. Damage due to expansion of the rust may occur. Wenzel and Maus [5] suggest at least 20mm of grout surround the bar. The use of stainless steel bars could also be considered, or the application of cathodic protection.

5.9 Replacing some or all of the spandrel fill with concrete

This method is used to stabilise outward movement of spandrel walls. When the whole of the fill is replaced, the method 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.

6. RELATIVE COST OF REPAIR METHODS

From the cost data collected during the survey it was 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 was examined. The costs (at 1990 prices) are given in table 2. The cost/m^2 of grouting was significantly different for the two examples examined in the survey, so two costings are included in the table.

Table 2 Cost of various repair methods for example bridge

Repair method	Cost (£)
Repoint arch ring	4000
Sprayed concrete (t=150mm)	10800
Grout (£269/m^2)	15300
Concrete saddle	23300
Grout (£433/m^2)	24700
Corrugated steel lining	57000

It should be noted particularly that the cost of repointing is modest compared with the other techniques which serves to re-emphasise the point made earlier that routine and timely maintenance is vital and cost-effective.

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8. ACKNOWLEDGEMENTS

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