NOVEL METHOD OF STRENGTHENING MASONRY ARCH BRIDGES

Carl L Brookes and Dr Graham P Tilly

PAPER PRESENTED TO 'STRUCTURAL FAULTS AND REPAIRS - 1999'

NOVEL METHOD OF STRENGTHENING MASONRY ARCH BRIDGES

Carl L Brookes and Dr Graham P Tilly
Gifford and Partners
Carlton House, Ringwood Road,
Woodlands
Southampton, SO40 7HT

INTRODUCTION

During recent years much attention has been given to the performance of masonry arches and it has attracted a considerable volume of research. In the UK there are some 40,000 masonry arch bridges in daily use on highways, railways and canals. Most are over 100 years old, some are 500 years old. Traffic loads have increased many times since construction and bridges are now being assessed to the new EC loading requirements. It has become evident that many bridges are not strong enough, either because they have been weathered and deteriorated over time or their design is inadequate. For these cases it is necessary to replace or strengthen the bridges by one means or another.[1]

Various methods of strengthening have been used, one of the most popular being saddling. Here, the fill is removed so that the top surface of the arch barrel is exposed. A reinforced concrete saddle is then cast in place over the original barrel. Saddling undoubtedly raises the strength by a sufficient margin but has the drawbacks of expense, considerable interruption to traffic and potentially major environmental disturbance. It is therefore appropriate to look at other more cost effective and flexible methods of strengthening.

STRENGTHENING SYSTEM

The ideal strengthening system would meet the following requirements:

- minimal change to the appearance of the bridge
- minimal interruption to traffic and other road users
- minimal impact on existing services in the bridge
- provide an adequate increase in load carrying capacity
- exhibit a ductile mechanism of failure
- exhibit long term durability
- be cost effective

To this end, Archtec, a novel system of internal strengthening has been developed where stainless steel reinforcing bars are inserted and grouted into the masonry. The use of stainless steel and a high performance grout ensures that there will be enhanced durability. Most importantly, the bars and grout are contained within a 'sock' which protects the surrounding masonry from being displaced or otherwise damaged by the grouting pressure of 3 to 4 bars. During inflation, the sock deforms and permits sufficient 'leakage' of grout to develop chemical and mechanical bonding with the masonry resulting in a structural connection. The efficacy of this connection is evaluated by pull-out tests. The reinforcement is positioned in the arch barrel in a longitudinal direction and tangential to the curvature. Depending on the condition of the structure, reinforcement may also be positioned in the barrel in a transverse direction.

Numbers and precise disposition of the bars are confirmed by numerical analysis using ELFEN, a nonlinear discrete element program. This enables the composite behaviour of the reinforced masonry to be predicted and allows accurate simulation of its response to permanent and live loads.

In order to obtain confidence in the method of analysis it was checked against a full-scale test to collapse carried out and reported by the Transport Research Laboratory (TRL)[2,3]

FULL-SCALE TESTING

TRL are carrying out a series of tests on full-scale models under controlled conditions in the laboratory[2]. The full scale model arch bridge is constructed in brick and is very similar to an original bridge at Torksey[3] which was tested to collapse in an earlier programme of field work. The arch barrel is composed of three rings of brick, the rings being separated by layers of sand so that they are not bonded together. This represents the commonly found fault in arch barrels of ring separation. The arch is 5m span, 1.25m rise at mid-span and 2m wide. There are no spandrels but, instead, steel containment walls, not connected to the arch barrel, enable fill to be placed and compacted in the normal way. The absence of spandrel walls reduces the structural behaviour to one of two dimensions. This behaviour was also evident for Torksey where the spandrels were disconnected from the arch barrel by wide cracks.

Loading was by a hydraulic jack positioned on a steel I-beam so that a nominal line load is applied across the top of the model bridge at its quarter-point. Initially loading is applied in increments of 1.0 tonne. When the response became significantly non-linear the control was changed to deflection. This enabled the load-deflection characteristics to be fully investigated and the collapse mechanism to be observed beyond maximum load. During the collapse phase the I-beam was replaced by a timber beam to avoid unnecessary damage.

The unstrengthened model bridge failed at a load of 20 tonne[2]. This is used as the reference to enable the effectiveness of strengthening to be assessed.

STRUCTURAL ANALYSIS

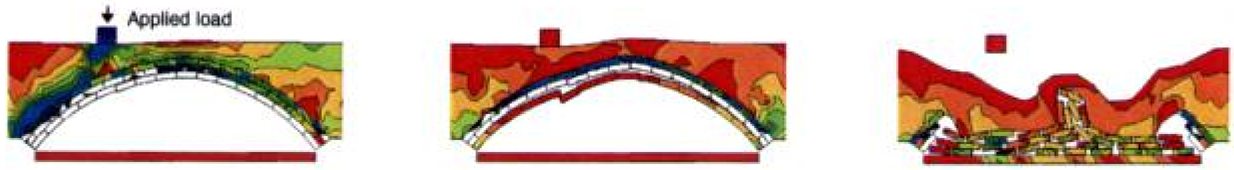
Structural analyses were carried out for the Torksey Bridge and the TRL laboratory model. The method of analysis enabled the structure, including the fill, to be properly modelled.

The analysis included the arch barrel where the masonry was represented by individual blocks, the fill modelled as a no-tension material and the test load as a platen moved vertically. By using the advanced discrete element technique the forces between the blocks, both normal and tangential, could be automatically calculated as the load was increased. In this manner the complex non-linear behaviour of masonry, that often defeats more conventional finite element analysis, is accurately simulated at a fundamental level. This has allowed successful simulations of failure mechanisms to the point where the masonry structure collapses into ‘a pile of rubble’ as occurs in practice.

The calculated failure load for Torksey Bridge was 108 tonne compared with the actual failure load of 109 tonne. Bearing in mind the normal variations in material properties, local deterioration in the bridge, and the assumptions made in the numerical modelling, the close correlation is considered to be a lithe fortuitous. Nevertheless, the analysis was not retrospectively ‘tuned’ to the data, as is often the case, and the results were very encouraging.

The calculated failure load for the laboratory model was 18.6 tonne compared with the actual failure load of 20 tonne. As for the Torksey calculations, there was no retrospective ‘tuning’ of the analysis so that the good correlation provided further confirmation that the method of analysis is sound. A computer simulation showing principal compressive stresses and illustrating the progressive mode of collapse is shown in Figure 1.

a) maximum applied load
b) onset of collapse
c) total collapse



a) maximum applied load b) onset of collapse c) total collapse

Figure 1 Unstrengthened Arch Predicted Mode of Collapse

STRENGTHENED ARCH TEST

Having obtained an understanding of the structural actions and behaviour of the three-ring masonry arch model, different strengthening strategies were considered. In practice the internal reinforcement can be applied from above the arch, beneath it or from the sides. The strengthening work can be done very rapidly causing minimal interruption to traffic. Selection of the preferred strategy would be dependent on the condition of the bridge, its location, traffic, etc. In the event it was decided to work from above the arch and position the anchor pins longitudinally and tangential to the curvature. In designing the strengthening scheme emphasis was placed on achieving an efficient scheme in preference to 'brute strength'. The final scheme employed just eight anchors.

A computer simulation of collapse of the strengthened model is given in Figure 2.

a) maximum applied load
b) onset of collapse
c) inner ring breaking away

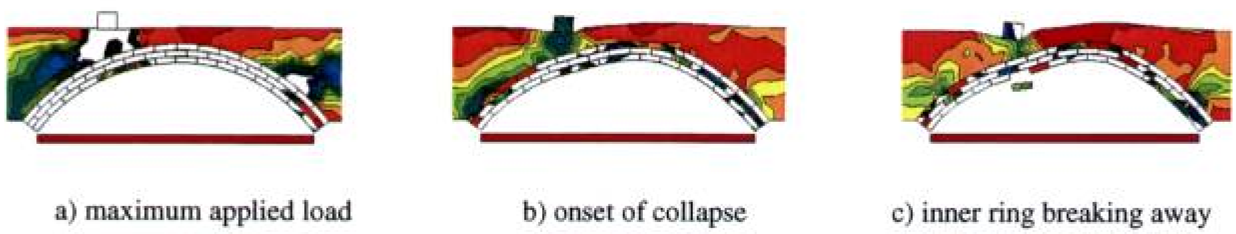


Figure 2 Strengthened Arch Predicted Mode of Collapse

TRL constructed a three-ring brick arch taking great care to ensure that it was identical to others used in their test programme. The same formwork and lime-based mortar were used. Soft hand-made bricks were obtained from the same supplier. The same bricklayer was employed to ensure the same quality of construction. Location of the Cintec anchors required accurate drilling to ensure that they did not stray outside the barrel. The main results are given in Table 1.

Table 1 Main Results

	Unstrengthened Arch	Strengthened Arch
Load to cracking, tonne	6	10
Load to first hinge, tonne	13	28
Maximum load, tonne	20	41
Deflection at maximum load, mm	27.4	16.5

At collapse the bottom ring of bricks fell away leaving the structural pins exposed, see Figure 3. This occurred at a load of 11.5 tonne. At this stage the arch still retained some remnant load carrying capacity. Further deflection was applied until the arch finally disintegrated at a deflection of 220 mm measured beneath the load line.

Figure 3 Collapse of Strengthened Arch

The load to cracking is a measure of the serviceability limit state. This is not normally assessed for bridges built before the introduction of BS5400 but is a useful indication of the potential durability of arches. In this case the cracking load has been increased by 67 per cent.

The maximum load has been increased by over 100 per cent. This is a large increase but is even more significant when it is considered in relation to the number of reinforcing bars used and the ease of construction.

The maximum deflection is a measure of the ductility and tolerance of the strengthened arch. With some systems of strengthening, the masonry can be less ductile and fail with little warning. It is therefore significant that with internal strengthening there was plenty of warning of failure. The calculated and measured load-deflection curves are shown in Figures 4 and 5.

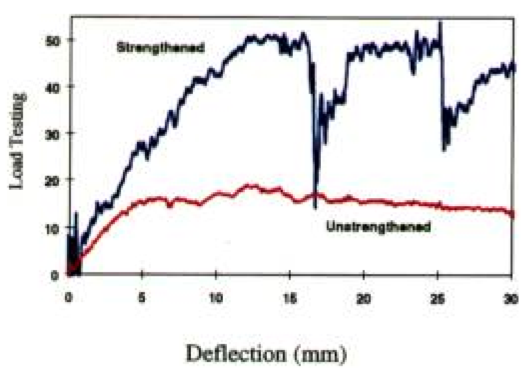


Figure 4 Calculated Load-Deflection

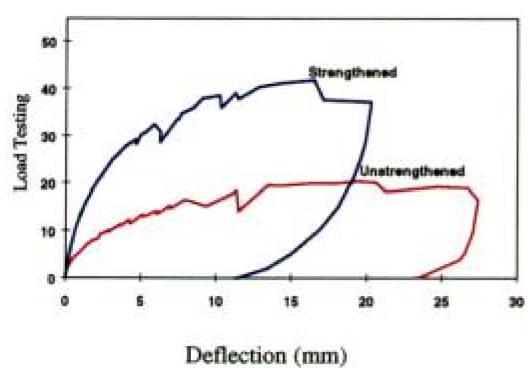


Figure 5 Test Results Load-Deflection

APPLICATIONS IN THE FIELD

To date, the Archtec method of strengthening has been used to raise the load carrying capacity of some 12 bridges in the field to 40 tonne. The experience has led to refinements in the construction operations albeit the engineering principles have been fully confirmed. Three case studies are outlined in the following sections.


Figure 6 Clifton Bridge

Clifton Bridge, Scottish Borders, is a two-span structure across Bowmont Water, a 15m wide river, Figure 6. One arch is badly distorted probably since construction. The spans are 7.2m and 7.6m and constructed of random whinstone and in excellent condition.

An assessment of the structured showed that it had a load carrying capacity of only 7.5 tonne. The bridge is located in a rural environment where there is no alternative route for some of the users, moreover Scottish Borders Council were restricted to a window of opportunity of just two weeks to suite the local farming community. In the event the strengthening was completed in time and the bridge was kept open to traffic during the works. Difficulties due to fragments of the fill clogging the holes being bored for the reinforcement were overcome on site by modifications to the boring technique. At locations where holes were being bored close to the soffit, the drill could sometimes be observed through joints in the masonry. This confirmed that the holes were correctly positioned. When the grouting was carried out the sock successfully prevented leakage and other damage.


Figure 7 Ambersham Bridge

Ambersham Bridge, West Sussex, is a two-span structure across the river Rother, Figure 7. It has a three-ring elliptical arch barrel and cut sandstone voussoirs. The main 5.9m span was assessed as having a 9 tonne load carrying capacity. As a Grade II Listed Structure it required a method of strengthening having minimal effect on its appearance and approval by English Heritage. The work was completed in four days. On this occasion one of the drilled holes broke through the soffit for a short length; this was subsequently made good. It was noted that for future arches having friable materials such as sandstone or soft brickwork, the soffits should be treated beforehand using an approved consolidant to strengthen the surface locally without changing its appearance in any way. The method of strengthening has also been approved in Wales by Cadw for work on Pont Llanafan, Ceredigian.

Figure 8 Ducie Street Bridge

Ducie Street Bridge, Manchester, is a single-span structure across Ashton Canal, Figure 8. The arch has a fairly flat circular profile with a span of 6.8m and is approximately 16m wide. It is constructed in brick having three rings with signs of distortion near the crown. Earlier brick repairs are evident along the north face of the barrel and at the crown directly under the most frequently loaded part of the carriageway. It was assessed as having a 25 tonne load carrying capacity by conventional mechanism analysis. The arch was in generally good condition but with areas of brick with very soft and friable surfaces.

During the design an unusual and critical shear failure of the barrel near the crown was identified. Also in this vicinity the results of the numerical simulation predicted damage and unrecoverable movement of bricks under traversing nominal loads. The predicted damage corresponded to the position of the earlier repairs in the arch crown.

Positioning of the reinforcement had to be designed to avoid extensive services, gas, water electricity, telecommunications located under the footways. Once the precise position of these services had been established using trial pits, final revisions to the design involving re-positioning of the reinforcement were made. The strengthening was carried out whilst maintaining two-way flow of traffic.

CONCLUDING REMARKS

1. The discrete element technique as implemented in ELFEN can be used to provide an accurate analysis of the strength of masonry arch bridges. This has been exemplified by calculations of collapse loads for tests on bridges both in the field and in full scale laboratory models.
2. The Archtec method of strengthening arch barrels is an efficient and practical method that has been demonstrated in a full scale laboratory model by TRL.
3. To date Archtec has been used to strengthen 12 masonry arch bridges constructed in different materials and geometries. The construction operation is carried out without causing significant interruption to traffic, in fact the bridges can usually be kept open to traffic throughout.
4. The method has been approved by Heritage Authorities.

ACKNOWLEDGEMENTS
The laboratory work was carried out by Mr. Sarwan K. Sumon of TRL Help and advice by Mr. Nigel Ricketts, of TRL, is also gratefully acknowledged. The Archtec reinforcement system is supplied by Cintec International Limited. ELFEN software is by Rockfield Software Limited.

The paper is published with the permission of Scottish Borders Council, West Sussex County Council and Manchester City Council.

REFERENCES

1. J Page. *A Guide to Repair and Strengthening Techniques for Brick and Stone Masonty Arch Bridges*. TRL Contractor Report 284, Crowthorne. 1996
2. S K Sumon and N Ricketts, *Strengthening of Masonry Arch Bridges*. Chapter in Arch Bridges. Publ Thomas Tellord, London, 1995
3. Page. *Load Tests to Collapse on Two Arch Bridges at Torksey and Shinafoot*. TRL Research Report 159, Crowthorne, 1988