STRENGTHENING MASONRY ARCH BRIDGES USING STAINLESS STEEL REINFORCEMENT

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1. ABSTRACT

The strengthening of existing masonry arch bridges by insertion of steel reinforcement is a relatively recent and cost effective concept. The technique allows existing masonry arch bridges to be strengthened with minimum inconvenience to the travelling public, and no disruption to public utilities, whilst retaining the appearance and maintaining the structural behaviour.

This paper outlines the results of comparative tests on model arches carried out at the Transport Research Laboratory (TRL) and at the University of Greenwich (UoG) and a load test on a full-scale installation on a 64 metre span masonry arch at Rochdale in the United Kingdom.

Tests at the TRL were carried out using on a 5 metre span segmental arch built with three rings of brickwork with sand between the rings to induce full ring separation. Tests at the UoG were carried out using on a 1.27 metre span segmental arch built with two bonded rings of brickwork. In both cases two tests were carried out: the first on an unreinforced arch and the second on an arch reinforced by the insertion of steel reinforcing bars. An increase in capacity of nearly 38% was obtained for the TRL test and 36% for the UoG test. The insertion of a stainless steel reinforcing cage at Rochdale increased the capacity of the arch from 7.5 tonne vehicles to 40 tonne vehicles.

The paper also examines methods of analysis of reinforced masonry arches including the adaptation of the author's own masonry arch analysis program, ASSARC, and proposes a method for the design of the steel reinforcement.

Keywords: Masonry; Arch; Bridge; Reinforcement; Strengthening

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2. INTRODUCTION

The reinforcement of existing masonry is not a new concept, it has been used widely in the building industry to stitch shrinkage and minor settlement cracks. The first ‘patent’ for the introduction of reinforcement into masonry bed joints was granted in 1927.

This concept has been extended to the repair and strengthening of masonry arch bridges by the insertion of small diameter stainless steel reinforcing bars into grooves cut into the soffit of the arch barrel.

Fig. 1 Schematic View of Arch Reinforcement Cage for Barrel only

Fig. 2 Enlarged View of Rebate
Having established the need to repair or strengthen masonry arch bridges, usually by inspection and assessment, the objectives must be set out in order to achieve a sound and serviceable structure which meets aesthetic and economic constraints. These objectives should include:

i) maintain and/or improve the fabric
ii) increase the load carrying capacity
iii) maintain/enhance appearance

Also it is necessary to know if the structure is classified as an ancient monument or listed structure. Consideration of the following will present the Engineer with a list of constraints:

i) maintenance of use by lorry, car, boat or train
ii) location and number of services, e.g. gas, water
iii) accessibility to carry out work - time available
iv) capacity to maintain performance, i.e. structural behaviour and durability
v) retention of stability and safety
vi) retention of appearance

A series of tests on large scale model brickwork arches has recently been carried out by the Transport Research Laboratory (TRL)(i) in order to quantify the benefits and limitations of various repair and strengthening methods. The results of these tests will be published in due course. This paper will examine the test on the model with induced ring separation strengthened using a stainless steel reinforcement cage inserted into the soffit of the arch barrel. It will also examine tests carried out at the University of Greenwich on a small scale model brickwork arch with no ring separation.

3. TRANSPORT RESEARCH LABORATORY (TRL) MODEL LOAD TEST

3.1 Construction of Model

The TRL model arch was segmental, with a span of 5m, a rise of 1.25m and a width of 2m. Materials used were representative of a typical pre-1900 arch bridge, constructed of non-engineering bricks and lime mortar. The 330mm thick barrel comprised three rings of brickwork with a layer of sand between them to simulate ring separation. Bricks were 215 x 100 x 65mm Swanage Handmade with a mean compressive strength of 18.4N/mm². The mortar consisted of a cement:lime:sand ratio of 1:3:12, with a mean compressive strength of 1.3N/mm². Brickwork prisms were tested and gave a mean compressive strength of 5.3N/mm². Tensile tests on the stainless steel to be inserted gave an average tensile strength of 480N/mm².

Type 2 road base material was used as fill to a level of 300mm above the crown. There were no spandrel walls and the fill was retained in a steel box constructed around the model in such a way that it did not interfere with the movement of the arch barrel. Loading was applied from a 3000kN hydraulic jack to the centre of a steel beam which extended to the full width of the top surface of the compacted fill over the third point of the arch. The jack had ball joints built in to the top and bottom to compensate for any uneven longitudinal or transverse movements while loading.
3.2 Load Test

Due to equipment problems, the arch was accidentally loaded to failure before the test took place. Two main hinges were formed at the load-line and at the crown. After the accident, it was decided to jack the arch back to its original profile and repair it.

The unreinforced repaired arch was loaded in increments to failure. The first hinge formed under the load line at 130kN and by 160kN, it was difficult to maintain the load as displacement was continuous. The second hinge was evident at the crown at 170kN and by 200kN a significant amount of debris was dropping from the soffit of the arch. 200kN was the maximum load that the arch could withstand.

The failed arch was again jacked back to its original shape and repaired. It was then strengthened using pairs of 6mm stainless steel reinforcing bars located in rebates cut longitudinally at 225mm centres into the soffit of the arch. These rebates were cut using a hand-held twin-bladed cutter. Transverse reinforcement was also provided at 450mm intervals around the soffit. The reinforcement cage was surrounded by a non-shrink, flexible and solvent-free structural adhesive applied under pressure and left to cure. It was tested in front of an invited audience of Bridge Engineers on the 6 March 1996 and, again it was loaded in increments to failure.

Hinge formation both under the load line and at the crown was evident at 175kN and by 258kN, there was an indication of creep in the structure. At a load of 276kN, there was evidence that a four hinge mechanism had developed with additional hinges at 1/8 and 7/8 span. The jack ball joint reached its limit of travel at this point and the load was slowly reduced to zero and the arch showed good recovery properties. This suggests that the repair system had increased the elastic properties of the arch.

The arch was then again loaded with a modified jack and collapsed at 320kN. Following this collapse, it was noted that significant radial cracking had occurred in the top and middle brick rings under the load line and the bottom reinforced ring remained intact over approximately two-thirds of the span. There was little loss of bond between the brickwork and reinforcement.

It was further noted that a normal pattern of hinges developed but the reinforcement delayed the formation of the first hinge under the load when compared to the unreinforced test.

<table>
<thead>
<tr>
<th>Model</th>
<th>LOAD to Failure (kN)</th>
<th>Max Displacement (mm)</th>
<th>Max Displacement after load removal (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unreinforced with ring separation</td>
<td>200</td>
<td>27.4</td>
<td>23.4</td>
</tr>
<tr>
<td>Ring separation but reinforced with steel cage</td>
<td>276 (320 max)</td>
<td>21.3</td>
<td>11.0</td>
</tr>
</tbody>
</table>

Table 1: Summary of TRL Model Tests

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4. UNIVERSITY OF GREENWICH MODEL ARCH LOAD TEST

4.1 Construction of Model

Two model arches were constructed for the UoG tests. Each model was segmental, with a span of 1.27m, a rise of 0.48m and a width of 0.35m. Construction was of engineering bricks and 1:6 cement:sand mortar. Each 60mm thick barrel comprised two rings of brickwork bonded together by a layer of mortar. Bricks had a mean compressive strength of 31N/mm² and the mortar had a mean compressive strength of 4.0N/mm².

The bricks used for the second UoG model had two 6mm grooves cut at 71mm from each end. Two rings of 1.6mm steel reinforcement were inserted into these grooves after the arch had been constructed and grouted under pressure using the same structural adhesive that was used in the TRL test. The reinforcement had a tensile strength of 414N/mm².

Fill material to both models comprised 10mm gravel aggregate and was compacted to a level of 120mm above the crown. There were no spandrel walls and the fill was retained in a steel framed box with strengthened glass panels constructed around the model in such a way that it did not interfere with the movement of the arch barrel. Loading was applied from a 10kN hydraulic jack to the centre of a timber block which extended to the full width of the top surface of the compacted fill over the quarter point of each arch.

4.2 Results of Test

The unreinforced arch was loaded in increments of 0.5kN to failure. The first hinge formed under the load line and the bridge failed at 2.2kN. The reinforced arch was also loaded in increments of 0.5kN to failure. Again, the first hinge formed under the load line and the bridge failed at 3.0kN when the reinforcement had become detached from the masonry in the vicinity of the line load. The reinforced barrel therefore gave an increase in strength of 36%. The reinforced arch at failure did, however, show evidence of severe ring separation.

5. ELASTIC ANALYSIS OF TRL MODEL ARCH

5.1 Plane Frame Analysis

The TRL model arch was idealised into 28 joints with 27 members pinned at the springings. The weight of the barrel and fill were applied as member loads on each appropriate segment of the barrel. A simulated axle load of 276kN was applied to the barrel at the quarter point at joint 8.

A plane frame analysis was carried out using NLSTRESS which is part of the SAND suite of software. This gave a maximum moment at joint 8 of 120.4kNm and an associated axial force of 250.5kN. The associated bending moment diagram is given in Fig. 3.
5.2 Analysis of Section

The strengthened arch was analysed as a reinforced concrete section under bending and axial load. The compressive strength of the masonry was taken as 5.3N/mm² and the yield strength of the reinforcement as 480N/mm². Partial factors for material strength were set at unity.

![Bending Moment Diagram for TRL Model Arch](image)

**Fig. 3 - Bending Moment Diagram for TRL Model Arch**

An analysis in accordance with reference (4) gave a moment capacity of the section of 135.46kNm. This is higher than value of 110.4kNm obtained from the plane frame analysis and therefore represents an overestimate of the failure load of 22.7%.

6. MODIFIED MECHANISM ANALYSIS OF THE TRL MODEL

6.1 Unreinforced Barrel

As described in reference (2), an analysis of the model arch using the ASSARC Modified Mechanism Method with all partial factors set to unity gave a collapse load of 220kN. This overestimates the failure load by 10% though, in arriving at this figure, no account was taken of ring separation. A similar analysis of another TRL model, with no ring separation and a slightly thinner barrel, gave a failure load of 190kN which was the same value as the test load at the point of unserviceability. This suggests that ring separation with no associated local bowing reduces the capacity by 10%. A discussion on the accuracy of the ASSARC Modified Mechanism Method is given in reference (3).
6.2 Reinforced Barrel

As it was noted from the test, the insertion of the reinforcement cage delayed the formation of the first hinge under the load line and hence the collapse of the arch under the increasing load regime. It can be observed from Fig. 3 that there is a significant moment causing tension at the extrados on the unloaded half of the barrel. The intrados reinforcement is ineffective in this region and the plane-frame analysis is not appropriate. The ASSARC modified mechanism method has thus been extended to allow a moment of resistance to be taken at the hinge under the load line.

![Diagram of Forces on Barrel at Mechanism Failure for Reinforced Section]

**Fig. 4 - Forces on Barrel at Mechanism Failure for Reinforced Section**

Taking moments about C:

\[
x_{bc}V_b = y_cH + \sum_{i=1}^{c} w_i (x_c - x_i) + \sum_{i=1}^{m} h_i (y_m - y_i) + M_c
\]

\[
\therefore V_b = \frac{y_cH}{x_{bc}} + \frac{x_c \sum_{i=1}^{c} w_i}{x_{bc}} - \frac{\sum_{i=1}^{c} w_i x_i}{x_{bc}} + \frac{y_m \sum_{i=1}^{m} h_i}{x_{bc}} - \frac{\sum_{i=1}^{m} h_i y_i}{x_{bc}} + \frac{M_c}{x_{bc}}
\]

Let \( \Omega_c = \frac{x_c \sum_{i=1}^{c} w_i}{x_{bc}} - \frac{\sum_{i=1}^{c} w_i x_i}{x_{bc}} \)

Let \( \Phi_c = \frac{y_m \sum_{i=1}^{m} h_i}{x_{bc}} - \frac{\sum_{i=1}^{m} h_i y_i}{x_{bc}} \)
\[
V_b = \frac{y_e H}{x_{bc}} + \Omega_e + \Phi_e + \frac{M_e}{x_{bc}} \quad \text{Eqn 1}
\]

Taking moments about \(D\):

\[
x_{bd} V_b = y_d H + \sum_{b} \frac{d}{b} w_i \times \sum_{b} (x_d - x_i) + \sum_{b} \frac{d}{b} h_i \times \sum_{b} (y_d - y_i)
\]

\[
\therefore V_b = \frac{y_d H}{x_{bd}} + \frac{x_d \sum_{b} w_i}{x_{bd}} - \frac{\sum_{b} w_i x_i}{x_{bd}} + \frac{y_d \sum_{b} h_i}{x_{bd}} - \frac{\sum_{b} h y_i}{x_{bd}}
\]

Let

\[
\Omega_d = \frac{x_d \sum_{b} w_i}{x_{bd}} - \frac{\sum_{b} w_i x_i}{x_{bd}}
\]

Let

\[
\Phi_d = \frac{y_d \sum_{b} h_i}{x_{bd}} - \frac{\sum_{b} h y_i}{x_{bd}}
\]

\[
\therefore V_b = \frac{y_d H}{x_{bd}} + \Omega_d + \Phi_d \quad \text{Eqn 2}
\]

Solving Equations 1 and 2 simultaneously for \(H\):

\[
\frac{y_e H}{x_{bc}} + \frac{\Phi_e}{x_{bc}} + \frac{M_e}{x_{bc}} = \frac{y_d H}{x_{bd}} + \Omega_d + \Phi_d
\]

\[
\therefore H = \frac{\left( \Omega_d - \Omega_e \right) + \left( \Phi_d - \Phi_e \right) - M_e / x_{bc}}{\left( y_e / x_{bc} - y_d / x_{bd} \right)}
\]

\(V_b\) can now be obtained from Equation 2 and the collapse load, \(W\), can now be found by taking moments about \(A\):

\[
x_{ca} W = x_{ba} V_b + y_{ab} H + \sum_{b} a w_i \times \sum_{b} (x_a - x_i) + \sum_{b} h_i \times \sum_{b} (y_m - y_i)
\]

This procedure is repeated for every permutation and combination of hinges to find the lowest value of collapse load for this particular position of load. The procedure is further repeated for each position of load from midspan to the right hand springing to find the lowest value of collapse load, \(W\), for the arch.

When the above theory is applied to the TRL model barrel and all partial safety factors are set to unity, a collapse load of 348.8kN is obtained. This collapse load does not take into account ring separation and compares favourably with the maximum load of 320kN recorded during the test.
7. ROCHDALE CANAL BRIDGE

The *Well I' th' Lane* masonry arch over the Rochdale Canal was the first bridge in service to be strengthened using a stainless steel reinforcement cage inserted into the soffit. The arch has a span of 6.4 metres with a central rise of 1.8 metres and a width of 7.2 metres. The barrel comprised a single 340mm ring of natural sandstone. The bridge had been widened to 11.5 metres using reinforced concrete extensions either side of the arch. The parapet walls had therefore been removed from the arch. After assessment using the ASSARC computer program, the capacity of the bridge was restricted to vehicles of 7.5 tonne gross weight.

The bridge was strengthened using 6mm stainless steel ribbed reinforcement bars at 150mm centres inserted into rebates cut into the soffit of the barrel. The reinforcement was encapsulated into the rebates with a low density structural adhesive similar to that used in the model tests. The adhesive was applied under pressure and finished to provide a mortar joint appearance. The reinforcing bars were extended into the concrete extensions to the arch to prevent differential movement.

After strengthening was completed, the structure was test loaded at the quarter point of the arch using kentledge. Strain was recorded using 140mm vibrating wire gauges attached to the intrados of the arch barrel and deflections were recorded using 50mm linear displacement transducers. Initially, the arch was loaded incrementally to design loading plus 25% (25.9 tonnes) and the arch behaved linearly throughout. The load was actually increased to 40 tonnes and the response remained linear with a maximum downward movement of 0.7 mm recorded at the soffit directly under the load. The load was removed incrementally and full recovery was achieved after removal of the load. This load test demonstrated that the arch was able to carry the full design loading of an 11.5 tonne single axle which is equivalent to a 40 tonne vehicle in accordance with reference (5).

Analysis of the reinforced arch using the analogy of reinforced concrete gave a moment of resistance of the reinforced section of 102.5 kNm. When this value is input into the modified mechanism method adapted for reinforcement, the allowable single axle load on the bridge is increased from 5.5 tonnes to 16.7 tonnes and the allowable gross vehicle weight is increased from 7.5 tonnes to an unrestricted 40 tonnes.

8. CONCLUSIONS

It is concluded that the insertion of a reinforcement cage is a simple and effective means of strengthening a masonry arch barrel. In the case of the TRL test, an increase in strength of 38% was achieved and a 36% increase in strength was achieved with the small scale UoG model. The full scale case study showed that the insertion of a reinforcing cage can increase the load capacity of an arch from 7.5 tonnes to 40 tonnes.

It was noted during the model tests that the arches retained their flexibility and that the inserted reinforcement cage did not alter the traditional pattern of deformation of the barrel. Indeed the collapse of the reinforced arch was less spectacular than a traditional
arch and after the initial failure load was removed, the arch almost recovered to its initial shape.

The assessment of the capacity of the critical section under the load line on the basis of reinforced concrete analysis using data from an elastic plane frame analysis, gave results 22.7% higher than the test load. It should be noted however that the assessment was carried out on the basis of a fully effective barrel thickness whereas the barrel tested had induced ring separation.

Because the mode of failure of the arch is not altered due to the fact that, under the above system, only a relatively small amount of reinforcement with small diameter bars is inserted, a mechanism analysis is still valid. The ASSARC modified mechanism method extended to allow a moment of resistance to be taken at the hinge under the load line is thus a valid and accurate means of analysis. The results obtained for the TRL model using this method compare favourably with the maximum load recorded during the test. Trials are continuing to confirm the validity of this approach.

Soffit reinforcement does not add weight to the structure, reduce the elevational area or detract from the appearance of the structure. It is durable and cheaper than other practical alternatives and the installation works can be planned sequentially to minimize inconvenience to users of the bridge. A major cost saving with the use of the method is the fact that statutory undertakings need not be disturbed.

9. ACKNOWLEDGEMENTS

The author would like to thank the Transport Research Laboratory for their assistance in testing the unreinforced and reinforced models and reporting the results and for reporting the results of the load test at Rochdale.

10. REFERENCES


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