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THE STRENGTHENING AND REPAIR OF MASONRY STRUCTURES USING THE MARS SYSTEM

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ABSTRACT

The strengthening of existing masonry arch bridges by insertion of steel reinforcement 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 describes the MARS System of masonry reinforcement which is a patented system that won the Design Council's Millennium Award for Innovation. The paper also outlines a case study of the system installed in a 9.22m masonry arch bridge at St. Andrews in Scotland that was increased in strength from a 7.5t weight restriction to full strength.

The MARS System was tested on full scale arches tested at the Transport Research Laboratory. Even though relatively low amounts of reinforcement were used, increases in capacity of arches strengthened using the System of up to 73% over an unreinforced arch were achieved.

The analysis of the system is carried out using software based on the unreinforced masonry arch analysis program, ASSARC, which has been used commercially by over 60 bridge authorities for over fourteen years. The design of the steel reinforcement is also described.

INTRODUCTION

The concept of repairing and strengthening masonry arch bridges by the insertion of small diameter stainless steel reinforcing bars into grooves cut into the soffit of the arch barrel is shown in Figures 1 and 2. This has been developed so that such bridges can be upgraded in strength without disturbing traffic and services and without the addition of unsightly arches below the barrel. These have the added disadvantage of reducing headroom.

A programme of tests on full scale model brickwork arches was carried out by the Transport Research Laboratory (TRL)[1&2] in order to quantify the benefits and limitations of various repair and strengthening methods. This paper examines the tests on the models strengthened using a stainless steel reinforcement cage inserted into the soffit of the arch barrel.

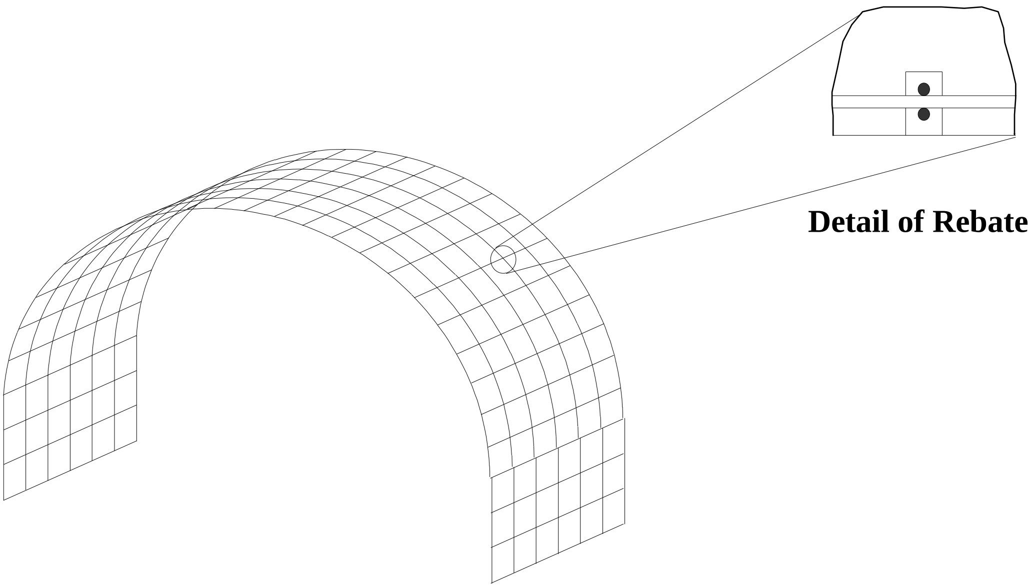

Figure 1   Schematic View of Arch Reinforcement Cage for Barrel only

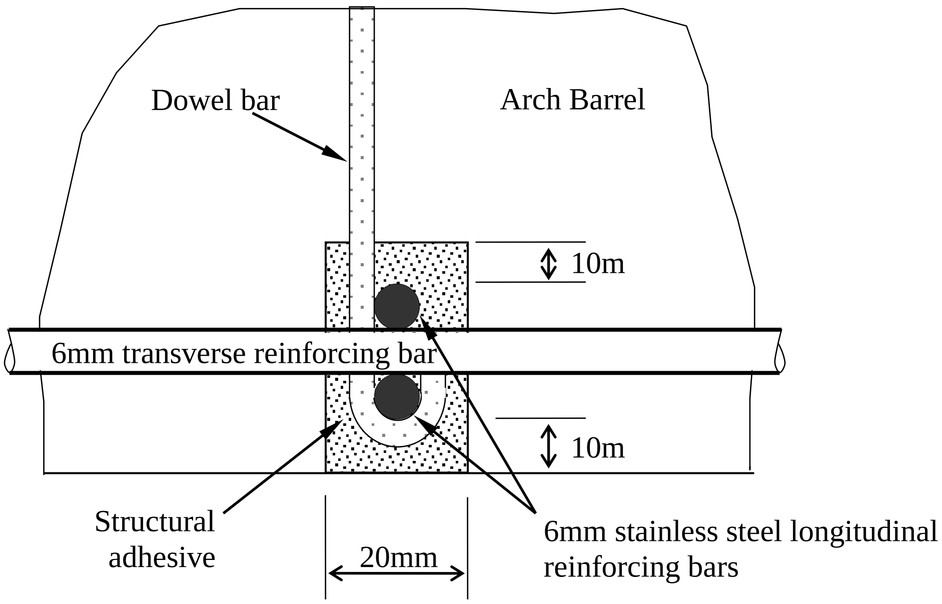

Figure 2   Enlarged View of Rebate

CONSTRUCTION OF TRL MODELS

Small scale model masonry arches (say less than 3m span) do not give results that can be extrapolated to predict the behaviour of full scale bridges. This is due to the fact that it is difficult to compact the fill sufficiently, the materials are new and have not suffered the effects of weathering which reduces elasticity. Also contact stresses between voussoirs are lower than in existing arches and it is impossible to simulate material crushing. Models without fill where the load is applied directly to the arch ring have only limited practical use and should never be used to predict the behaviour of full scale bridges. Thus, each TRL model arch had a span of 5m. Each was segmental in profile with 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/mm^2. The mortar consisted of a cement:lime:sand ratio of 1:3:12, with a mean compressive strength of 1.3N/mm^2. Brickwork prisms were tested and gave a mean compressive strength of 5.3N/mm^2. Tensile tests on the stainless steel to be inserted gave an average tensile strength of 480N/mm^2.

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.

TESTS ON TRL MODEL ARCHES

Three arches were tested. The first was unreinforced and the second was the same arch as the first but jacked back its original profile after failure. The MARS System without the dowels was then inserted into the soffit of the reformed arch and it was again loaded to failure. Each arch was loaded in increments of 10kN to failure

The MARS System used in the second and third arches comprised 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 and 6mm dowels were inserted through the barrel at the intersections of the main reinforcement. These dowels are hooked around main bars to mechanically anchor the system to the barrel. The rebates were filled using the MARFLEX structural adhesive applied under pressure and left to cure.

In both reinforced arches, it was 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. In the second and third tests, the jack reached its limit of travel and the load was reduced to zero. In each case, the arch showed good recovery properties. This suggests that the repair system had improved the elastic properties of the arch.

Table 1 Summary of TRL Model Tests

Model	LOAD to Failure (kN)	Max Displacement (mm)	Max Displacement after load removal (mm)
Unreinforced with ring separation	200	27.4	23.4
Barrel reinforced with surface steel only	276 (320 max)	21.3	11.0
Barrel reinforced with surface steel and dowels between rings.	320 (345 max)	11.0	7.6

MODIFIED MECHANISM ANALYSIS OF THE UNREINFORCED MODEL

Collapse Load of Unreinforced Barrel

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).

Design Load of Unreinforced Barrel

An analysis of the model arch using the ASSARC program with partial factors set to normal design values in accordance with reference (4) gave an axle load of 67.1kN which is equivalent to a notional weight restriction for the arch of 7.5 tonnes. Thus if an arch of equivalent dimensions existed in practice, it would only be able to carry vehicles of a maximum weight of 7.5 tonnes.

MODIFIED MECHANISM ANALYSIS OF THE REINFORCED MODEL

Extension of Modified Mechanism Analysis

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. 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.

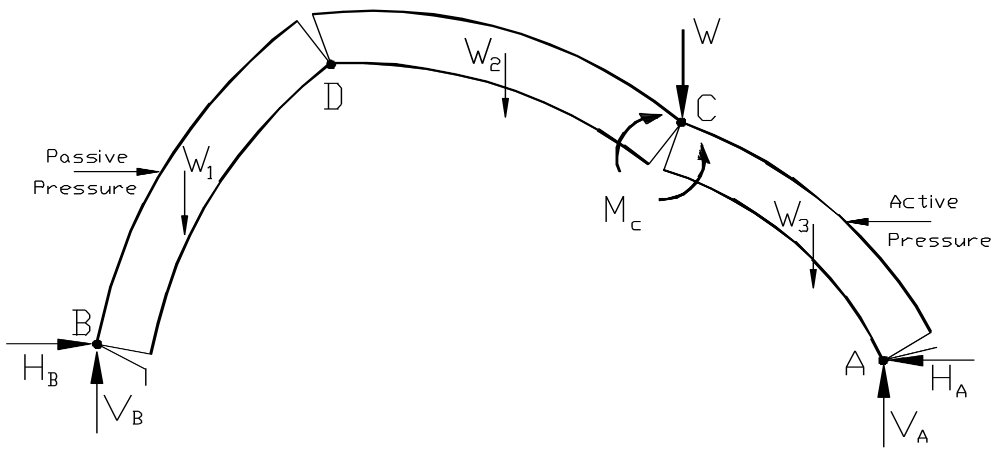

Figure 3 - Forces on Barrel at Mechanism Failure for Reinforced Section

Taking moments about C:

$$x_{bc}V_b = y_c H_B + \sum_b^c w_i \times \sum_b^c (x_c - x_i) + \sum_b^m h_i \times \sum_b^m (y_m - y_i) + M_c$$

$$\therefore V_b = \frac{y_c H_B}{x_{bc}} + \frac{x_c \sum_b^c w_i}{x_{bc}} - \frac{\sum_b^c w_i x_i}{x_{bc}} + \frac{y_m \sum_b^m h_i}{x_{bc}} - \frac{\sum_b^m h_i y_i}{x_{bc}} + \frac{M_c}{x_{bc}}$$

$$\text{Let} \quad \Omega_c = \frac{x_c \sum_b^c w_i}{x_{bc}} - \frac{\sum_b^c w_i x_i}{x_{bc}}$$

$$\text{Let} \quad \Phi_c = \frac{y_m \sum_b^m h_i}{x_{bc}} - \frac{\sum_b^m h_i y_i}{x_{bc}}$$

$$\therefore V_b = \frac{y_c H_B}{x_{bc}} + \Omega_c + \Phi_c + \frac{M_c}{x_{bc}}$$ -------------------------------- Eqn 1

Taking moments about D:

$$x_{bd}V_b = y_d H + \sum_b^d w_i \times \sum_b^d (x_d - x_i) + \sum_b^d h_i \times \sum_b^d (y_d - y_i)$$

$$\therefore V_b = \frac{y_d H}{x_{bd}} + \frac{x_d \sum_b^d w_i}{x_{bd}} - \frac{\sum_b^d w_i x_i}{x_{bd}} + \frac{y_d \sum_b^d h_i}{x_{bd}} - \frac{\sum_b^d h_i y_i}{x_{bd}}$$

$$\text{Let}\quad \Omega_d = \frac{x_d \sum_b^d w_i}{x_{bd}} - \frac{\sum_b^d w_i x_i}{x_{bd}}$$

$$\text{Let}\quad \Phi_d = \frac{y_d \sum_b^d h_i}{x_{bd}} - \frac{\sum_b^d h_i y_i}{x_{bd}}$$

$$\therefore V_b = \frac{y_d H}{x_{bd}} + \Omega_d + \Phi_d \qquad \text{Eqn 2}$$

Solving Equations 1 and 2 simultaneously for H :

$$\frac{y_c H}{x_{bc}} + \Omega_c + \Phi_c + \frac{M_c}{x_{bc}} = \frac{y_d H}{x_{bd}} + \Omega_d + \Phi_d$$

$$\therefore H = \frac{(\Omega_d - \Omega_c) + (\Phi_d - \Phi_c) - M_c / x_{bc}}{(y_c / x_{bc} - y_d / x_{bd})}$$

V_b can now be obtained from Equation 2.

The collapse load, W, can now be found by taking moments about A:

$$x_{ca}W = x_{ba}V_b + y_{ab}H + \sum_b^a w_i \times \sum_b^a (x_a - x_i) + \sum_b^m h_i \times \sum_b^m (y_m - y_i)$$

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 345kN recorded during the test on the third model which was dowelled to prevent ring separation.

DESIGN OF REINFORCEMENT FOR MODEL ARCH

Analysis of Section

The strengthened arch was analysed as a reinforced masonry section using a compressive strength of masonry of 5.3N/mm^2.and a yield strength of reinforcement of 480N/mm^2. This gave a moment of resistance at failure of 20.5kNm.

Design Loading of Reinforced Section
This moment was input into the MARSASS analysis and an analysis with partial factors set to normal design values in accordance with BD21/97[5] gave an axle load of 10.52kN which means that if an arch of equivalent dimensions existed in practice, it would now be able to just carry full highway loading and would not need to be subject to a weight restriction. Thus the reinforcement inserted into the model is just sufficient to take the arch from a notional 7.5tonne restriction to full highway loading.

CASE STUDY: SHORE BRIDGE, ST ANDREWS
Shore Bridge is a 9.22m span square masonry arch with a barrel constructed from tooled ashlar sandstone. The average ring thickness of the barrel is 387mm and there is a minimum of 482mm fill over the crown. A 10mm wide longitudinal crack extends from the south abutment to the quarter point of the arch.

Figure 4 Shore Bridge, St. Andrews

An assessment of the arch to BD21/97[5] gave a restricted loading of 7.5 tonnes. It was strengthened using the MARS System to carry 40 tonne EU vehicles and 37.5 units of HB loading.

The results of tests on masonry cores gave a masonry strength of 5.0 N/mm^2. The yield strength of the stainless steel reinforcement was taken as 480 N/mm^2.

Analysis
The MARSASS analysis found that a moment of resistance of 55 kNm is required at approximately quarter span to allow the barrel to carry full highway loading along with 37.5 units of HB loading.

An analysis to BS5628 : Part 2[4] using a partial safety factor of 2.5 for the masonry showed that this moment capacity could be achieved using a circumferential double layer grid of 8mm stainless steel bars at 225mm centres.

Transverse reinforcement should be in the form of 8mm stainless steel bars at 450mm centres with 6mm dowels inserted through the thickness of the barrel at every intersection of transverse and circumferential bars.

Temporary Condition

As part of the installation procedure, 20mm wide x 40mm deep circumferential chases are cut into the underside of the barrel prior to the insertion of the reinforcement and 20mm wide x 36mm deep transverse chases are also cut. This is a small proportion of the cross-sectional area of the barrel. Nevertheless, it is thus necessary to check that the arch can carry the existing loading in this temporary condition. An ASSARC analysis was therefore carried out with the 'depth to mortar' increased to 55mm to allow for overcutting the chases.

Figure 5 – Temporary Condition

This analysis showed that the existing weight restriction still applied when the arch was in this temporary condition. This is provided that any loss of mortar within the cuts is restored by either MARFLEX or a rapid drying epoxy mortar prior to the cutting of the reinforcement slots.

CONCLUSIONS

It is concluded that the insertion of a reinforcement cage is a simple and effective means of strengthening a masonry arch barrel. It is important to note that the reinforcement used in the TRL models was designed to just take the load carrying capacity of the arch from a notional 7.5tonne weight restriction to full capacity. This gave an increase in strength of 73%. Greater increases in strength would have been achieved for greater proportions of reinforcement. The case study also showed that the insertion of a small diameter reinforcing cage can increase the load capacity of an arch from 7.5tonnes to 40tonnes.

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 collapses of the reinforced arches were less spectacular than a traditional arch and after the initial failure load was removed, the arch almost recovered to its initial shape.

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 analysed using this method compare favourably with the maximum load recorded during the test and 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 retains the advantages of the flexibility of the arch without destroying its fabric. 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.

ACKNOWLEDGEMENTS

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PATENT

The system of strengthening masonry arches by the insertion of a reinforcement grid with corresponding dowel bars has been patented by MARS Ltd under patent nos: 9617342.2 (UK) & PCT/GB96/02026(International).

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