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An experimental investigation of retro-reinforced clay brick arches

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ABSTRACT

This paper describes the laboratory testing of eight 2.95m span segmental profile clay brick arches. Seven of the arches were strengthened with longitudinal intrados (soffit) reinforcement; the eighth was left unreinforced as an experimental control. Three of the arches also contained reinforcement to resist inter-ring shear. The barrel of each arch consisted of 3 rings of brickwork laid in stretcher bond; the compressive strength of the mortar used in the arch construction varied from 1.7 to 6.2 MPa. In each case a full width line load was applied incrementally to the arch extrados at quarter span until collapse occurred. Surface crack development and the vertical deflection profile of each arch were recorded at each load increment. In all cases, the longitudinal reinforcement was found to delay the onset of cracking and to increase the load carrying capacity. As expected, premature failure by ring separation was found to occur in the arches constructed with the weakest mortar without inter-ring reinforcement. Radial dowels were found to be the most effective means of preventing ring separation. The effect of the longitudinal reinforcement was found to be greatest in the arches where measures were taken to prevent ring separation.

Keywords: *Arches, bridges, reinforcement, repair, strengthening, testing*

1 INTRODUCTION

It is estimated that there are approximately 40,000 masonry arch highway bridges and 30,000 masonry arches carrying railways in the UK alone [1]. Most of these were constructed between the second half of the eighteenth century and the beginning of the twentieth century during the development of the canal and the railway transportation networks. Many of these structures are now in need of repair or strengthening to meet the demands of the 21st century. A number of repair and strengthening measures have been developed for masonry arch bridges and other masonry structures [2]. One such minimum disruption, minimum intervention technique is near-surface reinforcement or “retro-reinforcement” [3, 4]. This involves installing small diameter stainless steel reinforcing bars, typically 6mm to 12mm in diameter, into pre-cut grooves or pre-drilled holes in the near-surface zones of masonry that are likely to be subject to tensile stress. The principal aims of adding reinforcement are to improve flexural crack control, increase flexural and shear strength and to increase robustness and ductility. In the case of a masonry arch bridge, reinforcement is installed in the readily accessible surfaces, i.e. the intrados (or soffit) of the arch barrel and the exposed faces of the piers, abutments, spandrels, parapets and wingwalls.

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To date, experimental research of retro-reinforced arches has been limited to the small scale testing of single ring arches [5], small-scale tests in a centrifuge [6] or to tests on full-scale multi-ring arches in which very few parameters were varied [7, 8]. It is understood that these latter tests were carried out primarily as demonstrations for commercial purposes. As far as the authors are aware, this paper describes the first experimental research carried out at large scale in which parameters such as the mortar type, the amount of longitudinal reinforcement and the type and amount of shear connection to reduce or prevent ring separation, have been investigated.

2 THE TEST ARCHES

The testing was carried out in two phases with four arches tested per phase. The phase I tests (arches 1 to 4) were carried out to investigate the influence of longitudinal reinforcement on the structural behaviour. As will be explained later, ring separation was found to be a cause of premature failure in some of the phase I tests. As a result, the phase II tests (arches 5 to 8) were carried out to assess the performance of different arrangements of shear reinforcement to prevent ring separation.

All eight arches were of the same form of construction. Each had a segmental (i.e. part of a circle) profile with a clear span of 2.95m; a rise of 0.77m; a width of 1.34m and consisted of 3 rings of stretcher-bonded brickwork with a total nominal thickness of 328mm. All the arches were built onto removable timber centring spanning between 328mm thick brickwork abutments. These were built onto a self-straining structural steelwork test rig which was set up on the structural strong floor of the University of Bradford's heavy structures laboratory. Two identical rigs were used in the testing; each rig was wide enough to accommodate two arches. Hence, in each phase of testing, four arches were constructed on two test rigs. This had the advantage of allowing four arches to be built at the same time using the same bricklayer thereby minimising any variations in the standard of workmanship. Typical details of the arches and the steelwork test rig are shown in Figure 1. All the arches were constructed from solid clay bricks; the average properties of these bricks, measured from a randomly sampled batch of 20, are summarised in Table 1.

Table 1: Average Properties of Clay Bricks

Nominal size (length x breadth x height) [mm]	215.5 x 101.9 x 65.0
Density [kg/m^3]	2268
Initial rate of suction [g/m^2.min]	0.512
Water absorption [%]	4.1
Compressive strength [N/mm^2]	133.8

3 PHASE I TEST ARCHES

Three of the four phase I arches (numbers 2, 3 and 4) were reinforced with different amounts of 6mm diameter stainless steel longitudinal reinforcement. Arch 1 was built as an unreinforced experimental control. In arches 2 and 3, the longitudinal reinforcing bars, each fitted with twisted wire spacers, were installed in 6 no. 60mm deep x 20mm wide grooves cut into the arch intrados with a double-bladed circular saw. The grooves were spaced transversely across the arch at 225mm centres. Each groove was filled with a thixotropic cementitious grout, the aim being to ensure a full composite connection between the reinforcement and the arch. Arch 2 was reinforced with a total of 12 no. 6mm diameter stainless steel reinforcing bars distributed in pairs in each of the 6 grooves. Arch 3 was reinforced with only 6 bars (i.e. half the reinforcement of arch 2), with only one bar inserted in each groove. In arch 4, pairs of 6mm diameter bars were inserted into 20mm diameter holes that were drilled into the arch using a flexible drive drill. The flexible drive allowed each hole to be "steered" by the operator so that it remained approximately parallel with the arch intrados (or soffit). Arch 4 was reinforced in this manner as a trial to demonstrate that reinforcement could be installed in holes that are not visible on the underside of a bridge as an alternative to grooves which may be visually unacceptable to some bridge owners.

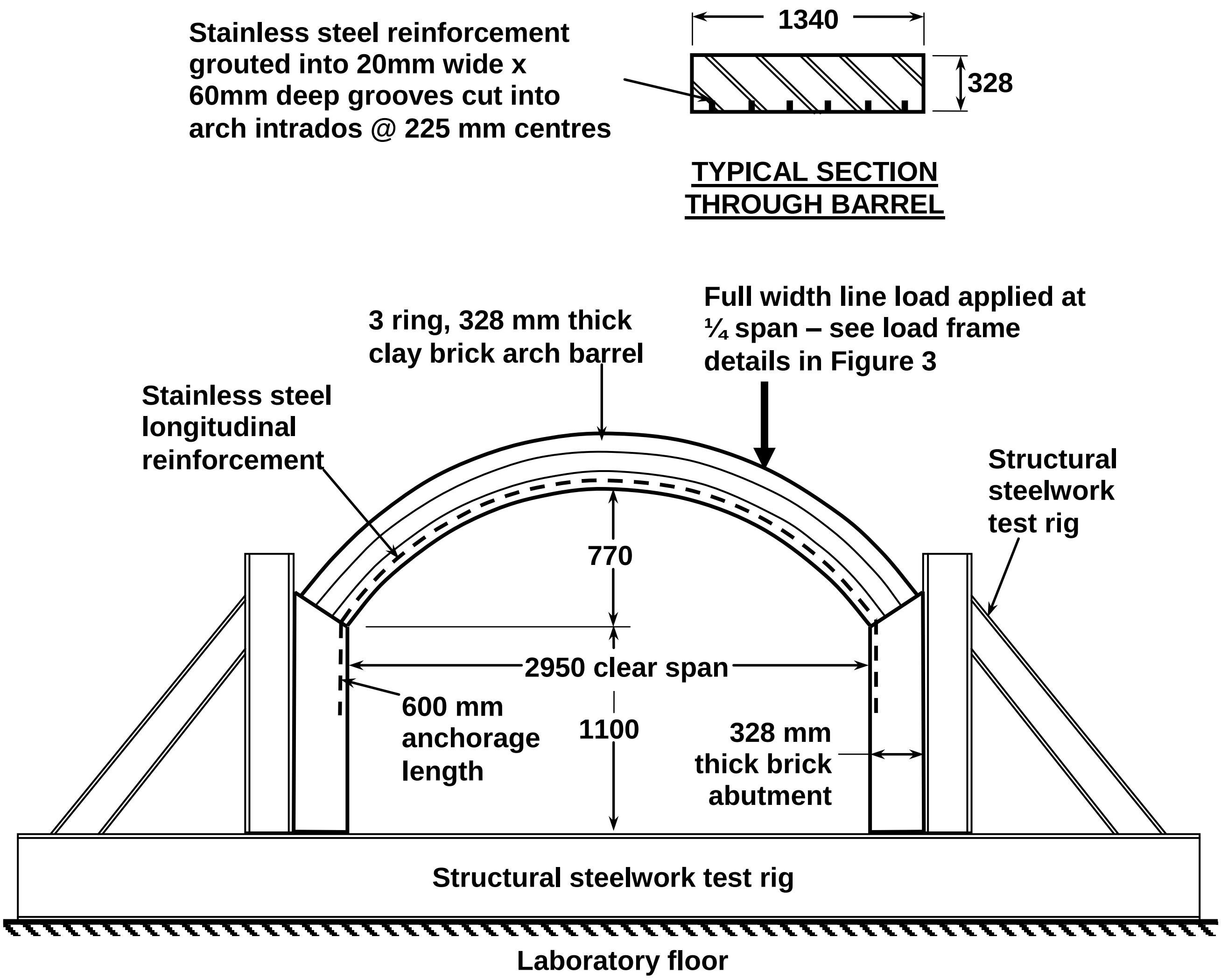
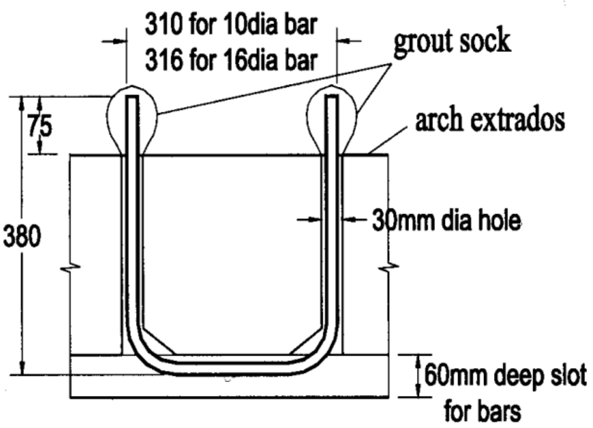


Figure 1. Typical test arch details showing the longitudinal reinforcement (all dimensions are in millimetres)

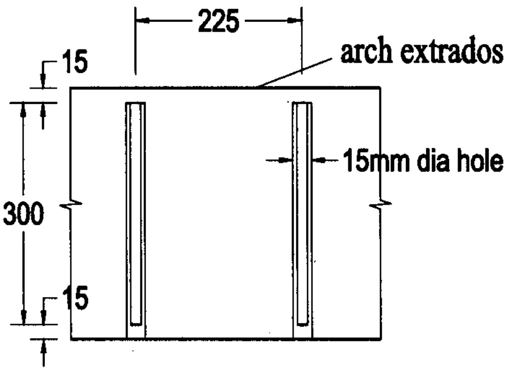
As the phase I tests were carried out, in part, as a pilot study, no close control was exerted on the batching of the mortar. This was specified as a 1:4½ (OPC:sand) mix to give fairly high early strengths to allow the arches to be strengthened and then tested without too much delay.

4 PHASE II TEST ARCHES

As explained later, ring separation, i.e. inter-ring shear failure, was found to be a cause of premature failure in some of the phase I tests. As a result, the phase II tests were carried out to investigate different forms of inter-ring shear connection. All the phase II arches (numbers 5 to 8, inclusive) had the same longitudinal reinforcement as arch 2, namely a total of 12 no. 6mm diameter stainless steel reinforcing bars distributed in pairs in 6 no. grooves spaced transversely across the arch at 225mm centres. Arches 6 and 7 were fitted with 10mm and 16mm diameter U-bar shear reinforcement spaced every 300mm (longitudinally and transversely), respectively; see Figure 2a. Arch 8 was fitted with 10mm diameter straight radial dowel bars spaced every 225mm (longitudinally and transversely); see Figure 2b. Arch 5 was the experimental control; it was longitudinally reinforced but not fitted with any shear reinforcement. All the reinforcement was inserted in pre-drilled grooves (in the case of the longitudinal reinforcement) or holes (in the case of the shear reinforcement) and the space between the brickwork and the reinforcement was filled with a thixotropic cementitious grout.



a). U-bars



b). Dowels

Figure 2. Stainless steel shear reinforcement (all dimensions are in millimetres)

The Phase II arches were built using a 1:9 OPC:sand mortar and with much closer control of the weigh batching and mixing than was the case with the phase I arches. A lower strength mortar than that used for the phase I tests was specified to increase the likelihood of ring separation during testing.

No special curing measures were used for any of the arches; they were all left to cure uncovered in the laboratory. Such conditions were likely to be much dryer and therefore more conducive to shrinkage of the mortar and grout than in practice. Indeed, some surface shrinkage cracks were noted on the exposed surface of the grout in the grooves. Judging from the behaviour of the reinforcement during testing, it seems that such cracks were very shallow as there was no evidence of any premature failure resulting from the shrinkage. On completion of the testing, the effective depth of the reinforcement was measured from the compression face of the brickwork, i.e. the extrados of each arch. In the case of arches 2, 3, 5, 6, 7 and 8, in which the reinforcement was fixed into pre-cut grooves, the effective depth was found to be between approximately 286mm and 292mm. In arch 4, in which the steel was fixed into pre-drilled holes, the effective depth was found to be 217mm.

During the construction and strengthening of each arch, 100mm x 100mm x 100mm samples of mortar and grout were taken and left to cure in the same conditions as the arches in the laboratory. In addition, 5 brick high stack bonded brickwork prisms were made by the bricklayer from the bricks and mortar used for the arch construction; these were also left to cure in the laboratory. All the compression test samples were tested on the same day as each arch was tested. These results are presented with the results of the load tests in Table 2 (Phase I test results) and Table 3 (Phase II test results). The grout for each phase of testing was made from a highly consistent pre-packed material and all 4 arches of each phase were strengthened using grout from the same batch. As a result, the grout strength quoted in Tables 2 and 3 is an average value that is representative of all the reinforced arches.

5 TEST ARRANGEMENT

Each arch was subjected to a full-width vertical line load applied at quarter span, as shown in Figure 1. The load was applied incrementally until collapse, using two 1000kN capacity hydraulic rams controlled from the same pump. The point loads from the two rams were applied to each arch via a steel spreader beam with a 32mm diameter steel roller welded to its bottom flange. The load from the beam and roller arrangement was applied through an in-situ concrete bed cast on to the arch extrados to provide a level surface. The reaction to the applied load was provided by a steel frame which was bolted to the reinforced concrete strong floor of the laboratory, as shown in Figure 3.

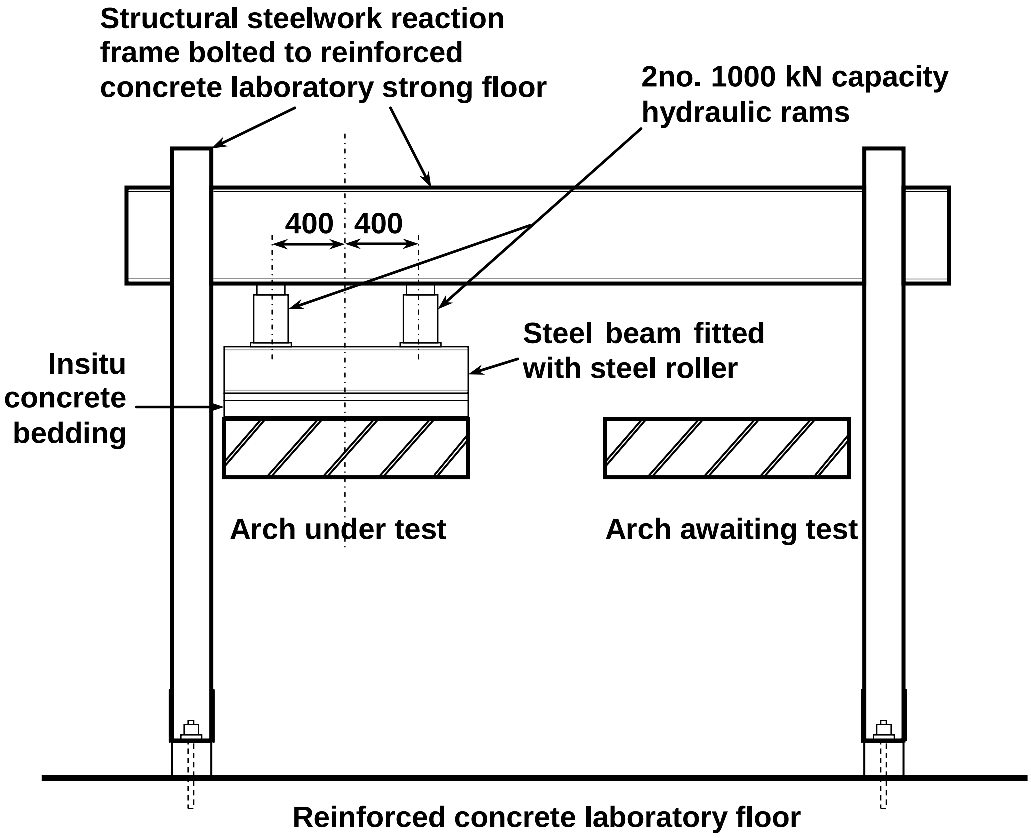


Figure 3. The arch test arrangement showing the structural steelwork reaction frame.

6 TEST RESULTS AND DISCUSSION

6.1 Test results

This section provides a summary of the test results; a more detailed description has been provided by Chen [9]. The test results for the phase I tests (arches 1 to 4, inclusive) are summarised in Table 2. Those for the phase II tests (arches 5 to 8, inclusive) are summarised in Table 3. All eight arches failed as a result of the formation of a 4-hinge collapse mechanism. In each case, a hinge initially formed directly beneath the applied load with a crack (or series of cracks) forming in the arch intrados (soffit) and a centre of rotation forming in the shallow compression zone in the brickwork close to the upper surface of the arch. A typical example of this is shown in Figure 4a. Soon afterwards, a second hinge was observed to form in the arch between ½ and ¾ span. In this case cracking occurred in the arch extrados (upper surface) with the centre of rotation forming in the shallow compression zone in the brickwork close to the intrados, as shown in Figure 4b. As the applied test load was increased, a third hinge formed at or close to the springing of the abutment adjacent to the applied load, with the crack forming on the upper surface of the brickwork and the centre of rotation occurring in the brickwork close to the intrados. Finally, at or close to the collapse condition, a fourth hinge formed in the springing of the other abutment. The 4 hinge collapse mechanism for arch 1 is shown in Figure 5. Some of the reinforced arches failed prematurely as a result of partial ring separation. Typically, this occurred as a result of a longitudinal crack propagating between the bottom two rings of brickwork from the second hinge towards the first hinge. This was followed by the rapid formation of the third and fourth hinges and collapse, as shown in Figure 6 (for arch 2). It should be noted that the cracking shown in Figure 6 has been deliberately accentuated by the continued loading of the arch after it sustained its maximum load.

a). 1st hinge forming beneath the applied line load   b). 2nd hinge forming in the arch extrados

Figure 4. 1st and 2nd hinges forming in the brickwork arch

Figure 5. Arch 1 (unreinforced control) showing the 4-hinge collapse mechanism

Table 2. Phase I test results (arches without shear reinforcement)

ARCH 1 (Unreinforced Control)	
Longitudinal Reinforcement: None	
Compressive strength of mortar:	5.5 MPa
Compressive strength of brickwork prisms:	39.9 MPa
Applied load at first visual signs of cracking:	45.0 kN
Maximum load sustained by the arch:	246.0 kN
Sudden 4-hinge collapse mechanism; little warning of collapse. See Figure 5.	
ARCH 2 (Reinforced)	
Longitudinal Reinforcement: Twelve 6mm dia. bars; 2 bars per groove. 6 grooves @ 225 mm centres (transverse spacing) Effective depth of steel = 286 mm	
Cross sectional area of longitudinal reinforcement:	340mm^2
Compressive strength of mortar:	3.6 MPa
Compressive strength of brickwork prisms:	39.7 MPa
Compressive strength of grout (average):	58.8 MPa
Applied load at first visual signs of cracking:	170 kN
Maximum load sustained by the arch:	351 kN
Gradual failure exhibited. Formation of hinges at ¼ and ½ span followed by premature failure caused by the partial separation of the lower ring from the upper 2 rings of the arch barrel. At collapse, hinges formed at both springings. See Figure 6.	
ARCH 3 (Reinforced)	
Longitudinal Reinforcement: Six 6mm dia. bars; 1 bar per groove. 6 grooves @ 225 mm centres (transverse spacing). Effective depth of steel = 292 mm	
Cross sectional area of longitudinal reinforcement:	170mm^2
Compressive strength of mortar:	6.2 MPa
Compressive strength of brickwork prisms:	35.1 MPa
Compressive strength of grout (average):	58.8 MPa
Applied load at first visual signs of cracking:	110 kN
Maximum load sustained by the arch:	504 kN
Gradual failure exhibited. Hinges formed at ¼ span, then ¾ span , then at the abutment adjacent to the applied load then, close to collapse, at the abutment remote from the applied load. Part of the bottom ring of brickwork separated from the upper two rings when the applied load was very close to the collapse value.	
ARCH 4 (Reinforced)	
Longitudinal Reinforcement: Six 6mm dia. bars; 1 no. bar per pre-drilled hole. 6 holes @ 225 mm centres (transverse spacing) Effective depth of steel = 217 mm	
Cross sectional area of longitudinal reinforcement:	170mm^2
Compressive strength of mortar:	3.1 MPa
Compressive strength of brickwork prisms:	35.4 MPa
Compressive strength of grout (average):	58.8 MPa
Applied load at first visual signs of cracking:	69 kN
Maximum load sustained by the arch:	376 kN
Mode of failure: as Arch 2.	

Table 3. Phase II test results (arches with shear reinforcement)

ARCH 5 (Control – no shear reinforcement)	
Longitudinal Reinforcement: Twelve 6mm dia. bars; 2 no. bars per groove. 6 grooves @ 225 mm centres (transverse spacing). Effective depth of steel = 286 mm	
Cross sectional area of longitudinal reinforcement:	340mm^2
Shear (inter-ring) reinforcement:	None
Compressive strength of mortar:	2.0 MPa
Compressive strength of brickwork prisms:	30.8 MPa
Compressive strength of grout (average):	58.8 MPa
Applied load at first visual signs of cracking:	69.0 kN
Maximum load sustained by the arch:	146.0 kN
Mode of failure: Gradual failure exhibited. Formation of hinges at ¼ and ¾ span followed by premature failure caused by the partial separation of the lower ring from the upper 2 rings of the arch barrel. At collapse, hinges formed at both springings.	
ARCH 6	
Longitudinal Reinforcement: As arch 5.	
Shear (inter-ring) reinforcement: 10mm dia. U-bars @ 300mm centres longitudinally & transversely	
Compressive strength of mortar:	2.1 MPa
Compressive strength of brickwork prisms:	34.1 MPa
Compressive strength of grout (average):	58.8 MPa
Applied load at first visual signs of cracking:	146 kN
Maximum load sustained by the arch:	338 kN
Mode of failure: Gradual failure exhibited. Formation of hinges at ¼ and ½ span followed by premature failure caused by the partial separation of the lower ring from the upper 2 rings of the arch barrel. At collapse, hinges formed at both springings.	
ARCH 7	
Longitudinal Reinforcement: As arch 5.	
Shear (inter-ring) reinforcement: 16mm dia. U-bars @ 300mm centres longitudinally & transversely	
Compressive strength of mortar:	2.9 MPa
Compressive strength of brickwork prisms:	30.1 MPa
Compressive strength of grout (average):	58.8 MPa
Applied load at first visual signs of cracking:	146 kN
Maximum load sustained by the arch:	338 kN
Mode of failure:	As arch 6.
ARCH 8	
Longitudinal Reinforcement: As arch 5.	
Shear (inter-ring) reinforcement: 10mm dia. radial dowels @ 225mm centres longitudinally & transversely	
Compressive strength of mortar:	3.1 MPa
Compressive strength of brickwork prisms:	35.4 MPa
Compressive strength of grout (average):	58.8 MPa
Applied load at first visual signs of cracking:	69 kN
Maximum load sustained by the arch:	376 kN
Gradual failure exhibited. Formation of two hinges close together at ¼ span followed by the formation of hinges at both springings/abutments. No evidence of ring separation.	

Figure 6. A reinforced arch (arch 2) without shear reinforcement showing premature partial ring separation and a 4-hinge collapse mechanism.

6.2 Brief discussion of the test results

There were no signs of failure of any of the longitudinal reinforcing bars during the testing. In particular there was no evidence of the grout surrounding the reinforcing bars becoming de-bonded from the adjacent brickwork or the reinforcement becoming de-bonded from the grout. Hence it appears that, with all the retro-reinforced arches, the reinforcement acted compositely with the brickwork to form a reinforced brickwork arch.

In all cases the addition of longitudinal reinforcement in the phase I arches was found to increase both the load at which first visible cracking occurred and the maximum load sustained by the arch. In addition, unlike the unreinforced control (arch 1) which failed very suddenly, arches 2, 3 and 4 each failed gradually with extensive warning signs of impending failure.

Arch 3 was the only reinforced arch in the phase I tests to fail without premature failure due to ring separation. This is almost certainly because the mortar was almost twice as strong as that used in the construction of arches 2 and 4. The steel reinforcement in arch 3 showed signs of yielding as the arch resisted a maximum load of 504kN; this is just over twice the load carried by the unreinforced control arch. The load to first visible cracking achieved by arch 4 (69kN) was noticeably less than that for the identically reinforced arch 3 (110kN). This is probably because the effective depth of the reinforcement in arch 4 was 75mm (or 23%) less than that in arch 3.

In the phase II tests, all the arches fitted with shear reinforcement carried more load than the unreinforced experimental control (arch 5). The U-bar shear reinforcement did not prove to be very effective as a means of preventing ring separation and was quite difficult to install even in the laboratory. Radial dowels were easier to install and proved to be the most effective form of shear connection, although it should be borne in mind that only one test was carried out.

7 PRINCIPAL FINDINGS

The main observations from the limited tests described in this paper are:

a). Longitudinal reinforcement installed in the arch intrados close to the surface was found to delay the onset of first cracking and to increase the load carrying capacity. This confirms the findings from the small-scale model arch tests previously carried out by Garrity [5].

b). Longitudinal reinforcement was found to be effective as a strengthening measure whether installed in pre-cut grooves or pre-drilled holes. Reinforcement installed in grooves is more structurally efficient because of the larger effective depth, but bars installed in pre-drilled holes are less visually intrusive.

c). The mortar strength had a significant influence on the performance of the reinforced arches. Those constructed using the weaker mortar were found to be more likely to develop ring separation and to fail at lower loads than those built of stronger mortar.

d). Radial dowel reinforcement, installed through the full depth of the arch ring, was found to be more effective at preventing an inter-ring shear failure (ring separation) than U-bars and was easier to install.

Further testing of an additional eight arches of two and three ring construction with span:depth ratios of 4:1 and 2:1 and with different arrangements of longitudinal steel will be carried out in the next part of the research project. All the arches will be made from sand-faced clay bricks with a high initial rate of suction to provide a low brick to mortar bond.

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REFERENCES

[1]. Page J. (Ed.), *State-of-the-art review: Masonry arch bridges*, Transport Research Laboratory, Department of Transport, Her Majesty’s Stationery Office, UK, 1993.

[2] McKibbins, L.D., Melbourne, C., Sawar, N, and Sicilia Gaillard, C., *Masonry arch bridges: conditional appraisal and remedial treatment*, CIRIA Report C656, Construction Industry Research and Information Association, London, 2006.

[3] Garrity, S.W., Retro-reinforcement of existing masonry structures, *Proceedings of the 10th International Brick & Block Masonry Conference*, Calgary, Masonry Council of Canada/Univ. of Calgary, 1994, 469-478.

[4] Garrity, S.W., Retro-reinforcement - a proposed repair system for masonry arch bridges, in *Arch Bridges*, ed. C.Melbourne, Thomas Telford Services Ltd, London, UK, 1995, 557-566.

[5] Garrity, S.W., Testing of small scale masonry arch bridges with surface reinforcement, *Proceedings of the 6th International Conference on Structural Faults and Repair*, London, UK, 1995, Vol. 1, 409 - 418.

[6] Baralos, P., *The small scale modelling of repair techniques for masonry arch bridges using a geotechnical centrifuge*, PhD thesis, Cardiff University, Wales, UK, 2002.

[7] Sumon, S.K., Repair and strengthening of five full scale masonry arch bridges, in *Arch Bridges: history, analysis, assessment, maintenance and repair,* ed. A. Sinopoli, Balkema, Rotterdam, 1998, 407-415.

[8] Sumon, S.K., Innovative retrofitted reinforcement techniques for masonry arch bridges, *Proceedings of the Institution of Civil Engineers, Bridge Engineering*, Vol. 158, Issue BE3, Sept. 2005, 91-99.

[9] Chen, Y., *Strengthening of masonry arch bridges with near-surface reinforcement. Analysis and testing of single-span brick arch bridges strengthened with near-surface reinforcement*, PhD thesis, University of Bradford, England, UK, 2004.