NEAR-SURFACE REINFORCEMENT OF MASONRY ARCH HIGHWAY BRIDGES

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ABSTRACT

Near-surface reinforcement is a minimum disruption strengthening measure for masonry arch bridges. It consists of grouting stainless steel reinforcing bars into pre-drilled holes and pre-sawn grooves in the exposed near-surface zones of the masonry where tensile stress levels are likely to result in cracking. This paper describes some of the recent uses of near-surface reinforcement for masonry bridge strengthening in the UK and provides a summary of recent analytical and experimental research and development.

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INTRODUCTION

Principal requirements – arch bridge strengthening

Stone or brick masonry arch structures such as bridges, culverts and tunnel linings are very common features of many of Europe's canal, highway and railway systems. Most of these structures were built well over 100 years ago and it is not surprising that an increasing number are in need of strengthening to meet modern operational and safety standards. In the author's experience, when selecting the most appropriate form of strengthening for masonry arch bridges and similar structures, it is usually necessary to ensure that the specified works can:

a). *Increase the load-carrying capacity*. All parts of the structure, not just the arch barrel, must be capable of resisting the increased live loading.

b). *Avoid changing the beneficial characteristics of masonry arch construction* as a result of over-strengthening or over-stiffening with excessive strengthening measures.

c). *Improve the in-service performance.* The specified strengthening measures should provide increased resistance to cracking and improved post-cracking performance.

d). *Avoid creating a significant increase in the self weight*. Strengthening works that create an increase in the self weight of the bridge could cause overloading of the foundations or could overstress other parts of the bridge.

e). *Create a safe working environment for the workforce on site*. Some forms of strengthening create temporary instability during construction and a risk of partial or even full collapse.

f). *Minimise disruption to the canal, road or railway system*. The temporary closure of a bridge and the resulting disruption to the bridge users is often not acceptable. In such situations the use of bridge strengthening measures such as saddling or the use of load relieving slabs which involve partial or full closure should be avoided. Such measures may also cause damage or disruption to water mains, gas mains, telecommunications cables and electricity cables located in the fill of the bridge.

g). *Avoid changing the arch profile*. This is particularly important in the case of railway overbridges, railway tunnels and flood alleviation culverts where a reduction in the space beneath the arch is usually unacceptable.

h). *Accommodate a variety of existing defects*. These include cracks in the masonry; ring separation; spandrel wall separation; extensive loss of mortar and de-bonding of the masonry units due to the leaching effects of rainwater combined with poor drainage; extensive damage of the surface or the internal masonry due to frost and salt crystallisation damage caused by prolonged exposure to damp conditions and numerous freeze-thaw cycles, etc.

i). *Accommodate the highly variable nature of the existing masonry*. This will be due to variations in the standard of workmanship and materials of the original construction and the range of different materials used in the subsequent maintenance and repair of the structure. When surveying an existing bridge in advance of any proposed repair or strengthening works it is common to discover evidence of the use of epoxy or polyester resin based patch repairs, inappropriate pointing materials, poorly bonded new brickwork construction and new bricks for patch repairs that are completely different to the original materials. In addition, it is likely that the exposed faces of the masonry will be of relatively high quality and consistent facing construction whereas parts of the internal masonry may consist of poorer quality and more variable rubble construction. In many cases the rubble construction will have a high void content. The geometry of the existing construction will also vary, e.g. the surface of the stone or brick masonry is likely to be very uneven, the arch barrel will vary in thickness and there may be internal spandrels built into the arch barrel.

j). *Improve the robustness and ductility of the existing construction*. Ideally the proposed strengthening measures should improve the load distribution characteristics of the structure so that it can accommodate future unforeseen problems without recourse to further repair or strengthening works which are likely to be costly and disruptive.

k). *Avoid the creation of localised highly stressed regions that could lead to future damage*. Of particular concern are localised strengthening measures surrounded by high strength, high stiffness grout. Although such measures may appear to have low initial costs, the creation of zones of high stiffness, particularly within the arch barrel, may lead to cracking when the structure is subjected to large magnitude moving loads (e.g. in the case of a heavily trafficked road or railway bridge). Strengthening measures that will permit the distribution of the effects of external loading throughout the bridge are less likely to lead to damage.

l). *Accommodate limited site occupation periods*. In many cases, access to the bridge will be for short periods of time during periods of canal, road or railway possession. The use of strengthening works that can be installed in stages may be necessary.

m). *Accommodate onerous site conditions*. Often repair or strengthening work is carried out during periods when the structure is least in use such as night time or winter periods. Similarly, the existing masonry is likely to be in a damp or saturated state and it will be virtually impossible to create dry, dust-free conditions. Materials that are tolerant of such variable and imperfect conditions should be used to ensure maximum bond between the existing masonry and the strengthening works;

n). *Offer sufficient versatility to accommodate the range of additional defects that are identified during the course of the strengthening works on site*. This is an extremely common problem with most repair and strengthening schemes where the full extent of the required work is only revealed once work starts on site.

o). *Maintain or improve the aesthetic appeal of the structure*.

p). *Minimise the impact on the environment*.

q). *Provide sufficiently rapid gains in strength*. This is important to ensure safety and stability of the existing structure during the installation of the strengthening measures.

r). *Avoid creating maintenance liabilities*. The proposed strengthening measures must be reliable and durable to minimise life-cycle costs.

s). *Be cost-effective within the constraints identified above*.

Near-surface reinforcement

Near-surface reinforcement (also known as “retro-reinforcement”) is a form of strengthening for masonry arch structures that was devised specifically to meet most or all of the above requirements. It was developed from a technique originally devised for the repair and strengthening of masonry buildings (Garrity 1994, 1995, 1995a, 1995b). It consists of grouting stainless steel reinforcing bars into pre-drilled holes or pre-sawn grooves into the exposed near-surface zones of the masonry where tensile stresses arising from external loads or settlement effects are likely to result in cracking.

Since the publication of the original proposals in 1995, a number of small bridges and culverts have been strengthened with near-surface reinforcement. The principal aims of this paper are to reflect the experience gained in the last few years by describing the construction techniques and materials that have recently been used in the UK. In addition, the paper provides an overview of recent analytical and experimental research into the behaviour of arches with near-surface reinforcement and some recommendations for design.

RECENT CONSTRUCTION TECHNIQUES AND MATERIALS

Construction

The most recent form of masonry bridge strengthening used in the UK is reflected in figure 1. This shows the near-surface reinforcement details that were used to strengthen a single span brick arch highway bridge to carry the standard 40 tonne assessment live load defined by the UK Highways Agency (Highways Agency et al. 1997).

The bridge on which figure 1 is based is located in North West England and is over 200 years old. It has a span of approximately 8.7m, a rise of 1.9m and has a 0.46m thick segmental arch barrel. It is fairly typical of the many arch bridges that span canals or railways in the UK. The principal stages of construction used for this and other similar bridges are summarised in Table 1.

Materials

Reinforcement and corrosion protection. All near-surface reinforcement should be austenitic stainless steel and should be fitted with stainless steel wire spacers to ensure that each bar is fully encapsulated with grout. It should be noted that pitting corrosion of stainless steel reinforcement is possible at locations of high chloride ion concentration. Such conditions may occur close to the springings where de-icing salt laden rainwater can percolate through the fill and run down the extrados of the arch barrel. At such locations corrosion may occur where the grout surrounding the reinforcement contains voids or is cracked. Even in such extreme situations, it is very likely that any corrosion will be limited to one or two bars which is unlikely to have a significant impact on the performance of the strengthening works. This demonstrates the advantage of using strengthening measures consisting of a large number of small bars instead of a much smaller number of larger diameter bars.

Grout and shear connection. Near-surface reinforcement can only be effective as a strengthening measure if it acts compositely with the existing masonry. To ensure this, the shear connection between the masonry and the grout and the grout and the reinforcement must be maximised otherwise premature bond failure at the grout/masonry interface or the grout/reinforcement interface may occur.

Clearly the selection of a grout material that is compatible with the existing masonry and the likely conditions on site is of considerable importance. In most cases the existing masonry will be damp because of the rainwater retained in the adjacent fill material. Water is also used as a lubricant during the drilling and groove sawing operations which also generate a great deal of small brick, stone or mortar particles that remain on the cut or drilled surfaces of the masonry.

In the author's experience, the use of epoxy or polyester resin based grouts is inappropriate for the repair and strengthening of masonry structures because of the inherent differences in their mechanical and physical properties when compared with most masonry materials. For example, the coefficients of linear thermal expansion and the elastic modulus values for epoxies and polyesters are markedly different to those for masonry. Although the insulating effect of the fill material means that temperature variations are unlikely to be large during the remaining design life of the strengthened bridge, such effects could, when combined with the strain variations due to live loading, lead to de-bonding of the grout from the existing masonry substrate. In addition, epoxy resin-based materials rely on having a dust free, dry environment for maximum performance. As noted previously such conditions are unlikely to exist in practice.

In contrast, damp conditions are ideal for cementitious materials that gain strength through hydration rather than polymerisation. Furthermore, the damp environment will also help to compensate for suction effects that may occur with the bricks or stone masonry, both of which may have a high initial rate of suction. The existing mortar is also likely to contain hydration products which will have broadly similar characteristics to the cementitious grout. Based on the great deal of experience gained from the development of concrete repair materials, the author also recommends the use of cementitious grouts containing microsilica and polymer additives to improve workability, adhesion and tensile strength. Given the variations likely in the existing masonry, the use of pre-construction grout trials is recommended. In particular, preliminary bond strength testing should be carried out to determine the best grout formulation to suit the range of site conditions and the near-surface porosity of the existing masonry (see Table 1).

OVERVIEW OF RECENT RESEARCH

Experimental Research

As part of a preliminary study, a programme of testing was carried out at the University of Bradford laboratories on a series of unreinforced and surface-reinforced 2m span clay brick arches (Garrity 1995a). The use of surface-reinforcement to tie the spandrel and parapet walls to the arch barrel was also investigated. In all cases, the surface reinforcement consisted of thin strips of steel glued to the brickwork with an epoxy adhesive. The tests demonstrated that the surface reinforcement delayed the formation of hinges that are normally initiated by cracking of the intrados in an unreinforced arch. In addition, the preliminary tests showed that where the spandrel and parapet walls had been connected to the arch barrel, the formation of cracks in the spandrels and at the spandrel/barrel interface was delayed when compared with a similar unreinforced structure. In summary, the strengthening measures were found to delay the onset of cracking, increase the reserve of strength after first cracking and increase the strength and the stiffness of the arch.

These findings were verified by a further programme of testing at the University of Bradford. A subsequent test was carried out by the Transport Research Laboratory (TRL) in the UK on a 5m span backfilled brick arch barrel with ring separation (Falconer 1997). The arch barrel was initially loaded until two hinges formed, then unloaded and retro-reinforced. The strengthened structure was then re-loaded to collapse and was found to behave in a similar manner to the 2m span arches tested by the author. Tests on small scale brick arches with near-surface reinforcement carried out in the centrifuge at the University of Wales, Cardiff also demonstrated similar improvements in performance identified by the author.

It is evident that further large-scale testing is required to help researchers to develop a better understanding of the behaviour of masonry arches with surface or near-surface reinforcement. Initially, the use of tests on reinforced and unreinforced arch barrels without spandrel walls and backfill is recommended as it is important to understand the behaviour of the arch barrel before introducing the further complications arising from the inclusion of spandrels and fill. At the time of writing the author is preparing to test a series of eight 3m span arch rings with different amounts of reinforcement and different thicknesses. The results from such experiments should provide useful data for the comparison and evaluation of the analytical techniques described below.

Analytical Research

As far as the author is aware, there is very little published research on the analysis of masonry arches with surface or near-surface reinforcement. To date, most research has concentrated on the development of plastic methods of analysis to predict the collapse loads of reinforced arches. Falconer has presented a mechanism analysis based on the lower bound theorem of plasticity. The capacity of the arch was estimated from considerations of moment and force equilibrium of the arch barrel at an assumed 4 hinge collapse mechanism with the moment capacity of one of the hinges enhanced by the presence of the intrados reinforcement (Falconer 1997). A yield line method based on the upper bound theorem of plasticity was also developed to account for the intrados reinforcement at two hinge positions (Ashour and Garrity 1998). This method has the potential to include the strengthening effects of the spandrel walls, wingwalls and parapets. A virtual work approach that accounts for the effects of the fill material, ring separation and crushing of the masonry has also recently been proposed (Chen et al. 2001). In both these latter cases, the collapse load is obtained by varying the hinge positions to correspond with the minimum energy or virtual work condition.

A method of assessing the strength of a masonry arch with near-surface reinforcement using the equilibrium limit method (Livesley 1972), based on the lower bound plasticity theorem, has also been published (Chen et al. 1999). In this case, the arch is divided into several rigid blocks and the force equilibrium equations and linear constraints are constructed for each block. A linear programming routine is then used to solve the equilibrium equations for the entire arch and an iterative approach is adopted to converge on the lower bound collapse load.

More recently, a numerical method has been developed to predict the in-service performance of a reinforced arch as well as the collapse load (Chen et al. 2001a) and a preliminary investigation of a typical single span masonry arch bridge has been carried

out using a 2-stage three-dimensional finite element analysis (Garrity and Toropova 2001).
Although the aforementioned methods of analysis require further development, all indicate that near-surface reinforcement produces a significant increase in the load carrying capacity of a masonry arch and show relatively close agreement with the limited available experimental data.

DESIGN RECOMMENDATIONS

It is evident from the above overview of research that near-surface reinforcement is a relatively new form of strengthening for masonry arches. Accordingly, a conservative approach is warranted when designing such measures until more information and experience is available. Wit this in mind, the following design assumptions are proposed:

a). Assume pinned end conditions. It is normally very difficult to be sure that full moment capacity will be achieved at the springings even if the longitudinal reinforcement can be anchored into the abutments. Any fixity that is achieved will reduce the stresses in the arch barrel.

b). Ignore any strengthening effects resulting from the lateral earth pressure acting on the arch barrel. Such pressures are a function of the complex interaction between the fill and the masonry and are difficult to quantify with any confidence.

c). Allowance should be made for the variation in the strength and position of the hinges that form near to the upper surface of the arch barrel (the extrados). Usually, it is found that the critical soffit (intrados) hinge position will lie somewhere between one third and one quarter of the span. It is common practice to assume that, in the collapse condition, an extrados hinge will lie somewhere between two thirds and three quarters of the span. This may not be the case as the condition of the extrados masonry (which cannot normally be visually inspected) may be severely weakened by the prolonged effects of weathering and leaching and a lack of routine maintenance.

d). At least two different methods of analysis should be used to evaluate the strength of the reinforced arch and that the relatively large partial safety factors recommended in the UK bridge assessment guidelines (Highways Agency et al. 1997), or similar, should be used.

e). When considering crack control under design service conditions, a limiting tensile strain of 1.5×10^{-4} (or 150 $\mu\varepsilon$) should be used. This is based on lateral tensile strain measurements obtained from vertical splitting tests on small specimens of brickwork (Ali and Page 1986) and previous measurements obtained by the author from tests on large-scale prestressed brickwork structures. This is contrary to the commonly used design guidance in the UK for masonry buildings, where values of limiting tensile strain in the range 5.0 x 10^{-4} to 10.0 x 10^{-4} (Burland and Wroth 1974, Cook et al. 2000) have been used.

CONCLUSIONS

Near-surface reinforcement details and a construction sequence are presented for a typical single span masonry arch highway bridge. A series of design requirements for the evaluation of alternative repair and strengthening methods for masonry arch bridges and similar structures is proposed. In considering such requirements it appears that near-surface reinforcement offers a number of advantages when compared with other forms of minimum-disruption strengthening including:

a). The opportunity to improve the quality of the existing barrel construction by grouting in advance of the main works;

b). Improved load distribution characteristics and improved robustness to resist the effects of differential settlement and unexpected patterns of patch loading;

c). The provision of a regular array of longitudinal and transverse reinforcement rather than isolated zones of strengthening that could be the cause of localised cracking in the future.

The type of grout used to ensure composite action between the reinforcement and the existing masonry is of considerable importance. The use of cementitious grouts that can tolerate damp site conditions and are more likely to be compatible with the existing materials is recommended.

A number of analytical methods are being developed to predict the in-service performance and strength of masonry arches with surface or near-surface reinforcement. Further large-scale experimental work is required to improve the understanding of the behaviour of reinforced masonry arches and to provide data for the evaluation of the different analytical methods.

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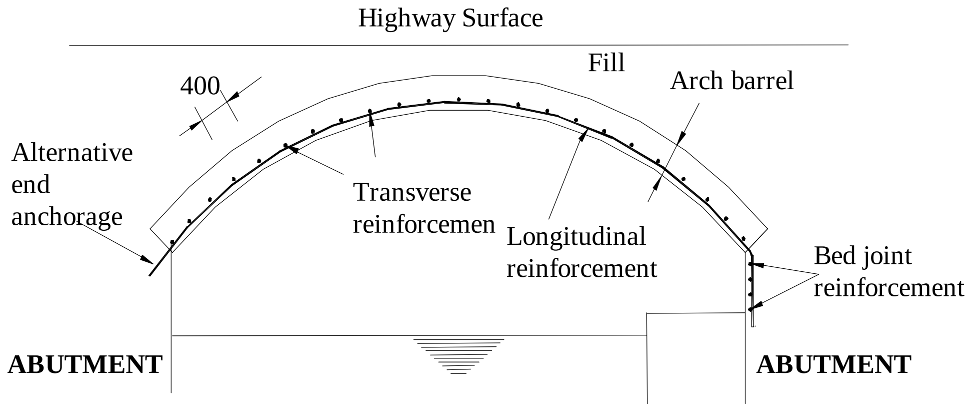
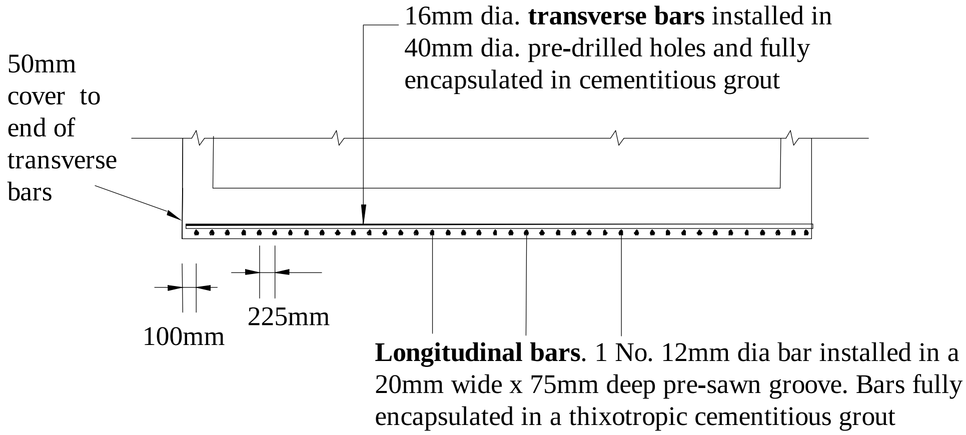


b). Longitudinal Section through Arch Barrel



a). Cross Section through Arch Barrel

Figure 1. Typical Details of Near-Surface Reinforcement
for a Brick Arch Highway Bridge

Table 1: Principal stages of construction

Pre-tender stage condition survey	
Carry out a detailed visual inspection to identify the condition of the exposed masonry including the presence of any cracks; surface damage of the bricks (due to salt crystallisation or frost damage); excessive deformation or ring separation. Extract cores from the arch barrel to determine its thickness and the presence of any voids. It may be necessary to use non-destructive testing techniques to identify the location and extent of any major voids in the masonry. Radar may be used to identify scouring of the ground supporting the abutments, piers or wingwalls. Such measures are often best carried out as part of a condition survey by the bridge owners when the capacity of the bridge is being assessed.	
Pre-construction trials	
Grout trials	Bond strength testing should be carried out with a range of grouts, masonry units (using units of different initial suction and water absorption rates) and surface conditions (either saturated surface dry or oven dried). This will help to optimise the grout formulation to produce maximum masonry to grout bond. A hinged axial tensile bond strength test has been used for this purpose by the author (Garrity 1998). Testing of different grouts should also be carried out to determine the rate of compressive strength gain.
Drilling trials	If possible, samples of the masonry units similar to those forming the arch barrel should be taken and trial drilling undertaken in advance of the main works to help the contractor to select the most effective drill bit.
Construction Stage 1 – Advanced grouting	
Initially, access scaffolding and protective sheeting is installed around the bridge to contain any construction debris and to provide safe and secure working conditions. Where the existing construction contains large voids or there is evidence of ring separation, cementitious grout should be injected into parts or all of the arch barrel prior to drilling the holes for the transverse reinforcement. It may also be necessary to carry out advanced grouting of other parts of the bridge.	
Construction Stage 2 - Installation of transverse reinforcement	
In each working shift, a series of transverse holes is to be drilled into the arch barrel. Grout is then pumped into the holes and stainless steel reinforcing bars are installed. This is repeated until the whole of the arch barrel contains transverse reinforcement. Such reinforcement helps to stabilise the barrel in advance of the stage 3 works; provides improved lateral load distribution characteristics (helps to distribute patch imposed loads and the effects of any future differential settlement); increases the transverse flexural strength of the arch and improves the general robustness of construction.	
Construction Stage 3 - Installation of longitudinal reinforcement	
Longitudinal grooves are sawn into the intrados of the arch barrel and a thixotropic grout is injected into each groove. The longitudinal stainless steel reinforcement (incorporating spacers) is then installed in the grooves and additional grout is injected over the reinforcement leaving sufficient space for surface pointing.	
Construction Stage 4 - Installation of bed joint reinforcement in abutments	

As the strengthened bridge will be able to support larger magnitude live loads than before, the author recommends that horizontal stainless steel bed joint reinforcement should be installed in the abutments to improve the distribution of live load into the supporting ground.