EXPERIMENTAL ANALYSIS OF MASONRY ARCHES STRENGTHENED BY INNOVATIVE COMPOSITE LAMINATES

Antonio Borri¹, Paolo Casadei², Giulio Castori³ and Skip Ebaugh⁴

Abstract

The present research project presents an experimental study aimed to investigate the efficiency of utilizing innovative composite materials, based on high strength twisted steel wires embedded in either an epoxy (Steel Reinforced Polymer) or cementitious matrix (Steel Reinforced Grout), to strengthen masonry arches. The aim of such a strengthening method is to combine to the traditional advantages (very low weight, easiness of application, durability, etc.) proper of Fiber Reinforced Polymers (FRP) the performances of this new family of composite materials, able to allow the same applications, inducing an increase of ductility and reducing installation and material costs particularly when a cementitious matrix is used. For these reasons the use of these materials could become extremely interesting in the restoration of the historical building, and, more so, of masonry arches, as well as in road, rail, and waterway infrastructures, according to the principles of the most rigorous maintenance of historical patrimony and according to the most effective criterions of use of the modern technologies. In the UK, for instance, there are over 40,000 masonry arch bridges, the majority of which, being at least 100 years old, are in need of repair due to natural deterioration or lack of maintenance, or in need of strengthening due to ever increasing traffic volume and vehicle weight.

In response to this situation an experimental study on the behavior of masonry arches strengthened with composite laminates is here presented. The influence of the type of fibers (steel and carbon), matrix (epoxy and cementitious), their location (intrados, extrados, both intrados and extrados) and boundary conditions are investigated in the laboratory on a series of nine specimens of arches built by concrete bricks arranged in a single skin (100 mm of thickness). The results have pointed out the enhancement in strength and ductility of the arches strengthened with SRG/SRP and the influence in the ultimate strength of the mechanical anchoring.

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Introduction

Thanks to their adaptability to the changes of their geometric configuration, masonry arches are able to distribute the strain along the mortar joints, avoiding the formation of significant cracks. In this way the collapse mechanism doesn’t depend by the materials’ limit strength, but it is due to the incapability of the structure to fit the horizontal and vertical displacements of the abutments. As a consequence it is clear that similar displacements should be considered when strengthening masonry arches, introducing only systems which are able to reinforce the arch without changing its constructive features.

Such aims have led researchers to suggest strengthening masonry shells with FRP laminates in the form of bonded surface reinforcements. There are several advantages related to this strengthening technique: very low weight, high tensile strength and low thermal expansion coefficient. On the contrary, their linear elastic behavior up – to – failure, which doesn’t confer any ductility to the system, their low fire resistance and their relatively high cost, may represent an obstacle for a widespread use.

A new family of composite materials (Hardwire, 2002) based on high strength twisted steel wires of fine diameter (0.20 – 0.35 mm), that can be impregnated with epoxy resin or cementitious grout is presented in this paper. SRP/SRG have the potentials to address the three shortcomings mentioned for FRP, in fact:

a) steel wire has inherent ductility and reduced cost when compared to carbon fibers;

b) impregnation of wire in cementitious matrix may overcome fire endurance problems and reduce installation costs.

The steel cords used in SRP/SRG are obtained from the same manufacturing process used for making the reinforcement of automotive tires, and re – manufactured, to obtain the shape of fabric tape prior to impregnation. The twisting of the cords allows some mechanical interlock between the cords and the matrix, and may also induce a ductile behavior upon stretching. Huang et al. (2002) investigated the mechanical properties of SRP/SRG, testing different kinds of matrix (epoxy and cementitious). Test results showed that the material does not experience a substantial yielding, but rather a similar behavior to the one experienced by high – strength steel used in prestressed concrete (PC) construction, with a slight non – linear range prior to rupture of the cords (Casadei et al., 2005).

Thus, to clarify the behavior of brick masonry arches strengthened by this new family of composite laminates, an experimental research has been recently completed at the University of Bath. Nine arch specimens have been tested under monotonic vertical loads applied at a quarter of their span. Such condition is the most severe case of loading for an arch, and can be considered to simulate particular loading configuration of arches (e.g. bridges, library, etc.) or the effects of seismic loads.

The aim of the study is to compare the behavior up to collapse of strengthened masonry arches, investigating types of fibers (steel and carbon) and matrices (epoxy and cementitious), location of the strengthening layer (intrados and extrados) and the presence of anchoring devices.

In the paper, the main experimental results are described and discussed.
Behavior of the strengthened arches

The use of advanced composite materials, as externally bonded strengthening laminates, can modify the failure mode of the masonry arch and significantly increase their load-carrying capacity, by bearing the stresses occurring at the tensed edges. Therefore, the brittle collapse mechanism of such structures, typically caused by the formation of four hinges, can be avoided. Depending on the position of the laminate, in fact, the formation of the forth hinge can be prevented (Foraboschi, 2004).

Particularly, in the case of extrados strengthening (Figure 1a) the line of thrust can fall outside the lower edge of the arch without any structural collapse. As a result, in the case of a vertical load applied at a quarter span, the haunch hinge formation is prevented and the arch becomes a statically determinate structure (it is a three hinges arch) consisting of two curved beams strengthened on their upper sides.

Conversely, in the case of a structure strengthened at the intrados (Figure 1b), although the outgoing static scheme is similar to the one adopted in the previous case, the distribution of the stress parameters is different: the thrust line falls outside the upper edge of the structure and the fibers prevent the forth hinge formation close to the load point.

Consequently, in both cases, the collapse is due to other mechanisms, which are involving the strength limits of the constituent materials (masonry and reinforcement) and their interactions at the local level (i.e. bond and localized shear).

Thus depending on the position and on the amount of the reinforcement, the modified failure mode are: masonry crushing, sliding along a mortar joint, debonding of the fibers and fiber rupture.

Analytical formulations are proposed for each of those mechanisms, calibrated on the basis of direct observation from the experimental tests (Valluzzi et al., 2001). In particular, the evaluation of the ultimate strength of reinforced sections under combined compressive and bending stresses allows determination, as for reinforced concrete (RC) structures, of the maximum resistant moment related to the masonry crushing and to the reinforcement rupture mechanism (Triantafillou, 1998).

Conversely, the other two mechanisms (sliding along the mortar joints and FRP debonding) are based on the local interaction among the constituent materials, so that, the relative design parameters (Foraboschi, 2004 and Borri, 2004), can be given through preliminary tests for the mechanical characterization of the behavior of such materials.

![Figure 1. Behavior of a strengthened arch: position of the thrust line for an extrados (a) and intrados (b) strengthening (Valluzzi et al., 2001).](image-url)
Experimental study

**Characterization of the materials and their interaction**

The experimental program comprised a series of preliminary tests for the mechanical characterization of the constitutive materials of the arches. Concrete bricks (200x100x50 mm) and an hydraulic lime mortar (ratio sand/binder = 5/2 in volume) have been considered. The bricks reached a compressive and a flexural stress equal to 43.3 and 10.9 MPa respectively, whereas compressive tests on mortar prisms after 28 days of curing gave 0.8 MPa (according to BS EN 772 and 1015 standards). To investigate the mechanisms of local interaction among the constituent materials adhesion tests were performed. Particularly, the adhesion properties between the masonry substrate and the strengthening material were investigated via pull – off tests, on sixteen strengthened specimens. Two groups of specimens were cast for this part of research, representing different type of reinforcement (SRG or SRP). The mean value of the tensile bond strength was 1.29 and 1.57 MPa for specimens strengthened with SRG and SRP, respectively. As for the failure mode, while all SRP specimens failed in the substrate (Figure 2a), denoting a good behavior of the adhesive systems, SRG specimens failed with two different modes, namely, a group of specimens failed in the interface (Figure 2b), while the remainder failed in the overlay (Figure 2c). This indicated that, while in the case of SRG specimens the obtained value is really equal to bond strength between fibers and masonry under perpendicular tension, in the second case (SRP specimens) it corresponds to the masonry tensile strength under perpendicular tension.

![Figure 2. Pull – off failure modes: a) substrate; b) interface; c1) and c2) overlay.](image_url)
Manufacturer’s mechanical properties of the strengthening materials are reported in Table 1.

<table>
<thead>
<tr>
<th>Property</th>
<th>Steel (3X2 – 4)</th>
<th>Steel (3SX – 12)</th>
<th>Carbon (T700 SC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile load (N/mm)</td>
<td>242</td>
<td>635</td>
<td>817</td>
</tr>
<tr>
<td>Elastic Modulus (MPa)</td>
<td>210000</td>
<td>210000</td>
<td>230000</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>0.89</td>
<td>0.81</td>
<td>0.44</td>
</tr>
<tr>
<td>Ultimate strain (%)</td>
<td>1.6</td>
<td>1.2</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Fibers where impregnated using a common epoxy resin and cementitious grout.

**Test Set Up and Test Matrix**

A series of nine arch specimens built with concrete bricks arranged in a single layer (100 mm of thickness) have been tested under monotonic vertical loads applied at a quarter of their span (Figure 3).

Due to the somewhat thin thickness, a catenary curve (parabolic shape), typical of many existing arches, as it is the ideal form to carry a uniformly distributed load, was chosen as directrix of the arches, in order to improve the stability of the structure under loading. A span of 1980 mm therefore means that the height of the arch is 490 mm above the springing level.

As already mentioned, different strengthening arrangements (extrados, intrados, both intrados and extrados), different types of matrix (polymeric or cementitious) and fibers (steel or carbon) and different number of plies (one or two) have been considered (Table 2).

All the specimens, except the control ones (UN.01), were strengthened using a different combination of above test variables.
Particularly, three specimens have been strengthened with steel fibers (3SX-12) at the extrados impregnated with cementitious grout (EX.01 and EX.03 tests) and polymeric matrix (EX.02 test), a specimen has been strengthened at the extrados with carbon fibers and a polymeric matrix (EX.04 test), three specimens have been strengthened with steel fibers (3X2-4) at the intrados by using a cementitious grout (IN.01 and IN.03 tests) and a polymeric matrix (IN.02 test), whereas steel fibers (3SX-12 and 3X2-4) and cementitious grout have been used to strengthen both intrados and extrados of the last specimen (IN+EX.01 test).

A single ply of laminate, 150 mm wide, has been applied for each arch, with the exception of the IN.03 specimen, where two plies of laminate have been used.

Furthermore, in two cases (EX.03 and IN.03 tests), in addition to the reinforcement, steel anchors were adopted: in the first case, in order to prevent sliding, two angle plates were used to anchor the ply to the abutments (Figure 4a), while in the second case flat plates, bolted to the bricks, were used to secure the ply to the arch soffit (Figure 4b).

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**Table 2. Test Matrix.**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Position of reinforcement</th>
<th>Composite type</th>
<th>No. of plies</th>
<th>Boundary conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Matrix</td>
<td>Reinforcement</td>
<td></td>
</tr>
<tr>
<td>UN.01</td>
<td>Extrados</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>EX.01</td>
<td>Extrados</td>
<td>Cementitious grout</td>
<td>Steel (3SX-12)</td>
<td>1</td>
</tr>
<tr>
<td>EX.02</td>
<td>Extrados</td>
<td>Polymeric resin</td>
<td>Steel (3SX-12)</td>
<td>1</td>
</tr>
<tr>
<td>EX.03</td>
<td>Extrados</td>
<td>Cementitious grout</td>
<td>Steel (3SX-12)</td>
<td>1</td>
</tr>
<tr>
<td>EX.04</td>
<td>Extrados</td>
<td>Polymeric resin</td>
<td>Carbon (T700S)</td>
<td>1</td>
</tr>
<tr>
<td>IN.01</td>
<td>Intrados</td>
<td>Cementitious grout</td>
<td>Steel (3X2-4)</td>
<td>1</td>
</tr>
<tr>
<td>IN.02</td>
<td>Intrados</td>
<td>Polymeric resin</td>
<td>Steel (3X2-4)</td>
<td>1</td>
</tr>
<tr>
<td>IN.03</td>
<td>Intrados</td>
<td>Cementitious grout</td>
<td>Steel (3X2-4)</td>
<td>2</td>
</tr>
<tr>
<td>IN.04*</td>
<td>Intrados</td>
<td>Polymeric resin</td>
<td>Carbon (T700S)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Intrados</td>
<td>Cementitious grout</td>
<td>Steel (3X2-4)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Extrados</td>
<td>Cementitious grout</td>
<td>Steel (3SX-12)</td>
<td>1</td>
</tr>
</tbody>
</table>

* Specimen tested in a previous experimental research (Boorer, 2005)
Also, to complete the analysis, the results of a previous experimental research (Boorer, 2005), performed on a specimen (IN.04 test), with the same dimensions and load conditions, strengthened at its intrados with a polymeric matrix and a single ply of CFRP, 150 mm wide, have been considered.

**Test Results**

The unreinforced arch, as predicted based on precedent study (Heyman, 1982), showed a brittle failure, due to the formation of four hinges (four hinges mechanism) with an ultimate load of 0.7 kN.

The tests performed on the arches strengthened at their extrados presented different patterns of collapse according to the different laminate arrangement. In particular, while the specimen EX.01 showed, because of a set-up problem, a notable rotation of the abutments, that not allowed any further increment in load, in the other two cases (specimens EX.02 and EX.03) the collapse occurred because of the sliding between brick and mortar in the first joint closest to the springer (Figure 5a) and to the edge of the steel anchor (Figure 5b), respectively; in both cases such collapse occurred without any warning. The ultimate load was 9.2 kN for specimen EX.01, whereas it was 13.3 and 23.5 kN for specimens EX.02 and EX.03, respectively.

Conversely, the arch reinforced at its extrados by CFRP (specimen EX.04) showed the same failure mode (sliding in the first joint closest to the springer), but a lower ultimate load capacity (11.5 kN).
Figure 5. Shear sliding along a mortar joint: a) first joint closest to the springer (specimen EX.02); first joint closest to the edge of the steel anchor (specimen EX.03).

The arches strengthened by steel fibers (3X2-4) at their intrados presented different patterns of collapse, despite having shown similar results in terms of global deformation. Particularly, specimens IN.01 and IN.02 showed a brittle failure due to the reinforcement rupture (Figure 6a), whereas in specimen IN.03, where the presence of two plies of laminate allowed to avoid the reinforcement rupture, the collapse occurred due to local debonding of the reinforcements under the point of application of the load (Figure 6b).

Figure 6. a) Laminate rupture: specimen IN.02; b) Laminate debonding: specimen IN.03.

In such case the failure was not brittle because the fibers contributed in holding the bricks together during the last phase. The ultimate load was 16.2 and 14.7 kN for specimens IN.01 and IN.02 respectively, whereas it was 23.0 kN for specimen IN.03.

Finally, the arch strengthened both at its extrados and intrados (specimen IN+EX.01) with 3SX-12 and 3X2-4 laminate, respectively, presented a different pattern of collapse due to the sliding along the mortar joint near the point of application of the load, which caused the consequent detachment of the fibers from the masonry (Figure 7). The ultimate load was considerably higher (32.8 kN).
Analysis of the results

The analysis of the experimental results allowed to evidence some particular aspects of the behavior of the strengthened arches and propose some suggestions about the use of SRP/SRG composite materials in real cases. Figure 8 illustrates a comparison between the load – deflection (measured at the location where load was applied) curves obtained from the experimental tests on the strengthened arches.

Despite different laminate arrangements and fiber types have been used, each strengthened specimens reached failure with a gradual stiffness deterioration, with the exception of specimen EX+IN.01, where there is a clear change in stiffness at about 5 mm of load point deflection (it is at this point that the shear sliding started to occur). As expected, a significant influence of the boundary conditions in the specimen stiffness is observed. The increase in stiffness due to the presence of steel anchors (specimens EX.03 and IN.03) is in fact very evident, particularly for the extrados application. Such response confirms the beneficial effect of mechanical anchors, not allowed, because of their weakness.
in terms of shear strength, in standard FRP applications, both in terms of stiffness and ultimate load capacity. Also, the application of SRG reinforcement both at the intrados and at the extrados (specimen EX+IN.01) resulted in increased stiffness in the linear – elastic region of the load deflection behavior.

As for the ultimate loading capacity, the results obtained from the experimental tests are compared in Figure 9. It can be noted that the steel fibers, despite their lower mechanical characteristics against the carbon ones, have involved an higher increase in terms of strength both for intrados and extrados applications. Moreover, as said, the presence of mechanical anchors have shown to allow a substantial increase in terms of ultimate load capacity.

As it regards the ultimate behavior of the strengthened structures, some important considerations can be drawn (Table 3).

For the arches strengthened at their extrados, despite different fiber types have been used, the results showed that masonry sliding is the prevalent failure mechanism. Such kind of failure takes place only on the arches strengthened at the extrados because the weakest point of the structure is the hinge forming at the abutment.

Thus, in the repair phase of real structures, a solution that could increase the ultimate load capacity could be achieved, as done in specimen EX.03, by anchoring the first ply to the abutment by means of steel plate bolted to the support and simply adhered to the reinforcement.

For the specimens strengthened at their intrados, the reinforcement rupture in proximity of the loaded section and the local debonding of the composite laminate have been detected to be the critical ones.

Thus, in the repair phase of real structures, a solution that could increase the ultimate load capacity could be, as seen with specimen IN.03, the use of two plies of laminate, to avoid the reinforcement rupture, and mechanical anchors, in the form of steel flat plates screwed in the masonry substrate (Figure 4b), able to tie the strip to the arch soffit retarding premature detachment of the fibers.

![Figure 9. Ultimate load capacity of the tested specimens.](image)

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Table 3. Comparison among the experimental results.
Finally the application of the reinforcement both at the intrados and at the extrados of the arch is clearly an ideal application, used as well as the unreinforced arch, to evaluate the efficiency of the adopted strengthening methods.

## Conclusions

The following conclusions may be drawn from this experimental program:

- SRP/SRG composite materials, despite their lower mechanical properties versus CFRP, have allowed an increase in terms of ultimate load capacity for both intrados and extrados strengthening applications.

- SRP/SRG composite materials, similar to FRP in terms of ease of installation, allow the same applications, reducing installation and material costs.

- Mechanical anchoring was shown to successfully improve the overall performance by allowing a substantial increase in terms of stiffness and ultimate load capacity, when used for SRG/SRP applications.

- Cementitious grout well behaved in bonding the steel tape to the masonry substrate and provided an overall better performance, in terms of ultimate load capacity, than epoxy resin, allowing better redistribution of stresses between the laminate and the substrate.

## Acknowledgments

The authors would like to acknowledge Hardwire LLC., Pocomoke City, MD, for providing the steel tapes, Toray Industries, Inc., for providing the carbon tapes, the Department of Architecture and Civil Engineering at the University of Bath for hosting this collaborative research and the Department of Civil Protection “Consorzio RELUISS” for supporting this collaborative research.
References


