SEISMIC UPGRADING OF MASONRY STRUCTURES WITH FRP

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Abstract

This study aims to provide a basic understanding of the behavior of masonry structures reinforced with Fiber Reinforced Polymers (FRP) epoxy-bonded to the masonry surfaces. The main investigation consists of three parts: the first relates to the determination of shear strength of masonry specimens reinforced using carbon and glass FRP. Several specimens have been tested in order to determine the tangential modulus of elasticity and the shear strength of the masonry. The second part of the investigation relates to the seismic upgrading of masonry vaults or arches. The use of carbon and glass FRP as a reinforcing method for different kinds of vaults or arches, as well as the different possible positions of the FRP sheets, is analyzed, and some solutions are proposed to avoid peeling problems and increase the efficiency of the bond surface. The third and final part of the investigation is concerned with a method of reinforcing masonry structures by wrapping FRP sheets around the external perimeters of buildings to avoid out-of-plane mechanisms.

Keywords: seismic upgrading, masonry structures, shear strength, vault, FRP sheet, out-of-plane mechanism

1. Introduction

Many un-reinforced masonry structures are widely present throughout Italy and other regions around the world. These structures seem to suffer the most severe damage during earthquakes. Not only the prohibitive cost of replacing all substandard structures, but also the conservation of the historic heritage of the country, necessitates the development of innovative techniques for rehabilitating deteriorating structures. As a consequence most of these structures need seismic upgrading work in order to ensure their conservation and functional use.

A considerable amount of research has been conducted in the past to improve the mechanical behavior of masonry structures using a variety of reinforcement techniques. The shear reinforcement of walls was realized by employing metallic bars, or injecting lime or cement based mortars.

In recent years, reinforcing concrete structures by the wrapping and bonding of Fiber-Reinforced Polymers made of sheets, straps, belts or procured shells has became increasingly popular, but limited
research has been conducted on the use of FRP reinforcement in masonry structures. In countries such as Italy, the use of brickwork as a building material has prompted a wide range of studies to investigate its structural behavior in a variety of applications. As an example, Di Tommaso and others first applied FRP in order to upgrade the seismic behavior of bell-towers [1]. This paper contains an abstract of the most part of research carried out by the authors during the years following the Umbrian-Marchigiano earthquake of 1997. References are reported at the end of this paper.

2. Shear reinforcement of masonry walls

Various kinds of intervention may be carried out to upgrade a wall. Currently, the most widespread technique consists of injecting lime-based grouts or fixing a metal net on masonry surfaces under a concrete jacket. Borri, Corradi and Vignoli applied this technique in order to upgrade several two-leaf and three-leaf walls. The results substantially showed that while the injection technique can be effective when used as a repair technique, its adoption as a preventive measure necessitates a previous, careful analysis of the masonry texture and of its characteristics, in order to understand if the grout can, in effect, penetrate it well.

The use of FRP on similar walls was also studied. These walls were tested under diagonal compression and shear-compression. This involved the use of panels of various dimensions. Five of ten panels were tested without strengthening, to determine the mechanical characteristics of the masonry. The remaining five were consolidated respectively with unidirectional carbon fibers and unidirectional fiber glass. Strengthening with one sheet of unidirectional carbon fiber or fiber glass was carried out on both sides of the panel, following the scheme presented in Figure 1.

Due to the great irregularity in the masonry texture, the strengthening of the panels was carried out only after spreading a layer of cement based mortar to create a sufficiently plane, uniform surface on which the composite was then applied. The mortar used was placed directly on the masonry once the original rendering had been removed.

2.1 Diagonal Compression Tests

The diagonal compression test was carried out on panels 120 x 120 cm (according to ASTM specifications [2]) with cross-sections of varying thicknesses, depending on the structure on which the intervention was effected. The aim of this test was to determine the shear-strength and the shear elastic modulus of the masonry. The panel was isolated from the rest of the masonry by means of the diamond wire cutting technique in order to leave it undisturbed (see Fig. 2).

The test mechanism was composed of a set of metallic elements joined together to obtain a closed system. The stress was applied to the panel by means of a compression load, coplanar to the panel itself and directed along one of its two diagonals. A jack placed along the diagonal, external to the panel, was positioned between two metallic elements which permitted it, on the one hand, to act directly on an edge
of the panel, while at the same time to remain rigidly connected to an analogous metal element located along the opposite edge. In correspondence to this edge the situation was analogous, except for the absence of the jack: the two most external metal elements were rigidly connected by means of two steel rods of equal length to allow a uniform distribution of the load throughout the thickness of the panel. The panel was instrumented on both sides with LVDT inductive transducers to measure the deformations occurring along the four diagonals. It was therefore possible to acquire the strains during the test as a function of time and the value of the load applied to the jack. The test procedure consisted of loading and unloading cycles of increasing maximum values, until the point of failure was reached. The load was applied following a series of equal couples of cycles, with increases of 10 kN, up to the point of failure. In the case of strengthened panels with failure loads greater than 80 kN, the interval between one couple and the other was increased to 20 kN.

2.2 Shear-Compression Tests

The shear-compression test was carried out on panels of dimension 180x90 cm, with a maximum section thickness of 65 cm. Eight transducers were placed along the diagonals of the four square surfaces, obtained by subdividing each of the two vertical sides of the panel in two equal parts. Three additional transducers were positioned on each side - to measure transversal movements - along the center line, and at the top of the panel. Two other transducers were placed vertically at the edge of one side of the panel to measure eventual rotations at the top of the panel. The shear-compression tests, analogous to the diagonal compression tests, were designed to determine the shear strength and shear elastic modulus characteristics of the masonry. The test consists of a monotonic loading up to the point of failure, under a state of constant compression for the duration of the test. The compression stress was applied up to a vertical stress of 0.3 MPa.

The horizontal shear force was applied by two steel rods which acted on a special metal element positioned at the center line of the panel. This element consists of two C shapes, coupled with plates welded to the webs, whose function is to distribute the concentrated load throughout the panel thickness. An oleo-dynamic jack is interposed between a I shape, used as a contrast element (positioned parallel to the height of the panel at a lateral opening in the masonry), and a metal beam similar to that at the center line of the panel. The actuator loads, on one side, the I shape, whose job is to distribute the load concentrated at the base and at the top of the opening, and on the other side, the metallic element to which are attached the two steel ties which thus result in tension. The upper part of the panel was contrasted by means of a couple of 100 kN jacks positioned horizontally, in order to avoid flexural failure mechanisms. This couple also allowed measurement of the horizontal reaction at the top of the panel. The condition of double bending results only in the hypothesis that the upper edge is prevented from translating and rotating. This condition is in part supplied thanks to the presence of the jack couple, blocked on the load assigned, and of the horizontal plate placed on the panel. Nevertheless, the stiffness of the apparatus at the top of the panel and of the vertical rods is not sufficient to act as a perfect constraint, as requested. This allowed a lack of symmetry in the distribution of the shear stresses between the upper and lower halves of the panel, which was taken into account during the elaboration of the data. In addition to the displacements of the sixteen inductive transducers, measurements were also acquired of both the time and the pressure in the two vertical and three horizontal jacks, for a total of twenty-one channels of acquisition.

2.3 Evaluation of the Results

Eight, of the ten panels, were double-leaf masonry walls, made of weakly connected roughly cut stone, while two were of solid brick. The cross section thickness of the panels in stone also turned out to be more or less constant with values varying from 48 to 57 cm, while differences of properties were noted in the mortars (all lime-based), depending also on the period in which the building was constructed. For the diagonal compression tests the interpretative models of structural behavior are the classic ones [2], while for the shear-compression tests Sheppard's model [3] is used, taking into account hypothesis and interpretative choices as in [4]. The results of shear-compression tests (see Tab. 1) show an increase in the strength, $\tau_s$, of the strengthened panels, relative to those non-strengthened, of approximately 55%, independent of the type
of fibers used. This essentially depends on the particular modality of failure, which did not involve the crisis of the composite, except at a limited area on some of the panels. In fact, the fibers remained attached to the cement-based mortar (used to create a uniform surface on which the FRP was applied), which in turn had detached from the masonry. Therefore, since the state of fiber stress was well below its failure level, it was only marginally engaged. For this reason, no difference resulted from the use of carbon fibers or fiber glass. However, in the successive diagonal compression tests the layer of mortar was replaced by a thinner layer of epoxy putty which bonded more efficiently with the masonry substrate and determined a better utilization of the fibers, which did not detach until the masonry-composite system failure was reached.

Tab. 1: Results of the shear compression tests (static scheme 1: double fixed end; static scheme 2: fixed end and fixed end with determined stiffness to 3 D.O.F.: vertical and horizontal translation and rotation in the panel’s plane)

<table>
<thead>
<tr>
<th>Index Code</th>
<th>Strengthening technique</th>
<th>Texture</th>
<th>Section [cm]</th>
<th>$P_{\text{max}}$ [kN]</th>
<th>$\tau_{\text{max}}$ [MPa]</th>
<th>$G$ [MPa] Scheme 1</th>
<th>$G$ [MPa] Scheme 2</th>
<th>$\tau_k$ [MPa] b=1,50</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-T-04-OR</td>
<td>None</td>
<td>double-leaf roughly cut stone masonry</td>
<td>48</td>
<td>180.70</td>
<td>0.219</td>
<td>546</td>
<td>328</td>
<td>0.130</td>
</tr>
<tr>
<td>B-T-05-FC</td>
<td>CFRP</td>
<td>double-leaf roughly cut stone masonry</td>
<td>48</td>
<td>241.40</td>
<td>0.352</td>
<td>467</td>
<td>771</td>
<td>0.262</td>
</tr>
<tr>
<td>V-T-06-FV</td>
<td>GFRP</td>
<td>double-leaf roughly cut stone masonry</td>
<td>48</td>
<td>231.30</td>
<td>0.334</td>
<td>245</td>
<td>249</td>
<td>0.245</td>
</tr>
<tr>
<td>P-T-15-OR</td>
<td>None</td>
<td>double-leaf roughly cut stone masonry</td>
<td>48</td>
<td>100.40</td>
<td>0.172</td>
<td>216</td>
<td>-</td>
<td>0.136</td>
</tr>
</tbody>
</table>

Tab. 2: Results of the diagonal compression tests.

<table>
<thead>
<tr>
<th>Index Code</th>
<th>Strengthening technique</th>
<th>Texture</th>
<th>Section [cm]</th>
<th>$P_{\text{max}}$ [kN]</th>
<th>$\tau_k$ [MPa]</th>
<th>$G_{1/3}$ [MPa]</th>
<th>$\gamma_{1/3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-D-02-OR</td>
<td>None</td>
<td>one-leaf solid brick masonry</td>
<td>48</td>
<td>34.31</td>
<td>0.069</td>
<td>131</td>
<td>0.136</td>
</tr>
<tr>
<td>B-D-03-FC</td>
<td>CFRP</td>
<td>one-leaf solid brick masonry</td>
<td>48</td>
<td>188.25</td>
<td>0.373</td>
<td>100</td>
<td>1.240</td>
</tr>
<tr>
<td>G-D-11-OR</td>
<td>None</td>
<td>double-leaf roughly cut stone masonry</td>
<td>57</td>
<td>51.14</td>
<td>0.053</td>
<td>26</td>
<td>0.643</td>
</tr>
<tr>
<td>G-D-12-FC</td>
<td>CFRP</td>
<td>double-leaf roughly cut stone masonry</td>
<td>57</td>
<td>121.53</td>
<td>0.127</td>
<td>55</td>
<td>0.699</td>
</tr>
<tr>
<td>P-D-13-OR</td>
<td>None</td>
<td>double-leaf roughly cut stone masonry</td>
<td>48</td>
<td>47.66</td>
<td>0.059</td>
<td>37</td>
<td>0.533</td>
</tr>
<tr>
<td>P-D-14-FC</td>
<td>CFRP</td>
<td>double-leaf roughly cut stone masonry</td>
<td>48</td>
<td>141.61</td>
<td>0.173</td>
<td>117</td>
<td>0.497</td>
</tr>
</tbody>
</table>

Figure 3 Diagonal compression tests (gray lines: panels un-strengthened, black lines: panels strengthened with CFRP)
For diagonal compression tests, the use of an epoxy putty in place of the cement based mortar determined an increase in shear strength of 240% compared to the non-strengthened panels. The masonry panel (code: B-D-02-OR), made of solid brick, presented a notably low failure stress of 0.069 MPa for the non-strengthened panel (see Tab. 2). Instead, the masonry-composite system of the panel strengthened with CFRP was shown to be very resistant, with a failure stress of 0.373 MPa, thanks to the effect of confinement the fibers induced on the masonry as well as to the presence of diatons, which acted as connectors. At the failure load, the masonry fractured in compression, determining the expulsion of small portions of brick from the panel, while the CFRP applied on a thin layer of epoxy putty remained attached to the panel.

The results for the shear elastic modulus $G$, measured following ASTM specifications at 1/3 maximum load, were between 26-131 MPa for non-strengthened panels subjected to diagonal compression tests. Strengthening by means of fibers in composites does not result in sharp increases in the shear elastic modulus: panels for diagonal compression tests, strengthened with carbon fibers, resulted stiffer, however, with average values of approximately 250%, while in one case there was a practically negligible increase. The composite does not alter the static scheme of the structure nor does it determine major redistribution of stiffness (above all for fiber glass), but mainly shows up as an increase in the shear strength of the masonry by means of the mobilization of the fiber traction strength. Comparisons in the behavior of panels subjected to diagonal compression tests are shown on a $\tau-\gamma$ graph in Figure 3. Both the similarity in behaviour among the non-strengthened panels, as well as the significant increase in shear strength of the strengthened panels, can be noted. This latter aspect turns out to be particularly evident for the injected panels.

3. Seismic upgrading of masonry vaults or arches

It is known that an intervention on a masonry vault or an arc bridge should be designed to prevent all possible mechanisms and constrain the masonry structure to fail only by crushing. Over the last two centuries many procedures aimed at upgrading a vault or an arc bridge have been introduced. The introduction of steel tendons was an efficient technique and has been used up to the present. However, the most common seismic upgrading intervention consisted of fixing a reinforced concrete shell connected to the masonry structure at the extrados of the vaults. This procedure could cause several negative consequences, such as the decompression of the masonry structure, the irreversibility and intrusiveness of the intervention, as well as the formation of moisture accumulation due to the loss of porosity of the masonry structure. Arc bridges and vaults adapt well to variations in geometrical configuration, being able to distribute the deformations along the mortar joints without significant crack forming. These structures can collapse due to different types of mechanisms: the local compressive crushing or the formation of four hinges asymmetrically located in the arc. Another type of mechanism is characterized by the formation of five hinges: three in the arc and the remaining two in the abutments (see Fig.4).

![Figure 4: A possible failure mechanism of an arc bridge and the position of FRP](image)

Several studies were carried out in order to investigate the use of FRP for seismic upgrading of masonry arc bridges and vaults. Faccio and others (2000, [5]) tested different arch bridges using this technique. Modena and others (1999, [6]) applied this technique to some types of masonry vaults. However the tests carried out by researchers consisted mainly in soliciting masonry structures by static vertical loads.
The test program, still ongoing at the moment, involves the loading to failure of 3 full-scale arc bridges. These structures have a span of 5000 mm and are solicited by vertical and horizontal dynamic loads. All the specimens have identical geometry (thickness 125 mm, width 1370 mm) and are made up of solid brick. The CFRP reinforcement is disposed in different positions at the extrados and the intrados (see Fig. 5).

Considering that the dynamic test is non-destructive, the same test apparatus was used for testing before and after the reinforcing operations in order to measure the specimen displacements.

Avorio, Borri and others (1999 [7]) applied this technique on the vaults of the town hall of Assisi. This important complex contains vaults of various types, as well as from different periods. The most frequent type occurring here is the cross vault, but there are also barrel vaults with lunettes. The strengthening of masonry vaults raises serious considerations, since the majority of them are of considerable architectural and historical importance.

The FRP sheets were fixed at the extrados of half-brick cross vaults (see Figures 6, 7, 8 and 9). The work involved removal of the support up to the hauches, where the bricks of the arched lintel are inserted into the outer wall.

After the surface of the outer vault areas had been thoroughly cleaned by sanding and water-cleaning, and then levelled, four bending bands were created using suitable mortar. Following the few days required for the curing of the mortar, the surface was prepared with a suitable primer and the first unidirectional layer of FRP was laid with epoxi-resin. A second layer was then laid.
With regard to the site operation, the first step of the upgrading intervention is the cleaning of the vault surface by sanding and water-cleaning. A band made of a layer of epoxy-mortar is then laid using a suitable epoxy-resin primer. It should be noted that, despite careful preparation of the extrados of the vault, areas with abrupt variations in curvature may occur. In these cases, experimental tests showed a high degree of weakness of the individual unidirectional sheet, due to the onset of stress at right angles to the fibres. The pack with two sheets instead proved to be far less sensitive to this effect, thanks also to the imperfect alignment of the directrices of the fibres as well as the distribution effect exerted by a thicker layer of resin.

In order to avoid mechanisms involving the abutments and to prevent peeling or debonding problems of the unidirectional CFRP sheets, a steel or CFRP bar is recommended for the anchorage. A hole is made and should be carefully cleaned before injecting a grout suitable for that particular masonry. Then the CFRP or steel bar can be inserted (see Figures 10 and 11).

Figure 8  The fixing operation at the extrados of the vault
Figure 9:  The strengthening intervention of cross vaults

Figure 10-11 A proposed solution to the problem of peeling and debonding of FRP from masonry. This solution also allows a better strengthening action.
The connection between the CFRP sheet and CFRP bar was studied and the results of the experimental tests are reported in [8]. If a steel bar is used for the anchorage, the head of the bar is fixed to a slab of concrete by means of a nut and load-distributing wedge.

The intervention can be completed in the traditional way, by the construction of low hollow-brick walls as shown in Figure 6, separated by a distance equivalent to that of the overlying hollow floor slab (approx. 80-100 cm).

This technique was also applied by the same researchers [7] on four Welsh cloister vaults. These vaults only have a decorative function and the space separating them from the roof is simply a garret with just enough height to carry out routine maintenance. All the vaults were of half brick thickness and highly visible cracks had formed at the corners to the intrados where there were frescos. The work with FRP strips in these cases was quite easy, due to the absence of filling above the vaults and to the light weight and relatively small size of the materials used. As for the cross vaults, the preliminary operation was to clean the vault and level the areas to be clad with special mortars.

4. Reinforcing of masonry structures by the wrapping of FRP

Fiber wrapping, or encasement of masonry buildings in fiber-reinforced polymers (FRP) shells, may significantly enhance the strength and ductility of masonry structures. Most masonry walls are not correctly connected to each other, and this makes these structures particularly vulnerable to seismic action. The walls orthogonal to the direction of the seismic action often collapse following out-of-plane mechanisms.

In order to connect masonry walls different procedures have been introduced during the last decades. The most popular technique consists of the realization of a reinforced concrete ring beam along the perimeter walls.

Ten masonry panels were assembled to form two masonry cells: six of the them had a masonry texture of roughly cut calcareous stones with lime-based mortar (panel thickness 50 cm), while the remaining four panels had a texture made up of hollow bricks (panel thickness 25 cm). The complete results of this experimental research are reported in [9].

The walls were constructed using lime based mortar and sand in volume ratio 1:2. The height of the walls from the base is 150 cm and the length is 90 cm (see Fig. 12).

Preparation of the wall surface for the strengthening operation is a quick procedure, consisting of the use of a grinder to remove the external blaster. The application of CFRP reinforcement is carried out after having spread an epoxy-primer and an epoxy-mortar on the surface of panels. Two bands of CFRP are...
applied along the external perimeter in order to wrap the masonry cell with one band near the base and with another near the upper border.

A hydraulic jack was introduced inside the masonry cells at the level of the upper FRP sheet in order to stress the masonry panels. The masonry cells were loaded monotonically up to failure with load increments of 10 kN. In order to distribute the load, two metallic T shapes were introduced between the masonry panels and the hydraulic jack.

The solid brick and the stone masonry cells failed respectively at a load of 70 kN and of 90 kN. The low flexural stiffness of the CFRP sheet caused large lateral deformations at the maximum load. The experiment showed that the FRP reinforcement maintains its effectiveness until the crushing strain of masonry is attained.

A significant consequence of the presence of the FRP reinforcement was the absence of the out-of-plane collapse of the masonry wall. The FRP sheet was in fact able to contain the stones and bricks resulting from the crumbling of the masonry wall (see Fig. 13).

The process of the crumbling of the masonry panel started long before the maximum load was reached. At the maximum load, large deformations were measured highlighting the high ductility characteristics of the masonry reinforced with CFRP polymers. The use of the two CFRP sheets placed one upon the other (the total number of sheets used is four, considering that two bands of two sheets were placed around the masonry cell) did not cause problems at the four angles.

Several strain gauges were fixed along the FRP sheets in order to measure the stress tensile status of the composite (see Fig. 14). This allowed us to confirm that the FRP reinforcing technique carried out its strengthening action, as well as to measure the degree of utilization of the FRP.

However, the abrupt variation in curvature occurring at the four angles of the masonry cells should be avoided. CFRP sheets have a high degree of weakness due to the onset of stress at right angles to the fibres. In this case, the problem was partially solved thanks to the introduction of steel L shapes characterized by a radius of curvature of 2 cm.
Moreover, the use of L shapes with a height greater than the height of the CFRP sheet causes a better distribution of compressive stresses on the masonry surface and in part avoids the masonry crushing at the angles of the cell (see Fig. 15).

However the effect of using CFRP strengthening on corrosion confinement of steel elements should be studied and carried out with care. Many researchers have attempted to characterize the performance of corrosion damaged RC structures reinforced with CFRP sheets, showing the importance of the resin layer in separating steel and carbon reinforcements.

The use of FRP to wrap masonry buildings may be a provisional or a definitive intervention. Even in the case of a provisional use the advantages are significant, considering the rapidity with which it can be realized and the possibility of putting in security damaged masonry structures. This technique may also be applied to non-rectangular structures. In these cases a possible solution is shown in Figures 16 and 17: a tendon composed of a CFRP bar (or a metallic one) is connected, by means of FRP strips, to the external FRP band in order to avoid debonding of the FRP sheet from the surface of the masonry structure. The connection of CFRP bars to orthogonal sheets is now studied and preliminary results indicate its effectiveness.
5. Conclusions

This paper presents the results obtained in a feasibility study on the seismic upgrading and repair of masonry shear walls, vaults and cells using externally bonded carbon and glass fiber sheets. Several shear wall specimens have been tested in the present study and an interesting increase in shear strength, shear elasticity and ductility was obtained.

Regarding the shear strengthening of masonry walls with sheets of unidirectional carbon or glass fiber, the shear compression tests carried out on panels of varying dimensions have highlighted the fact that the adhesion between the panel and the mortar used as a base for the fibers was the weakest element in the system. When a cement based mortar was applied, failure resulted from the separation of the layer of the mortar from the panel, with almost equal increases in strength and stiffness for both carbon fibers and fiber glass. The subsequent diagonal compression tests, carried out using carbon fibers on a thin layer of epoxy plaster applied directly on the surface of the panels, demonstrated greater increases in both strength and stiffness. Failure resulted, in the case of stone panels, from a separation of the two masonry leaf walls, while in the case of the panel in brick diatons it resulted from the crushing of the bricks at high load values. For this masonry texture a comparison of the results with those for non-strengthened panels gives very high increases in shear strength. The application of this type of intervention resulted more effective in the case of panels made of adequately connected masonry multiple-leaf walls or, as in the case of the brick panel, consisting of a single leaf masonry wall, so that crisis mechanisms due to bending moment and axial forces were avoided.

The reinforcing of masonry arch bridges or vaults seems to be more efficacious compared to traditional reinforcing procedures. This technique was applied on a historic building located in Assisi, Italy, after its effectiveness had been laboratory-tested on full-scale prototypes with dynamic and static loading tests up to collapse. In addition, the problem of fixing the FRP sheet to the masonry structure was studied, in order to avoid debonding problems.

Fiber wrapping of masonry buildings in FRP may enhance the strength of this kind of structure: the use of FRP inhibits the out-of-plane mechanisms of masonry walls and permits the transfer of stresses to the wall parallel to the direction of seismic action. This technique may be used for provisional or definitive interventions and it shows positive characteristics with regard to several aspects, such as the increase in ductility of the masonry structure. Based on test results, it can be concluded that the application of externally bonded carbon or glass fiber sheets may be considered as an effective seismic strengthening and repair procedure for some types of problems of masonry structures.

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