Strengthening techniques tested on masonry structures struck by the Umbria–Marche earthquake of 1997–1998

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Abstract

The results of experiments carried out on structures damaged in the Umbria–Marche earthquake of 1997–1998 are presented. These tests were carried out in situ on masonry panels of various dimensions, which had been strengthened with either traditional or innovative materials and techniques. Concerning traditional methods, panels injected with new limed-based mixes were tested. Other tests were realized by gluing to the wallettes sheets of monodirectional carbon fiber (CFRP) or fiber glass (GFRP) with epoxy resins. In both cases the purpose of the tests was to analyze the effectiveness of the intervention, above all as a technique of seismic-upgrading against in-plane mechanisms of collapse. The results show a significant increase in strength. The experiments carried out allowed to obtain interesting indications for their practical utilization of the studied technique. The injection technique is substantially more efficient when used as a method of repair damaged panels, confirming that a preliminary evaluation of dimension and distribution of voids is necessary before adopting this technique. The experimental work showed that the use of composite materials on double-leaf roughly cut stone masonry is more effective when conducted with other stabilization schemes. The failure of the double leaf roughly cut stone panels strengthened with composite materials resulted from the separation of the two masonry leaves. In both cases the strengthening showed remarkable benefits in terms of increase in strength, providing the masonry with greater shear strength. The increase in stiffness following the intervention, as well as its effect, was also analyzed.

Keywords: Masonry; Earthquakes; Strengthening; Carbon fibre; Epoxy resin

1. Introduction

This short study presents and comments the experimental work carried out as part of a research project commissioned to the Laboratory on Anti-seismic Research, RITAM, of Terni by the Deputy Commissioner for interventions in the areas damaged by the earthquake in Umbria. The aim of this work was to characterize the behavior of the masonry typical of the areas struck by the seismic events of 1997–1998 and to study the effectiveness of the seismic-upgrading both on undamaged and damaged walls.

The research project includes a series of in situ tests performed on panels cut using the diamond-wire technique and isolated from the remaining masonry wall. The 15 panels used during this on site research were obtained from seven structures located within the towns of Foligno and Sellano. However, this paper presents only the results of the tests carried out on a series of strengthened panels of identical texture, materials and mortar type. The results of some virgin panels are reported with the only purpose to quantitatively evaluate the effectiveness of the interventions by means of comparison. The reader can refer to another study for the part regarding the investigation of the mechanical behavior of the masonry [1].

2. Traditional strengthening techniques

In the area of reinforcing techniques most widely used nowadays, the injection of hydraulic grouts has often been considered the remedy in most cases of damaged masonry. The technique basically consists of filling the voids and/or cracks inside the wall by...
injecting of new mortar, in order to restore its continuity. The injection, therefore, permits the homogenization of the masonry behavior by saturating the cavities.

This procedure can be theoretically utilized as a technique of seismic-upgrading as well as to increase the strength under the action of static loads (vertical and horizontal). In both cases it can be also carried out to repair masonry walls already damaged.

Injection of grouts, which represents the most frequent use in present building practice, must be preceded by an evaluation of the effective possibility for the injected hydraulic grout to be distributed inside the masonry in an adequate way. Therefore the choice of the grout according to the typology of the wall texture, assumes particular importance since it can determine whether or not the reinforcing is effective. Three-leaf masonry walls are doubtlessly more suitable compared to double-leaf masonry walls consisting of large square blocks [2]. Several authors have analyzed the use of this technique [3] and the criteria for the optimal choice of grouts [4].

The experimental research was carried out using lime-based grouts, which are more compatible with the original masonry and mortar. The mechanical characteristic values of these grouts, given by the producer, are shown in Table 1.

### 3. The use of FRP materials as a strengthening technique

The use of these materials in structural strengthening is an innovative technique, which, although it is already of widespread application today, still needs further experimental analysis. CFRP and GFRP (Carbon and Glass Fiber Reinforced Polymers) materials are composites of continuous phase, defined matrix, often made of a bi-component epoxy resin. This encloses a discontinuous phase material, which demonstrate elevated mechanical tensile characteristics.

Research in this field was originally carried out in US and Japan, where the first applications on new structures were performed in the 1990s on concrete structures [5,6]. The recent seismic events which struck Umbria and Marche in 1997–1998 have led building designers to anticipate the use of these materials on existing historic masonry structures, due to the remarkable lightness, non-invasiveness, and reversibility which characterize this method of intervention.

The damage caused by the earthquake highlighted the fact that even correctly assembled masonry work, which is essentially effective to vertical static loads presents, however, some inadequacies due to its almost total lack of strength to tensile stresses due to seismic actions. The aim of the experimental work was to verify the effectiveness of the masonry-FRP system, in which, briefly stated the composite has the job of absorbing the tension stresses caused by the earthquake.

Most of the research found in the bibliography refers to laboratory tests in which we endeavored to represent and reproduce masonry, following traditional building techniques. The uncertainties due to the substantially different types of mortar used today as well as the difficulty in exactly duplicating construction techniques, with an exception perhaps for the brick-masonry, involved limitations on possibility of utilizing the results obtained.

Tables 2 and 3 list the characteristic values, given by the producer, for the epoxy resins and fibers used during the experimental research.

### 4. Experimental

The walls were tested under compression, diagonal compression and shear-compression. These involved the use of panels of various dimensions.

#### 4.1. Compression tests

The compression tests were carried out on panels of 180×90 cm dimension, with maximum section thickness of 65 cm. Since these tests are designed to find the

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**Table 1**

<table>
<thead>
<tr>
<th>Components</th>
<th>Lime based hydraulic grout, kaolin calcined at low temperature, carbonates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granulometry of the components (μm)</td>
<td>60</td>
</tr>
<tr>
<td>Compression strength (28 days) (MPa)</td>
<td>8</td>
</tr>
<tr>
<td>Injection pressure (atm)</td>
<td>1</td>
</tr>
<tr>
<td>Built density (kgf/dm³)</td>
<td>1.75</td>
</tr>
<tr>
<td>H₂O/cement weight ratio</td>
<td>0.45</td>
</tr>
</tbody>
</table>

**Table 2**

<table>
<thead>
<tr>
<th></th>
<th>Carbon Fiber</th>
<th>E Glass Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superficial density (Kg m⁻²)</td>
<td>0.300</td>
<td>0.300</td>
</tr>
<tr>
<td>Equivalent width (mm)</td>
<td>0.165</td>
<td>0.118</td>
</tr>
<tr>
<td>Tensile Strength (MPa)</td>
<td>3430</td>
<td>1550</td>
</tr>
<tr>
<td>Tensile Young’s modulus (MPa)</td>
<td>23 0000</td>
<td>75000</td>
</tr>
<tr>
<td>Elongation at failure, ε, (%)</td>
<td>1.5</td>
<td>2.1</td>
</tr>
</tbody>
</table>
stiffness characteristics (Young’s Modulus for masonry) they are non-destructive experiments even though the stresses applied, though limited, caused a non-linear reaction with small residues at unloading. As a consequence it was successively possible to subject the same panels to shear-compression tests.

The panels were instrumented with eight inductive transducers for the compression tests. Three were positioned vertically and one horizontally at the centerline on each of the two sides. Once the panel had been obtained by means of the diamond wire technique, it was separated from the remaining masonry except for the lower horizontal edge; this part remained connected to the rest of the masonry. Two steel plates on which two hydraulic jacks were interposed in parallel allowed to subject the panel to uniformly distributed compressive stress. The first plate was placed under the two jacks and rested directly on the panels on a bed of mortar. The second plate was instead positioned above the two jacks and rigidly connected to the base of the panel by means of twelve ties made of steel rods anchored to two metallic elements, creating a closed system in which the elongation of the jacks was contrasted by a system of rods and plates (Fig. 1).

The parameters registered, in addition to the movements of the eight transducers, were the time and the oil pressure of the two jacks. The test consisted in three cycles of loading and unloading of increasing maximum values, in order to subject the masonry to a compression stress with maximum values respectively of 0.1, 0.2 and 0.3 MPa.

4.2. Diagonal compression tests

The diagonal compression test was carried out on panel’s 120×120 cm (according to ASTM specifications [10]) with cross-sections of varying thickness, depending on the structure on which the intervention was carried out. The aim of this test is to determine the shear-strength \( \tau_k \) and the shear elastic modulus of the masonry \( G \). The panel was isolated from the rest of the masonry by means of the diamond wire cutting technique in order to leave it undisturbed.

The test mechanism is composed of a set of metallic elements joined together to obtain a closed system. The stress is 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, is positioned between two metallic elements which permit it, on the one hand, to act directly on an edge of the panel, while at the same time resulting rigidly connected to an analogous metal element located along the opposite edge. In correspondence to this edge the situation is analogous, except for the absence of the jack: the two most external metal elements are 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 (Figs. 2 and 3). 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

Table 3
Mechanical properties of used epoxy resins

<table>
<thead>
<tr>
<th></th>
<th>Primer</th>
<th>Saturant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength (ASTM D638) (Mpa)</td>
<td>&gt;12</td>
<td>&gt;50</td>
</tr>
<tr>
<td>Tensile Strength from bending test (ASTM D790) (MPa)</td>
<td>&gt;24</td>
<td>&gt;120</td>
</tr>
<tr>
<td>Compression Strength (ASTM D695) (MPa)</td>
<td>–</td>
<td>&gt;80</td>
</tr>
<tr>
<td>Tensile strain (ASTM D638) (%)</td>
<td>3.0</td>
<td>2.5</td>
</tr>
<tr>
<td>Flexural Young’s modulus (ASTM D790) (MPa)</td>
<td>&gt;580</td>
<td>&gt;3500</td>
</tr>
<tr>
<td>Tensile Young’s modulus (ASTM D638) (MPa)</td>
<td>&gt;700</td>
<td>&gt;3000</td>
</tr>
</tbody>
</table>
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.

4.3. Shear-compression tests

The shear-compression test successively carried out on the same panels used for the compression tests caused the re-positioning of the transducers, now 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. An additional three transducers were positioned on each side to measure transversal movements, along the centerline, 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 (Fig. 4). 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 in a monotonic loading up to the point of failure, under a state of constant compression for the duration of the test.

The horizontal shear force was applied by two steel rods, which act on a special metal element positioned at the centerline 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. A hydraulic jack is interposed between an I shape, used as a contrast element, and another metallic element similar to that at the centerline of the panel. On one side the hydraulic jack loads the I shape while, on the other side, it loads the metallic element, to which two steel rods are connected (Fig. 5).
The compression stress was applied as in the case of Section 4.1 up to a vertical stress of 0.3 MPa using two hydraulic jacks positioned above the panel.

The panel was loaded at the top by means of a couple of 100 kN hydraulic jacks positioned laterally, to avoid flexural failure mechanisms. This couple of jacks 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 part of the panel is prevented from translating or rotating. This condition is satisfied by the presence of the 4 jacks (2 positioned laterally and 2 positioned above). Nevertheless, the stiffness of the apparatus at the top of the panel and of the vertical rods is not enough to be a perfect constraint. This caused a differing distribution of shear load between the upper and lower halves of the panel, which was taken into account during the elaboration of the data. Two different static schemes were used in the elaboration of the data (Fig. 6).

In addition to the displacements of the sixteen inductive transducers, measurements were also acquired of the time and of the pressure in the 5 jacks, for a total of twenty-one channels of acquisition.

5. Evaluation of the results

Nine, of the eleven panels, were double-leaf masonry walls, made of roughly cut stone, weakly connected, while two were of solid bricks (Figs. 7 and 8). 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 of construction: those from Ponte Postignano (built in the 1950s) are good lime-based mortars, while those from Soglio (19th Century) are very poor.

For the diagonal compression tests the interpretative models of structural behavior are the classic ones \(^9\times\), while for the shear-compression tests Sheppard’s model \(^{11}\times\) is used, taking into account hypothesis and interpretative choices as in [1].

Strengthening with one sheet of CFRP or GFRP was carried out on both sides of the panel, following the schemes presented in Figs. 9 and 10.
The grout was injected at a pressure of 1 atm. after drilling approximately 10 holes per m² on both sides of the panel. However, the injection of the material was carried out using only a small number of the holes (15–20% of the total number of holes drilled on both sides), always injecting from the same side. The remaining holes were only made to control the effective distribution of the grout inside the panel.

The panels are identified by a four index code, in which the first indicates the location of the structure where the panels were obtained (B=Belfiore, V=Vescia, G=Soglio, P=Ponte Postignano); the second, the type of test (D=diagonal compression, T=shear-compression, C=compression), the third gives the identification number of the panel, while the fourth index indicates the type of intervention carried out (FC=strengthening with carbon fiber; FV=strengthening with fiber glass; IN=strengthening using injection; SI=deep repointing of mortar joints and grout injection; OR=unstrengthening panel.

5.1. The Vescia and Belfiore buildings

The first two buildings, located in Vescia and in Belfiore, are both schools, built at the beginning of the last century using substantially similar materials and techniques. In both cases, the average thickness of the masonry turned out to be approximately 48 cm. The material used was a roughly cut calcareous stone and brick. Two rows of solid brick were interposed at intervals of approximately one meter (Fig. 7b). Two larger-sized panels (approx. 180×90 cm) for the shear-compression test and two (120×120 cm) for the diagonal compression test were obtained at the school of Belfiore. The two panels tested under diagonal compression were situated at the upper floor of the school and consisted of a different masonry texture, made only of solid brick (dimension of brick 30×15×6.5 cm) (Fig. 7a and Fig. 8). Two 180×90 cm panels, one strengthened using GFRP sheets and the other via injection, were obtained at the school of Vescia.

Of the four panels obtained for the shear-compression test, the first was tested without strengthening, to determine its mechanical characteristics. The remaining three were consolidated respectively with CFRP, GFRP and by means of injection.

Due to the great irregularity in the masonry texture, strengthening of the panels was carried out only after spreading a layer of cement based mortar (thickness 4–8 mm) to create a sufficiently plane, uniform surface on which the composite was applied. The mortar used was placed directly on the masonry once the original rendering had been removed.

The panels strengthened with fibers (Table 4 and Fig. 11) show an increase in strength $\tau_k$ compared to the unstrengthened panels, of approximately 55%, independent of the type of fiber used. This essentially depends on the particular type of failure, which did not involve the failure of the composite material. In fact, the fiber remained attached to the cement-based mortar, which in turn had detached from the masonry. For this reason the use of carbon fibers or fiberglass resulted in limited differences of shear strength $\tau_k$.

However, in the successive diagonal compression tests...
Table 4
Results of the shear compression tests

<table>
<thead>
<tr>
<th>Index Code</th>
<th>Strengthening technique</th>
<th>Texture</th>
<th>Section (cm)</th>
<th>$H_{max}$ (kN)</th>
<th>$\tau_{max}$ (MPa)</th>
<th>$G$ (MPa)</th>
<th>$G$ (MPa)</th>
<th>$\tau_k$ (MPa)</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>0.224</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>V-T-07-IN</td>
<td>Injection</td>
<td>Double-leaf roughly cut stone masonry</td>
<td>48</td>
<td>161.30</td>
<td>0.237</td>
<td>450</td>
<td>308</td>
<td>0.149</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>203</td>
<td>0.136</td>
</tr>
<tr>
<td>P-T-15-IN</td>
<td>Panel repaired by injection</td>
<td>Double-leaf roughly cut stone masonry</td>
<td>48</td>
<td>266.30</td>
<td>0.465</td>
<td>645</td>
<td>598</td>
<td>0.375</td>
</tr>
</tbody>
</table>

the layer of cement based mortar was replaced by a thinner layer (2–4 mm) of epoxy putty which bonded more efficiently with the masonry substrate and determined a better utilization of the fibers, which did not detach until failure of the panel was reached.

The injected panel did not cause an appreciable increase in terms of shear strength $\tau_k$ compared to an unstrengthened similar panel. This shows the inefficiency of this strengthening method for the particular masonry texture to which it had been applied.

Of the two panels subjected to diagonal compression tests, the first was strengthened with carbon fiber, while the second was left unstrengthened. The masonry, made of solid bricks, gave a failure stress notably low for the unstrengthened panel equal to 0.069 MPa. The panel strengthened with carbon fiber instead, due to the effect of confinement the fibers caused on the masonry and due to the particular brick texture, demonstrated to be very resistant, with a failure stress of 0.373 MPa. At the failure load, the masonry fractured in compression, causing the expulsion of small portions of bricks from the panel, while the composite material (CFRP) remained attached to the panel.

5.2. The Soglio building

The second intervention was carried out on a structure found in Soglio. This was an isolated 19th century stone farmhouse, built with prevalently small stones, and a poor lime-based mortar. The texture was made of double-leaf roughly cut stone masonry. Two equal-sized diagonal panels were obtained at this structure, one of which was initially tested without any type of prior strengthening, subsequently repaired by injection and re-tested; the second panel was instead strengthened with sheets of carbon fiber, following the pattern previously indicated.

The failure stress of the injected panel resulted much higher than that of the unstrengthened panel, with increases of approximately 145%, highlighting the effi-
Fig. 12. The panel located in Ponte Postignano strengthened with carbon fibers.

Efficiency of this technique of intervention in repairing, while the shear stiffness \( G_{1/3} \) demonstrated an extremely high increase, from 26 to 685 MPa. The panel strengthened with carbon fibers showed instead a 140% increase in strength and a 110% increase in shear stiffness. The failure of the panel strengthened with carbon fiber resulted from the separation of the two masonry leaf walls.

5.3. The Ponte Postignano building

A third series of panels were obtained at a structure built in the 1950s in Ponte Postignano. The masonry texture of this building slightly differs from that of the other structures. The walls, again composed of double leaf roughly cut masonry walls, were built with calcareous stones and sponge travertine, while the original mortar had a good lime base (Fig. 7d).

Three panels were cut: two \((120 \times 120 \text{ cm})\) for diagonal compression tests, and the third \((180 \times 90 \text{ cm})\) for a shear-compression test. The thickness of the panels was 48 cm. As had been done at the building in Soglio, three tests were carried out on the two panels subjected to diagonal compression: one on an unstrengthened panel, one an undamaged panel strengthened with CFRP (Fig. 12) and one on a panel repaired by injection and deep repointing of joints.

The 180 \(\times 90\) cm panel subjected to shear compression test was initially tested without any type of prior strengthening, subsequently repaired by injection (Fig. 13) and re-tested.

The results obtained show significant increases in strength and shear stiffness (see Tables 4 and 5). The results of diagonal compression tests are very similar to those obtained in Soglio. Although the panels from these two buildings differ in the size of the cross-sections (48 cm at Ponte Postignano and 57 cm at Soglio), in texture and in constituting material, they demonstrated similar increases. The increase in strength, slightly greater for the panel strengthened with fibers, was of the order of 190%. The failure of the panel strengthened with CFRP

### Table 5

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>Angular strain ( \gamma_{1/3} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-D-02-OR</td>
<td>None</td>
<td>Single-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>Single-leaf solid brick masonry</td>
<td>48</td>
<td>188.25</td>
<td>0.373</td>
<td>100</td>
<td>1.240</td>
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<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-11-IN</td>
<td>Panel repaired by injection</td>
<td>Double-leaf roughly cut stone masonry</td>
<td>57</td>
<td>124.85</td>
<td>0.129</td>
<td>685</td>
<td>0.061</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-13-SI</td>
<td>Panel repaired by injection and deep repointing</td>
<td>Double-leaf roughly cut stone masonry</td>
<td>48</td>
<td>127.71</td>
<td>0.157</td>
<td>731</td>
<td>0.070</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>
resulted again from the separation of the two masonry leaf walls.

5.4. Evaluation of the stiffness

For the Young's modulus of the masonry, measured on five panels $180 \times 90$ cm for each of three cycles of compression loading and unloading, the results obtained showed that an increase varying from 200 to 280% was measured in the case of carbon fiber (Fig. 14; Table 6). The strengthening via injection gave similar increases in strength, highlighting however a low increase in the modulus of elasticity for the Vescia panel, while very high increases were obtained at Ponte Postignano on a panel repaired using this technique and then re-tested (Fig. 15).

The results for the shear elastic modulus $G_{1/3}$, measured following ASTM specifications at $1/3$ maximum load, were between 26–131 MPa for unstrengthened panels subjected to diagonal compression tests, while they exceeded 731 MPa in the case of strengthened panels.

It is significant to note that the injection technique, when applied to suitable masonry, causes a strong increase in shear stiffness. Panels repaired with this technique and re-tested showed increases with minimum values 20 times superior to those obtained on the same panels previously tested before strengthening. This important aspect should be further analyzed, considering its effects on the stiffness redistribution among the various walls stressed by seismic action.

The shear-compression test on the injected panel at the Vescia structure gave a shear elastic modulus $G_{1/3}$ measurement similar to that obtained from the test on an unstrengthened panel. In this type of masonry, the strengthening of a panel by injection did not give significant results either in strength or stiffness increases, highlighting the importance of a correct preliminary analysis of the masonry texture.

Compared to the results obtained using injection techniques, strengthening by means of fibers in composites does not result in very high increases in the shear elastic modulus $G_{1/3}$; panels for diagonal compression tests showed an increased stiffness of approximately...
The composite does not modify the static scheme of the structure nor does it cause major redistribution of stiffness, but mainly shows up as an increase in the shear strength of the masonry.

Comparisons in the behavior of panels subjected to diagonal compression tests are shown on a $\tau-\gamma$ graph in Fig. 16. A significant increase in stiffness can be seen for the panels repaired by means of injection.

In contrast to the other panels, the panel marked P-D-13-SI was not only injected but also underwent a deep repointing of joints with a cement lime mortar. After removing the original mortar for a deep of 6–7 cm, the joints were reintegrated with the same mortar used for injections. This further strengthening described in detail in [12] causes an increase of 167% in terms of strength and one 19 times greater for the shear elastic modulus $G_{1/3}$, compared to the unstrengthened panel.

6. Conclusions

The strengthening of masonry structural elements through traditional or innovative techniques presents numerous interesting aspects and the results of the experiments carried out, although varying according to the test performed, have highlighted their limitations as well as their advantages.
The results obtained for the diagonal compression tests carried out on panels repaired by means of injection showed significant high increases both in terms of shear strength and stiffness. However, it must be pointed out that the presence of cracks (these cracks were caused by the initially tests on the same unstrengthened panels) facilitated the distribution of the injected grout within the panels.

At the Vescia building, the injection technique was applied on an undamaged panel used for the shear compression test. In this case a comparison of the strength values measured for the injected panel and a similar unstrengthened one showed much smaller increases in strength and stiffness. This result substantially showed that while the injection technique can be effective when used as a repair technique, its adoption on undamaged structures needs a previous and careful analysis of the texture and characteristics, in order to understand if the grout can be properly distributed within the masonry.

With regard to the strengthening with sheets of monodirectional carbon or glass fiber, the first shear compression tests carried out on panels at Vescia and Belfiore have highlighted the fact that the adhesion between the panel and the concrete-based mortar used as a base for the fibers was the weakest element in the system. The failure resulted from the separation of the layer of cement-based mortar and fiber from the panel. 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 caused high increases in shear strength. The failure resulted, in the case of stone panels, from a separation of the two masonry leaves, while in the case of the panel in brick it resulted from crushing of the bricks with 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 this particular type of failure due to the separation of masonry leaf walls can be avoided.

Investigation is being carried out on the influence of the size of the strengthening mesh and on the long-term behavior of the adhesion. These aspects will be the object of further experimentation, now in the planning stage.

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