Experimental analysis and modelling of masonry vaults strengthened by FRP

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ABSTRACT: A comprehensive study on the behavior of brick masonry vaults strengthened by FRP laminates is here presented. The influence of the type of fibers (Carbon, Glass) and their position (intrados or extrados) are investigated by experimental tests on laboratory samples. The obtained results allowed to clarify the failure mechanisms modified by the presence of the reinforcement and to define and calibrate the related analytical models.

1 INTRODUCTION

Arches and vaults are very common in the European historical buildings and their conservation and preservation as cultural heritage represents a very topical subject. Beside traditional repair techniques, the use of FRP (Fiber Reinforced Polymer) materials is more and more considered all over the world in large scale to upgrade existing masonry structures and provide a proper safety level, especially when antisymmetric loads are applied (Schwegler 1995).

Several kinds of fibers (carbon, glass, etc.) are nowadays available in different products (bars, strips) for varied uses and applications on structures. The advantages in using such products are several: very low weight, corrosion immunity, high tensile strength and low thermal expansion coefficient. On the contrary, their up-to-failure linear elastic behaviour does not allow to base the ductility of the system on the plastic behaviour of the strengthening material itself. However, the possibility of binding or wrapping structural elements made of brittle materials (like masonry) allows, in most cases, to avoid the collapse of the structure and so assure the pursued safety conditions. Moreover, despite their still high cost, the somewhat easiness of execution of the intervention, even in difficult operative conditions, allows a wide range of possible applications in several situations of damage. Anyway, despite their diffusion, specific models and design recommendations for masonry structures, both at local and global levels, are not available yet and some aspects of their behaviour still need to be deeply investigated.

To clarify the behavior of brick masonry vaults strengthened by FRP laminates, an experimental research has been recently completed at the University of Padua. Six samples have been tested under monotonic vertical loads applied to ¼ of their span. Such condition is the most severe case of loading for an arch, and can be considered to simulate particular situations of the vaults (e.g. library, bridges, etc.) or the effects of seismic loads. The aims of the study are: (i) to compare the behavior up to the ultimate conditions of vaults strengthened by different types of fibers (carbon - CFRP and glass -GFRP), having different strip widths (total predicted strength contribution being equal) and by placing the reinforcement in different positions (intrados or extrados); (ii) to formulate analytical models able to predict the ultimate strength in agreement with the observed failure mechanisms.

In the paper, the main experimental results are described and discussed. Moreover, the reliability of the proposed analytical model is examined on the light of the experimental evidence and of the similar proposals available in literature. Finally, some suggestions about the application of FRP laminates in real cases are discussed.

2 BEHAVIOR OF THE STRENGTHENED VAULTS

The application of FRP strips modifies the static behavior of an arch because the fibers can bear the stresses occurring at the tensed edges. Therefore, the brittle failure of such structures, typically caused by the formation of four hinges (Heyman 1982) (s. Fig. 1), can be avoided. Depending on the position of the laminate, in fact, the formation of the forth hinge can be prevented: referring to Fig. 2, the hinge formation in the B and in the A position are inhibited in the case of the extrados (a) and the intrados (b) strengthening respectively.

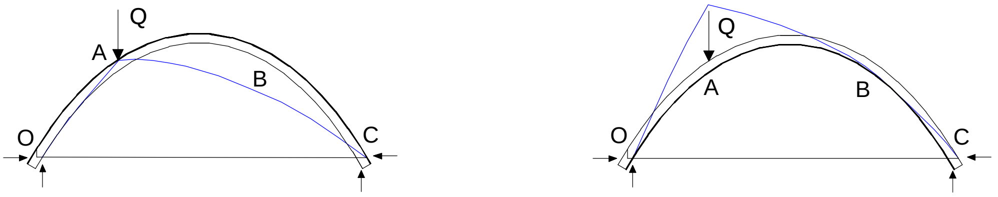
As a consequence, the collapse of the structure is due to other mechanisms, which are involving the limits of strength of the constituent materials (original masonry and reinforcement) and the structural interactions of them at the local level. Thus, in the strengthened structures, depending on the position and of the amount of the reinforcement, the modified collapse mechanisms are: (i) the masonry crushing, (ii) the detachment of the fibers, and (iii) the sliding along a mortar joint due to the shear stresses.

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 to detect the maximum resistant moment related to the crushing mechanism. The other two models are based on the local interaction among the constituent materials, and the relative parameters are given by simple mechanical tests.

The analytical models able to clarify the contribution of the abovementioned mechanisms are schematized in Fig. 3.

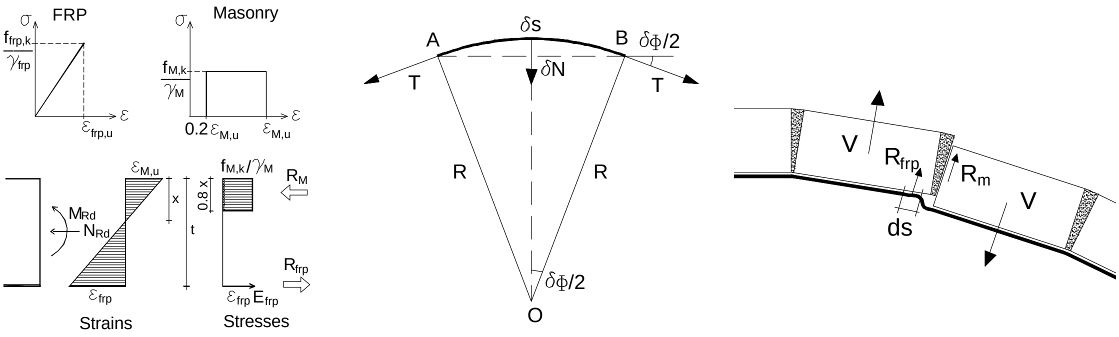
(a) (b)

Figure 1 : Behaviour of a plain arch: line of thrust (a) and collapse mechanism (b).



(a) (b)

Figure 2 : Behaviour of a strengthened arch: line of thrust for a for extrados (a) and intrados (b) strengthening.



(a) (b) (c)

Figure 3 : Analytical model schemes proposed for the failure mechanisms of the strengthened vaults: (a) masonry crushing, (b) detachment of the fibers, (c) shear sliding along a mortar joint.

As for the masonry crushing, the resistance of the strengthened sections (which are in combined compressive and bending stresses), likewise to reinforced concrete structures, depends on the masonry compression strength and on the fiber tensile strength (s. Fig. 3.a). Assuming a linear elastic behavior for the reinforcement and a rectangular stress-block law for the masonry (Triantafillou 1998a, 1998b), the design formulation is given by equations (1). Symbols are as follows: M_{Rd} and N_{Rd} are the design bending moment and the design axial load acting in the section of the vault ($g_M = 2.5$ is the partial safety factor for the masonry), x is the neutral axis depth, t and l are the height and the width of the section respectively, w is the FRP normalized area fraction, A_{frp} is the FRP cross sectional area, E_{frp} is the Young's modulus of the fibers, $e_{frp,u}$ and $e_{M,u}$ are the ultimate tensile and compressive strains for the fibers and the masonry respectively, and $f_{M,k}$ is the compressive strength of the masonry.

$$\begin{cases} \dfrac{M_{Rd}}{l t^2 f_{M,k}} = \dfrac{1}{2} w \dfrac{\left(1 - \dfrac{x}{t}\right)}{\dfrac{x}{t}} + \dfrac{0.4}{g_M} \dfrac{x}{t}\left(1 - 0.8\dfrac{x}{t}\right) \\ \dfrac{x}{t} = \dfrac{g_M}{1.6}\left[\dfrac{N_{Rd}}{l\,t\,f_{M,k}} - w + \sqrt{\left(w - \dfrac{N_{Rd}}{l\,t\,f_{M,k}}\right)^2 + \dfrac{3.2}{g_M} w}\right] \end{cases} \tag{1}$$

where $w = \dfrac{e_{M,u} E_{frp}}{f_{M,k}} \dfrac{A_{frp}}{lt}$.

The detachment of the reinforcement from the support is caused by the presence of a component perpendicular to the directrix of the curve of the tensed fibers, which is responsible for an action that can be definable like a "tear" (Fig. 3b). If the arch equation and the tensile stress T (assumed constant) of the fiber are known, the component dN normal to the segment AB (having length ds and radius of curvature R) which is responsible for the phenomenon, is given by eq. (2).

$$\frac{dN}{ds} = \frac{T}{R} \tag{2}$$

Finally, for the sliding along a mortar joint, it is supposed that the sliding resistance is caused by two main components, as shown in Fig. 3c and eq. (3): R_M is due to the masonry and R_{frp} to the FRP laminate. As for the masonry contribution, a friction model following the Coulomb law is hypothesized, whereas a dowel action effect can be considered for the reinforcement.

$$R_{tot} = V = R_M + R_{frp} \tag{3}$$

Such models have demonstrated a good agreement with the results obtained from the experimental tests on the vaults, as described in the following.

3 EXPERIMENTAL STUDY

The experimental program comprises a series of preliminary tests for the mechanical characterization of the constitutive materials of the vaults (brick, mortar, fibers) and the masonry (compressive tests).

To investigate the mechanisms of local interaction among the constituent materials, adhesion and pull-off tests were performed. Those tests can give information about the bond strength between the masonry and the fibers, in order to define the parameters useful for the models application. To clarify the sliding mechanisms a series of triplets and dowel action tests have been planned. Moreover, flexural tests on reinforced plane panels allowed the preliminary validation of the crushing mechanism of the masonry.

Finally, full scale masonry vaults built by bricks arranged in a single skin, strengthened at their intrados or extrados by carbon or glass laminates, were tested under concentrated vertical loads.

3.1 Characterization of the materials and their interaction

Solid clay bricks (25x12x5.5 cm) and a precasted cement-based mortar (ratio sand/binder = 2.5/1 in volume) were used for the construction of the vaults and the specimens for the local tests. The bricks reached a compressive stress equal to 8.60 MPa, whereas flexural and compressive tests on mortar prisms after 28 days of curing gave 0.36 MPa e 6.03 MPa respectively.

Uniaxial compressive tests carried out on plane panels (around 55x55x12 cm) gave a mean strength of 6.00 MPa and a modulus of elasticity of 950 MPa. Similar tests conducted on plane panels but built with the bricks placed on sheet (around 40x40x5.5 cm), that is with the same thickness of the vaults, showed roughly the same value of the modulus of elasticity and a lower compressive strength (around 4 MPa) and ultimate strain. Such comparison allowed to evaluate the influence of the brick anisotropy and of the different confinement of the mortar on the strength and the deformation of the masonry.

Table 1 resumes some geometrical, physical and mechanical characteristics of the carbon and the glass fibers used as strengthening material. It can be noted that the two fibers have different strength and stiffness, so their contribution on the strengthening of the vaults has been balanced by a different width of the laminate (in particular, 20 cm for the GFRP and 7 cm for the CFRP have been adopted). As for the adhesion system, epoxy resins in different layers were applied under and above the laminate, with particular attention in making uniform the surface of the substrate of application.

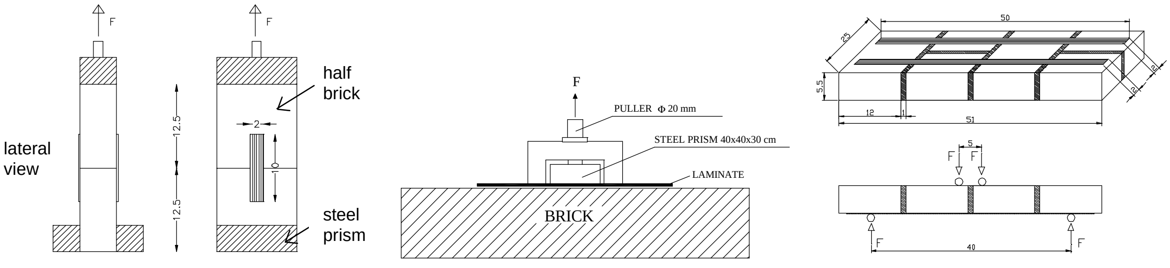
Table 1 : Properties of the laminates.

Property	FRP Type	
	Carbon (C1-30)	Glass (G-73R)
Tensile Strength (MPa)	3430	1700
Elastic Modulus (GPa)	230	65
Density (kg/m3)	1820	2600
Thickness (mm)	0.165	0.161
Ultimate Strain (%)	1.50	2.80

In order to characterize the collaboration between the masonry and the fibers a series of strengthened specimens of small dimensions were tested. In particular, adhesion and flexural tests on samples strengthened by CFRP strips were performed.

The adhesion properties were investigated both for loads parallel and perpendicular (pull-off tests) to the fibers (s. Fig. 4ab), on six samples each. As for the tension parallel to the fibers, the failure of the bricks was detected (mean value of 2.5 MPa); this indicated that the limit of the adhesion strength due to shear stresses has not been reached at the interface between fibers and bricks. As for the “pull-off” tests, in all the specimens the detachment of a portion of the glued surface of the brick was observed (peeling). Therefore, the obtained value (0.44 MPa, somewhat low) is not the bond strength between fibers and masonry under normal stresses but it corresponds to the masonry tensile strength under perpendicular tension.

The flexural tests (Fig. 4.c) were performed on four single skin masonry panels strengthened at one side by CFRP or GFRP. In all cases the collapse occurred due to the crushing of the masonry at the upper edge close to the mid-span of the specimen, so the experimental validation of the related model was possible. In such connection, the model gave a maximum flexural moment equal to 600 Nm and 940 Nm for the CFRP and the GFRP respectively, whereas the experimental tests gave mean values equal to 660 Nm and 870 Nm respectively. Therefore, a good agreement between the theoretical and the experimental maximum moment was found.



(a) (b) (c)

Figure 4 : Local behavior investigations: adhesion parallel (a) and perpendicular (b) to the fibers, and flexural tests (c).

3.2 Tests on the strengthened vaults

A series of six strengthened samples of vaults built by bricks arranged in a single skin (5.5 cm of thickness) have been tested under monotonic vertical loads applied to ¼ of their span. Due to the somewhat thin thickness (5.5 cm), a catenary curve was chosen as directrix of the vaults, with coefficients close to the ones of a depressed arch, in order to improve the stability of the structure under loading.

As already mentioned, two different laminates arrangements (intrados and extrados) and two different types of fibers have been used. In particular, two samples have been strengthened with carbon fibers at the extrados (EX.C.01 and EX.C.02 tests) and two the intrados (IN.C.01 and IN.C.02 tests), whereas glass fibers have been used for the strengthening at the extrados (EX.G.01 and EX.G.02 tests). For each vault two strips of laminate have been applied; in order to have the same strength contribution a width of 7 cm of CFRP and 20 cm of GFRP were cadopted.

Fig. 5 shows the dimensions of the vaults and the load condition, whereas in Fig. 6 a vault ready to be tested and the arrangement of the displacement measure points are given.

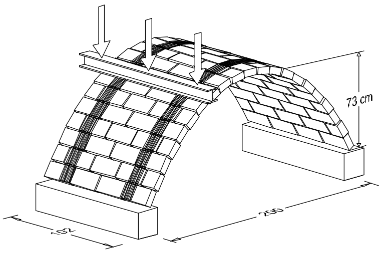


Figure 5 : Dimensions of the samples and scheme of loading.

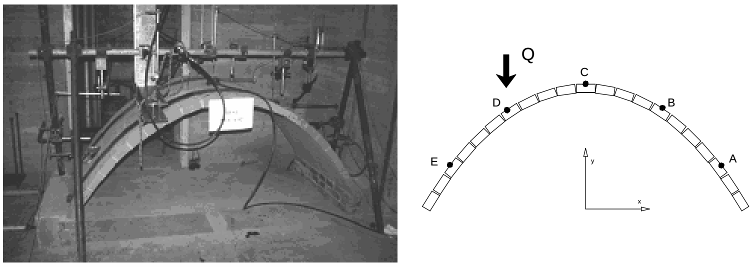


Figure 6 : Experimental set-up and position of the transducers.

The two vaults strengthened at their extrados with glass fibers (EX.G samples) showed very similar results both in terms of the global deformation and of the ultimate carrying load capacity. The ultimate load was 20.25 and 19.70 kN for the EX.C0.01 and 02 samples respectively. In both cases the collapse occurred because of the sliding between brick and mortar in the first joint closest to the springer; such collapse occurred without any warning. An image of the detected failure mechanism is shown in Fig. 7.

The vaults strengthened by carbon fibers at their extrados presented different patterns of collapse, despite having shown a very similar ultimate load capacity (15.30 and 15.40 kN for the EX.C0.01 and 02 samples respectively). In particular, likewise the EX.G. cases, the EX.C.01 sample failed because of the sliding between brick and mortar in the first joint closest to the springer, whereas the vault EX.C.02 showed a notable global deformation (s. Fig. 8a) that not allowed any further increment in load. Due to the confinement effect caused by the limited width of the carbon strips a notable transversal deformation (Fig. 8b) was detected; moreover, lengthwise cracks were observed close to the middle of the structure (Fig. 8cd).

As example, Fig. 9 gives the load vs. displacement diagrams obtained for the EX.C.01 vault (note that the curves represent the behavior of the vaults up to about the 80% of the ultimate load, due to the removing of the instruments from the specimens).

Figure 7 : Shear sliding along a mortar joint: final global deformation and details of the failure in the first joint closest to the springer (EX.C.01 and EX.G samples).

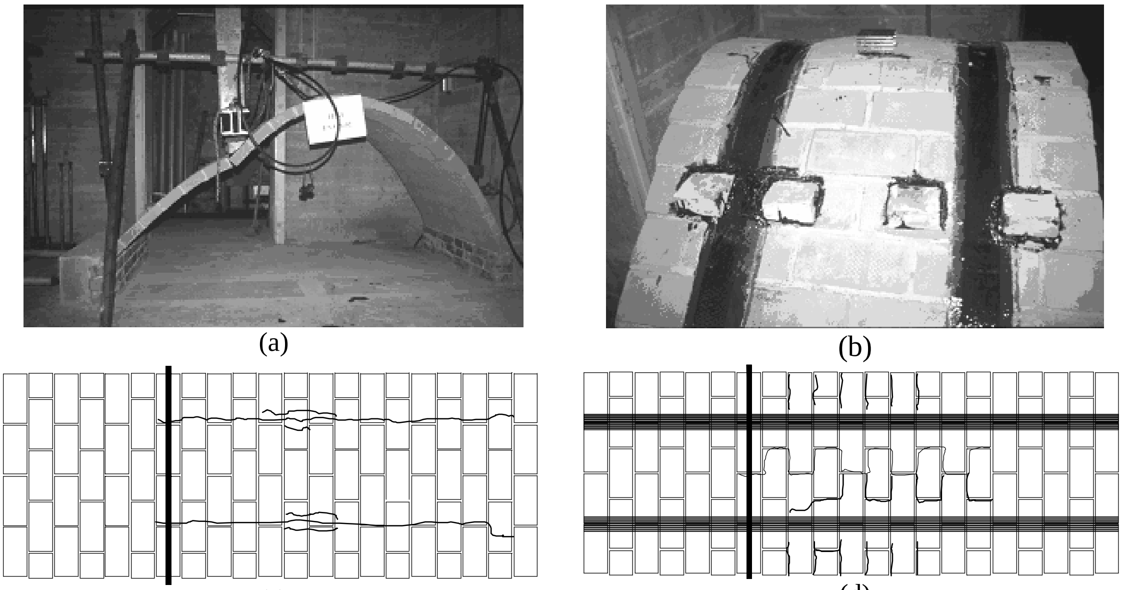
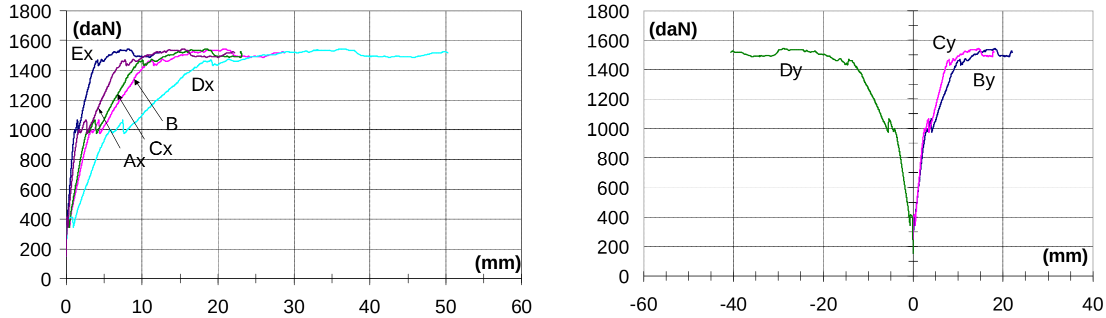


Figure 8 : Details of the EX.C.02 test: final global deformation (a), effect of excessive confinement of the fibers (b) and crack pattern detected at the end of the test at the intradox (c) and the extradox (d).



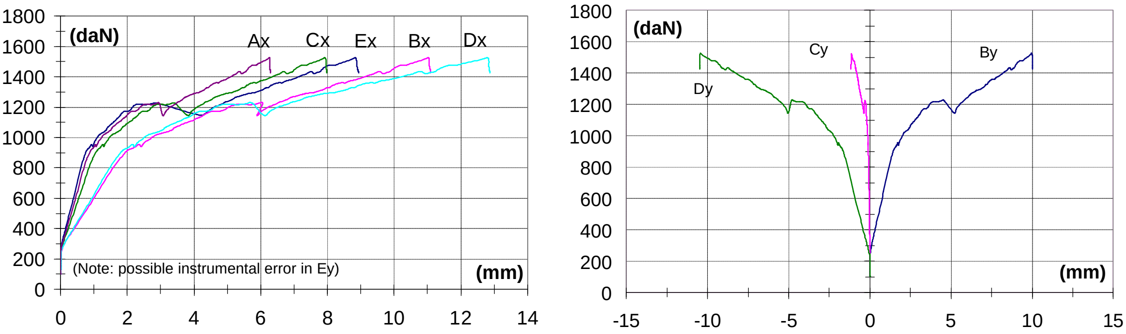
(a) (b)

Figure 9: EX.C.01 test results: horizontal (a) and vertical (b) displacement detected in the measurement points (s. also Fig. 6).

The tests of the two vaults strengthened at their intrados by carbon fibers were in good agreement both in terms of ultimate strength (15.20 and 13.90 kN for the IN.C.01 and 02 tests respectively) and deformations. In both cases the failure occurred due to the detachment of the fibers from the masonry in proximity to the point of application of the load (s. Fig. 10). In such case the failure was not brittle because the fibers contributed in holding the bricks together during the last phase. Fig. 11 gives the load vs. displacement diagrams obtained for the IN.C.01 vault.

(a) (b)

Figure 10 : Detachment of the fibers: final phase of loading (a) and detail of the mechanism of failure (b) (IN.C tests).



(a) (b)

Figure 11: IN.C.01 test results: horizontal (a) and vertical (b) displacement detected in the measurement points (s. also Fig. 6).

4 ANALYSIS OF THE RESULTS

The analysis of the experimental results and the application of the collapse mechanisms models allowed to point out some particular aspects of the behavior of the strengthened vaults and to propose some suggestions about the application of FRP laminates in real cases.

The comparison between the trends of the vertical displacements measured under the point directly loaded for the extrados and the intrados cases is shown in Fig. 12; it concerns the recorded behavior up to about 80% of the ultimate load (when measure instruments have been removed from the specimens).

As regards the ultimate loading capacity, the results obtained from the proposed theoretical models and the experimental tests (average values) are compared in Fig. 13. Since the analytical model describing the sliding along a mortar joint has not been made clear yet, the comparison between theoretical and experimental results for all cases is not possible yet. However, to sum up, the reliability of the masonry crushing model has been validated by the flexural tests previously described, whereas the detachment of the fiber ones has revealed a very good agreement in connection with the tests of the vaults (the difference is less then the 2%, s. Fig. 13).

As for the ultimate behavior of the strengthened structures, some important considerations can be drawn. For the vaults strengthened at their extrados, despite different fiber types have been used, the results have shown the masonry sliding as prevalent failure mechanism. Such kind of failure takes place only on the vaults strengthened at the extrados because the weakest point of the structure is the hinge closeness to the springer. The cracked section below the loading section has the same failure potentiality of the above mentioned one, but it has a higher normal stress which consequently increases the shear strength. In the repair phase of real structures, a solution that could avoid such brittle type of failure and, at the same time, optimize the quantity of the applied FRP, could be the increase of the surface of the reinforcement only in proximity of the springers. The application of a larger width of the fibers strips would involve, in fact, a better resistant area able to prevents the sliding. In such context, a higher or lower strength and stiffness of the fibers does not influence the ultimate strength of the structure.

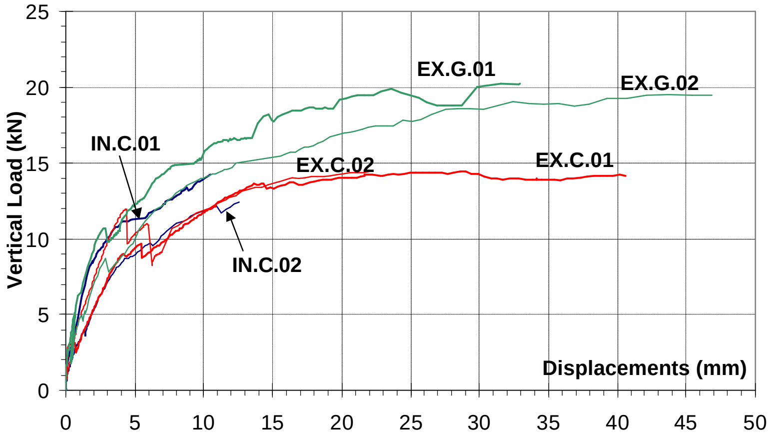
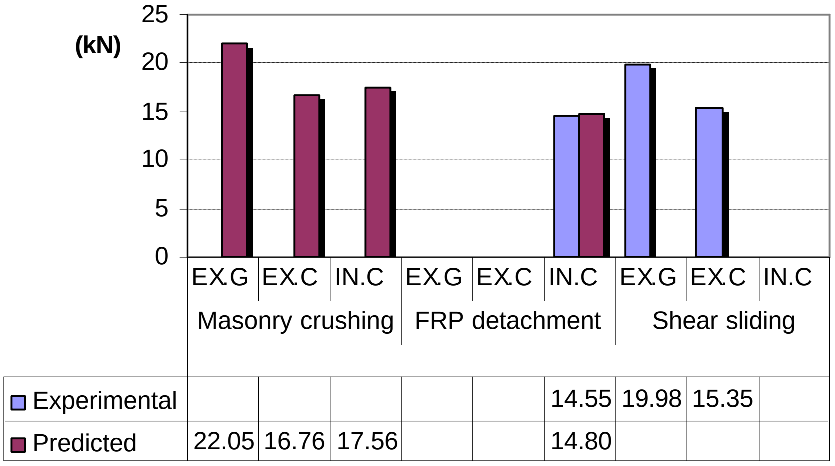


Figure 12 : Load-displacement curves obtained from the experimental tests on the strengthened vaults.



	Masonry crushing			FRP detachment			Shear sliding		
	EX.G	EX.C	IN.C	EX.G	EX.C	IN.C	EX.G	EX.C	IN.C
🟦 Experimental						14.55	19.98	15.35	
🟥 Predicted	22.05	16.76	17.56			14.80			

Figure 13 : Comparison among the experimental results (average values) and the models prediction.

Moreover, it is important to notice that, in the real situations, the presence of a lateral fill (s. Fig. 14) can modify the failure mechanism of the vaults. The fill, in fact, could cause the raising of the point of formation of the plastic hinge without modifying, however, the carrying load capacity of the structure.

Furthermore, it has been observed that the distance between the strips and/or their width can influence the mechanism of failure. In the case of the carbon strengthening, a secondary effect of excessive confinement has been observed, with a consequent “transversal” deformation. The combination of the small width of the strips and of the high modulus of elasticity of the fibers provokes, in fact, an uneven distribution of stresses with concentration in the limited zone located underneath the reinforcement. Such phenomenon contributes to decrease the global resistance. The glass fibers, in fact, despite their lower mechanical characteristics against the carbon ones, have involved a higher increase of strength.

In the cases of application of the fibers at the intrados of the vaults, the detachment of the adhesion system from the masonry in proximity of the loaded section has been detected. The analytical model, able to predict the ultimate load with sufficient accuracy is very simple, and its calibration can be obtained by simple experimental tests. Moreover, since the component perpendicular to the fibers, which is responsible for the failure, is proportional to the tension in the fibers, it should be better to employ fibers not having a high strength and, at the same time, increase the width of the strips.

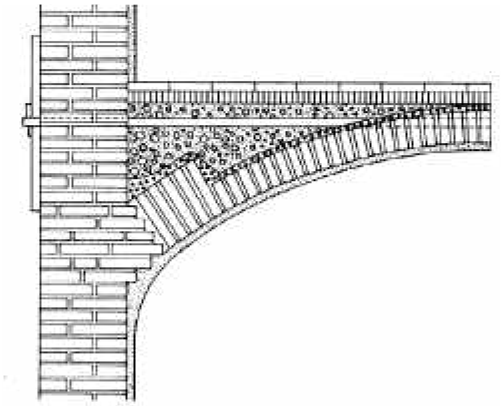


Figure 14 : Example of a vault with fill in a existing masonry building.

5 CONCLUSIONS

As predominant mechanisms, the experimental tests exhibits the detachment of the fibers for the intrados strengthening case, and the mortar to brick sliding for the extrados one. In all cases the obtained results have pointed out the enhancement in strength and ductility of the strengthened vaults, and the influence in the ultimate strength of the width and of the bond length of the strips.

The detachment of the fibers perpendicularly to the masonry interface is located in a limited zone, so the binding action of the strips can still avoid the collapse of the structure. The ultimate strength of such mechanism can be found by a very simple analytical model, based on the results of simple laboratory tests (pull-off of the fibers glued on a brick).

The sliding between mortar and bricks can be prevented by placing a proper amount of fibers distributed in the springers zone. Due to the larger surfaces available for the adhesion, higher values of ultimate strength of the vaults have been detected for the fibers with lower mechanical characteristics. Further experiments will allow to clarify the phenomenon in relation to the materials interaction and to compare the experimental values with the predicted strength.

ACKNOWLEDGEMENTS

The experimental tests were performed at the Laboratory of Material Testing of the Department of Structural and Transportation Engineering of the University of Padua, Italy.
Fiber materials and the adhesion system were supplied by MAC S.p.A. (Treviso, Italy).

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