

Experimental Analysis on Durability of Brick-Masonry Panels Subjected to Cyclic Loads

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Abstract: During the last decades FRP materials have been utilized in many civil engineering applications for their good performances in substituting traditional restoration techniques, especially in reinforcing and restoring damaged structures. At present, the use of composite materials is greatly increasing as a consequence of the fact that conservation and restoration of existing historic heritage are becoming key issues for civil engineers and architects. This paper deals with the behavior of brick masonry models subjected to cyclic loads with the aim of studying their performances and durability. Firstly the models were damaged by imposing a strain history until they reached a fixed damage level, then they were strengthened with carbon fiber strips and tested again following the same experimental procedure. The experimental results show that the strengthened models reached a higher number of cycles and consequently increased their durability and strength with respect to cyclic loads.

keyword: Masonry, Cyclic loads, FRP-Composite materials, Durability.

1 Introduction

The use of FRP materials in civil and structural engineering is increased both for the reduced production cost and for the increased interest toward such new materials from the researchers and from the customers also. The most common FRP-materials applications in civil engineering go from the strengthening of existing reinforced concrete beams or masonry elements, replacing the traditional reinforcement techniques, to the construction of new structures entirely realized with FRP elements, see Modena (1997) and Sacco and Luciano (1998).

While traditional restoration techniques, such as insertion of steel bars in masonry zones subjected to tension, are intrusive and show many disadvantages, like steel bar

corrosion, the recent use of FRP tissue or laminates results very effective with respect both to their easy application and to the structures increase of strength.

Moreover, recently, the editing of new guidelines on the use of FRP materials has been promoted by the Italian researchers, see AA. VV. (2004), to give a useful guide for the design of FRP reinforced structures and to avoid the incorrect use of these new materials in strengthening applications.

However, the use of FRP materials still necessitates research into the long-time effectiveness of the remedial interventions, with reference to chemical-physical and mechanical phenomena, viscous effects and long term chemical compatibility between the FRP materials and existing masonry components.

This work studies both the effectiveness and durability of strengthening and restoring interventions on masonry structures with respect to cyclic loads, see Mazars (1984), in order to estimate the restoration effectiveness threshold and long term structural security conditions.

The experimental results are related to one-brick masonry panels made up of common bricks and mortar joints, endowed with reinforced concrete beams both in the upper and in the lower surfaces, subjected to cyclic loads. Firstly, cyclic load test were performed onto the panels; successively, the cyclic tests were repeated on the damaged elements reinforced by FRP-materials with the aim of estimating the strength improvement and durability deriving from the FRP application.

2 Masonry subjected to cyclic loads

The study of the fatigue behavior of materials or of structural elements is essential to define the life of a structure. The most common way of studying fatigue phenomenon is the analysis of the causes and the evolution of damage in the structure. Such a phenomenon is evident in materials showing no tension behavior, such as masonry, which gives the structure a different stiffness depending on the

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applied load.

The problem of the response of a masonry panel to seismic forces can be experimentally studied by means of two test configurations given schematically in Fig. 1.

In the first one (Fig.1a) the panel is subjected to a distributed vertical load for which the resultant is P , applied at the top of the panel, kept constant and centered on it. Successively a monotonic cyclic displacement is applied to the head of the panel, generating a shear force F , leaving the top surface of it free to rotate. The vertical load and shear force transmission to the masonry panel is realized by means of a rigid cross bar which allows the stress distribution over the wall length.

In the second configuration (Fig. 1b) the superior cross bar rigidly translates without rotating, realizing a double fixed condition, so that the upper and lower compressive resultants have opposite sign eccentricities, increasing with the growth of the shear force F . The second configuration better approximates the real constraint conditions of a masonry panel inside a building.

In both cases, the response of the structure in terms of shear-displacement curves shows two important types of behavior: the first representing failure due to normal stresses (overturn and/or crushing of compressed masonry) and the latter associated to shear mechanisms. Within shear failure mechanisms we can distinguish between a sliding mechanism along horizontal fracture directions (horizontal joints) and a failure mechanism with wide diagonal cracks through the height of the panel. Such diagonal cracks can involve the joints or the bricks depending on the relative strength of joints and bricks respectively and on the level of the applied compressive load. In both cases of overturn or combined compressive and bending stress than shear the response in terms of shear force - displacement curves is strongly non linear and it is mainly due to the section reduction, caused by the negligible tensile strength of mortar beds as well as by a progressive growth of inelastic strains due to shear and compressive loads in the reacting sections.

3 Masonry models and experimental procedures

According to the results obtained during a previous experimental work carried on masonry macro-elements at the Department of Structural Engineering of University of Calabria, see Olivito and Zuccarello (2004), the present work was carried on one-brick masonry panels

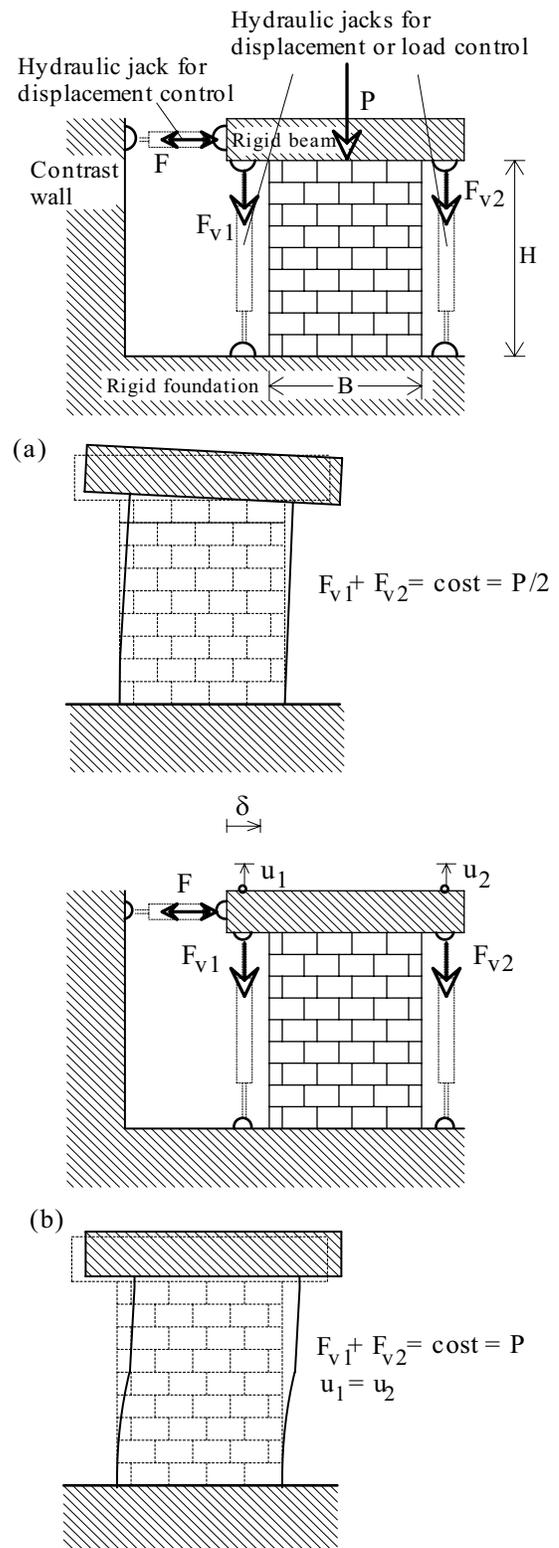


Figure 1 : Test configurations on masonry panels

made up of common bricks and mortar joints, provided of reinforced concrete beams both in the upper and in the lower surfaces, such as to better reproduce the real geometric, static and constraint conditions of masonry walls inside a building (Fig. 2).

The mechanical properties of these masonry models were obtained by uniaxial compression tests and the average experimental values obtained were:

- Young modulus: $E = 3640 \text{ N/mm}^2$;
- Poisson ratio: $\nu = 0.220$;
- Ultimate compressive strength: $\sigma_{uc} = 8.0 \text{ N/mm}^2$.

The mechanical characterization tests were carried out by means of a hydraulic press with a closed loop governing system while the displacement values were recorded by means of inductive transducers connected to a data acquiring device.

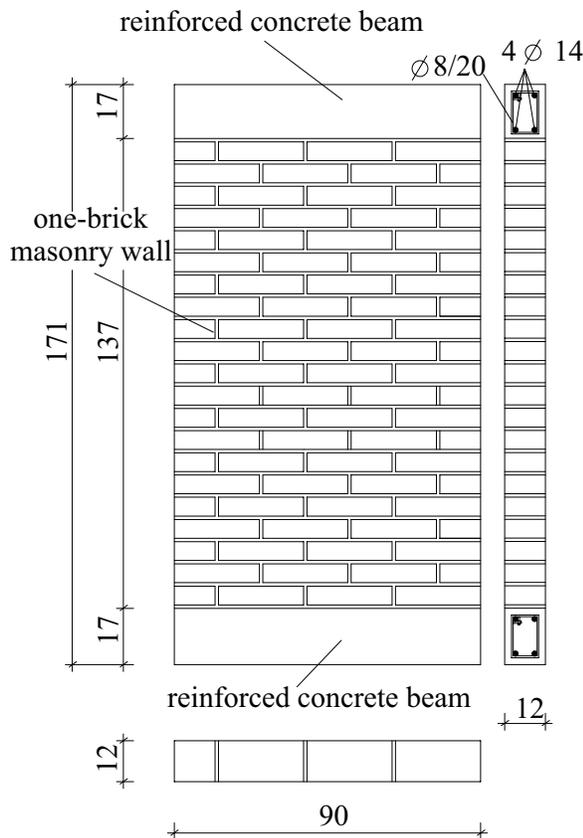


Figure 2 : One-brick masonry model

Cyclic loading tests were conducted by means of a steel frame composed of: two vertical hydraulic jacks which allowed controlled load and controlled displacement tests with a capacity of 300 kN, a 700 kN horizontal hydraulic jack which allowed controlled displacement tests, a personal computer with software which allowed us to follow the cyclic loading/unloading tests set in a specified time period. The displacement control between the vertical and horizontal jacks is independent and the same is true for the vertical ones (Fig. 3).

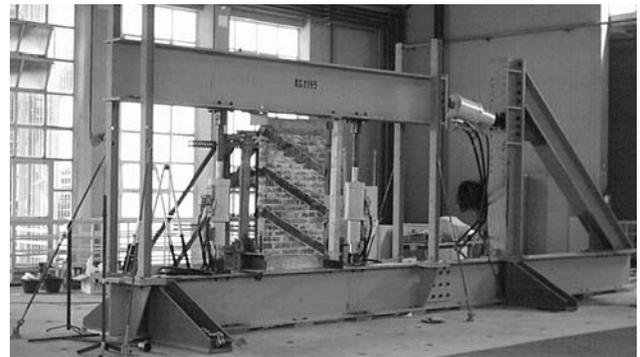


Figure 3 : Steel frame for cyclic tests

During each test the input data and the corresponding displacement and load values versus time were recorded by a personal computer.

Cyclic tests were carried out following the second type of test configuration described above (Fig. 1b). The panel was arranged on the steel frame and subjected to a vertical load of 150 kN uniformly distributed on the upper surface of the model; the vertical load was kept vertical and constant during each test by means of the horizontal rigid beam of the frame, realizing in this way a double fixed condition, see Anthoine, Magenes and Magonette (1995). Successively, a horizontal cyclic displacement was applied at the top of the panel, corresponding to the reinforced concrete beam, following specific deformation histories. It was possible to record the horizontal load value related to each horizontal displacement by means of the data acquiring software.

In particular, two kinds of cyclic tests were conducted, namely series 1 and series 2 respectively. The following history of deformation was given to the first series of panels: the horizontal displacement applied by means of the horizontal hydraulic jack passed from 0 to 4 mm in 20 seconds, while the vertical load was kept constant and

uniformly distributed; the basic cycle lasted 40 seconds and was repeated until the first cracks appeared on the panel.

The following history of deformation was given to the second series of panels: the horizontal displacement applied at the top of the model passed from 0 to 7 mm in 35 seconds, so that the loading velocity was the same for both series; the basic cycle lasted 70 seconds and was repeated until the first cracks appeared on the panel.

Linear inductive displacement transducers were used to detect the crack propagation onto the panels (Fig. 4).

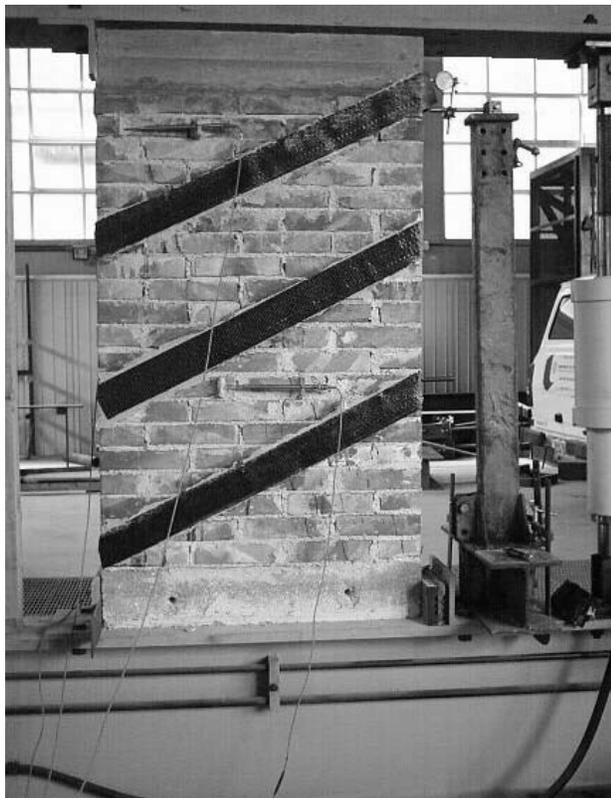


Figure 4 : LVDT's arrangement and FRP disposition

After being damaged, the masonry models were repaired by means of three 10 cm wide unidirectional carbon fiber strips glued to the masonry surfaces by means of a two component glue and were subjected to new cyclic tests up to failure. FRP strips were applied perpendicularly to the crack direction following the CNR DT200/2004 recommendations (Fig. 4).

4 Numerical analysis

In this section, a numerical analysis of the masonry panels subjected to cyclic loads is presented. The analysis was carried out by means of a commercial finite element code.

It is known that masonry is a material which exhibits different directional properties, depending on its structure and on the kind of loads acting on it. It is possible to use different modeling strategies, obtaining different accuracy levels. In a detailed micro-modeling, for instance, units, mortar and joint interfaces are considered separately; this approach is preferably used for structures with small dimensions, due to the high computational effort needed for the thick discretization. A second way is represented by the macro-modeling. In this case, units and mortar are merged together into a continuous material having average mechanical properties. In the present work, the in-plane behavior of masonry panels was studied, so the out-of-plane strains and stresses could be neglected and according to it, macro-modeling was used. In this way, masonry panel behavior was represented by a continuous, homogeneous and isotropic material meshed by plane finite elements. In particular, following the mechanical characterization carried out in the laboratory (§3), average mechanical properties were assigned to the model and an elastic-perfectly plastic constitutive behavior was adopted.

The panels were discretized by means of 8 nodes plane elements, defining in this way the mesh of the model. The discretization followed the real texture of the masonry panels.

Once the geometric, load and material properties of the model were defined, it was possible to study the tension and strain distribution in every point of it. The governing equations are the classical ones from structural mechanics theory, namely equilibrium, compatibility and constitutive law equations.

Due to the non-linear behavior of the model, the solution was obtained using the Newton-Raphson method of analysis.

Using the mechanical properties derived from experimental characterization, the σ - ϵ curve was introduced through the finite element code and assigned to the models.

The constraint conditions given to the lower surface of the model avoid rotations and displacements (fixed con-

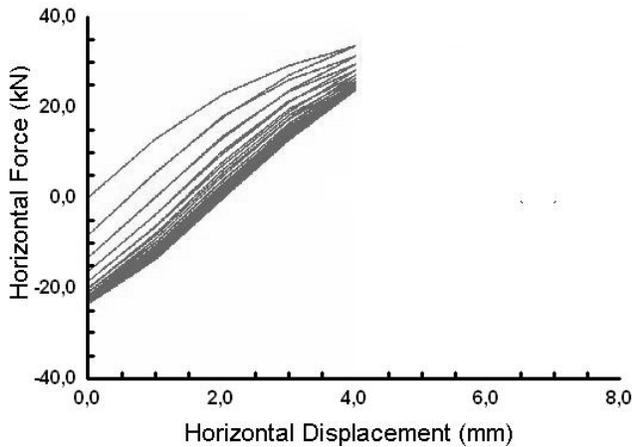


Figure 5 : Numerical analysis: series 1

dition). The pulsating shear force was simulated assigning horizontal translation to each node of the upper surface. The analysis procedure followed the one adopted during the experimental tests. In particular, the time-displacement history was built and assigned to the upper face nodes of the models.

The series 1 models were subjected to a 150 kN constant vertical load and to a 4 mm horizontal displacement applied at the top. The horizontal displacement changed from 0 to 4 mm and then went back to 0 and the basic cycle was repeated until the failure of the panel was reached. Figure 5 shows the horizontal force-horizontal displacement curve related to the first series of masonry models. The maximum horizontal load reached during the numerical simulation was less than 40 kN; it represents the model response to the applied horizontal displacement.

The series 2 models were subjected to the same vertical load and to a 7 mm horizontal displacement. In this case the horizontal displacement changed from 0 to 7 mm and then went back to 0 and the analysis was performed repeating the basic cycle until failure. Figure 6 shows the horizontal force-horizontal displacement curve related to the second series of masonry models. In this case, the maximum horizontal load reached during the numerical simulation was a bit more than 40 kN.

5 Experimental results

For the sake of brevity only the experimental results related to two masonry models are shown.

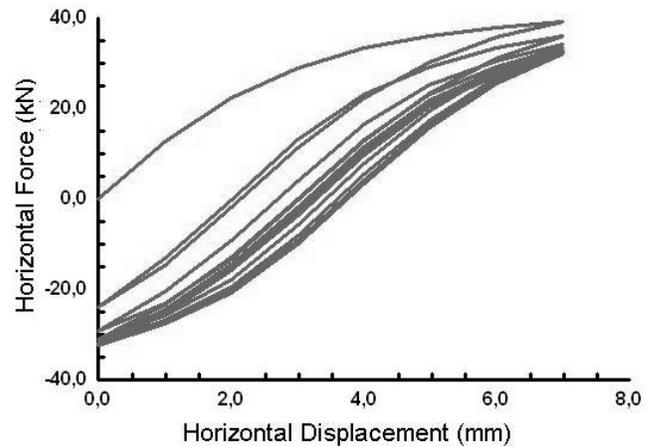


Figure 6 : Numerical analysis: series 2

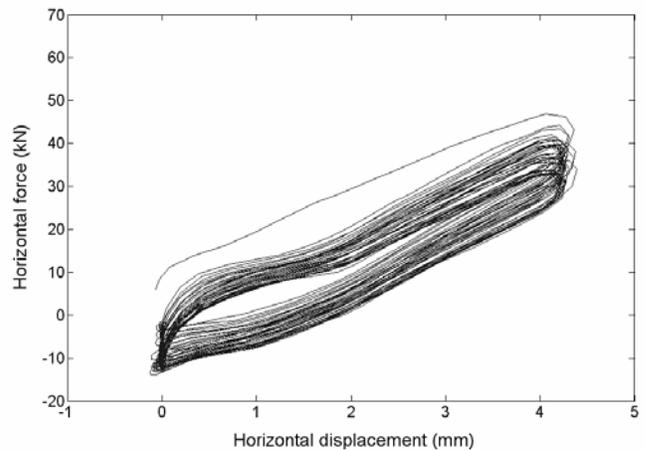


Figure 7 : Experimental curve: series 1

5.1 Series 1 masonry model

The maximum horizontal load reached by this panel during the cyclic test was about 46 kN after 162 number of cycles. The test was stopped when the first visible cracks appeared onto the panel surface; in particular, the test was arrested when the cracks were visible but less than 1 mm wide, so that it was possible to glue the FRP strips on the panels after the first tests and repeat the cyclic test on the reinforced models. Figure 7 shows the horizontal force-horizontal displacement curve obtained from the data recorded during the test.

The crack direction was almost diagonal and it interested the whole height of the masonry panel, see fig. 8.

The damaged panel was then reinforced by means of carbon fiber strips applied on both the lateral surfaces of it



Figure 8 : Crack pattern

and then it was subjected to the same cyclic test procedure adopted previously. Figure 9 shows the horizontal force-horizontal displacement curve relative to the first reinforced panel.

As it can be seen from the picture, the reinforced panel reached a horizontal load of 56 kN after 280 load cycles. In this case, the test was arrested when the debonding of the reinforced concrete lower beam occurred, while the diagonal crack previously repaired with FRP strips didn't change in shape.

5.2 Series 2 masonry model

The maximum horizontal load reached by this panel during the cyclic test was about 50 kN after 156 number of cycles. Also in this case, the test was arrested when the first visible diagonal cracks appeared onto the panel surface; in particular, the test was arrested when the cracks were visible and interested the whole height of the panel

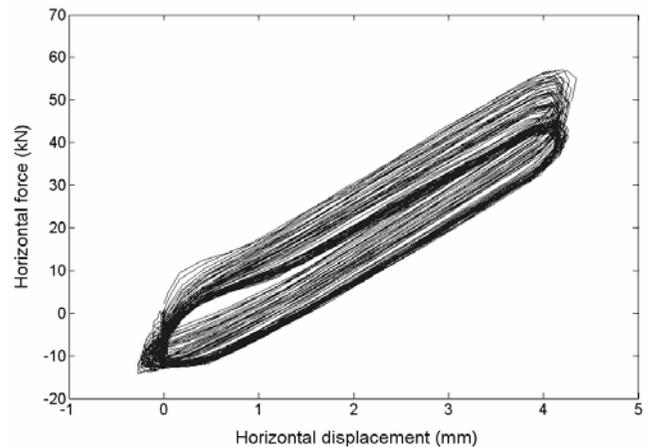


Figure 9 : Experimental curve: series 1 reinforced panel

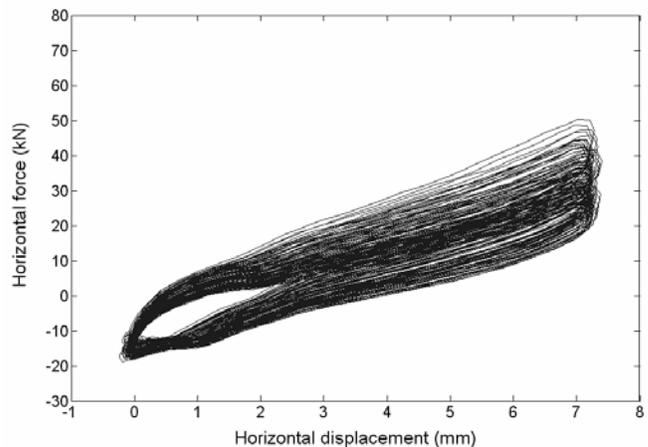


Figure 10 : Experimental curve: series 2

but were less than 1 mm wide, so that it was possible to glue the FRP strips on the panels after the first tests and repeat the cyclic test on the reinforced models, as explained previously. Figure 10 shows the horizontal force-horizontal displacement curve obtained from the data recorded during the test.

The damaged panel was reinforced by means of carbon fiber strips applied on both the lateral surfaces and then subjected to the same cyclic test procedure adopted previously. Figure 11 shows the horizontal force-horizontal displacement curve relative to the second reinforced panel.

The reinforced panel reached a horizontal load of 75 kN after 289 load cycles. The test was arrested when the debonding of the reinforced concrete lower beam occurred.

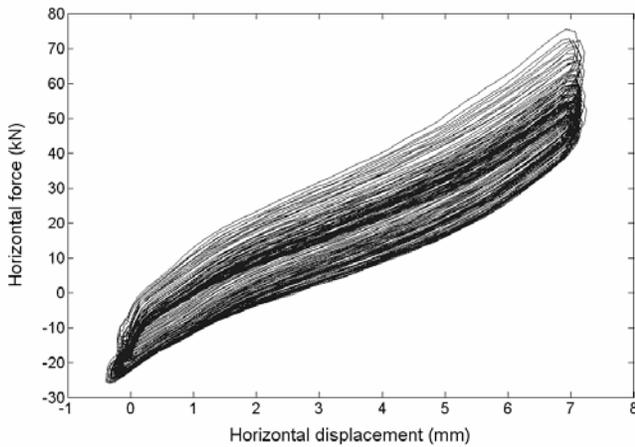


Figure 11 : Experimental curve: series 2 reinforced panel

6 Durability

The durability of ancient masonry buildings depends on external factors such as surrounding and load conditions. From earlier studies, it has been seen that the damage (D) can be expressed by the following linear form:

$$D = \alpha_t D_t + \alpha_c D_c \quad (1)$$

where the subscripts “t” and “c” denote tensile strength or compression respectively and α_t and α_c are coefficients which depend on the present strain state and are defined as:

$$\alpha_t + \alpha_c = 1 \quad (2)$$

where $\alpha_t = 1$ is the simple tensile state and $\alpha_c = 1$ is simple compression state.

The laws of evolution regarding the two quantities D_t and D_c are defined as:

$$D_i = 1 - \frac{\epsilon_{D_o}(1 - A_i)}{\bar{\epsilon}} - \frac{A_i}{\exp[B_i(\bar{\epsilon} - \epsilon_{D_o})]} \quad (3)$$

where the subscript “i” is equal to “t” or “c” for tensile strength or compression respectively, and A_i and B_i are material parameters, see Mazars (1984).

In a previous work, see Olivito and Zuccarello (2004), the following damage function was proposed as:

$$D = 1 - \frac{1}{\exp\left(\frac{B \cdot N}{A}\right)} \quad (4)$$

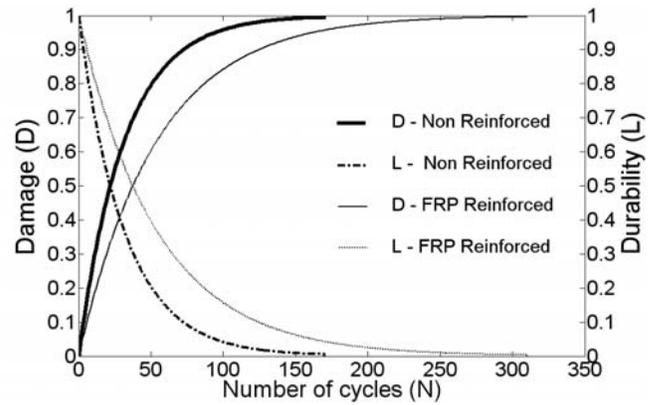


Figure 12 : Damage and Durability vs number of cycles

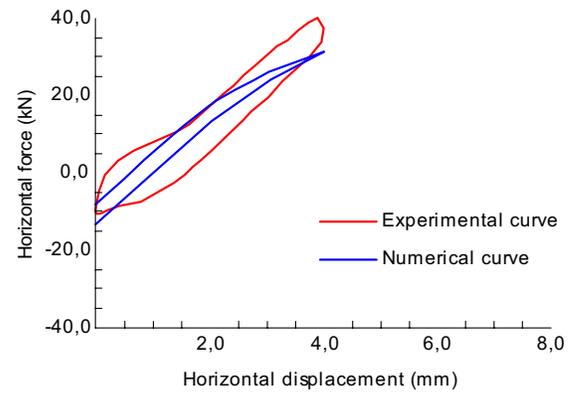


Figure 13 : Comparison between numerical and experimental curves: series 1 panel

where N is the cycle number, A is a parameter depending on the material and B depends on the loading direction. In particular B is equal to 0 for vertical loading and 1 for the horizontal one.

Consequently, the durability function (L) was defined as:

$$L = 1 - D \quad (5)$$

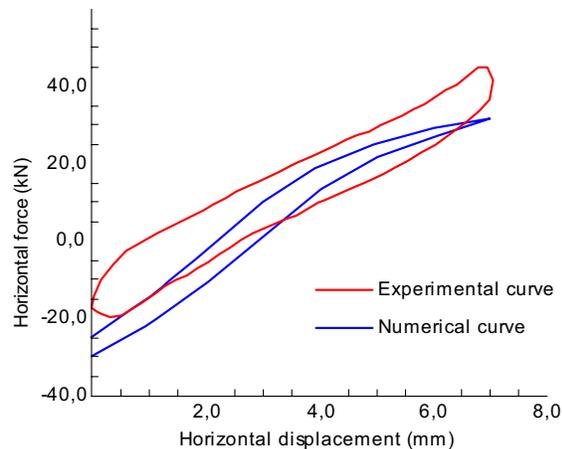
Figure 12 shows the damage and durability function trend for the two masonry models, versus the number of cycles reached during the experimental tests.

It is plain the beneficent effect of FRP materials to the durability of brick masonry models.

Obviously, this proposal needs to be validated by more experimental tests which will be carried out at University of Calabria.

Table 1 : Comparison between strengthened and non- strengthened masonry models

	Masonry models			
	Series 1		Series 2	
	Non-Reinforced	FRP-Reinforced	Non-Reinforced	FRP-Reinforced
Maximum Horizontal Load (kN)	46	56	50	75
Number of Cycles	162	280	156	289

**Figure 14** : Comparison between numerical and experimental curves: series 2 panel

7 Conclusions

The numerical results can be compared with the experimental ones: the panels tested in laboratory reached a higher horizontal load than the FEM models did.

Figures 13 and 14 show a comparison between both curves, numerical and experimental, related to series 1 and 2 respectively.

The area enclosed by the experimental curve is greater than the one enclosed by the numerical one for both series of panels, and this shows the greater energy dissipated during the experimental tests. Of course, the numerical results strongly depend on the necessary simplifications introduced when modeling mechanical behavior of masonry subjected to cyclic loads and thus these don't take into account the materials and construction defects of the panels.

The experimental tests carried out to this day pointed out that carbon-fiber reinforced panels increased their strength with respect to horizontal loads than the unreinforced ones, both in terms of maximum horizontal force and number of cycles which is almost double, see

Table 1.

Furthermore, the reinforced panels failure didn't occur in correspondence of the existing diagonal crack settled by FRP strips, but it was caused by the r.c. beam debonding. Finally, the crack pattern almost didn't change; only few micro-cracks parallel to the wider diagonal one appeared. During the tests, none of the following defects compared:

- Intrinsic defects of the FRP reinforcement, such as the presence of air bubbles;
- Interfacial defects, such as voids or areas with an excess of gluing resin caused by wrong surface preparation or by irregular adhesive application or by the use of overdue materials. These defects consequence is an inadequate load transfer between the constitutive elements and can cause premature failure for delamination or short durability;
- Resin defects.

This confirms the perfect and regular FRP application to the masonry model according to the CNR DT 200/2004 recommendations.

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