Title	EXPERIMENTAL INVESTIGATION OF MASONRY CALCAREOUS WALLS REPAIRED AND STRENGTHENED BY C-FRP
Author(s)	ANANIA, L.; BADALA', A.; COSTA, S.; D'AGATA, G.; GIACQUINTA, C.
Citation	Proceedings of the Thirteenth East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-13), September 11-13, 2013, Sapporo, Japan, H-5-4., H-5-4
Issue Date	2013-09-13
Doc URL	http://hdl.handle.net/2115/54464
Type	proceedings
Note	The Thirteenth East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-13), September 11-13, 2013, Sapporo, Japan.
File Information	easec13-H-5-4.pdf

EXPERIMENTAL INVESTIGATION OF MASONRY CALCAREOUS WALLS REPAIRED AND STRENGTHENED BY C-FRP

L. ANANIA[1*†], A. BADALA'[1], S. COSTA[1], G. D'AGATA[1] and C.GIACQUINTA[1]

[1]*Dipartimento d'Ingegneria Civile ed Ambientale, University of Catania- Italy*

ABSTRACT

The objective of this current research was to investigate effective and practical approaches for strengthening calcareous block walls with openings to resist the hazard of the in-plane shear loads. Afer a previous experimental analisys aimed to determine the mechanical propiertes of the employed materials developed by the same authors, a numerical investigation by F.E.M. capable of cacthing even the most complex phenomena both in the behavior and the failure mode of the masonry-FRP system, was carried out. In order to obtain a real effectiveness of the composite system, different distributions of the CFRP were considered. The most effective distribution of the composite system in terms of resistance, ductility and economy was that of grid and it was adopted to perform the laboratory samples. Four masonry panels with openings scaled 1:2 in size were constructed and tested. The specimens were tested under static and cyclic loads. It was found that both the strength and ductility of tested specimens were significantly enhanced with the proposed strengthening technique.

Keywords: FRP, masonry, in-of-plane loading, strengthening, design.

1. INTRODUCTION

Many existing unreinforced masonry structures, are vulnerable to extreme loading and so the collapse of these structures is often catastrophic, and extreme loading events can lead to severe property damage and loss of life. Many existing masonry structures need retrofitting to reduce the risk of collapse under extreme loading such as those caused by a seismic event. Conventional strengthening techniques are often time-consuming, costly, and add significant weight to the structure (Triantafillou 1998). These limitations have encouraged the development of alternatives such as the fiber-reinforced polymer (FRP) strengthening systems, which are lightweight, can be rapidly applied, and do not require prolonged evacuation of the structure. Polymer composites have been accepted by the construction industry worldwide as a structurally-efficient and cost-effective repair and rehabilitation systems. For the past decades, fiber reinforced polymer (FRP) composites have been successfully used to strengthen seismically-deficient and corroded reinforced concrete members, as well as masonry and wood members. Many experimental studies (Santa Maria 2011, Papanicolaou 2011, Nanni 2001) on the masonry elements with various forms and locations of the

---

[*] Presenter: Email: : lanania@dica.unict.it

[†] Corresponding author: Email: lanania@dica.unict.it

FRPs are reported in the literature where significant increases in the shear strength and stiffness of FRP masonry elements were observed. But all this research related masonry panel without opening. The literature lacks in results about masonry panels with openings. This paper discusses key design considerations for FRP retrofitted calcareous brick masonry typical of Eastern Sicily (including the ancient and historical architecture), based on experimental observations (i.e. FRP retrofitting technique, material and placement). Results are intended to contribute to better understand the in plane behavior of calcareous brick masonry structures in view of seismic strengthening using composite materials .

2. MECHANICAL FEATURES OF THE MATERIAL

The mechanical features of the employed materials were previously tested by the same authors; they are discussed and referred to Anania et al. 1995, 2012. Deeper experimental tests were carried out to determine the mechanical proprieties of the masonry-CFRP composite as well as of the CFRP-masonry bond, the latter are referred in Anania et al. 2013 The main parameters so obtained, are reported in table 1 and 2:

Table 1. Mechanical properties of materials of URM

Materials	Tensile Strength f_{mtm} (N/mmq)	Compressive Strength f_{mk} (N/mmq *(MPa)*	*γ (kN/m^3)*	*E (Mpa)*
Mortar	-	0.795	15	675
Brick	1	12.8	20	12190
Panel	-	4.76	16.5	3500

Table 2. Mechanical properties of materials of reinforced specimens

Material	Tensile Strength f_{mtm} (N/mmq)	Compressive Strength f_{mk} (N/mmq)	E (N/mmq)	Substrate Adhesion (N/mmq)	Equivalent Thickness (mm)
Composite Panel	-	5.76.60	5700	-	-
CFRP Uniaxial 300	4.830	-	230.000	>3	0.166
CFRP Bi-axial 230/20	4.800	-	230.000	>3	0.1
Epoxy resin	40	40	3.000	>3	-

3. TEST SET UP

On the basis of this background an experimental campaign carried out on the masonry panel with openings developed by the authors is now discussed. So, two couples of half-scale walls were tested under simulated seismic loading to develop a seismic retrofit strategy for these structures. The same geometry was selected for both couples of walls. Each panel is composed by only one level structure and presents two openings (Anania et al. 1999). To reproduce the typical load-bearing walls found in Southern Italy heritage, first a uniformly distributed vertical load was applied by means of the weight of the r.c. beam located at the top of the masonry panel capable of simulating the gravity service loads typically acting at the lowest storey. Then a cyclic horizontal load, applied by means of a hydraulic actuator at double action (thrusting and traction) connected to the curb by a bilateral constrain, was applied in order to simulate lateral loads. The vertical load is equal to 3.55 kN/m in the reduced scale, corresponding to a real vertical load applied on the structure of 7.1 kN/m and kept constant during the tests. The panel was founded on a stiff concrete support shaped so as not to have any rigid movements during the testing process (fig. 1). The shear load was applied; the test set up was designed in order to provide the basic parameters of the masonry behavior, such as strength, cracking pattern and deformations.

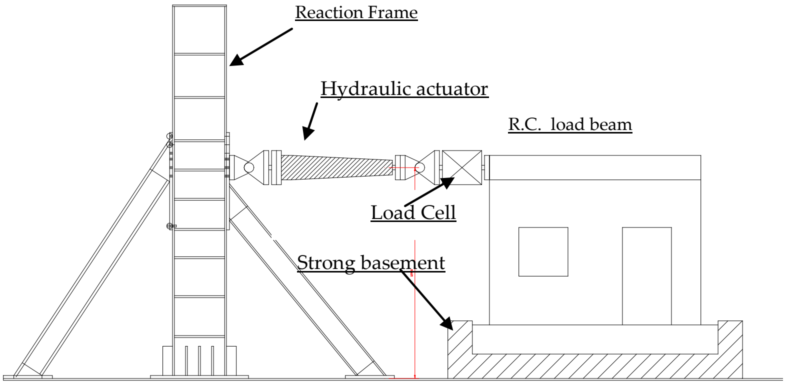
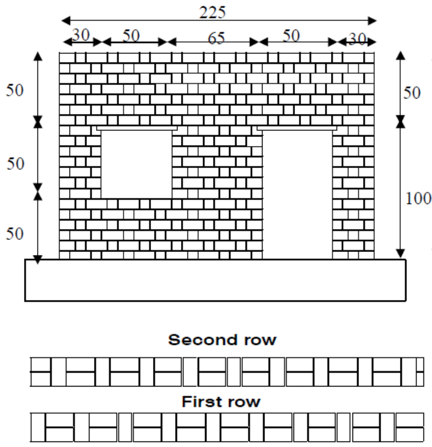


Figure 1. Overview of thetest apparatus

4. AS-BUILT WALL

The unreinforced control “as-built” wall (URM) was cyclically tested up to the failure. The panel is 150 cm high and 225 cm wide with a thickness equal to 15 cm. They are built by using a gothic disposition (Anania et al. 1995, 1997) at double thickness, of white calcareous rock bricks (fig. 2-3). This stone was taken from a local quarry and cut in bricks with dimensions equal to 7x7x15 cm^3. The bricks are joined together by means of a cement mortar named “M4” in accordance with the Italian rules. The ratio between the thickness of mortar joints and the height of the bricks is kept equal to 11 as we can often see in practice. The masonry panel is instrumented in order to record the displacement in the same direction of the increasing horizontal load, as well as the displacement and the rotation of bays of wall and the flat arches and the relative shift, measured along the axes of the bay of wall, between flat arches and bays. The instruments’ disposition is drawn in figure 3. Under these conditions a sidesway mechanism (fig.4) is obtained for a collapse load of 7,5 kN, this is due to the presence of the r.c. beam which works like the curb used to reinforce the flat arch. The wall cracking pattern is displayed in Figure 4 and the hysteretic loops of the wall are shown in Figure 5, illustrating the sudden degradation of strength and stiffness of the as-built wall specimen at a low ductility level (maximum displacement of 0,96 mm).



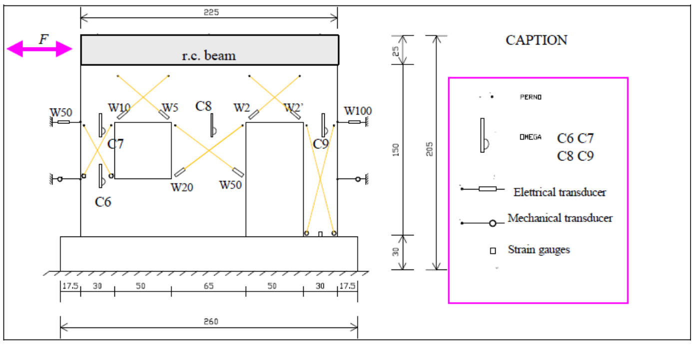
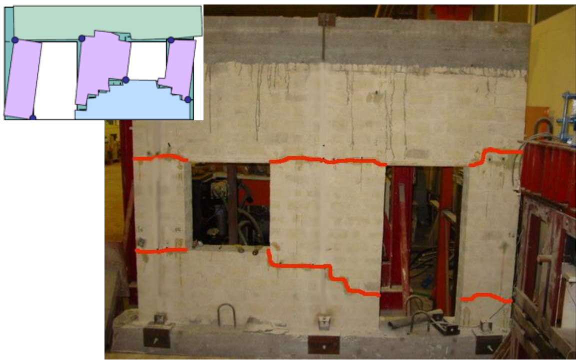


Figure 2. **Brick disposition in the wall**

Figure 3. **Instruments disposition**



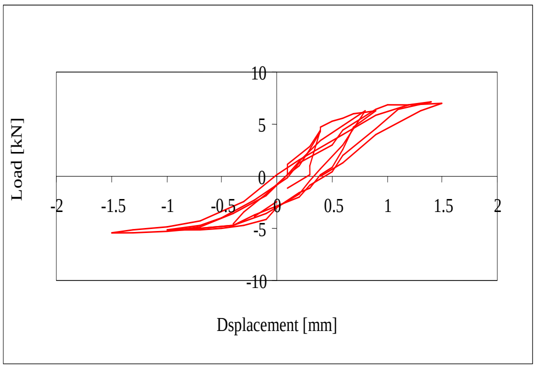


Figure 4. **URM Cracks pattern Sidesway mechanism**

Figure 5. **URM :F vs Dispacement plot**

5. REPAIRED WALL

5.1. The strengthened panel set up

To demonstrate the use of composite laminates in the possible repair of a cracked wall, the pre-cracked wall specimen were repaired, strengthened and then, tested.

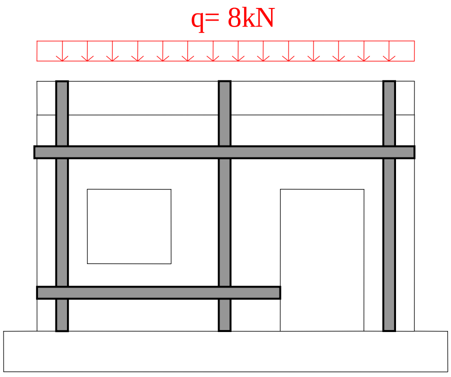


Figure 6. **The strengthening panel model under gravity service loads**

Figure 7. **Overview of the strengthened model out of plane constrained**

To this aim the cracks were, firstly, repaired either by filling them with high strength epoxy resin or, sometimes, by re-building some highly damaged small masonry portions; then, a grid of single layer uniaxial carbon/epoxy composite laminate 100 mm wide was applied on each side of the wall. The free extremities of the CFRP strips were special anchored transversally by placing a bi-axial CFRP strip at the extremity of the reinforcement (Anania et al. 2007, 2013). The connection between the strip and the basement of the panel was ensured by L steel profiles bolted to the basement (fig.8-9)

Figure 8. Anchorage at the free extremities

Figure 9. CFRP -basement Connection

5.2. Numerical investigation

The model was studied by a finite element analysis carried out by Lusas numerical code. Brick and mortar were meshed by an isoparametric element at 20 nodes solid element. The composite was modelled by a quadratic semiloof curved thin shell elements. The masonry model is based on a multy-surface plasticity approach capable of representing non linear behaviour of material both in tension and in compression.

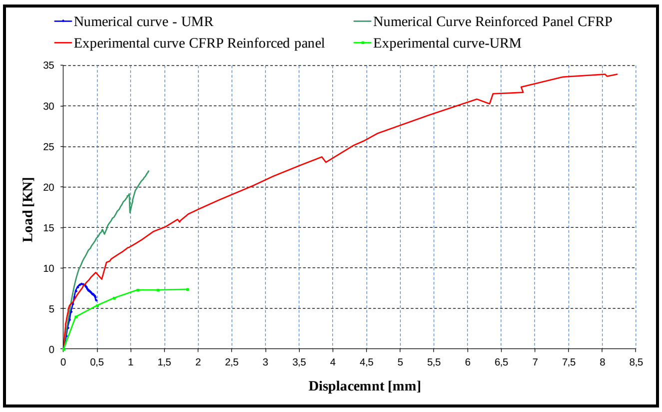


Figure 10. F vs δ curves comparison

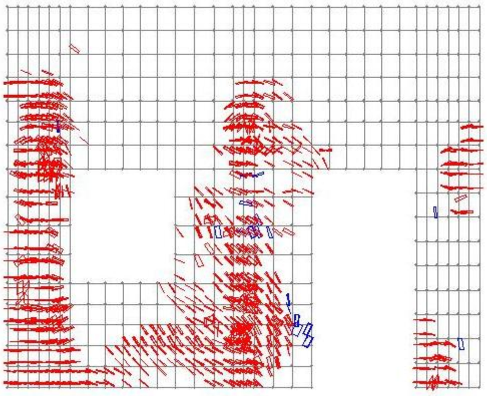


Figure 11. Numerical cracking pattern

The composite material was modeled by referring to a elastic linear homogeneous and orthotropic behavior both in the case of uniaxial and biaxial fiber sheets. The stress state is checked by verifying the collapse stress both in tension and in compression. The debonding phenomena occurring at the masonry-. Composite interface were also taking into account by referring to the possible modes assumed by the Italian rules (CNR-DT200/2004). The numerical output is reported in figures 15-18 in terms of load vs displacement diagram Cracking pattern and main stresses.

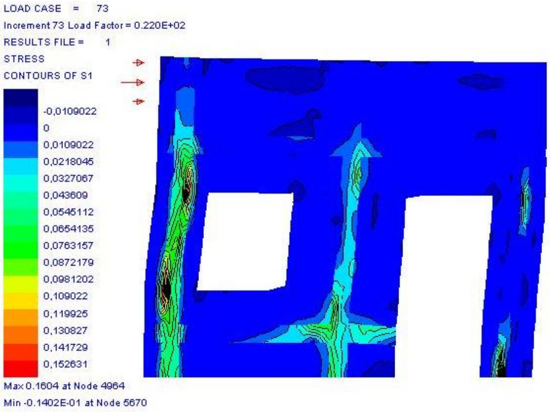


Figure 12. Principal stresses S1

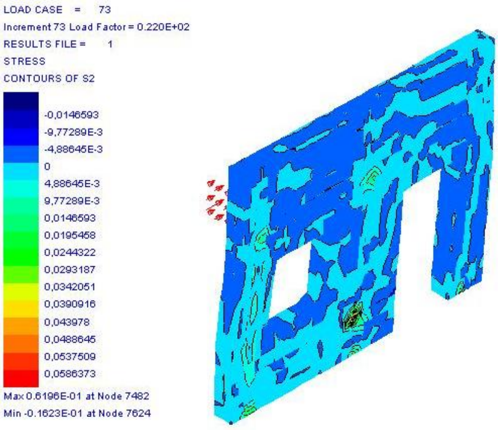


Figure 13. Principal stresses S2

5.3. Experimental test on reinforced masonry panel

As in the case of the control specimen, the horizontal shear force was applied in cyclic sinusoidal stages with a frequency equal to 0,01 Hz and measuring the *F* force until following the load history reported in fig. 14. The panel was instrumented as shown in figure 15. Compared to the as built wall more strain gauges were located along the fiber sheets. Reinforced wall equipped with a CFRP grid, reached failure for an ultimate load of 32,5 kN, with a sufficiently high ductility coefficient value (fig.16) and higher shear resistance if compared to URM panel. Cumulative energy plot (fig. 13) shows that no damage and dissipation occurs during the first 1200 steps (for a displacement of 0,1 mm). After this point the dissipated energy is equal to 2/3 of the inputted one. In this phase the dissipative attitude of the panel varies slightly in all the cycles of equal amplitude even observed the loops recorded on the central bay of wall (fig. 17).

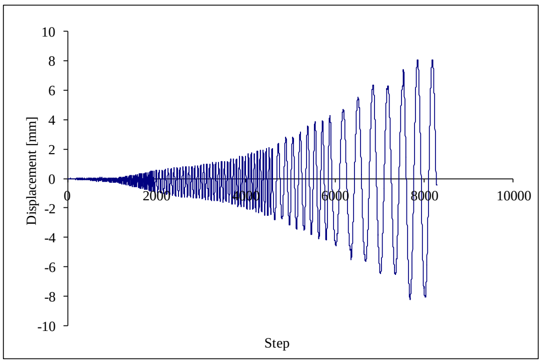


Figure 14. Load history

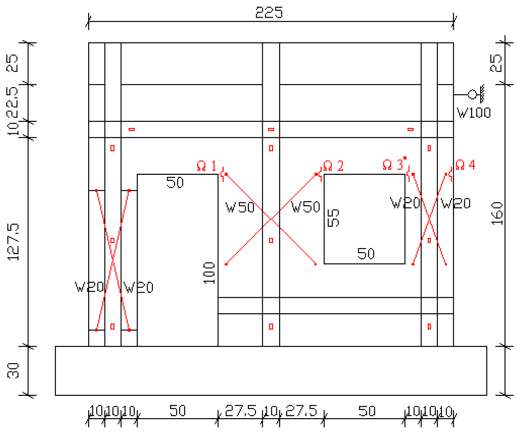


Figure 15. Instrumeted FRP reinforced specimen

At the ultimate loading step, the failure of the reinforced wall is a consequence of a global sliding of the masonry along the mortar bed located near the basement just below the CFRP strip; while a limited delamination is observed in the vertical deployed strips (fig.18-19).

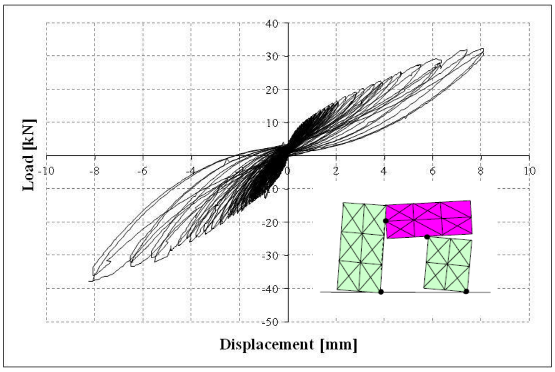


Figure 16. F vs displacement loops at the top

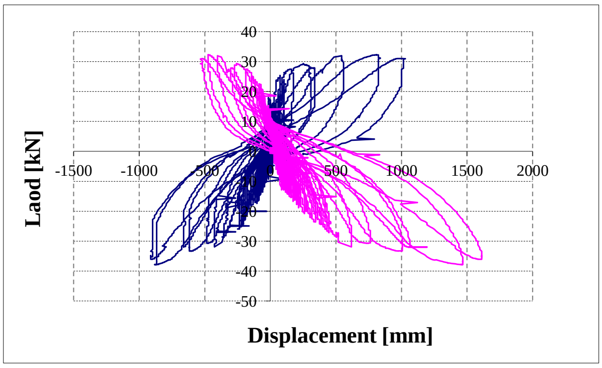


Figure 17. F vs displacement loops on the central bay of wall

The mechanism (fig.20) obtained is a combined mechanism characterized by a sliding of the upper part of the wall on one the horizontal mortar joints as well as by a shear failure due to the presence of principal tensile stresses higher than the tensile strength of masonry materials, according to the results obtained by the numerical investigation.

Figure 18. Delamination at the top of the coulumn

Figure 19. Sliding along the mortar bed

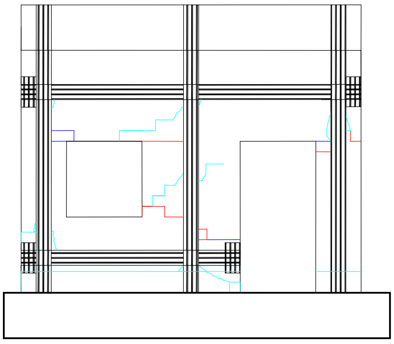


Figure 20. Crack pattern: Combined mechanism

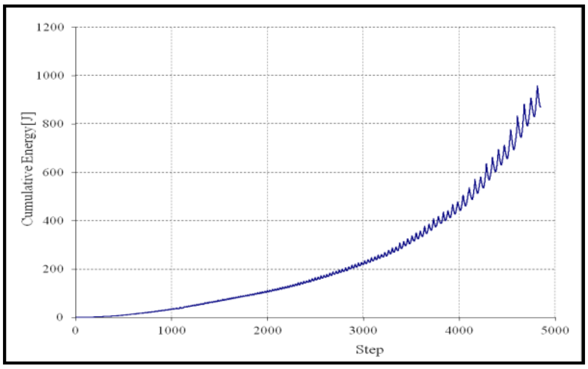


Figure 21. Cumulative energy in terms of displacement

6. CONCLUSIONS

When the performance of the repaired and strengthened wall is compared with that of the as-built wall, it becomes clear that the repair technique has improved the shear strength and energy dissipation of the wall due to the friction between the cracks within masonry elements as well as the deformation of the FRPs. It not only succeeded in restoring the capacity of the original wall, but also increased it by four times to that of the original wall capacity. The application of the composite laminates to the two sides of the wall specimens gave an appreciable stiffness gain of the double which was evident from the displacement profiles of such specimens. The envelope diagram of the experimental load displacement curve of strengthened panel shows a very stable hardening up to displacements of 8 mm. In the strengthened model a greater capacity of undergoing wide horizontal movements can be observed. This goal depends on the quality of the CFRP extremities anchorage able to offer their support to the masonry even after the peeling. The damage pattern shows and homogeneous distribution of the stresses in the strengthened panel; this fact improves the mechanical properties of the structural element and change the global collapse mechanism of the panel. The difference found in the measurements of the relative displacement between bay of walls and flat arches is also very interesting. In fact, this is in the order of 30% higher if compared to the URM test panel. In addition, cycles showed less damage. The tests results made possible to identify two possible modes of failure. One shear sliding failure related to the parent material (i.e. masonry) while another related to the reinforced material (debonding of FRP). The strengthened walls showed stability (no loose material was observed) after failure. This fact can reduce risk of injuries due to partial or total collapse of walls.

REFERENCES

Tumialan J.G., Morbin A., Nanni A., and Modena C. (2001).“Shear Strengthening of Masonry Walls with FRP Composites,” Composites 2001 Convention and Trade Show, Composites Fabricators Association, Tampa, FL, October 3-6, 2001, 6 pp. CD-ROM

Papanicolaou C., Triantafillou T., Lekka M.(2011) Externally bonded grids as strengthening and seismic retrofitting materials of masonry panels. Construction and Building Materials 25 pp. 504–514

Santa-Maria H., Alcaino P.(2011).Repair of in-plane shear damaged masonry walls with external FRP. Construction and Building Materials 25. pp.1172–1180

Anania L, Badala A, D’Agata G (2013).Effective bond length of FRP sheets externally bonded to natural calcareous stone with standard and reinforced anchorage” accepted to AMR www.scientific.net.

Anania L, Badala A et al.(2012) The stones in monumental masonry buildings of the "Val di Noto" area: new data on the relationships between petrographic characters and physical-mechanical properties. JCBM Vol.33C pp.122-132

Anania L, Badala, Cuomo M. (1995). Mechanical characterization of historical mortars of Eastern Sicily “. Masonry International -Journal Of British Masonry Society. -London October 1995 - vol. 7. pp. 382-387 ISSN: 0950-9615.

Anania L, Badala A, D’Agata G, Giaquinta C (2007). Pull off tests on calcareous bricks bonded to CFRP . In: dr. Ct Tam, prof. K C G Ong, dr. T.h. Tan. The conceptual approach to structural design. Orchard plaza, Singapore 238: Ci-Premier pte ltd, ISBN/ISSN: 981-05-3547

Anania L, Badala A, Costa S. (2000). Retrofitting of masonry buildings constituted by calcareous block stone: theoretical and experimental analysis. In: Computational Methods in Enginneering, San Paolo: dep. de eng. de Estrut. e fund., p. 268.1-268.15, ISBN/ISSN: 85-901027-1-8