EXPERIMENTAL BEHAVIOUR OF MASONRY VAULTS STRENGTHENED BY INNOVATIVE COMPOSITE MATERIALS

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ABSTRACT

In this paper, the results of an experimental investigation on full-scale masonry vaults, strengthened at the extrados with different composite materials, is presented. Eight vaults were built with low strength brick and lime mortar to obtain mechanical characteristics as similar as possible to existing elements. Five reinforced systems were tested: steel fibres and basalt net, applied with a lime mortar matrix (SRG and BTRM), steel reinforced polymer and carbon fibres reinforced polymer (SRP and CFRP) and extrados stiffening diaphragms (‘frenelli’) reinforced with SRP and SRG. Two reference vaults, unstrengthened and reinforced with SRG strips, were tested under monotonic vertical loads, applied at the quarter of the span. Six reinforced vaults were tested under cyclic vertical loads, alternately applied at the quarters of the span. Results of tests carried out allowed comparing the global behaviour of the various specimens and the influence of the type of reinforcement (fibre -steel, basalt and carbon, and matrices -organic and inorganic). In addition, modal identification analysis was performed at incremental steps during the tests, to find correspondence between dynamic behaviour and damage state of the vaults.

KEYWORDS: vaults, masonry, composite materials, SRG, extrados stiffening diaphragms, reinforcement.

INTRODUCTION

Masonry buildings are a significant part of our cultural heritage as well as one of the most widespread structural systems in Europe and in many other non-European Countries. Decay conditions, static problems and seismic risk are becoming more relevant, and often make necessary structural interventions to preserve the integrity of historic heritage. Focusing on masonry vaulted structures, in recent years new materials and strengthening techniques to improve their structural condition and preserve them from further damage have been developed. However, these new materials and techniques are sometimes applied without prior verification of their applicability and effectiveness. Recent Italian earthquakes (Salò, 2004; Abruzzo, 2009; Emilia 2012 [1]) confirmed the limits and consequences of some intervention techniques developed in the recent past [2-4].

In the last decades, fiber reinforced polymers (FRP) have been often used for reinforcement of masonry vaults. FRPs have many advantages, such as high strength/weight ratio, absence of electrochemical corrosion, high tensile strength, low coefficient of thermal expansion and the relatively thin profile of cured FRP systems are often desirable in applications where aesthetics or access is a concern [5]. On the other hand, the elasto-brittle behaviour, low resistance to fire, the lack of vapour permeability, the necessity of adopting skilled labour and some critical stages of implementation, in practice can lead to severe problems of realization, compatibility, and reversibility, that would be desirable to overcome [6]. With this intention, a new family of composite materials made of unidirectional high strength twisted steel wires (SRG) or bidirectional basalt fibers (BTRM), laid in inorganic matrix, has been recently introduced.

Several experiments performed on masonry arches strengthened with composite materials are reported in literature. This technique can change the brittle mechanism caused by the formation of hinges, and increases the collapse load and the ductility behavior of the structural elements. However, the influence of the different composite materials [7-12] and the combination with extrados stiffening diaphragms ("*frenelli*", [13-14]) is not totally clear. This paper reports and discusses the results of an experimental program on the behaviour of masonry vaults, unreinforced and reinforced, carried out at the University of Padova. Various strengthening techniques and materials were tested. The aim was comparing the behaviour of different types of extrados strengthening, validating the effectiveness of each technique, and investigating the global dynamic properties of the specimens.

EXPERIMENTAL PROGRAM

For a reliable experimental simulation of the structural behaviour of historic masonry vaults elements, the selection of appropriate bricks and mortar is fundamental. The stability and safety of curved structures depend on their geometry and on the mechanical characteristics of the constituent materials [7]. Therefore, before performing monotonic and cyclic test on real scale masonry vaults, some preliminary mechanical characterization of the materials employed to build and strengthen the specimens was performed.

MATERIAL CHARACTERIZATION

Vaults were made of solid clay brick (250x120x55 mm) type Rosso Vivo A6R55W produced by San Marco-Terreal Italia (Noale-VE, Italy) and joints of lime mortar T30 V produced by Tassullo (Tassullo-TN, Italy). The strengthened systems applied used an inorganic matrix of lime-based mortar TD13 K produced by HD System (Tassullo-TN, Italy), two types of organic matrix Fidsaturant and four different fibres, FidSteel 3x2-G4 (SRG), FidBasalt Grid 300 C95 (BTRM), FidSteel 3x2-B12 (SRP) and FidCarbon Unidir 300 H240, all provided by Fidia (Perugia, Italy).

Three-point bending tests were performed on 12 clay bricks, and the two portions obtained after failure were subjected to compressive and splitting tests. Eight T30 V and three TD13 K mortar specimens 40x40x160 mm were tested in bending and the two portions obtained in compression; elastic modulus was measured on other eight T30 V and three TD13 K prisms of mortars. Five cords of steel fibres were tested in tension to determine the mechanical properties and to evaluate their stress-strain curves. Test results indicated that material behaves linearly to failure and there is practically no yielding.

Four masonry panels were tested in compression and initial shear strength was measured on twelve three bricks specimens. See Table 1 for the results.

Table 1: Mechanical properties of materials (CoV brackets)

Material	Compressive strength [N/mm^2]	Flexural strength [N/mm^2]	Splitting strength [N/mm^2]	Elastic modulus [N/mm^2]	Tensile strength [N/mm^2]	Shear strength [N/mm^2]
Brick	17.68 (6.2%)	4.43 (10.2%)	2.99 (11.2%)	-	-	-
Mortar T30 V	1.75 (15.6%)	0.74 (14.4%)	-	3570 (21.2%)	-	-
Mortar TD13 K	10.47	3.10	-	9674	-	-
Steel cords	-	-	-	-	3033 (1.2%)	-
Masonry	5.97	-	-	1193	-	0.173 $\alpha = 28.48°$

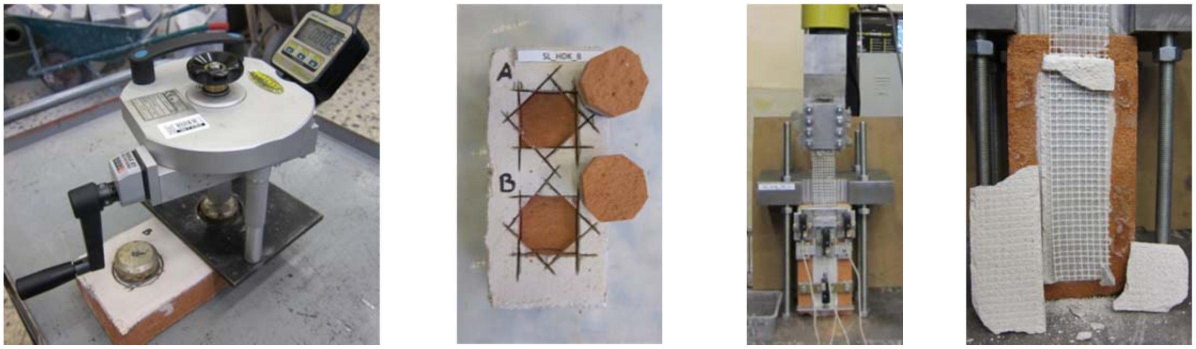
CHARACTERIZATION OF THE REINFORCEMENT

The efficacy of any reinforcement depends on the bond that exists between reinforcement and base structure, as this is dependent on stress transfer. Therefore, the behaviour of materials at the interface is of great interest for the structural analysis. With the objective of characterizing the interface between masonry and composites applied with base-lime mortars (SRG and BTRM), pull-off [15-16] and single-lap shear tests [17] were carried out on specimens of small dimensions. Pull-off tests are commonly used to verify the perpendicular bond strength of overlay or repair materials applied on a substrate, while single-lap shear test consist of loading in tension a reinforcement strip, connected to the support, in order to create shear stresses at the interface and to force the brittle support to be subjected to compressive stresses [18-19]. Table 2 shows the test matrix and the results of pull-off and shear tests, where f_{p-o} is the pull-off tensile strength, P_{max}/b_{fm} the ratio between the maximum load and the width of the strip and $\sigma_{max}/f_{t,frp}$ the ratio between the maximum and the ultimate fibres tensile strength.

Table 2: Test matrix and results of local interaction tests (CoV brackets)

Materials	Pull-off			Single-lap Shear			
	N.	f_{p-o} [N/mm^2]	Failure modes [12]	N. (adhesion length 200 mm)	P_{max}/b_{fm} [N/mm]	$\sigma_{max}/f_{t,frp}$ [%]	Failure mode
Brick	28	1.03 (11.7%)		-	-	-	-
SRG	10	0.949 (15.2%)	40% type A 50% type C 10% type D	5	131.73 (17.6%)	63.0%	matrix
BTRM	10	0.441 (36.0%)	100% type C	5	29.52 (10.2%)	32.2%	fibres

Pull-off results revealed that SRG specimens failed in the substrate (40%, Figure 1 (b)) and in the matrix (50%) with mean values of tensile strength similar to those obtained for bricks (92.1%), while BTRM specimens failed all in the matrix with lower mean values (42.8%). Shear tests showed high maximum load and rupture of the matrix in SRG composite. Conversely, in the case of BTRM, there were some problems due to different inner and outer bond characteristics, hence the failure mechanism, after exceeding the maximum shear load, was a so called ‘‘telescopic failure’’, i.e. a successive break down layer by layer from the sleeve to the core filaments [20]. Both composites exhibited a brittle behaviour during shear tests.



(a) (b) (c) (d)

Figure 1: pull-off: (a) test setup, (b) failure mode type “A”, SRG; shear test: (c) test setup (d) failure mode type “matrix”, SRG

The pull-off are a very simple and cheaper tests, and allow obtaining a first general information on composites behavior, e.g. low tensile strength and failure mode type “C”, means that the texture of the fibers is too thick or the density (cord/cm) is too high. The results of shear tests showed different failure modes of inorganic matrix compared to epoxy matrix. In the first case, all SRG specimens revealed the complete detachment of fibers from the matrix and the failure did not involve the support, unlike the epoxy matrix. This indicated that single-lap shear tests with steel fibers, although more laborious, are preferable to pull-off tests to characterize the behavior of SRG.

TESTS ON MASONRY VAULTS

To study the behaviour of reinforced vaults, seven masonry barrel vaults were built with brick arranged in a single layer with a thickness of 12 cm, width 77 cm, span 298 cm and rise 114 cm.

(a) (b) (c) (d)

Figure 2: (a) geometry and load condition, (b) vault with extrados stiffening diaphragms, (c) SRG spikes and strips, (d) BTRM application

Two different types of strengthening (strips on the extrados or extrados stiffening diaphragms, “*frenelli*”, with strips of composite materials, Figure 2) were applied. All interventions were applied on the entire length of the extrados and connected at the supports by two types of spikes made of the same fibres used in the strips (steel and basalt). The composite system used to strengthen the arches included three different types of fibres (steel, basalt and carbon) applied with organic (SRG, BTRM) and inorganic matrix (SRP, CFRP). Table 3 present the test matrix and the used composite materials.

Two samples, unreinforced and reinforced with SRG, were tested under monotonic sub-vertical loads applied at 1/4 of their span. After the first test on unreinforced sample, the vault was strengthened with CFRP and the remaining five vaults were tested under cyclic load applied alternatively at 1/4 and 3/4 of their span (Figure 2). Table 3 lists the experimental tests program on the vaults.

Table 3: Experimental program of vaults

Vault	Type of test	Fibres	Matrix
VM	Monotonic	-	-
VM_SRG	Cyclic	2 strips, 12 cm wide, with 18 steel cord each and 4 steel spikes on the basement	Inorganic
VC_SRG	Cyclic	2 strips, 12 cm wide, with 18 steel cord each and 4 steel spikes on the basement	Inorganic
VC_BTRM	Cyclic	Basalt net, cover all the surface and 8 basalt spikes on the basement	Inorganic
VC_SRP	Cyclic	2 strips, 11 cm wide, with 94 steel cord each and 4 steel spikes on the basement	Organic
VC_CFRP	Cyclic	2 strips, 12 cm wide, and 4 basalt spikes on the basement	Organic
VC_FR_SRG	Cyclic	Extrados stiffening diaphragms with 1 strip, 12 cm wide, with 18 steel cord and 4 steel spikes on the basement	Inorganic
VC_FR_SRP	Cyclic	Extrados stiffening diaphragms with 1 strip strips, 11 cm wide, with 94 steel cord and 4 steel spikes on the basement	Organic

The test setup was constituted of one or two hydraulic jacks equipped with load cells and connected with two hinges at the top to the reaction structures, and at the bottom on the reinforced "U" steel element, used for uniform load distribution on the vault extrados. The tests were performed in displacement control with different displacement increase rates (minimum 0.5 μm/s, maximum 3 μm/s); displacement, opening hinges and deformation on the strips were recorded. During the tests, a visual inspection of the arch was continuously performed to register opening and cracking of mortar joints as well as strips detachment, hinges location and failure pattern. Furthermore, piezoelectric accelerometers, were used to perform dynamic identification of the specimens at different level of damage.

TEST RESULTS

The monotonic test on the unreinforced sample presented a rigid behaviour and brittle failure with the formation of four hinges. The rigid block mechanism was activated after it reached the maximum load (1.38 kN) corresponding to a displacement at the keystone equal to 0.36 mm. In the other seven tests, with strengthening applied at the extrados preventing the opening of hinges on the extrados, the vaults presented different behaviour and patterns of collapse.

The vaults reinforced with SRG in monotonic and cyclic tests (VM_SRG and VC_SRG) presented the same failure (Figure 3 (a)) with sliding between brick and mortar in the joints closest to the load application points and a similar maximum load capacity (respectively 13.5kN and 14.3kN). The vaults presented a notable global deformation and displacement (equal to 21.8mm and 20.9mm at the keystone); near the springing, sliding was prevented by the steel spikes inserted in the supports and connected with the strips.

The test VC_BTRM exhibited the same failure mechanism (rigid block) of the control specimen but load and displacements were increased (11.5kN and 10.1mm); the behaviour presented a short plastic branch and a brittle tensile rupture of the fibres inside the mortar (Figure 3 (b)).

The vaults strengthened with epoxy matrix (VC_SRP and VC_CFRP) showed the highest maximum loads with brittle collapse (respectively 22.6kN and 15.6kN), the failure observed were in the first case crushing of masonry and in the second case sliding close to the springing with shear failure of the carbon spikes.

The last two specimens had extrados stiffening diaphragms and only one strip of composite materials applied on the top of the masonry elements. In this case, the maximum loads were the lowest of the experimental campaign, but the failure mode was characterized by a ductile collapse with the damaged zone concentrated on the stiffening diaphragms, and notable global displacement. Collapse occurred after the formations of plastic hinges on the vaults (Figure 4).

(a) (b) (c)

Figure 3: (a) sliding VC_SRG, (b) hinge VC_BTRM, (c) crushing VC_CFRP

(a) (b) (c)

Figure 4: (a) diaphragm VC_FR_SRG, (b) hinge VC_FR_SRP, (c) damage of diaphragm VC_FR_SRP

Table 4: Experimental results

Vault	Maximum load [kN]	Displacement on keystone [mm]	Load increase [-]	Mode of failure
VM	1.38	0.36	-	Mechanism
VM_SRG	13.47	21.77	9.77	Shear sliding
VC_SRG	14.33	20.95	10.40	Shear sliding
VC_BTRM	11.49	10.11	8.33	Mechanism
VC_SRP	22.63	14.08	16.42	Crushing
VC_CFRP	15.56	12.48	11.29	Shear collapse of spikes + Crushing
VC_FR_SRG	9.53	7.44	6.91	Mechanism
VC_FR_SRP	11.57	7.53	8.40	Mechanism

The envelopes of the load-displacement diagrams, in Figure 5, showed a first linear branch, during the first cycles of the tests, until the opening of a hinge under the loading points. After this first branch, the different techniques showed different behaviour, brittle for the reinforcements with epoxy matrix, rather ductile for BTRM material and ductile for SRG and extrados stiffening diaphragm with composite materials.

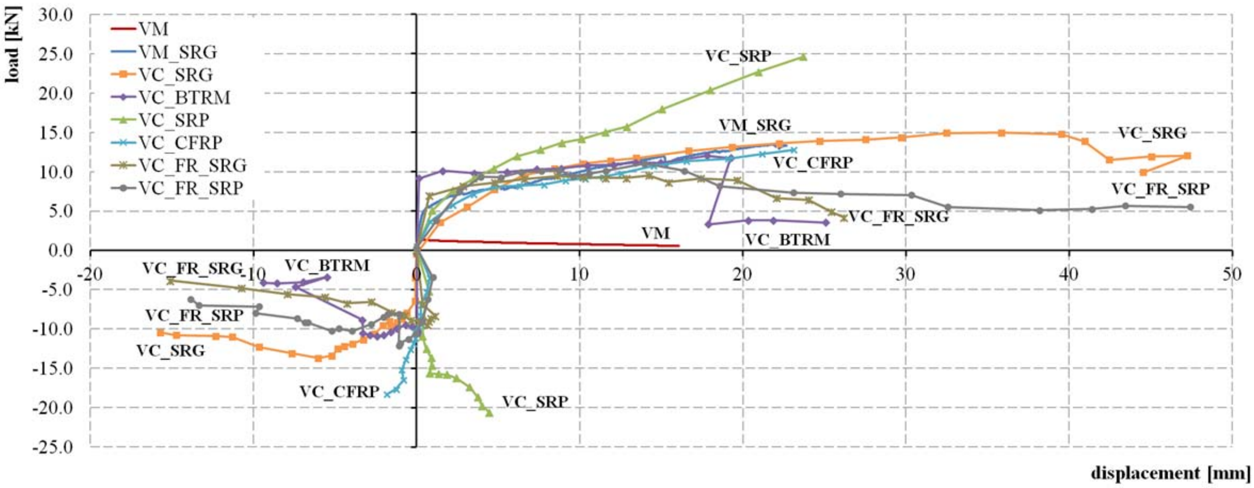


Figure 5: Envelope of Load-displacement curves, measured on the keystone

Furthermore, in the experimental tests, values corresponding to the yielding point (Fy_y, d_y) were calculated following the procedure indicated by the standard, while the values corresponding to the ultimate load (Fy_u, d_u) derive from the envelope curve [21]. The global stiffness of the vault is calculated as follow:

$$K_y = \frac{Fy_y}{d_y} \tag{1}$$

$$K_u = \frac{Fy_u}{d_u} \tag{2}$$

The global stiffness at the yield point, K_y, is greater in the specimens reinforced with inorganic matrix, while the value at the ultimate points, K_u, is less than the epoxy matrix reinforcement (Figure 6), with the exception of the tests VC_SRG and specimens reinforced with extrados stiffening diaphragms that present a intermediate behaviour.

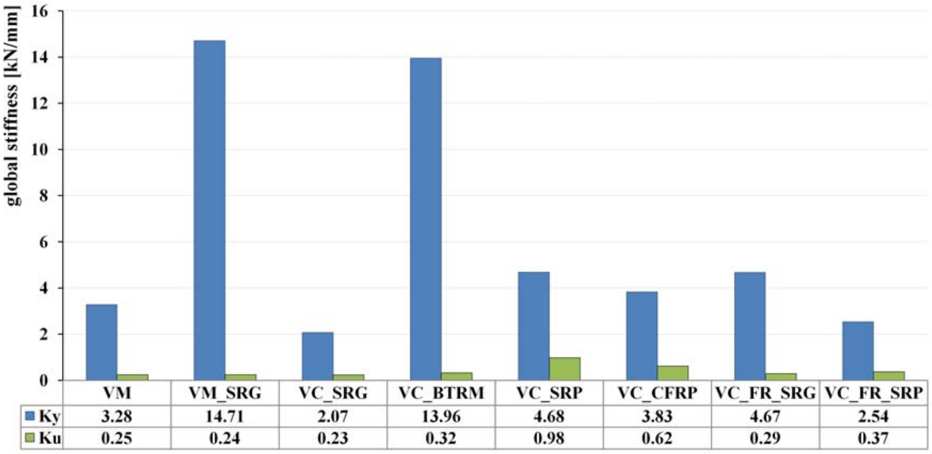


Figure 6: Global stiffness

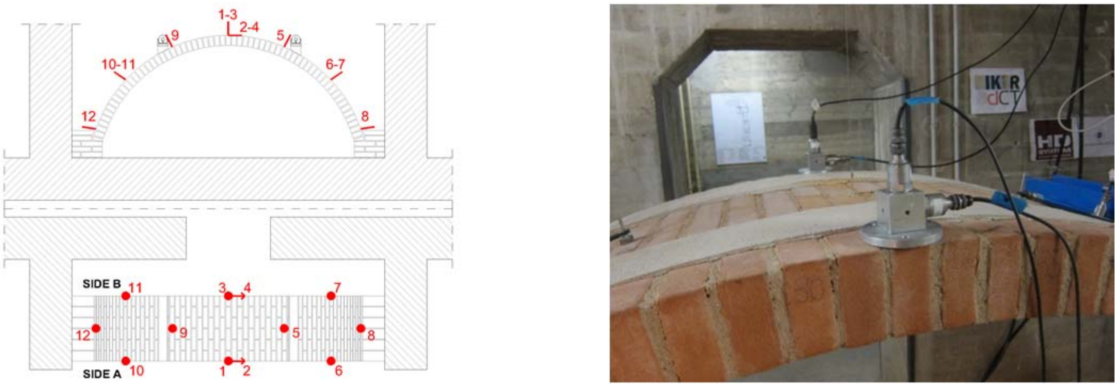
The results presented in Figure 5 and Table 4 highlight the potential of innovative composite material with lime-based mortar matrix to provide an alternative to traditional techniques with epoxy matrix. The failure modes, without crushing, of SRG and BTRM tests emphasize the mechanical compatibility of these techniques with existing structures. A comparison between vaults with equivalent reinforcement and epoxy matrix highlights a strength increases provided by steel cords were greater than those obtained using carbon fibres (respectively 16.4 and 11.2 times the load of the unreinforced vault). A significant role of the stiffness of spikes was observed, in the CFRP test the carbon spike failed under shear stress, while in the other tests the steel fibres anchor did not allow shear sliding of bricks along joints, making possible to achieve better results.

DYNAMIC IDENTIFICATION

The global structural behaviour of the vaults was evaluated also applying dynamic tests before, during and after the loading test. The dynamic identification was carried out applying the output-only modal identification technique (or ambient vibration technique). The recorded signals were analyzed in frequency domain applying the Enhanced Frequency Domain Decomposition method [22].

The test setup, shown in Figure 7, used twelve accelerometers in the specimens without extrados stiffening elements and fourteen in the other two cases, all acquisitions were repeated twice and performed by acquiring all accelerometers simultaneously, at a frequency of 200 Hz.
The acquisitions were carried out at the beginning, without (T1-NA) and with (T1-A) the actuators connected at the specimen. The other three acquisitions (T2, T3, T4) were carried out during the test, respectively at the end of the 4th, 11th and 17th cycle. At the end of the test other two acquisitions were carried out, with (T5-A) and without (T5-NA) actuators connected at the specimen.

From the analysis of dynamic tests with ARTeMIS Extractor, it was possible to identify the first four mode shapes shown in Figure 8.



(a) (b)

Figure 7: (a) location of the measuring points for the dynamic tests, (b) test setup

1st mode 2nd mode 3rd mode 4th mode

Figure 8: modal identification for the first four modes

Table 5 shows the acquisitions performed at the beginning (T1-NA) and end (T5-NA) of the test, without actuators. It shows an evident decrease of frequencies between the two acquisitions without actuators performed at the beginning and end of test. The monotonic tests (VM and VM_SRG) show a minor variation of frequency due to the smaller damage observed compared to cyclic tests. In addition, the control specimen (VM), presents frequencies that are lower than those of the reinforced vaults.

The decrease in frequencies is greater in samples reinforced with inorganic matrix and extrados stiffening diaphragms, probably due to the fact that tests have endured a greater number of cycles than vaults reinforced with epoxy matrices. The load-displacement graphs of Figure 5 show that the more ductile specimens present a significantly lower ultimate load, and a major decrease of frequencies. The cyclic test VC_BTRM showed a frequency degradation that may be due to the failure of the basalt fibres. There are also some anomalies for the third mode (torsional) in the specimens VC_SRG and VC_FR_SRP, in which there is a frequency increment at the end of test.

Table 5: Natural frequency at beginning and end of loading test, without actuators

Vault	**Test phase**	**1st mode [Hz]**	**2nd mode [Hz]**	**3rd mode [Hz]**	**4th mode [Hz]**	**Vault**	**Test phase**	**1st mode [Hz]**	**2nd mode [Hz]**	**3rd mode [Hz]**	**4th mode [Hz]**
VM	T1-NA	15.21	35.36	28.89	-	VC_SRP	T1-NA	21.91	48.81	80.46	90.43
	T5-NA	11.99	32.48	27.21	-		T5-NA	12.54	35.78	90.82	72.10
	Variation	-0.21	-0.08	-0.06	-		Variation	-0.43	-0.27	0.13	-0.20
VM_SRG	T1-NA	24.20	51.56	60.83	88.75	VC_CFRP	T1-NA	14.20	36.40	49.32	70.58
	T5-NA	13.03	29.14	54.13	74.03		T5-NA	8.57	26.96	35.92	-
	Variation	-0.46	-0.43	-0.11	-0.17		Variation	-0.40	-0.26	-0.27	-
VC_SRG	T1-NA	23.95	51.86	73.12	85.43	VC_FR_SRG	T1-NA	23.76	59.55	66.87	94.33
	T5-NA	4.66	16.31	30.01	-		T5-NA	5.50	23.58	88.25	72.83
	Variation	-0.81	-0.69	-0.59	-		Variation	-0.77	-0.60	0.32	-0.23
VC_BTRM	T1-NA	24.90	61.87	78.98	74.24	VC_FR_SRP	T1-NA	24.74	53.74	88.40	94.06
	T5-NA	9.22	20.46	50.83	-		T5-NA	7.78	22.86	68.23	62.88
	Variation	-0.63	-0.67	-0.36	-		Variation	-0.69	-0.57	-0.23	-0.33

CONCLUSIONS

The following conclusions are deduced for experimental results:

- Single-lap shear test with steel fibers, although more laborious,s are preferable to pull-off in order to characterize the behaviour of composite materials.
- Pull-off and shear tests represent a useful investigation procedure for a first selection of proper combinations of inorganic matrices and steel or basalt net reinforcement systems.
- SRG composite materials present a more ductile behaviour and reduced installation costs compared to SRP and CFRP.
- Steel spikes at the vault springing prevent sliding on the first joints near the supports and increase the maximum loads of the specimens.
- Lime-based mortar is a good alternative to epoxy matrix, as it creates good bond between steel fibres and masonry substrate and increases the ductility of the strengthening system.
- Basalt net with inorganic matrix present a maximum load that is lower than SRG with a short plastic branch and a brittle behaviour controlled by a strong bonding of the external filaments in the strand and a slip of the inner filaments [16].
- Extrados stiffening diaphragms reinforced with SRG/SRP present an overall performance in terms of displacement and failure mechanisms which is even better than that of single SRP or CFRP reinforcement.
- Damage identification gave very good results, consistent with the test phases and the experimental observations, and allowed defining some ranges of frequency decrease that can be related to increasing damage conditions and different strengthening techniques.

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REFERENCES

1. http://www.ingv.it/
2. Modena, C., Dalla Benetta, M., Carraro, M., Ghedina, T. and de Sabbatta, A. (2010) “The S. Marco church in L’Aquila: provisional interventions after the 2009 Abruzzo earthquake” 7th Int. Conf. on Structural Analysis of Historical Constructions - SAHC, Shanghai, China.
3. da Porto, F., Silva, B., Costa, C., Modena, C. (2012). “Macro-scale analysis of damage to churches after earthquake in Abruzzo (Italy) on April 6, 2009”. Journal of Earthquake Engineering, Taylor & Francis Publishers; 16(6):739-758.
4. Borri, A., De Maria, A. and Piccarreta, M. (2004) “Osservazione dei danni negli edifici di aggregazioni storiche dell’Umbria” 9th Congresso Nazionale “L’Ingegneria Sismica in Italia”, Genova, Italy, on CD–ROM (in Italian).
5. ACI 440.2R-08 (2008) “Guide for the design and construction of externally bonded frp systems for strengthening concrete structures” American Concrete Institute.
6. CNR-DT 200/2004 (2004) “Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures” National Research Council.
7. Valluzzi, M.R., Valdemarca, M. and Modena, C. (2001) “Behavior of brick masonry vaults strengthened by FRP laminates” Journal of composites for construction, 5(3), pp. 163-169.
8. Barbieri, A., Borri, A., Corradi, M., Di Tommaso, A. (2002) “Behaviour of masonry vaults repaired with frp: experimental analysis” 6th Int. Masonry Conf. of the British Masonry Society, Siracusa, Italy.
9. Foraboschi, P. (2004) “Strengthening of masonry arches with Fiber-Reinforced Polymer Strips” Journal of composites for construction, 8(3), pp. 191-202.
10. Briccoli Bati, S., Rovero, L., Tonietti, U. (2007) “Strengthening masonry arches with composite materials” Journal of Composites for Construction, 11(1), pp. 33–41.
11. Oliveira, D.V., Basilio, I., Lourenço P.B. (2010) “Experimental behavior of FRP strengthened masonry arches” Journal of composites for construction, 14(3), pp. 312-322.
12. Focacci, F. (2008) “Rinforzo di murature con materiali compositi” Flaccovio Dario, Palermo, Italy (in Italian).
13. Mastrodicasa, S. (1993). “Dissesti statici delle strutture edilizie” Hoepli, Milano (in Italian).
14. Modena, C., Casarin, F., da Porto, F., Garbin, E., Mazzon, N., Munari, M., Panizza, M., Valluzzi, M. R. (2009) “Structural interventions on historical masonry buildings: review of Eurocode 8 provisions in the light of the italian experience” Quali prospettive per l’Eurocodice 8 alla luce delle esperienze italiane, Workshop Reluis-UNI, Napoli, Italy.
15. ASTM C1583 (2004) “Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method)” American Society for Testing and Materials.
16. UNI-EN 1015-12 (2002) “Determinazione dell’aderenza al supporto di malte da intonaco esterno ed interno” Ente Nazionale Italiano perl’Unificazione.

17. RILEM Technical Committee 223-MSC (2013) “Masonry Strengthening with Composite materials”; http://rilem223msc.isqweb.it/
18. Nakaba, K., Kanakubo, T., Furuta, T., Yoshizawa, H. (2001) “Bond behavior between fiber reinforced polymer laminates ad concretes” ACI Structural Journal, 98(3), pp. 359-367.
19. Yao, J., Teng, J., Chen, J. (2005) “Experimental study on frp-to-concrete bonded joints” Composites Part B: Engineering, 36, pp. 99-113.
20. Banholzer, B., Brockmann, T., Brameshuber, W. (2006) “Material and bonding characteristics for dimensioning and modelling of textile reinforced concrete (trc) elements” Materials and Structures, 39, pp. 749–763.
21. UNI-EN 12512 (2006) “Timber structures – test methods- cyclic testing of joints made with mechanical fasteners” Ente Nazionale Italiano per l’Unificazione.
22. Brincker, R., Andersen, P. (2000) “Ambient response analysis of the heritage court tower building structure” 18th Conf. on Structural Dynamics - IMAC, pp. 1081–1087.