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PRELIMINARY RESULTS OF EXPERIMENTAL INVESTIGATION AND MODELLING OF STRENGTHENED BARRELL VAULTS

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Abstract

Recent earthquakes showed that most existing structures are characterized by high seismic vulnerability. In particular, the observations of the damages have individuated in masonry arches and barrel vaults the most critical elements in the seismic vulnerability of existing structures. Therefore, the understanding of their seismic performance has become a crucial problem in the field of structural engineering. Their dynamic behavior is generally evaluated according to simplified methods or, as an alternative, to complex FEM analyses. However, a deep knowledge of their dynamic behavior is still lacking from an experimental point of view and, so far, only few experimental researches have been conducted. At this regard, shaking table tests have been performed to investigate the seismic behavior of a full scale masonry vault with abutments. The vault presents a segmental arch with a span of 298 cm, a rise of 114 cm and 116 cm depth. The vault is made of solid facing clay brick and pozzolanic masonry mortar. The use of composite materials has shown to be effective for these structures. In this background the experimental tests can provide an efficient contribution to the interpretation of the reinforcement effects. The present paper presents a comprehensive overview of the main results of the experimental tests. In particular, the experimental results of an innovative reinforced system coupled with other traditional strengthened systems are herein presented. The reinforcement technique is based on TRM system (Textile Reinforced Mortar). The effects have been investigated by using the shaking table tests, both before and after the TRM reinforcement application. The strengthening systems have been applied to a full-scale masonry vault typically used as roofs in religious buildings. After strengthening, the seismic behavior of the vault was significantly improved. Increasing the PGA, the instrumental response of the specimen started to change, however first visible damage occurred at an almost doubled PGA. The seismic capacity of the unreinforced specimen was more than doubled and the vulnerability moved from the curved element to the masonry abutments. Therefore, additional interventions should be eventually made on the lateral abutments. The strengthening strategy (combination of innovative and traditional systems) was effective in preventing failure of the masonry vault.

Keywords: Masonry vaults, Seismic performance, Shaking table test, Strengthening, Textile Reinforced Mortar

1. Introduction

The strong heterogeneity of masonry structures often makes the assessments of their seismic response very complex [1-4]. The seismic response can be evaluated by means of complex numerical analyses, too [5]. Often, the high number of required parameters makes these analyses unreliable, if conducted without experimental support and validation.

Therefore it is important that the experimental phase supports the numerical analysis. The experimental tests of masonry structures on shaking table are preferable to assess the seismic behavior. Such experimental tests are not numerous in scientific literature [3]. In this paper the preliminary analyses and experimental results of dynamic tests of masonry vaults on shaking table are shown. Experimental tests have been conducted at the Department of Structures for Engineering and Architecture, University of Naples Federico II.

The structural assessment of strengthened masonry vaults is a fundamental topic. In particular, several dynamic tests on masonry vaults with abutments typical of religious roofs have been performed. The present study is aimed to the assessment of the structural performances of TRM strengthening combined with other traditional strengthening systems. The structural assessment of strengthening system has been conducted by means of comparison between the performance detected on the unreinforced and strengthened specimens. The experimental results have been supported by preliminary calculations. Numerical models by using both FEM approaches and simplified analytical modelling approaches have been conducted.

2. Preliminary results

In order to ensure the success of the experimental program a preliminary analysis is needed both to evaluate the seismic capacity of the specimen and the characteristics of the seismic signals applied by means of the control system [6].

Engineering applications aimed at assessing the load capacity of masonry arches, are commonly conducted under no-tension assumption. For masonry arches the Heyman's approach [7] is commonly adopted. No-tensile and infinite compressive strengths are the main assumptions used in Heyman's theory, along with no sliding. In predictive models the hinge mechanism is the only considered collapse mode, as supported by experimental evidence.

According to the Heyman's theory (i.e. limit analysis), for a generic load pattern, the resultant's envelope of the acting compressive stress distribution (thrust line) must be contained entirely within the structure boundaries [8]. Each element is able to carry the acting load exclusively by means of compressive stress. According to the lower bound theorem, any thrust line which is placed within the geometry of vault, corresponds to an equilibrium configuration of arch element. The equilibrium is satisfied under a generic acting load pattern if a thrust line entirely contained in the geometry of vault can be found.

The previous classical model for particular cases could provide inaccurate solutions [9]. The arches characterized by both a high span/thickness ratios (slender vaults) and without any backfill (churches roofs), failed by hinge mechanism under horizontal loads [7]. Therefore, the classical Heyman's model can predict a premature collapse even under gravity loads [9]. For slender unfilled structures without a minimum of tensile strength, even under a gravity self-weight load, the plastic compatibility condition is violated. It's due to the very low axial stress values and consequently, the eccentricities due to permanent gravity loads could not be properly equilibrated. For the unreinforced specimen an analytical model taking into account tensile strength has been used [9].

2.1 Specimen characteristics

The specimen is a full scale masonry vault that has the following characteristics. The masonry material is made of solid facing clay bricks (25×5.5×12) cm^3 and pozzolanic mortar joints, 1 cm thick. The geometry of the specimen is representative of a masonry vaulted roof commonly found in historical religious buildings (i.e. without any filling). The geometry of the vault is characterised by a segmental arch profile which is less than a semicircle. Span and rise of the masonry vault are 298 cm and 114 cm, respectively. The depth of the specimen is different for the base and arch elements, which are 220 cm and 116 cm, respectively (Fig. 1).

The curved element is built over two masonry walls. By means of these panels the vault's imposts are at a height of 114 cm with respect to the bases (Fig. 1). Moreover the masonry lateral walls have been raised up to 234 cm height.

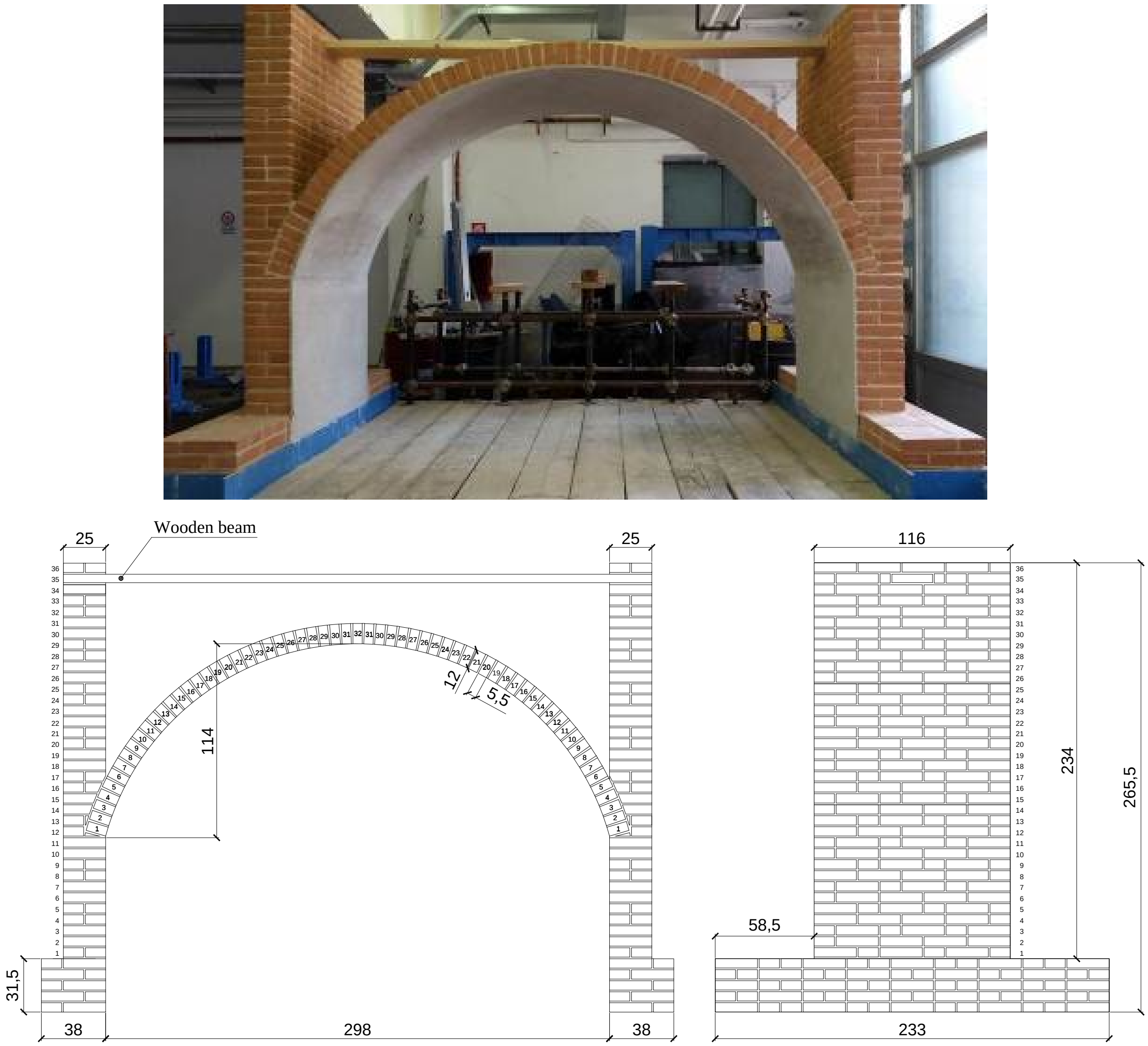

Figure 1 - Geometrical characteristics of the tested unreinforced specimen (dimensions in cm)

The global geometric characteristics of the strengthened vault compared to the unreinforced specimen are similar.

The specimen, failed after first test phase, has been partially rebuilt with same material and workmanship; hence it can be assumed that vault recovered the undamaged condition. The strengthening technique is based on Textile Reinforced Mortar (TRM) coupled with traditional techniques to improve the seismic performance of the masonry curved elements. The strengthening involves different innovative and traditional techniques merged together in a system. Indeed, this strengthening system has been applied at the extrados of the curved element. The TRM was made by a first mortar layer 0.5 cm thick applied to the masonry substrate (extrados of the curved element). Over the mortar layer an alkali-resistant primed fibre grid has been placed. Finally, a second mortar layer, entirely covering the basalt grid was built. The installation of the grid has been performed according to the manufacturer and covering the entire depth of the arch element.

Additionally, interventions by means of repointing of the cracked joints and grout injections were performed in the abutments to repair damages occurred due to hinge mechanism. The repointing has been performed by means of a premixed mortar. This mixture is made of natural hydraulic lime (NHL), several special additives, natural sand and synthetic polymers.

A masonry rib was built over the extrados, in the middle of the curved element. The masonry was made of clay hollow bricks (25×25×25) cm^3 and pozzolana-based mortar joints with a thickness of 1 cm. Finally, an innovative stainless steel tie was built over the masonry rib. This last strengthening system was made of unidirectional steel fibres generally characterized by very low prestress. The steel tie is located at a height approximately corresponding to the crown of the masonry vault. The steel tie crossed the walls through a removed brick and it was perfectly bonded to the lateral masonry abutments by means of two lateral steel devices. Each end of the tie element was constrained by using two coupled steel angles. In order to avoid a detachment between the masonry rib and the extrados of the vault, an additional TRM layer has been applied over the rib. Then, the strengthened specimen has been tested again by means of a new set of seismic signals.

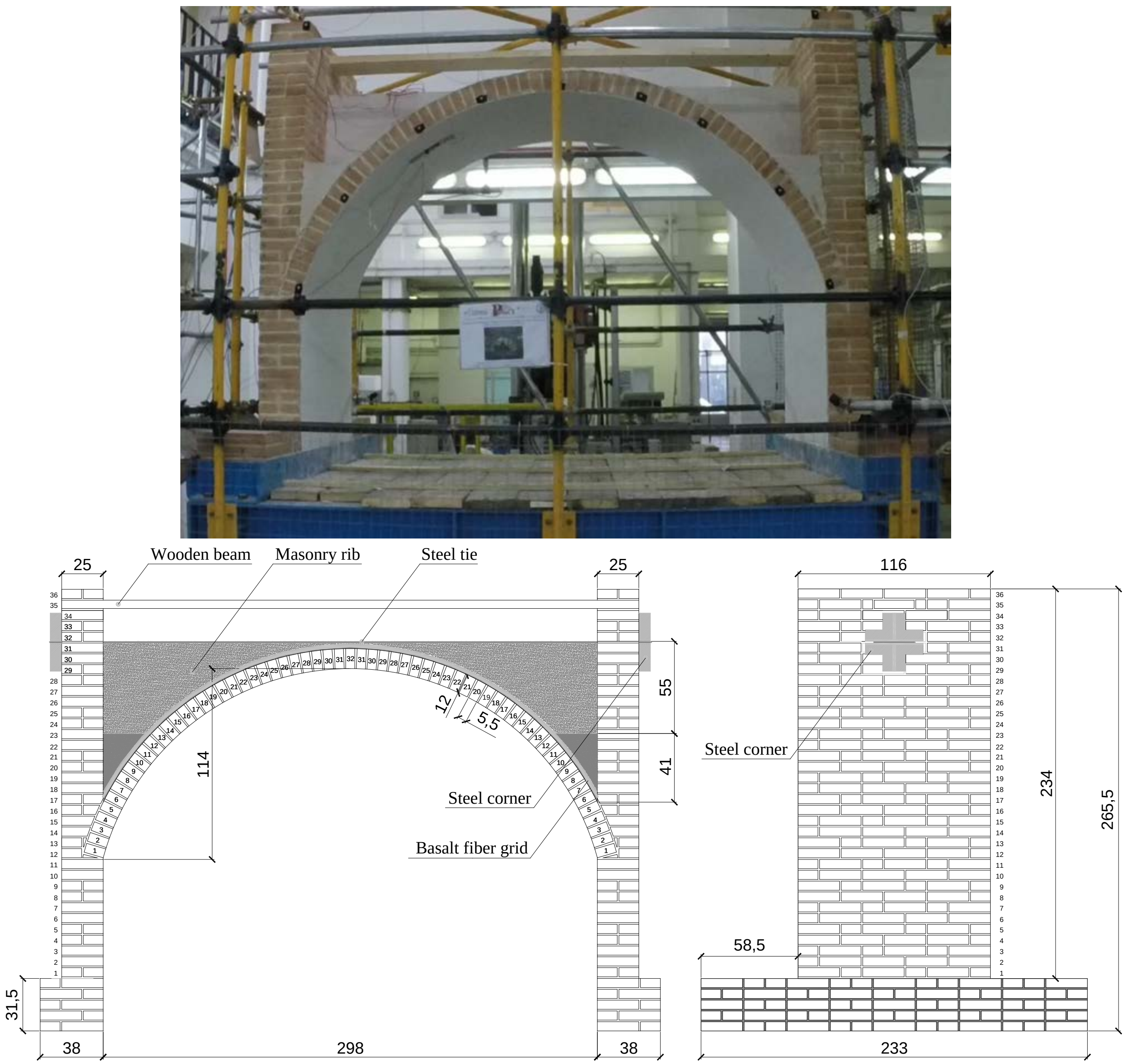

Figure 2 - Geometrical characteristics of the tested strengthened specimen (dimensions in cm)

2.1 Static non-linear analysis

It is essential to evaluate the ultimate capacity of the specimen that is going to be tested, in a simplified manner. In this case, simplified incremental analyses have been conducted up to the collapse. In this phase the unreinforced masonry vault has been modelled through a homogeneous material approach. The analyses take into account variability of the mechanical properties. Parametric analyses were carried out providing a reasonable variation range of the collapse accelerations for the specimen.

The ranges of the mechanical characteristics are shown in Table 1 and, for each set of parameters, the collapse acceleration is provided too. In particular, both the Young's modulus and compressive strength are the minimum, average and maximum values provided by the Italian Building Code 2009 for clay brick masonry [10].

The tensile strength value was estimated by means of an additional static vertical load test on a similar specimen previously tested in the laboratory of the University of Naples, Federico II [1].

The experimental estimation of the mechanical properties was limited to the tensile strength only (0.32 MPa experimentally estimated, and it was assumed halved and doubled, too, for preliminary parametric analyses). According to these analyses, the experimental tests have been planned. Results are shown for the unreinforced masonry vault only.

Table 1 - Mechanical characteristics of the homogeneous material used and preliminary results by static non-linear analyses

Parameters values		Minimum	Mean	Maximum
Young modulus	[MPa]	1200	1500	1800
Compressive Strength	[MPa]	2.4	3.2	4
Tensile Strength	[MPa]	0.16	0.32	0.64
Collapse acceleration values	[g]	0.16	0.23	0.41

As outlined below, the previous results identified the range of expected structural capacities. Indeed, the actual collapse of the unreinforced masonry vault in terms of Peak Ground Acceleration (PGA) is equal to 0.22g. Furthermore, these preliminary results provide the collapse mechanism for the unreinforced specimen as shown in Fig. 3a.

For the strengthened specimen the masonry abutments are the most vulnerable elements (especially at the base). The arch element by means of the several strengthening systems achieves an extremely high stiffness. The TRM system usually does not provide additional stiffness, but coupled with the rib provides relevant stiffness to the curved portion, as confirmed by experimental evidence. For this reason, in a preliminary calculation, the structural elements located above the level of the vault's imposts have been modelled as a rigid block. Therefore, the structural model for the strengthened specimen is very simple. It provides both the collapse acceleration and the collapse configuration. In particular, the collapse mechanism, due to the strengthening techniques adopted, is localized in the lower portion of the masonry abutments. In particular the hinge mechanism is achieved formerly at the base of each abutment and later at the vault's imposts. The prototype model provides a collapse's acceleration of 0.5 g (with a tensile strength of 0.32 MPa) and a hinge mechanism according to the experimental evidence (Fig. 3b).

2.2 Investigation of dynamic behavior

The ultimate lateral capacity of the structures is not sufficient to design tests on shaking table. The choice of the signals and their characteristics are critical aspects to ensure that the specimen is appropriately tested. Indeed it is required to guarantee that in the input signal the natural frequency of the structure is represented. In addition, the signal should cover frequency variations due to the progressive damage during testing. For this reason modal analyses have been conducted in order to make an estimation of the modal structural frequencies. In order to obtain a reliable estimate of the structural dynamic characteristics of the vault, a numerical FEM model was developed through a micro-modelling approach.

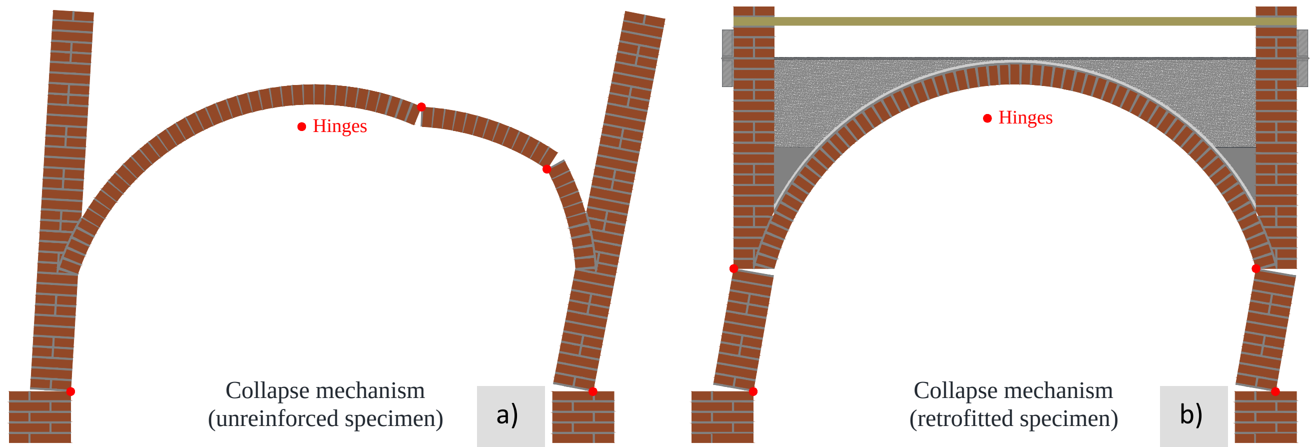

Figure 3 - Location of the hinges at collapse for the unreinforced specimen a) and strengthened specimen b) provided by the preliminary calculations

Previous experimental results showed that the seismic response of such vaulted structures is governed primarily by the mortar-brick interface [1]. A modelling that does not take into account the interface behavior would lead to meaningless results. For this reason, numerical models considering both a perfect bond at the interface between mortar and brick and a specific interface bond law were developed. An explicit calibration of the bond, after the experimental tests, has been carried out. The results of the calibration performed are shown in Table 2. However, in order to obtain a first estimate of the dynamic characteristics of the specimen, previous dynamic test results have been used [1]. Previous tests were performed in the laboratory of the Department of Structures for Engineering and Architecture, University of Naples Federico II, on a similar masonry vault. Comparing the models with equivalent homogeneous material (hence perfect bond between mortar and brick) and with interface interaction, the importance of considering the interface interaction between mortar and brick, is remarked. A comparison of results for the unreinforced and strengthened masonry vault is shown in Table 3.

In Fig. 4 the results of the modal analysis, modelling the interface between mortar and brick, for unreinforced and strengthened vault, respectively, are shown.

Table 2 - Mechanical characteristics of the bond at the interface between mortar and brick

Mechanical parameter		Numerical value
Normal stiffness modulus	[N/mm^3]	46
Shear stiffness modulus	[N/mm^3]	46
Cohesion	[MPa]	0.15
Friction angle	[°]	38.02

Table 3 - Dynamic characteristics by means of FEM model, unreinforced and reinforced specimen

Modelling strategy		Natural frequency
Homogeneous material modelling (unreinforced specimen)	[Hz]	11.29
Non-linear interface brick-mortar modelling (unreinforced specimen)	[Hz]	7.25
Homogeneous material modelling (strengthened specimen)	[Hz]	15.90
Non-linear interface brick-mortar modelling (strengthened specimen)	[Hz]	11.23

a) b)

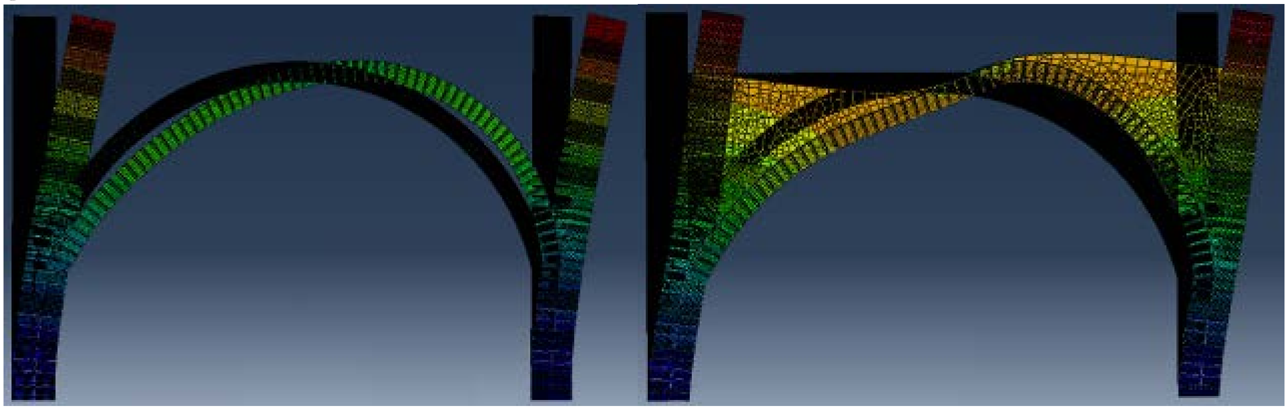

Figure 4 - First mode shape for the a) unreinforced and b) strengthened masonry vault.

3. Experimental test

The masonry specimen has been tested on the shaking table by means of signals with a progressively increasing intensity. The masonry vault has been loaded in one direction only. In order to identify the structural dynamic behavior of the specimen, each shaking has been preceded by a random signal at low intensity. The low intensity of the signal is to avoid a premature damage to the specimen. The random signal has a very ample frequency content allowing the dynamic identification.

In the first phase the tests were performed on the unreinforced vault. In the second part the tests were performed on the strengthened specimen after the partial reconstruction and strengthened by means of Textile Reinforced Mortar (TRM) [11-16]. A masonry rib has been built over the vault and over this rib a steel grid has been placed (as a wide tie). This strengthening technique has been combined with mortar joint repointing and grout injection.

3.1 Monitoring instrumentation

The specimen has been instrumented in order to monitor the structural behaviour of the vault on the shaking table during the experimental tests. The instruments were placed in the main sections of the specimen. The instrumentation setup is slightly different for the unreinforced and strengthened specimen. For the unreinforced vault, in order to monitor the accelerations, 8 devices (SN) were placed on the longitudinal profile of the vault (Fig. 5a).

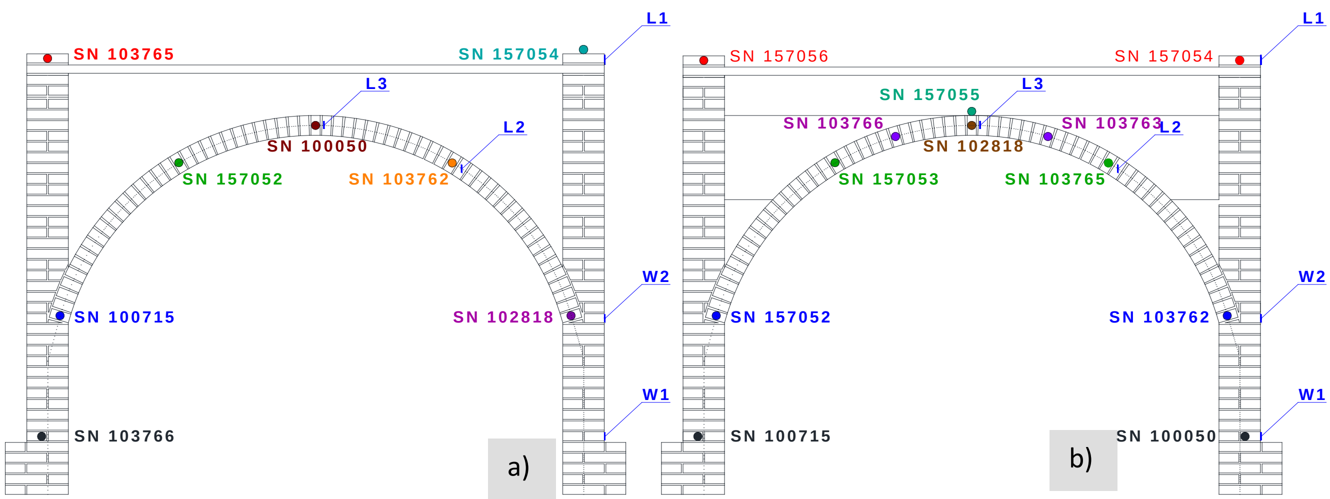

Figure 5 - Instrumentation: a) unreinforced and b) strengthened specimen, respectively.

Instead, the structural displacements have been monitored by means of 5 laser displacement transducers (L and W). On the strengthened specimen a greater number of instruments (shown in Fig. 5b) has been used. The monitoring system recorded experimental data with a frequency equal to 100Hz.

3.2 Signal choice

A dynamic test of a specimen on a shaking table must be able to highlight its dynamic behavior. So it is essential the selection of the input signal. The selection of the appropriate signal through the results obtained from the preliminary numerical analysis has been conducted. These analyses allowed both to have a first estimate of the collapse acceleration of the specimen and the frequency content. The modal preliminary analyses have shown a natural frequency of the unreinforced specimen of about 7Hz. This value has been confirmed by the analysis of recorded data after experimental tests.

The sets of seismic signals for the unreinforced and strengthened specimen are different. The signal chosen for first test (unreinforced specimen) is the one recorded in Sturno (Campania, Italy) during the 1980 earthquake. The original signal has a PGA equal to 0.18g. This signal has been scaled up to the collapse. The strengthened specimen has been subjected to another acceleration set in addition to the Sturno signal. A new set of seismic signal recorded during the Gemona (Friuli, Italy) 1976 earthquake has been adopted after the Sturno seismic sequence. This latter signal has an original PGA equal to 0.31g.

In order to allow the dynamic identification of the specimen, before and after each seismic signal, some random signals have been applied to the specimen. Each random signal has been scaled down to a PGA of 0.025g. Fig. 6 shows the accelerograms of Sturno and Gemona earthquakes, respectively.

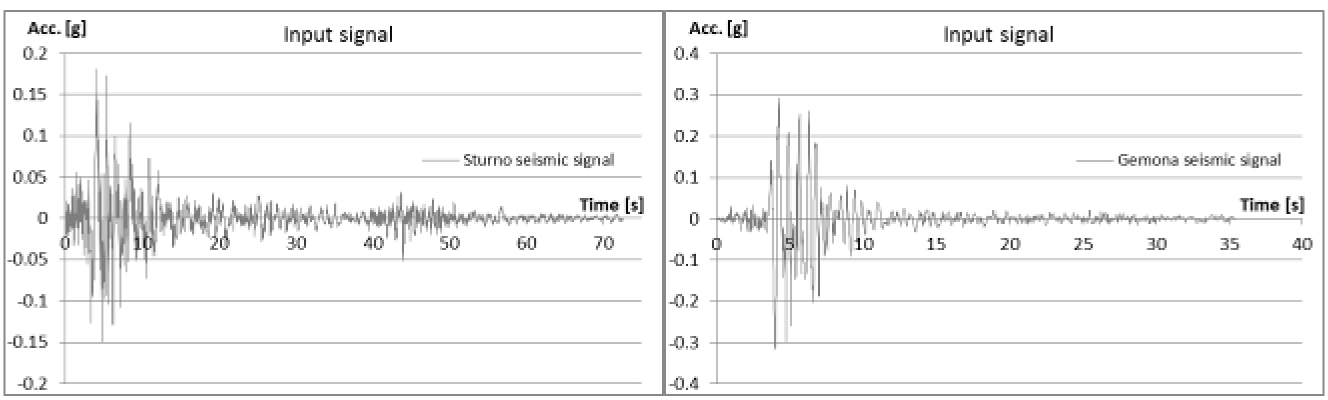

Figure 6 - Seismic input signals.

4. Experimental results

The unreinforced specimen was tested with the increasing Sturno 1980 signal up to the collapse (Fig. 7a). At the end of each test, visual surveys on the specimen have been conducted. Till the last signal having a scale factor equal to 125%, visual survey did not show any evident damage.

The collapse occurred with four plastic hinges formed almost instantly when scale factor was equal to 125%, as shown in Fig. 7a (i.e. PGA equal to 0.22g). The strengthened specimen exhibited a great increase of seismic capacity. The first visible damage manifested at a scale factor equal to 250% (i.e. PGA equal to 0.45g).

After the first evident damage occurred, the signal with a scale factor of 125% (i.e. the shaking yielding to collapse of the unreinforced specimen) has been repeated. After this repetition, the specimen did not show any additional damage. Then the specimen was loaded by the new set of signals (Gemona 1976) with increasing intensity. Heavy damage, hence failure condition, occurred at a PGA equal to 0.52g (Fig. 7b) during the last signal (Gemona signal) with a scale factor of 175%.

For the unreinforced and strengthened specimen, the preliminary calculations provided a reliable estimate of the collapse accelerations of 0.23g and 0.50g respectively, if compared to the experimental values (0.22g and 0.52g, respectively).

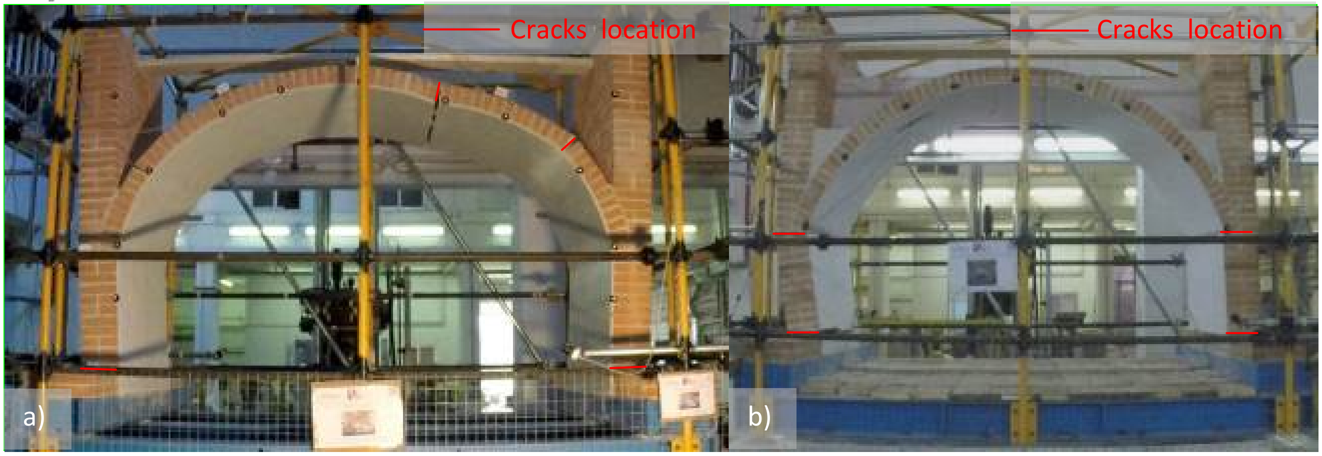

Figure 7 - a) Collapse at Sturno 125% for the unreinforced specimen, b) collapse at Gemona 175% for the strengthened specimen

Furthermore, the collapse modes of unreinforced and strengthened specimen were predicted by the preliminary calculations (Fig. 3a and Fig. 3b, respectively).

4.1 Specimen damage evaluation

The continuous monitoring of the specimen allowed to estimate its damage. Indeed, the unreinforced specimen during the entire test did not exhibit any visible damage prior to the collapse. For this reason it is necessary to analyse the dynamic structural behaviour to get information about the damage state. In particular, the study of the transfer function between the signal generated on the base and monitored on the structure allows the estimation of the natural frequency. The transfer function was evaluated for each random signal.

Fig. 8 shows the transfer functions obtained by means of the random signal generated by the shaking table before the first seismic signal assigned and before to the signal which has generated the collapse. The Fig. 8a) shows the transfer function of unreinforced specimen whereas the transfer function of the strengthened vault in the Fig. 8b) is shown.

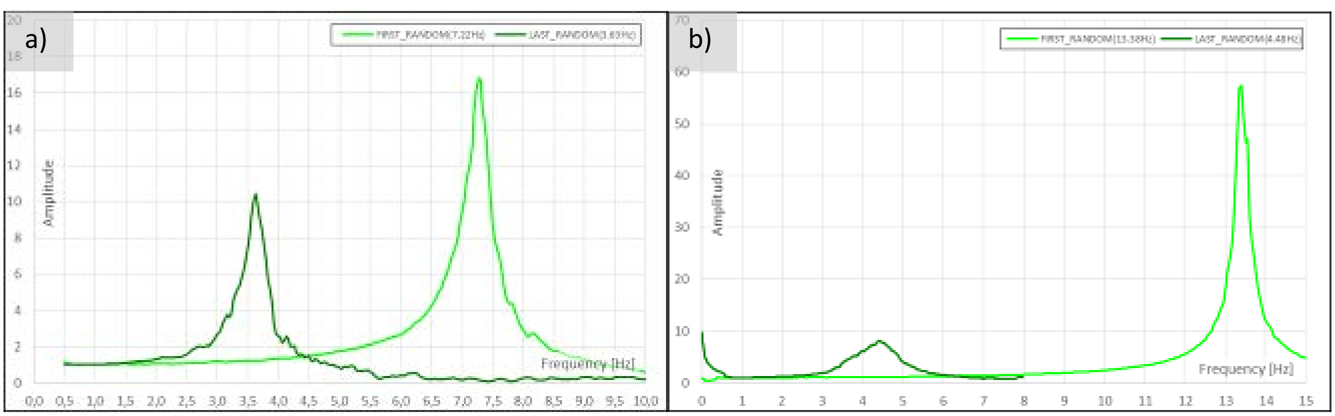

Figure 8 - Transfer functions of undamaged vault and before collapse for a) unreinforced and b) strengthened vault, respectively

For the unreinforced specimen the natural frequency is 7.22Hz. The transfer functions also show the gradual degradation of stiffness due to the progressive damage. The transfer function calculated by means of the random signal shows how the natural structural frequency is halved (3.63Hz) before collapse. For the strengthened specimen a natural frequency equal to 13.38Hz has been observed. Before the collapse the natural frequency is reduced up to -67% (4.48Hz).

4.2 Acceleration and displacement profiles

Interesting is the analysis of the maximum accelerations induced in different monitored sections of the masonry vault. The maximum acceleration on the structure is obtained for each test. Fig. 9 shows how the maximum accelerations are distributed in the unreinforced specimen during the Sturno signal set for the left and right sides. The acceleration profiles with scale factors equal to 25%, 50%, 75%, 100% and 125% (collapse) are represented. The horizontal acceleration profile shows a symmetrical behavior of left and right sides of the vault.

A similar analysis for the strengthened vault has been conducted as shown in Fig. 10, at the same scale factors. The shape and intensity variations allow some principal effects of the reinforcement system to be discussed.

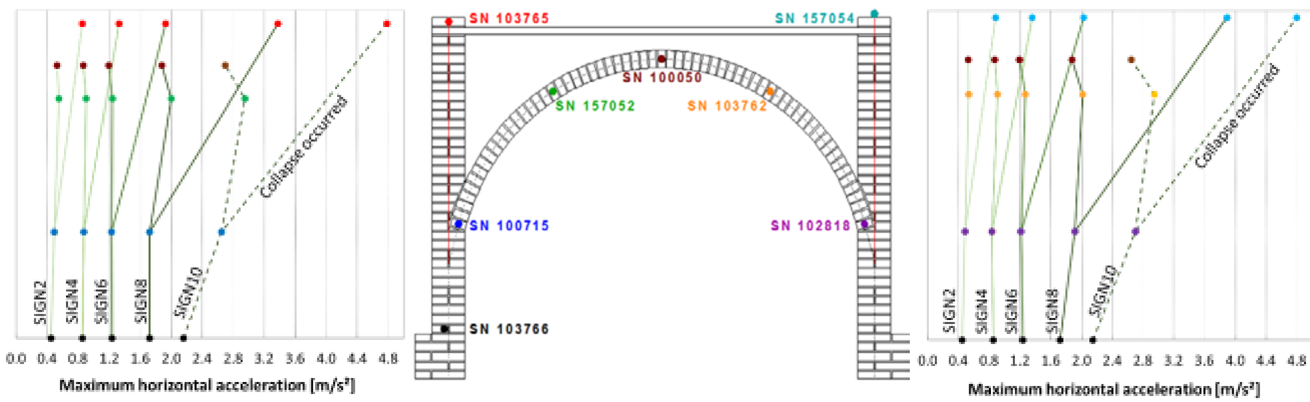

Figure 9 - Acceleration profiles of the unreinforced specimen (curved element and abutments comparison for the left and right sides)

Fig. 10 shows also how the stiffness increased due to the reinforcement. This effect is clear for the curved portion and the lateral walls presenting a sort of rigid motion since the profiles are almost overlapping. Similar considerations can be repeated looking at the relative displacements (not shown here).

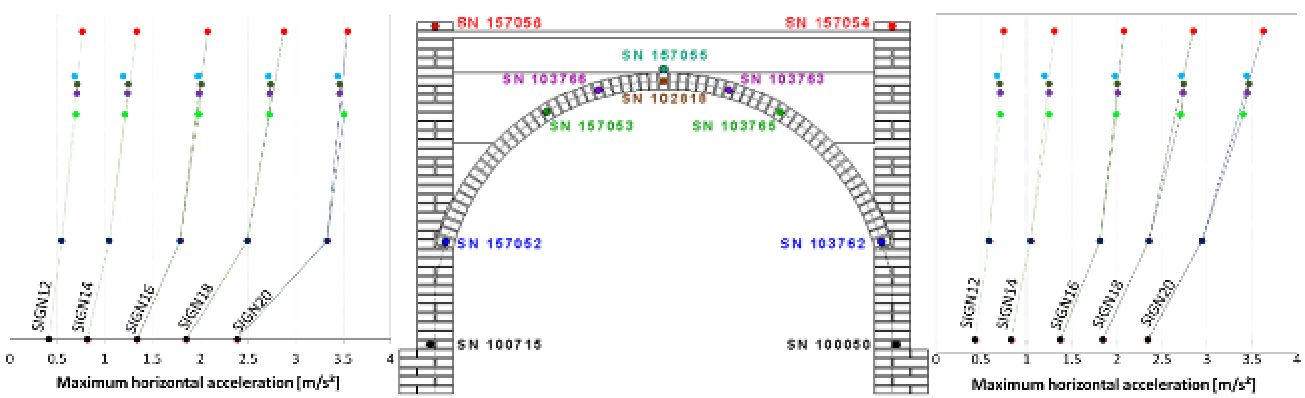

Figure 10 - Acceleration profiles of the strengthened specimen (curved element and abutments comparison for the left and right sides)

5. Conclusions

Shaking table tests have been carried out on full-scale masonry vaults. The experimental results of the unreinforced and strengthened specimens have been briefly discussed in the present work. The vault has been tested without any vertical load (e.g. filling) acting at the extrados. Such load condition has been explicitly adopted in order to simulate typical vaulted roofs in historical religious buildings. During the experimental tests, the unreinforced and strengthened vaults have been monitored by means of accelerometers and laser-optical displacement sensors. After each test the masonry vault has been inspected in order to detect the damage.

After the first tests on the unreinforced specimen, in several locations, crack openings were not evident at the interfaces between mortar and brick. The vault reached the collapse (four hinges activated) without a warning damage. This result confirms the hinge mechanism to be the limiting failure mode in masonry vaults (rather than sliding or crushing failure). However the analysis of instrumental data showed a progressive variation of natural frequency, hence a damage development too small to be directly observed.

By the numerical and experimental comparison, the preliminary calculations have been validated. For the unreinforced specimen, by assuming the same average mechanical properties, the preliminary calculation provided both the actual collapse mode and the collapse acceleration of 0.23g very close to an experimental value of 0.22g.

The strengthened vault presented a noticeable increase in seismic capacity. Global collapse activated at 0.22g (5^{th} shaking) for unreinforced vault, while first visible damage occurred at 0.45g (13^{th} shaking) for strengthened counterpart. However a further repetition (14^{th} shaking) at 0.22g (i.e. the collapse of unreinforced specimen) produced no evident increase of damage to the strengthened vault. Hence, even after first damage the capacity of the strengthened vault is still higher than the unreinforced one. It is worth noting that the signal repetition does not yield to an identical test because even if the signal is the same, the structure changed its dynamic propertied with damage. A new set of signals (Gemona earthquake in 1976) with gradually increasing acceleration yields to collapse of strengthened vault at 0.52g (18^{th} shaking). Effect of replicas could be relevant and it requires further studies.

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