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EXTRADOS STRENGTHENING OF SINGLE-LEAF VAULTS AGAINST SEISMIC ACTIONS

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Abstract. *Single-leaf vaults are acknowledged among the most vulnerable components of historical masonry constructions with respect to earthquake loads, particularly when featuring large span to thickness ratios, as in the case of single leaf covering the main nave of churches. These elements often require structural strengthening against seismic actions. In this paper, two different extrados techniques are tested: lightweight plywood restraining elements and FRP laminates embedded in a lime mortar layer. The techniques are tested on single leaf vaults having a very unfavorable span to thickness ratio.*

A previous study on less slender vaults, showed that lightweight plywood centerings, applying passive confinement to the vault extrados, inhibit the onset of the typical four-hinges failure mechanism. This lightweight, dry solution can be easily prefabricated, transferred and assembled at the construction site. The technique is reversible and fully compliant with the major preservation principles. FRP is also effective against the onset of the failure mechanism but entails larger deformations of the retrofitted vault, which may be detrimental in the case of possible decorations. The solution requires special man labor to ensure correct smoothening and cleaning of the vault extrados and to trigger effective bond between the mortar and the vault extrados. Both solutions are shown to enable small relative displacements of the vault springing, which may follow the deformation of possible internal ties.

The effectiveness of these retrofit techniques was comparatively verified through experimental tests on single-leaf barrel vault stripes at 1:2 scale subjected to cyclic distributed unsymmetrical loads and through comparison with the seismic response of a reference unreinforced single-leaf vault.

1 INTRODUCTION

Single leaf vaults are thin vaults (about 50 mm thick) adopted in churches and historical buildings all over the European territory [1-3] as lightweight false ceilings, typically decorated with stuccos and frescoes. These elements, which are made of a single layer of bricks laid flat and usually lacking any extrados backfilling material and lunettes, are acknowledged among the most vulnerable components of historical masonry buildings with respect to earthquake loads, particularly when featuring quite large span to thickness ratios. Single leaf vaults may bridge spans ranging between 3 and 6m in residential historical buildings and between 6 to 10m in the main naves of churches.

Considering single-leaf barrel vaults lacking backfill material, equilibrium is guaranteed as long as the thrust line, associated with both static and seismic loads, develops within the vault thickness [4-8]. Unsymmetrical load distributions may be detrimental for these structures provided that the ideal resisting arch has a reduced possibility to shift and modify within such a reduced thickness. This problem could be emphasized in the case the vault has not a catenary geometry, but rather a circular geometry, in which case the thrust line in static conditions does not overlap the centroid axis. As a result, these structures are particularly vulnerable even for low-intensity earthquakes, as confirmed by the collapses observed after recent earthquakes [9].

As stated in [9-10], 3 mechanisms may be experienced by thin single-leaf vaults in the case of a seismic event: (a) indirect differential bending of the vault crown caused by the rotation of the vault springing due to the unconstrained rocking motion of the supporting wall (Fig. 1a); (b) severe shear distortion stresses and distortions due to the onset of the differential rocking mechanism along the nave ends – usually as a result of the different stiffness of the façade and the transverse arches (Fig. 1b); and (c) direct differential bending with the onset of a four hinge mechanism due to the distributed seismic actions associated to the vault mass (Fig. 1c).

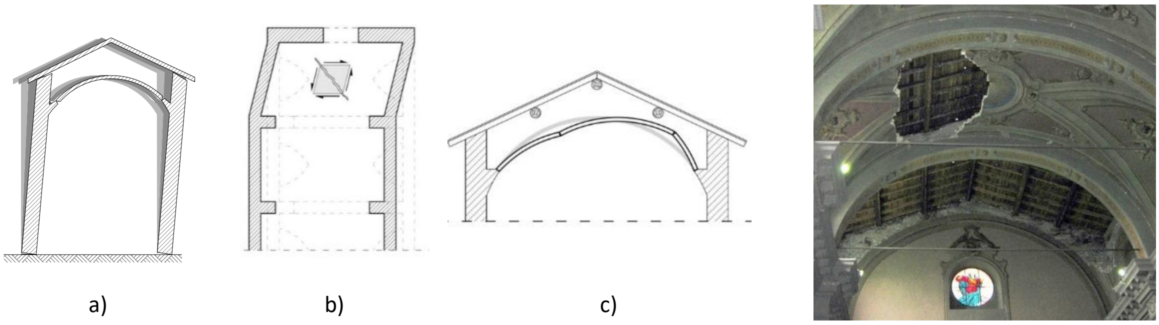


Figure 1: Main seismic vulnerabilities of single-leaf vaults: (a) indirect bending following rocking of the abutments; (b) shear distortion following differential rocking; (c) direct bending of the vault due to its own mass (from [17]). On the right: total collapse of the first bay (due to mechanism b) and partial collapse of the second bay (due to mechanism c) of the main nave of S.Pietro Church, Vobarno, Italy, after Salò earthquake, 2004 [9].

The two former mechanisms can be limited or inhibited through global interventions, such as either perimeter ties (mechanism a), or roof and floor diaphragms (mechanism a and b), which reduce the vault impost rotation and relative displacement [11]. On the contrary, the direct differential bending (mechanism c) cannot be inhibited, unless special targeted interventions are carried out on the structural element. Possible collapse induced by direct differential bending was addressed in a research carried out at the University of Brescia, in which a series of strengthening solutions were proposed and tested on full scale single-leaf vaults having 1/100 thickness to span ratio and a span of 5m [12-17].

In the present paper, the study was extended to assess the effectiveness of some strengthening solutions in the case of thinner single-leaf vaults, with 1/200 thickness-to-span ratio, thus bridging larger spans up to 10m. Two different extrados techniques were proposed, namely: lightweight plywood restraining elements, and FRP laminates embedded in a lime mortar layer. To this end, 1:2 scaled single-leaf barrel vault stripes subjected to cyclic distributed unsymmetrical loads were tested. Results were compared with the seismic response of a reference unreinforced single-leaf vault.

2 STRENGTHENING TECHNIQUES INHIBITING DIRECT DIFFERENTIAL BENDING MECHANISM

The strengthening of single leaf barrel vaults with respect to direct differential bending mechanism usually adopts techniques derived from the traditional strengthening of masonry vaults, selecting those which do not increase the vault mass and avoiding unsymmetrical load sets [12]. The most common techniques entail the adoption of masonry spandrel walls [18] [10] [12-13], RC extrados slabs, or high-performance lime mortar extrados slabs strengthened with fiber mesh [12-13]. The former solution constrains the deformation of the vault crown and allows the thrust line to migrate within the spandrel wall height. The latter techniques enforce a composite structure behavior, allowing the ideal resisting arch to adjust within a higher thickness, but increases the mass of the vault and, more importantly, in seismic conditions, the migration of the thrust line may lead to a decompression of the vault crown, entailing the risk of debonding and unthreading of bricks from the existing structure [17]. Innovative lightweight ribs overlaying the vault extrados profile, made of lime mortar reinforced with inorganic matrix grids and of an inner polystyrene core, were also proposed [14].

Extrados stiff lightweight plywood retaining structures (also referred to as ‘centerings’) simply overlaying and not connected to the existing vault were also proposed [16-17]. The adoption of extrados centerings is a passive solution, which is conceived to maintain the structural role of the vault in static conditions and to provide the necessary passive confinement in seismic conditions (Fig. 2 left). The system is designed as a 3-hinged arch overlaying the existing vault extrados, hinged at the abutments and with an internal hinge at the vault key section (Fig. 2 right). Connections along the centering-to-vault interface are avoided as to prevent the decompression of the vault. This is a lightweight, dry and cost-effective solution, fully reversible, minimally impairing, and not requiring any special man labor. The effectiveness of the system against direct differential bending was verified on single-leaf vaults having 1/100 thickness-to-span ratio [16-17]; in the tests, the collapse mechanism was inhibited for accelerations up to 4 times those causing the collapse of the unreinforced vault, and the stiffness of the vault was increased.

The use of fiber-reinforced polymer (FRP) strips is another efficient solution [19]. In this case, failure of the strengthened structure may arise due to possible shear failure close to the springing, as the technique enhances the sole bending capacity, or due to delamination of the FRP strips, triggered either by the uneven surface of the vault or by failure of the bond between the vault and the laminate. In order to solve durability issues and decay processes due to loss of transpiration potential, steel-reinforced grouts (SRG) [20], or inorganic matrix grids (IMG) embedded in lime-based mortar are alternative techniques [21-22]. In the present study, FRP laminates embedded in a lime mortar layer were considered.

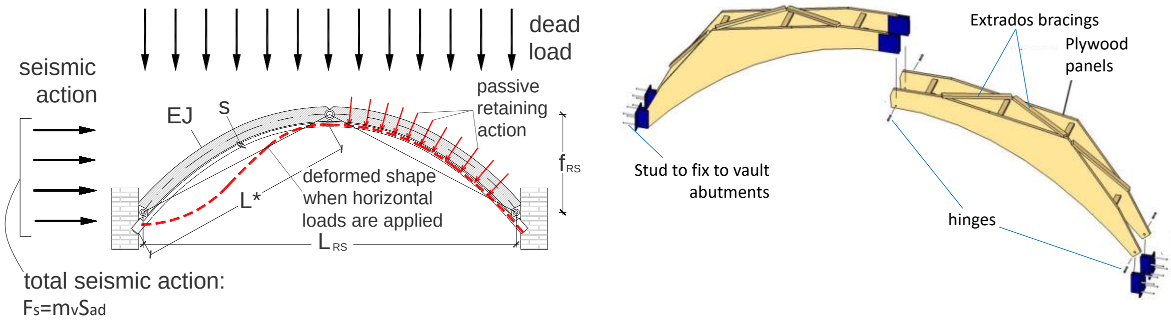


Figure 2: Confining action of the plywood centering in case of earthquake (left) and details of the centering components and of the hinge location (right) [17]

3 EXPERIMENTAL TESTS

The experimental campaign was aimed at assessing the effectiveness of lightweight plywood centerings and FRP laminates for single-leaf vaults with very unfavorable thickness-to-span ratio (1/200) and was inspired by the campaign carried out at the University of Brescia on medium-span single-leaf vaults (1/100) [15-17]. The same testing bench was adopted, and the thickness of the vault was reduced to resemble a 50mm vault bridging about 10m span.

3.1 Modelling hypothesis

According to the previous studies [15-17], the single-leaf vault was modelled as a series of transversal adjoining vault stripes, thus disregarding the possible tridimensional confining effects due the longitudinal arches developing between the head walls or transverse arches, which is a conservative assumption.

In addition, it was assumed that both indirect differential bending and shear distortion (mechanism a and b of Fig. 1) are inhibited through global interventions; so, it is considered that the vault is affected by the sole direct differential bending (mechanism c of Fig. 1).

Based on these two assumptions, a single barrel vault stripe of unit width was modelled in the experimental specimen, and the vault springing were assumed as fixed to the testing bench.

3.2 Description of the unreinforced experimental specimen

The experimental masonry vault specimen is a basic single-leaf barrel vault stripe of unit width at a scale 1:2 with a polycentric profile (span L=5m, rise f=1.42m, thickness t=27mm) (Fig. 3), thus representing a real vault of span L=10m, rise f=2.84m and thickness t=54mm.

A flat brick arrangement with a running bond masonry texture was adopted; the ultimate capacity of possible plastic hinges is thus associated with the tensile resistance of the joints. The vault stripe is embedded at the springing and pre-stressing clamps and anchoring bars were installed to fix the vault abutments to the testing bench.

Mechanical properties of the adopted bricks and mortar (7.5% NHL 3.5, 8.5% lime putty, 34% 1.5mm aggregates, 34% 3.0mm aggregates, 16% H_2O) are reported in Table 1.

Table 1: Average mechanical properties of bricks and mortar

Solid Clay Bricks (27x120x250mm)	Mortar (bed joints 7-8mm)
Compressive strength: 2.245 MPa	Compressive strength: 0.337 MPa
Flexural strength: 4.79 MPa	Flexural strength: 0.180 MPa
Young's modulus: 10883.26 MPa	Flexural strength (joint): 0.328 MPa

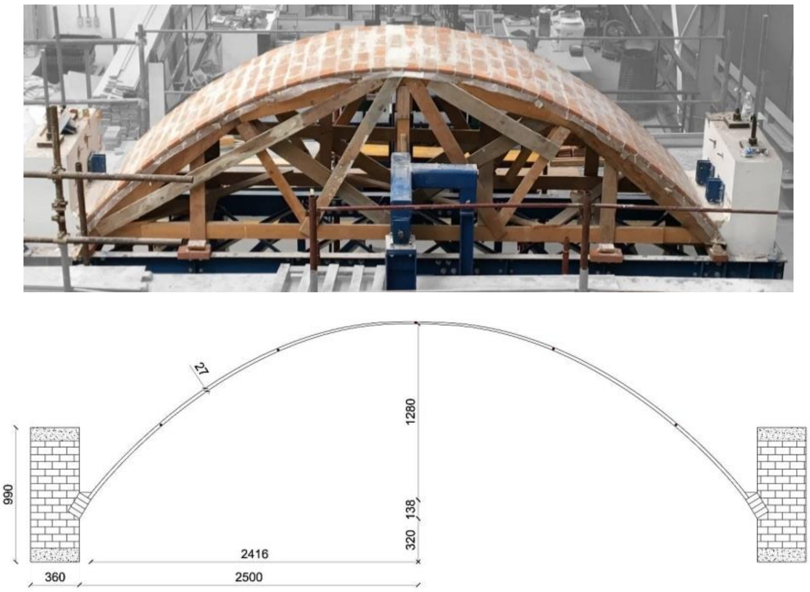


Figure 3: Side view (top) and geometry (bottom) of the unreinforced vault stripe layout (depth = 970mm)

3.3 Description of the experimental specimen reinforced with plywood centering

The single leaf vault specimen is strengthened by means of two extrados lightweight 3-hinge wooden centerings, made of 30mm thick plywood panels, braced along the extrados edge to avoid buckling (Fig. 4). The extrados reinforcement is designed as a 3-hinged arch. Such a structural scheme enables small relative displacements of the vault springing, which may follow the deformation of the possible internal ties or of the roof box structure. The effectiveness of the system, both in the case of fixed supports and of a possible horizontal settlement of the vault abutments, was studied in a previous research [17].

The centering physical hinges at the springing and at the vault key are located as close as possible to the centering-to-vault extrados interface, as to reduce the offset of the vault centroid axis with respect to the centering. This reduces the relative displacements of the two structures both in the case of unsymmetrical load conditions (such as in the case of an earthquake) and in the case of spreading supports. No shear transfer is allowed along the vault-to-centering interface, whilst initial contact between the centering and the vault is enforced through thin wooden wedges. More about the design of the strengthening intervention in terms of flexural stiffness of the plywood centering may be found in [17].

Two tests were carried out on this specimen. In the first test, the wooden wedges were positioned between the vault and the centering and were simply glued to the vault, to enable a passive confining action; in the second test, the wedges were forced in correspondence of the vault-to-centering interface and were fixed in that position, thus leading to an active confining intervention. The results of both the tests are reported and commented in the following.

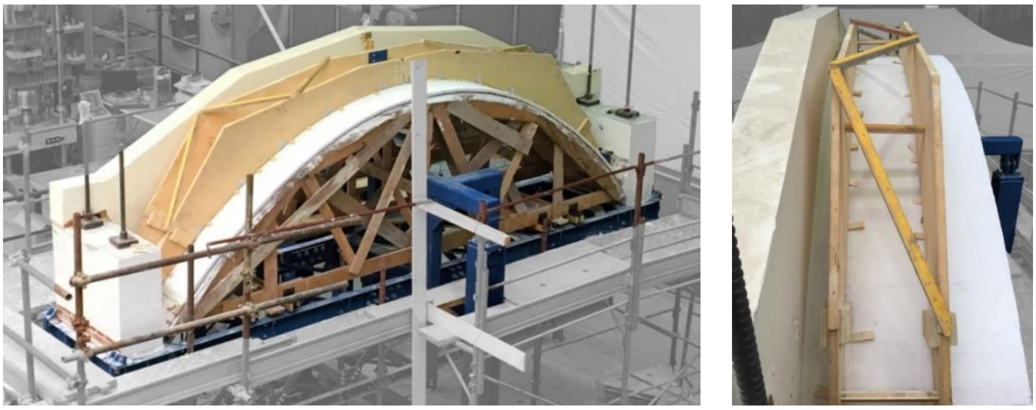


Figure 4: Side and top view of the vault stripe reinforced with the plywood centering

3.4 Description of the experimental specimen reinforced with FRP laminates

The single leaf vault specimen is strengthened by means of FRP laminates embedded in a pozzolanic hydraulic lime mortar layer (Fig. 5 left). The choice of an inorganic matrix was aimed at improving the transpiration potential of the retrofit intervention with respect to a polymer matrix, for the sake of durability.

A first layer of 3-4mm thickness was laid on the bare vault extrados and on the abutments, the carbon fiber mesh was embedded and then covered with a second layer of mortar with equal thickness (Fig. 5 right). The mechanical properties of the mesh and of the mortar are reported in Table 2.

Figure 5: Side view of the vault stripe reinforced with the FRP laminates before the test (left) and top view of the vault during the strengthening operations (right)

Table 2: Average mechanical properties of carbon fiber grid and mortar

Carbon fiber mesh	Mortar matrix
Ultimate tensile strength: 4830 MPa	Compressive strength: 20.98 MPa
Elongation at break: 1.9%	Flexural strength: 4.83 MPa
Young's modulus: 240000 MPa	Young's modulus: 10633 MPa

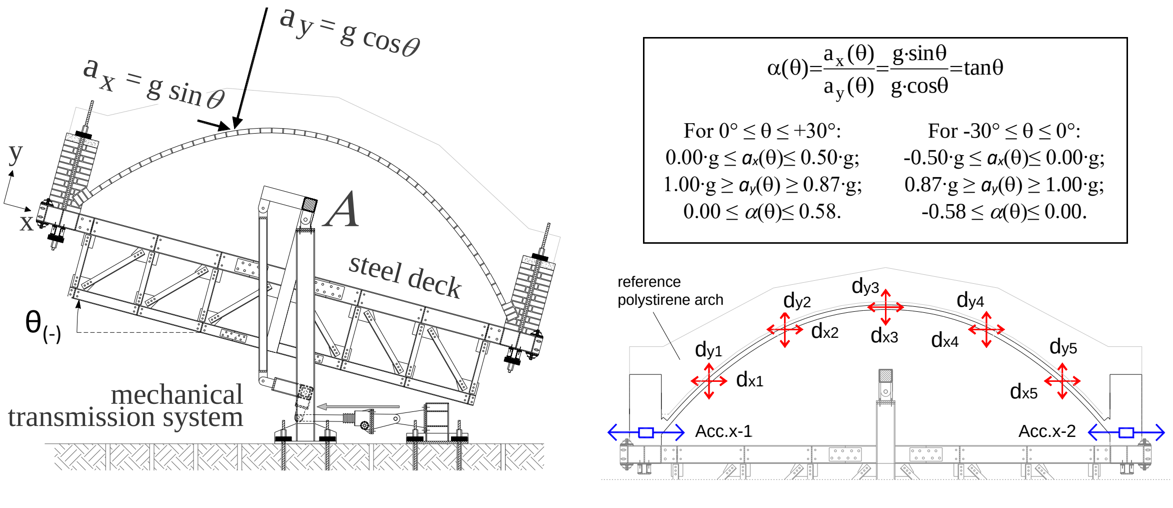
3.5 Test set-up

The same test set-up proposed in [15-17] was adopted. The single leaf vault strip was assembled on a special swinging steel frame (Fig. 6a). By swinging the testing frame, increasing uniformly distributed inertia forces are applied along the vault crown. Rotation, and thus inertia forces, can be increased either up to failure of the specimen or up to the maximum rotation capacity of the testing bench. Dynamic effects cannot be considered.

The testing bench is composed by a rigid steel deck rotating both clockwise and counter-clockwise about a pivot point A on a vertical frame fixed to the ground. The deck rotation is applied through a mechanical transmission system, actuated by an electromechanical jack (Fig. 6a).

By assuming local reference fixed to the deck, the rotation of the specimen due to the swinging of the testing bench causes the gravity acceleration to decompose into one component parallel (horizontal, $a_x(\theta)$) and into a component orthogonal (vertical, $a_y(\theta)$) to the deck. For increasing the tilting angle (θ) from 0 to 30°, $a_x(\theta)$ increases, simulating earthquakes of increasing intensity; on the other hand, $a_y(\theta)$ slightly reduces, thus simulating a reduction of the vertical load in static conditions ranging between 0 and 13.4%. The horizontal-to-vertical spectral ratio $\alpha(\theta)=a_x(\theta)/a_y(\theta)$ can be easily determined (box in Fig. 6).

During all tests, the vault ring differential deflection was monitored in five points through vertical and horizontal displacement transducers, pinned to the vault mid axis and to a rigid polystyrene arch fixed to the abutments (Fig. 6b). The deck tilting angle was monitored by two one-direction accelerometers fixed to the specimen abutments and directed as the local reference horizontal axis x. Further details may be found in [15-17].



a) b)

Figure 6: a) Side view of the swinging testing frame in the tilted position (in the box: clockwise and counter-clockwise maximum rotations and corresponding extreme values of relative accelerations and horizontal-to-vertical acceleration ratio); b) instruments set-up: red arrows represent displacement transducers (d_x, d_y) and blue arrows represent accelerometers (Acc.x) [17].

4 EXPERIMENTAL TEST RESULTS AND DISCUSSION

Four experimental tests were carried out. In the first test (Test 0), the tilting angles corresponding to the first cracking and to the collapse of the unreinforced vault were determined as reference values. Only counter-clockwise rotations were imposed to the specimen in order to avoid damage on both sides of the vault crown. The test was stopped at the tilting angle corresponding to the collapse of the vault (Fig 7a). Three tests on the reinforced vault were then carried out: two tests on the vault reinforced by means of plywood centerings with unforced (Test 1a) and forced (Test 1b) wooden wedges; and a test on the vault strengthened with FRP laminates (Test 2). Applied rotation cycles are shown in Fig. 7. All tests were interrupted for overcoming the rotation capacity of the testing frame (θ=30°), corresponding to an $a_x(\theta)$ of about 0.50g and $\alpha(\theta)$ of about 0.58.

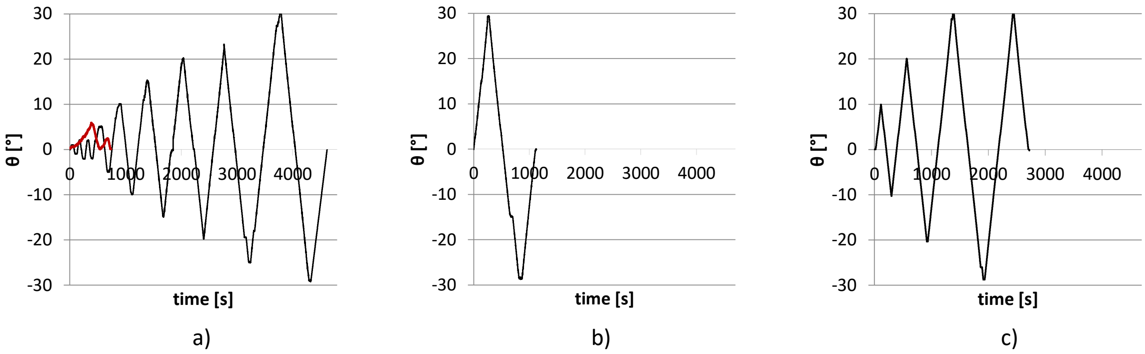


Figure 7: Applied rotation cycles in the case of: a) the unreinforced vault (Test 0) (bold red line) and of the vault reinforced with plywood centering with unforced wedges (Test 1a) (black line); b) vault reinforced with plywood centering with forced wedges (Test 1b); c) vault reinforced with FRP laminates (Test 2).

In Test 0, the unreinforced specimen was rotated up to the onset of the first crack. For a tilting angle θ=5.8° (corresponding to α=0.105), the windward vault segment collapsed leaning against the construction framework kept beneath the specimen (Fig. 8). The testing bench was then brought back to the horizontal position, and the vault restored the initial uncracked configuration. In a second cycle, the tilting angle was increased up to a second collapse of the vault. This time, the unreinforced vault collapsed for a tilting angle θ=2.4°, lower than that experienced in the previous cycle, since the specimen was already damaged. The ultimate horizontal-to-vertical spectral ratio was thus considered α =0.044 for the damaged vault.

Figure 8: Side view of the vault for a counter-clockwise rotation θ=5.8°, corresponding to the first collapse. The red arrow and the figure on the right show the vault leaning against the construction framework.

In the second phase of the experimental campaign, the vault was reinforced without repairing the cracking triggered during Test 0, so as to be representative of a damaged existing vault.

The vault was first reinforced by means of plywood centerings with unforced wooden wedges ensuring contact at the vault-to-centering interface. In this first test (Test 1a), the vault did not collapse even for tilting angles up to ±30° (Fig. 9 left); however, deformations higher than expected were recorded. Two corrective measures were thus applied as to reduce the vault deformations (Test 1b): the wooden wedges at the vault-to-centering interface were forced as to simulate an active strengthening intervention, and an additional restraint was positioned at the centering ends as to limit possible vertical movements of the hinges. In this case, substantially smaller vertical displacements of the reinforced vaults were observed (Fig. 10). In both cases, the effectiveness of the plywood centerings in constraining the upward vertical displacement was verified.

Finally, the vault was reinforced by means of FRP laminates embedded in the lime mortar layer (Test 2). In this case, a crack opened in correspondence of the measuring point 2 (Fig. 6b) for a tilting angle θ=25.9°; however, collapse of the vault was not triggered even for tilting angles up to the testing bench capacity ±30°.

A side view of the vault strengthened with plywood centerings and FRP laminates in correspondence of a counter-clockwise rotation equal to 30° is shown in Fig. 9.

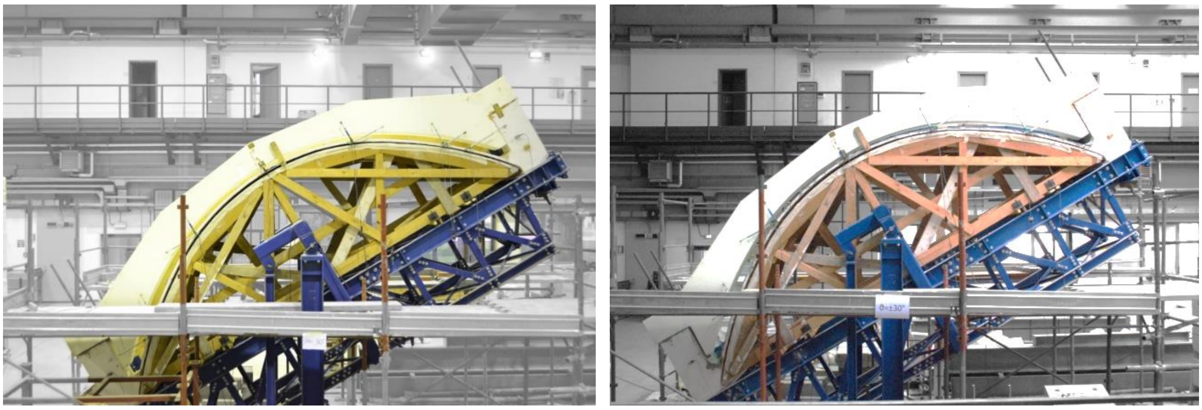
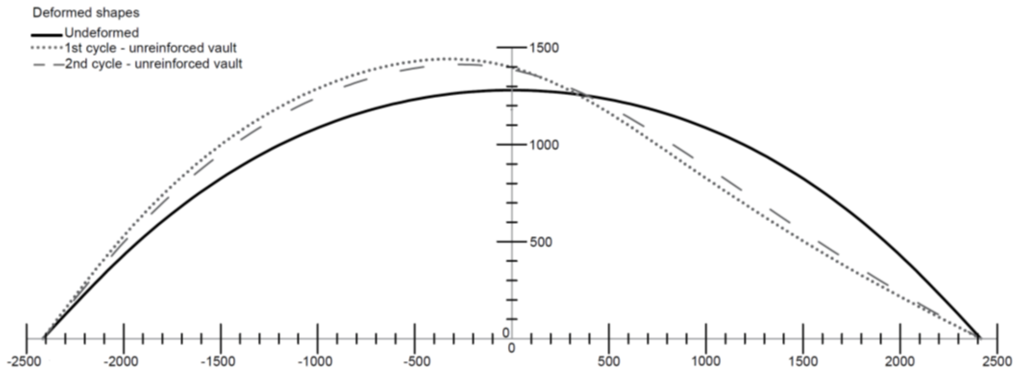


Figure 9: Side view of the vault for a counter-clockwise rotation θ=30°, corresponding to the rotation capacity of testing bench, for the vault strengthened with plywood centerings (left) and FRP laminates (right)

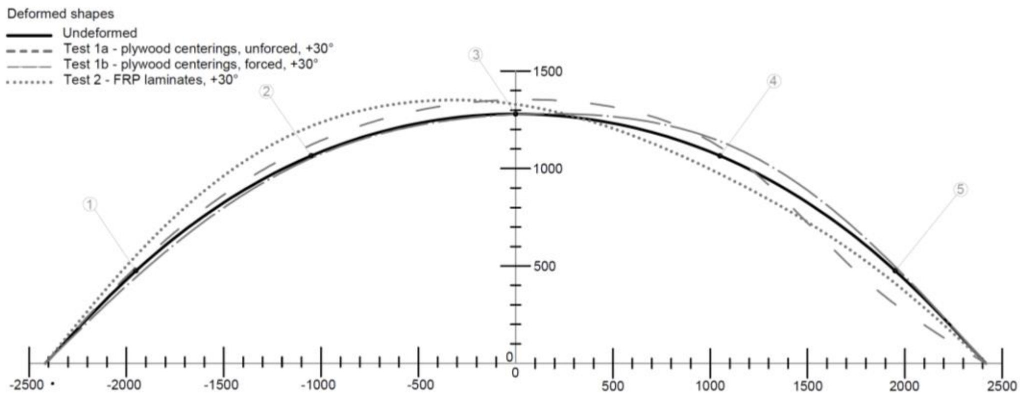
The deformed shape of the vault in the unreinforced condition is compared to the deformed shape for a counter-clockwise rotation of 30° in Figure 10a. Figure 10b shows the comparison of the deformed shapes of the vaults retrofitted with the three different strengthening solutions for a tilting angle equal to a counter-clockwise rotation of 30°. Deformations are magnified by a factor of 20. It should be noted that in Test 1b, the undeformed shape of the vault shown in the figure is not representative of the actual initial shape of the vault since the forcing operation of the wooding wedges was neither perfectly homogeneous nor symmetric along the vault extrados.

In all tests, for increasing rotation, the leeward part of the vault moves upward whereas the windward part moves downward. In case of centering strengthening, the leeward part of the vault pushes on the centering whereas the windward part may detach from it, thus leading to higher displacements in the windward part with respect to the leeward one. Displacements of the retrofitted vault are quite small even in correspondence of tilting angles approaching the rotation capacity of the testing frame. In the case of FRP strengthening, the behavior is similar meaning that the deformed shape shows the windward vault segment moving downwards, and the leeward segment moving upwards, but, in this case, larger displacements are observed with respect to the case of centering strengthening.

All the proposed techniques are proved to be effective solutions in improving the seismic response of the single leaf vault. However, the compatibility of the higher deformations exhibited by the vault strengthened with FRP laminates with the conservation of possible frescoes or stuccos on the vault intrados needs to be verified.



a)



b)

Figure 10: Deformed shape of the unreinforced vault (a) and comparison of the deformed shapes of the vaults retrofitted with the three different strengthening solutions (b) for counter-clockwise rotation of 30°

5 CONCLUDING REMARKS

In this paper the seismic strengthening of barrel single-leaf masonry vaults with large span to thickness ratios, lacking lunettes and backfill material, is addressed. Such a typology is quite frequently found in churches, where single leaf vaults cover the main naves. The three major failure mechanisms of single leaf vaults subjected to earthquake were addressed, and focus was made on the strengthening against direct differential bending, which was acknowledged as the mechanism that cannot be inhibited by means of global seismic retrofit techniques (such as perimeter ties and roof or floor diaphragms) but rather requires specific strengthening of the vault. In particular, focus was made on vaults with large span-to-thickness ratios.

An overview of possible strengthening techniques against direct bending mechanism was presented, and two different extrados solutions were proposed and tested: lightweight plywood restraining elements and FRP laminates embedded in a lime mortar layer.

Plywood centerings apply passive confinement to the vault extrados. The reinforcement is designed as a 3-hinged arch to allow accommodating possible small relative displacements of the vault springing, which may follow the deformation of internal ties or roof box structure. The solution may be conceived as passive or slightly active, in the latter case wooden wedges are forced along the vault-to-centering interface. FRP strengthening consists in embedding a carbon fiber grid into an inorganic pozzolanic lime mortar matrix.

The effectiveness of the retrofit techniques was verified through experimental tests on single-leaf barrel vault stripes at 1:2 scale, subjected to cyclic distributed unsymmetrical loads and through comparison with the seismic response of a reference unreinforced vault.

Lightweight plywood centerings were shown to inhibit the onset of the typical four-hinges failure mechanism. This lightweight, dry solution can be easily prefabricated, transferred and assembled at the construction site. The technique is reversible and fully compliant with the major preservation principles. FRP is also effective against the onset of the failure mechanism but entails larger deformations of the retrofitted vault, which may be detrimental in the case of possible decorations. The solution requires special man labor to ensure correct smoothening and cleaning of the vault extrados and to trigger effective bond between the mortar and the vault extrados. Both solutions are shown to enable small relative displacements of the vault springing, which may follow the deformation of possible internal ties.

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