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Pre-damaging test of a full-scale masonry cross vault subjected to in-plane cyclic shear loading: main results and design of the FRCM-based strengthening intervention

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Abstract

An extensive experimental campaign has been started within the frame of the project REVHEAL (Structural Rehabilitation of Vaults in Heritage Asset Learning), funded by the Italian PRIN 2022 PNRR research program, to investigate the behavior of masonry cross vaults subjected to in-plane shear resulting from seismic actions. A full-scale cross vault was constructed in the laboratory "P. Pisa" of the University of Brescia, where a test rig was built to replicate seismic effects through quasi-static reverse cyclic displacements applied at two moving abutments. The vault, representative of heritage constructions, features arches on three sides and a perimeter wall on the fourth. The experiment investigates structural behavior before and after retrofitting with a Fiber Reinforced Cementitious Matrix (FRCM) system, consisting of a basalt fiber mesh applied exclusively to the vault's extrados. The study emphasizes the integration of Geomatics and Structural Engineering to create reality-based models that account for typically neglected aspects in historic masonry analysis, such as deformed geometry and block arrangement. This paper reports on the first research phase, focusing on loading cycles designed to simulate severe pre-damage conditions typical of a structure approaching ultimate capacity. Results from the cyclic test are discussed in terms of strength, damage progression, and displacement capacity. An extensive 3D metric survey campaign supported the structural tests, producing dense point clouds with RGB data from LiDAR and photogrammetry. Additional topographic measurements ensured model accuracy and provided high-quality reference data for future comparisons.

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1. Introduction

Masonry vault systems are a fundamental component of the European architectural and structural heritage that require careful study, preservation, and, when needed, retrofitting. Gaining a comprehensive understanding of these structures requires examining their construction techniques, materials and structural behavior under various loading conditions, including both static and seismic actions. As thrust-based structures, masonry vaults were historically built without scientific analysis, presenting significant challenges to architects and builders, who relied on empirical methods and adapted technical solutions to the conditions of each site. Although these structures typically perform well under static loads, vaults are particularly vulnerable to seismic actions. In cases such as cloisters or churches, the lack of seismic-resistant systems, like ties and floor or roof diaphragms, can lead to the activation of rocking mechanisms in columns or transverse arches that support the vaults, which, in turn, may experience differential settlements at supports. Damage surveys conducted after various earthquakes that struck Italy in recent decades have shown that the in-plane shear stresses induced by these settlements are frequently the primary cause of sudden and severe collapses of masonry vaults. Among the different vault typologies, cross vaults are probably the most vulnerable to seismic actions and, therefore, they deserve to be experimentally investigated to improve the current knowledge about their structural behavior and to support the development of innovative retrofitting technologies. The digital documentation itself can benefit nowadays from experimental integrated advanced survey technologies that can deliver accurate 3D models supporting assessment of structural conditions (Barazzetti et al, 2009 and Previtali et al., 2022).

The literature reports a limited number of research studies that have experimentally investigated the in-plane behavior of masonry cross vaults, employing either full-scale specimens or small-scale prototypes (Rossi et al., 2016 and Bianchini et al., 2024). The present research, which has been developed within the frame of the project “REVHEAL” (Structural Rehabilitation of Vaults in Heritage Asset Learning) supported by the Italian research program PRIN 2022 PNRR, was performed to investigate the response of cross-vaults subjected to in-plane shear due to the differential settlement of supports (Monaco et al., 2025 and Gandelli et al., 2025). In more detail, the project planned to construct a total of two full-scale vaults made with different masonry patterns (i.e., radial and diagonal) that will be both tested before and after repairing with a basalt Fabric-Reinforced Cementitious Matrix (FRCM) applied only to the extrados of the vault. The present work focuses on the first part of the research program involving the construction of a cross vault made with a radial brick arrangement. The specimen was built in the laboratory “P. Pisa” of the university of Brescia (Italy) and tested under quasi-static reverse cyclic shear. Unlike other laboratory protypes (Bianchini et al., 2024) with similar macro-geometry (span, rise and thickness of the vault), the one adopted herein was constructed adopting transverse arches running along three of the four sides of the vault, whereas the fourth side was leant against a fixed wall. A test rig was designed to apply controlled lateral displacements to two of the four piers supporting the corners of the vault in order to simulate the horizontal settlement typically exhibited by the supporting columns during a seismic event. The following sections describe the test on the unstrengthened vault, focusing on the specimen geometry, test setup, preliminary 3D documentation, and key results. The experiment aimed to induce lateral deflections sufficient to produce cracking representative of earthquake damage at the ultimate limit state. The final section presents a strengthening intervention using basalt FRCM, detailing its application to the pre-damaged specimen.

2. Experimental program

As outlined in the introduction, this experimental study involves testing a full-scale cross vault subjected to cyclic shear loading to simulate pre-damage relevant to the structure’s ultimate limit state condition. The test was carried out to a severe damage level in order to evaluate the effectiveness of FRCM in enhancing the initial stiffness and lateral resistance of the vault after repairing. The following subsections provide a summary of the experimental program, including a description of the specimen, the test setup, and key data from the mechanical characterization of the materials used in the vault’s construction and strengthening.

2.1. Specimen description

The schematics of Fig. 1 show the geometry of the specimen as well as of the test rig adopted to perform the cyclic test. The cross vault had plan dimensions of 3.5×3.5 m² (excluding the arches), with a span of 2.85 m, a rise of 0.85 m, and a uniform thickness of 105 mm. It was built using solid clay brick masonry arranged in a radial pattern typically used in historical constructions. The same masonry material was also used to construct the three bounding arches. These arches had a total depth of 235 mm, a width of 500 mm, and were built with their intrados aligned with the vault's soffit. Moreover, as was typical in traditional construction practice, the three arches were leaned against the sides of the vault without any connection achieved through brick interlocking. The springings of the vault and of the arches were laid on the four reinforced concrete piers forming the test rig. As shown in Fig. 1, two of the four reinforced concrete piers, here referred to as the "movable piers", were placed on spherical steel rollers embedded in a 0.9×0.9×0.05 m^3 high-strength mortar slab positioned on the laboratory floor.

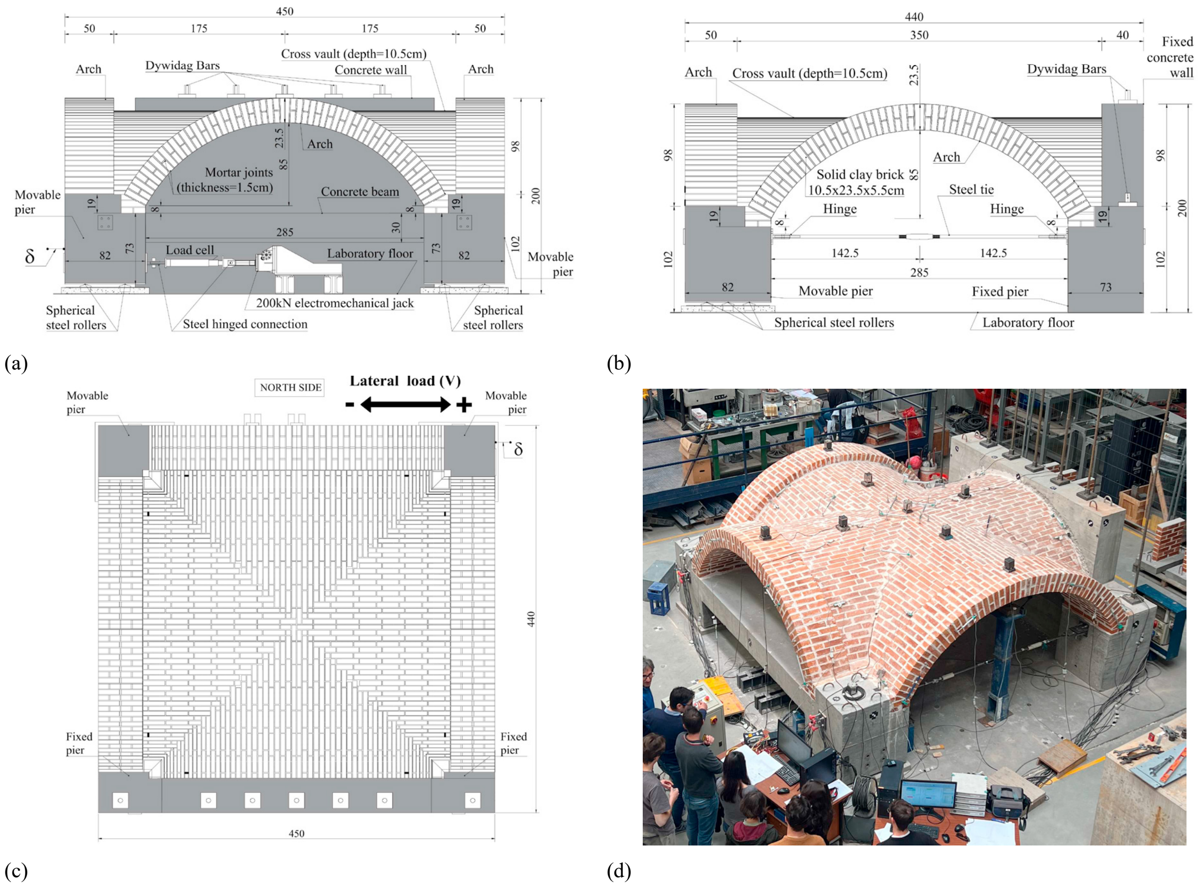


Fig. 1. Schematic of the full-scale cross vault and the test rig: (a) north-side; (b) west-side; (c) plan. (d) Actual view. (Dimensions in [cm])

To reduce friction between the piers and the rollers, the lower side of each movable pier was fitted with a 1 mm-thick polished stainless-steel (AISI 304) sheet, which was embedded in the formwork prior to concrete casting. A concrete beam with a cross section of 0.3×0.82 m^2 connected the two movable piers so that they were forced to rigidly translate according to the loading direction. On the opposite side of the vault (i.e., the south side), the springings were supported by two piers that were part of a reinforced concrete wall fixed to the floor by seven post-tensioned Dywidag bars. Note that the south side of the vault was simply leant onto the wall surface using a layer of mortar with the same properties as that used in the masonry joints. To increase the roughness of the mortar-to-concrete interface, the wall surface was texturized with a pneumatic bush hammer, resulting in an average surface roughness of approximately 10 mm. To restrain the horizontal thrusts generated by the vault and the arches, a steel tie rod (Fig. 1b) with a diameter of 30 mm was hinged to the concrete piers supporting the springings located on both the west and east side of the specimen. The movable piers were subjected to horizontal loading using a 200 kN capacity electromechanical screw-jack positioned beneath the concrete beam (Fig. 1a) and anchored to the laboratory's strong floor. A double-hinged steel truss linked the jack to one of the piers, enabling the transmission of axial force. The two hinges allowed the truss to accommodate horizontal displacements and potential rotations of the piers about their vertical axis without introducing additional restraining forces. An overall view of the test specimen is reported in Fig. 1d.

2.2. Materials

The materials used to construct masonry were selected trying to replicate the properties of historical solid clay brick masonry used in some areas of Northern Italy. To this end, both masonry and its components were characterized to get accurate data about their mechanical properties. The solid clay bricks, having dimensions of 110×235×55 mm^3 and an average specific weight of 1844 kg/m^3, were tested under uniaxial compression to determine both the compressive strength and the elastic modulus. A total of four units were collected during the construction of the vault and then tested according to EN 772-1:2011. The tests provided a mean compressive strength and an elastic modulus of 14.8 MPa (CoV = 7.5%) and 9150 MPa (CoV = 1.5%), respectively. The joints of masonry were filled with a totally concrete-free hydraulic lime mortar made with a mixture of pure limestone sands having a maximum grain size of 2.5 mm. The only binder included in the mortar mix is natural hydraulic lime NHL5 according to EN 459-1. A total of 81 mortar prisms with dimensions of 160×40×40 mm^3 were continuously cast and collected during the construction of the vault and the arches. After 24 days from casting, the first series of prisms, including a total of 12 specimens, were tested according to EN 1015-11 to determine the Modulus of Rupture (MOR) and the compressive strength of mortar. Before performing the tests, the prisms were weighed resulting in an average specific weight of 1730 kg/m^3. The tensile-flexural and the compression tests provided mean strengths equal respectively to 0.49 MPa (Cov = 20.8%) and 1.35 MPa (CoV = 12.4%), respectively. To determine the uniaxial compressive strength of masonry, 4 masonry panels having dimensions of 560x500x105 mm^3 were tested according to EN 1052-1:2001 under uniaxial static and cyclic compression. The tests provided a mean compressive strength of 5.4 MPa (CoV = 15.7%).

2.3. Instrumentation and loading history

The reverse cyclic test on the vault was carried out by controlling the lateral displacement applied to the concrete pier connected to the screw-jack. The double-hinged steel truss connecting screw-jack to the pier was provided with a load cell that allowed to continuously detect the total load applied to the vault. To monitor the specimen, a total of 58 displacement transducers were installed on both the upper and the lower surfaces of the vault. For brevity, only some of the instruments adopted are indicated in the schematic of Fig. 2a. To capture diagonal cracking, eight potentiometric transducers, named DD1–DD8, were placed at different locations along the diagonals on the upper surface of the vault. To measure relative tangential slip between the arches/walls and the vault, the potentiometers RS1–RS8 were installed along the vault's perimeter. At the same locations, the potentiometers RD1–RD8 were used to detect normal slip (i.e., separation) between the arches and the vault. Both RS and RD transducers were mounted on the vault's upper surface. In contrast, the potentiometers HAD, HDV, VDA, and VDV were installed on the intrados of the vault and arches to measure lateral (HAD and HDV) and vertical displacements (VDA and VDV) relative to the laboratory floor. Although post-tensioned vertical Dywidag bars were used, the concrete wall was expected to undergo minor lateral slip, which needed to be accounted for when determining the net lateral displacement of the loaded piers. To capture this movement, a potentiometer named RDW was installed to measure the wall's displacement relative to the floor.

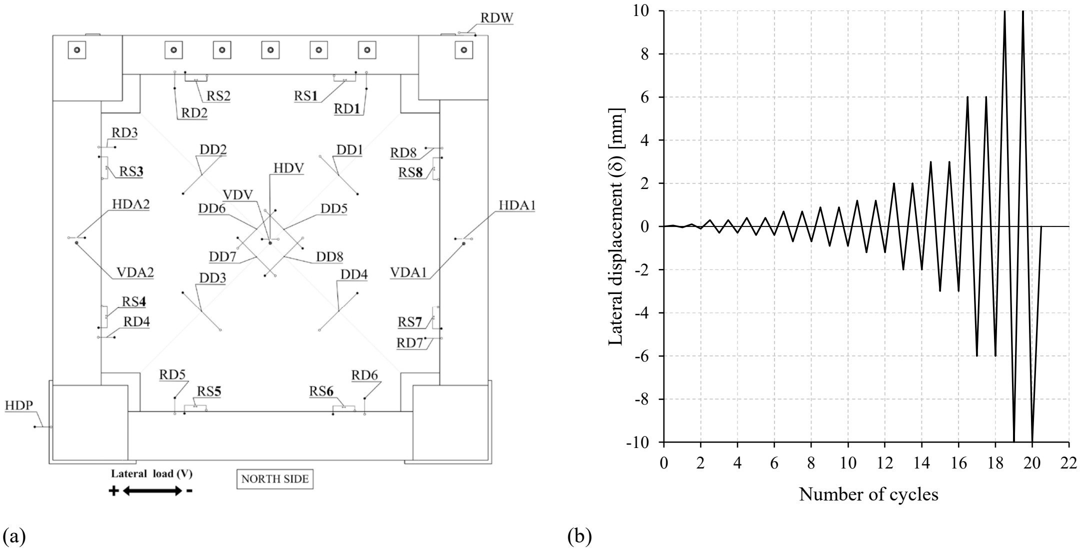


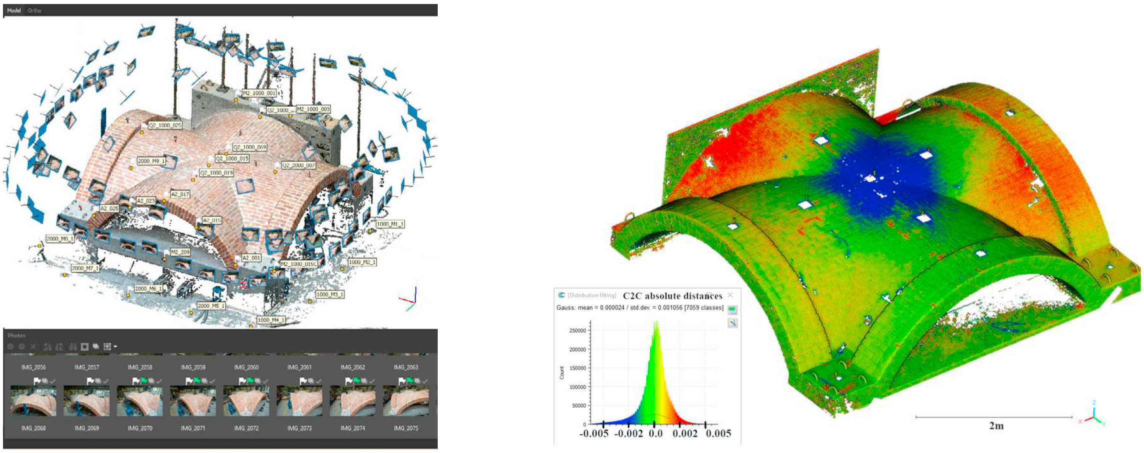
Fig. 2. Schematic of the instrumentation (a). Loading history (b).

The screw-jack induces lateral movement in the concrete piers, aligned with the direction of the lateral force (V) shown in Fig. 2a. As the piers shift laterally, the steel ties act to restrain any displacement perpendicular to the direction of this force. This restraining effect caused continuous variations in the tensile forces within the steel ties throughout the test, thus requiring constant monitoring. To capture these variations in axial strain, a couple of strain gauges were installed on each tie. These gauges recorded strain changes both during the cyclic loading and in the initial phase when the centering used to support the vault during construction was removed.

The lateral displacement (δ) of the pier connected to the screw-jack was detected by the Linear Variable Displacement Transformer (LVDT) named HDP. As illustrated in Fig. 2b, the loading protocol involved repeated reverse cycles with step-wise increasing lateral displacements, starting from 0.04 mm and reaching a maximum of 10 mm after significant damage had occurred in the vault. Following FEMA 461 guidelines for quasi-static cyclic testing, two cycles were executed at each displacement amplitude, resulting in a total of 11 displacement increments. The cyclic test was stopped once the specimen exhibited a decrease of the post-peak lateral resistance not lower than 15% of the maximum lateral resistance. The present experimental campaign included also dynamic identification tests to determine the natural frequencies and the mode shapes of the masonry specimen. To this end, 16 piezoelectric Wilcoxon 731A-P31 accelerometers with a sensitivity of 10 V/g and a spectral noise density of 0.01 μg/ √ Hz (10Hz) were fixed to the extrados of the vault and the arches. To assess the influence of damaging on the dynamic properties of the structure, the dynamic identification was performed both before and after the completion of the test. Based on the preliminary results, sixteen mode shapes falling within the frequency range 4-35 Hz were identified including vertical, transversal and hybrid modes. A description of these tests is reported in Rota et al. (2025).

2.4. 3D metric survey strategy

The measurement accuracy related to the as-built condition of the specimen and its geometry during the test steps was guaranteed by a planned integrated 3D metric survey approach based on LiDAR scans and digital photogrammetry. The monitoring process was divided into three main stages: T0, corresponding to the vault's construction phase prior to centring removal; T1, corresponding to centring removal; and T2, referring to the period following the conclusion of the cyclic test. During the test steps T1 and T2, 20 scans from FARO Focus 330 scanner and 80 images from Canon EOS 5D with fix focal length 20mm were performed. The topographic set of measurements, organized and executed using a network adjustment in order to minimize error propagation, ensured millimetric accuracy for twofold purposes. First, a set of point was collected by punctual repeated measurements with high accuracy (±2mm), and distributed on the vault extrados, verifying the vertical deflection resulting from centring removal (T0-T1). Moreover, the use of a set of topographic Control Points (CPs and GCPs) is fundamental for establishing the unique reference and verify accuracy for the test setup and consequently for LiDAR co-registration and photogrammetric 3D reconstruction and metric check. The T1-T2 (after testing) photogrammetric model (Fig.3a) and derived metric products (e.g. orthoimage in Fig.4b) have a verified accuracy on GCP, RMSE=0.001m and CP, RMSE=0.002. Fig. 3b depicts a preliminary 3D model of the specimen geometry obtained from high-scale photogrammetric reconstruction, with color range corresponding to a deviation map determined from the comparison after the test T1-T2 according to only Z vector. As indicated by the histogram, green areas correspond to points affected by quasi-zero vertical (±1mm). On the contrary, blue areas indicate points with a negative displacement vector, while red areas denote points with a positive displacement vector, with variations of up to ±5 mm. Note that in this first step of the research the LiDAR model was used exclusively as ground-truth data.

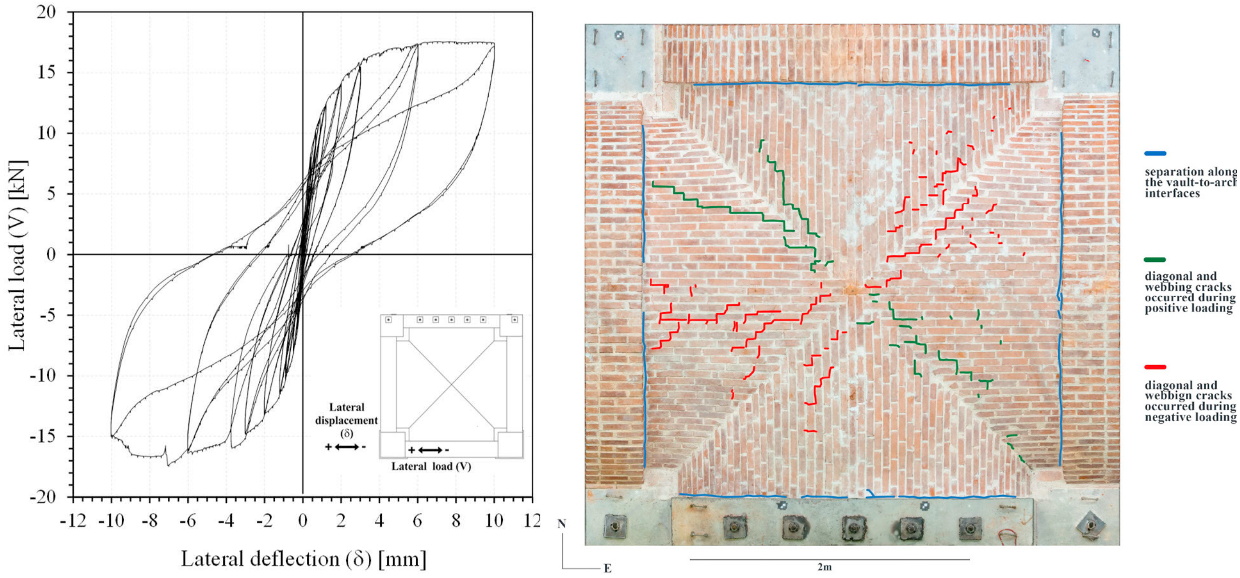


(a) (b)

Fig. 3. Preliminary metric results from the 3D geomatic model: (a) the photogrammetric 3D dense cloud model from the set of images, and distribution of CPs; (b) deviation map showing Z displacements between 3D models, before and after the first step of the test (T1-T2).

3. Test results

Fig. 4a reports the hysteretic response of the specimen obtained from plotting the total lateral load (V) against the deflection (δ). It is worth remarking that the lateral load is the total force detected by the load cell connected to the screw jack. Therefore, it disregards the friction of roller supports, which will be carefully measured after completion of this research project. The diagram illustrates that the vault initially exhibited a linear response, characterized by lateral stiffness values of 24 kN/mm and 21 kN/mm in positive and negative directions, respectively. During this early stage, the arches along the west and east sides began to gradually detach from the vault due to tensile forces acting at the vault-to-arch interfaces. When the lateral load reached approximately 10 kN, a marked reduction in lateral stiffness was observed. This reduction was attributed to the formation of diagonal cracks (Fig. 4b) that initiated at the crown of the vault. As lateral displacement increased, these cracks propagated along the diagonals and progressively widened, reaching maximum widths between 2.5 mm and 3.5 mm by the end of the test. The peak lateral loads attained by the vault were 17.6 kN in the positive direction and 17.5 kN in the negative direction. As in Fig. 4b, the two principal diagonal cracks extended toward the supports on the east side but gradually deviated toward the east arch. Near the end of the test, these cracks exhibited a rapid increase in width, resulting in a drop in lateral resistance that is clearly visible in Fig. 4a for displacements between –9 mm and –10 mm. The test terminated at a lateral displacement of –10 mm, at which point the corresponding load decreased by 15% from the maximum recorded resistance in the negative direction. Figure 4b also illustrates the crack pattern on the photogrammetric orthophoto (pixel dimension, GSD=0.5 mm), with red and green lines indicating cracks along the diagonals and webbings (according to two directions of stress), and blue lines highlighting separation along the vault-to-arch interfaces.



(a) (b)

Fig. 4. Hysteretic response (a). Main cracks detected and mapped on the orthoimage for the upper surface of the vault at the end of the test (b).

4. Description of the FRCM-based strengthening intervention

After performing the pre-damaging test, the vault's cracks were repaired with a fluid pure NHL lime mortar, class M15, and then the masonry substrate was prepared for the application of the FRCM strengthening system. The FRCM material was made with a basalt fiber mesh with approximate dimensions 16x16 mm, embedded in a natural hydraulic lime-based mortar specifically designed for structural reinforcement, with a maximum aggregate size smaller than 2 mm and average compressive strength equal to 16.7 MPa (CoV = 3%). The basalt mesh was characterized by means of direct tensile tests on five specimens with three yarns and a gauge length of 200 mm, obtaining an average tensile strength of 1260 MPa (CoV = 15.6%) calculated considering the transversal area of the specimen equal to 1.67 mm^2. The composite coupons were also tested through a direct tensile test with the clevis grip method performed on specimens with dimensions 500x50x8 mm and a free gauge length of 200 mm. The average tensile strength was equal to 1237 MPa (CoV = 7%), calculated considering the textile transversal area, in line with the failure stress of the latter.

(a) (b) (c)

Fig. 5. Schematic of the FRCM strengthening intervention layout (plan view of the extrados) (a). GFRP connectors installed at the vault-to-arch interface (b). GFRP connectors between masonry and the FRCM system (c).

The cross vault was strengthened according to the scheme reported in Fig. 5a. First, two diagonal strips were placed and overlapped each other; then each web was strengthened with a trapezoidal basalt sheet, with an overlapping length of about 250 mm with the diagonal reinforcement. GFRP connectors were also applied (Fig. 5b) to make a connection between the FRCM system and the lateral arches and the wall. Then, 200 mm spaced GFPR connectors were installed all over the extrados of the vault between masonry and the FRCM system (Fig. 5c). Finally, a finishing layer of mortar was applied over the extrados to get a total thickness of mortar equal to 10-12 mm. The test on the repaired specimen will be carried out within 40 days following the completion of the strengthening intervention.

5. Conclusions and future developments

This paper presents the experimental tests performed on a full-scale brick masonry cross vault subjected to a reverse cyclic shear displacement at two abutments. The vault was bounded by three deformable arches and a rigid wall on the fourth side. The displacement was applied in a quasi-static manner and aimed at simulating the seismic effect on the cross vault, which might be part of a porch or a nave in a real case. The test was conducted up to the attainment of a severe pre-damaging condition approaching the ultimate structural capacity. In particular, the test was terminated at a lateral base displacement of about 10 mm, which corresponded to a 15% decrease in lateral load capacity. As expected, the crack pattern showed the slight detachment of the vault's webs from its boundary elements, cracks along the diagonal arches, and the opening of cracks at the extrados aligned along the key of the west web. Based on this crack pattern, after the damage, the vault was repaired and strengthened by a basalt-FRCM system at the extrados. Finally, geomatics acquisitions were made in order to build, in the near future, the reality-based model of the tested vault. Within this scope, an integrated 3D metric survey based on LiDAR scans and digital photogrammetry was conducted, and preliminary deviation 3D maps were generated showing the specimen geometry from photogrammetric reconstruction, with the comparison between the configuration measured before and after the test. Future developments will regard the accurate comparison between these models and traditional sensors (e.g., LVDT) measurements.

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