Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2025) 1013-1019

ECCOMAS
Proceedia

COMPDYN 2025
10th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15-18 June 2025

# STRENGTHENING OF MASONRY CROSS-VAULTS UNDER SHEAR SETTLEMENTS: COMPARISON BETWEEN DIFFERENT FRCM SYSTEMS

**Emanuele Gandelli**[1], **Alessia Monaco**[2], **Marco Alforno**[2], **Luca Facconi**[1], **and Fausto Minelli**[1]

[1] Department Civil, Environmental, Architectural Engineering and Mathematics (DICATAM), University of Brescia, Italy
{emanuele.gandelli, luca.facconi, fausto.minelli}@unibs.it

[2] Politecnico di Torino, Department of Architecture and Design
Viale Pier Andrea Mattioli, 39, 10125 Torino, Italy
{alessia.monaco, marco.alforno}@polito.it

**Abstract**

*In this study, Finite Element (FE) models are adopted to assess the response of strengthened and unstrengthened masonry cross-vaults. Within the REVHEAL project, a full-scale (about 3.5 x 3.5 m) specimen inspired by vaults belonging to the "Palazzata" of the sanctuary "Regina Montis Regalis" (Vicoforte, Italy) has been built at Pisa Lab. of the University of Brescia, Italy. The response of the bare (i.e., unreinforced) cross-vault is predicted through the numerical simulation of full-scale tests reproducing the shear-sliding of two abutments. This loading protocol generates both shear and flexural cracks in the cross-vault and in the three boundary arches. The effectiveness of different strengthening systems, aiming at restoring the structural integrity of the cross-vault, are then investigated: (a) Fiber-Reinforced Cementitious Matrix with carbon fibers (C-FRCM); (b) Natural FRCM system with basalt fibers (B-FRCM). The modelling approach adopted to simulate the response of the FRCM systems is validated through comparison with the results of tensile tests performed by some of the authors, and other tests already available in the literature. Eventually, a numerical prediction of the shear response of the cross-vault alternatively strengthened with these systems is provided, highlighting their effectiveness in enhancing the overall lateral strength of the vault.*

**Keywords:** Masonry, Cross-vaults, FRCM, Shear mechanism, Finite element analysis.

ISSN:2623-3347 © 2025 The Authors. Published by Eccomas Proceedia.
Peer-review under responsibility of the organizing committee of COMPDYN 2025.
doi: 10.7712/120125.12466.25253

## 1 INTRODUCTION

Cross vaults represent a significant element of Western architectural heritage. In recent seismic events, the collapse of such structures has led to substantial losses in both cultural assets and human lives, and in some cases, has critically influenced the overall seismic performance of the buildings. During earthquakes, vaults are capable of accommodating considerable displacements at their supports through the formation of shear and flexural cracks, often exhibiting complex three-dimensional pattern. Among possible strengthening solutions, composite materials have been adopted in ancient masonry structures for decades. Such materials exploit the combination of thin matrix layers with an embedded reinforcement. The matrix can be made of polymeric or mineral materials: in the first case, traditional resin matrices are employed in Fibre Reinforced Polymer (FRP) systems; in the second case, cementitious or lime-based mortars are employed in innovative Fabric Reinforced Cementitious Matrix (FRCM) composites. As regards the embedded reinforcement, traditional carbon, glass or aramid fibres are commonly adopted in FRP materials, while fibre textiles are employed in FRCM systems. In the latter case, in recent years, the growing concern towards sustainability and compatibility with ancient masonry substrates has increased the interest in investigating the efficacy of natural materials; therefore, basalt fabrics have been recently studied as reinforcement of Natural-FRCM (N-FRCM) composites. The assessment of the effectiveness of Basalt-FRCM (B-FRCM) composite for the seismic strengthening of a masonry cross-vault is one of the major targets of the authors' REVHEAL project [1, 2]. Within this framework, Section-2 of this paper presents the results of tensile tests conducted to characterize Basalt-FRCM (B-FRCM) specimens. In Section-3, these experimental results, along with data from literature on Carbon-FRCM (C-FRCM), are reproduced using a macro-scale finite element modeling approach. Finally, Section 4 focuses on a 3.5x3.5m case-study cross vault. The seismic response of the unreinforced vault under horizontal/shear displacements applied to two abutments is simulated and compared with the behavior predicted when the vault is strengthened using the two FRCM systems applied to its extrados.

## 2 EXPERIMENTAL CHARACTERIZATION OF BASALT FRCM

An experimental campaign was previously conducted by some of the authors [3] on B-FRCM coupons for their tensile mechanical characterization. The main results are summarized here, with the scope of highlighting the mechanical parameters that will be subsequently adopted in the FE model of the strengthened vault.

Each coupon was 500 × 50 × 8 mm, manufactured with one layer of basalt fabric within two layers of mortar. The basalt fabric was characterized by a squared mesh grid of about 19 mm, with each basalt yarn sided by two steel filaments (Figure 1a). The test set-up was organized with a clevis-grip method, in which two hinges are created at both ends of the specimen within aluminium tabs glued to the coupons so that a resulting free gauge length of 200 mm was obtained (Figure 1b).

Figure 2 depicts the stress-strain curves of the tested specimens (five specimens) in terms of envelope curve and mean curve. Moreover, the trilinear schematization of the mean curve is reported. It can be observed that the specimens exhibited the typical four-stage behaviour in which, after an initial linear-elastic phase, there is the crack development up to saturation and, finally, an almost linear stage up to the achievement of the maximum strength before the rupture of the textile. On average, the specimens exhibited a first cracking stress equal to 298 MPa ($CoV$ = 33%) and a corresponding strain of 0.01% ($CoV$ = 17%), while the average maximum tensile strength was 1234 MPa ($CoV$ = 8%) with a corresponding strain of 2.3% ($CoV$ = 3%).

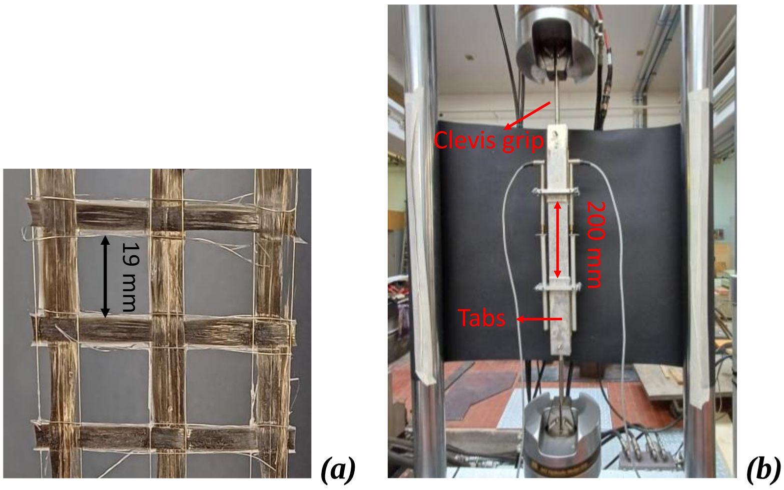



Figure 1: B-FRCM coupons: (a) basalt fabric; (b) test set-up.

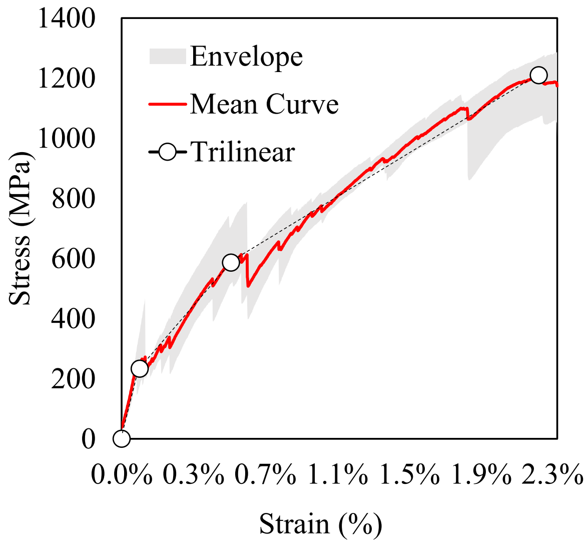



Figure 2: Stress-strain curves of B-FRCM coupons.

## 3 FE MACRO-MODELLING OF TRM COMPOSITES

In this Section, the aforementioned tensile tests on B-FRCM coupons, along with similar tests on C-FRCM specimens described in literature [4], are numerically simulated in Abaqus v. 2024 software [5] employing the macro-modelling FE approach. In this regard, the "Concrete Damage Plasticity" (CDP) model, with compression and tensile response shown in Figure 3, was adopted [5]. For the sake of brevity, the equations ruling the CDP are described in [1]. Both kinds of FRCM coupons were modelled by mean of two layers of shell elements, one for the mortar and one for the internal reinforcing grid, with tie constrains at their interface, i.e. an ideal perfect bonding was assumed. The structural mesh consisted of 500 linear quadrilateral elements of type S4R [5] with characteristic size of 10 mm. The bottom-side nodes of the coupon were clamped while a monotonic tensile displacement was applied to the nodes of the top side in order to generate a strain level of about 2%. The comparison between experimental and numerical results is provided by Figure 4 showing the tensile force (per unit of coupon width) vs. the tensile strain. Concerning the B-FRCM coupons (Figure 4a), an acceptable agreement among the two plots can be appreciated for strain levels lower than 1% while afterwards a substantial discrepancy is evident. This can be justified by the adopted testing method (clevis-grip method) or by the debonding between the mortar and the internal basalt fibers experimentally observed before the fiber rupture. On the contrary, for the C-FRCM coupons (Figure 4b), an excellent agreement between the experimental and the numerical results can be appreciated even for strain levels higher than 1.2%. Indeed, in this case a special primer was employed to promote the mortar-textile net bonding and an ad-hoc solution to improve the grip within the clamps [4].

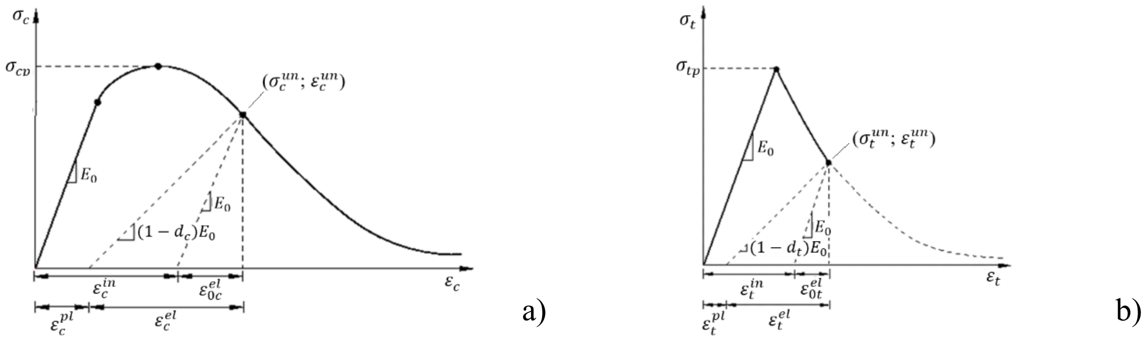



Figure 3. Uniaxial nonlinear response of CDP model: (a) compression; (b) tension. Adapted from [5].

| Parameter | | Unit | B-FRCM | | C-FRCM | |
|---|---|---|---|---|---|---|
| | | | mortar | textile | mortar | textile |
| elastic modulus | $E_0$ | [MPa] | 5430 | 81000 | 8500 | 102000 |
| mass density | $\rho$ | [kg/m$^3$] | 2300 | 2700 | 2300 | 3570 |
| Poisson ratio | $\nu$ | [-] | 0.2 | 0.3 | 0.2 | 0.3 |
| compression strength | $\sigma_{cp}$ | [MPa] | 5.5 | n.a. | 8.6 | n.a. |
| peak and ultimate compr. strain | $\varepsilon_{cp}$- $\varepsilon_{cu}$ | [%] | 0.2-0.6 | n.a. | 0.2-0.6 | n.a. |
| tensile strength | $\sigma_{tp}$ | [MPa] | 1.24 | n.a. | 1.10 | n.a. |
| peak and ultimate tensile strain$^{(*)}$ | $\varepsilon_{tp}$- $\varepsilon_{tu}$ | [%] | 0.02-0.8 | n.a. | 0.01-0.9 | n.a. |
| mode-I fracture energy | $G_{f,I}$ | [N/mm] | 0.02 | n.a. | 0.02 | n.a. |

$^{(*)}$ mesh seed of shell elements = 10mm

Table 1: Mechanical properties adopted to simulate the tensile tests of B-FRCM and C-FRCM coupons.

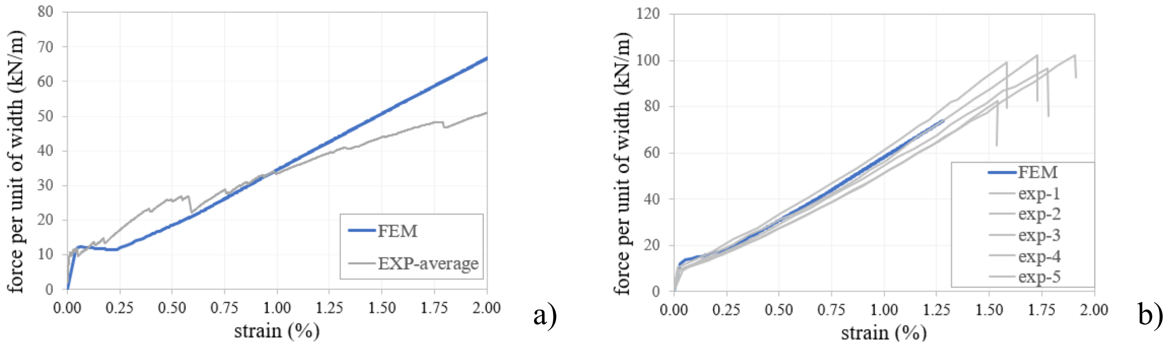


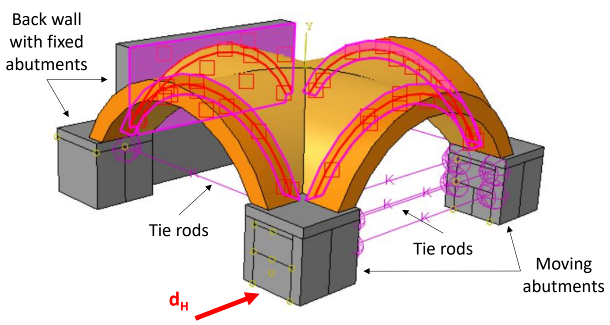

Figure 4. Comparison between experimental (EXP) and numerical (FEM) results of tensile tests on B-FRCM (a) and C-FRCM coupons (b).

## 4 FE MODELLING OF A REINFORCED MASONRY CROSS-VAULT

Based on the abovementioned results, the FE model of a full-scale masonry cross-vault was developed with the software Abaqus v. 2024 [5]. The vault has a span of about 3 m and a rise of about 0.85 m; it is constrained by three boundary arches and placed against a rigid back wall (Figure 5). The two abutments next to the back wall are fixed, while the other two abutments are movable. A rigid truss connects the latter, and a lateral shear displacement of 60 mm is applied using a linear quasi-static loading protocol. A rigid truss connection is also established between the back and front abutments in order to simulate the presence of ideal steel rods.

The finite elements adopted for the masonry parts are linear bricks of type C3D8R with an approximate mesh size of 80 mm. The "penalty" formulation, with a Coulomb friction coefficient equal to 0.50, was employed to simulate the tangential interactions (highlighted in magenta in Figure 5a) between the arches and the vault and between the clamped wall and the vault. In the normal direction, the "hard-contact" algorithm was enrolled. The FE model of both the unreinforced and strengthened vault was developed; the FRCM reinforcement was modelled by means of shell elements of type S4R with a thickness of 8 mm. In particular, two layers of shells were overlapped for modelling the mortar matrix with the embedded textile. As previously discussed, a perfect bond was assumed between the two shell layers and also between the FRCM composite and the masonry substrate. In this regard, it has to be noted that an upper bound of the load and displacement capacity of the strengthened vault is expected from the numerical simulation, because, conversely, in real applications, the bond properties within the FRCM material and between composite system and substrate play a crucial role in the efficacy of the strengthening technique. For the simulations, the masonry properties were set to the literature values suggested in Bianchini et al. 2024 [6]: elastic modulus of 960 MPa, density of 2260 kg/m$^3$, Poisson's ratio 0.2, compressive strength of 9.1 MPa, tensile strength of 0.1 MPa, mode-I fracture energy of 0.02 N/m. The mechanical properties adopted for the FRCM systems were those reported in the previous sections for both B-FRCM and C-FRCM reinforcement.

Figure 6 reports the load-displacement curves of the predicted response of the unstrengthened vault, compared to the B-FRCM and C-FRCM strengthened specimens. It can be observed that the strengthened vaults presented an increased stiffness of about 38% (from 7.9 kN/m to 10.9 kN/m) and lateral strength. In this regard, while the unreinforced specimen presented a peak load of about 26 kN, the FRCM strengthened specimens presented an increasing load capacity up to the ultimate applied displacement of 60 mm, showing a relevant post-cracking hardening slope.



a)

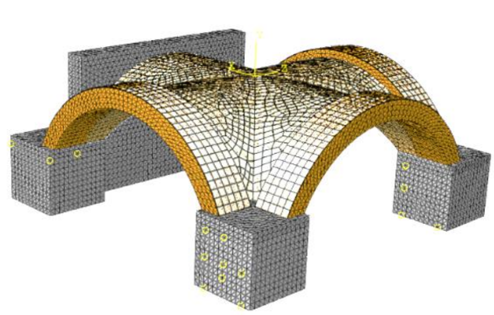

b)

Figure 5: Finite element model: a) boundary conditions, b) mesh.

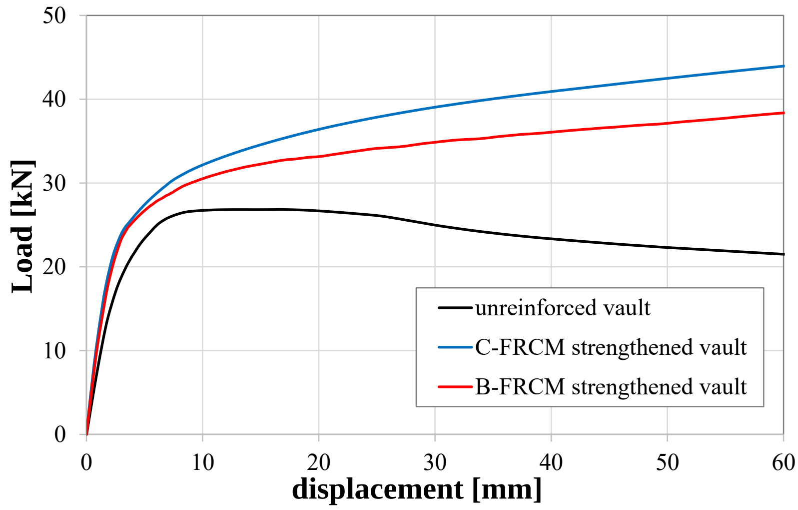



Figure 6: Numerical load-displacement curves of unreinforced and strengthened vaults.

## 5 CONCULSIONS

This study presents a numerical investigation on the seismic response of masonry cross-vaults subjected to shear-induced abutment displacements, with a particular focus on the effectiveness of Fiber-Reinforced Cementitious Matrix (FRCM) systems as strengthening solution. Tensile tests were carried out to characterize the mechanical response of Basalt-FRCM (B-FRCM) coupons. A FE macro-modelling approach was employed to simulate these tests along with those of Carbon-FRCM (C-FRCM) specimens reported in literature. In both cases, the agreement between the numerical (FEM) and experimental results (EXP) was satisfactory for strain levels lower than 1%. Eventually, the simulations carried out on a 3.5 x 3.5m case-study cross-vault showed that both FRCM solutions significantly enhance the lateral stiffness and load-bearing capacity of the structure. In particular, the strengthened vaults demonstrated a 38% increase in initial stiffness compared to the unreinforced configuration. While the bare vault exhibited a peak load capacity of approximately 26 kN, the strengthened specimens maintained a stable response beyond this limit, with evident post-cracking hardening behavior. The results confirm the potential of both natural (basalt-based) and synthetic (carbon-based) FRCM composites in improving the structural performance of historical masonry vaults under lateral loading. Additionally, it is worth noting the relevance of proper interface modeling between reinforcement and substrate to achieve realistic predictions. For these reasons, future developments will aim at including more refined bond-slip laws and calibrating the numerical model through comparison with ongoing experimental tests within the REVHEAL project.


## ACKNOWLEDGEMENTS

This study was carried out within the “Structural Rehabilitation of Vaults in Heritage As-set Learning: collapse identification and design of compatible strengthening systems supported by adaptive 3D models - REVHEAL” project – funded by European Union – Next Generation EU within the PRIN 2022 PNRR program (D.D.1409 del 14/09/2022 Ministero dell’Università e della Ricerca). This manuscript reflects only the authors’ views and opinions and the Ministry cannot be considered responsible for them.

## REFERENCES


[1] E. Gandelli, L. Facconi, S. Faini, F. Minelli, M. Alforno, C. Ferrero, E. Matta, G. Sammartano, F. Venuti, A. Monaco. The REVHEAL project: preliminary FE simulations of full-scale tests on masonry cross vaults. In 5th International Conference on Protection of Historical Constructions PROHITECH 2025. Lecture Notes in Civil Engineering, **596**, 294–301, Springer Nature.

[2] A. Monaco, F. Venuti, M. Alforno, C. Ferrero, E. Matta, G. Sammartano, L. Facconi, E. Gandelli, F. Minelli. The REVHEAL project: Design of Pilot-Scale Prototypes of Masonry Cross Vaults. In 5th International Conference on Protection of Historical Constructions PROHITECH 2025. Lecture Notes in Civil Engineering, **596**, 286–293, Springer Nature

[3] A. Monaco, E. Gandelli, L. Facconi, M. Baldassari, Characterization of NTRM systems for the structural strengthening of masonry cross vaults. In 12th International Conference on FRP Composites in Civil Engineering CICE 2025, 14-16 July 2025, Lisbon (PT).

[4] I. Boem, N. Gattesco, Composite Reinforced Mortar (CRM) and Fiber-Reinforced Cementitious Matrix (FRCM) for the seismic protection of masonry vaults. In XIX ANIDIS Conference, Seismic Engineering in Italy, 12-15 September 2022, Turin (IT).

[5] ABAQUS (2024). Abaqus analysis User’s guide (v. 2024). Dassault Systemes Simulia Corp., Providence, RI, USA.

[6] N. Bianchini, N. Mendes, P.B. Lourenço, C. Calderini, Modelling of the Dynamic Response of a Full-Scale Masonry Groin Vault: Unstrengthened and Strengthened with Textile-Reinforced Mortar (TRM). *International Journal of Architectural Heritage*, **18** (12), 2042-2066, 2024.