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# Experimental investigation on tensile and shear bond behaviour of Basalt-FRCM composites for strengthening calcarenite masonry elements

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**Abstract**

The use of Fabric Reinforced Cementitious Matrix (FRCM) composites for structural retrofit has seen an increased interest among the scientific community, during the last decade. Various studies have revealed their effectiveness as external retrofitting technique of masonry elements, offering numerous advantages respect to the well know Fibre Reinforced Polymer (FRP) in terms of compatibility with masonry support, reversibility of intervention and sustainability. Despite the growing use, the characterization of FRCM mechanical behaviour is still an open issue, due to numerous uncertainties involved in test set-up adopted and fibre-mortar combination. The proposed experimental study aims to investigate the tensile and shear bond behaviour of Basalt-FRCM for strengthening calcarenite masonry elements. Calcarenite is a natural stone with sedimentary origin and it is widely present in existing buildings of the Mediterranean areas. Direct tensile tests are performed on two types of Basalt-FRCM coupons, with cement-based and lime-based mortar, adopting two different test-set-up based on clamping and clevis grip methods. Moreover, double shear bond tests are carried out to evaluate the adhesion properties of the two types of Basalt-FRCM with calcarenite support. Experimental outcomes are compared in terms of stress-strain curves, evaluating the influence of mortar grade and test set-up on the mechanical performances of Basalt-FRCM composites. The comparisons provide information about the mechanical stress transfer phenomena that occur at the fibre-to-matrix and FRCM-to-substrate interface level and the failure modes.


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*Keywords:* FRCM; Basalt; Masonry; Tensile behaviour; Shear bond behaviour.

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## 1. Introduction

The preservation of existing masonry structures is a topic of relevant interest among the scientific community. Recently, numerous studies of literature focus on the use of innovative fibre-reinforced materials for the consolidation and restoration of historic buildings, improving the structural safety level with particular reference to the seismic risk. Among innovative retrofitting techniques, the FRCM composites have received great attention since they represent a promising solution for strengthening masonry structural elements such as columns (Aiello et al (2021)), arches, vaults (De Santis et al. (2018)) and walls. They offer good performance related to the use of inorganic matrix (e.g. cement/lime based mortar, polymer-modified and fibre-reinforced mortars), promoting a more compatibility with the masonry support, transpiration, sustainability, easiness of application, possibility of removal, fire resistance, with respect to that obtained with the use of FRP. Even if the use of FRCM composites for structural retrofitting of existing structures is increasing, exhaustive design procedures and standardized test criteria are still need to be fully defined. Italian guidelines C.S.LL.PP. (2018) and American Acceptance Criteria AC 434 (2013) recommend direct tensile test and shear bond test in order to characterize the FRCM strengthening systems by deducing the main mechanical properties. However, several scientific studies have proven a large scatter of experimental results, due to numerous variables involved in the mechanical characterization (Leone et al. (2017), Lignola et al. (2017) and Donnini and Corinaldesi (2017)), such as testing procedures, nature and treatment of fibre, mortar type, nature of substrate. Indeed, fibre and mortar interact to each other establishing a chemical, physical and mechanical bond strictly depending on the parameters listed above. Consequently, complex stress transfer mechanisms can occur in interfacial layers, at fibre-to-mortar and FRCM-to-substrate interface as confirmed by several theoretical studies (Grande and Milani (2018), Minafò et al. (2022), Monaco et al. (2019), Nerilli et al. (2020)). The interface phenomena play a key role in both local and global response of FRCM systems, significantly affecting the performance and failure mode. However, it is really difficult to measure experimentally the shear stress-slip profiles at the interface levels in a composite system which develops several cracks when loaded in tension (Saidi and Gabor (2019)).

This experimental work aims to investigate on mechanical behaviour and testing procedures for Basalt-FRCM composite systems. In details, the influence of two different matrices, a cement-based and lime-based mortar, is analysed. The constitutive behaviour is evaluated by performing tensile tests adopting clamping and clevis type grips, according to Italian guidelines C.S.LL.PP. (2018) and guidelines provide by RILEM TC 232-TDT (2016), respectively. The comparisons of experimental results in terms of stress-axial strain curves allow the assessment of constraint conditions in the gripping area for defining the FRCM mechanical response. Moreover, double shear bond tests according to guidelines provided by RILEM TC 250-CSM (De Felice et al. (2018)) were performed to evaluate the adhesion properties of the two types of Basalt-FRCM with the calcarenite masonry support.

## 2. Experimental investigation

The experimental investigation provides tensile and shear bond tests on two types of Basalt-FRCM strengthening systems applied on calcarenite support. The two types of FRCM composites consist of a coated bi-directional basalt fibre mesh embedded inside two mortar types: a two-component fibre-reinforced cementitious mortar and a two-component fibre-reinforced natural hydraulic lime-based mortar. Nine coupons for each type of Basalt-FRCM were manufactured for tensile characterization adopting for each series of specimens, two test set-up based on clamping and clevis grip method. Moreover, double shear bond behaviour on six samples (i.e. three repetition for each type of the two Basalt-FRCM system) are performed to investigate the adhesion properties of Basalt-FRCM on calcarenite block.

### *2.1. Materials and specimens*

A coated bi-directional alkali-resistant basalt fibre grid was adopted for FRCM composite system, with cell size of 6×6 mm, density of 250 g/m$^2$ and equivalent dry fibre thickness of 0.039 mm. A total of nine coupons of basalt fibre, with dimension of 50 × 400 mm, were tested in tension in order to deduce the main mechanical properties, according to ISO 13934-1 (2013). Results of tensile tests on the basalt fibre grid are summarized in Table 1.

Table 1. Average mechanical properties of the basalt fibre grid.

| Tensile strength [MPa] | Ultimate tensile strain [%] | Elastic modulus [MPa] |
|---|---|---|
| 1142 | 1.6 | 72000 |

Two bi-component mortar types were adopted for the Basalt-FRCM systems, one cement-based (C) and another one hydraulic lime-based (L). The mechanical properties of each mortar types were deduced from three-point bending tests on six 40×40×160 mm prisms and subsequent compressive tests on twelve pieces, after 28 days of curing, according to EN 1015-11 (2001). Average experimental results are listed in Table 2.

Table 2. Average mechanical properties of the mortar types.

| Type of mortar | Compressive strength [MPa] | Flexural strength [MPa] |
|---|---|---|
| Cement-based (C) | 40.8 | 6.6 |
| Hydraulic-lime based (L) | 16.0 | 6.3 |

Calcarenite stone units (with dimension of 200×250×380 mm) coming from the Sabucina (Sicily, Italy) quarry was used in order to investigate the bond behaviour of the Basalt-FRCM reinforcements. Mechanical properties from data sheet provided a compressive strength equal to 11 MPa, an elastic modulus in compression equal to 10935 MPa and a unit weight equal to 18 kN/m$^3$.

Tensile behaviour was evaluated on nine samples of the two Basalt-FRCM systems by adopting two test set-up. For sake of clarity, coupons were renamed with the following notations (BC or BL)_(TF or TH)_n, were B indicates the basalt fibre; C and L indicate the mortar type, cement or hydraulic based, respectively; TF and TH refer to tensile test set-up, with clamping grip method and extremities fixed or with clevis grip method with hinge constraint at the extremities, respectively; finally n specify the specimen number. Coupons tested by clamping grip method had dimension of 10×50×400 mm in accordance with Italian guidelines C.S.LL.PP. (2018). Moreover, aluminium tabs were glued at the extremities of samples, by using a thin layer of epoxy adhesive ensuring the adhesion of the tabs to the FRCM strip from one hand and a reinforced layer in the clamping area on the other. Tensile tests with clevis grip method were performed on coupons with dimensions of 10×60×500 mm, in accordance with recommendations provide by RILEM TC 232-TDT (2016). The extremities of samples were clamped between two sufficiently stiff steel plates by bolts, for a length of 125 mm, allowing at least a rotational capacity in plane.

Moreover, Double Shear Bond (DSB) tests were carried out on prismatic calcarenite blocks with dimension of 200×250×380 mm, as shown in Fig. 1.

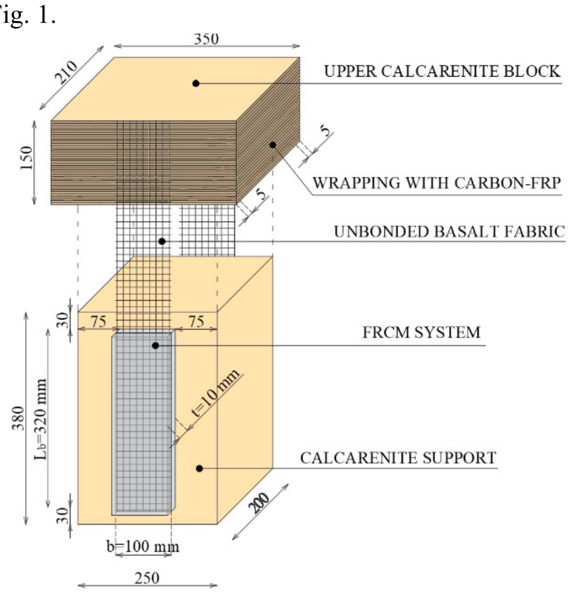


Fig. 1. Specimen for Double Shear Bond test (DSB).

The proposed test set-up was inspired to the one already validated by the research unity of Palermo for double shear bond test for FRP composites by Accardi et al. (2007). The FRCM strips were applied on the two larger opposite surfaces of the calcarenite support (250×380 mm), resulting in a bond length of $L_b$=320 mm, bond width of b=100 mm and thickness of t=10 mm. The unbonded extremities of the two basalt fibre strips were constrained to a further upper calcarenite block by a Carbon-FRP wrapping system. The tensile load applied to the upper calcarenite block is transferred as two shear forces in the Basalt-FRCM strips bonded onto each surface of the lower calcarenite block. The proposed set-up was designed to ensure the correct alignment of the tensile load applied to the unbonded basalt fibre grid with the plane of the FRCM strips. A total of six specimens (i.e. three for each Basalt-FRCM system) were manufactured, naming them as follows: (BC or BL)_DSB_n, where BC is for Basalt-FRCM with cement based mortar and BL for Basalt-FRCM with hydraulic lime based-mortar; DSB indicates double shear bond test; n is the progressive number assigned to samples.

### 2.2. Tensile test set up: clamping and clevis system

Direct tensile tests on Basalt-FRCM were performed by a universal testing machine Zwick-Roell with force capacity equal to 600 kN. In the case of clamping grip method, the specimen was clamped by hydraulic grips which transferred the tensile load to the FRCM strip, preventing any sliding and rotation. Moreover, aluminium tabs (2 mm of thickness and bond length equal to 100 mm) were glued to the surface of the specimen to better distribute the clamping pressure and to minimize the damage associated with possible local crushing, see Fig. 2a. Tensile load was transferred to specimens by friction when clevis grip method was adopted. In this case the samples were clamped between two metal plates by bolts and equipped with a hinge at the loading end providing free rotation in the plane to the specimen, see Fig. 2b. Both tensile test set-ups were carried out in controlled displacement mode adopting a rate equal to 0.2 mm/min up to failure. The testing machine provided the response in terms of load-global displacement.

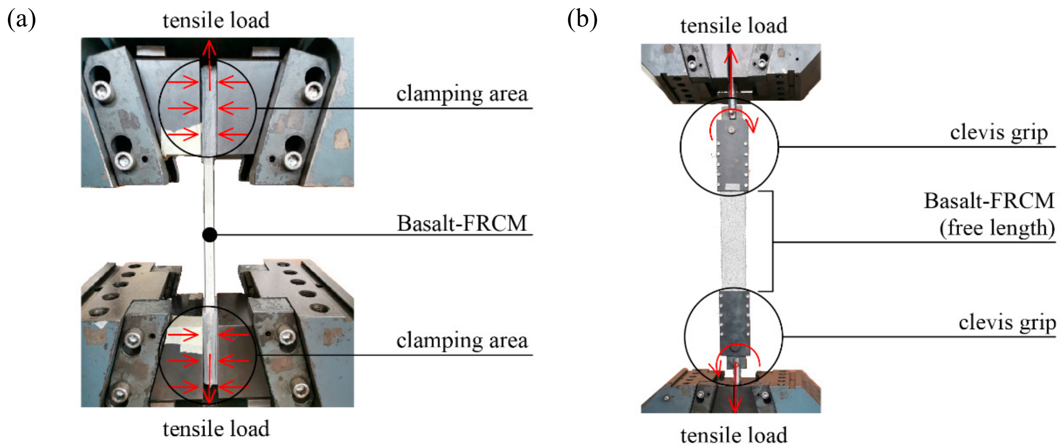


Fig. 2. Tensile test set up for Basalt-FRCM coupons: (a) clamping grip method (TF); (b) clevis grip method (TH).

### 2.3. Double-lap shear bond test set-up

Double shear bond tests were carried out with the purpose to evaluate the adhesion properties of Basalt-FRCM to the calcarenite support. Specimens consisted of two calcarenite blocks: lower block with the bonded FRCM system was fixed by a rigid steel frame; upper block wrapped the two unbonded fibre strips and transferred two balanced tensile force to them. Specimens were settled in a universal testing machine, Zwick Roell, with capacity equal to 600 kN. Double shear bond tests were carried out in displacement control mode, adopting a rate of 0.2 mm/min up the failure. The load cell of testing machine recorded the total tensile load transferred to the two fibre strips. The system caused the direct shear on the two Basalt-FRCM strips. Two digital absolute displacement indicators were arranged on the two faces measuring the local fibre-to-support slip close the loading ends, as shown in Fig. 3. Moreover, data from digital absolute displacement provided information about any phenomena related to possible eccentric loading.

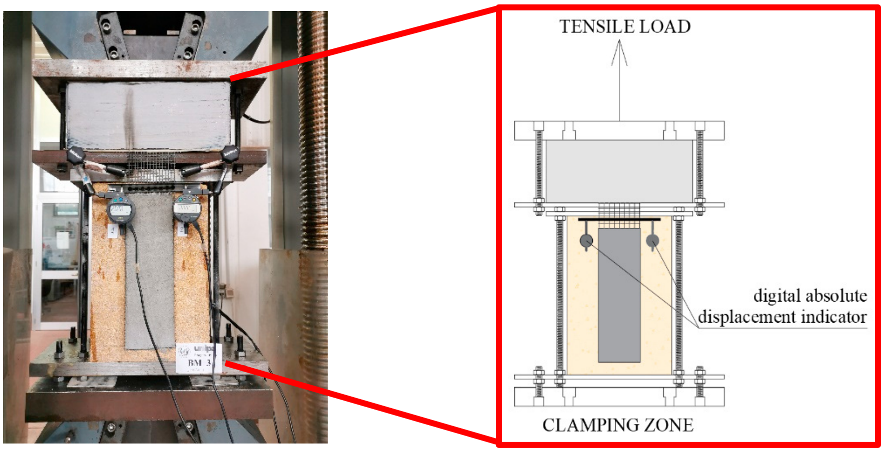


Fig. 3. Double shear bond test set up for Basalt-FRCM-to-calcarenite support.

## 3. Results and discussion

### *3.1. Tensile tests on Basalt-FRCM systems*

The two Basalt-FRCM systems (BC and BL) tested in tension are divided in four groups as function of mortar type (cement based or hydraulic lime based) and test set-up (clamping or clevis grip method): BC_TF, BC_TH, BL_TF and BL_TH group. Results are plotted in terms of stress-axial strain curves, as shown in Fig. 4. Stress values are calculated by dividing load values by the cross-section equivalent area of basalt fibre. Moreover, the average stress-strain trend from tensile tests on basalt grid is reported in red.

Experimental curves for Basalt-FRCM with cement-based mortar (BC_TF and BC_TH series) do not follow the typical trilinear trend generally observed for FRCM composites tested in tension, see Fig. 4a and Fig. 4b. In this case, the first linear branch of the curve depends on the strength and stiffness of mortar, while the second phase of transition is mainly governed by the fibre and has a limited extension, due to the under-reinforced cross-section of the FRCM system. When the first cracking load is achieved, the fibre reinforcement has almost reached its maximum strength and the FRCM system fails for low values of strain. Experimental results from the two tensile test set-up provide comparable average maximum strengths, i.e. 1108 MPa and 1031 MPa for clamping and clevis grip method, respectively. However, initial stiffness is different as well as the trend of the second stage. In details, specimens tested with clevis method provide a second stage characterized by load drops corresponding to the crack opening. It is worth highlighting that the basalt fibre and the cement-based mortar have established a good adhesion and the failure mode observed is the fibre rupture near the gripping area with the formation of few cracks.

The typical trilinear behaviour is observed for Basalt-FRCM coupons with hydraulic lime-based mortar (BL_TF and BL_TH), Fig. 6c and Fig. 6d. The first stage of the curves is mainly governed by mortar stiffness up to reach the first cracking load, in the second stage the cracks opening occurs simultaneously with the activation of interface phenomena up the cracking stabilization, finally in the third stage the mainly contribute is given by fibre reinforcement. Both the test set-up methods provide comparable average values of the first cracking stress (633 MPa and 531 MPa for clamping and clevis method, respectively) and maximum strength (1216 MPa and 1269 MPa for clamping and clevis method, respectively). However, different strain values are achieved. Results from tensile tests with clevis grip method provide a second phase less extended than clamping grip method, reaching an average maximum strain value of 1.7 %, (Fig. 4d), against 2.3% referred to clamping method (Fig. 4c). A different failure mode is observed for Basalt-FRCM systems with hydraulic lime-based mortar. In particular, the delamination at the fibre-mortar interface and the formation of several cracks in the mortar layers is observed, finally the composite system fails due to fibre rupture far from the gripping area.

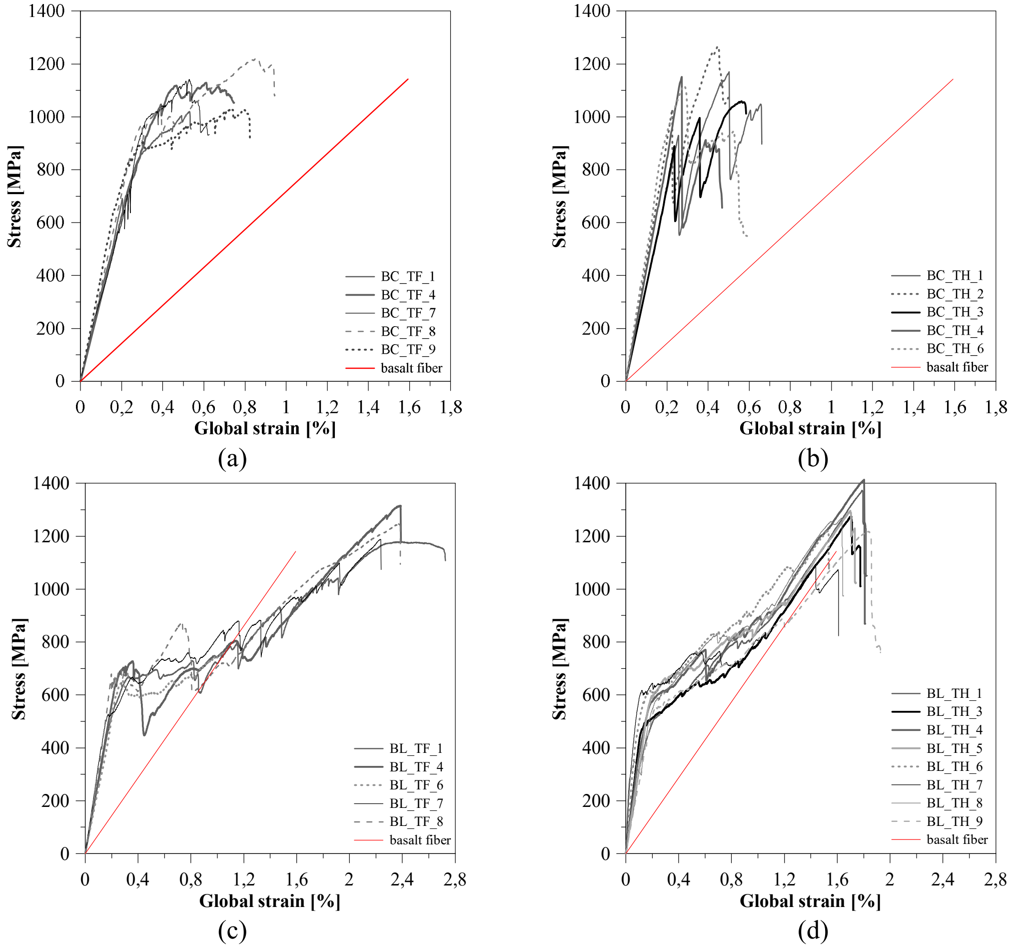


Fig. 4. Experimental curves from tensile tests: (a) Basalt-FRCM with cement-based mortar, tested with clamping grip method (BC_TF); (b) Basalt-FRCM with cement-based mortar, tested with clevis grip method (BC_TH); Basalt-FRCM with hydraulic lime-based mortar, tested with clamping grip method (BL_TF); Basalt-FRCM with hydraulic lime-based mortar, tested with clevis grip method (BL_TH).

### *3.2. Double shear bond tests on Basalt-FRCM-to-support*

The adhesion properties of the two FRCM systems (BC and BL) to calcarenite support are evaluated from double shear bond tests. Results are plotted in terms of stress-global displacement curves, as shown in Fig. 5a and 5b. Moreover, curves in terms of stress-slip are reported in Fig. 6a and 6b. In this case, the slip values are calculated considering the average values of data recorded by two digital absolute displacement indicators settled in the front and rear side of samples, in order to record the relative slip between fibre and substrate, and also to give information about eccentricity phenomena.

The axial stress values are calculated by dividing the axial force applied to the upper block with the equivalent cross-section of the two basalt fibre strips. A different global behaviour merges from the comparison of the experimental curves related to the two groups of samples (BC_DSB and BL_DSB), see Fig. Fig. 5a and 5b. Cement based mortar has established a good adhesion with basalt fibre, for this reason experimental curves of BC_DSB group show a linear elastic behaviour up the maximum fibre strength followed by a limited post-peak phase and the failure mode is governed by the fibre rupture in the unbonded length. Despite a great scatter is observed for samples of BC_DSB group, data recorder by the digital absolute displacement indicators (Fig. 6a) confirm that no eccentricity phenomena occur in the samples, so the variability of results is probably due to some defects in the fibre strips. Samples of BL_DSB group (Fig. 5b) highlight a different global behaviour characterized by a first linear branch up to reach the load of debonding. Then, the delamination of the upper mortar layer spread from the loaded end to the entire bond length causing the total slip of the fibre. Also, in this case negligible eccentricity phenomena are observed, with the exception of sample BL_DSB_1.

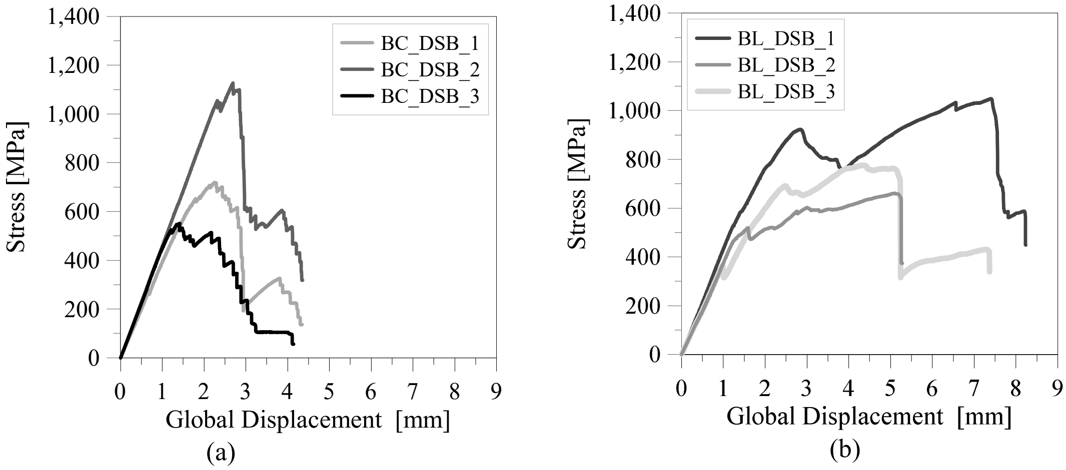


Fig. 5. Experimental results from double shear bond tests, stress-global displacement curves: (a) Basalt-FRCM with cement-based mortar, (BC_DSB); (b) Basalt-FRCM with hydraulic lime-based mortar (BL_DSB).

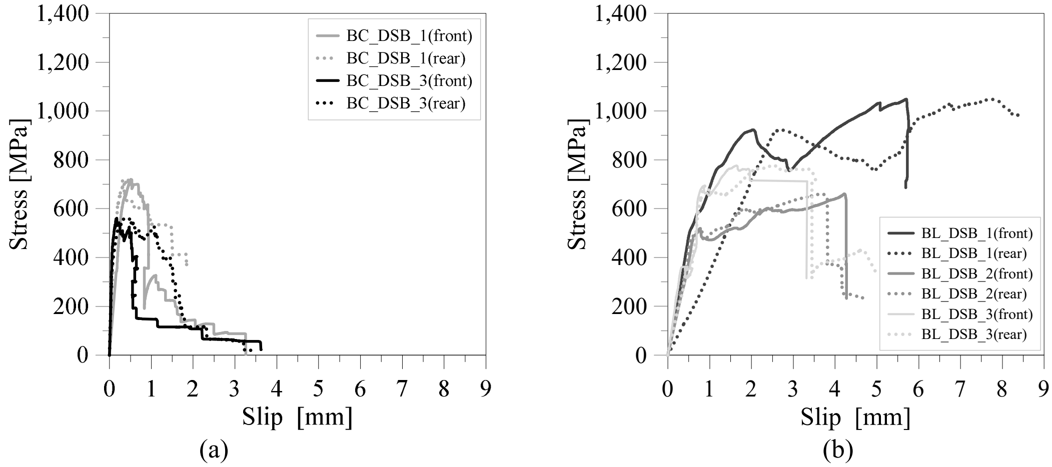


Fig. 6. Experimental outcomes from digital absolute displacement indicators, stress- slip curves: (a) Basalt-FRCM with cement-based mortar, (BC_DSB); (b) Basalt-FRCM with hydraulic lime-based mortar (BL_DSB).

## 4. Conclusions

The aim of the present work is to draw some conclusions about tensile and shear bond-behaviour of FRCM composites applied on calcarenite support. The effect of test set-up on the tensile performances of FRCM composites and the influences of mortar type on the tensile and shear bond behaviour of Basalt-FRCM composites applied on calcarenite support are investigated. Experimental outcomes from tensile tests confirm the repeatability of results in terms of first cracking stress and maximum strength, while the exploitation of the transient phase in samples of BL_TF and BL_TH group and the maximum strain depends on the grip method adopted. The typical trilinear trend for tensile curves not always is observed due to the mortar properties and the mechanical percentage of fibre reinforcement. In fact, when the FRCM cross-section is under-reinforced the exploitation of the typical tri-linear trend is not achieved, consequently the FRCM system fails for low values of strain. A new test set-up is proposed for double shear bond test. It is representative of the strengthened masonry structural elements. Results provide the reliability of the proposed test set-up allowing to overcome some of the drawbacks related to shear bond test. Experimental outcomes proved that the nature of mortar (cement or lime based) significantly affected the mechanical response and the failure mode due to the adhesion properties achieved at the fibre-mortar interface. In details, cement-based mortar has established a good adhesion with the basalt fibre; for this reason, the composite system fails when the tensile strength is achieved in the unbonded fibre strip. While, fibre slippage occurs when lime-based mortar is considered causing the delamination of the upper mortar layer.

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## References

AC434-13 I, 2013. Acceptance Criteria for Masonry and Concrete Strengthening Using Fiber-Reinforced Cementitious Matrix (FRCM) Composite Systems; ICC-Evaluation Service: Whittier, CA, USA.

Accardi, M., Cucchiara, C., and La Mendola, L., 2007. Bond behavior between CFRP strips and calcarenite stone. In Proceedings of the 6th international conference on fracture mechanics of concrete and concrete structures, Catania, Italy (pp. 17-22).

Aiello, M. A., Bencardino, F., Cascardi, A., D'Antino, T., Fagone, M., Frana, I., La Mendola, L., Lignola, G.P., Mazzotti, C., Micelli, F., Minafò, G., Napoli, A., Ombres, L., Oddo, M.C, Poggi, C., Prota, A., Ramaglia, G., Ranocchiai, G., Realfonzo, R., and Verre, S., 2021. Masonry columns confined with fabric reinforced cementitious matrix (FRCM) systems: A round robin test. Construction and Building Materials, 298, 123816.

De Felice, G., Aiello, M. A., Caggegi, C., Ceroni, F., De Santis, S., Garbin, E., Gattesco, N., Hojdys, L., Krajewski, P., Kwiecien, A., Leone, M., Lignola, G.P., Mazzotti, C., Oliveira, D., Papanicolaou, C., Poggi, C., Triantafillou, T., Valluzzi, M.R., and Viskovic, A., 2018. Recommendation of RILEM Technical Committee 250-CSM: Test method for Textile Reinforced Mortar to substrate bond characterization. Materials and Structures, 51(4), 1-9.

De Santis, S., Roscini, F., and de Felice, G. 2018. Full-scale tests on masonry vaults strengthened with Steel Reinforced Grout. Composites Part B: Engineering, 141, 20-36.

Donnini, J., and Corinaldesi, V., 2017. Mechanical characterization of different FRCM systems for structural reinforcement. Construction and Building Materials, 145, 565-575.

EN 1015-11, 2001. Methods of test for mortar for masonry - Determination of flexural and compressive strentgth of hardened mortar.

Grande, E., and Milani, G., 2018. Interface modeling approach for the study of the bond behavior of FRCM strengthening systems. Composites Part B: Engineering, 141, 221-233.

ISO 13934-1, 2013. Textiles – tensile properties of fabrics - determination of maximum force and elongation at maximum force using the strip method. CEN – European Committee for Standardization.

Italian Guideline for the Identification, Qualification and Acceptance Control of Fibre Reinforced Cementitious Matrix (FRCM) Used for the Structural Consolidation of Existing Constructions. C.S.LL.PP.

Leone, M., Aiello, M. A., Balsamo, A., Carozzi, F. G., Ceroni, F., Corradi, M., Gams, M., Garbin, E., Gattesco, N., Krajewski, P., Mazzotti, C., Oliveira, D., Papanicolaou, C., Ranocchiai, G., Roscini, F., and Saenger, D., 2017. Glass fabric reinforced cementitious matrix: Tensile properties and bond performance on masonry substrate. Composites Part B: Engineering, 127, 196-214.

Lignola, G. P., Caggegi, C., Ceroni, F., De Santis, S., Krajewski, P., Lourenço, P. B., Morganti, M., Papanicolaou, C., Pellegrino, C., Prota A., and Zuccarino, L., 2017. Performance assessment of basalt FRCM for retrofit applications on masonry. Composites Part B: Engineering, 128, 1-18.

Minafò, G., Oddo, M. C., and La Mendola, L., 2022. Formulation of a truss element for modelling the tensile response of FRCM strips. Construction and Building Materials, 315, 125576.

Monaco, A., D'Anna, J., Oddo, M. C., Minafò, G., and La Mendola, L., 2019. Numerical modelling of the tensile behaviour of BFRCM strips. In Key Engineering Materials (Vol. 817, pp. 15-22). Trans Tech Publications Ltd.

Nerilli, F., Marfia, S., and Sacco, E., 2020. Micromechanical modeling of the constitutive response of FRCM composites. Construction and Building Materials, 236, 117539.

RILEM Technical Committee 232-TDT, 2016. Recommendation of RILEM TC 232-TDT: test methods and design of textile reinforced concrete: uniaxial tensile test: test method to determine the load bearing behavior of tensile specimens made of textile reinforced concrete. Materials and Structures, 49(12), 4923-4927.

Saidi, M., and Gabor, A., 2019. Use of distributed optical fibre as a strain sensor in textile reinforced cementitious matrix composites. Measurement, 140, 323-333.