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Experimental and numerical bond behavior of PBO FRCM tested using a pull-out set-up

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Abstract

Fabric-reinforced cementitious matrix (FRCM) composites have become increasingly popular in the field of externally bonded (EB) reinforcement of existing concrete and masonry structures. They are used as flexural, shear, and torsional strengthening of reinforced concrete (RC) members. They are comprised of high strength textiles embedded in an inorganic-based matrix. FRCM tensile mechanical properties are characterized by clamping-grip or clevis-grip tensile tests, whereas their bond behavior by indirect or single- and double-lap direct shear tests. The eccentricity between the applied load and the restraint in single-lap direct shear tests entails for the presence of normal stresses that can affect the bond stress-transfer mechanism. Furthermore, direct shear tests require relatively large and heavy specimens. To overcome these issues, a new pull-out test set-up was proposed in the literature to investigate the bond behavior of FRCM composites that fail at the textile-matrix interface. In this paper, nine pull-out tests are performed on PBO FRCM composites. Bonded lengths shorter and longer than the textile-matrix interface effective bond length are considered. Six specimens have a short bonded length (i.e., 150 mm), whereas three have a long bonded length (i.e., 450 mm). Applied stress – global slip curves of the specimens tested highlight the presence of friction at the textile-matrix interface. The results of the pull-out tests are compared with those of corresponding single-lap direct shear tests presented in a previous work with the same PBO FRCM composite and the same bonded length and width. The applied stress – global slip curves obtained from the two sets of test show good agreement. Finally, the pull-out test set-up is validated by means of a three-dimensional finite element model.

Keywords: PBO, FRCM, pull-out, CML, numerical modelling.

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1. Introduction

Fiber-reinforced cementitious matrix (FRCM) composites have become increasingly popular in the field of externally bonded (EB) reinforcement of existing concrete and masonry structures. They are comprised of high strength open mesh textiles embedded in an inorganic matrix. Different types of textile and matrix can be used to create an FRCM composite, such as carbon, PBO, glass or steel fibers and lime- or cement-based mortars. PBO FRCM have been effectively used to strengthen existing masonry structures against in-plane and out-of-plane actions and as flexural, shear, and torsional reinforcement of concrete members. Thanks to their high strength- and stiffness-to-weight ratios, FRCM represents a promising strengthening technique also in seismic-vulnerable areas. FRCMs overcome some of the drawbacks of fiber-reinforced polymers (FRPs) related to the use of epoxy resin, such as the low resistance to UV light, to (relatively) high temperature, and the irreversibility of the application. FRCMs are resistant to corrosion and have high compatibility with both concrete and masonry substrates.

FRCM tensile mechanical properties are usually characterized by clamping-grip or clevis-grip tensile tests (Arboleda et al. (2016), Monaco et al. (2020), De Domenico et al. (2022), Focacci et al. (2022), Ferretti et al. (2022)), whereas their bond behavior is usually studied using single- or double-lap direct shear tests performed on FRCM applied on specific concrete or masonry blocks (Sneed et al. (2015), Carozzi et al. (2016), Raoof et al. (2016), Donnini et al. (2020), Rovero et al. (2020)). Various failure modes can be observed in FRCM-substrate joints, depending on the textile and matrix used. Failure can be attained i. within a thin layer of concrete, ii. at the FRCM-substrate interface, iii. at the textile-matrix interface (associated with textile slippage from the mortar matrix), and iv. due to fiber tensile failure (that can happen both inside the FRCM strip or outside the bonded length). In failure type iii., slippage of the textile within the matrix can be associated with progressive tensile failure of the external fiber filaments within each bundle or with matrix interlaminar cracking (Hartig et al. (2012), Santandrea et al. (2020), Ombres et al. (2022), Bertolli et al. (2023)). When one layer of textile is employed, failure is generally attained at the textile-matrix interface (failure mode iii.) and the substrate mechanical and geometrical properties do not play a significant role. Within this context, the bond behavior of the textile-matrix interface is described using a cohesive contact approach where the relation between the shear stress τ and the relative displacement s at the interface is described by a cohesive material law (CML). Different shapes of the CML were proposed in the literature and were used to analytically and numerically describe the bond behavior of various FRCM composites (D'Ambrisi et al. (2013), Zou et al. (2020), Bilotta and Lignola (2021), Mirzaei et al. (2021), Bertolli and D'Antino (2022)). This approach allows for studying the effect of FRCM-substrate joint bonded length and for confirming the presence of an effective bond length, i.e., the minimum length needed to fully establish the bond stress transfer mechanism (Malena (2018)).

Although single- and double-lap direct shear tests are largely used to study the bond behavior of FRCM-substrate joints, they require the use of relatively large and heavy specimens and can be hardly considered for in situ quality control tests. With the aim of providing a simple tool to assess the FRCM bond behavior without the need of performing single- or double-lap direct shear tests, a new pull-out test set-up was proposed by D'Antino et al. (2017) to study FRCM composites that fail at the textile-matrix interface. Differently from direct shear tests, the pull-out test set-up does not require the use of the specific (masonry or concrete) substrate, which makes the pull-out specimen lighter and easier to handle. Considering that the substrate does not significantly affect the stress-transfer mechanism when debonding occurs at the textile-matrix interface, in pull-out tests the FRCM strip is epoxy-bonded to two metal plates connected to the testing machine, whereas the bare textile protruding from the FRCM strip is directly gripped by the machine wedges and pulled out of the matrix. This set-up limits the effects of the inherent eccentricity of single-lap direct shear tests, mitigating the presence of a fracture mechanics mode-I loading condition (Calabrese et al. (2019)). Furthermore, pull-out tests specimens can be cast easier and in situ for quality control assessment.

In this paper, the pull-out test set-up is adopted to test nine PBO FRCM specimens. Six of them had a short bonded length (L = 150 mm), whereas the remaining three had a long bonded length (L = 450 mm). A comparison is made between the results of pull-out tests reported in this work and those of direct shear tests presented in a previous work by the authors (Bertolli and D'Antino (2022)). These direct shear tests comprised the same PBO textile and cement-based mortar matrix and had the same bonded length and width of pull-out tests. Finally, the pull-out test set-up is validated by means of a three-dimensional finite element numerical model.

2. Materials and methods

The pull-out test set-up presented in D'Antino et al. (2017) and used in Calabrese et al. (2019) was considered in this work to assess the bond behavior of a PBO FRCM composite that attained failure at the textile-matrix interface (Fig. 1a). Nine pull-out tests were performed on PBO FRCM specimens comprising a single layer of unbalanced open mesh PBO textile with equivalent thickness t_f = 0.0455 mm and yarn center-to-center spacing i_f = 10 mm (Ruregold S.r.L. (2019)), and a cementitious mortar specifically designed for concrete substrates (Ruregold S.r.L. (2020)). The PBO textile was embedded in two 4 mm-thick mortar layers. Each specimen comprised six PBO longitudinal fiber bundles, which resulted in a specimen width b_f = 60 mm. The textile cross-sectional area and contact perimeter were A_f =2.76 mm^2 and p=10 mm, respectively. Six specimens had a textile-matrix bonded length L equal to 150 mm, whereas the remaining three had L = 450 mm.

A portion of 170 mm of the textile was left bare (i.e., non-impregnated with the mortar) at the specimen loaded end (Fig. 1b). Two (600 mm long, 60 mm wide, and 3 mm thick) steel plates were attached on both sides of the FRCM specimen at the opposite end (i.e., the free end) using epoxy resin. The matrix-plates bonded length was equal to the bonded length of the specimen. The steel plates were connected to the testing machine using a spherical joint, whereas the bare textile was gripped by the machine wedges through thin steel plates attached to the textile to facilitate gripping. A picture of the test set-up is reported in Fig. 1a. Two aluminum L-shaped plates were attached to the textile immediately outside the FRCM strip and reacted-off of three linear variable displacement transformers (LVDTs) attached to the steel plates. LVDT_0 was placed on one side of the specimen and was used to control the test, which was performed in displacement control at a rate of 0.00084 mm/s. The remaining LVDTs, LVDT_1 and LVDT_2, were positioned on the opposite side of the specimen and were used to control possible uneven distributions of the applied stress that result in rotation of the L-shaped plates. The average of their measurement was defined as the global slip g.

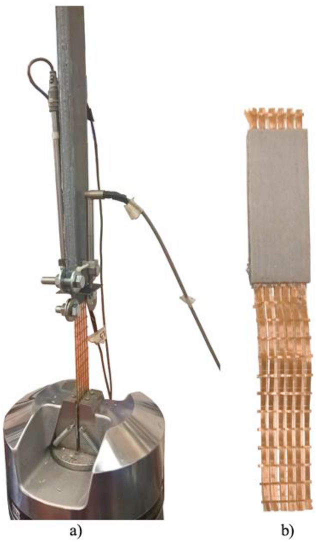

Fig. 1 a) Specimen PO_450_60_1 during the test and b) picture of specimen PO_150_60_D_1.

Specimens were named PO_X_Y_D_N, where PO = pull-out, X = textile-matrix and matrix-plate bonded length (in mm), Y = textile-matrix and matrix-plate bonded width (in mm), D (if present) = test conducted until a constant residual applied load was present, and N = specimen number.

The bond behavior of the same PBO FRCM composite was investigated using single-lap direct shear (DS) tests in Bertolli and D'Antino (2022). These specimens were named using a nomenclature analogous to that used for pull-out specimens where PO was substituted by DS to indicate a direct shear test. The same bonded width and lengths considered for pull-out tests were considered for direct shear tests, with specimen group DS_150_60 having a bonded length L = 150 mm, and specimen group DS_450_60 having bonded length L = 450 mm. Specimens that attained failure due to fiber rupture (DS_450_60_1,3,5) were disregarded. Details of these specimens preparation and test set-up can be found in Bertolli and D'Antino (2022).

3. Experimental results

Fig. 2a and b report the applied stress σ – global slip *g* curves of all specimens tested, as well as the envelopes of the curves obtained. The applied stress was obtained by dividing the applied load *P* measured by the testing machine by the textile cross-sectional area, A_f. The main parameters obtained by each pull-out and direct shear test specimen, as well as average values for nominally equal specimens (indicated with the subscript *avg*), are reported in Table 1.

All specimens attained failure at the textile-matrix interface associated with slippage of the textile with respect to the matrix. In specimen PO_150_60_D_3, the test was interrupted before failure due to a technical issue with the testing machine. This specimen was not considered in the curve envelopes.

The PBO FRCM composite considered showed friction at the textile-matrix interface, which was responsible for the residual applied stress at the end of the test of specimens PO_150_60_D and DS_450_60. All specimens tested showed the so-called telescopic behavior, where external (sleeve) fiber filaments fail before the internal (core) filaments due to the different impregnation by the inorganic matrix (Banholzer (2004)). Impregnation of core filaments was hindered by the granulometry of the mortar matrix (Carozzi et al. (2016)). This phenomenon was particularly evident for (both pull-out and direct shear) specimens with a bonded length of 450 mm, for which the final frictional branch (if present) attained lower values of stresses, due to bond degradation caused by the progressive failure of sleeve filaments. Comparison between results of pull-out tests performed on specimens with L = 150 mm and L = 450 mm showed that higher average peak stress σ^*_{avg} was attained for specimens with higher bonded length. The same holds for the average values of corresponding global slip. The same trend was observed in direct shear test results (Fig. 2c and d). This confirms that FRCM specimens that present friction at the textile-matrix interface provides a higher bond capacity with increasing the bonded length. However, difference in σ^*_{avg} between the specimens tested could also be attributed to a bonded length of 150 mm that is lower than the effective bonded length, l_{eff}, of the PBO FRCM composite considered, which is usually assumed as 260 mm (Zou et al. (2020)). Fig. 2e and f compare the applied stress σ – global slip *g* curves of pull-out and direct shear tests for specimens with L = 150 mm and 450 mm, respectively. While specimens with L = 150 mm showed consistent results, direct shear tests of specimens with L = 450 mm provided higher peak stresses than corresponding specimens tested using the pull-out set-up. This difference was attributed to different properties of the mortar matrix used in the two cases. In fact, results of direct shear tests on FRCM-concrete joints with the same PBO textile and inorganic matrix used in this work and discussed in D'Antino et al. (2018) reported peak applied stresses consistent with those of pull-out tests in this paper.

Table 1. Pull-out and direct shear test experimental results.

Pull-out test specimens	P^* [kN]	P^*_{avg} [kN] (CoV)	σ^* [MPa]	σ^*_{avg} [MPa] (CoV)	Direct shear test specimens	P^* [kN]	P^*_{avg} [kN] (CoV)	σ^* [MPa]	σ^*_{avg} [MPa] (CoV)
PO_150_60_D_1	4.39		1589		DS_450_60_1	5.58		2022	
PO_150_60_D_2	5.40		1955		DS_450_60_2	4.74		1716	
PO_150_60_D_3	-	4.42 (15.35 %)	-	1600 (15.35 %)	DS_450_60_3	5.79	5.35 (10.41 %)	2098	1937 (10.41 %)
PO_150_60_D_4	3.65		1324		DS_450_60_4	4.73		1712	
PO_150_60_D_5	3.95		1430		DS_450_60_5	6.06		2196	
PO_150_60_D_6	4.69		1700		DS_450_60_6	5.18		1876	
PO_450_60_1	9.36		4.05		DS_450_60_2	6.68		2421	
PO_450_60_2	8.31	5.36 (3.17 %)	3.59	1943 (3.17 %)	DS_450_60_4	6.00	6.44 (5.95 %)	2173	2333 (5.95 %)
PO_450_60_3	8.91		3.85		DS_450_60_6	6.64		2404	

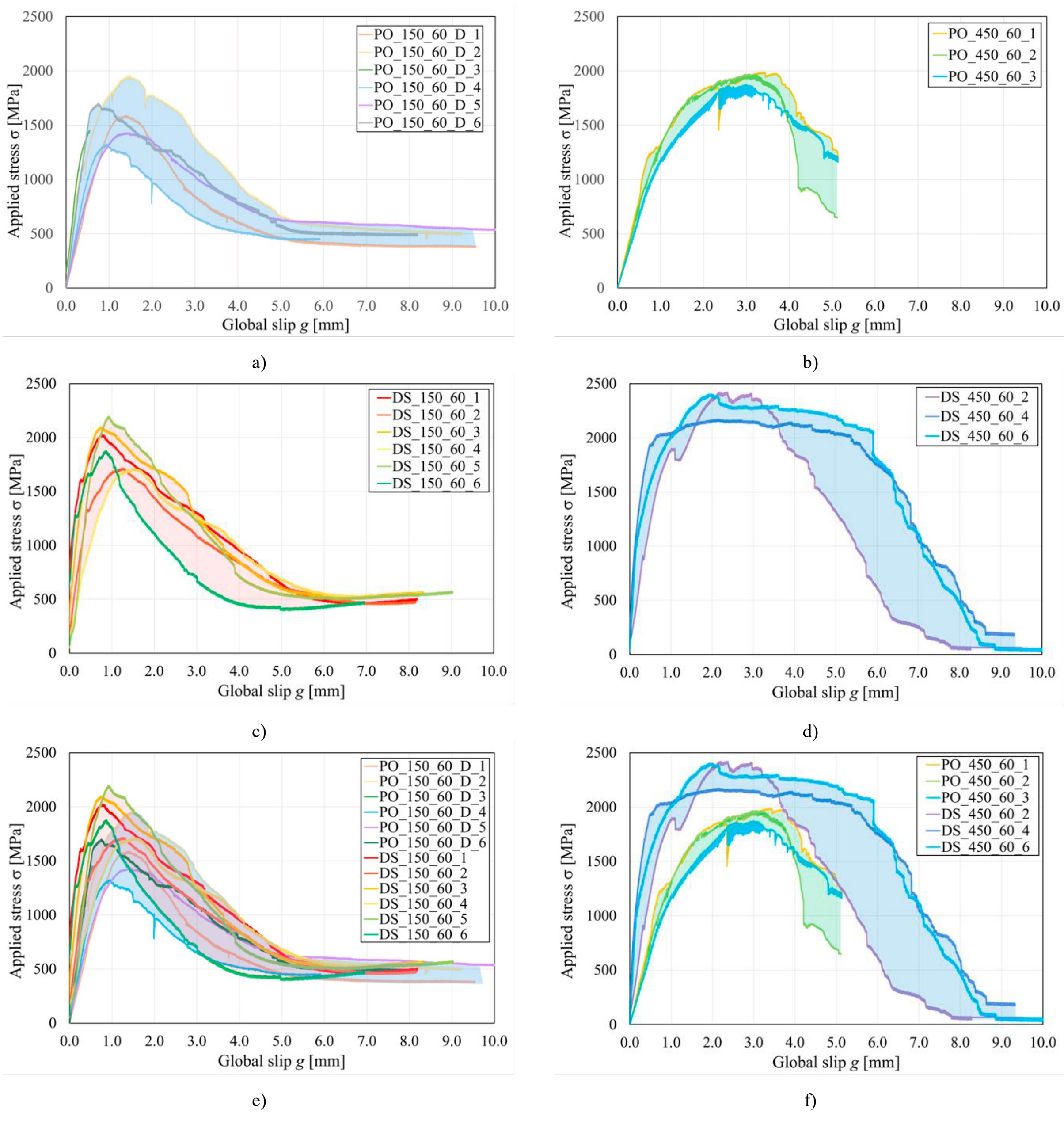

Fig. 2 Applied stress σ – global slip *g* curves of specimens a) PO_150_60_D, b) PO_450_60, c) DS_150_60, and d) DS_450_60. Comparison between σ – *g* curves of specimens with e) *L* = 150 mm and f) *L* = 450 mm.

4. Numerical results

Three-dimensional numerical models of pull-out specimens with *L* = 150 mm and 450 mm were developed with a commercial finite element software (Simulia 2013). The components of the set-up and the specimen were modeled with their geometry and discretized using 8-node brick elements. All materials were assumed as homogenous, isotropic, and with a linear-elastic behavior up to failure. The adoption of a linear-elastic behavior for the mortar matrix was justified by the absence of cracks in the matrix during the tests and was confirmed by numerical results, which showed matrix stresses always lower than the matrix tensile and compressive strengths. Each interface between materials (i.e., matrix-matrix, textile-matrix, and matrix-plate) was modeled with a zero thickness interface controlled by cohesive contact-damage laws. A trilinear CML was considered for the textile-matrix interface. This CML was calibrated by enforcing four parameters obtained from the load responses of pull-out tests. The calibration procedure proposed in D'Antino et al. (2018) was used. As a first attempt to account for the fiber filament failure observed in specimens with long bonded length, a different value of the shear stress associated with the friction branch at the end of the CML was enforced for specimens with L = 150 mm and 450 mm. The CML obtained for specimens with L = 150 mm and 450 mm, named CML_150 and CML_450, respectively, are shown in Fig. 3. The assumption of different constant friction branches did not provide significant differences in the ascending and descending portions of the CMLs.

For the interface between the two layers of matrix embedding the textile (i.e., the matrix-matrix interface), the contact law proposed in Carloni et al. (2018) for the same inorganic matrix considered in this study was adopted.

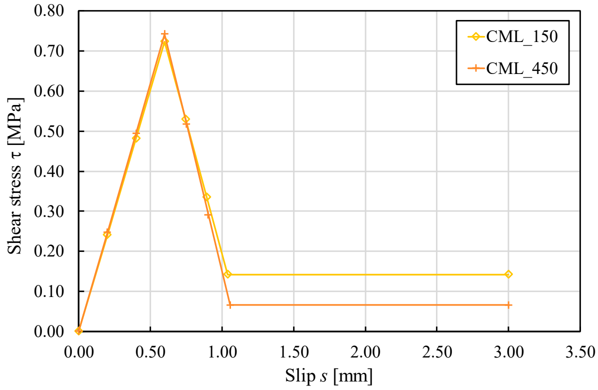

Fig. 3 CMLs obtained for specimens with L =150 mm and 450 mm.

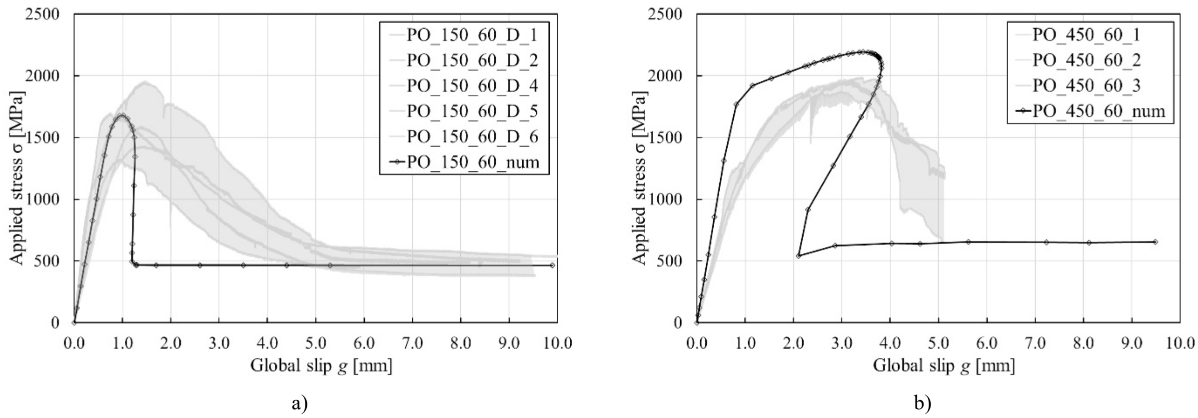

Fig. 4 Comparison between experimental envelope and numerical applied stress σ – global slip g curves of specimen series a) PO_150_60_num and b) PO_450_60_num.

The numerical models showed pure debonding of the fibers from the mortar with negligible effect of mixed mode-I and II loading condition at any interface. The applied stress – global slip curves obtained by the numerical models, named PO_150_60_num and PO_450_60_num, are compared with the envelope of corresponding experimental curves in Fig. 4. Results in Fig. 4 show a good agreement between experimental and numerical curves of specimens with L = 150 mm. However, an overestimation of the experimental peak stress was obtained with the numerical model of specimens with L = 450 mm, whereas the corresponding experimental and numerical global slips were similar. This difference on the peak stress was attributed to failure of (sleeve) fiber filaments observed in specimens with high bonded length, which did not allow for attaing a peak stress consistent with the CML calibrated with specimens with short bonded length and limited damage to the fiber filaments. Further studies are needed to clarify the effect of fiber damage on PBO FRCM bond behavior. However, the results showed the capability of the numerical model in reproducing the results of pull-out tests and in turn confirmed that the pull-out test set-up generates a stress condition at the textile-matrix interface similar to that of the single-lap direct shear test (i.e., a pure fracture mechanics mode-II loading condition can be assumed).

5. Conclusions

In this paper, the results of nine pull-out tests performed on PBO FRCM composites with the same bonded width and two different bonded lengths were presented. All specimens tested failed at the textile-matrix interface with fiber slippage. The presence of a residual applied stress at the end of the test was attributed to the presence of friction at the textile-matrix interface. Comparison between the applied stress – global slip curves of specimens with different bonded lengths showed an increase of average applied stress. Comparison with direct shear tests performed on the same PBO FRCM reported in a previous study confirmed that the pull-out test set-up proposed can be effectively used to investigate the bond behavior of FRCM composites when failure is attained at the textile-matrix interface for both long and short bonded lengths. Finally, a three-dimensional finite element numerical model was used to simulate the pull-out tests performed and confirmed that the pull-out set-up generates a stress condition at the textile-matrix interface similar to that of the single-lap direct shear test, i.e., a pure fracture mechanics mode-II loading condition.

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References

Arboleda, D., Carozzi, F. G., Nanni, A., and Poggi, C., 2016. Testing procedures for the uniaxial tensile characterization of fabric-reinforced cementitious matrix composites, Journal of Composites for Construction, 20(3).
Banholzer, B., 2004. Bond Behaviour of a Multi-Filament Yarn Embedded in a Cementitious Matrix, RWTH Aachen University, Aached (DE).
Bertolli, V., and D'Antino, T., 2022. Modeling the behavior of externally bonded reinforcement using a rigid-trilinear cohesive material law, International Journal of Solids and Structures, 248, 111641.
Bertolli, V., Signorini, C., Nobili, A., and D'Antino, T., 2023. Influence of severe thermal preconditioning on the bond between carbon FRCM and masonry substrate: Effect of textile pre-impregnation, Construction and Building Materials, 409, 134028.
Bilotta, A., and Lignola, G. P., 2021. Effect of fiber-to-matrix bond on the performance of inorganic matrix composites, Composite Structures, 265, 113655.
Calabrese, A. S., Colombi, P., and D'Antino, T., 2019. Analytical solution of the bond behavior of FRCM composites using a rigid-softening cohesive material law, Composites Part B: Engineering, 174.
Carloni, C., D'Antino, T., Sneed, L. H., and Pellegrino, C., 2018. Three-Dimensional Numerical Modeling of Single-Lap Direct Shear Tests of FRCM-Concrete Joints Using a Cohesive Damaged Contact Approach, Journal of Composites for Construction, 22(1), 04017048.
Carozzi, F. G., Colombi, P., Fava, G., and Poggi, C., 2016. A cohesive interface crack model for the matrix–textile debonding in FRCM composites, Composite Structures, 143, 230–41.
D'Ambrisi, A., Feo, L., and Focacci, F., 2013. Experimental and analytical investigation on bond between Carbon-FRCM materials and masonry, Composites Part B: Engineering, 46, 15–20.
D'Antino, T., Carozzi, F. G., Colombi, P., and Poggi, C., 2017. A New Pull-Out Test to Study the Bond Behavior of Fiber Reinforced Cementitious Composites, Key Engineering Materials, 747, 258–65.
D'Antino, T., Colombi, P., Carloni, C., and Sneed, L. H., 2018. Estimation of a matrix-fiber interface cohesive material law in FRCM-concrete joints, Composite Structures, 193, 103–12.
De Domenico, D., Maugeri, N., Longo, P., Ricciardi, G., Gullì, G., and Calabrese, L., 2022. Clevis-Grip Tensile Tests on Basalt, Carbon and Steel FRCM Systems Realized with Customized Cement-Based Matrices, Journal of Composites Science, 6(9), 275.
Donnini, J., Bompadre, F., and Corinaldesi, V., 2020. Tensile Behavior of a Glass FRCM System after Different Environmental Exposures, Processes, 8(9), 1074.
Ferretti, F., Tilocca, A. R., Incerti, A., Mazzotti, C., and Savoia, M., 2022. Tensile Behavior of FRCM Coupons under Thermal Stresses, Key Engineering Materials, 916, 50–7.

Focacci, F., D'Antino, T., and Carloni, C., 2022. Tensile Testing of FRCM Coupons for Material Characterization: Discussion of Critical Aspects, Journal of Composites for Construction, 26(4), 04022039.
Hartig, J., Jesse, F., Schicktanz, K., and Häußler-Combe, U., 2012. Influence of experimental setups on the apparent uniaxial tensile load-bearing capacity of Textile Reinforced Concrete specimens, Materials and Structures, 45(3), 433–46.
Malena, M., 2018. Closed-form solution to the debonding of mortar based composites on curved substrates, Composites Part B: Engineering, 139, 249–58.
Mirzaei, A. M., Corrado, M., Sapora, A., and Cornetti, P., 2021. Analytical Modeling of Debonding Mechanism for Long and Short Bond Lengths in Direct Shear Tests Accounting for Residual Strength, Materials, 14(21), 6690.
Monaco, A., Minafò, G., D'Anna, J., Oddo, M. C., and La Mendola, L., 2020. Constitutive Numerical Model of FRCM Strips Under Traction, Frontiers in Built Environment, 6, 60.
Ombres, L., Mazzuca, P., and Verre, S., 2022. Effects of the Thermal Conditioning on the Mechanical Properties of an FRCM (Fiber Reinforced Cementitious Matrix) Strengthening System, In Proceedings of the 3rd RILEM Spring Convention and Conference (RSCC 2020) (eds. J. Sena-Cruz, L. Correia, and M. Azenha), Vol. 34, 89–98, RILEM Bookseries, Springer International Publishing, Cham.
Raoof, S. M., Koutas, L. N., and Bournas, D. A., 2016. Bond between textile-reinforced mortar (TRM) and concrete substrates: Experimental investigation, Composites Part B: Engineering, 98, 350–61.
Rovero, L., Galassi, S., and Misseri, G., 2020. Experimental and analytical investigation of bond behavior in glass fiber-reinforced composites based on gypsum and cement matrices, Composites Part B: Engineering, 194, 1–10.
Ruregold S.r.L., 2019. Technical datasheet of PBO-Mesh Gold 70/18.
Ruregold S.r.L., 2020. Technical datasheet of MX-PBO calcestruzzo.
Santandrea, M., Focacci, F., Mazzotti, C., Ubertini, F., and Carloni, C., 2020. Determination of the interfacial cohesive material law for SRG composites bonded to a masonry substrate, Engineering Failure Analysis, 111, 104322.
Simulia, Abaqus 6.13 Documentation, URL: http://dsk.ippt.pan.pl/docs/abaqus/v6.13/index.html.
Sneed, L. H., D'Antino, T., Carloni, C., and Pellegrino, C., 2015. A comparison of the bond behavior of PBO-FRCM composites determined by double-lap and single-lap shear tests, Cement and Concrete Composites, 64, 37–48.
Zou, X., Sneed, L. H., and D'Antino, T., 2020. Full-range behavior of fiber reinforced cementitious matrix (FRCM)-concrete joints using a trilinear bond-slip relationship, Composite Structures, 239, 112024.