Review of FRCM strengthening solutions for structural wall panels

Cristian Sabau, Cosmin Popescu, Gabriel Sas, Thomas Blanksvärd and Björn Täljsten

Synopsis: This paper summarizes the state-of-the-art on the topic of structural wall panels strengthened using fabric reinforced cementitious matrix composites (FRCM) composites. A systematic review of the literature is carried out to identify gaps in the available literature. A database of experimental tests, relevant for structural panels, was created and used to assess the influence of parameters such as test method, fiber type and material compressive strength, on the performance of FRCM strengthening. Since experimental investigations on walls strengthened with FRCM composites is still limited and mostly focused on shear, further investigations on walls as compression members can be considered timely, especially walls with openings, which have been overlooked. Experimental tests performed by the authors on reinforced concrete walls with openings are presented and assessed relative to the complete database. It was shown that FRCM composites are suitable repair solutions when new openings need to be created in existing walls.

Keywords: FRCM, concrete, masonry, strengthening, structural walls

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INTRODUCTION

The upgrading of existing structures to ever changing requirements has been of great importance over the last decades due to environmental induced degradation, lack of maintenance, functionality changes, or need to meet higher safety standards. Fiber reinforced polymers (FRP) have been widely used for strengthening existing structurally over the last three decades. Strengthening with externally bonded FRP composites is nowadays a common alternative that minimizes inconvenience due to limitations in use of the structure during repairs. However, strengthening with FRP entails a few drawbacks mainly associated with the use of epoxy resins (i.e. their inability to apply on wet or moist surfaces, poor performance at high temperatures, and high working hazards).

Fabric reinforced cementitious matrix composites (FRCM) composites for strengthening existing structures have been shown high interest by the research community since almost two decades ago [1]. Inorganic cement based matrixes or mortars, represent a sustainable and durable alternative to epoxy used in FRP composites. The mortar matrix is reinforced with continuous fibers in the form of a unidirectional sheet or a bidirectional net to create the FRCM composite. Different names are used for this type of composite including mineral based composites (MBC), textile reinforced mortar (TRM), textile reinforced concrete (TRC), and fiber reinforced cementitious matrix (FRCM) composites. In this paper, the term FRCM composites will be used as defined in ACI 549.4R [2]. Types of fibers commonly used in FRCM composites are carbon, glass, steel, or polyparaphenylene benzobisoxazole (PBO) [3]. Other type of fibers used to a lesser extent are natural flax fibers, fibers made from recyclable plastics such as polypropylene (PP) and polyethylene terephthalate (PET), and aramid fibers.

Bonding FRCM instead of FRP composites to existing structural members is an increasingly attractive strengthening or repair solution for buildings. The main advantages of FRCM over FRP – good compatibility with masonry or concrete substrates, good fire resistance, and good durability – are inherent to the use of inorganic binders instead of epoxy resins. However, owing to the properties of inorganic matrixes the behavior of FRCM differs substantially from that of FRP composites and depends on multiple parameters such as the type of fibers used, substrate mechanical properties, and the matrix strength. FRCM systems proved to be an efficient strengthening system for masonry specimens, in some cases even more effective in terms of deformability than similar FRP configurations [4].

Externally bonded FRCM composites have been studied mostly for beams subjected to flexure or shear, and on cylinders or prisms subjected to axial compression. Recently, Gonzalez-Libreros et al. [5] summarized the state of research on FRCM-strengthened reinforced concrete (RC) beams in shear. The study [5] concluded that FRCM composites can increase the shear strength of RC beams by 55% on average, with values varying between 3% and 195% depending on parameters including, concrete compressive strength, fiber type, and strengthening configuration. In addition it was pointed out that additional work is required to improve the prediction capacity of available design models. To the authors' knowledge, similar comprehensive studies on the performance of FRCM composites for strengthening other types of structural elements are currently lacking.

An extensive literature review presented on concrete wall panels acting as compression members [6] concluded that relatively few experimental tests have been carried out on concrete panels with openings, and the topic of strengthening RC walls with composites is even less studied. In this paper a systematic assessment of experimental studies on FRCM strengthened structural walls is presented.

In the first part of the paper, a bibliographical review of the literature on FRCM strengthened structural wall panels using FRCM composites is carried out. The review highlights the major findings and serves to identify important gaps. In the second part of the paper, the results of an experimental study carried out by the authors are briefly presented and discussed in the wider context of the experimental database.

RESEARCH SIGNIFICANCE

FRCM composites have recently been shown great interest by the research community for strengthening of RC and masonry structures, and several researchers have investigated the performance of FRCM composites by means of experimental tests. Comprehensive studies on the performance of FRCM composites for strengthening structural wall panels are lacking and can prove relevant for directing the focus of future efforts on the topic.

REVIEW OF EXPERIMENAL TESTS

Experimental database

A systematic method [7] was employed in an attempt to identify all relevant tests reported in established peer-reviewed scientific journals. A manual search for articles was run in four bibliographic databases, namely Scopus, Science Direct, Web of Science and Google Scholar. A combination of the following keywords: “FRCM”, “TRM”, “TRC”, “MBC”, “FRIP”, “SRG”, “FRG”, “fabric”, “textile”, “concrete”, “masonry”, “wall”, “strengthening” was used. The search returned 242 different publications.

Twenty-six published articles related to wall panels strengthened with FRCM were found in the technical literature. A database that includes the material and geometrical characteristic of tested panels, the testing method, the size of the opening if applicable, and the country where the tests were carried out (assumed to be the same as the affiliation of the corresponding author) are presented in Annex A (Table A). The database contains 162 tested specimens.

The 26 articles included in Table A were obtained after screening the total number of papers based a number of criteria. The inclusion criteria in this case were: (1) original experimental research published in English in a peer reviewed journal, (2) experimental tests relevant for structural walls, (i.e. three- or four-point bending tests without axial loads were excluded, as well as tests on RC frames with infill panels), and (3), FRCM type composites were used for strengthening.

The testing method refers to the kind of test reportedly used to determine the flexural, shear, or axial capacity for each specimen. The shear capacity test methods were classified as diagonal compression (DC) or in plane shear with compression (IP-S+C). The flexural capacity of wall subjected to out of plane bending were classified as out of plane bending with compression (OPB+C) or out of plane bending with only the weight of the specimen as compression OPB+S (Figure 1). For all tests in categories IP-S+C and OPB+C, a hydraulic jack was used to apply a compression force concentrically at the top of the specimen. The compression force was reportedly maintained constant during testing. For IP-S+C tests hydraulic actuators were used to apply the shear force through a loading beam at the top of the specimen. For OPB+C and OPB+S tests, airbags were used to apply a uniformly distributed lateral load perpendicular to the surface of the panel. The tests for axial capacity were classified based as concentric compression (CC) or eccentric compression (EC) depending on how the load was applied relative to the specimen's cross-section.

In all cases the loads were applied in a quasi static manner, following a monotonically ascending trend or alternating cycles of increasing magnitude. For cases where the load was applied in a cyclic fashion, the average between the maximum loads reported for each direction was taken as the capacity of the specimen.

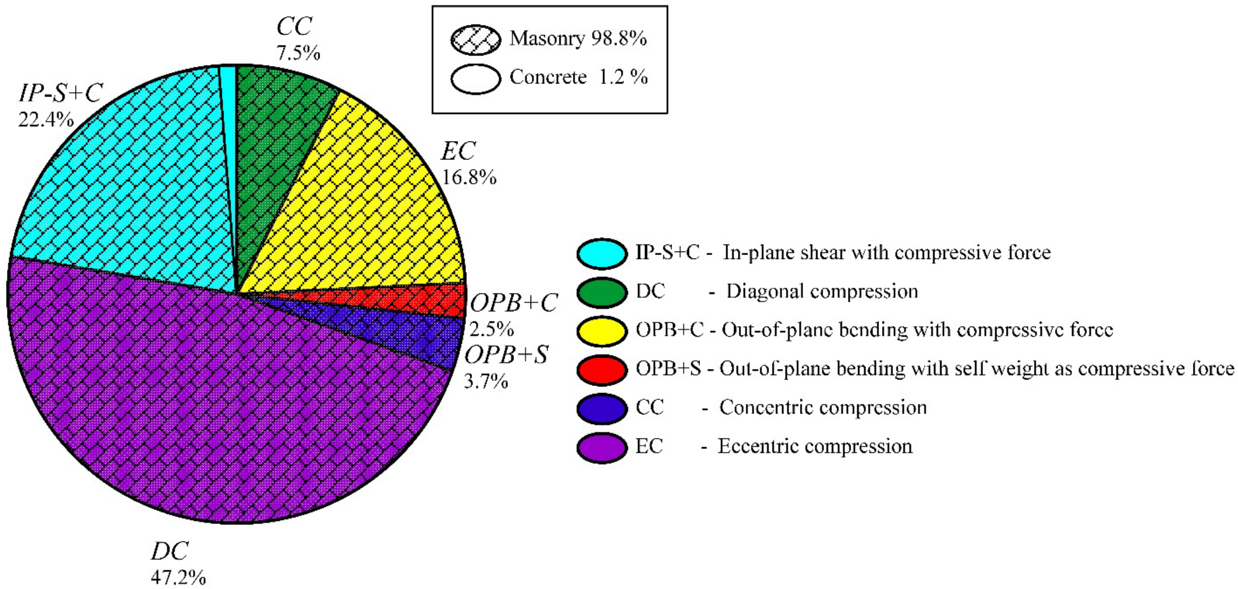

Figure 2 - Distribution of tested specimens by test method and material

The majority of tests investigated the shear behavior of walls (78.6%) and far less investigated walls subjected to the combined effects of out-of-plane bending and gravitational loads (23.8%). The remaining specimens (3.8%) were tested in concentric compression. Moreover, the vast majority of test were carried out on masonry, 98.7 % of the specimens, while only two concrete walls were reportedly tested using an in-plane shear setup. In addition, only 2.6% of the total tested specimens had openings, and all were subjected to in-plane shear (i.e. IP-S+C). The result of a quantitative assessment of available literature reporting experimental tests of FRCM strengthened structural walls is presented in Figure 2.

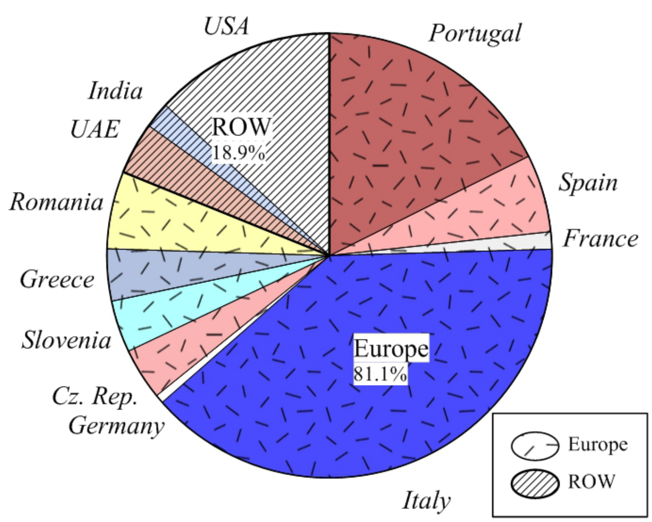

Figure 3 - Distribution of tested specimens by country and region (i.e. Europe, ROW – rest of the word)

Figure 2 shows that the majority of experimental studies on walls strengthened with FRCM were done in Europe, in particular Italy and Portugal, both countries with many historical masonry buildings situated in seismic areas. This explains why the majority of experimental tests were done for masonry elements subjected to shear (i.e. DC and IP-S+C), leaving the topic of concrete walls uncovered.

Evaluation of experimental database

The performance of FRCM strengthening is evaluated based on the ratio between the capacity of the strengthened specimens (R_{FRCM}) and the capacity of the reference specimen (R_{REF}). For each case the terms R_{FRCM} and R_{REF} refer to the respective, flexural, shear, or axial capacity.

Figure 3, Figure 4, and Figure 5 present the variation of the ratio R_{FRCM}/R_{REF} as a function of the test method, material compressive strength, and type of FRCM fiber nets, respectively. The number of tests in each category and the percentage relative to the total number of tests, are indicated at the top of each figure.

The ratio R_{FRCM}/R_{REF} for specimens presented in Figure 3, Figure 4, and Figure 5 varies between 0.8 and 7.73. Two IP-S+C tests on masonry panels reported in [4] for which R_{FRCM}/R_{REF} is approximately 15 are not graphically represented, however they are considered for further analysis.

The ratio R_{FRCM}/R_{REF} for six IP-S+C tests and three CC tests is less than unity. In three IP-S+C cases and the three CC cases the FRCM systems detached prematurely reportedly due large difference between the high modulus of elasticity of the FRCM matrix and the low modulus of elasticity of the matrix [8, 9]. The premature detachment of the FRCM weakened the panel [9], thus leading to capacities lower than that of the unstrengthened panel. In the other three IP-S+C cases, the strengthening was applied on panels that were tested to failure before strengthening [10, 11], thus the capacity of the strengthened panels was approximately that of the reference panel, however, slightly lower. Due to insufficient information provided, the ratio R_{FRCM}/R_{REF} cannot be evaluated for Kolsch [12], therefore, the tests were not included in further analysis.

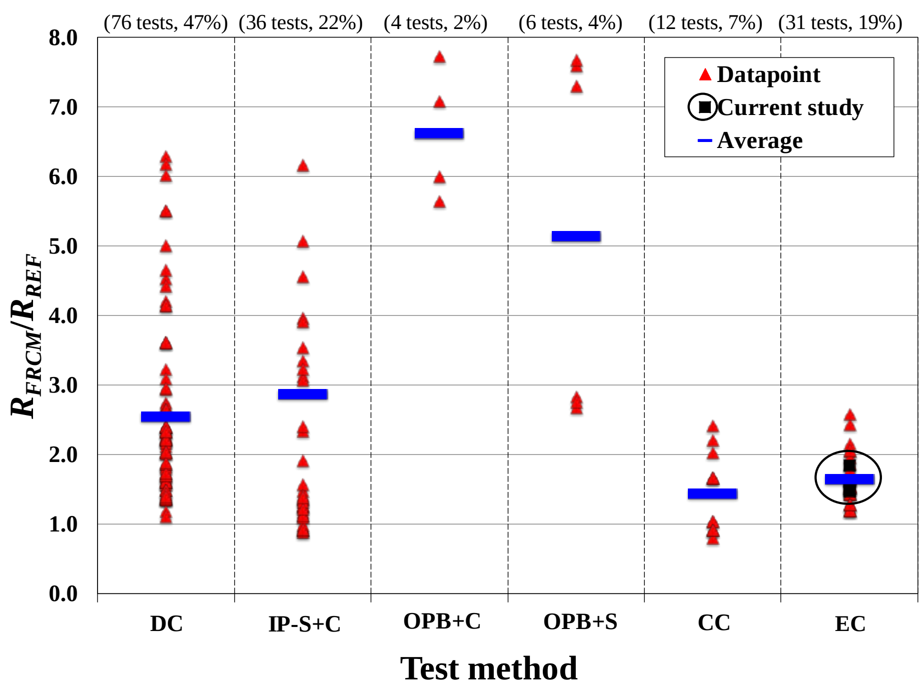

Figure 4 - Distribution of R_{FRCM}/R_{REF} as a function of test method

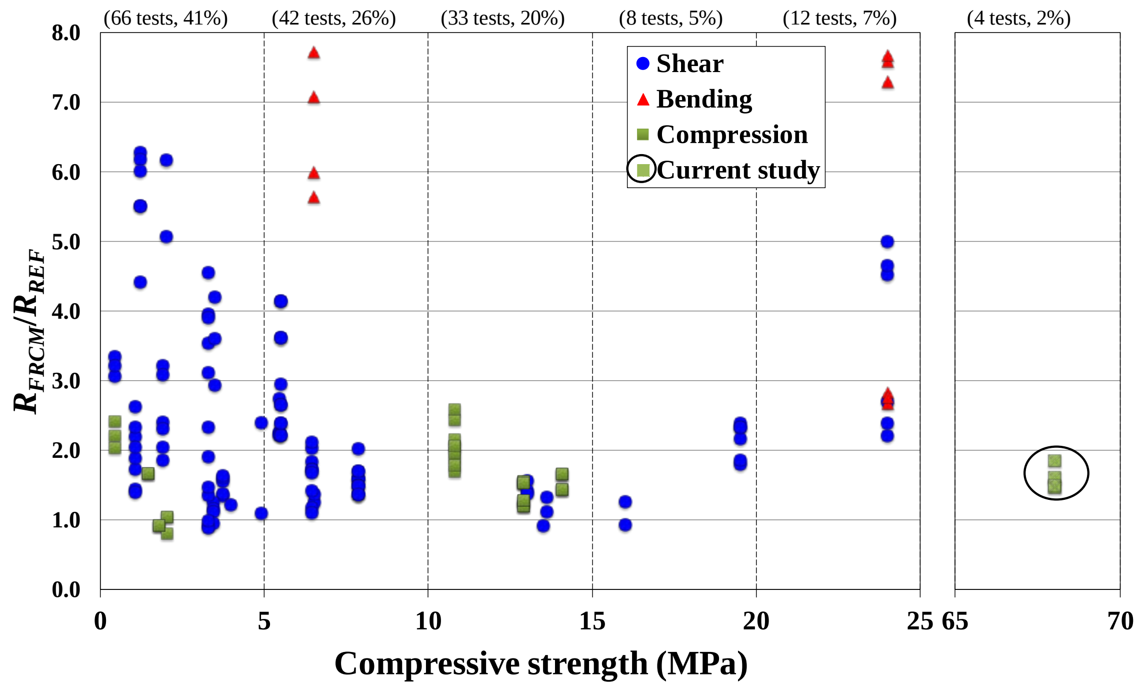

Figure 5 - Distribution of R_{FRCM}/R_{REF} as a function of concrete and masonry compressive strength

Figure 3 presents the variation of R_{FRCM}/R_{REF} as a function of the testing method. Figure 3 shows that R_{FRCM}/R_{REF} ratios for elements tested in shear varies between 0.96 and 18.6 with an average of about 2.65. It can be observed that both the DC and IP-S+C test methods show similar results in terms of average and spread. The ratio R_{FRCM}/R_{REF} varies between 2.6 and 7.7 for panels subjected to out of plane bending. Considerably fewer experimental tests have been performed in this configuration, however the FRCM strengthening solution proved highly effective, increasing the bending capacity of the tested panels by a factor of 5.5 on average. For CC and EC tested specimens, the ratio R_{FRCM}/R_{REF} varies between 0.8 and 2.4 with an average of approximately 1.5.

Figure 4 and Figure 5 present the variation of R_{FRCM}/R_{REF} as function of the compressive strength of masonry or concrete for test methods group into three categories, namely, shear (i.e. DC and IP-S+C), bending (i.e. OPB+C and OPB+S), and compression (i.e. CC and EC).

Figure 4 presents the variation of R_{FRCM}/R_{REF} as function of the compressive strength of masonry or concrete. The majority of tested specimens (67%) were masonry panels with a compressive strength lower than 10 MPa. The rest of the panels had compressive strengths of up to 25 MPa (3625.94 psi). The distribution shown in **Figure 4** suggests that for specimens subjected to shear the efficiency of FRCM strengthening is high for elements with a low compressive strengths and decreases with the increase of the compressive strength. On the other hand for specimens tested in bending and compression, the compressive strength of the element does not seem to influence the efficiency of the FRCM strengthening. However future tests should be done on concrete and masonry panels with compressive strengths higher than 15 MPa (2175.57 psi) in order to verify this trend.

In Figure 5, R_{FRCM}/R_{REF} is presented as a function of the type of fibers used in the FRCM composite. The type of fibers are sorted from left to right in ascending order based on the average modulus of elasticity of each fiber type. Out of the total tested panels 35% were strengthened with glass fibers, followed by carbon fibers (25%), and stainless steel wires (16%). Relatively fewer tests were performed using other types of fibers. The highest average strength increment, about 6.5, can be observed for specimens with glass and aramid fibers subjected to bending, however for a limited number of tested specimens and having high variation. For panels strengthened with carbon fibers, overall R_{FRCM}/R_{REF} is observed to vary in the same intervals as for panels strengthened with glass fibers. However, for shear strengthening carbon fibers appear to be considerably more effective than glass fibers. For strengthening axially loaded specimens both carbon and glass fiber show similar performance on average. Panels strengthened with FRCM composites having steel wire meshes were show a similar performance to those using glass fibers, however, only shear tests have been carried out so far. PET, PP, and basalt fibers show an average strength increment between 1.1 and 1.4, which is relatively low compared to glass fibers and steel wires and substantially lower compared with carbon fibers. Flax and PBO fibers have been investigated only for axially loaded specimens. The average strength increment, about 1.4, is slightly lower than for glass and carbon fibers, however better than that of PP fibers.

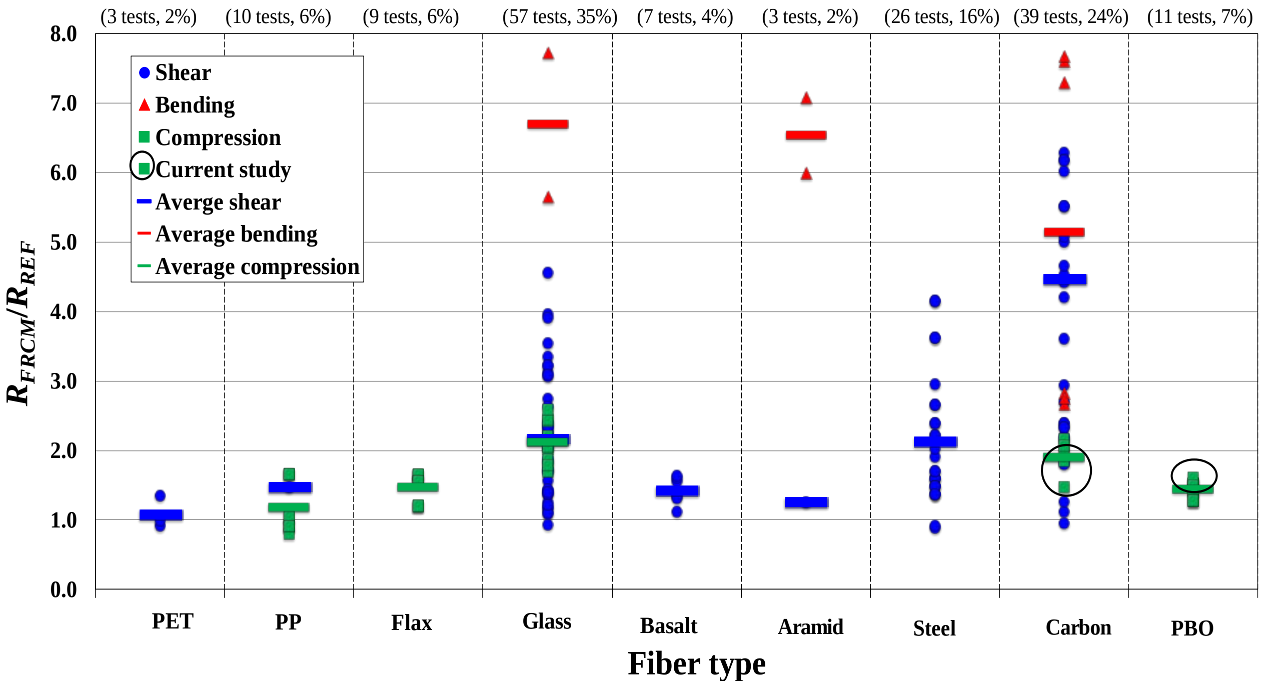

Figure 6 - Distribution of R_{FRCM}/R_{REF} as a function of fiber type

FRCM STRENGHTENED RC WALLS WITH OPENINGS – EXPERIMENTAL TESTS

Tested specimens and materials

The experimental program was designed to address the previously mentioned gaps identified in the literature, namely, high strength concrete panels with openings subjected to eccentric compression.

The experimental program consisted of five precast RC wall panels. Each wall had nominal length, height, and thickness of 1800, 1350, and 60 mm (70.87, 53.15, and 2.36 in), respectively. One was a solid panel (SW), while the other panels had door type openings located in the middle of the panels. Two panels had openings of 450x1050 mm (17.7x41.34 in), hereafter referred to as small openings, and other two panels had openings of 900x1050 mm (35.4x41.34 in), hereafter referred to as large openings. Panels were designated following the notation SO# and LO#, where SO and LO refers to size of the opening, and # indicates the FRCM system used for strengthening, where # is 1 for C-FRCM system and 2 for PBO-FRCM system. A summary of the tested specimens is presented in Table 1.

Table 1 - Summary of experimental results

Specimen ID	Description	Strengthening system	Axial capacity: Reference R_{REF} (kN)	Axial capacity: Tested R_{FRCM} (kN)	R_{FRCM}/R_{REF}
SO1	Strengthened wall with small opening	Carbon-FRCM	1150	2130	1.85
LO1	Strengthened wall with large opening	Carbon-FRCM	900	1330	1.48
SO2	Strengthened wall with small opening	PBO-FRCM	1150	1860	1.61
LO2	Strengthened wall with large opening	PBO-FRCM	900	1350	1.50

1 kN = 0.224809 lbs;

The panels were cast using self-consolidating concrete with 68 MPa (9863 psi) average compressive strength. The compressive strength was determined on 150 mm (5.9 in) concrete cubes. The internal reinforcement consisted of one layer of 5 mm welded steel wire fabric. The steel reinforcement net was placed in the centre of the concrete section, having the steel bars in the vertical and horizontal directions, with 100 mm (3.94 in) spacing between bars. The detailing of reinforcement (centrally placed wire mesh) is considered representative of precast concrete panels acting as compression members. Ghosh [13] summarised the result of a survey of the construction industry conducted in 1984. The survey revealed that, according to the industry respondents, over many years, when one layer of steel mesh was used as reinforcement in precast concrete panels, a satisfactory performance the member was observed.

The FRCM strengthening solution was chosen based on the analysis of failure modes, crack profiles, and strain distribution of similar tests [14, 15] that indicated a need to provide additional reinforcement to prevent the formation and opening of cracks in both vertical and horizontal direction. One layer of FRCM composite was applied on each side of the strengthened panel. The two FRCM systems were comprised of the fiber nets and corresponding mortar. The properties of the fiber nets, center-to-center bundle spacing b_f, equivalent dry-fiber thickness t_f, the ultimate tensile strength f_f, ultimate tensile strain ε_f, and modulus of elasticity E_f are given in Table 2 together with the corresponding matrix properties, compressive strength f_{cm}, flexural strength f_{tm}, and modulus of elasticity E_{cm}.

Table 2 - FRCM mechanical properties (provided by manufacturer)

FRCM system	b (mm)	t_f (mm)	f_f (MPa)	ε_f (%)	E_f (GPa)	f_{cm} (MPa)	f_{tm} (MPa)	E_{cm} (GPa)
C-FRCM	20 × 20	0.046	4700	18	240	25	-	15
PBO-FRCM	3 × 12	0.0455	5800	21.5	270	30	4	7

1 mm = 0.0394 in; 1 MPa = 145.038 psi; 1GPa= 145.038 ksi

The experimental setup was designed to replicate structural walls subjected to eccentrically applied gravitational loads and supported on each side by walls in the transversal direction. A 10 mm (0.39 in) eccentricity, representing 1/6 of the panel thickness, was provided at the top and bottom side through a steel rod welded to the loading beam and in contact with the top side of the wall through a steel plate. A more detailed description of the experimental setup can be found in [15]. The load was applied using four hydraulic jacks and was measured using hydraulic pressure transducers. The loading was done in displacement control at a rate of 0.003 mm/s (0.000118 in/s). An overview of the experimental setup presented in Figure 6.

Figure 7 - Overview of experimental setup

Test results

The maximum load bearing capacity of the solid wall was 1800 kN (404.65 lbs). This represents the control value with respect to which the capacity of reference walls is evaluated. Axial strength enhancement is defined as the ratio between the additional capacity associated with a strengthened specimen and that of a reference specimen, usually the same type of specimen without strengthening. In this case the reference values are determined based on the results of a similar experimental study conducted by the authors [15], where it was observed that introducing a small and large openings in a solid panel leads to a decrease of 36% and 50% of the panel's capacity, respectively. Reference values corresponding to 36% and 50% of the capacity of the tested solid panel are presented in Table 1.

Compared to the capacity of reference panels, the capacity of panels with carbon-FRCM strengthening increased by 85% and 48% for specimens with *large openings* and *small openings*, respectively. Similarly, the capacity of panels with carbon-FRCM strengthening increased by 61% and 50% for specimens with *large openings* and *small openings*, respectively (Table 1). It should be noted that the steel reinforcement detailing and ratio (two meshes, one on each face, instead of one mesh centrally placed, as used in this study) could affect the effectiveness of the FRCM strengthening. Further studies are necessary to quantify the influence the internal reinforcement on the effectiveness of FRCM strengthening.

The R_{FRCM}/R_{REF} ratios corresponding to the four tested panels are shown in Figures 3-5, as black squares and surrounded by a black circle. Figure 3 indicates that the R_{FRCM}/R_{REF} ratio for all four tested panels is approximately equal to the average strengthening increment obtain for all other specimens in the same category (i.e. EC).

It was previously mentioned that R_{FRCM}/R_{REF} for axially loaded specimens appear to not be influenced by the concrete compressive strength. Based on the additional tests described in this study, Figure 4 further suggests that FRCM strengthening maintains similar levels of effectiveness even for elements made of high strength concrete.

The performance of the carbon and PBO fiber FRCM systems was similar for the four walls with openings. In Figure 5, the performance of each FRCM systems is compared with the performance of specimens tested with similar fibers. It can be observed that for both the carbon and PBO fibers the performance is similar to that of other previously tested specimens. Figure 5 suggests that FRCM composites with glass and flax fibers could prove similarly effective, however additional experimental tests are needed.

SUMMARY AND CONCLUDING REMARKS

In this paper a systematic assessment of experimental studies on FRCM strengthened structural walls is presented. Experimental investigations on concrete and masonry walls strengthened with FRCM composites is still limited and mostly focused on shear. As the literature survey points out, further investigations on walls as compression members can be considered timely, especially concrete walls and walls with openings that have been overlooked. FRCM composites with natural fibers such as flax and fibers made of recyclable plastics such as PP and PET have been used recently, however to much lesser extent than carbon and glass fibers.

Based on the assessment of the experimental database the following conclusion can be drawn. The shear strength increment provided by FRCM systems for structural wall panels tends to decrease for higher masonry or concrete compressive strength. The decrease appears to be more pronounced for compressive strengths between 1 and 15 MPa and less important for compressive strengths higher than 15 MPa (2175.57 psi). On the other hand the strength increment appears to not be influenced by the compressive strength of elements in the case of bending and compression.

FRCM composites with carbon and glass fibers appear to be the most effective for increasing the shear and bending capacity of structural wall panels, respectively. Furthermore, for strengthening axially loaded elements FRCM composites with carbon and glass fibers appear to be similarly effective. However, more tests, in particular on elements with high compressive strengths are required to confirm these trends.

Based on the experimental tests on reinforced concrete walls with openings summarized herein, FRCM composites using carbon and PBO fibers are suitable repair solutions when new openings need to be created in RC walls. In addition FRCM systems using flax fibers could prove similarly effective.

Future experimental tests on structural walls strengthened with FRCM should be focused on concrete and masonry panels with openings. The use of natural fibers such as flax fibers shows promise and should be further investigated. Because experimental tests on full-scale structural panels are financially and time demanding, finite element method models could represent a powerful tool to aid identify the critical parameters that govern the effectiveness of FRCM strengthening. However, finite element models alone cannot fully substitute the need for additional experimental tests.

ACKNOWLEDGEMENTS

This work was supported by the European Commission (Contract number MC-ITN-2013-607851) and Development Fund of the Swedish Construction Industry (SBUF). The first author would like to acknowledge the support of the European Network for Durable Reinforcement and Rehabilitation Solutions (endure), a Marie Skłodowska Curie Initial Training Network. The assistance and guidance provided by Jaime Gonzalez-Libreros from University of Padova and Dr. Lesley Sneed from Missouri University of Science and Technology (Missouri S&T) is gratefully acknowledged.

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Annex A – Experimental database

Table A - Database experimental tests on walls strengthened with FRCM

Reference	Designation	Test method	Material	Country	Specimen dimensions			Opening dimension		Compressive strength	FRCM fiber type	R_{FRCM}/R_{REF}
			M- masonry C- concrete		H (mm)	L (mm)	t (mm)	L_o (mm)	H_o (mm)	f_c (MPa)		
Marcari et al. [16]	RPS1	DC	M	Italy	1000	1000	250			3.72	Basalt	1.56
	RPS2	DC	M	Italy	1000	1000	250			3.72	Basalt	1.35
	RPS3	DC	M	Italy	1000	1000	250			3.72	Basalt	1.38
	RPD1	DC	M	Italy	1000	1000	250			3.72	Basalt	1.61
	RPD2	DC	M	Italy	1000	1000	250			3.72	Basalt	1.64
Prakash et al. [8]	S - 1:3 - 1	CC	M	India	415	220	100			2.03	PP	1.04
	S - 1:3 - 2	CC	M	India	415	220	100			2.03	PP	1.04
	S - 1:3 - 3	CC	M	India	415	220	100			1.78	PP	0.80
	S - 1:4.5 - 1	CC	M	India	415	220	100			1.78	PP	0.92
	S - 1:4.5 - 2	CC	M	India	415	220	100			1.78	PP	0.92
	S - 1:4.5 - 3	CC	M	India	415	220	100			1.45	PP	0.92
	S - 1:6 - 1	CC	M	India	415	220	100			1.45	PP	1.66
	S - 1:6 - 2	CC	M	India	415	220	100			1.45	PP	1.66
	S - 1:6 - 3	CC	M	India	415	220	100			2.03	PP	1.66
Popa et al. [11]	2	IP-S+C	M	Romania	1750	2100	250			3.43	Glass	1.25
	3	IP-S+C	M	Romania	1750	2100	250			3.43	Glass	1.16
	4	IP-S+C	M	Romania	1750	2100	250			3.43	Carbon	1.12
	5	IP-S+C	M	Romania	1750	2100	250			3.43	Carbon	0.96
Ismail and Ingham [17]	TMI-2	IP-S+C	M	UAE	2652	4428	220	1228	1710	6.50	Aramid	1.26
	TMI-3	IP-S+C	M	UAE	2652	4428	220	1228	1710	6.50	Glass	1.37
	TMO-5	OP-B+C	M	UAE	3670	1200	220			6.50	Aramid	6.00
	TMO-5'	OP-B+C	M	UAE	3670	1200	220			6.50	Aramid	7.08
	TMO-6	OP-B+C	M	UAE	3670	1200	220			6.50	Glass	5.65
	TMO-6'	OP-B+C	M	UAE	3670	1200	220			6.50	Glass	7.73
Hracov et al. [9]	ABW-2	IP-S+C	M	Cz. Republic	1367	1050	240			3.28	Steel	1.91
	ABW-3	IP-S+C	M	Cz. Republic	1367	1050	240			3.28	PET	1.35

Reference	Designation	Test method	Material (M- masonry, C- concrete)	Country	Specimen dimensions H (mm)	Specimen dimensions L (mm)	Specimen dimensions t (mm)	Opening dimension L_o (mm)	Opening dimension H_o (mm)	Compressive strength f_c (MPa)	FRCM fiber type	R_{FRCM}/R_{REF}
	ABW-5	IP-S+C	M	Cz. Republic	1367	1050	240			3.28	PET	0.92
	ABW-5’	IP-S+C	M	Cz. Republic	1367	1050	240			3.28	PP	1.48
	DBW-2	IP-S+C	M	Cz-Republic	1367	1050	240			3.28	Steel	0.89
	DBW-3	IP-S+C	M	Cz. Republic	1367	1050	240			3.28	PET	0.99
Capozucca [18]	M-LW3	IP-S+C	M	Italy	633	630	50			13.5	Steel	0.92
Tomaževič et al. [19]	SM-4S	IP-S+C	M	Slovenia	1500	1000	500			3.28	Glass	3.12
	SM-6S	IP-S+C	M	Slovenia	1500	1000	500			3.28	Glass	2.34
	SM-3S	IP-S+C	M	Slovenia	1500	1000	500			3.28	Glass	3.55
	SM-5S	IP-S+C	M	Slovenia	1500	1000	500			3.28	Glass	3.97
	SM-9S	IP-S+C	M	Slovenia	1500	1000	500			3.28	Glass	4.56
	SM-10S	IP-S+C	M	Slovenia	1500	1000	500			3.28	Glass	3.91
Todut et al. [10]	10	IP-S+C	C	Romania	2150	2750	100	1750	1000	16.0	Glass	0.93
	11	IP-S+C	C	Romania	2150	2750	100	750	1000	16.0	Carbon	1.27
Pinho et al. [20]	M14	IP-S+C	M	Portugal	1200	1200	400			0.43	Glass	3.07
	M19	IP-S+C	M	Portugal	1200	1200	400			0.43	Glass	3.35
	M11	IP-S+C	M	Portugal	1200	1200	400			0.43	Glass	3.23
	M27	CC	M	Portugal	1200	800	400			0.43	Glass	2.21
	M29	CC	M	Portugal	1200	800	400			0.43	Glass	2.03
	M34	CC	M	Portugal	1200	800	400			0.43	Glass	2.42
Cevallos et al. [21]	P-flax-1	EC	M	Italy	250	120	335			14.1	Flax	1.65
	P-flax-2	EC	M	Italy	250	120	335			14.1	Flax	1.65
	P-flax-3	EC	M	Italy	250	120	335			14.1	Flax	1.65
	M-flax-1	EC	M	Italy	510	250	660			12.9	Flax	1.56
	M-flax-2	EC	M	Italy	510	250	660			12.9	Flax	1.56
	M-flax-3	EC	M	Italy	510	250	660			12.9	Flax	1.56
	C-flax-1	EC	M	Italy	250	250	1115			12.9	Flax	1.20
	C-flax-2	EC	M	Italy	250	250	1115			12.9	Flax	1.20

Reference	Designation	Test method	Material	Country	Specimen dimensions			Opening dimension		Compressive strength	FRCM fiber type	R_{FRCM}/R_{REF}
			M- masonry C- concrete		H (mm)	L (mm)	t (mm)	L_o (mm)	H_o (mm)	f_c (MPa)		
	C-flax-3	EC	M	Italy	250	250	1115			12.9	PBO	1.20
	P-PBO-1	EC	M	Italy	250	120	335			14.1	PBO	1.43
	P-PBO-2	EC	M	Italy	250	120	335			14.1	PBO	1.43
	P-PBO-3	EC	M	Italy	250	120	335			14.1	PBO	1.43
	M-PBO-1	EC	M	Italy	510	250	660			12.9	PBO	1.28
	M-PBO-2	EC	M	Italy	510	250	660			12.9	PBO	1.28
	M-PBO-3	EC	M	Italy	510	250	660			12.9	PBO	1.28
	C-PBO-1	EC	M	Italy	250	250	1115			12.9	PBO	1.53
	C-PBO-2	EC	M	Italy	250	250	1115			12.9	PBO	1.53
	C-PBO-3	EC	M	Italy	250	250	1115			12.9	PBO	1.53
Bui et al. [22]	TRCRW1	IP-S+C	M	France	1260	1030	75			4.89	Glass	1.09
	TRCRW2	IP-S+C	M	France	1260	1030	75			4.89	Glass	2.40
Almeida et al. [23]	FRMCcom1	DC	M	Portugal	990	990	110			3.48	Carbon	4.21
	FRMCcom2	DC	M	Portugal	990	990	110			3.48	Carbon	3.61
	FRMCcom3	DC	M	Portugal	990	990	110			3.48	Carbon	2.95
Borri et al. [24]	MP-1-I-N	DC	M	Portugal	1160	1180	400			6.43	Glass	1.83
	MP-2-I-N	DC	M	Portugal	1160	1180	400			6.43	Glass	2.04
	MP-1-I-P	DC	M	Portugal	1160	1180	400			6.43	Glass	1.74
	MP-2-I-P	DC	M	Portugal	1160	1180	400			6.43	Glass	2.12
	MD-1-I-V	DC	M	Portugal	1160	1180	250			6.43	Glass	1.18
	MD-2-I-V	DC	M	Portugal	1160	1180	250			6.43	Glass	1.73
	MD-1-I-H	DC	M	Portugal	1160	1180	250			6.43	Glass	1.68
	MD-2-I-H	DC	M	Portugal	1160	1180	250			6.43	Glass	1.42
	MD-1r-I-V	DC	M	Portugal	1160	1180	250			6.43	Glass	1.11
	MC-1-I-P	DC	M	Portugal	1160	1180	400			5.44	Glass	2.75
	MC-2-I-p	DC	M	Portugal	1160	1180	400			5.44	Glass	2.26
	MC-1-I-N	DC	M	Portugal	1160	1180	400			5.44	Glass	2.25
	MC-2-I-N	DC	M	Portugal	1160	1180	400			5.44	Glass	2.23
Babaeidarabad et al. [25]	1ply - 1	DC	M	USA	1145	1220	92			24.0	Carbon	2.21
	1ply - 2	DC	M	USA	1145	1220	92			24.0	Carbon	2.70

Reference	Designation	Test method	Material M- masonry C- concrete	Country	Specimen dimensions H (mm)	Specimen dimensions L (mm)	Specimen dimensions t (mm)	Opening dimension L_o (mm)	Opening dimension H_o (mm)	Compressive strength f_c (MPa)	FRCM fiber type	R_{FRCM}/R_{REF}
	1ply - 3	DC	M	USA	1145	1220	92			24.0	Carbon	2.39
	4ply - 1	DC	M	USA	1145	1220	92			24.0	Carbon	5.01
	4ply - 2	DC	M	USA	1145	1220	92			24.0	Carbon	4.53
	4ply - 3	DC	M	USA	1145	1220	92			24.0	Carbon	4.66
Babaeidarabad et al. [26]	OP-CL-1ply-1	OP-B+S	M	USA	1422	1220	92			24.0	Carbon	2.83
	OP-CL-1ply-2	OP-B+S	M	USA	1422	1220	92			24.0	Carbon	2.67
	OP-CL-1ply-3	OP-B+S	M	USA	1422	1220	92			24.0	Carbon	2.76
	OP-CL-4ply-1	OP-B+S	M	USA	1422	1220	92			24.0	Carbon	7.59
	OP-CL-4ply-2	OP-B+S	M	USA	1422	1220	92			24.0	Carbon	7.30
	OP-CL-4ply-3	OP-B+S	M	USA	1422	1220	92			24.0	Carbon	7.68
Babaeidarabad et al. [27]	1ply - 1	DC	M	USA	1220	1220	92			19.5	Carbon	2.17
	1ply - 2	DC	M	USA	1220	1220	92			19.5	Carbon	1.81
	1ply - 3	DC	M	USA	1220	1220	92			19.5	Carbon	1.86
	4ply - 1	DC	M	USA	1220	1220	92			19.5	Carbon	2.39
	4ply - 2	DC	M	USA	1220	1220	92			19.5	Carbon	2.33
	4ply - 3	DC	M	USA	1220	1220	92			19.5	Carbon	2.34
Parisi et al. [28]	PR1	DC	M	Italy	1220	1220	31			1.90	Glass	2.05
	PR2	DC	M	Italy	1220	1220	31			1.90	Glass	1.86
	PRF1	DC	M	Italy	1220	1220	31			1.90	Glass	2.41
	PRF2	DC	M	Italy	1220	1220	31			1.90	Glass	2.32
	PRR1	DC	M	Italy	1220	1220	31			1.90	Glass	3.23
	PRR2	DC	M	Italy	1220	1220	31			1.90	Glass	3.09
Bernat et al. [29]	W#21	DC	M	Spain	1700	900	132			10.8	Glass	1.87
	W#22	DC	M	Spain	1700	900	132			10.8	Glass	2.05
	W#26	DC	M	Spain	1700	900	132			10.8	Glass	2.44
	W#23	DC	M	Spain	1700	900	132			10.8	Glass	1.69
	W#24	DC	M	Spain	1700	900	132			10.8	Glass	1.79
	W#25	DC	M	Spain	1700	900	132			10.8	Glass	2.59
	W#27	DC	M	Spain	1700	900	132			10.8	Carbon	2.16
	W#28	DC	M	Spain	1700	900	132			10.8	Carbon	1.96

Reference	Designation	Test method	Material	Country	Specimen dimensions			Opening dimension		Compressive strength	FRCM fiber type	R_{FRCM}/R_{REF}
			M- masonry C- concrete		H (mm)	L (mm)	t (mm)	L_o (mm)	H_o (mm)	f_c (MPa)		
	W#29	DC	M	Spain	1700	900	132			10.8	Carbon	2.06
Papanicolaou et al. [30]	I3%_SW_FB1	IP-S+C	M	Greece	1200	1120	95			13.6	Basalt	1.32
	I3%_SW_LB1	IP-S+C	M	Greece	1200	1120	95			13.6	Basalt	1.12
Borri et al. [31]	PRN7	DC	M	Italy	551	510	125			5.49	Steel	4.15
	PRN8	DC	M	Italy	551	510	125			5.49	Steel	4.15
	PRN9	DC	M	Italy	551	510	125			5.49	Steel	3.62
	PRN10	DC	M	Italy	551	510	125			5.49	Steel	3.62
	PRN11	DC	M	Italy	551	510	125			5.49	Steel	2.22
	PRN12	DC	M	Italy	551	510	125			5.49	Steel	2.22
	PRN13	DC	M	Italy	551	510	125			5.49	Steel	2.39
	PRN14	DC	M	Italy	551	510	125			5.49	Steel	2.39
	PRN15	DC	M	Italy	551	510	125			5.49	Steel	2.96
	PRN16	DC	M	Italy	551	510	125			5.49	Steel	2.66
	PRN17	DC	M	Italy	551	510	125			7.86	Steel	2.66
	PRC3	DC	M	Italy	551	510	125			7.86	Steel	1.60
	PRC4	DC	M	Italy	551	510	125			7.86	Steel	1.60
	PRC5	DC	M	Italy	551	510	125			7.86	Steel	1.60
	PRC6	DC	M	Italy	551	510	125			7.86	Steel	1.37
	PRC7	DC	M	Italy	551	510	125			7.86	Steel	1.37
	PRC8	DC	M	Italy	551	510	125			7.86	Steel	2.02
	PRC9	DC	M	Italy	551	510	125			7.86	Steel	1.49
	PRC10	DC	M	Italy	551	510	125			7.86	Steel	1.49
	PRC11	DC	M	Italy	551	510	125			7.86	Steel	1.49
	PRC12	DC	M	Italy	551	510	125			7.86	Steel	1.70
	PRC13	DC	M	Italy	551	510	125			7.86	Steel	1.70
	PRC14	DC	M	Italy	551	510	125			5.49	Steel	1.37
Faella et al. [32]	4	DC	M	Italy	1160	1160	330			1.21	Carbon	6.29
	5	DC	M	Italy	1160	1160	330			1.21	Carbon	6.18
	6	DC	M	Italy	1160	1160	330			1.21	Carbon	6.02
	7	DC	M	Italy	1160	1160	330			1.21	Carbon	5.51
	8	DC	M	Italy	1160	1160	330			1.21	Carbon	4.42

Reference	Designation	Test method	Material M- masonry C- concrete	Country	Specimen dimensions H (mm)	L (mm)	t (mm)	Opening dimension L_o (mm)	H_o (mm)	Compressive strength f_c (MPa)	FRCM fiber type	R_{FRCM}/R_{REF}
	9	DC	M	Italy	1160	1160	330			1.21	Carbon	5.52
Augenti et al. [33]	1	IP-S+C	M	Italy	3620	5100	310	1700	2300	3.96	Glass	1.22
Papanicolaou et al. [4]	A_M1_10%	IP-S+C	M	Greece	800	1300	85			2.00	Carbon	5.08
	A_M2_10%	IP-S+C	M	Greece	800	1300	85			2.00	Carbon	6.17
	A_M1_2.5%	IP-S+C	M	Greece	800	1300	85			2.00	Carbon	12.96
	A_M2_2.5%	IP-S+C	M	Greece	800	1300	85			2.00	Carbon	18.59
Prota et al. [34].	PS#1	DC	M	Italy	925	1065	120			1.06	Glass	2.21
	PS#2	DC	M	Italy	925	1065	120			1.06	Glass	2.63
	PS#3	DC	M	Italy	925	1065	120			1.06	Glass	2.34
	PS#4	DC	M	Italy	925	1065	120			1.06	Glass	1.74
	PT#1	DC	M	Italy	925	1065	120			1.06	Glass	1.44
	PT#2	DC	M	Italy	925	1065	120			1.06	Glass	1.89
	PT#3	DC	M	Italy	925	1065	120			1.06	Glass	2.04
	PT#4	DC	M	Italy	925	1065	120			1.06	Glass	1.40
Aldea et al. [35].	1	IP-S+C	M	USA	1200	1200	200			13.0	Glass	1.57
	2	IP-S+C	M	USA	1200	1200	200			13.0	Glass	1.42
	3	IP-S+C	M	USA	1200	1200	200			13.0	Glass	1.38
Kolsch [12]	1	OP-B+S	M	Germany	3000	3000	240					

1 mm = 0.0394 in; 1 MPa = 145.038 psi

List of notations

The following notations are used in this paper:

RC = reinforced concrete

FRP = fiber reinforced polymer

PBO = polyparaphenylene benzobisoxazole

L = length of wall panel (horizontal)

H = Height of wall panel (vertical)

t = Thickness of wall panel

L_o = length of opening (horizontal)

H_o = Height of opening (vertical)

SW = solid wall panel (without opening)

SO = wall panel with small opening

LO = wall panel with large opening

f_f = ultimate tensile strength of fiber bundles

ε_f = ultimate tensile strain of fiber bundles

E_f = elastic modulus of fiber bundles

f_{tm} = flexural strength of mortar matrix

f_{cm} = compressive strength of mortar matrix

E_{cm} = modulus of elasticity of the mortar matrix

f_c = compressive strength

IP-S+C = in-plane shear with compressive force

DC = diagonal compression

OPB+C - out-of-plane shear with compressive force

OPB+S - out-of-plane shear with self weight as compressive force

CC = concentric compression

EC = Eccentric compression

PP = polypropylene

PET = polyethylene terephthalate

R_{REF} = capacity of the reference specimen

R_{FRCM} = capacity of the strengthened specimen