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## Methods of testing systems for strengthening masonry structures based on cement composites reinforced with glass fiber mesh

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### ABSTRACT

The paper presents the testing methods used for the contemporary masonry strengthening system, FRCM (fibre-reinforced cementitious matrix), which consists of glass fabric and mortar matrix. The FRCM system is suitable for strengthening masonry structures since it doesn't significantly change their mass and stiffness but increases the capacity for certain loads, especially ones induced by earthquakes. Following the recommendations, the mechanical properties of component materials and three groups (fibers, fibers in mortar, and masonry system) of specimens were tested. The main parameters necessary for calculating this system were defined and compared with the results found in the literature. It was shown that the chosen geometry for the mechanical test was appropriate for comparing the results within different groups. The importance of the type of fixtures used for the specimens (clevis- or clamping-grip) was more pronounced in the second group of specimens. Results of the first and the third group of specimens were in accordance with the literature, with the ultimate tensile stress of the dry fabric reaching 742,2 MPa, and the ultimate tensile strain of the dry fabric reaching 1.53%. The conventional strain obtained from the third group of specimens was 1.28%.

## 1 Introduction

Masonry structures represent a considerable percentage of the human-built heritage. After intense urbanization and the use of natural materials on large scales, contemporary society strives to apply principles of sustainable development in all areas of civil engineering. Therefore, one of the development directions in the building sector is strengthening and preserving existing structures and prolonging their service life [1].

Although masonry structures are very durable, they are vulnerable to seismic forces [2]. Masonry walls are the most sensitive part of the system, and under seismic loads perpendicular to the wall, they can lose stability very quickly. The damage level and type of the structure determine the rehabilitation methods for masonry structures damaged by seismic loads.

Traditional strengthening methods, such as: injecting, shotcreting, reticulating, or overlaying the walls with cement-based mortars, are still widely used [3]. These techniques can sometimes be complicated for application; they usually increase the structure's mass and often influence the building's appearance [4].

The development of a fiber-reinforced cementitious matrix (FRCM) system primarily targeted masonry walls. It is considered a substitute for the system with mortar and steel

reinforcement since it is corrosion-resistant. The FRCM system fixes some problems with the fiber-reinforced polymer (FRP) system, like the fact that it is easily damaged by fire, does not work with masonry substrates, and cannot be used on damp walls [5]. It consists of cement-based composites reinforced with fibre-based grids that can be of different origins: basalt, carbon, steel, or glass, usually overlaid with the inorganic matrix. Carbon fibers possess the highest tensile strength, elasticity, and durability. In contrast, glass and basalt fibers have lower tensile strength and modulus of elasticity and require additional alkali-resistant protective layers, but they are more economical [6]. Furthermore, glass and basalt fibers are better suited for masonry structures, known for their low modulus of elasticity.

To enable the application of the FRCM systems, it was necessary to develop testing methods for determination of the most important properties of the system, used in the calculations. Since it is a complex system, testing all component materials individually and then the system as a whole was obligatory. A group of researchers within the RILEM Technical Committee 250-CSM formed a document titled "Test Method for Textile Reinforced Mortar to Substrate Bond Characterization" [7], and published results from the Round Robin test performed within this RILEM committee [8]. Similarly, European Assessment Document – EAD 340275-00-0104 was developed for composite systems with

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inorganic matrixes to strengthen concrete and masonry structures externally [9]. The National Research Council of Italy, Advisory Committee on Technical Recommendations for Construction, has published CNR-DT 215/2018: Guideline for designing and constructing externally bonded fibre-reinforced *inorganic matrix systems for strengthening existing structures* [10]. This document presents the main points in the calculation and placement of FRCM systems. The document is optional, but it contains recommendations to help engineers apply these systems. Based on this document, testing methods for the system have been described in the document titled: „Linea Guida per la identificazione, la qualificazione ed il controllo di accettazione di compositi fibrorinforzati a matrice inorganica (FRCM) da utilizzarsi per il consolidamento strutturale di costruzioni esistenti“ [11].

## 2 Methodology

The paper presents the results of mechanical testing the FRCM system. The testing was divided into three groups:

1. testing the dry fabric in tension,
2. testing the composite specimen consisting of two mortar layers, with a glass-fibre grid placed between them,
3. testing the specimens with joint configuration (the wall strengthened with FRCM).

When the second group of specimens is concerned, the behaviour of the composite can be divided into three stages, according to the results. In stage A, the cement mortar matrix does not show any damage or cracks; the stress at the moment of the formation of the crack should be approximately equal to the tensile strength of the mortar [12]. Nevertheless, the differences in the production and curing of the specimens can lead to different measured stresses at the end of stage A. In stage B, which begins with the formation of the first crack, new cracks are expected to appear in the mortar matrix. The appearance of each new crack is visible in the stress-strain diagram as a sharp drop of stress. This phase ends when stress and strain again reach a linear relation. In the final stage (stage C), the existing cracks in the matrix start to widen, and the fabric becomes visible. The complete tensile strength is entrusted to the fabric in this phase. Stage C ends with the fracture of the specimen. For some of the composites, especially ones with glass fibre grid, the second stage is not visible in the diagram, and their behaviour is usually described as bilinear [12].

Apart from the behaviour of the system composed of cement-based mortar and fabric, it is important to test the relation between this system and the substrate. Therefore, the third group of specimens is usually tested by putting the ends of the fabric through a tensile test while the masonry substrate is restrained (push-pull method).

Different fracture types can be expected in this group of specimens. As observed in the literature, for mortar matrix with glass fiber fabric, the tensile failure of the fabric is the most common. [8].

According to the Italian document CNR-DT 215/2018 [10] for the calculation of the strengthening system the following parameters need to be measured:

- 1) first group of specimens:
  - ultimate tensile stress of the dry fabric,  $\sigma_{u,f}$ ,
  - elastic modulus of the dry fabric ( $E_f$ ),
  - ultimate tensile strain of the dry fabric  $\varepsilon_{u,f} = \sigma_{u,f}/E_f$ ,
- 2) second group of specimens:
  - tensile stiffness of the specimens in the stage A, if detectable ( $E_1$ ),
  - ultimate tensile stress  $\sigma_u$  and ultimate tensile strain  $\varepsilon_u$  of the FRCM composite that are calculated based on the maximum force (at failure),
- 3) third group of specimens:
  - conventional stress  $\sigma_{lim,conv}$  and conventional strain  $\varepsilon_{lim,conv} = \sigma_{lim,conv}/E_f$ .

The main property of the matrix (mortar) that needs to be determined is its compressive strength  $f_{c,mat}$ . The compressive strength of masonry ( $f_{m,d}$ ) and the elastic modulus of masonry ( $E_m$ ) are important parameters for the substrate.

Stresses are, within all tests, referred to the cross-sectional area of the dry fabric, regardless of the presence of the matrix/mortar. The conventional stress limit, which is evaluated through the bond test (third group of specimens), represents the bond strength of the specific FRCM system. It depends both on the type of substrate and on the properties of the system. The conventional strain limit is calculated based on the conventional stress limit and elastic modulus of dry fabric. It is then commonly used in the design of the strengthening interventions [9].

In the large-scale Round Robin test organised by the RILEM Technical Committee 250-CSM [8], 19 research centres were involved in defining the basic mechanical properties of the 30 FRCM, SRG (steel-reinforced grout) and other strengthening systems present in the market. All three groups of specimens were produced and tested. The testing was performed using the clamping-grip method [8].

The main differences in the results obtained on similar FRCM systems are a consequence of two possible methods for the seizing of the specimens in the tensile machine, known as clamping- and clevis-grip, as shown in Figure 1.

According to Arboleda et al. [12], it can be expected that specimens tested using the clamping-grip method reach higher values of strength when compared to the specimens tested using the clevis-grip method. It is assumed that this is a consequence of additional lateral pressures that are developed when the clamping-grip method is applied. In conclusion, the authors state that the clevis-grip method presents a more realistic behaviour of the composite and, therefore, a more realistic stress-strain diagram, but the final tensile strength values are more realistic for the clamping grip method.

The presented research's objective was to test the FRCM strengthening system with a cement-mortar matrix and a glass-fibre grid. Based on the testing of the three groups of specimens, the main parameters necessary for calculating this system were defined. Also, the benefits and flaws of the applied testing methods for each group of specimens were analyzed.

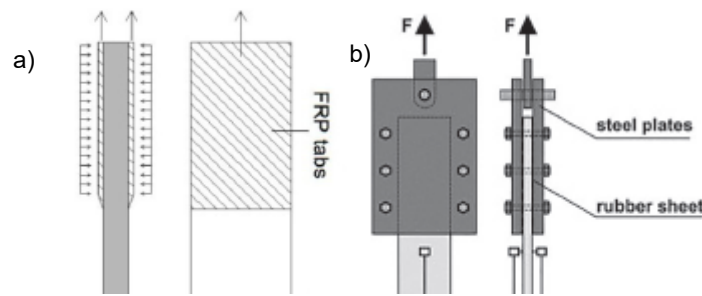


Figure 1. Presentation of the two gripping methods: a) clamping-grip [12], b) clevis-grip [13]

### 3 Experimental procedures

#### 3.1 Materials

The present paper investigates the FRCM system comprised of glass-fibre mesh embedded within the cementitious mortar matrix.

The fabric used in this experiment is a bi-directional glass fibre mesh equipped with an alkali-resistant coating. The fabric is packed in rolls, where one roll has a width of 1m and a length of 50 m. Glass fibre yarns are oriented in the warp (longitudinal) and weft (transversal) directions. Warp direction is assumed as the direction of the main resistance. The average mesh size between warp fibre yarns is 18.2 mm, while weft fibre yarns have an axial distance of 14.2 mm. Mesh openings for warp and weft fibre yarns are 16 mm and 10.7 mm, respectively. The declared dry fibre density is 2.6 g/cm<sup>3</sup>. According to the producer, its tensile strength is approximately equal in both directions and equals 77 kN/m. Cross section area of one glass fibre yarn is one of the main variables influencing fabric mechanical properties in the direction that is dominantly exposed to tension. This value is not defined in the official product datasheet but should be calculated according to the procedure given in EAD 340275-00-0104 [9]. The cross-section area should always be calculated for a single yarn. To calculate the total grid specimen cross-section area, a value of one yarn area should be multiplied by the number of yarns that make a grid specimen. The calculation of the cross-section area of one glass fibre yarn should be done based on the following formula:

$$A_f = \frac{p_{yarn}}{\rho * l_{yarn}} * 1000 \quad (1)$$

where:

- $p_{yarn}$  is mass of one yarn [g], measured based on instrument resolution of at least 0.01 g,
- $l_{yarn}$  is length of one yarn [mm],
- $\rho$  is fibre density [g/cm<sup>3</sup>].

Four specimens, each 1000 mm long and made of a single yarn, underwent mass measurements. The average mass measurement was equal to 2.446 g, which determined the value of cross sectional area equal to 0.941 mm<sup>2</sup>. The cross-sectional area of one yarn determined above is used in the following stress calculations.

As a mortar matrix, pre-mix fiber-reinforced cementitious mortar, Sika MonoTop-722 Mur, with a maximum grain size of 1.4 mm was used. This mortar is delivered as dry-mix of cement, aggregate, fibers, and different mineral and

chemical admixtures. During production, it was mixed with water, where mass of water to mass of dry-mix was 1:4.

Mortar prisms were prepared for testing mechanical characteristics of the hardened mortar; 15 prisms (40 x 40 x 160 mm) were prepared using a dry mix and an additional 20% of water. Specimens were cured in standard laboratory atmospheric conditions (temperature 23±2°C, relative humidity 50±5%). Flexural and compressive strength testing (Figure 2) were executed per EN 1015-11. Average values calculated out of three specimens for flexural strength and six specimens for compressive strength are given in Table 1. According to the results,  $f_{c,mat}$  of 26.8 MPa was obtained at the age of 28 days.

Table 1. Mechanical properties of the tested mortar

Age [days]	Flexural strength [MPa]	Compressive strength [MPa]
1	1.9	5.0
7	4.6	19.5
14	5.1	22.5
28	6.8	26.8

Besides mechanical properties, the water absorption coefficient due to capillary action was determined on prisms (40 x 40 x 80 mm) per EN 1015-18 (Table 2). After adequately preparing the specimens, they were placed into the water at a 5-10 mm depth. Their mass was measured 10 and 90 minutes after the first contact with water. The water absorption coefficient due to capillary action was determined based on the following formula:

$$C = 0,1 (M_3 - M_0) \quad (2)$$

where:

- $M_0$  mass of dry prism [g],
- $M_3$  mass of prism after finalization of the test [g].

Table 2. Water absorption coefficient due to capillary action

Age [days]	Prism	Water absorption coefficient [kg/(m <sup>2</sup> ·min <sup>0.5</sup> )]
28	1	0.219
	2	0.220
	3	0.214
	average	0.218



Figure 2. Testing of the mortar specimen

### 3.2 Specimen preparation

Three groups of specimens were prepared to investigate the characteristics of the FRCM composite:

Group I) Dry fabric

Group II) FRCM coupons (fabric embedded in mortar matrix)

Group III) FRCM system applied on masonry element with dry fabric overhang

Specimens were prepared following previously mentioned and available guides, technical documentation, manuals, papers, and studies [7, 8, 9, 11]. In these documents minimal requirements for the width, length, and number of yarns of one specimen are defined. Nevertheless, it is up to the researchers to define the optimum specimen dimensions for the tests in question. To approximate realistic conditions, the specimens were as wide as possible, preserving the recommended ratio between the width and the length of the specimens.

The first group of specimens (I) consists of dry fibre fabric specimens that are 75 mm wide (4 warp yarns) and 500 mm long. Those specimens were cut out of a roll using scissors. At the end of fabric specimens steel tabs (75 x 100 x 3 mm) were bonded using epoxy resin. Three specimens were prepared in this manner.

The second group of specimens (II) consists of FRCM coupons made of two mortar layers (5 mm thick) with glass fibre fabric embedded between them. Specimens were prepared by the lay-up procedure in a few steps, using timber

moulds (Figure 3.a), ensuring the proper dimension of each coupon (75 x 500 x 10 mm). In the first step, moulds are made of longitudinal and transversal timber battens with a thickness of 5 mm. After the 1<sup>st</sup> layer of mortar was applied, the moulds were exposed to vibration on the vibro-table for 5-10 s. In the next step, dry fabric pre-cut with 75 x 500 mm dimensions is slightly embedded in the first mortar layer (Figure 3.b). The control of fabric alignment in the middle of coupon thickness is crucial in such a procedure. In the last step (Figure 3.c), the additional timber battens with a thickness of 5 mm are mounted on the existing moulds, ensuring a total mould thickness of 10 mm. The top layer of mortar was then applied and flattened using a finishing trowel. It is essential to complete the lay-up procedure within the pot life of the mortar. Prepared specimens were cured in moulds for 7 days in standard laboratory atmospheric conditions and then cured in water for the next 21 days.

Since the geometry of specimens in the second group is specific due to their length-to-thickness ratio, EAD 340275-00-0104 [9] requires testing at least 20 specimens to determine appropriate insight into the characteristics of the coupons.

In the third group of specimens (III), the FRCM system is applied on masonry element. Before applying the FRCM system, it was necessary to investigate the mechanical properties of bricks and mortar joints, properly prepare the substrate that the system will be applied on, and investigate the substrate's quality.



Figure 3. Preparation of the specimens (group II): a) moulds before lay-up procedure, b) embedding of fabric on the 1<sup>st</sup> mortar layer, c) coupons prepared in molds

EAD 340275-00-0104 [9] requires brick testing according to EN 771-1 (Figure 4) since the compressive strength of brick should not exceed 25 MPa. The tested brick specimens were 50 x 50 x 65 mm and 250 x 120 x 65 mm. The average compressive strength was 33.8 MPa for cubic specimens and 27.6 MPa for prismatic specimens. Although, the measured compressive strength of bricks was higher than required, no negative consequences on the behaviour of the specimens were noticed. The substrate's modulus of elasticity was not tested within this study, although it the determination of this parameter is recommended for the strengthening calculations.

EAD 340275-00-0104 [9] requires testing of mortar joints since the mortar class should not be higher than M5 according to EN 998-2. The mortar used for the joint had a density of 1728 kg/m<sup>3</sup> in a fresh state. During the preparation of masonry elements, six prisms 40 x 40 x 160 mm were made and cured in standard laboratory conditions. Hardened mortar density was measured after 7 and 28 days, as well as mortar flexure and compressive strength. Average values are given in Table 3. Testing results prove that mortar class is not higher than M5 by EN 998-2.

Table 3. Mechanical properties of mortar used for joints

Age [days]	Hardened mortar density [kg/m <sup>3</sup> ]	Flexure strength [MPa]	Compressive strength [MPa]
7	1634	1.10	3.12
28	1607	1.45	4.20



In the third group of specimens, the FRCM system with dimensions 75 x 300 x 10 mm was applied on a masonry element made of 6 half-bricks (125 x 120 x 60 mm) and mortar joints (10 mm thick). Before applying the FRCM system, the masonry substrate had to be prepared appropriately following the manufacturer's pre-treatment guide. The substrate to be strengthened was treated with sand blasting as long as a rough texture with visible pores was achieved. All the masonry surfaces were thoroughly cleaned and dust-free (Figure 5a). Before applying the FRCM system, the substrate was thoroughly pre-wetted to be saturated but surface-dry (Figure 5b). The brick substrate measured 410 x 125 mm, with the FRCM system applied 20 mm shorter at the top and 80 mm shorter at the bottom than the substrate edges (Figure 5c). Bare glass fibre fabric was continuously extended from a bonded system over masonry elements at a 250 mm overhang length. Steel tabs were bonded at the end of the bare fabric in 100 x 75 x 3 mm. Five specimens of the third group were prepared in total (Figure 5c).

The quality of the substrate was tested on individual masonry elements. EAD 340275-00-0104[9] requires testing of substrate quality according to EN 1542. The masonry substrate was properly cleaned by sandblasting before the mortar was applied to a thickness of 10 mm. After the mortar was cured in standard laboratory conditions, steel dollies with a diameter of 50 mm were arranged and bonded on adequately prepared substrate. Repair mortar was drilled using a diamond coring barrel at 5-10 mm depth. „Pull-off“ tensile stress was measured on 5 individual dolly-fields (Figure 6). Results of tensile stress measurement and description of failure type are given in Table 4.



Figure 4. Preparation and testing of brick specimens

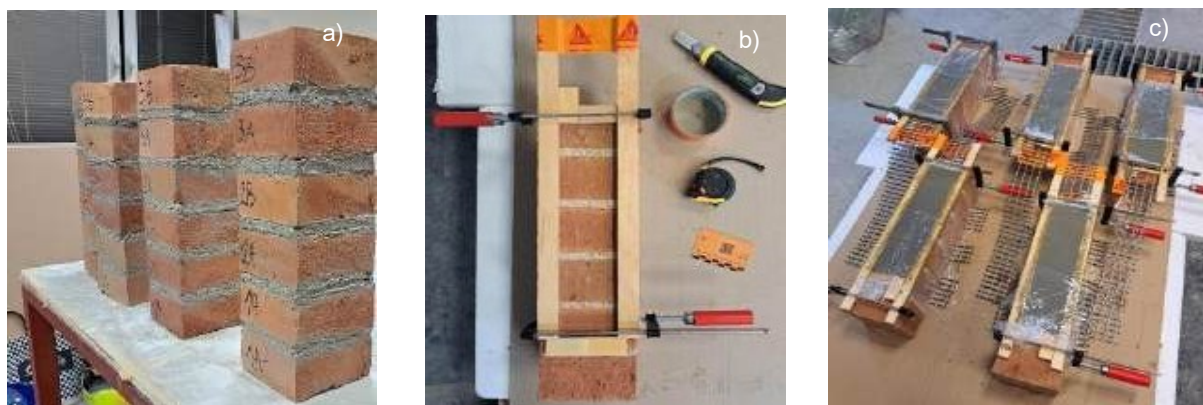


Figure 5. Preparation of the specimens (group III): a) masonry elements, b) area to be strengthened, c) FRCM system applied on masonry element with overhang fabric

Table 4. Substrate quality determination using the „pull-off“ method

Dolly no.	Tensile strength [MPa]	Description of failure type	Failure type
1	1.85	Combined failure in substrate and in the 2 <sup>nd</sup> layer	A:C=40:60
2	2.33	Combined failure in substrate and in the 2 <sup>nd</sup> layer	A:C=70:30
3	2.34	Combined failure in substrate and in the 2 <sup>nd</sup> layer	A:C=30:70
4	1.70	Cohesion failure in the 2 <sup>nd</sup> layer	C
5	2.27	Cohesion failure in the 2 <sup>nd</sup> layer	C



Figure 6. Brick specimens after the „pull-off“ test was done

Following EN 1542 and EN 1504-3, the adhesion strength of mortar and substrate quality meet the requirements of standards, since all of the results are higher than 1.5 MPa.

### 3.3 Testing the FRCM system

The study aimed to determine the mechanical properties of the dry fabric (group I) and fabric as part of the FRCM system (groups II and III), as well as the performance of the strengthening system. All specimens were exposed to tensile force, while the strain was measured using extensometers. In group III, the relative displacement between the bare overhang fabric and masonry support was also necessary to measure. For that purpose, one steel profile „L“ shape was bonded at the beginning of the overhang fabric length while two LVDTs were bonded on masonry substrate next to each FRCM side and in touch with the „L“ profile, forming the 60 mm measuring base.

After considering all of the investigated and available testing methods, the clevis-grip method was adopted as suitable due to the fact that several specimens should be tested and the available testing equipment. A pair of steel plates holds the end of the specimen, while slippage prevention is ensured using rubber sheets. Each pair of steel plates is joined by bolts and fixed into the grips of the standard testing machine, allowing for torsional rotation and thus ensuring specimen alignment before the beginning of the test. This gripping method ensures stress transition by shear, without additional compressive forces perpendicular to the plane of the specimen.

The dimensions of the steel plates used for gripping were defined according to the dimensions of the specimens. The dimensions of the steel plates were adopted to be 100 x 200 x 10 mm so the specimen could be positioned in the central part of the plate. Six Ø15 mm bolt holes were made at each steel plate, ensuring connection by M14 bolts (Figure 7).

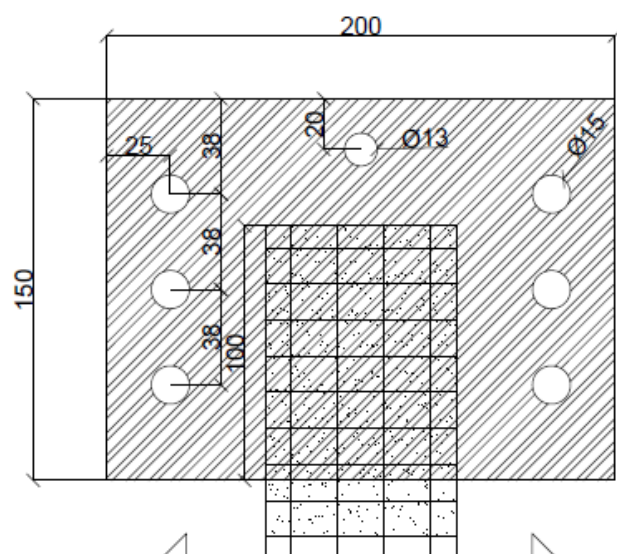


Figure 7. Arrangement of gripp using steel plates (measures are presented in [mm])

The first and the third groups required additional gripping and support equipment. Both groups had a part of dry fabric (without mortar matrix) that should be additionally prepared to ensure additional slippage prevention. A pair of steel tabs with 75 x 100 x 3 mm dimensions were bonded at each end of the fabric using epoxy resin. After the resin was cured, steel tabs were held by steel plates and specimens were exposed to testing (Figure 8).

As previously mentioned, strain measurement is arranged in the central part of the specimens' length using an Epsilon extensometer with gauge lengths of 100 mm and 200 mm for groups I and II, respectively. Slip of the fabric along the overhang length is measured in group III, using a pair of LVDTs („HBM WA-L“, 0-10 mm measurement range) located next to the FRCM bonded area. Tensile tests were performed using the universal testing machine „ShimadzuAG-X plus“ with 300 kN capacity.

## 4 Results and discussions

### 4.1 First group of specimens

Tensile tests were performed on three specimens cut from the glass fibre fabric. Based on the stress-strain diagrams (Figure 9), the modulus of elasticity of the fabric was estimated, following the EAD 340275-00-0104[9], referring to the stresses and deformations measured in the range of  $F_u/10$  and  $F_u/2$ .

Based on the mean values of the fabric's ultimate stress and elastic modulus, the ultimate strain of fabric was determined  $\epsilon_{u,f} = (\sigma_{u,f} / E_f)$ . These two parameters are crucial when calculating the reinforcement of masonry structures.

Testing the fabric through the clevis-grip method resulted in fibre failure at the clamping area. This failure mode is characteristic of the system in service with insufficient anchorage length. Test results largely correspond to the results from the literature (Table 5).

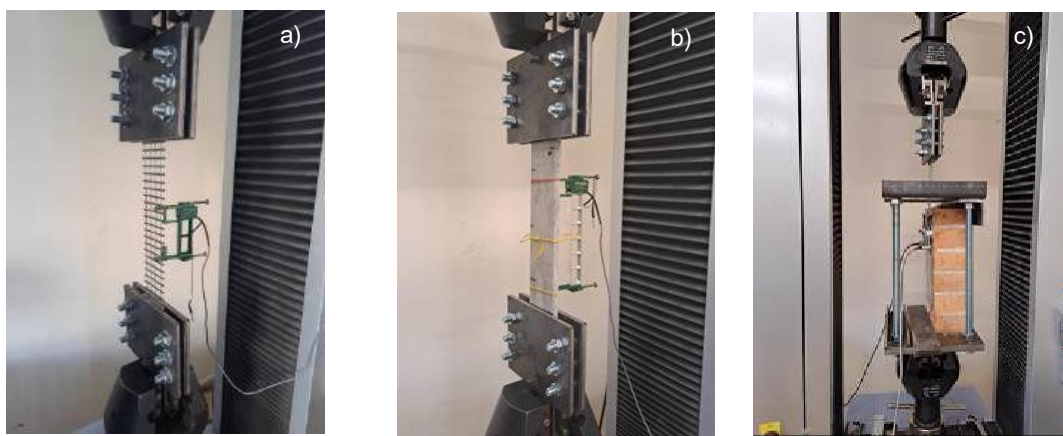


Figure 8. Specimens during the testing a) represent of group I, b) represent of group II, c) represent of group III

Table 5: Comparison of the test results of the first group (I) with results from the literature

SpecimenGroup	$\sigma_{u,f}$ [MPa]	$E_f$ [GPa]	$\epsilon_{u,f}$ [%]
I	742.2	48.4	1.53
ACI 549.6R-20 [8]	750.0	50.0	1.50

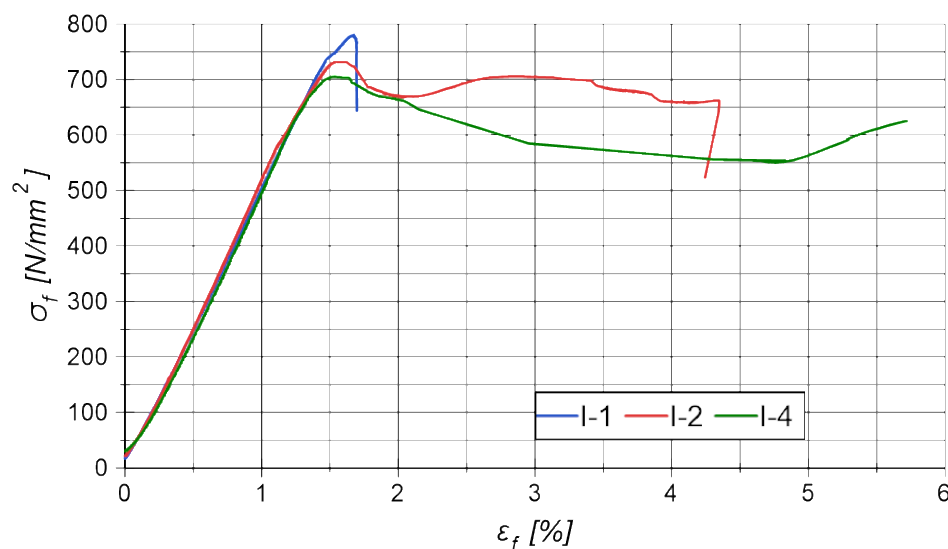


Figure 9. Stress-strain diagram for the first group of specimens [14, 15]

4.2 Second group of specimens

This experimental campaign tested 10 prismatic FRCM specimens with 75 × 500 × 10 mm dimensions. The expected behaviour of this type of specimen was described in the section Methodology.

The behaviour of the FRCM composites during the tensile testing is characterised by considerable scattering of test results. The first crack within the extensometer gauge was observed for five specimens, leaving the other five out of the further analysis.

The stress-strain diagrams are presented in Figure 10. Following the EAD, the tensile stiffness moduli of stages A and C are calculated based on the change of stress and strain between the beginning and end of each phase (Tables 6 and 7). The line obtained by connecting the two points chosen for calculating the stiffness modulus should closely follow the trend of the response curve in the region, which was the case for the specimens in question. In stage A, the specimen shows composite behaviour, where the mortar (matrix) prevents the development of deformations in the glass fibres, and mortar and mesh deform together. For the stress-strain diagrams shown in Figure 10, the stress was calculated using cross-sectional area of the dry fabric. In order to determine the slope of the uncracked portion of the stress-strain diagram of the stage A, stresses were calculated both using the cross-sectional area of dry fabric ( $\sigma_{min,f}$  and  $\sigma_{mas,f}$ ) and using the cross-sectional area of the whole specimen ( $\sigma_{min,m}$  and  $\sigma_{mas,m}$ ), as shown in Table 6.

When the values obtained for fabric are analyzed ( $E_{1,f}$ ), it can be noticed that the values are unusually high. Nevertheless, it is in confinement with the results obtained in the Round Robin test and presented in ACI 549.6R-20. The values calculated based on stresses in the mortar matrix ranged between 0.44 GPa and 10.95 GPa.

According to the Aveston-Cooper-Kelly theory (ACK) during the stage A, FRCM obeys the law of mixtures, and modulus of elasticity of composite ( $E_c$ ) can be calculated as follows:

$$E_c = E_f \cdot v_f + E_m \cdot v_m \tag{3}$$

where  $E_f$  represents Young's modulus of the fabric,  $E_m$  is Young modulus of the matrix, and  $v_f$  and  $v_m$  are the volumetric fractions of the fibers and matrix, respectively. In the presented research the modulus of elasticity for the fabric has been measured for the specimens in group I, while the modulus of elasticity of mortar matrix was not measured. According to Mercedes et al. [16] this modulus can be approximated based on the compressive strength of mortar  $f_c$  in [MPa]:

$$E_{ci} = 0.3 \cdot 8500^3 \sqrt{f_c} \tag{4}$$

If these equations are applied on the obtained results, the modulus of elasticity of mortar matrix is equal to 7.63 GPa, while the modulus of elasticity of the composite (eq.3) is equal to 7.83 GPa.

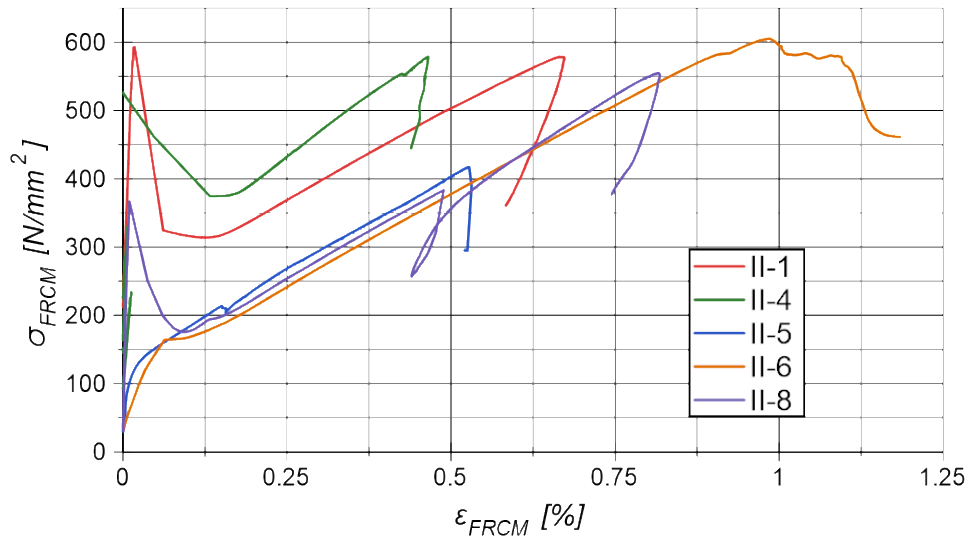


Figure 10. Stress-strain diagram for the second group of specimens [14,15]

Table 6. Measured values of stress, strain and calculated moduli for stage A

Specimen	Stage A									
	$F_{min}$ [kN]	$F_{max}$ [kN]	$\sigma_{min,f}$ [MPa]	$\sigma_{max,f}$ [MPa]	$\sigma_{min,m}$ [MPa]	$\sigma_{max,m}$ [MPa]	$\epsilon_{min}$ [%]	$\epsilon_{max}$ [%]	$E_{1,f}$ [GPa]	$E_{1,m}$ [GPa]
II-1	0.119	2.209	25.3	587.2	0.032	0.737	0	0.0214	2627.3	8.24
II-4	0.444	0.870	93.9	228.8	0.118	0.287	0	0.0124	1090.7	3.41
II-5	0.196	0.805	41.4	91.7	0.052	0.115	0.0029	0.0074	1123.2	2.14
II-6	0.154	0.627	32.8	166.6	0.041	0.209	0	0.0951	140.7	0.44
II-8	0.150	1.441	31.9	361.8	0.040	0.454	0	0.0094	3494.8	10.95

The corresponding stress-strain diagrams show that the stiffness moduli of stage C can be easily obtained from Figure 10 and Table 7. The values presented, and the linear behaviour in stage C align with the fabric's tensile behaviour.

Table 7. Measured values of stress and strain for stage C

Specimen	Stage C				
	$\sigma_{min}$ [MPa]	$\sigma_{max}$ [MPa]	$\epsilon_{min}$ [%]	$\epsilon_{max}$ [%]	$E_3$ [GPa]
II-1	315.1	577.2	0.13755	0.66028	50.1
II-4	377.6	577.0	0.17068	0.46153	68.6
II-5	215.3	416.3	0.16775	0.52731	55.9
II-6	173.3	582.8	0.11655	0.91178	51.5
II-8	197.8	379.0	0.14892	0.48022	54.7
<b>Average</b>	<b>56.2</b>				

According to the Italian Guide [10], the stiffness moduli of stage A should be recorded if possible. The values calculated within this research exhibit a high discrepancy in results. Due to the high scattering of the results, and the fact that in this test the boundary conditions differ from those experienced in the structural applications, the tensile modulus of dry fabric ( $E_f$ ) is used in calculations, instead of the values measured for the composite FRCM specimens [8]. Values obtained in the stage C for the stiffness modulus are close to the modulus of elasticity of the dry fabric, measured for the first group of specimens. This is in accordance with the theoretical assumption that in the final phase, the properties of the system rely on the properties of the dry fabric.

In presented stress-strain diagrams, the extensometer readings and the corresponding stress values are

proportionally lower than the results from the literature. The smaller strain readings could be caused by insufficient contact between the extensometer and the composite, although much attention was paid to the proper connection of the extensometer to the specimen. On the other hand, estimated stiffness modulus values, as a primary outcome of this test, align with the literature, see Table 8.

Table 8. Comparison of test results of the second group (II) with results from the literature

Specimen Group	$\sigma_u$ [MPa]	$\epsilon_u$ [%]	$E_1$ [GPa]	$E_3$ [GPa]
II	658.0	0.57	2404	56.2
ACI 549.6R-20 [8]	1250.0	1.50	2200	50.0

As confirmed by the tests, this group of specimens shows the highest degree of dispersion of results. Therefore, the requirement of standard EAD 340275-00-0104[9] for testing at least 20 specimens of this group is justified.

### 4.3 Third group of specimens

Testing the third group of specimens reveals the bond properties of the composite system adhesively applied to a flat masonry substrate. For this purpose, the single-lap shear test was performed as defined by EAD 340275-00-0104[9]. The force-slip diagrams are presented in Figure 11.

During the test, no cracks were observed along the composite, and the load-bearing failure occurred due to the tearing of the exposed part of the fabric (Figure 12). This failure mode designated as "F" in the literature, is expected for this type of reinforcement. As presented in Table 9, stress values are comparable to the corresponding values from the literature. The obtained slip value is lower than expected, although it can be significantly affected by the gauge length.

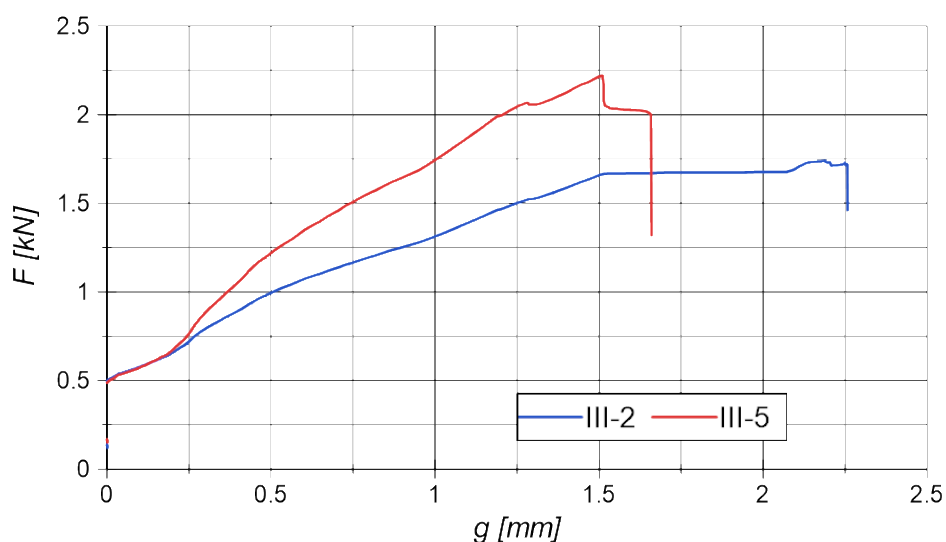


Figure 11. Force-slip diagram for the third group of specimens [14, 15]



Figure 12. One specimen of the group III after the failure

The conventional strain was calculated as 1.28% using conventional stress and elastic modulus of dry fabric.

Table 9. Comparison of test results of the third group (III) with results from the literature

Specimen Group	$\sigma_{lim,conv}$ [MPa]	$g_{max}$ [mm]
III	621.4	2.1
ACI 549.6R-20 [8]	620.0	2.8

## 5 Conclusions

The main objective of this study was to test the most important mechanical properties of the FRCM system used for the strengthening of the masonry elements. To achieve this, first, the components of the systems were tested, followed by the tests performed on the three groups (fibers, fibers in mortar, and masonry system) of specimens. The experiments were designed according to the recommendations found in the literature and using the available equipment and resources. Through the result analysis, different parameters affecting the results were discussed and explained.

The following conclusions can be made:

- Recommended mechanical properties of the component materials used for the specimen production were tested. The compressive strength of the mortar used as a matrix was 26.8 MPa at 28 days, adhesion strength was 2.1 MPa at the same age, and capillary water absorption was 0.218 kg/(m<sup>2</sup>·min<sup>0.5</sup>). The compressive strength of the bricks used for the third group of specimens was 33.8 MPa (measured on the cubic specimens cut out from the bricks). At 28 days, the mortar for the wall joints demonstrated a compressive strength of 4.2 MPa.

- Three important parameters obtained from the first group of specimens were ultimate tensile stress of the dry

fabric,  $\sigma_{u,f} = 742,2$  MPa, elastic modulus of the dry fabric  $E = 48.4$  GPa, and ultimate tensile strain of the dry fabric  $\varepsilon_{u,f} = 1.53\%$ . Testing the composite specimens (second group) exposed very high dispersion of the results. The unusually high value of the slope of the uncracked phase in stage A is obtained when the stresses are calculated using the cross-sectional area of dry fabric. Although, the used guidelines [8,9] recommend measuring of this value, referred to as stiffness or stiffness moduli of the uncracked stage, the high scattering of the results is still an obstacle to its realistic measurements and application in calculations. When the modulus of elasticity of the stage A is calculated using the ACK model, the obtained value is 7.83 GPa. The ultimate tensile stress for this group of specimens was 658 MPa, while the ultimate strain was 0.57%. The third group of specimens obtained conventional stress at 621.4 MPa, while the conventional strain was 1.28%.

- The obtained results were, in most cases, in accordance with the results presented in the literature, especially the results of the Round Robin test performed within the RILEM TC 250 [8]. The main differences were noticed for the ultimate tensile stress and strain in the second group of specimens. The obtained stress value was 1.8 times lower than values found in the literature, while the strain was 2.6 times lower. The differences were probably the consequence of the different gripping methods applied and the different types of glass-fibre grid dimensions.

- All three groups of specimens used for the mechanical testing of one FRCM system were tested using the clevis-grip method. The chosen geometry of the specimens in different groups enabled the comparison of the obtained results and showed overall satisfying behavior. In the chosen geometry, the anchoring length was reduced to 100 mm, which was not satisfactory for the first group of specimens because the failure was induced near the gripping area. For this group, the recommended anchoring length of 125 mm should be applied in future tests.

- The importance of the way of seizing the specimens (clevis- or clamping-grip) was pronounced in the second group of the specimens. The clevis-grip method used for the performed tests gave realistic results with simpler and less expensive specimen preparation. In this way, most equipment parts may be used multiple times. The ultimate stress values obtained in the second group were lower than in the literature, which may be the consequence of the applied testing method. These specimens in the second group were also quite demanding for preparation.

- The third group of specimens was the most challenging to prepare, but it indicates the whole system's behaviour, which makes it very important. The failure mode in this group was through the fabric, which is expected for this type of FRCM system.

- As an important part of future investigations, different durability properties of the system, and their influence on the durability of the masonry structure should also be tested and discussed.

### Credit authorship contribution statement:

**Milica Petrović:** Formal analysis, State-of-the-art, Visualization, Writing - original draft. **Marko Popović:** Conceptualization, Methodology, State-of-the-art, Testing, Writing - original draft. **Marina Skondrić:** Conceptualization, Methodology, Funding acquisition, Visualization, Writing - original draft. **Aleksandar Savić:** Methodology, Writing - Control and editing. **Dimitrije Zakić:** Methodology, Writing - Control and editing.

### Declaration of Competing Interests:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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