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note finali coverage

(Article begins on next page)

1 **TENSILE BEHAVIOUR OF GLASS FRCM SYSTEMS WITH FABRICS' OVERLAP:**
2 **EXPERIMENTAL RESULTS AND NUMERICAL MODELING**

3
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15 **HIGHLIGHTS**

- 16 • Tensile tests on glass FRCM systems with different fabrics' overlap lengths have been
17 performed.
18 • DIC has been successfully employed to provide the FRCM strain field.
19 • A variational model has been numerically implemented to simulate the FRCM tensile
20 behaviour.
21
22
23

24 **ABSTRACT**

25 The use of Fabric Reinforced Cementitious Matrix (FRCM) systems to reinforce existing masonry
26 and concrete structures is nowadays a well-established practice. The mechanical characterization
27 of FRCM systems is of fundamental importance to define the correct parameters needed to design
28 a strengthening intervention. However, some aspects regarding FRCM tensile behaviour need to
29 be further investigated.

30 The aim of this paper is to provide a detailed overview on the mechanical behaviour of FRCM
31 specimens subjected to tensile tests. In this context, the effect of fabrics' overlapping on the global
32 behaviour of the system is extensively analyzed. Different sample's configurations have been
33 studied: one reinforced with a single layer of bidirectional glass fabric and three others with
34 different fabrics' overlap lengths, varying between 100 and 200 mm. Digital Image Correlation
35 (DIC) has been also used to measure displacements in experimental testing.

36 A phase-field model, that accounts for brittle fracture of cementitious matrix and fabric
37 reinforcement and possible slippage at the fabric-to-matrix interface, has been developed. The

1 variational formulation has been implemented in a finite element code to simulate the tensile
2 behaviour of FRCM systems and the effects of using different fabrics' overlap lengths.

3
4 **Keywords:**

5 FRCM; strengthening; tensile behaviour; overlap; Digital Image Correlation; modeling.

6
7 **1. Introduction**

8 The use of composite materials, consisting of inorganic matrices reinforced with fabrics in the
9 form of open mesh textiles (Fabric Reinforced Cementitious Matrix), externally applied to
10 masonry walls or concrete elements, is nowadays considered an effective and compatible
11 reinforcement solution. FRCM have considerable advantages if compared to more traditional
12 strengthening systems (e.g. Fiber Reinforced Polymer (FRP) or steel plates), such as high strength-
13 to-weight ratio, ease of installation, high compatibility with masonry or concrete substrates,
14 applicability on wet surfaces, resistance to high temperatures and safety for operators during
15 installation [1-5].

16 FRCM systems have been successfully employed for flexural and shear strengthening of concrete
17 beams [6-12], to confine concrete columns [13-17] and as in-plane and out-of-plane reinforcement
18 of masonry walls [18-23]. However, there are still no standardized procedures for the mechanical
19 characterization of FRCM systems, and, to date, ACI549.4 R-13 is the only guideline that provides
20 for the design of reinforcement interventions with these systems [24].

21 The tensile characterization of FRCM systems is usually carried out by means of two test setups,
22 the clevis-grip method, required by ACI549.4 R-13 and described in AC434-13 [25], and the
23 clamping-grip method, recommended by Rilem TC 232-TDT [26]. These two test methods provide
24 for different boundary conditions at the specimens' ends and can lead to significantly different
25 results [27,28]. Even if the mechanical characterization of FRCM systems has been investigated
26 by several authors [27-30], with different techniques and different materials, there are still some
27 aspects that need further investigation.

28 One that deserves attention is represented by the fabrics' overlap. The limited width of the rolls in
29 which the fabric is provided by manufactories (about 1 meter), often causes the need to overlap
30 the fabrics. The minimum overlap length between two fabrics, which should be defined for each
31 FRCM system, guarantees the complete transfer of tensile stresses from one fabric to another. An
32 overlap length greater than the minimum overlap length, should promote the failure of the FRCM
33 reinforcement before debonding of the overlapped FRCM fabrics. Tensile tests on FRCM coupons
34 with fabrics' overlap are required by AC434 [25] and the most recent Italian guideline issued by
35 CSLP [31]. During FRCM installation, it is important to provide sufficient overlap when splicing
36 fiber fabrics, as determined according to test methods specified in [25]. The required overlap, or
37 lap-splice length, depends on the tensile strength and thickness of the FRCM material system and
38 on the bond strength between adjacent layers of FRCM reinforcement [24].

39 In this study, the effects of different glass fabrics' overlap lengths on the mechanical behaviour of
40 the composite material have been analyzed through tensile tests on prismatic coupons, and then a
41 minimum overlap length related to the system analyzed has been identified. It is important to
42 understand if the lap can cause the formation of a weak section with respect to the continuous
43 fabric section. The objective is to determine the minimum fabrics' overlap length able to maintain
44 fabric continuity and to avoid a loss of tensile strength in FRCM specimens.

1 Furthermore, in order to obtain the mechanical parameters needed for the strengthening design, it
2 is also important to identify a reliable way to measure the deformations of FRCM systems during
3 tensile tests. For this kind of material, consisting of both an inorganic matrix that cracks when
4 subjected to tensile stresses and a fabric that can slip within the matrix, it may be difficult to
5 measure displacements and deformations in an accurately way relying on traditional sensors.
6 Strain gauges can measure only local values and do not allow to monitor the ‘tension stiffening’
7 effect of the mortar after the formation of cracks. As for LVDTs, the position of the instruments
8 with respect to the cracking pattern, clearly unknown before the test, can affect the reliability of
9 results.

10 The use of full-field contactless optical methods, such as Digital Image Correlation (DIC), could
11 be a possible solution that does not interfere with the specimen during the test, and it is not affected
12 by the formation of cracks on the specimen surface. This method has been already successfully
13 applied by the authors in testing of metals [32], brittle materials such as ceramics [33], rubber [34],
14 foam [35] and cork [36]. The application of DIC to FRCM systems has been investigated by
15 Tekieli et al. [37] and Bilotta et al. [38]. In both cases DIC provided reliable results and additional
16 information that would have been unavailable otherwise.

17 In this study, DIC has been successfully used to monitor the evolution of the strain field during
18 tensile tests and has been able to provide important information about the evolution of the cracks
19 pattern, local deformations and width of the cracks.

20 For a better comprehension of the experimental results, a damage model has been numerically
21 implemented in a finite element code, and simulations have been performed to reproduce the
22 FRCM tensile response. A phase-field approach has been followed to develop the model,
23 according to which fracture is approximated by a smooth damage variable and governing and
24 evolution equations are variationally deduced by minimizing proper energy functionals, depending
25 on damage and its gradient [39]. In the last years, following the pioneering paper [40] (see [41] for
26 a more detailed description), several variational formulations were proposed to reproduce many
27 different failure modes (e.g., shear fracture [42], rupture due only to tensile loads [43,44], ductile
28 failure [45]), and to describe failure of different materials (rubbers [46], cement mortar [47], fiber
29 reinforced concretes [48], etc.). Variational approaches were also applied to plasticity in [49-51],
30 and to coupled damage and plasticity in [52]. Applications of phase-field models to FRCM systems
31 were proposed in [53,54]. Debonding of fiber yarns was modeled in [53] by assuming that the
32 damage energy of the yarn-to-matrix interface has the form of power functions, while, in [54], a
33 specific damage dependent energy term was included in the interface energy, to account for
34 frictional slippage.

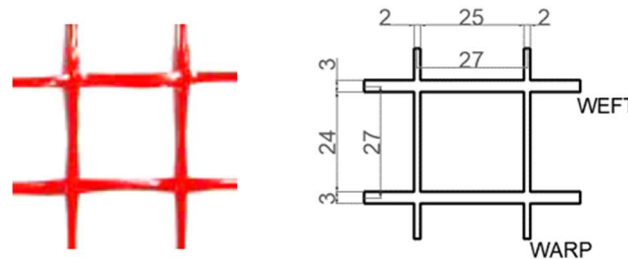
35 In this paper, the model proposed in [55] for hybrid laminates, is revised and adapted to the specific
36 problem of tensile FRCM systems. FRCM specimens are schematized as multilayer systems
37 constituted by layers of mortar and reinforcement. Each layer is modeled as a brittle bar that
38 elastically stretches and, when a limit stress is reached, it breaks. Its energy collects three
39 contributions, as usually in phase field theories [39]: an elastic term, a local damage term and a
40 non-local gradient part. Different stiffnesses and strengths have been assigned to the anchor parts
41 and to the central free parts of mortar layers. Each layer is connected to the adjacent one by non-
42 linear springs, which allow elastic shear strain and slippage in regime of stress softening. Balance
43 and evolution equations are determined by energy minimization. Regarding the evolution, an
44 incremental procedure is adopted, consisting in solving a constrained programming problem at
45 each increment of the imposed tensile deformation. A similar evolution scheme was analytically
46 solved in [48], in a simplified one-dimensional context, providing parametric and stability

1 analyses. Here the evolution problem is solved numerically, by implementing the model in a finite
2 element code. Simulations are performed by considering specimens with a single reinforcement
3 layer and with overlapped double reinforcement layers. All the evolution phases that leads to
4 specimens' failure are accurately captured by simulations, whose predictions are in good
5 agreement with the experimental evidences.
6

7 The paper is organized as follows: after a description of the materials used to manufacture FRCM
8 coupons (Section 2) and of the tensile test setup adopted (Section 3), experimental results are
9 reported in Section 4. In this section the effect of fabrics' overlapping on the mechanical behaviour
10 of FRCM systems is analyzed. The possibility of using different measurement methods (DIC,
11 displacement transducer and extensometer) is also discussed. Finally, a phase-field model has been
12 developed (Section 5), in order to reproduce the tensile behaviour of FRCM coupons reinforced
13 with single or overlapped layers of glass fabrics. Numerical results have been described in Section
14 6 and compared with those obtained in experiments.
15

16 2. Materials

17
18 A bidirectional fabric made of alkali resistant (AR) glass fibers coated with a layer of polyvinyl
19 alcohol (PVA) was considered. The fabric structure is attained through leno wave technique, with
20 weft yarns that pass through the warp yarns. Geometrical properties of the glass fabric employed
21 are reported in Fig. 1.



22
23 Fig. 1 – Geometrical properties of the glass fabric employed (250 g/m²)
24

25 The mechanical properties of the glass fabric were determined through tensile tests on single fiber
26 yarns taken from the warp direction. Tensile tests on glass fiber yarns were performed in
27 displacement-control at a rate of 0.5 mm/min, by using a tensile testing machine with a load
28 bearing capacity of 50 kN. Specimens comprised one fiber yarn 300 mm long. FRP tabs were
29 epoxy-bonded to the ends of the specimen to ensure slip-free gripping by the testing machine. The
30 cross-sectional area of the single yarn A_f (Table 1) was computed from the nominal thickness
31 provided by the manufacturer. A macro extensometer with a length of 50 mm was positioned at
32 the center of each specimen to measure the strain of the yarn. The mean tensile strength σ_f , the
33 corresponding strain ε_f , and the elastic modulus E_f are obtained by averaging the results of 5
34 specimens and are reported in Table 1 together with the corresponding coefficient of variation,
35 CoV.

36 A lime-based mortar was used as FRCM matrix. Three prismatic specimens (40x40x160 mm³)
37 were cast, cured at laboratory conditions (20 °C, 70% RH) up to 28 days and tested according to
38 EN 1015-11 [56]. The average flexural strength $\sigma_{m,f}$, compressive strength $\sigma_{m,c}$ and elastic modulus

1 in compression E_m , are reported in Table 1 together with the corresponding Coefficient of
 2 Variation, CoV.

3

4

Table 1 – Mechanical properties of glass yarns (warp direction) and inorganic matrix

Material		σ_f [MPa]	ε_f [%]	E_f [GPa]	A_f [mm ²]	$\sigma_{m,f}$ [MPa]	$\sigma_{m,c}$ [MPa]	E_m [GPa]
Glass 250	Average	1405	2.4	57.1	0.923	-	-	-
	CoV	0.102	0.061	0.087	-	-	-	-
Matrix	Average	-	-	-	-	4.1	10.2	9.5
	CoV	-	-	-	-	2.9	0.025	-

5

6

3. Experimental investigation

7

8

3.1 Specimens preparation

9 FRCM coupons (dimensions of 70x400x10 mm³) were manufactured by first applying a thin layer
 10 of mortar of about 5 mm, using a wooden formwork. A layer of glass fabric was then placed on
 11 top of the mortar and covered with a second layer of mortar with same thickness. Coupons were
 12 cured at laboratory ambient conditions at 20 °C and 70% relative humidity for 28 days. After that,
 13 four metal tabs were applied with epoxy at the ends of each specimen (Fig. 2) with an anchor
 14 length of 150 mm, as indicated in the AC434.

15 In addition to the one ply specimen (Fig. 3a), panels with a lap splice overlap of 100, 150 and 200
 16 mm were manufactured, following the same procedure. Geometrical properties of FRCM
 17 specimens with fabrics' overlap are illustrated in Fig. 3b. The free length of the specimen (equal
 18 to the distance between the metal plates) has been varied according to the overlap length. The
 19 anchor length between metal plates and specimen has been kept constant (150 mm).

20

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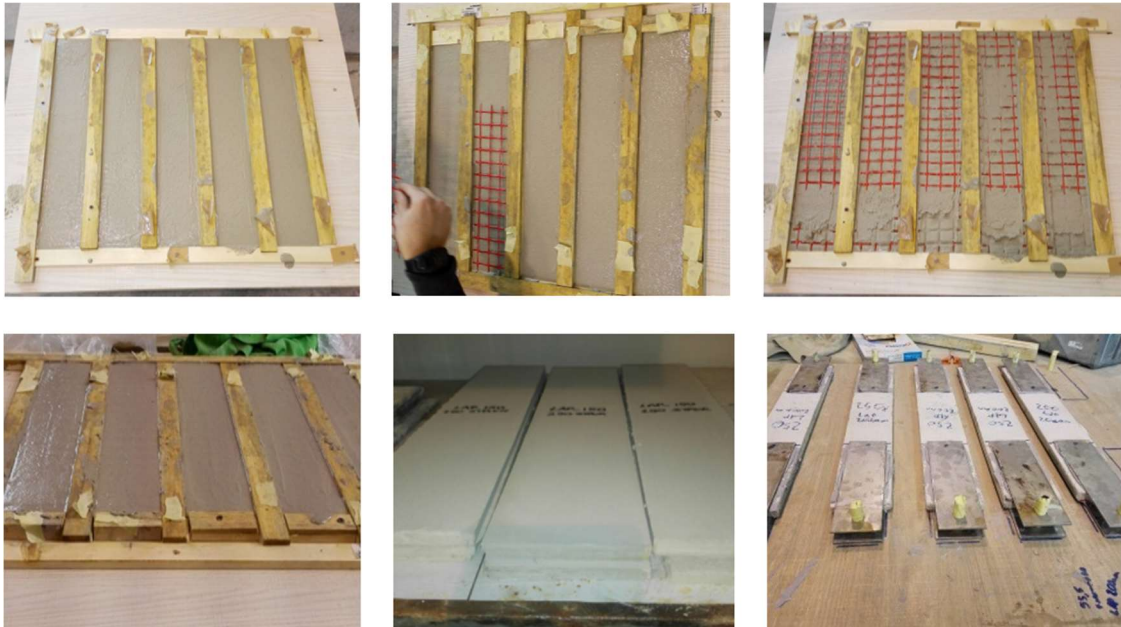


Fig. 2 – Preparation of FRCM coupons with fabrics' overlap

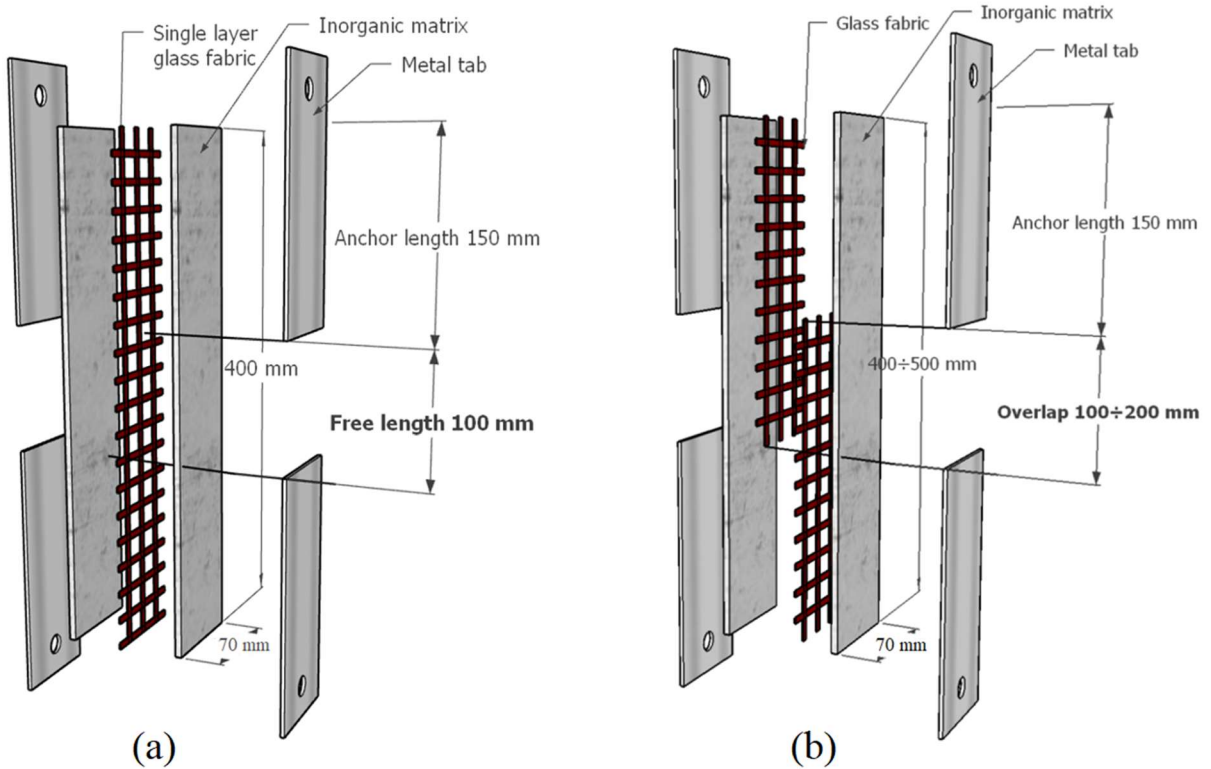
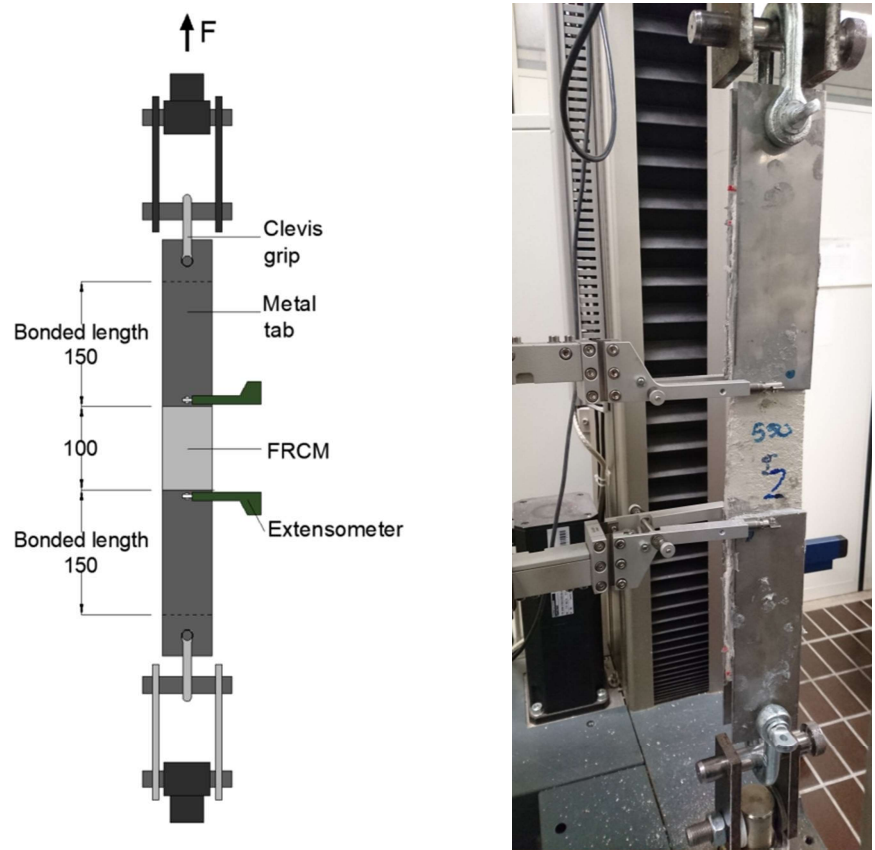


Fig. 3 - Geometrical properties of FRCM coupons with a single layer of glass fabric (a) and with fabrics' overlap (b).

3.2 Tensile Test Setup

1 A total of 20 specimens have been manufactured and tested using a clevis-type gripping system,
2 as recommended by the US guideline AC434.13 Annex A, in which the load is transferred from
3 the testing machine to the mortar by shear adhesion, using metal tabs directly bonded to the mortar
4 surface. If compared to the test setup proposed by RILEM TC 232-TDT (“clamping grip” is the
5 term used for load application through compressive stress normal to the specimen's plane), the
6 system proposed by AC434 (“clevis grip”) does not provide for the application of compressive
7 forces at the specimen’s ends, leaving the fabric free to slip within the mortar. This system is
8 connected to the testing frame with a clevis joint (Fig. 4). Tests were conducted under displacement
9 control at 0.5 mm/min by using a tensile machine with a load bearing capacity of 50 kN. The
10 global displacement was recorded by the LVDT integrated in the testing machine, while the local
11 axial deformation was measured using a clip-on extensometer with a 100 mm gauge length directly
12 applied at the ends of the metal tabs (Fig. 4).
13



14
15 *Fig. 4 – FRCM tensile test setup: strains measured with macro extensometer*
16

17 3.3 Digital Image Correlation

18 Digital Image Correlation (DIC) was also used as additional measurement system. DIC offers
19 the possibility to monitor strains and displacements on the whole surface of the specimen and
20 allows to select the area of the sample in which the strain field is required (in this case the area in
21 between the metal tabs).

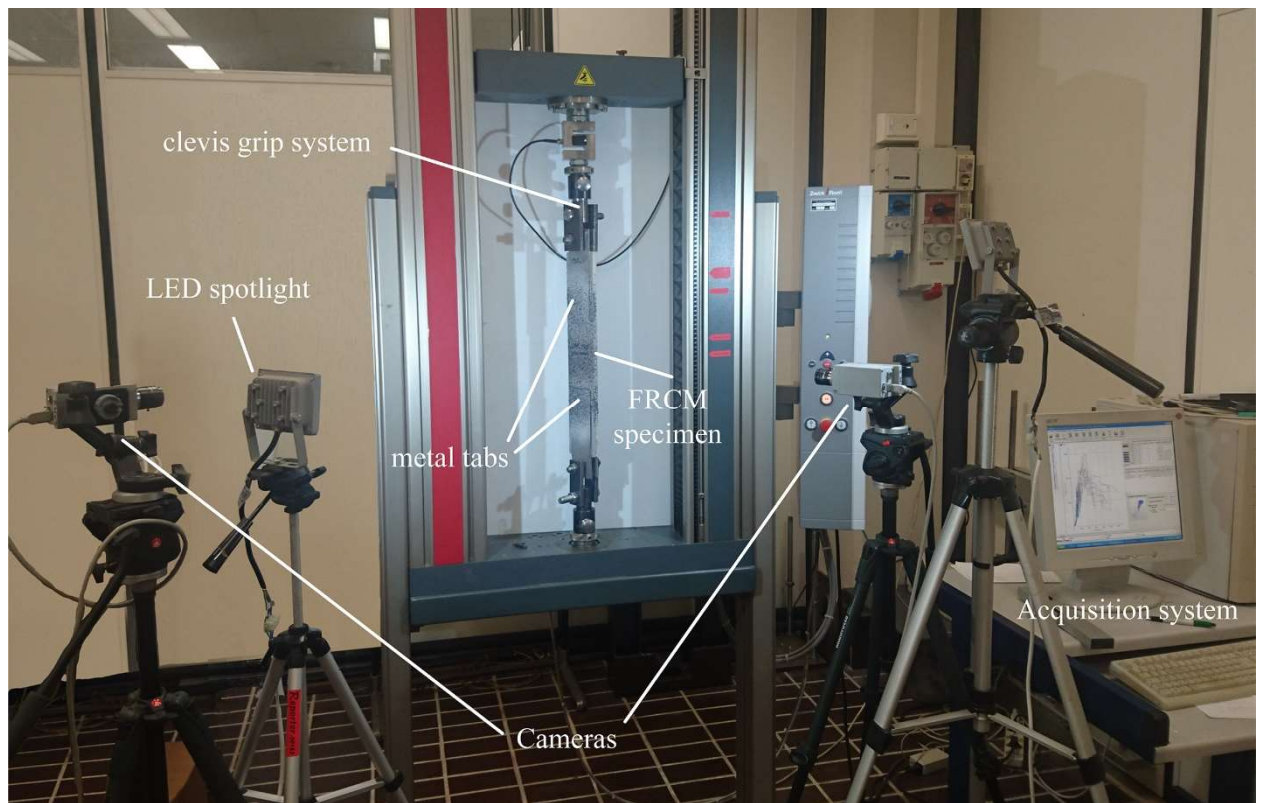
22 The main characteristics of experimental and DIC set-up are given in Table 2 and shown in Fig.
23 5.

1
2

Table 2 – Optical set-up and DIC characteristics

Sensor	[Type]	CMOS
Sensor pixel size	[μm]	6.8×6.8
Sensor resolution	[pixel]	1280×1024
Frame rate	[fps]	27
Lens	[Type, mm]	C mount, 16
Working distance	[mm]	≈ 800
Sensor noise	[gray level, dB]	0.94, -19
Subset size	[pixel, mm]	24, 3
Displ. accuracy (st. dev)	[pixel, mm]	$\pm[0.01, 0.05]$
Strain accuracy (st. dev)	[mm/mm]	± 0.00022

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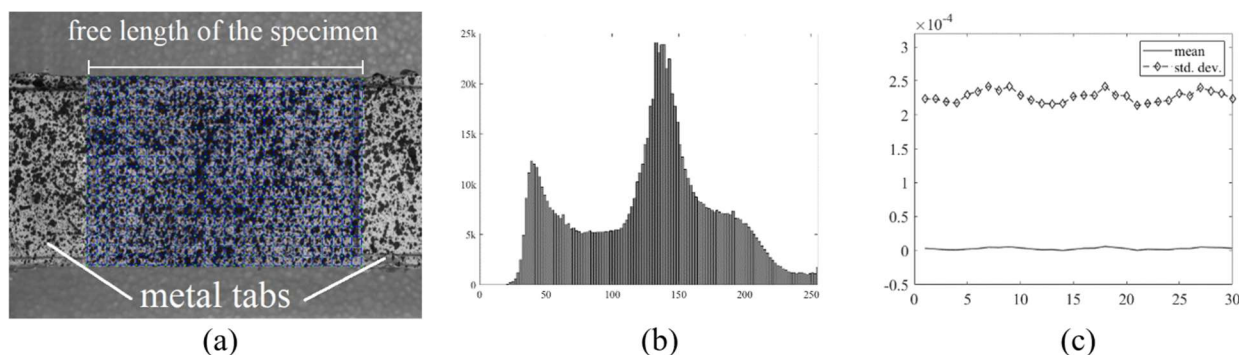
Fig. 5 – FRCM tensile test setup with Digital Image Correlation (DIC) acquisition system

6

7

8 During the tests, pictures of the frontal surface of the specimens have been acquired by a digital
9 camera (model Pixelink® B371F - camera on the left in Fig. 5) at 2 frame per second, collecting
10 about 600 images. The camera was equipped with a lens having a focal length of 16 mm and placed
11 about 800 mm away from the specimen, in order to reduce the perspective errors due to eventual
12 out-of-plane motions. The specimen was illuminated using an LED spotlight. A second camera,
13 placed on the right side (camera on the right in Fig. 5), was used to monitor possible motions out
14 of the plane.

1 A speckle pattern, consisting of black dots randomly distributed over the specimen surface, was
 2 firstly realized by means of spray painting. The size of the spots was chosen in relation to the size
 3 of the specimens and the position of the cameras. The pictures acquired during the tests have been
 4 post-processed by an in-house developed DIC software. The correlation method here adopted is
 5 based on global DIC, which incorporates the assembling approach of Finite Element method. A
 6 grid of points was drawn on the free surface of the specimen, in order to measure displacements
 7 and deformations over the free length of the specimen. Displacements of all nodes of the grid
 8 are obtained by minimizing the correlation error computed all over the current frame with respect to
 9 the reference frame [57]. The zero-mean sum of square difference (ZSSD) criterion was adopted
 10 to avoid the effects of lighting offset and inhomogeneity. A typical picture recorded by the camera
 11 and the grid drawn on the specimen, together with its histogram and strain noise evaluation are
 12 shown in Fig. 6.



14
 15 *Fig. 6 – Grid (a), histogram (b), and strain noise evaluation for the DIC image (c)*

16
 17 The picture on the left (Fig. 6a) show the subsets discretization used for the image analysis: the
 18 subset size was typically 24×24 pixels that means a measure point about each 3 mm.
 19 The strain used in the subsequent elaboration has been computed by means of the Cauchy-Green
 20 theory, within the framework of large displacements and large deformations, starting from the
 21 node displacements. The components of the Hencky strain tensor ϵ_x , ϵ_y , and ϵ_{xy} have been
 22 computed.

23 To assess the quality of the correlation technique and strain measurement, a set of 30 stationary
 24 images was acquired and analyzed before the test of the specimen; the average values of the strain
 25 distribution and its standard deviation within each frame are shown on Fig. 6b,c. No bias is
 26 observed since the average strains present small random oscillations around zero. The standard
 27 deviations are nearly constant, in the order of $220 \mu\epsilon$.

28 Strains reported in Table 3 ($\epsilon_{u,DIC}$), and those of the experimental curves of Fig.7, were calculated
 29 by means of DIC. Global strain was calculated by measuring the mean strain over the free length
 30 of the specimen (Fig. 7a). By doing so, results obtained with the use of macro-extensometer
 31 (applied at the ends of the metal tabs) can be compared. A sequence of axial displacement and
 32 strain maps measured at different instants is reported in next section (Fig.8).

33 34 **4. Experimental results**

35 36 *4.1 Tensile tests on glass FRCM systems*

1 The results of tensile tests on glass FRCM systems in terms of stiffness modulus (E_u), ultimate
 2 stress (σ_u) and ultimate strain (ϵ_u), together with the failure mode observed and the corresponding
 3 coefficient of variation (CoV), are reported in Table 3.

4 Ultimate strain has been determined in different ways: by dividing the total displacement measured
 5 at the load cell for the total length of the specimen ($\epsilon_{u,TOT}$), by means of an extensometer with
 6 gauge length of 100 mm directly applied at the ends of the metal plates ($\epsilon_{u,Ext}$) and with the use of
 7 digital image correlation (DIC) technology ($\epsilon_{u,DIC}$). In the case of specimens G-250_Lap150 and
 8 G-250_Lap200 the extensometer could not be used due to the distance between the metal plates
 9 exceeding 100 mm.

10 For the determination of the ultimate stress, the measured force (F) was divided by the cross-
 11 section of the textile reinforcement (A_f) in the load direction. The modulus of the cracked specimen
 12 (E_u) was calculated as the slope of the segment of the response curve between two points equal to
 13 $0.90 \sigma_u$ and $0.60 \sigma_u$ as indicated in the AC434.13.

15 Table 3 – Results of Tensile Tests [according to AC434, Annex A]

Specimen		F_{max} [kN]	σ_u [MPa]	$\epsilon_{u,TOT}$	$\epsilon_{u,Ext}$	$\epsilon_{u,DIC}$	E_u [GPa]	Failure mode
G250	Average	3.53	1275	0.0139	0.049	0.047	28.92	F
	CoV	0.059	0.059	0.125	0.218	0.112	0.129	
G250_Lap100	Average	2.16	780	0.0150	0.044	0.041	9.52	S
	CoV	0.036	0.036	0.124	0.232	0.278	0.243	
G250_Lap150	Average	3.52	1270	0.0117	-	0.027	41.27	F
	CoV	0.057	0.057	0.071	-	0.156	0.077	
G250_Lap200	Average	3.43	1239	0.0118	-	0.021	44.05	F
	CoV	0.091	0.091	0.128	-	0.158	0.182	

16 S) Slippage of the fabric within the matrix

17 F) Fabric breakage

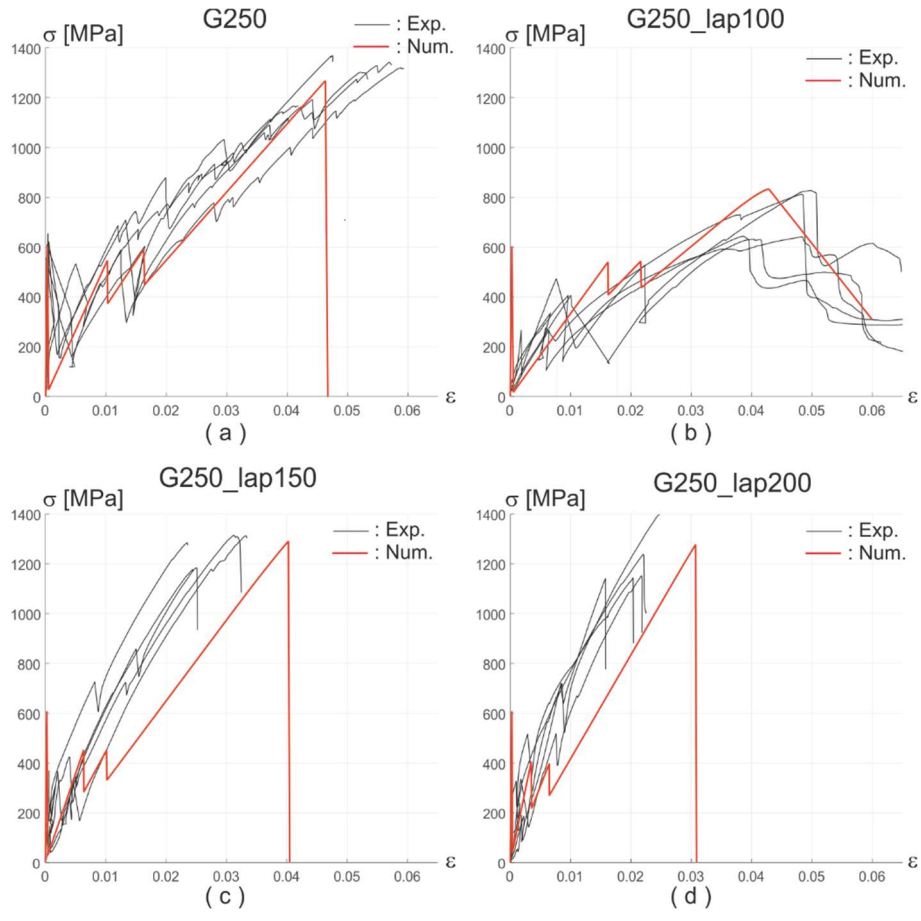
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 19 Experimental stress-strain curves are reported in Fig.7, together with curves obtained from
 20 numerical simulations, which will be discussed in Section 6.

21 The first segment of the curve represents the uncracked state, where the composite properties
 22 depend on the matrix characteristics. The load drop after the formation of the first crack is mainly
 23 due to the modest fabric volume. After this phase, once the transfer of stress from the matrix to
 24 the fabric has occurred, the load starts to increase again, with an evident post-cracking hardening
 25 phase. This phase is mainly governed by the fabric properties and bond properties at the interface
 26 between fabric and mortar. The presence of ‘jumps’ on the second part of the stress-strain curve is
 27 due to the formation of further small cracks within the mortar, which however do not significantly
 28 affect the FRCM hardening behavior.

29 Results show that a fabrics’ overlap length of 100 mm (G250_Lap100) is not enough to guarantee
 30 the complete transfer of tensile stresses from one fabric to another. Fabrics slip on each other and
 31 the maximum load reached is almost half of that obtained with a single fabric layer (G250).

1 Increasing the overlap length up to 150 mm allows to restore the specimen integrity and to reach
 2 an ultimate stress equal to that of the specimen with continuous fabric.
 3 Longitudinal strains measured by extensometer ($\epsilon_{u,Ext}$) and DIC ($\epsilon_{u,DIC}$) of specimens G250 and
 4 G250_Lap100 are in good agreement, and thus demonstrate that the two measurement methods
 5 are reliable and both can be used.
 6 Specimens with fabrics' overlap equal or greater than 150 mm showed higher stiffness with respect
 7 to specimens with continuous fabric (G250). The stiffness modulus of the cracked phase (E_u) for
 8 specimens G250_lap150 and G250_lap200 is about 45% greater than that of specimens G250. The
 9 higher stiffness is due to the presence of two layers of fabrics over the free length of the specimen.
 10 However, the failure of the specimens with fabrics' overlap always occurs for stress values equal
 11 or slightly lower to those of specimens with continuous fabric. This is due to the failure mode that
 12 always involves only one layer of fabric, at the end of the overlap and close to the metal tabs (see
 13 Fig. 8c,d).

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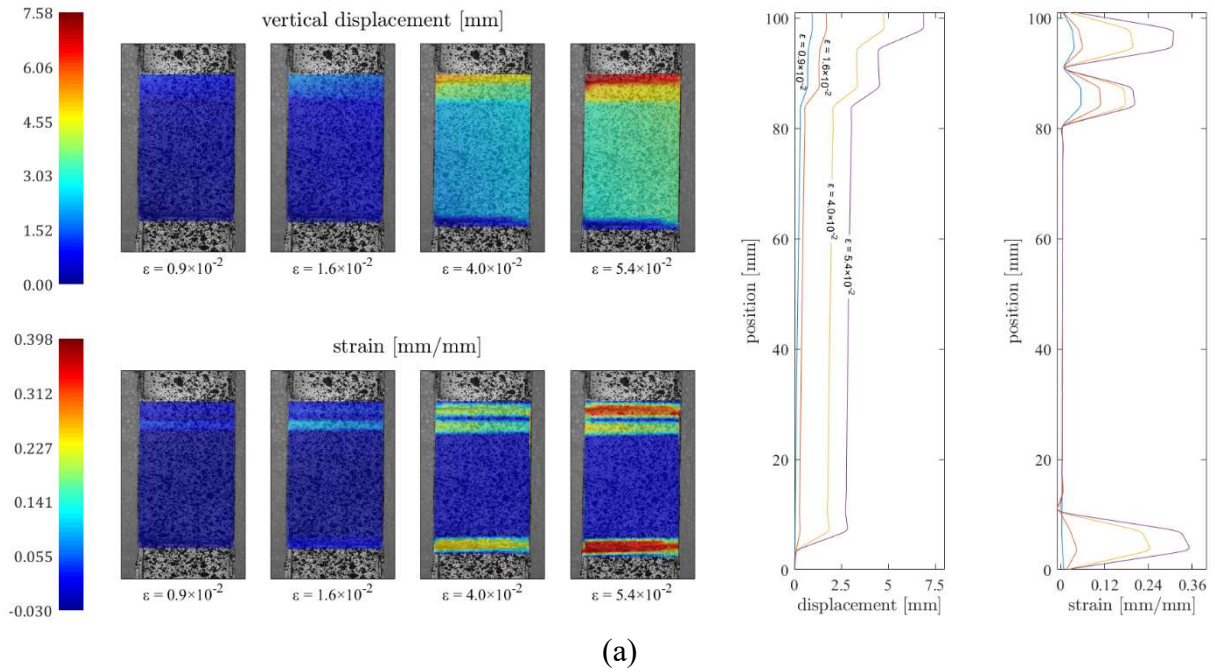


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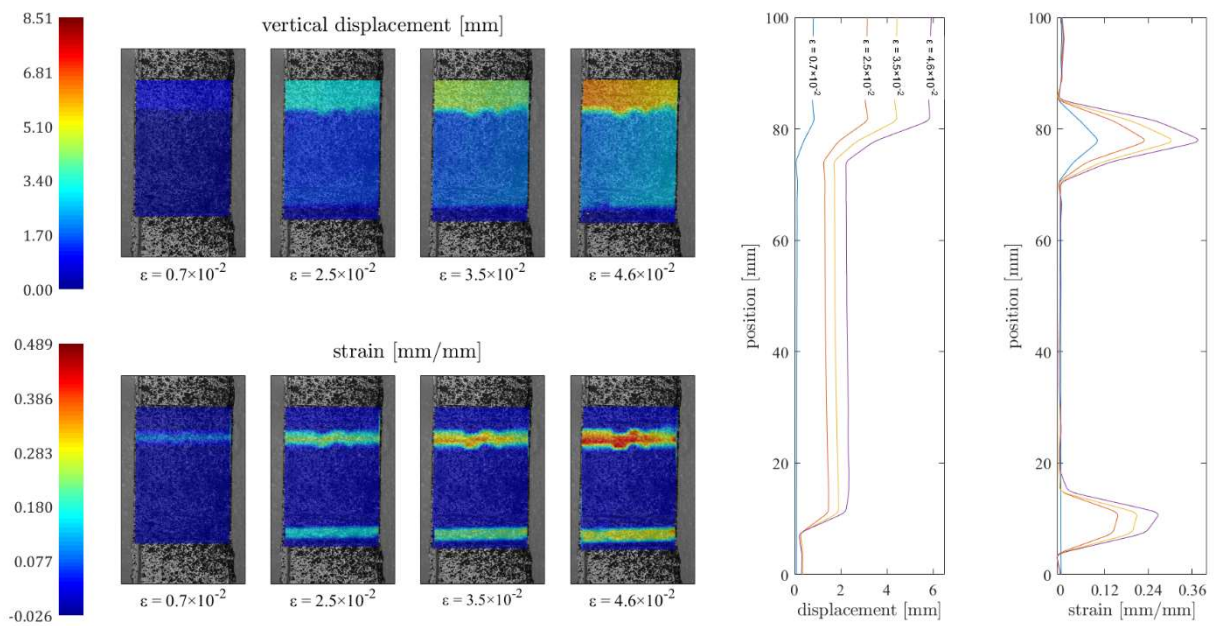
Fig. 7 – Experimental and numerical stress-strain curves of Glass-FRCM with a single fabric reinforcement layer (a), and two layers with a lap splice overlap of 100, 150 and 200 mm (b,c,d)

1 Displacement and strain fields over the free length of the FRCM and the evolution of cracks
 2 formation under increasing loads have been recorded by DIC and reported in Fig. 8. It can be
 3 clearly observed that maximum deformations are recorded in correspondence with the formation
 4 of two or three major cracks, which evolve as the load increases, while the portion of mortar
 5 between the cracks remains almost undeformed.
 6 Strain peaks are smaller for specimens with fabrics' overlap length of 150 and 200 mm, thus
 7 indicating the formation of smaller cracks within the mortar.

G250



G250_lap100



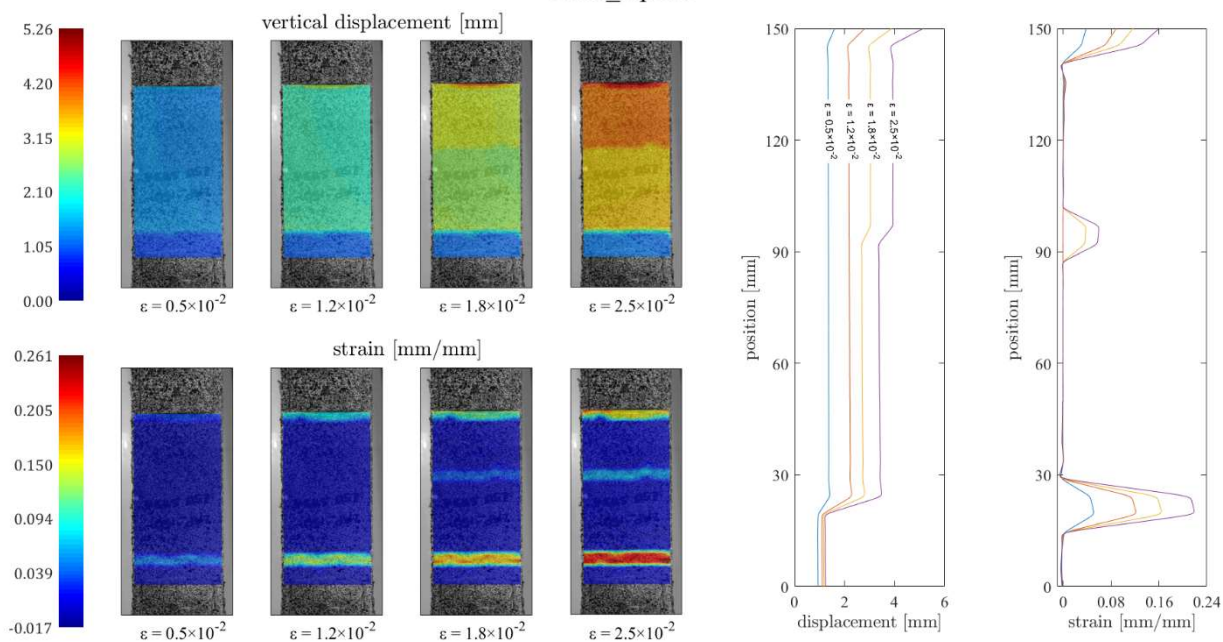
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(b)

G250_lap150



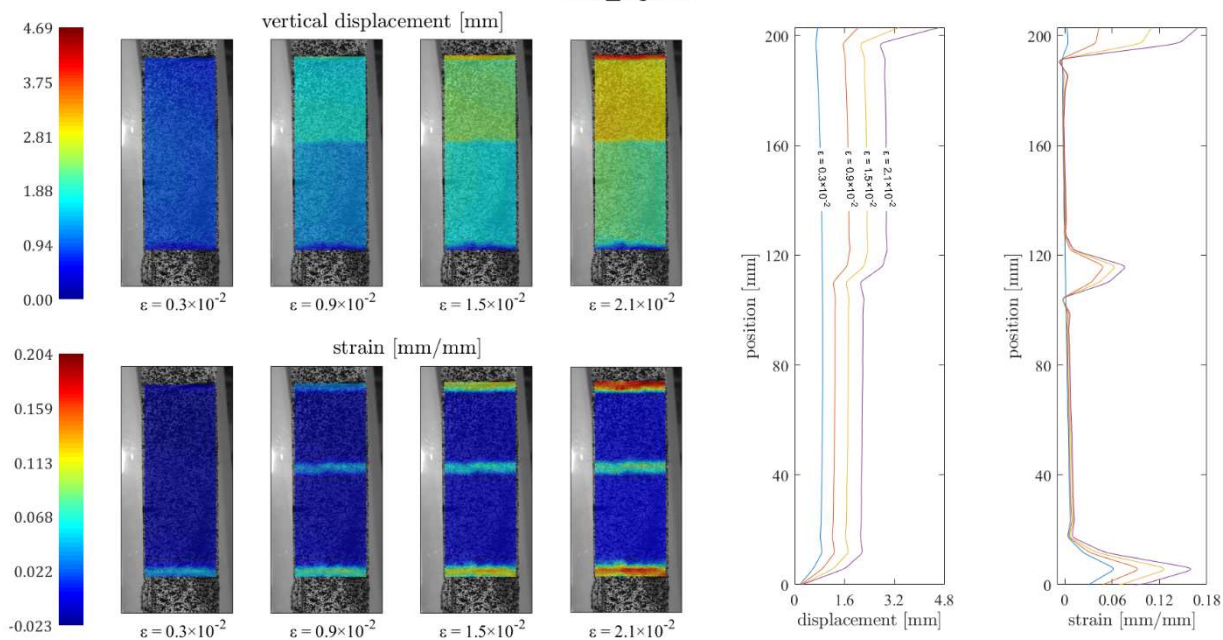
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(c)

G250_lap200



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(d)

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Fig. 8 – Evolution of the strain field during tensile tests on glass FRCM specimens, acquired with DIC, for different lengths of fabric overlapping.

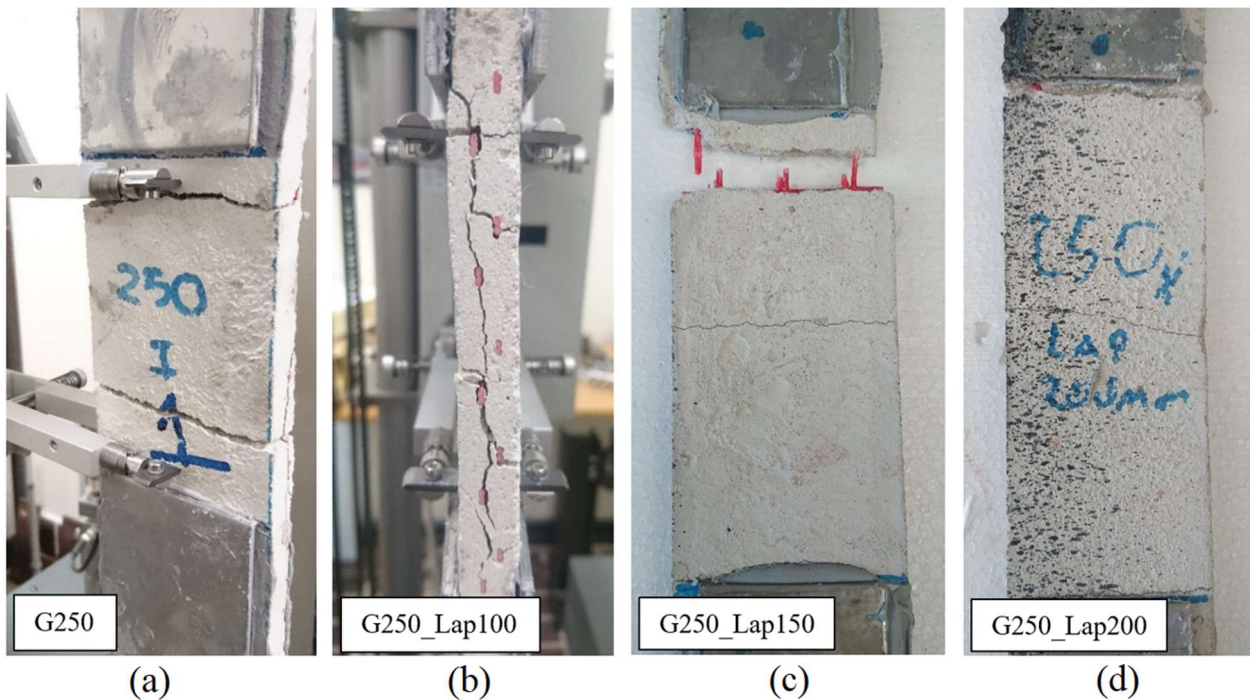
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4.2 Failure modes

Different failure modes have been observed depending on the configuration of the glass fabric reinforcement. FRCM specimens reinforced with a continuous layer of fabric failed after the formation of two or three cracks within the mortar matrix. Usually, after the formation of cracks, one or two of them propagate and their opening increases up to reach the specimen failure. Even after the formation of cracks, the load carried by the specimen increases, until reaching the breakage of the yarns close to one of the cracks.

In the case of G250_Lap100, the formation of a longitudinal cracks is clearly observed at the interface between the fabrics' overlap (Fig. 9). This effect is caused by the slippage of the fabrics along the overlay interface, until the specimen is broken.

For longer overlap lengths (G250_lap150, G250_lap200), the formation of longitudinal cracks and the slippage between fabrics is prevented. The failure mode observed is similar to that of specimens with a single fabric layer. However, it can be observed that the cracks width of specimens with overlapped fabrics is smaller than that of specimens with single layer. The presence of a double layer of fabric limits the cracks opening by increasing the stiffness of the composite.



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Fig. 9 – Failure modes of FRCM specimens: (a,c,d) fabric breakage, (b) slippage at the fabric-to-matrix interface

5. Variational Model

5.1 Model assumptions and governing equations

1 FRCM specimens are modeled as series of layers of mortar and reinforcement fabrics, connected
2 to each other by elastic interfaces, as illustrated in the geometrical scheme of Fig. 10(a). The
3 kinematical descriptors of each layer are the longitudinal displacement $u_i = u_i(x)$ and the damage
4 parameter $\alpha_i = \alpha_i(x)$, with x the longitudinal coordinate, and the index i referring to the i -th layer.
5 Damage α_i assumes values in the interval $[0,1]$: $\alpha_i = 0$ means that the material is sound, and $\alpha_i = 1$
6 means that it is completely broken. In the following, a prime will be used for derivative with
7 respect to x , and a dot for derivation with respect to the evolution parameter t , called *time* for
8 simplicity and introduced in the following.

9 To avoid damage healing, the irreversibility condition

$$10 \quad \dot{\alpha}_i \geq 0 \quad (1)$$

11 is assumed.

12 For each layer of length $l + 2\hat{l}$, with l the free length and \hat{l} the anchor length, the internal energy
13 is

$$14 \quad \mathfrak{E}_i(u_i, \alpha_i) = \int_0^{l+2\hat{l}} \left\{ \frac{1}{2} (1 - \alpha_i)^2 A_i E_i u_i'^2 + \frac{A_i}{E_i} \sigma_{e,i}^2 \left(\alpha_i + \frac{l_i^2}{16} \alpha_i'^2 \right) \right\} dx. \quad (2)$$

15 As usually assumed in phase-field approaches [38], the energy is sum of two terms: an elastic
16 energy (first term of the integral), which is a quadratic function of the strain u_i' , and a fracture
17 energy (second term of the integral), which has a local contribution, linear with respect to α_i , and
18 a non-local contribution, depending on the gradient of α_i . Geometrical and material parameters to
19 be assigned within the energy (2) are the cross-section area A_i , the Young's modulus E_i , the
20 maximum tensile stress $\sigma_{e,i}$ that material can sustain before breaking, and the size l_i of the process
21 zone where damage localizes and coalesces into fracture.

22 Interfaces between adjacent layers are linearly elastic. The energy between the j -th and the $(j+1)$ -
23 th layer is

$$24 \quad \mathfrak{E}_{j,j+1}(u_j, u_{j+1}) = h \int_0^{l+2\hat{l}} \frac{1}{2} k_{j,j+1} (u_j - u_{j+1})^2 dx, \quad (3)$$

25 where $k_{j,j+1}$ is the elastic coefficient, and h is the width of the interface. The total internal energy
26 of the system is

$$27 \quad \mathfrak{E} = \sum_{i=1}^N \mathfrak{E}_i(u_i, \alpha_i) + \sum_{j=1}^{N-1} \mathfrak{E}_{j,j+1}(u_j, u_{j+1}), \quad (4)$$

28 where $N=3$ and $N=4$ in the cases of single ply and lap-spliced plies samples, respectively. The
29 constitutive parameters E_i , $\sigma_{e,i}$ and l_i in (2), and $k_{j,j+1}$ in (3) are assumed constant at least in each
30 part of the samples (central part or ending reinforced parts), according to the schemes drawn in
31 Fig. 10(a,b) for the one ply specimen and the lap splice overlap specimen, respectively. Different
32 colors are used in Fig. 10(a,b) to distinguish the different materials and interfaces. Parameters of
33 the mortar layers are the Young's modulus E_m , the peak elastic stress $\sigma_{e,m}$ and the internal length
34 l_m . The ending parts of the mortar layers are assumed to be unbreakable. The constitutive
35 parameters of the fabric layers are E_f , $\sigma_{e,f}$ and l_f .

36 Three different interfaces are considered. The fabric-to-mortar interface is linearly elastic with
37 elastic modulus k_{fm} . Indeed, according to [54], the shear stress leading to fabric slippage is larger
38 than 1 MPa, value never attained in simulations. A bilinear shear stress-displacement law is

1 assumed for the fabric-to-fabric interface, as drawn in Fig. 11, where the softening branch account
 2 for debonding and slippage. Mortar-to-mortar interface, which is present in the geometrical
 3 scheme of the lap-spliced sample of Fig. 10(c), is supposed to be rigid to guarantee continuity
 4 among adjacent layers. Criteria to calibrate all the above-mentioned parameters and values used
 5 in simulations are given in the next Subsect. 5.2.

6 Longitudinal stresses σ_i in the layers and shear stresses $\tau_{j,j+1}$ at interfaces are obtained by
 7 differentiating (2) with respect to the strain u_i' , and (3) with respect to the relative displacement
 8 $(u_j - u_{j+1})$ respectively,

$$9 \quad \sigma_i = (1 - \alpha_i)^2 E_i u_i'^2, \quad \tau_{j,j+1} = k_{j,j+1} (u_j - u_{j+1}). \quad (5)$$

10 In experiments, tensile displacement is imposed at the upper extremity of the specimen, where a
 11 clevis joint connects the sample to the testing frame. To reproduce this situation, the bottom ends
 12 of the mortar layers are fixed, and the displacement

$$13 \quad u = t(l + 2\hat{l}), \quad (6)$$

14 is imposed at the upper ends (see Fig. 10(b,c)). The assigned deformation t is positive and
 15 increasing. It represents the evolution parameter, called *time* for brevity. Since the clevis-grip
 16 method allows for the slippage of the fabric from the inorganic matrix, boundaries of the fabric
 17 layers are left free to move.

18 Since external loads are not considered, and body loads (as weight loads) are neglected, the internal
 19 energy (4) coincides with the total energy of the system. By following a standard variational
 20 procedure, balance equations are obtained by requiring the first variation of energy (4) to be non-
 21 negative for any admissible perturbation, and they read

$$22 \quad \frac{A_i}{h} \sigma_i' - \tau_{i,i+1} + \tau_{i-1,i} = 0, \quad (7)$$

$$(1 - \alpha_i) A_i E_i u_i'^2 - \frac{h_i}{E_i} \sigma_{e,i}^2 \left(1 - \frac{l_i^2}{16} \alpha_i'' \right) \leq 0, \quad i = 1, \dots, N.$$

23 The first equation is the i -th macroscopic balance equation, which is coupled with the $(i-1)$ -th and
 24 $(i+1)$ -th equations through the shear stresses $\tau_{i-1,i}$ and $\tau_{i,i+1}$. The second equation is the yielding
 25 condition for damage α_i , which has the form of an inequality because of the constrain (1). Using
 26 (4)₁, it rewrites

$$27 \quad \sigma_i \leq \sigma_{e,i} \sqrt{(1 - \alpha_i)^3 \left(1 - \frac{l_i^2}{16} \alpha_i'' \right)} = \sigma_{y,i}(\alpha_i), \quad (8)$$

28 which states that the stress σ_i in the i -th layer can never exceed the yield stress $\sigma_{y,i}$, and, when it is
 29 equal to the yield stress, damage can develop.

30 In an evolution process of increasing stretching, starting from an initial unstretched state, the
 31 system experiences elastic deformation, which develops as long as $\sigma_i < \sigma_{y,i}(0) = \sigma_{e,i}$. When σ_i
 32 reaches the limit value $\sigma_{e,i}$, damage forms and coalesces into a fracture. Accordingly, $\sigma_{e,i}$ is the
 33 maximum elastic stress that the i -th layer can sustain before failure.

34 The evolution problem is formulated as a constrained quadratic programming problem solved at
 35 each time increment. Hereinafter, the problem is briefly presented, and the reader is referred to
 36 [48-50] for an in-depth description. Time t is discretized into finite intervals of size τ , and, within
 37 each time step $t \rightarrow t + \tau$, variables are approximated by the linear expressions

$$u_i(x, t + \tau) = u_i(x, t) + \tau \dot{u}_i(x, t), \quad \alpha_i(x, t + \tau) = \alpha_i(x, t) + \tau \dot{\alpha}_i(x, t), \quad (9)$$

and the energy (4) is developed up to the second order, around the configuration at time t ,

$$\xi(t + \tau) = \xi(t) + \tau \dot{\xi}(t) + \frac{1}{2} \tau^2 \ddot{\xi}(t), \quad (10)$$

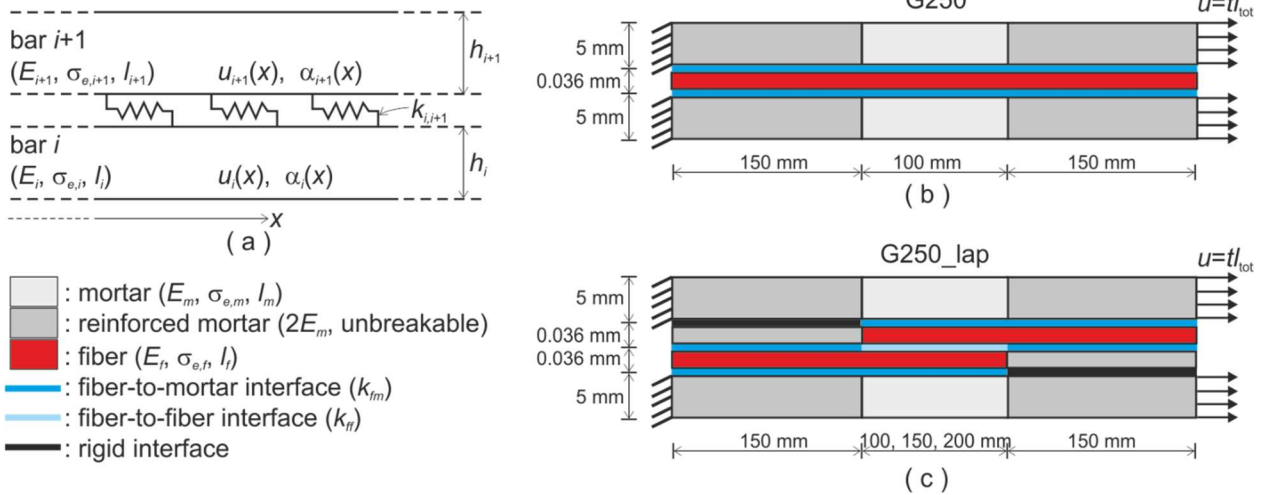
which can be rewritten as sum of a constant term and a quadratic functional of \dot{u}_i and $\dot{\alpha}_i$ in the following form

$$\xi(t + \tau) = \text{const} + \tau \mathcal{F}(\dot{u}_i, \dot{\alpha}_i), \quad i = 1, \dots, N. \quad (11)$$

If $u_i(x, t)$ and $\alpha_i(x, t)$, $i=1, \dots, N$, are known at the instant t , the solution (9) at the instant $t + \tau$ is determined by (9), where the rates \dot{u}_i and $\dot{\alpha}_i$ solve the constrained programming problem

$$(\dot{u}_i, \dot{\alpha}_i) = \arg \min \{ \mathcal{F}(\dot{u}_i, \dot{\alpha}_i), \quad \dot{\alpha}_i \geq 0, \quad i = 1, \dots, N, \quad + b.c. \} \quad (12)$$

This minimum problem is numerically solved by means of a finite element code which implements an alternate iterative minimization procedure, consisting in minimizing the energy functional with respect to the unknown fields separately.



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15 *Fig. 10 – Geometrical schemes: (a) generic multilayer beam, (b) sample with a single fabric*
16 *reinforcement layer, (c) sample with two overlapped layers.*

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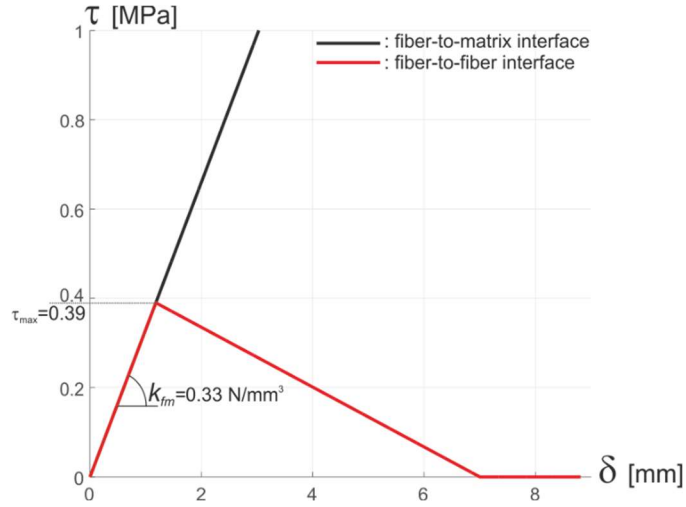


Fig. 11 Constitutive laws of fiber-to-matrix and fiber-to-fiber interfaces.

5.2 Parameters calibration and setting

Specimens geometrical schemes are drawn in Fig. 10. The anchor length is $\hat{l}=150$ mm. For the one ply specimen (G250), the free length is $l=100$ mm, and, for the lap-spliced samples, three different lengths $l=100, 150$ and 200 mm are considered. The thickness of mortar layers is 5 mm, and the thickness of fabric layer is 0.04 mm, which is obtained by distributing the cross-section area of the fabric ($A_f=2.77$ mm², corresponding to the cross-section areas of three yarns) through the layer width $h=70$ mm.

Concerning the constitutive parameters, Young's moduli of Glass 250 fabric and mortar are given in Table 1, and they are $E_f=57.1$ GPa, and $E_m=9.5$ GPa, respectively. Also the yarns peak stress $\sigma_{e,f}=1405$ MPa is reported in Table 1. The matrix ultimate tensile stress $\sigma_{e,m}=2.4$ MPa is the average stress that leads to the opening of the first crack in the matrix recorded during tensile tests on one-ply specimens. Values of internal lengths are $l_m=0.6$ mm, as acquired with DIC, and $l_f=0.1$ mm.

The elastic coefficient of yarn-to-matrix interface has been estimated in [54], where the value $k=3.10$ MPa has been found. Since the interface area per unit length of the fabric is 15 mm² (three longitudinal yarns are considered), and the multilayer geometrical scheme of the model accounts for an interface area per unit length equal to 140 mm², the equivalent elastic coefficient is $k_{fm} = (15 / 140)k = 0.33$ MPa.

A piecewise linear law has been chosen for the fiber-to-fiber interface, as shown in Fig. 11, the slope of the first increasing branch is k_{fm} . The value of the maximum shear stress is $\tau_{max}=0.39$ MPa, which allows to reproduce failure by slippage and failure by fabric breakage when the lap splice overlap is 100 and 150 mm, respectively, as found in experiments. The slope of the softening branch has been fixed by curve fitting.

6. Numerical results

Numerical stress-strain curves are compared to the experimental curves in Fig.7. Numerical curves accurately fit the experimental ones. Only in cases of G250_Lap150 and G250_Lap200, strains are slightly overestimated. Each stress drop of the numerical curves corresponds to the

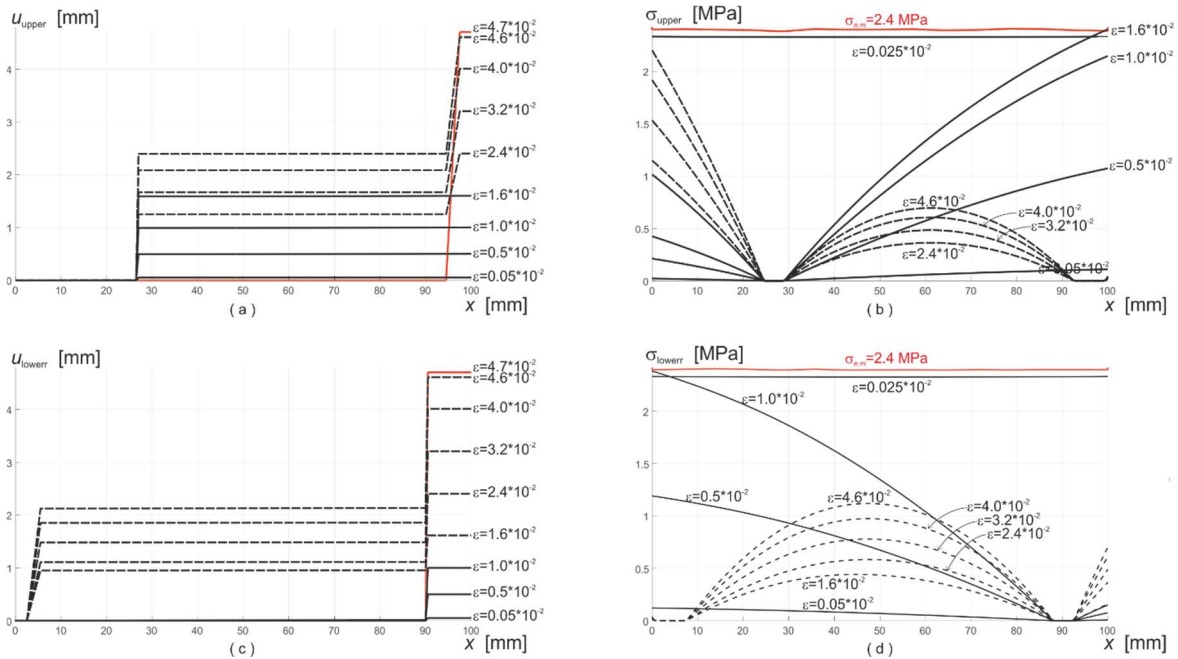
1 opening of a fracture. Failure by reinforcement breakage is observed in specimens G250,
2 G250_Lap150 and G250_Lap200. In these cases, fabric failure leads to brutal stress drop to
3 zero. Failure by interface slippage is registered in G250_Lap100, and the slippage process is
4 associated to the softening branch of Fig. 7(b).

5
6 The tensile test of G250 sample is simulated for first. Fig. 12 shows profiles of u and σ at
7 different strains ε in the central part of the upper and lower mortar layers. Initially, the
8 stretching process is linearly elastic, and stresses homogeneously grow in the layers. When the
9 stress on the mortar reaches the peak limit value $\sigma_{e,m}$, two cracks form simultaneously, one in
10 each mortar layer. In simulations, the value $\sigma_{e,m}=2.4$ MPa is perturbed with a random function
11 of amplitude equal to 2% of $\sigma_{e,m}$. Looking to Fig. 12(a,c), where cracks correspond to
12 displacement jumps, the first two cracks forms at $x=26$ mm in the upper layer and $x=90$ mm in
13 the lower one. Their openings correspond to the first jump of the response curve of Fig. 7(a).
14 From this point on, displacements and stresses evolve according to the solid line profiles of
15 Fig. 12. Notice that stresses nullify at crack, and they progressively increase away from it. At
16 $\varepsilon = 1 \cdot 10^{-2}$, σ reaches $\sigma_{e,m}$ at the left endpoint of the lower layer, and, consequently, a crack
17 opens there. It corresponds to the second drop of the stress-strain curve. In the upper layer, the
18 second fracture forms later, at $\varepsilon = 1.6 \cdot 10^{-2}$, when the peak stress is reached at the right
19 endpoint (third drop of the stress-strain curve). Dashed profiles in Fig. 12 refer to the evolution
20 with two cracks in each mortar layer. Profiles of σ in the reinforcement layer are plotted in
21 Fig. 13 for different values of the imposed strain ε . In those points where mortar layers are
22 cracked, stresses attain the maximum values, because of stresses transfer from the matrix to
23 the reinforcement. At $\varepsilon = 4.6 \cdot 10^{-2}$, the yield stress $\sigma_{e,f}=1405$ MPa is attained on the right side
24 of the reinforcement layer, close to the right endpoint, where both the upper and lower mortar
25 layers are fractured. At this point the fabric layer breaks and a passing crack leads the sample
26 to failure. Damage fields α_i in each layer at the final failure stage are plotted in Fig. 14, using
27 different colors. Numbers indicate the sequence of cracks opening in the evolution process. A
28 sketch of the broken sample is also drawn in Fig. 14.

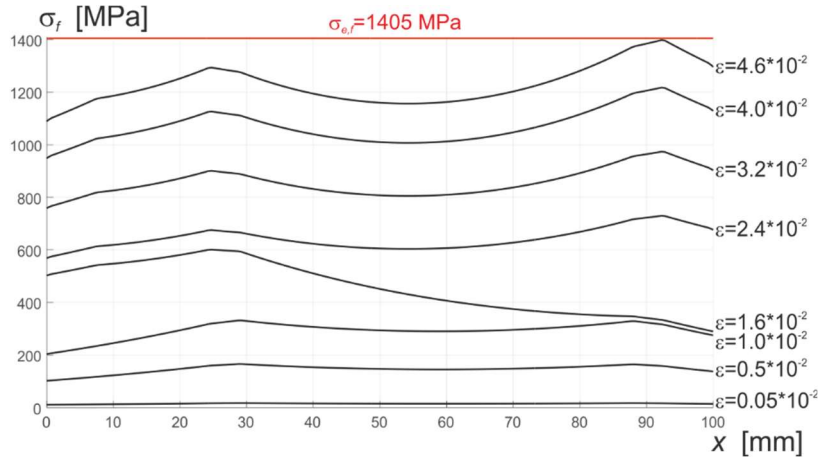
29 Finally, notice the large similarity between the profiles of u of Fig. 8(a) and the displacement
30 evolution in the lower layer found by simulations, plotted in Fig. 12c. In both the cases, a first
31 crack opens in a point close to the right endpoint, and, later, a second crack forms at the left
32 endpoint. This sequence of two cracks formation in the mortar layer, the first in an arbitrary
33 point, often close to one endpoint, and the second at the most distant endpoint from the first
34 crack, has been observed in experiments and found in simulations.

35 Results of tensile tests on lap-spliced specimens are described in Figs. 15 and 16. First, the
36 overlap length $l=100$ mm is considered. Fig. 15 shows the displacement profiles in the four
37 layers of the specimen at instants which correspond to the opening of cracks and to the final
38 interfacial slippage. Initially, two cracks open simultaneously in the mortar layers in
39 correspondence of the fabrics' extremities, where strength is reduced by the pre-cracks
40 introduced to separate fabrics from mortar (Fig. 15a). The opening of these fractures
41 corresponds to the first deep drop of the stress-strain curve of Fig. 7b. The next two fractures
42 open in the mortar layers at sides opposite to those of the first two cracks. They form at
43 different instants, first in the upper layer (Fig. 15b) and then in the lower one (Fig. 15c),
44 corresponding to the second and third drops of the response curve. At this point, stresses are
45 basically transferred from one side of the sample to the other by the two overlapped

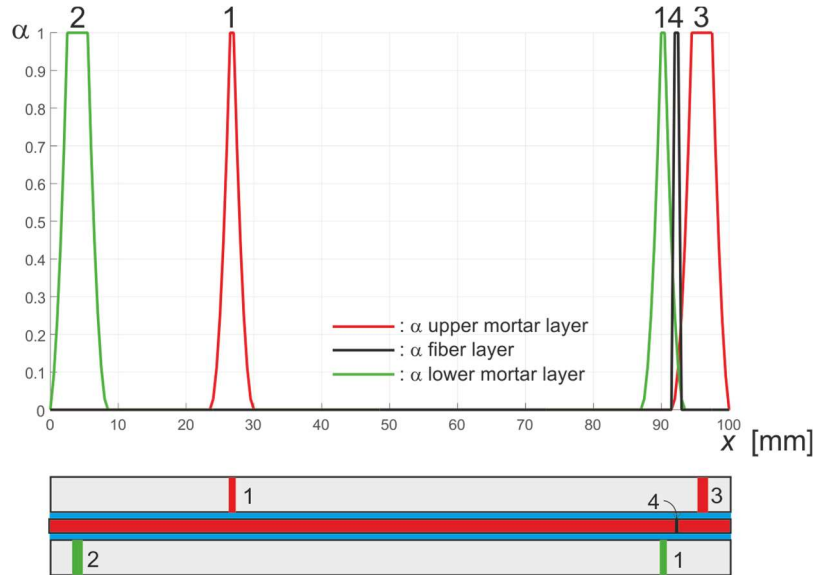
1 reinforcements and thus large amount of shear stresses develop at the interface between them.
 2 When the shear stress reaches the maximum value τ_{max} (see Fig. 11), then slippage initiates
 3 and evolves. This phase corresponds to the softening branch of the response curve. The
 4 slipping displacement δ at the end of the slippage stage is reported in Fig. 15d.
 5 Notice that cracks open at the extremities of the specimens also in experiments. An example
 6 is shown in Fig. 8(b), where displacement profiles given by DIC are plotted at different strains.
 7 In this case, the first fracture forms on the right side, and the second one opens close to the left
 8 boundary.
 9 In case of larger overlap lengths ($l=150, 200$ mm), shear stresses distribute on larger interface
 10 surfaces and thus smaller values of τ are attained. As a result, slippage does not activate, and
 11 failure occurs by fabric breaking. Fig. 16a shows the displacement profiles of the four layers
 12 of the system right before failure, when the overlapping length $l=150$ mm is chosen. Even now,
 13 four cracks forms in the mortar at the boundaries of the specimen free area, two in each side
 14 (Fig. 16c). Stresses in the two fabrics before failure are plotted in Fig. 16b. They decrease
 15 going toward the ending sections. In the right side of the upper fabric, the fracture stress
 16 $\sigma_{e,f}=1405$ MPa is approached, and, as a result, a crack forms therein, leading the specimen to
 17 failure (Fig. 16d). In this case, the limit shear stress τ_{max} is never reached at the interface
 18 between fabrics, and, accordingly, slippage does not activate.



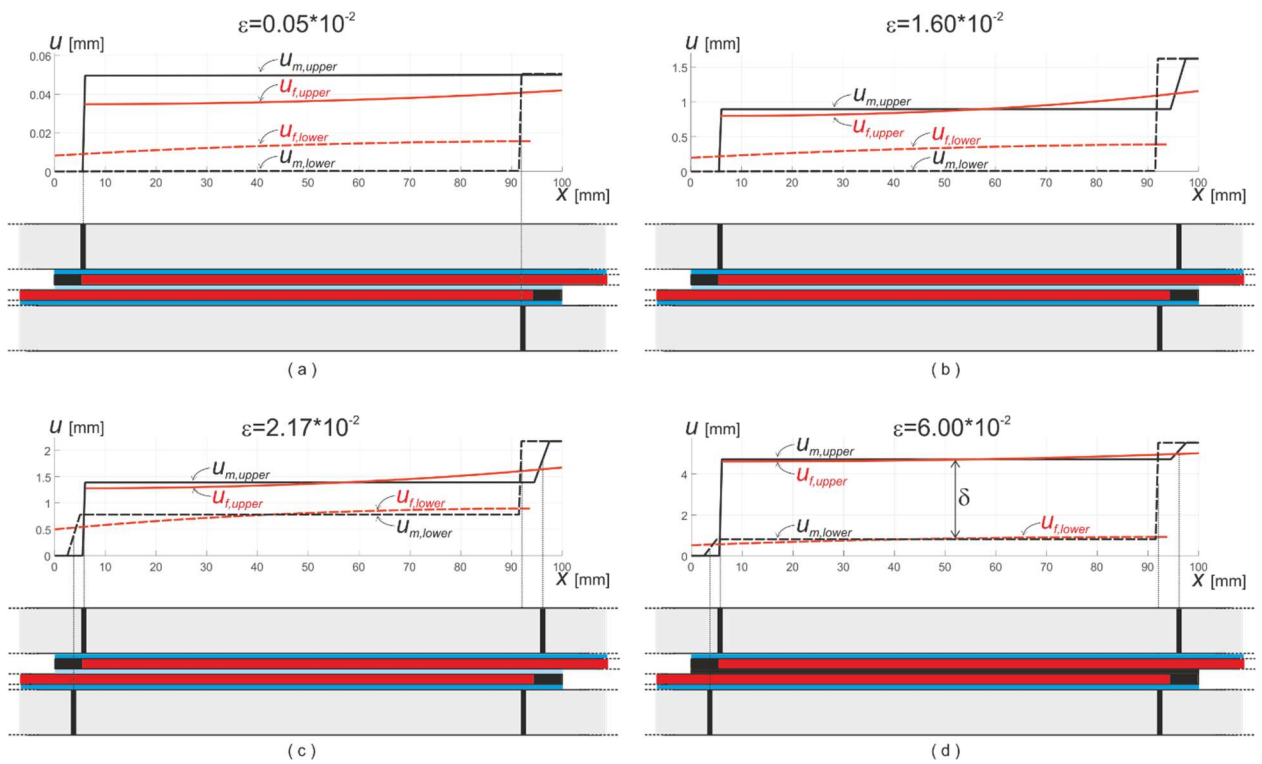
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 21 *Fig. 12 – Specimen with a single fabric reinforcement layer. Profiles of u at different strains*
 22 *ϵ in the upper (a) and lower (c) mortar layers; profiles of stress σ in the upper (b) and lower*
 23 *(d) mortar layers.*



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Fig. 13 – Specimen with a single fabric reinforcement layer. Profiles of stress σ at different strains ϵ in the fiber reinforcement layer.

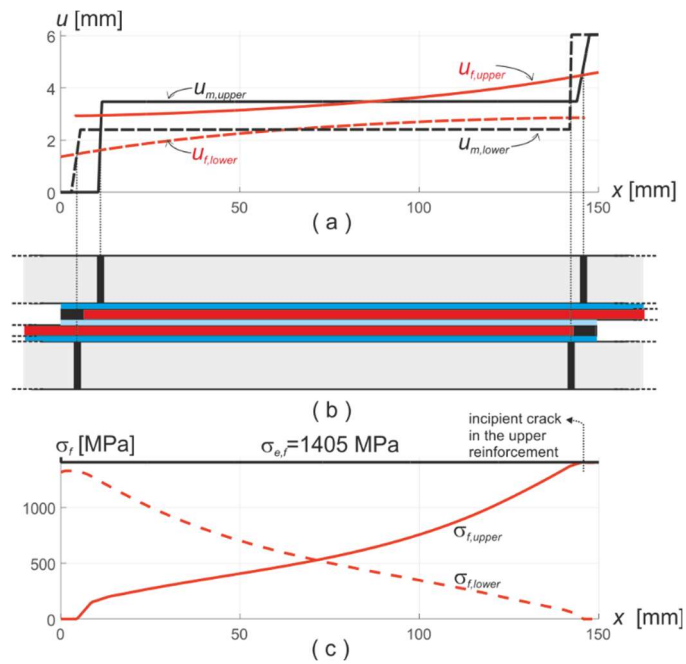


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Fig. 14 – Specimen with a single fabric reinforcement layer. Damage fields in the different layers at failure. Numbers refer to the sequence of crack opening.



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Fig. 15 – Specimen with overlapped fabric layers with lap splice overlap of 100 mm. Profiles of u in the four layers at different strains ε , and sketches of fracture positions in the multilayer system.



6

1 *Fig. 16 – Specimen with overlapped fabric layers with lap splice overlap of 150 mm. Profiles*
2 *of u in the four layers (a), cracks positions in the specimen (b), and profiles of σ in the*
3 *reinforcement layers (b) at $\varepsilon=0.04$, before failure.*
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6 **7. Conclusions**

7
8 Tensile characterization of FRCM specimens with continuous and overlapped glass fabrics has
9 been carried out by using a clevis type gripping method. Deformations and failure modes of FRCM
10 specimens have been deeply investigated by means of DIC and compared with numerical
11 simulations.
12

- 13 • Different failure modes have been observed in tensile tests, depending on the overlap
14 length. Specimens reinforced with a single layer of glass fabric failed due to fabric rupture
15 within the free length of the specimen, after the formation of two or three cracks. FRCM
16 specimens with fabrics' overlap length of 100 mm failed due to slippage at the overlay
17 interface. Increasing the overlap length to 150 and 200 mm led to the breakage of one of
18 the glass fabric layers.
- 19 • The minimum glass fabrics' overlap length, which allows to restore the specimen's
20 integrity and the complete transfer of tensile stresses from one fabric to another, is about
21 150 mm. With this overlap length, the maximum stress attained at failure is almost the
22 same of that of specimens with continuous fabric, while the stiffness is greatly increased.
23 In case of smaller overlap lengths, the maximum tensile stress to which the fabric is
24 subjected is much lower and the failure occurs at the interface between the two layers of
25 fabrics.
- 26 • DIC was able to provide important information about the mechanical behaviour of FRCM
27 specimens during tensile tests. It allowed to detect the number and width of the cracks at
28 any load value and the strain field on the whole surface of the specimen.
- 29 • A variational model has been developed to provide a thorough understanding of failure
30 mechanisms of the different FRCM systems, subjected to tensile loads. Specimens have
31 been schematized as a sequence of one-dimensional brittle bars, coupled by non-linear
32 elastic connections. Different stiffnesses and strengths were given to the central and side
33 parts of the mortar bars to take into account the clevis type anchoring system, and different
34 constitutive laws were assigned to fiber-to-matrix and fiber-to-fiber interfaces to simulate
35 the FRCM behaviour with continuous and overlapped fabrics. The evolution problem,
36 formulated as an incremental constrained minimum problem, has been implemented in a
37 finite element code.
- 38 • The model, despite its simplicity, has accurately captured all the evolution stages leading
39 to specimens' failure modes that have been observed in experiments. The evolution of
40 crack patterning in the mortar layers has been carefully described, and the two different
41 mechanisms of failure, breakage of the reinforcement and slippage at fiber-to-fiber
42 interface, have been reproduced. Finally, the stress-strain curves obtained from simulations
43 have been compared with the experimental ones providing a great predictive capability.
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Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study

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