# COMPORTAREA LA TRACȚIUNE A MATRICEI CIMENTOASE ARMATE CU FIBRE DIN STICLĂ PENTRU CONSOLIDAREA ZIDĂRIEI
# TENSILE BEHAVIOUR OF GLASS FIBRES REINFORCED CEMENTITIOUS MATRIX FOR MASONRY STRENGTHENING

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***Externally bonded composite systems constructed of textiles with high mechanical strength and embedded in a mortar matrix, known as Fabric Reinforced Cementitious Matrix (FRCM) have received significant attention since they are promising solutions for the strengthening of historical structures. The mechanical characterization of FRCM systems is of fundamental importance to define the appropriate parameters needed to design a strengthening intervention. Nevertheless, improved knowledge still needs to be gained on their tensile behaviour and incidence over structural performance. The purpose of this paper is to investigate the mechanical behaviour of Glass FRCM samples subjected to tensile tests. In this context, the effect of fabrics overlapped with system global behaviour is analyzed in this paper. The tensile tests were carried out on Glass FRCM coupons with different fabric overlap lengths, varying between 100 mm and 200 mm. The objective is to determine the minimum fabric overlap length required to maintain fabric continuity and to avoid the loss of tensile strength in FRCM samples.***

***Sistemele compozite realizate din materiale textile cu rezistență mecanică ridicată și încorporate într-o matrice de mortar (cunoscute și sub denumirea de matrice cementoase armate cu plasă de fibre - FRCM) se bucură de o atenție deosebită dat fiind faptul că utilizarea acestui material la consolidarea clădirilor de patrimoniu este promițătoare. Caracterizarea mecanică a sistemelor FRCM are o importanță deosebita în definirea corectă a parametrilor folosiți la proiectarea lucrărilor de consolidare. Cu toate acestea, este necesară evaluarea corectă a comportamentului la tracțiune a FRCM și influența acestuia asupra performanței structurale. Scopul acestei lucrări este de a analiza comportamentul mecanic al probelor FRCM supuse la tracțiune. În acest scop, lucrarea studiază efectul suprapunerii fibrelor în contextul general al sistemului. Încercările de tracțiune s-au efectuat pe cupoane din FRCM cu lungimi de suprapunere a fibrelor ce variază între 100 și 200 mm. Obiectivul este determinarea lungimii minime necesare de suprapunere a fibrelor astfel încât continuitatea fibrei să fie menținută și să fie păstrată rezistența la tracțiune în a probelor de FRCM.***

***Keywords:*** *Composite materials; FRCM; overlap; tensile test; strengthening.*

## 1. Introduction

Textile Reinforced Mortar (TRM) systems or Fabric Reinforced Cementitious Matrix (FRCM) composites, comprising high strength textiles embedded into inorganic matrices, have been recently developed and are currently utilized for the repair and rehabilitation of structures [1].

In the case of historical and preserved buildings, which require the fulfilment of specific preservation criteria, using an inorganic matrix instead of epoxy resin is of great interest due to higher compatibility with substrates, vapor permeability and durability to external agents. They also offer advantages regarding cost and time installation, essentially on irregular surfaces [2-4].

Several theoretical and experimental investigations have shown the high effectiveness of FRCM systems for confinement, shear and flexural strengthening of both reinforced concrete (RC) and masonry structural elements. Several studies on RC columns, beams, and slabs were carried out [5-12]. However, there are still no standardized procedures for the mechanical characterization of FRCM systems. The lack of universally accepted methods to characterize and design FRCM reinforcement systems does not enable the development of these systems on a larger scale. Currently, the ACI 549 [13], RILEM TC 250-CSM and 232-TDT Scientific Committees [14, 15] are the only guidelines that support the design of strengthening interventions with these systems. In addition, tensile tests are used, to characterize the mechanical behaviour of TRM coupons [16].

Even if the mechanical characterization of FRCM systems has been studied by several authors [17-24] with various techniques and different materials, there are still some aspects that need further investigation.

One aspect that deserves special attention is the fabrics overlap; during TRM installation, an overlap of the fibre fabrics is needed due to the limited width of the rolls as provided by manufacturers (about one meter).

This work provides an overview of the mechanical characterization of Glass FRCM composite systems; it also, analyses the effect of the variation of the fabrics overlap lengths between 100

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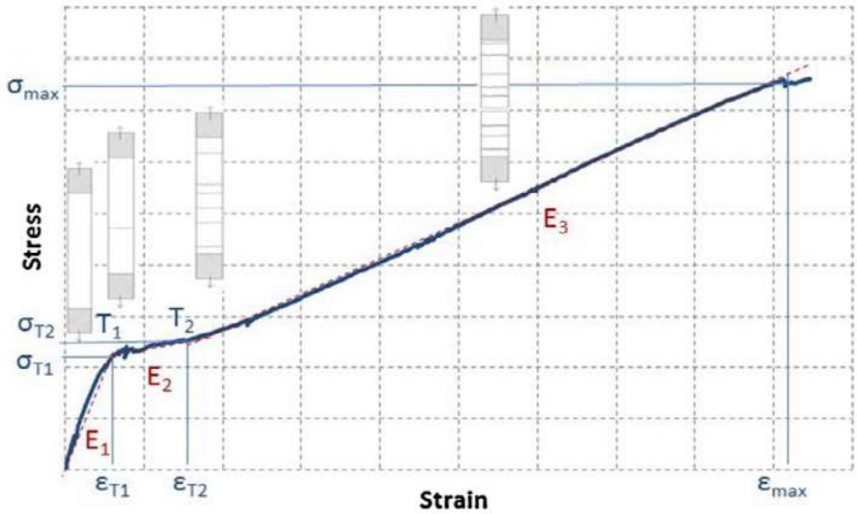


Fig. 1 - Typical three-stages Stress–strain behaviour of TRM composites subjected to tensile test */ Comportarea tipică în trei stadii a compozitelor TRM solicitate la întindere axială [25]*

and 200 mm on the mechanical behaviour of these composite solutions.

## 2. Mechanical behaviour of FRCM in tension

Fig.1 shows a typical stress-strain curve of FRCM under tensile loading. It consists of three main branches. The first one represents the un-cracked stage, where the slope of the stress-strain curve reflects the elastic behaviour of the matrix. Then, as the load increases, the stress is transferred from the mortar to the fabric, accompanied by the multi-cracking process of the matrix (the second branch). In this state, there is a significant stiffness decrease. The slope of this portion of the curve depends on the textile and matrix bond [25]. After this phase, once the transfer of stress from the matrix to the fabric occurred, the load further increases. The slope is close to the dry fibre elastic modulus, lasting up to the sample failure.

## 3. Experimental investigation

This work aims to characterize the FRCM systems subjected to tension. It also investigates the influence of the grid resolution on the global behaviour of the system. To achieve this goal, glass FRCM coupons, of various configurations were manufactured and tested in tension: one sample was reinforced with a single layer of bidirectional glass grid and the others with different grid overlap lengths, varying between 100 and 200 mm.

### *3.1. Materials*

The textile reinforcement used in the current experimental research consisted of balanced bi-directional Glass fibre grids, with an alkali-resistant coating Sika Wrap 350G Grid, Figure 2 [26].

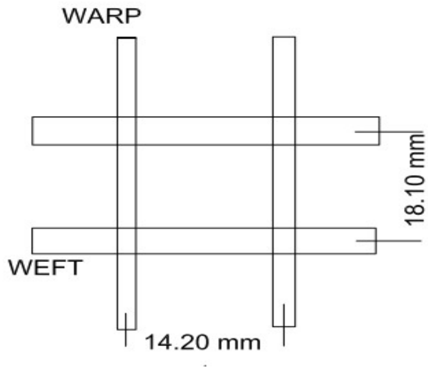


Fig. 2 - Geometrical properties of the glass grid, warp (longitudinal), weft (transverse) / *Caracteristicile geometrice ale rețelei din fibre de sticlă.*

Table 1 gives the mechanical properties of the glass grid, as provided by the manufacturers.

**Table 1**
Properties of the fibres used as FRCM reinforcement (Provided by the manufacturer)

| **Characteristics** | **Unit** | **Dry Fibre Properties** |
|---|---|---|
| Fibre orientation | - | Bi-directional |
| Tensile strength | MPa | 2600 |
| Tensile Modulus of Elasticity | GPa | 80 |
| Fibre Density | g/cm$^3$ | 2.6 |
| Weight per Area | g/cm$^3$ | 295 |

A high-strength cement-based mortar served as an FRCM matrix [27]. The mixture components are compatible with the spacing between the reinforcing strips, so that the mortar penetration through the Glass FRCM mesh was achieved. Three 50-mm samples mortar cubes were cast,

**Table 2**

The mechanical properties of the mortar matrix / *Proprietățile mecanice ale mortarului*

| Test specimen | Standard | N° of specimens | Test type | Strength (MPa) |
|---|---|---|---|---|
| Mortar for reinforcement matrix | ASTM C109 | 3 | Compression test | 17.56 |
| | EN 1015-11 | 6 | Flexural test | 5.64 |

cured in laboratory conditions for 28 days and tested according to ASTM C109 [28]. The average compressive strength, experimentally determined, was17.56 MPa. The flexural strength was determined on six 40x40x160 mm mortar prisms, after 28 days, according to EN1015-11 [29]; the flexural loading was performed using the three-point bending test. The average flexural strength was equal to 5.64 MPa. Table 2 summarizes the mechanical properties of the mortar matrix.

### *3.2. Specimen preparation*

The specimens were dimensioned and prepared according to AC434 [21]. All the specimens were cured for 28 days before testing.
The prismatic samples (400 x 60 x10 mm) were prepared by first applying a thin layer of mortar (about 5 mm), using a wooden formwork, followed by a layer of reinforcing grid and, finally, a top mortar layer with the same thickness (Fig.3). In addition to the one-ply sample, panels with an overlap of 100, 150 and 200 mm were manufactured, following the same procedure.

After the complete curing of the specimens , 3-mm thickness metal tabs were attached at the ends of each sample using an epoxy adhesive. The metal tabs were used to prevent the crushing of the sample ends and to assure the needed gripping. The tab length equal to 75 mm were selected according to AC434 (Section 4.4.2.) [21].

Experimental results showed that a 150-mm contact length seemed sufficient for a complete description of different FRCM systems, therefore this value was selected for the testing procedure.

Some variability of the test results might be observed, mainly due to the manual fabrication conditions during sample preparation. In addition, the pressure exerted on the components of the samples may slightly change the position of the grid reinforcements in between the two layers of mortar.

## 4. Tensile test set-up

Tensile tests were performed according to Annex A of AC 434 [21], (Fig.4). The selected alternative clamping method gives the possibility to reach the ultimate stress of the textile reinforcement and explore the third phase of the stress-strain plot while limiting the slipping of the fibres [25, 30].

A uniaxial tensile load was monotonically applied, in a displacement-controlled regime, at a loading rate of 0.2 mm/min in the first phase. After the occurrence of the first crack, the speed was increased gradually up to 1.2 mm/min.

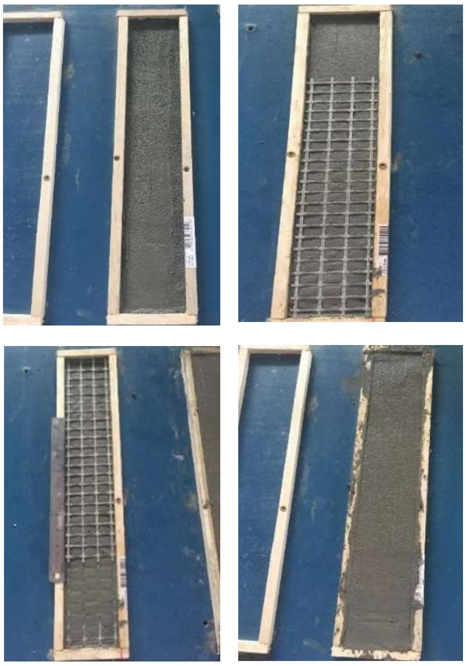

Fig. 3 - The preparation stages of the FRCM samples. / *Stadiile de preparare a epruvetelor din FRCM*

Fig. 4 - Specimen fixed in the testing machine. / *Epruvetă montată în mașina de testare.*

## 5.Experimental results

### *5.1. Tensile tests on glass FRCM samples*

The results of the tensile tests that were performed on the glass FRCM samples, in terms of elasticity modulus (E), ultimate stress ($\sigma_u$) and

**Table 3**

Tensile tests results. / *Rezultatele testelor la tracțiune*

| Sample | Fmax (KN) | $\sigma_u$ (Mpa) | E (GPa) | $\xi_u$ | Failure Mode |
|---|---|---|---|---|---|
| | Average value | | | | |
| **F0** | 3.64 | 1277.19 | 54.73 | 0.02 | F +Failure at the grips ends |
| **F100** | 2.02 | 708.77 | 50.62 | 0.022 | F |
| **F150** | 3.6 | 1263.15 | 39.06 | 0.023 | F |
| **F200** | 4.26 | 1494.73 | 64.06 | 0.020 | F |

F: Fabric breakage

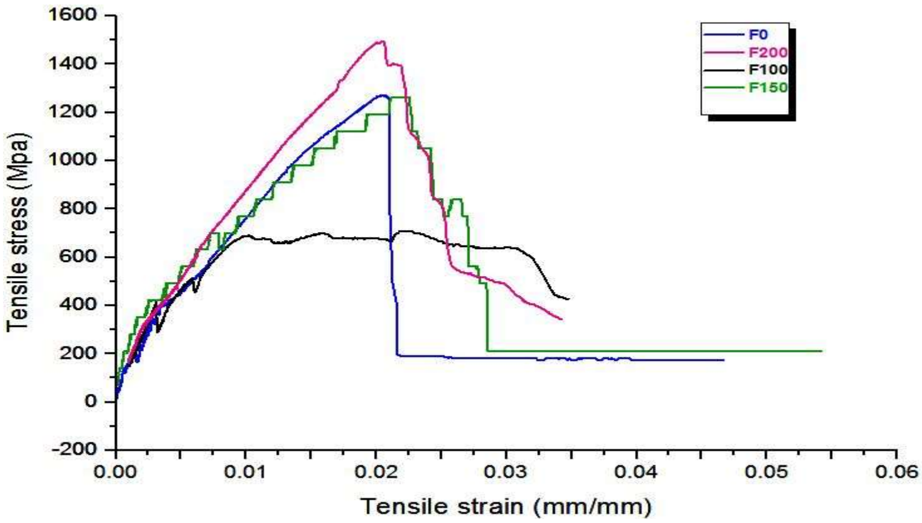


Fig. 5 - Experimental stress-strain curves of Glass-FRCM with a single grid reinforcement (F0) and two layers with overlap of 100 (F100), 150 (F150) and 200 (F200) mm. / *Curbe experimentale tensiune-deformație specifice epruvetelor FRCM armate cu un singur strat și cu suprapuneri de 100 (F100), 150 (F150) și 200 (F200) mm.*

ultimate strain ($\varepsilon_u$), along with the observed failure mode, are reported in Table 3.

The ultimate stress was determined by dividing the ultimate force (F) by the cross-section of the textile reinforcement (Af; Fiber Area per Unit Width *Af* (mm$^2$/mm) = 0.0475 [30]) in the load direction. The modulus of elasticity (E) was determined according to the specification given in AC434 Annex A [21]. Thus, two data points were picked from the cracked response curve to form a segment with stress levels of $\sigma_1 = 0.60\ \sigma_u$ and $\sigma_2 = 0.90\ \sigma_u$, along with their corresponding strain values. The slope of the line connecting these two data points represents the cracked tensile modulus of elasticity (E) of the material, as calculated in Eq. (1):

$$E = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1} \qquad (1)$$

Where:
$\sigma_1$ and $\sigma_2$ are the values of the tensile stresses corresponding to $0.6\sigma_u$ and $0.9\sigma_u$, respectively;
$\varepsilon_1$ and $\varepsilon_2$ are the strain values corresponding to the above mentioned stresses.

The ultimate strain was determined by dividing the total elongation of the sample by the reference length of the specimen [17,21]

The experimental tensile stress-strain curves of TRM coupons are plotted in Fig.5. Each curve is depicted for a representative test specimen of every TRM configuration.

Tensile tests performed on FRCM samples with a single-ply (F0) showed a drastic drop of the tensile load after the occurrence of the first crack in the matrix due to a low amount of reinforcement area, insufficient to absorb the energy released at first crack. The utilization of multiple ply-fabrics makes transition from the un-cracked to the cracked state more gradual.

By analysing the tests results, the following findings can be noticed:

- A grid overlap length of 100 mm (F100) is not sufficient to guarantee the complete transfer of tensile stresses from one strip to another.
- The ultimate load reached for F100 is almost 1.25 times lower than the value recorded for the specimen with a single fabric layer (F0).
- Increasing the overlap length to 150 mm enables the occurrence of the ultimate stress equal to that of the specimen with continuous fabric.
- The maximum load reached for F200 is almost 1.22 times higher than the value obtained for the specimen with a single fabric layer (F0).

### *5.2.* Failure mode

Figure 6 illustrates the typical failure modes of each type of FRCM samples. In most cases, the failure occurred by reinforcement rupture, which means that the sample fixing was appropriate.


Fig. 6 continues on next page.

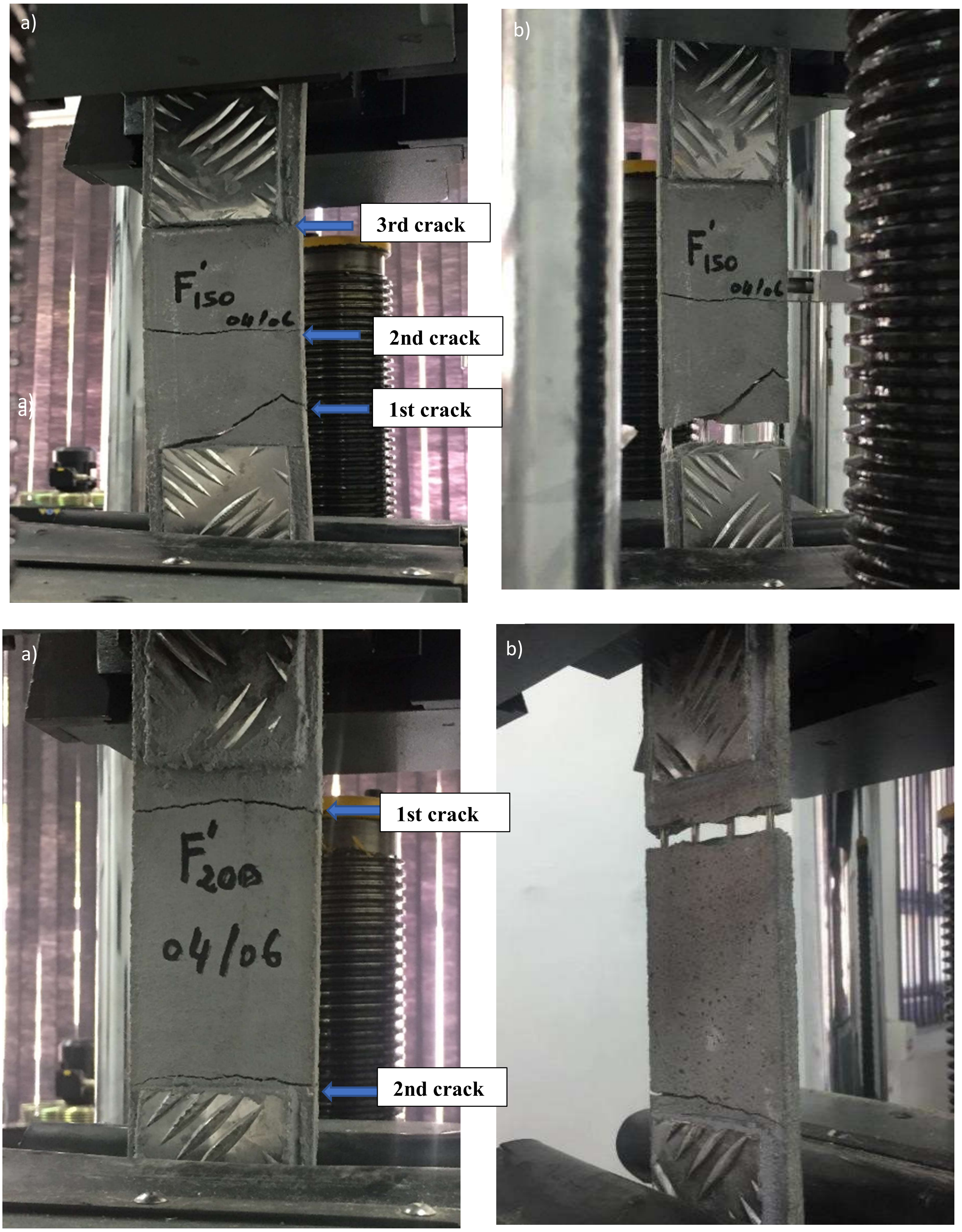


Fig. 6 - Failure mode of G-FRCM specimens subjected to tensile test a) multiple cracks in the mortar, b) ultimate failure. / *Moduri caracteristice de cedare ale probelor FRCM: a) dezvoltarea fisurilor multiple în mortar, b) cedare*

FRCM specimens reinforced with one continuous Glass grid failed after the formation of one or two cracks in the mortar matrix. Usually, after the crack formation, one of them propagate, and their opening increases up to reaching the failure. Even after the crack formation, the specimen load increases until the yarn breakage near a crack occurs.

The failure mode noticed in specimens with longer overlap lengths (F150, F200) is similar to that of samples with a single grid layer. However, the width of cracks of specimens with overlapped grids is smaller than that of single-layer units. The presence of a double layer of grid limits the crack opening by increasing the composite stiffness.

## 6. Conclusions

This paper presents the results of an experimental program performed on Glass FRCM systems. In particular, the tensile tests performed on specimens with continuous and overlapped glass fabric/grids to determine the minimum overlap length in order to maintain the reinforcement continuity and avoid the dramatic decrease of the tensile strength.

Based on the experimental results, the following conclusion can be formulated:

· The tensile structural response of FRCM consists of three different stages: (i) the elastic stage; (ii) the crack progression stage, and (iii) the fully cracked stage.

· The mechanic characteristics, strength and stiffness were provided mainly by the (i) mortar matrix, (ii) bonding behaviour of the textile and matrix, and (iii) reinforcement, respectively.

· The minimum reinforcement overlap length, which ensures the complete transfer of the tensile stresses is about 150 mm. For this overlap length, the maximum tension attained at failure is almost the same as that of samples with continuous reinforcement. For smaller overlap lengths, the reinforcement's maximum tensile stress is much lower, and the failure occurs at the interface between the two layers of grid yarns.

· The ultimate load recorded for F200 is almost 1.22 times higher than the value obtained for the sample with a single layer (F0).

· Different failure modes occurred in the tensile tests. Specimens reinforced with a single-layer glass grid failed due to rupture within the free length. Increasing the overlap length to 150 and 200 mm led to the breakage of one of the glass reinforcement layers.

· The tensile strength of FRCM systems proved to be highly influenced by the fabrics overlap length. An overlap length of 150 mm seems to be the most suitable dimension qualified to restore the specimen's integrity.

***Conflict of interest***

*None.*

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