FRP vs FRCM in flexural strengthening of masonry

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ABSTRACT: In recent years giant progress has been made in the understanding of structural behaviour and the development of proficient intervention strategies on existing masonry structures. The retrofit using compatible and efficient structural strengthening techniques was investigated primarily considering new technologies based on Fiber Reinforced Polymers (FRP), i.e. fibres with an organic resin matrix. Lot of knowledge was developed, mainly based on the assumption of linear elasticity for FRP. However nowadays resin matrix has been substituted by inorganic mortar matrices, yielding to the family of Fiber Reinforced Cementitious Matrix (FRCM) systems. Mortar matrix is more compatible with masonry, however FRCM does not behave like as FRP because the matrix cracks before fibre rupture and the contribution of matrix (in terms of stiffness in particular) is not negligible as it is for the resin, hence linear behaviour is substituted by a bi- or even tri-linear behaviour. The easiest way was to extend the models for FRP to FRCM, however it has never been clarified the impact of peculiar behaviour of FRCM on the analyses conducted assuming FRP, i.e. fiber only, behaviour and no compressive strength.

The main aim of this study is to develop a general model for flexural behaviour of FRCM strengthened masonry based on dimensionless analysis. In fact, being independent on the geometrical and mechanical parameters of the masonry and of the strengthening system, the results represent the basis for the development of standardized design and / or verification methodologies. In particular it is remarked the impact of different local behaviours of FRCM (and FRP for comparison purposes) materials on the global flexural response of strengthened masonry.

1 INTRODUCTION

The strengthening intervention strategies and structural rehabilitation of existing buildings through the application of thin composites are today one of the main activities in the field of structural engineering. Thin composites have a high strength/weight ratio, so they can be used to increase the ultimate strength of the structural element without adding significant additional mass to the structure. In this view, huge progress has been made in understanding the structural behaviour of masonry structures strengthened, also and above all, under the emotional pressure of recent seismic events, in particular Central Italy (2016).

The first kind of thin composites adopted as a strengthening solution was Fiber Reinforced Plastic (FRP). The FRP is a composite material made of a polymer matrix reinforced with fibres of different nature; the most used are carbon, glass, aramid and basalt. Afterwards the organic matrix was substituted with a cementitious one, leading to the birth of a new material system, i.e. Fiber Reinforced Cementitious Matrix (FRCM), which offered better performance under elevated temperatures and better compatibility with masonry substrates. Some attention was also paid to the improvement of bond before or even after (as repair) delamination of the FRP composites to masonry, (Kwiecień et al., 2016). Despite the development in the field of practical applications (Parisi et al. 2013, Ramaglia et al. 2016, 2017a, 2017b, 2018, Fabbrocino et al. 2019), more studies are needed to understand the influence of the characteristics of the strengthening systems on the behaviour of masonry element. Unfortunately, there is still no general consensus on the calculation model to be used for design and verification of masonry elements reinforced with FRCM. The calculation models proposed by the guidelines and international codes, provide reliable results for FRP, where the contribution of the matrix can be neglected, an assumption that is not directly extensible to the case of FRCM. In fact FRCM is usually composed of fibers in the form of grids with an equivalent thickness similar to FRP dry fiber component and mortar matrix with a reduced thickness of about 10mm, so about one order of magnitude higher than FRP resin matrix.

In Ramaglia et al. (2019), the proposed calculation model allowed to obtain results (P-M domains) expressed completely in dimensionless form, incorporating any geometrical and mechanical parameters of the cross section and of the strengthening system. This paper aims to extend the model proposed in Ramaglia et al. (2019), also considering the influence of the composite in compression, thus representing the basis for the development of standardized design or verification methodologies for the analysis of the flexural behaviour of masonry structures strengthened with FRCM.

2 BEHAVIOUR OF MATERIALS

To describe the mechanical behaviour of masonry, scientific literature offers different stress–strain relationships, (Lourenço, 1998). For the present paper, two different stress–strain relationships in compression and tension have been used. In compression it was used the model suggested by CEN Eurocode 6 (2005), where the post-peak softening is neglected, idealizing the behaviour after peak as perfectly plastic (as shown in Figure 1). While in tension, the material has an elastic-brittle behaviour with a slope equal to Young's modulus in compression, however when strengthening is applied, such tensile contribution is negligible.

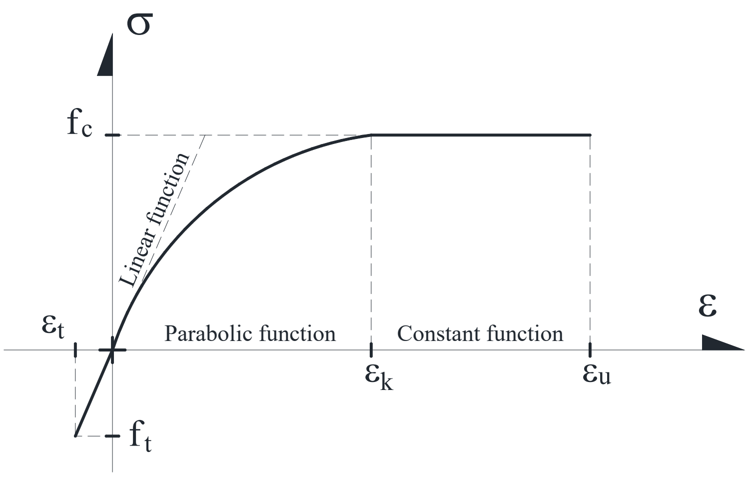


Figure 1. Stress-strain relationship of the masonry–compression (positive) and tension (negative).

Due to its mixed nature of fibres and matrix, the FRCM composite is subject to several phenomena such as matrix cracking or slip and debonding phenomena related to the fibre-matrix system. However, it is possible to provide a general stress–strain relationship able to simulate the behaviour of the composite system as a whole, taking into account the factors that influence it most. The stress-strain of the composite system can be simulated through three types of relationship: linear behaviour, bilinear and trilinear behaviour, (De Felice et al., 2018). Bilinear and trilinear behaviour accounts for the effect of matrix cracking and subsequent tension stiffening effects, while linear behaviour neglects the matrix contribution or accounts for already cracked matrix (CNR DT215, 2018).
For the purposes of this work, it will be considered only the linear and bilinear behaviour (see the Figure 2), thus comparing the behaviour of a typical FRP with a FRCM characterized by synthetic fibers.

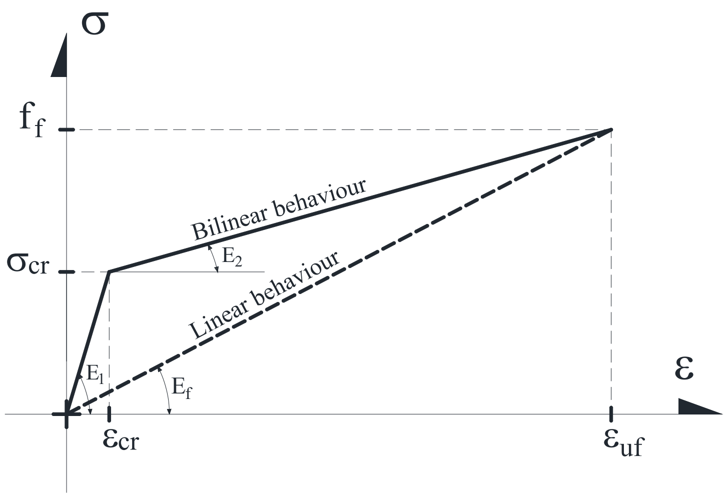


Figure 2. Different stress-strain relationship for composite system (referred to dry fiber thickness).

3 STRUCTURAL EVALUATION

An excessive amount of reinforcement can be detrimental, above all for ductility and failure mode, thus the knowledge of the bending moment and ultimate curvature capacity is really important for strengthened cross sections. In the presence of materials like as the masonry, characterized by reduced tensile strength, it is suitable to ignore the tensile strength in the calculation model, (Xu et al., 2012).
The numerical analysis of the section is based on the classic assumptions used also for RC cross sections in the technical approach. To provide generalizable results for different geometric and mechanical parameters, a process of adimensionalization has been carried out which takes into account the contribution to compression of the mortar matrix as well.
Given a generic cross section, the following normalized parameters are introduced:

$$n = \frac{N}{B \cdot H \cdot f_c} \qquad m = \frac{6 \cdot M}{B \cdot H^2 \cdot f_c} \tag{1}$$

where:

- B and H are the base and the height of the cross section;
- f_c is the compressive strength of the masonry;

- N is the axial force;
- M is the bending moment.

For the strengthening systems, the normalization was performed with reference to the ultimate tensile strength of the dry fibres for the tensile component (Ramaglia et al., 2019), however it is noted that the textile strength may differ due to several reasons related to production technique or to application. On the other hand, the contribution of the mortar matrix in compression is normalized with reference to its ultimate compressive strength. It is worth to observe that the translation and rotation equilibrium equations, which lead to the definition of compression and bending capacities, written in normalized form, depend only on a few parameters. The parameters adopted herein vary in a typical range according to commonly available composite systems.
To established the depth of the neutral axis, x, the horizontal equilibrium equation (2) is:

$$n = \psi \cdot \xi - \omega_f \cdot \overline{\sigma_f} + \omega_m \cdot \overline{\sigma_m} \quad (2)$$

where (see Figure 3):

- ψ is the factor (dimensionless) that correlate the real non-linear stress distribution to the stress block resultant (function of the maximum masonry strain) (Lignola et al., 2014);
- ξ is the depth of neutral axis normalized with respect to cross section height, $\xi = x/H$;
- ω_f is the mechanical fiber reinforcement ratio, defined as:

$$\omega_f = \frac{A_f \cdot f_f}{B \cdot H \cdot f_c}$$

  in which A_f and f_f are respectively cross section and tensile strength of dry fiber;
- $\overline{\sigma_f}$ is the stress of the composite (tensile side) normalized to the strength of dry fiber;
- ω_m is the mechanical compressed mortar matrix reinforcement ratio, defined as:

$$\omega_m = \frac{A_{mor} \cdot f_{mor}}{B \cdot H \cdot f_c}$$

  in which A_{mor} and f_{mor} are respectively the cross section and compressive strength of the mortar matrix.
- $\overline{\sigma_m}$ is the stress of the matrix (compression side) normalized to the compressive strength of the mortar matrix;

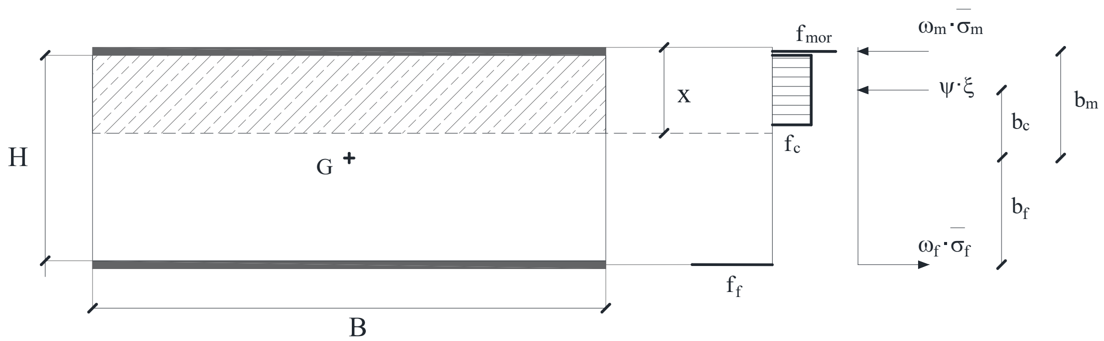


Figure 3. Equilibrium of strengthened masonry section under no-tensile strength assumption for masonry.

Afterwards, the bending capacity is evaluated according to rotational equilibrium around the centroid G of the cross section:

$$m = \psi \cdot \xi \cdot b_c + \omega_f \cdot \overline{\sigma_f} \cdot b_f + \omega_m \cdot \overline{\sigma_m} \cdot b_m \tag{3}$$

where b_c, b_f and b_m are respectively the lever arms of compression and tensile resultants. Manipulating Eq. (2), the following Equation is obtained:

$$m = \psi \cdot \xi \cdot (3 - 6 \cdot \lambda \cdot \xi) + \left(\omega_f \cdot \overline{\sigma_f} + \omega_m \cdot \overline{\sigma_m} \right) \cdot (3 + 3 \cdot \rho_m) \tag{4}$$

in which:

- λ is the factor (dimensionless) that correlates the real distance of the centroid of nonlinear stress distribution with the neutral axis depth, (Lignola et al., 2014);
- ρ_m is the ratio between cross sections of the composite in compression and masonry:

$$\rho_m = \frac{A_{mor}}{B \cdot H}$$

4 STRUCTURAL ANALYSIS

The structural analysis of the cross section was carried out considering appropriate values for the normalized stress–strain relationships for the masonry and the composite systems, (Papanicolaou et al., 2008). The bending moment–curvature diagrams presented in Figure 4 are dimensionless, therefore independent on the geometrical and mechanical parameters of the cross section and of the composite system. The main objective was to analyse how the structural performance of the cross section of strengthened masonry changes considering the influence of different stress–strain relationships of the composite and observing, at the same time, the structural response of cross section with, or without, the contribution in compression of the mortar matrix. It is worth to note how the response of the structural cross section changes when applying the strengthening system on the tensile side only; it can be observed an increase of bending capacity, but a reduction in the ultimate curvature, at the same level of axial force.

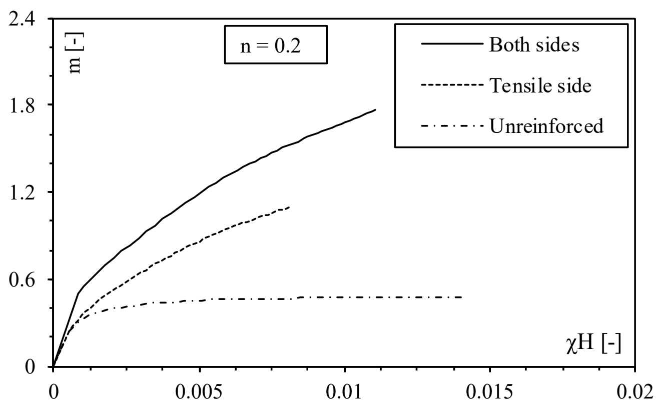


Figure 4. Theoretical moment–curvature diagrams for several configurations of strengthening.

Due to reinforcement in tension, the compression component has to increase for equilibrium. So given the ultimate strain in compression, an increase of neutral axis depth yields to a reduction in ultimate curvature compared to unreinforced masonry.

The composite on both sides, on the other hand, not only increases the bending capacity, but it enhances the ultimate curvature if compared to the case of strengthening on tensile side only. The contribution of the mortar in compression, as opposed to that in tension, reduces the neutral axis depth, hence it plays a positive role on the ultimate curvature. As FRCM is in compression, the mortar matrix and not the fibers provides strength. It is also interesting to observe how the performance of the cross section changes by varying the type of constitutive relationship of the composite, thus making a comparison between FRP and FRCM. Once the dry fiber properties are given, the comparison between linear and bilinear behaviour allows to analyse the contribution of the matrix on the structural response of strengthened cross section. In this case, even if it is considered a strengthening on both sides, the FRP contributes, by its nature, only on the tensile side.
In order to highlight this comparison, on a purely theoretical/analytical basis, the following cases are defined:

a) FRCM with mortar contribution in compression and bilinear behaviour in tension;
b) FRCM with mortar contribution in compression and linear behaviour in tension;
c) FRCM without mortar contribution in compression and bilinear behaviour in tension;
d) FRP on both side, hence no mortar contribution in compression and linear behaviour in tension.

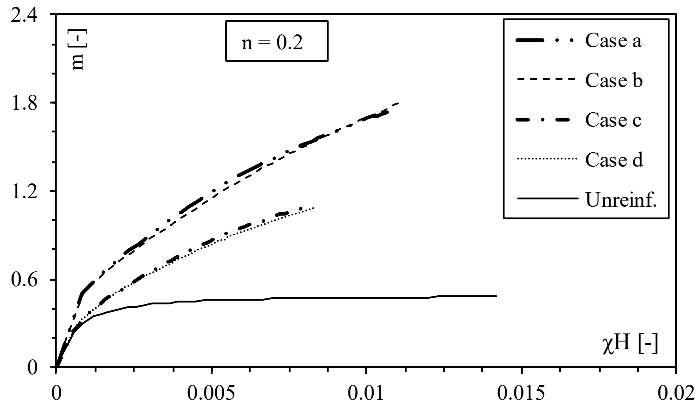


Figure 5. Theoretical comparison of different bending moment – curvature diagrams.

In order to validate the proposal, it was carried out a comparison with experimental values; in this context, the Figures 4 and 5 were obtained with the specimens and materials experimentally tested by Papanicolaou et al. (2008). The normalized parameters are listed in Table 1.

Table 1. Normalized parameters adopted for analyses in Figures 4, 5 and 7

Normalized parameters adopted						
E_1/f_f	E_2/f_f	ε_{cr}	ε_{uf}	ω_f	ω_m	ρ_m
[-]	[-]	[-]	[-]	[-]	[-]	[-]
75.2	64.9	0.003	0.01489	0.43	0.17	0.024

A very subtle difference emerges from the comparison of Figure 5: slight increases are perceived for the *Case a* and *Case c* compared to the *Case b* and *Case d*. It depends on the adopted mechanical parameters; in fact the Young's modulus of mortar (E_m=630 MPa) is quite low, so the bilinear behaviour is similar to the linear one. Adopting a stiffer mortar (i.e.

E_m=4000 MPa), the difference due to adopted the constitutive relationships is clear (see Figure 6).

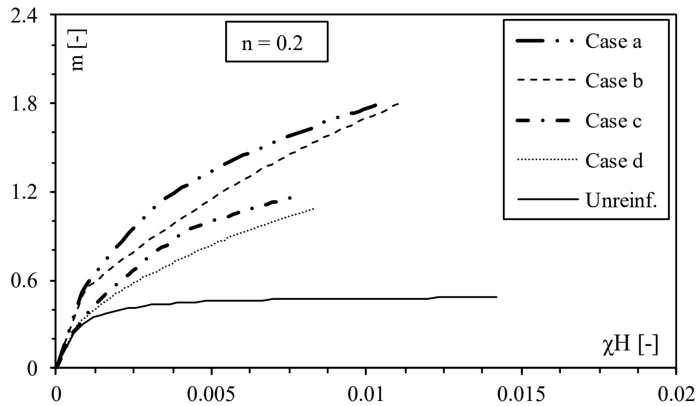
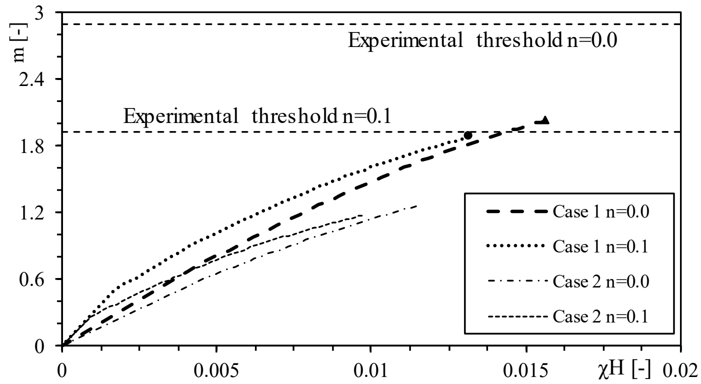
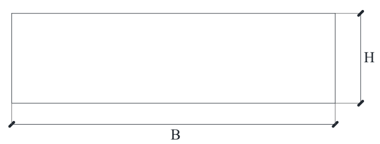


Figure 6. Theoretical bending moment–curvature diagrams for several cases of strengthening.

Figure 7a shows a comparison between the theoretical bending moment capacity and the experimental values by Papanicolaou et al. (2008). Case 1 and 2 are respectively the cross section strengthened with FRCM on both sides and on tensile side only. It is worth to note the importance of mortar in compression in order not to underestimate excessively the bending capacity of the structural element.





f_c [MPa]	4.3	f_{mor} [MPa]	31.36
f_f [MPa]	3350	A_f [mm^2]	18.8
E_m [MPa]	630	E_f [GPa]	225
σ_{cr} [MPa]	836	A_{mor}[mm^2]	800

Figure 7. a) Comparison between theoretical diagrams and experimental values; b) Experimental data adopted for the normalized parameters of Table 1.

5 CONCLUSIONS

In the present work the behaviour of masonry cross sections strengthened with FRP or FRCM composite systems was evaluated by varying the different tensile behaviours of the composite, and observing the influence of the mortar in compression. All the results were generalized through an adimensionalization process, providing extremely useful results for the design phase. The advantage of normalization is that it allows to supply general results for whatever the geometric and mechanical parameters. It is highlighted how the reinforcement modelling plays a fundamental role and the type of constitutive relationship to be adopted is strongly correlated to the type of reinforcement chosen, for example FRP vs FRCM. Contrary to FRP, the peculiarities of FRCM, due to the stiffness and strength of its matrix, provide non-negligible effects, even in compression behaviour, leading to an increase in strength and ultimate curvature. The results provided in a dimensionless form are the basis for a valid support for the design of interventions using fibre composites on masonry structures. The reliability of the model presented in this paper can be further validated by comparing the analytical results with further available experimental data.

6 REFERENCES

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