A numerical study on the effect of the interface material model on the tensile behaviour of FRCM strips

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ABSTRACT

Fibre Reinforced Cementitious Matrix (FRCM) composites are becoming increasingly popular for strengthening masonry structures for which the compatibility of the inorganic matrix with the chemical and physical properties of the support makes it advantageous to adopt such systems.

However, despite the large use of FRCMs for strengthening applications, the characterization and modelling of the mechanical response in tension of these systems is an open issue. In fact, the constitutive tensile law of the composite shows to be affected by different variables, such as the clamping system adopted during tensile test, the gauge length used for recording strains, the number of yarns and the planarity of the textile within the composite thickness. In addition to these parameters, which influence the experimental tensile characterization, few information is available on the constitutive law that rules the fibre-matrix interface, which is essential for evaluating the load transfer during the post-crack stage of the composite, as already shown in the literature. For these reasons, the studies that provide indications on analytical or numerical modeling of the tensile behaviour of FRCM materials are still limited.

This study presents the results of a series of FE numerical simulations, aimed at evaluating the tensile behaviour of FRCM composites. The elaborations are carried out through an appropriate definition of the sliding laws between the components (fibres and mortar) and a parametric analysis is performed by varying the type of fibre, the mechanical characteristics of the mortar and the interface bond law. The purpose of the study is to provide indications on the modeling of the tensile response of FRCMs, with particular regards to the evaluation of the fibre-matrix interface behaviour. The numerical results are validated through comparison with some experimental data selected from the literature. The performed analyses allow evaluating the influence of the selected parameters and obtaining a qualitative comparison on the mechanical performances of different types of reinforcement in terms of maximum tensile strength and ultimate strain.

1 INTRODUCTION

The use of composites with inorganic matrix is becoming increasingly popular in the field of retrofitting applications of existing structures. Their adoption allows to overcome the well-known drawbacks related to the use of Fiber-Reinforced Polymers (FRPs), and fulfil the requirements of reversibility, compatibility with the substrate and minimum invasiveness in the conservation and restoration interventions of existing historic buildings. For these reasons, several research works investigated on the mechanical characterization of Fabric Reinforced Cementitious Matrix (FRCM) materials and on their possible adoption in retrofitting applications. Generally, experimental studies presented in the literature have shown that the characterization of the tensile behaviour of FRCMs is of crucial importance for assessing the structural performance of this kind of composites, and the role of the matrix-fabric interaction is more important with respect to that observed in polymer-based composite materials. In fact, the mechanical characterization of the single constituents (matrix and fibre) does not provide indications on the behaviour of the FRCM material due to the influence of the stress transfer mechanism between matrix and fabric on the global tensile response (Mazzucco et al. 2018).

Consequently, several recent studies were addressed to the investigation of the tensile behaviour of FRCMs by studying the main variables involved, such as: - the role of the test set-up; -the characteristics of mortar and fabric; - the reinforcing fabric ratio.

The role of the test set-up was studied by several authors (Contamine et al. 2011, Arboleda et al. 2015, D'Antino and Papanicolaou 2018). It was demonstrated that the clamping method plays a fundamental role in achieving a uniform load distribution and may significantly influence the stress-strain response of composite specimens.

The tensile load can be applied to strip specimens through two clamping methods with the machine wedges: clamping-grip or clevis-grip. The clamping grip method is recommended by RILEM TC 232 TDT. It blocks the rotational capacity and limits the sliding between fibre and matrix during the test. Differently, the clevis-grip method required by the American code ACI 549, provides metallic plates bonded to the specimen ends and connected to the machine through a transversal pin that allows the sliding between matrix and fabric. In this case the fibre does not reach the maximum strength value since the crisis occurs due to slippage.

The large number of available fabric textiles and mortar grades results in a wide variability of possible combinations of composites, and consequently different mechanical responses can be recorded. For this reason, several experimental studies were carried out on composite materials made with different types of fibres, especially glass, carbon and aramid fibres, while growing attention is also paid to basalt fabric.

All the experimental works pointed out that the tensile response of FRCMs can be idealized as a tri-linear curve, characterized by three different stages: i) linear elastic behaviour up to the first cracking of the matrix, ii) second branch characterized by spreading of mortar cracks and by sliding of longitudinal fibres, iii) third branch corresponding to the behaviour of the bare fibres up to failure. The complexity of such tensile behaviour is due to different micro-mechanical phenomena involving the mortar and the damage of the fibre-mortar interface.

For this reason, it was also found experimentally that the trend of the load-deformation curves is influenced by the fabric reinforcing ratio (Donnini and Corinaldesi 2017 and Zhou et al. 2019) but the increase of the ultimate tensile capacity is not directly proportional to the number of fabric layers. This phenomenon is due to the fact that for great reinforcing ratios the fabric layers are surrounded by thinner layers of mortar, and consequently the fibres cannot be properly embedded in the mortar. This fact can induce slippage at the interface between the two phases and consequently the stress transmission between mortar and the different fabric layers in the post-cracking stage can be not uniform.

It is evident that the matrix-fabric interface is crucial for modelling the tensile behaviour of FRCM materials. The description of the stresses transmission mechanism between several layers in contact within the system is very complex and still not adequately studied. While several experimental works were developed for studying the tensile behaviour of FRCM materials, few studies are currently available on possible theoretical approaches for its prediction.

In this framework, this paper focuses on the numerical modelling of the tensile behaviour of FRCM strips, with particular reference on the evaluation of the effect of the interface calibration on the global load-displacement response. The study is carried out through the generation of 3D Finite Element (FE) models capable of reproducing the tensile response of FRCM strips with different number of layers of grid. For the simulations, the classical approach of micro-modelling is adopted with different levels of detail. In particular, fibres and substrate are modelled separately and the interface behaviour between the two components is simulated introducing the perfect bond behaviour, on one hand, and numerical contact properties for reproducing the cohesive tangential behaviour, on the other hand. The role of the constitutive law of the interface is discussed in deep, and it is shown that a proper material model of the interface needs to be adopted for a reliable prediction of the tensile behaviour of the FRCM composite.

The accuracy of the FE models is validated against the results available in the literature with different kinds of fabric, mortar and different reinforcing fabric ratios. Results are presented in terms of load-displacement curves, colorplot of principal stresses and parametric graphs, which show the dependence of the tensile response by the main parameters defining the interface model.

2 NUMERICAL INVESTIGATION

The numerical study was performed by building 3D FE models by taking advantage of the code ABAQUS, here adopted for its capabilities in modelling contact problems.

Generally, two kinds of models were generated (Figure 1): - T1 models, in which perfect contact was assumed between mortar and fabric; -T2 models, in which a cohesive contact was introduced between fabric and matrix. The features of the geometrical and material modelling are described in detail in the following for each component.

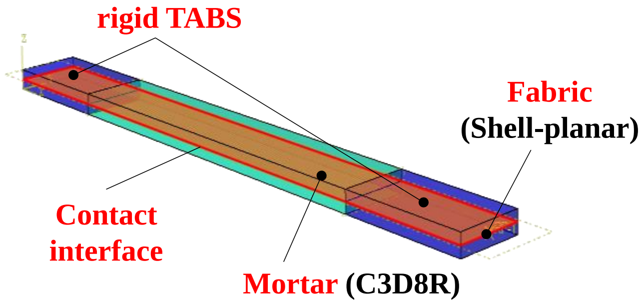


Figure 1. 3D FE model of FRCM strip

2.1 *Fibre fabric: elastic orthotropic behaviour*

In all the models, the fibre fabric was modelled by a shell-planar element with thickness equal to the equivalent value.

Generally, the fibre phase of FRCM materials is made by bidirectional textiles, where longitudinal and transversal bundles are kept together by a secondary low-strength fibre net. For this reason, the behaviour of the element was assumed as elastic orthotropic.

Two principal directions were defined: direction 1, which is determined by the longitudinal direction of the fibre filaments, and direction 2, which is along the transverse bundles.

Along direction 1 the elastic modulus was associated with that recorded in the warp direction of the fabric, while that along direction 2 is that associated to the weft. The values of Poisson's coefficient were assumed equal along the two directions, while the shear moduli are calculated on the basis of the well-known elastic relationship between the shear modulus, the elastic modulus and the Poisson's coefficient, in the form

$$G_{12} = \frac{E_1}{2 \cdot (1 + \nu_{12})} \tag{1a}$$

$$G_{23} = \frac{E_2}{2 \cdot (1 + \nu_{21})} \tag{1b}$$

2.2 *Mortar: plastic-damage model*

The mortar matrix was modelled through linear brick elements C3D8R with reduced integration, 8 integration points and hourglass control. The constitutive law of the mortar was implemented through the classical Concrete Damaged Plasticity (CDP) model, which assumes a non-linear uniaxial stress-strain law in compression and isotropic damage of the material. In particular, the compressive response was modelled by the constitutive relationship proposed originally by Sargin (1971) for unconfined concrete. It is expressed by the following equation:

$$\tilde{\sigma} = \frac{A\tilde{\varepsilon} + \left(D' - 1\right)\tilde{\varepsilon}^2}{1 + \left(A - 2\right)\tilde{\varepsilon} + D'\tilde{\varepsilon}^2} \tag{2}$$

where $\tilde{\sigma} = \sigma / f_{mc}$, $\tilde{\varepsilon} = \varepsilon / \varepsilon_{c0}$ with f_{mc} the compressive strength of the mortar; A = E_t/E_s is the ratio between tangent modulus at the origin and the secant modulus at the peak of the curve, to be chosen in the range 2-3; D′ calibrated in the range between 0 and 2(A-1).

A linear stress-strain response was assumed in tension up to the maximum tensile stress.

The CDP model is ruled by the flow potential hyperbolic function by Drucker and Prager and the yield function by Lubliner et al. (1989). In the model, the dilation angle was set equal to 31° while the ratio of the second stress invariant on the tensile meridian, which rules the shape of the yield function, was set equal to 0.0667.

Several analytical laws are also available in the literature for the definition of the damage evolution in compression and tension of the mortar. Mazzucco et al. 2018 suggested calculating the inelastic compressive and tensile strains of the mortar, ε_c^{pl} and ε_t^{pl}, through the following equation:

$$\varepsilon_x^{pl} = \varepsilon_x - \varepsilon_{0,el} \frac{1}{1 - d_x} \tag{3}$$

where x=c for compression, x=t for tension. In Eq. (3) the terms d_c or d_t represent the damage variables. Such variables are defined according to the classical model by Mazars and Pijaudier-Cabot (1989):

$$d_c = 1 - \left(1 - A_c\right)\frac{\lambda_c}{\varepsilon_{eq}^p} - A_c e^{[-B_c(\varepsilon_c - \lambda_c)]} \tag{4a}$$

$$d_t = 1 - \left(1 - A_t\right)\frac{\lambda_t}{\varepsilon_{eq}^p} - A_t e^{[-B_t(\varepsilon_t - \lambda_t)]} \tag{4b}$$

In Eqs. (4a-b) the coefficients A_t, B_t, λ_t, A_c, B_c, λ_c represent material parameters experimentally calibrated from laboratory tests and here assumed as suggested in Mazzucco et al. (2018), while the term ε_c and ε_t represent the plastic strain of the flow potential function in compression and in tension respectively. The trend of Eq.(4) is plotted in Figure 2.

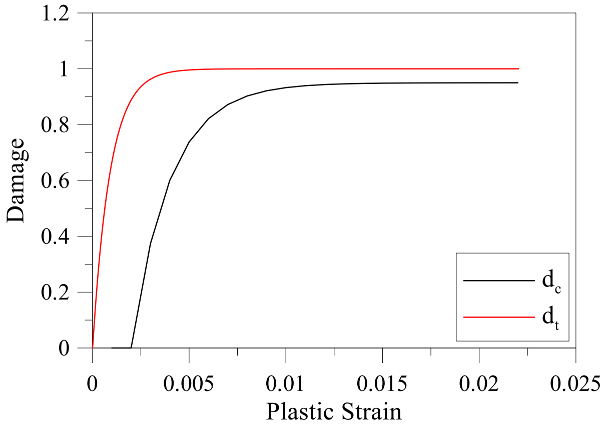


Figure 2. Damage law of the mortar in tension and in compression

2.3 *Matrix-Mortar cohesive interface*

Two types of models were generated for simulating the interface behaviour. In model T1 the perfect bond between basalt fibres and mortar is assumed as a simplified hypothesis. In such a model, a rigid internal constraint was used for the degrees of freedom of each node of the basalt lamina, which is embedded with the host region, i.e. the mortar material. In this case, every tangential slip and normal opening between the two components is neglected.

Conversely, a cohesive behaviour was assumed in model T2, even though uncoupled in the tangential and normal direction.

The contact was introduced by defining the fabric as the “master” surface and the mortar as the “slave” surface as shown in Figure 3.

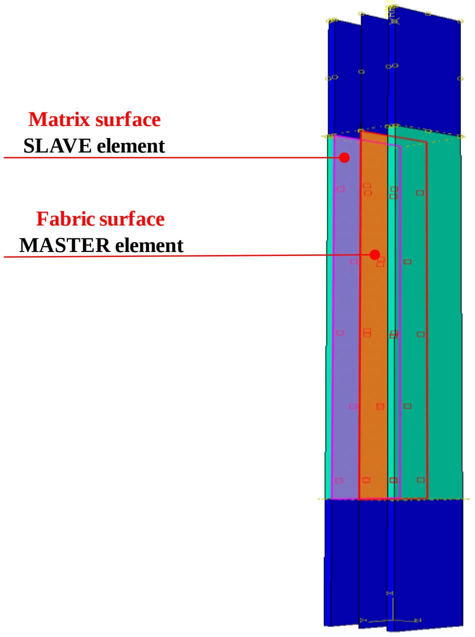


Figure 3. Definition of Master and Slave elements in T2 models.

The shear stress-slip law was defined as in Figure 4, and characterized by an initial linear branch up to a maximum value of tangential stress, and by a post-elastic response. This last is ruled by the evolution of a damage variable D, whose values are in the range 0-1 (undamaged condition-maximum damage). The parameters used in the present study were calibrated on those suggested in the literature by Carozzi et al. (2016).

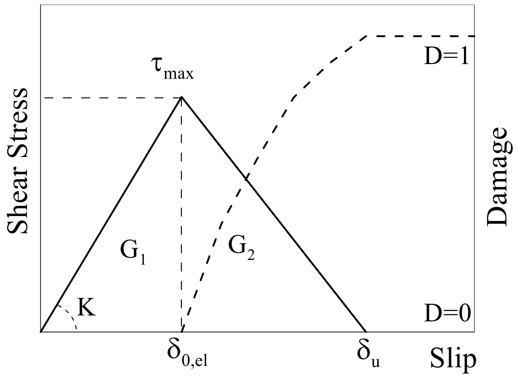


Figure 4. Shear stress-slip law and damage evolution of the interface

2.4 *Analysis definition*

Mesh generation was performed before running the analysis by a calibration test. The size of the elements was progressively reduced in order to have a result independent from the mesh dimension. The current study refers only to specimens loaded with clamped ends. For this reason, rigid tabs were simulated at the extremities of each model, assumed with perfect contact with the specimen.

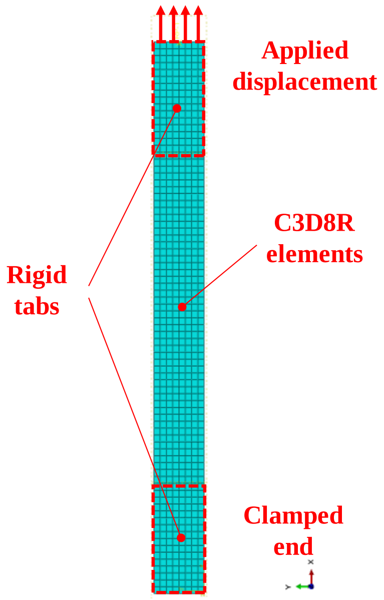


Figure 5. Geometrical definition of the model and boundary conditions

One tab was clamped by restraining all the degrees of freedom and recorders were placed for measuring the reacting force, while in the other tab only the rotation was restrained (Figure 5). At the first analysis step, an axial displacement equal to 1/1000 of the ultimate axial elongation of the fabric was imposed, while for successive steps the automatic load stepping control algorithm available on Abaqus was adopted to reduce the analysis time. The adopted integration algorithm was Full Newton Raphson.

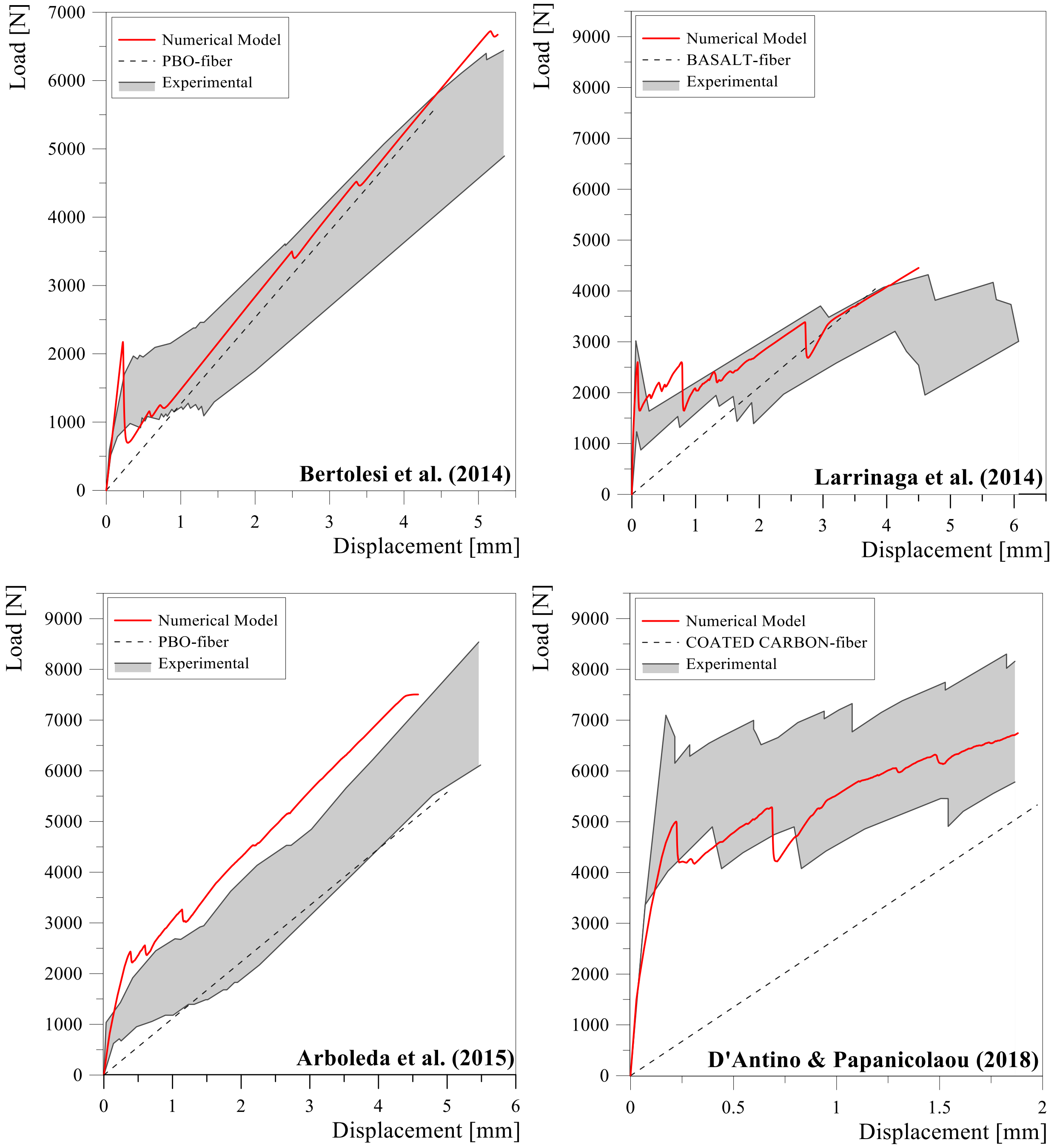


Figure 6. Comparison between experimental data and numerical predictions

3 MODEL VALIDATION AND COMPARISON WITH EXPERIMENTAL DATA

The adopted modelling approach was validated against experimental data available in the literature. In particular the experimental investigations of Bertolesi et al. (2014), Larrinaga et al.(2014), Arboleda et al. (2015) and D’Antino and Papanicolaou (2018) were considered, referring to specimens with different kind of fibres (PBO, carbon and basalt) and different reinforcing fabric ratio, as reported in Table 1, which resumes the main characteristics of specimens adopted for validation and which results are available in the literature.

The comparison between the simulation and some experimental data is shown in Figure 6 in terms of tensile Load-Displacement curves.

Table 1. Characteristics of test specimens adopted for validation

Investigation	Type of mortar	Type of fibre	No. of layers	f_f [MPa]	E_f [GPa]	f_m [MPa]	E_m [GPa]
Bertolesi et al. (2014)	Cementitious with a low dosage of dry polymers	PBO	1	3397	216	4.75	>6
Larrinaga et al. (2014)	Cement-based	Basalt	1	2100	67	2.48*	8.25
Arboleda et al. (2015)	Cementitious enriched with short fibers (<5%)	PBO	1	3400	216	4.75*	>6
D'Antino and Papanicolaou (2018)	Cement-based	Coated-carbon	1	1890	219	6.7	15

f_f: tensile strength of the fibre; E_f: elastic modulus in tension of the fibre; f_m: tensile-bending strength of the mortar; E_m: elastic modulus in compression of the mortar (*values determined by direct tensile tests)

In particular, the range of variability of the tests reported in the literature is drawn in gray, while the result of the numerical simulation is plotted in red. Additionally, the theoretical response of the bare fibre fabric is reported for comparing the slope of the third stage of the tensile response of the FRCM with the axial stiffness of the bare fabric. It is worth noting that all the simulations gave results in accordance with experimental data. The numerical response provides reasonable values of the first cracking load, while the second and third stage are generally predicted within the average values of the experimental results. It is also worth noting that the slope of the final stage is not always in accordance with the axial stiffness of the fibre fabric, depending on the analyzed case.

4 PARAMETRIC ANALYSIS

Despite comparisons with experimental results proved the reliability of models in predicting the tensile response of FRCM composites, the effect of some input parameters on the obtained results is investigated in order to check their influence on the achievable numerical response.

4.1 *Effect of the interface parameters*

The effect of the constitutive law assigned to the contact interface between matrix and fabric was studied. In particular, two shapes of shear stress-slip laws were considered, by keeping constant the ratio between the elastic energy G_1 and the energy associated to the softening branch G_2 (Figure 4). In the first case, it was assumed $G_1=0.50G_2$ (Figure 7a), while in the second case the two values of energy were considered equal $G_1=G_2$ (Figure 7b). For each case, different characteristic configurations were assumed. The first configuration corresponds to a softer interface with a great value of ultimate slip, and minimum values of maximum shear stress and stiffness (Interface D1). The opposite situation is that of the stronger and stiffer interface with a steep post-peak branch (Interface A1).

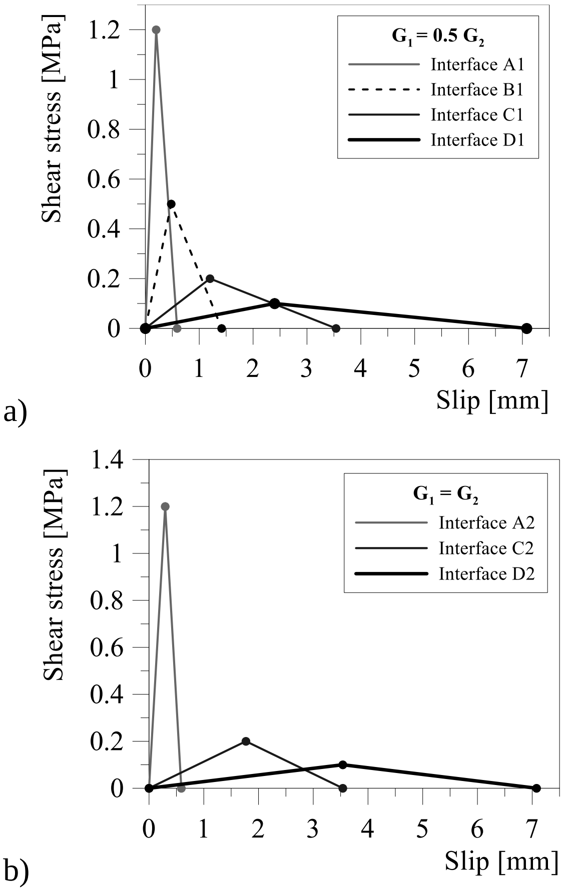
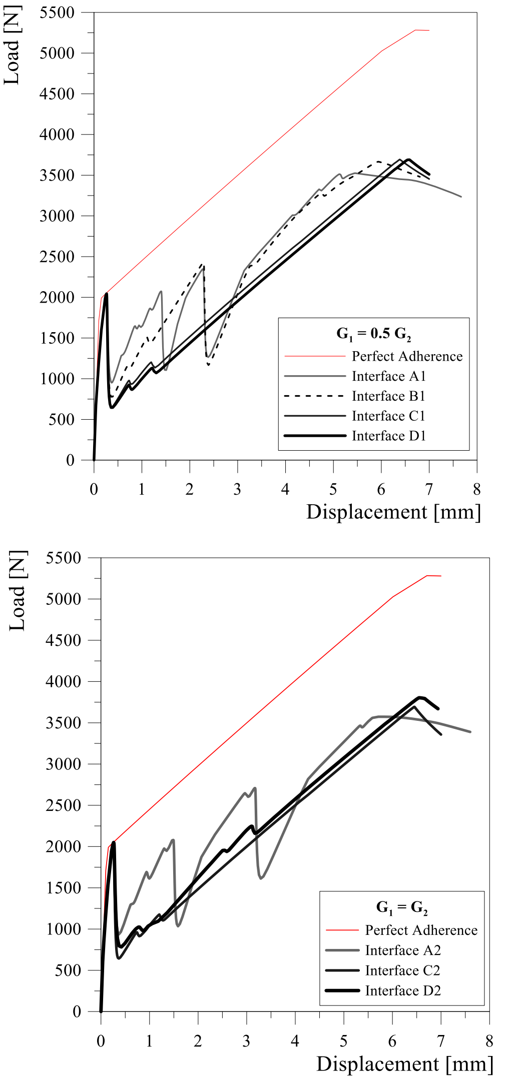


Figure 7. Adopted interface models for parametric analysis: a) $G_1=0.50G_2$; b) $G_1=G_2$

The other two constitutive laws can be considered intermediate between these limit cases. Results in terms of tensile Load-Displacement response are plotted in Figure 8, which shows the numerical results also for the case of perfect connection between matrix and fabric.



a)

b)

Figure 8. Tensile response of the FRCM strips for different interface parameters: a) G_1=0.51G_2; b) G_1=G_2

It is worth noting as the introduction of the interface constitutive law influences significantly the tensile capacity of the strip. The Load-Displacement response of the model with perfect contact between matrix and fabric is approximately defined by a bilinear trend, in which the two stages correspond to the elastic behaviour of the composite and the response of the bare fibre fabric respectively. As expected, the interface model keeps unchanged the first branch of the tensile response up to the cracking load. This last is followed by a sudden drop of the load, whose amplitude depends on the features of the interface model. It is clear to observe that the post-cracking branch is strongly influenced by the parameters adopted for the interface. In fact, the trend of this branch becomes more stable and tends to be linear for softer interfaces – i.e. for lower values of interface stiffness and strength, and greater values ultimate slip. It can be also observed as the ultimate slip influences also the ultimate elongation of the model. Greater elongation capacities are achieved numerically when the interface is defined by greater values of ultimate slip. These considerations are independent by the energy ratio, being the responses similar between Figure 8a and 8b.

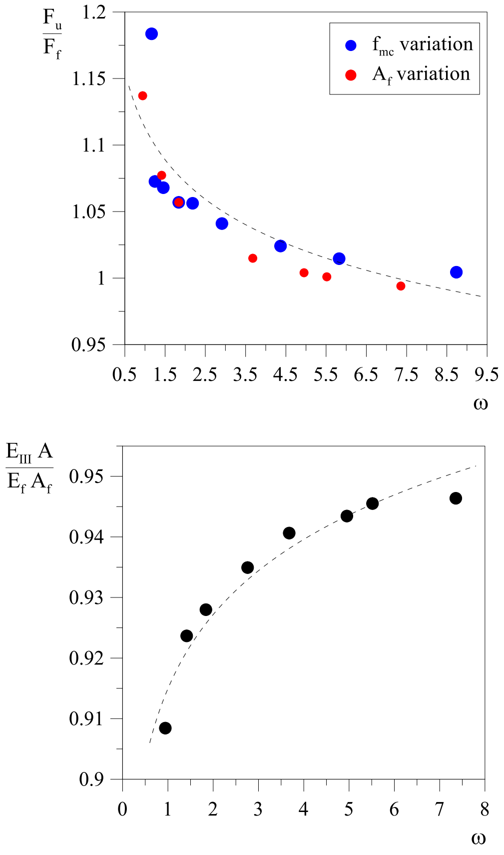
4.2 Effect of the mechanical ratio of fibre fabric

The variation of the numerical results was evaluated also with respect to the mechanical ratio of reinforcing fabric. This last is defined as:

$$\omega = \frac{A_f\, f_f}{b \cdot t \cdot f_{mc}} \qquad (5)$$

being A_f the total area of fibre fabric in the longitudinal direction of the strip, b and t the width and the depth of the specimen and f_{mc} the compressive strength of the mortar matrix.

Results are briefly summarized in Figure 9.



a)

b)

Figure 9. Effect of the mechanical ratio of reinforcing fabric on the tensile response: a) Normalised tensile load capacity as a function of ω; b) Normalised third stage slope as a function of ω

In particular Figure 9a shows the trend of the ultimate tensile capacity recorded numerically F_u normalised with respect to the tensile axial capacity of the bare fibre fabric F_f as a function of ω. Simulations were carried out by varying A_f or f_{mc} in order to check if the parameter ω represents adequately the variation parameter of the normalised tensile capacity. It is observed that numerical results are fitted by a non-linear descending curve, showing that the contribution of the mortar matrix to the tensile capacity of FRCM strips becomes evident only for low ratios of fibre fabric, while for great values of ω the effect of the mortar on the axial capacity can be considered negligible. It is also evident that results keep the same trend, independently by the variation of A_f or f_{mc}, confirming the parametric importance of ω.

Similarly, Figure 9b shows the trend of the axial stiffness of the FRCM strip with transverse cross area equal to A in the post-cracking stage normalised with respect to the same quantity calculated for the bare fibre fabric, as a function of ω. It can be observed that the trend of the numerical results is fitted by a non linear ascending curve, which tends in asymptotic way to a values of 1 for ω tending to infinity. As expected, the mortar deformability can affect the slope of the third branch of the tensile response of the FRCM composite especially for low reinforcing fabric ratios, as observed experimentally in the literature.

5 CONCLUSIONS

This paper described the results of a study on a possible numerical modelling approach of the tensile behaviour of FRCM strips. The study was supported by non-linear finite element simulations, in which particular care was addressed on the constitutive law of the fabric-to-matrix interface, and whose results were validated against some experimental data available in the literature. On the basis of the results obtained and for the ranges of variables included, the following conclusions can be drawn:

- a cohesive model can be adopted for describing the behaviour of the fabric-matrix interface. The inclusion of a bilinear shear stress-slip constitutive law of the interface is fundamental for assessing the tensile response of the composite;
- the interface strength and stiffness among a limited range do not influence the tensile load capacity and the initial stiffness of the FRCM. Their values affect significantly the trend of the post-cracking branch of the tensile response, including the load drop after that first cracking load is achieved;
- proposed numerical approach is able to provide the effect of the reinforcing fabric ratio ω on the tensile response. In particular, it is shown that for increasing values of ω, the contribution of the mortar to the tensile load capacity and on the axial stiffness of the FRCM strip tends to be negligible.

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