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STATE OF THE ART ON BOND BETWEEN FRCM SYSTEMS AND MASONRY/CONCRETE SUBSTRATE: DATABASE ANALYSIS AND IMPROVED MODELS

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Abstract

The use of the *Fabric Reinforced Cementitious Mortars* (FRCMs) is nowadays a promising solution for the strengthening of both reinforced concrete and masonry structural elements. The application consists of a bond-dependent *face-to-face* plastering of an open grid or mesh by means of an inorganic-based matrix, i.e. a cement-based mortar. The main advantage of such a strengthening technique is the good compatibility with different types of substrates since the most suitable matrix can be selected focusing on the most similar breathability and stiffness. On the other side, the strengthening efficiency could be over-estimated if the potential bond failure is neglected. The FRCM-bond behaviour depends on many parameters, e.g., mechanical properties of substrate and reinforcement, environmental conditions, etc. Due to the wide range of variability of these parameters, nowadays, formulations for a reliable prediction of the maximum strain which the FRCM is able to develop for avoiding bond failure are not available. At this scope, the present paper collects a large database of experimental results of bond tests available in literature in order to investigate the main parameters influencing the performance of this strengthening technique, to identify the aspects that have to be further studied, and to calibrate an empirically-based analytical model proposed by the authors to predict the maximum design strain in the FRCM reinforcement. The parameters assumed in the model are the following: type of substrate (i.e. masonry or concrete), type of fabric (i.e. carbon, glass, steel, basalt), type of matrix (i.e. cement, lime, alkali-activated based) and failure mode (detachment, slippage, rupture, etc.). The database was clustered depending on the failure mode in order to calibrate targeted and more accurate equations.

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Keywords: FRCM, Bond, Masonry, Concrete, Design-oriented model

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1. Background and research scope

Nowadays the extension of the service life for the existing building heritage is accepted to be a key-challenge for limiting the human impact on the environment. Preservation and maintenance are, indeed, more green-oriented approaches in comparison with the construction of new structures. Innovative strengthening solutions based on the use of high strength fibres coupled with an inorganic matrix, such as the FRCM (Fabric Reinforced Cementitious Mortar) materials, have been recently developed. FRCM-systems consist of bidirectional fibres (Basalt, PBO, AR Glass, Carbon, etc.) arranged in form of a 'grid' and inorganic mortars (cementitious, lime based, alkali-activated based, etc.). Their main characteristics are the high resistance to fire and UV, a breathability comparable to that of the support, the applicability on wet surface and on rough and irregular support, the reversibility of the retrofitting, the high tensile performance of the fibres, the lightness and the reduced thickness of the strengthening layers, the easiness of installation. As well-known, the effectiveness of the strengthening is strongly related to the bond behaviour between the reinforcement system and the substrate itself, which is influenced by different parameters. Moreover, since the adhesion develops at different inter-layers, i.e., the substrate-to-matrix or the fabric-to-matrix, bond failures can occur at different interface and often mixed with the cracking of the matrix (CNR DT-2015/2018). When the matrix cracks, the fibres, indeed, more easily slip within it and the yarns may be not equally tensioned anymore. Nowadays several experimental tests, aimed to investigate the bond failures and the performance of FRCM materials applied on both concrete and masonry substrates, are available, but an overall critical analysis of the experimental outcomes related to different substrates and types of FRCM materials as well as design-oriented models for predicting the maximum strain in the reinforcements are lacking.

Nomenclature

A_f	area of dry fibre
E_f	elastic modulus of dry fibre
t_f	equivalent thickness of dry fibre
$f_{c,s}$	compressive strength of substrate
$f_{c,m}$	compressive strength of matrix
$f_{t,s}$	tensile strength of substrate
$f_{t,m}$	tensile strength of matrix

2. Analysis of the database

The experimental data of bond tests on FRCM materials available in literature were collected in a database that summarizes: geometrical and mechanical properties of substrate (masonry or concrete) and reinforcement (when available), test set-up, results of direct tensile tests on FRCMs (when available), results of bond-shear tests, i.e. peak load, conventional limit stress, slip and failure mode. A total of 1258 experimental results were considered. Within the whole database, 411 data concern bond tests on concrete specimens, while 847 bond tests on masonry specimens (Fig. 1). All 411 concrete samples are made of a single prism, while, among the 847 masonry specimens, 88 are constituted by a single masonry block and the remaining 759 are small-scale masonry walls, i.e. several blocks connected with mortar joints. Almost all the masonry samples (97%) are made of clay bricks (Fig. 1b) and the remainder of tuff blocks (Fig. 1c). This circumstance highlights that further bond tests should be done by using natural stones to increase the experimental data available on these substrates and on other different types of substrates.

(a) (b) (c)

Fig. 1. (a) Distribution of the substrate types in the database, (b) example of small-scale wall made of clay bricks (from Bellini et al. (2021)); (c) example of specimen made of single tuff stone (from Bilotta et al. (2017)).

First, for both concrete and masonry specimens, the distribution of the compression strength of substrate [MPa] and of the reinforcement matrix [MPa], the dry fiber type, and the failure mode were evaluated and are plotted in Figure 2 and 3, respectively. The failure modes are classified according to the suggestions provided in CNR-DT 215-2018. For the tests conducted on concrete elements (Younis & Ebead (2018a), Younis & Ebead (2018b), D'Antino et al. (2015), Sneed et al. (2014), Raoof et al. (2016), D'Ambrisi et al. (2013), Ombres et al. (2015), Carloni et al. (2017), D'Antino et al. (2015), Sabau et al. (2017), De Domenico et al. (2020), Sneed et al. (2015), D'Antino et al. (2014)), in almost 90% of cases, the compressive strength is variable between 30 and 50 MPa (Fig. 2a), while for almost 70% of samples the compressive strength of the matrix falls in the range 25-35 MPa (Fig. 2b). For concrete specimens, the most adopted strengthening system (75% of the tests) is a single PBO layer (Fig. 2c). The failure mode "C" (debonding at the textile-to-matrix interface) is predominant over the others, since it was observed in 65% of the samples (Fig. 2d), followed by the slippage of the textile within the matrix (type "D", 8.5%). The most used set-up is the single lap test. The bond length varies in the range 50-450 mm. The equivalent thickness of the dry fibers is variable in 0.045-0.095 mm.

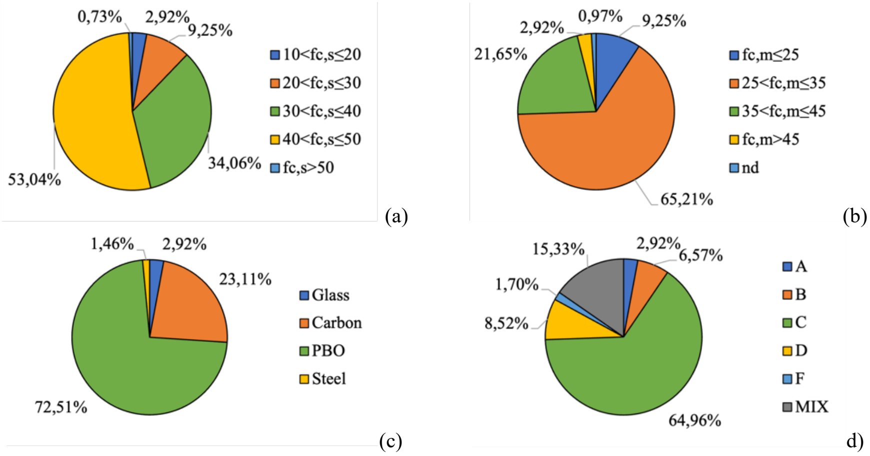

Fig. 2. Description of concrete full database: (a) compressive strength of substrate, (b) compressive strength of matrix, (c) type of dry fibre, (d) failure modes.

For the masonry specimens (Bilotta et al. (2017), Leone et al. (2017), Miccoli et al. (2019), Gattesco & Boem (2017), Askouni & Papanicolau (2017, September), Bellini & Mazzotti (2016), Askouni & Papanicolau (2019), Bellini et al. (2019), Carrozzi & Poggi (2015), Olivito et al. (2016), Lignola et al. (2017), Bilotta et al. (2017a), De Santis et al. (2017), Carozzi et al. (2017), Ombres et al. (2019), D'Ambrisi et al. (2013), Donnini et al. (2016), Bellini & Mazzotti (2018, June), Garbin et al. (2018), De Felice et al. (2014), Ascione et al. (2015), Calabrese et al. (2020), Türkmen et al. (2019), Bellini et al. (2019), Donnini & Corinaldesi (2017), Calabrese et al. (2021), Rovero et al. (2020), Bilotta et al. (2017b), Alecci et al. (2016), Caggegi et al. (2017), most of the substrates have a compressive strength ranging in 10-20 MPa (68.4%) and in 20-30 MPa (13.4%, Fig. 3a), which corresponds to the predominant use of clay bricks. Similarly, a reduction of the mechanical properties of the reinforcing mortar can be observed, since only 10% of the samples has mortar with a compressive strength higher than 25 MPa (Fig. 3b), while the same value is exceeded for almost 90% of the data in case of concrete samples. A wider variety of the dry fibres can be observed in comparison with the applications on concrete specimens: Glass, Carbon and Steel fibres are, indeed, the most used FRCM systems (85%, Fig. 3c). Differently from concrete, for masonry substrates, the failure modes are more variegated: the most frequent ones are the tensile rupture of the fibres at the free end (type "F", 36.3%), the slippage of the textile within the matrix (type "D", 20.7%), and a mixed failure mode involving both slippage and debonding phenomena (22.2%). Conversely, the most common failure mode observed in concrete substrate, i.e., the type 'C', debonding at the matrix-to-substrate interface, is attained in masonry specimens only for the 9.7% of cases. The equivalent thickness of the dry fibres is variable in 0.014-0.188 mm. The number of layers is mainly equal to one. Differently from what observed in concrete specimens, almost all the masonry samples (99%) are characterized by a bond length lower or equal than 300 mm. Even in this case, the single lap is the most used set-up.

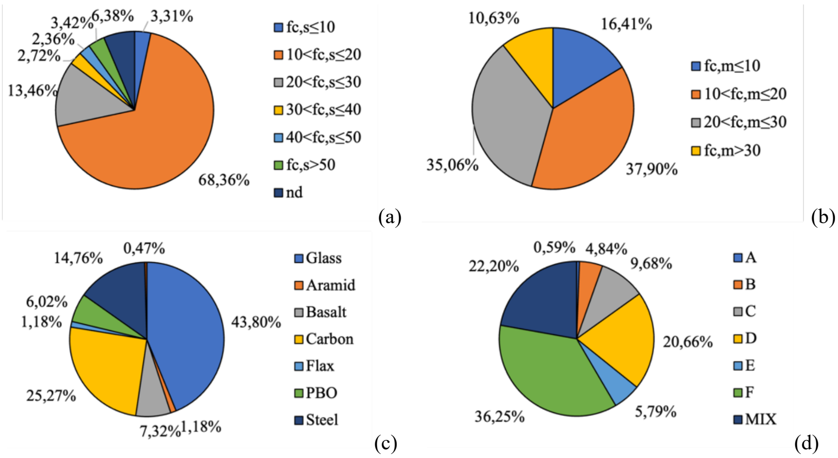

Fig. 3. Description of masonry full database: (a) compressive strength of substrate, (b) compressive strength of matrix, (c) type of dry fibre, (d) failure modes.

In Table 1 and Table 2, the average values of the equivalent thickness, t_f, and of the elastic modulus, E_f, of the dry fibres are summarized, in addition to the compressive strength of substrate, $f_{c,s}$, and of matrix, $f_{c,m}$, for both concrete and masonry specimens. Note that the average values are calculated with reference to both all data and to the data grouped according to observed failure modes. In detail, "Debonding" includes crisis type "A", "B" and "C", "Slippage" crisis type "D" and "E", "Tensile Failure" the only crisis type "F", and "Mix" includes a combination of two or more failures falling in "Debonding" and "Slippage".

Table 1. Average geometric and mechanical properties for FRCM-concrete tests

	Total	*Debonding*	*Slippage*	*Tensile failure*	*Mix*
#	411	306	35	7	63
# *[%]*	100.00	74.75	8.52	1.70	15.33
t_f *[mm]*	0.087	0.088	0.075	0.047	0.090
E_f *[GPa]*	210.16	212.28	242.96	78.57	204.45
$f_{c,s}$ *[MPa]*	38.41	39.33	34.48	35.49	34.36
$f_{c,m}$ *[MPa]*	29.87	29.13	34.50	38.17	30.75

Table 2. Average geometric and mechanical properties for FRCM-masonry tests

	Total	*Debonding*	*Slippage*	*Tensile failure*	*Mix*
#	847	128	224	307	188
# *[%]*	100.00	15.11	26.45	36.25	22.20
t_f *[mm]*	0.064	0.075	0.063	0.061	0.063
E_f *[GPa]*	133.81	159.32	134.56	108.54	155.28
$f_{c,s}$ *[MPa]*	19.40	18.40	23.34	15.04	19.84
$f_{c,m}$ *[MPa]*	22.36	21.51	24.17	18.35	25.80

3. Available design-oriented models (DOMs)

The predictive equations for maximum strain in the FRCM reinforcement, $\varepsilon_{maxt,th}$, proposed in Ceroni & Salzano (2018) for different failure modes in concrete and masonry specimens and assessed on the basis of a calibration carried out on 758 results of bond tests are compared with the more extended collected database presented in this paper. The formulations, named in the following as 'Design-Oriented Models' (DOMs), propose a dependence of $\varepsilon_{maxt,th}$ on the axial stiffness of the reinforcement E_fA_f [*N*], being A_f the transversal area of the dry fibers, for both concrete (Eq. 1) and masonry (Eqs. 2, 3, 4) specimens. For concrete specimens, a direct dependence on the compressive strength of the substrate, $f_{c,s}$ [*MPa*], is individuated, while for the masonry ones a dependence on the tensile strength of the substrate, $f_{t,s}$ [*MPa*], is proposed. For masonry, a formulation (Eq. 4) introducing also the tensile strength of the matrix, $f_{t,m}$ [*MPa*], is provided:

$\varepsilon_{max,th} = 0.008(E_f A_f)^{-0.30} f_{c,s}{}^{1.15}$ Concrete samples – Debonding failure (1)
$\varepsilon_{max,th} = 21(E_f A_f)^{-0.79} f_{t,s}{}^{2.48}$ Masonry samples – Debonding failure (2)
$\varepsilon_{max,th} = 304(E_f A_f)^{-0.96} f_{t,s}{}^{2.05}$ Masonry samples – Debonding + Slippage failure (3)
$\varepsilon_{max,th} = 4476(E_f A_f)^{-1.20} f_{t,s}{}^{2.10} f_{t,m}{}^{0.43}$ Masonry samples – Debonding + Slippage failure (4)

4. Improved design-oriented models (IDOMs)

Basing on the more numerous results collected in the extended database, Improved Design-Oriented Models (IDOMs) are herein proposed by means of the following Eqs (5) - (8), where the same structure of Eqs. (1)-(4) is adopted and only the numerical coefficients are changed depending on the new calibration. The numerical coefficients, named in the following section as α, β, γ and, when needed, δ, for both models, are assessed by a best fitting multi-variate procedure aimed to minimize the scatter between the theoretical predictions and the experimental results. It is worth noting that, lacking experimental information about the tensile strength of matrix and masonry in most cases of the new database, the following assumptions, based on the correlations observed in the available data, are done: $f_{t,s} = 0.20\,f_{c,s}$ and $f_{t,m} = 0.10\,f_{c,m}$. Note that in the database used in Ceroni & Salzano (2018), $f_{t,s}$ was available in most cases and, when not, it was assumed $f_{t,s} = 0.10\,f_{c,s}$, as for the matrix. These different assumptions, mainly related to the lack of experimental data in the new database, should lead to a different accuracy of the Eqs. (1)-(4) when applied to the extended database and highlight the importance of a reliable estimate of the tensile strength of substrate and matrix:

$\varepsilon_{max,th} = 0.008(E_f A_f)^{-0.26} f_{c,s}{}^{1.00}$ Concrete samples – Debonding failure (5)
$\varepsilon_{max,th} = 0.824(E_f A_f)^{-0.42} f_{t,s}{}^{0.54}$ Masonry samples – Debonding failure (6)
$\varepsilon_{max,th} = 2.492(E_f A_f)^{-0.44} f_{t,s}{}^{-0.33}$ Masonry samples – Debonding + Slippage failure (7)
$\varepsilon_{max,th} = 19.14(E_f A_f)^{-0.58} f_{t,s}{}^{-0.16} f_{t,m}{}^{-0.58}$ Masonry samples – Debonding + Slippage failure (8)

5. Experimental versus predicted comparisons

Empirical-based formulations are suitable tools since the simplicity of the equations is appreciated by the practitioners. The amount of data, the cleaning of anomalous results and the efficiency of the clusterization are highly dependent on the dimension of the dataset used for the calibration. At this scope, the present section compares the findings of the DOMs versus the IDOMs in term of the experimental/predicted strain ratio, δ, since the availability of a more extended database requests to check accuracy and precision of DOMs. Clearly, $\delta = 1$ corresponds to a perfect fitting between experimental results and theoretical predictions, $\delta > 1$ should indicate that the predictions are safe, and $\delta < 1$ that they are unsafe. Accuracy and correlation of the predictions are evaluated by means of the probability density functions, PDF, i.e. the *Gaussian* curves plotted in Fig. 4a-d, and the statistical indexes (mean, median, mode, standard deviation, skew of the PDF of δ, and R^2 associated to each regression) listed in Table 3, both referred to the experimental/predicted strain ratio, δ. The parameter R^2, standard deviation and skew give an estimate of the accuracy, while mean, median and mode values measure the precision of the theoretical predictions.

Firstly, Table 3 shows that, as expected, the R^2 values associated to the best fitting multi-variate regression is improved for all the IDOMs in comparisons with the DOMs, since the latter were calibrated on a reduced set of data and different assumptions on the substrate tensile strength were done. Positive values of skew indicate a PDF with an asymmetric tail extending toward more positive values, while a negative skew indicates a PDF with an asymmetric tail extending toward more negative values. Since the values of skew are positive for all DOMs and IDOMs, this means that as higher than 0 is the skew, greater is the mean with respect to the median.

Fig. 4a compares the results provided by Eqs. (1) and (5), i.e. refers to concrete specimens failed for debonding. The two PDFs are very close to overlap each other, the coefficients α, β, γ are quite the same and the statistical indexes manifest comparable mean, median and mode, thus evidencing almost the same results. It should be remarked also that the skew of the IDOM is significantly lower than that of the DOM (0.42 vs. 1.23) meaning the improved model is more symmetric with respect to the mid-line. In fact, in IDOMs mean, median and mode are closer to 1 than in DOMs.

Fig. 4b compares the results provided by Eqs. (2) and (6), i.e. refers to masonry specimens failed for debonding. In this case, the new calibration provides very different values for coefficients α, β, γ. Eq. (6) is mainly on the safe side as Eq.(2), but both precision and accuracy are quite improved, since the mean value associated to of Eq. (6) is closer to 1 (1.36 vs. 1.46) and the standard deviation is lower (σ = 1.32 vs. 2.38).

Fig. 4c compares the results provided by Eqs. (3) and (7), i.e. refers to masonry specimens where the debonding occurred combined with slippage failure. Again, the new coefficients are different from those of Eq. (3), but the predictions are relevantly improved both in term of precision and accuracy since the mean value associated to Eq. (7) is more proximal to 1 and mainly on the safe side (1.10 vs. 0.83) and the standard deviation is significantly lower (σ = 0.60 vs. 1.81).

Finally, Fig. 4d compares the results provided by Eqs. (4) and (8), where the additional dependence on the tensile strength of the mortar, $f_{t,m}$, is introduced. For this case, the IDOM significantly upgrades the predictive capacity that are mainly safe (mean value 1.14 vs. 0.80) and less scattered (σ = 0.49 vs. 0.90) in comparison with the DOM.

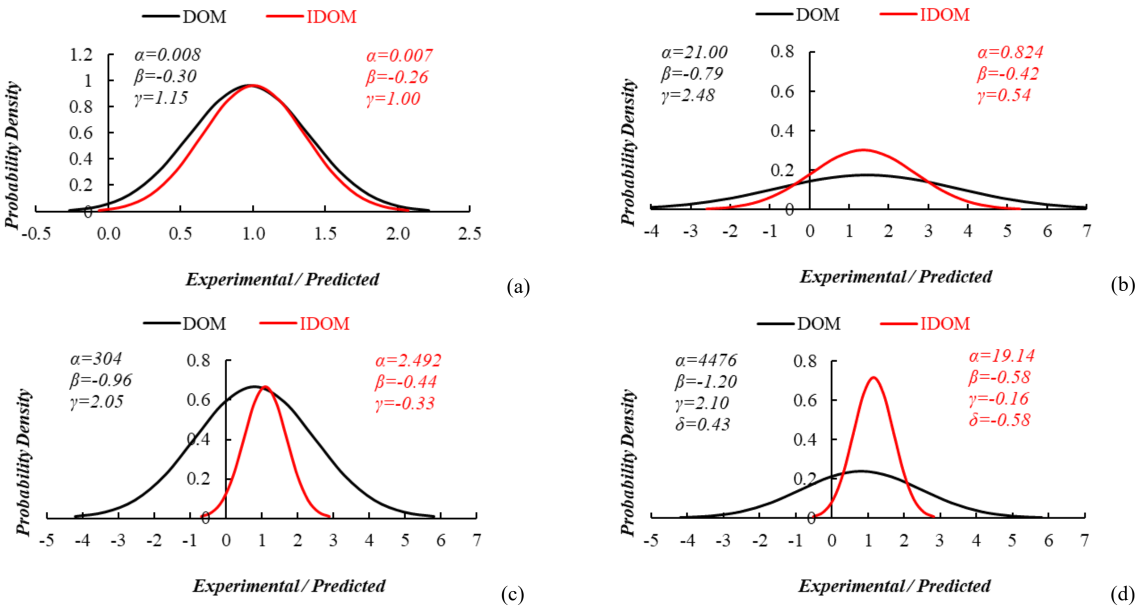

Fig. 4. DOMs vs IDOMs: (a) concrete – debonding, Eqs. (1) and Eq. (5), (b) masonry – debonding Eq. (2) and Eq. (6), (c) masonry – debonding + slippage, Eqs. (3) and Eq. (7), (d) masonry – debonding + slippage, Eqs. (4) and Eq. (8).

Table 3. Statistical analysis of the experimental/predicted strain ratio, *δ*.

	DOM				IDOM			
	concrete	*masonry*			*concrete*	*masonry*		
	debonding Eq. (1)	*debonding Eq. (2)*	*deb. +slippage Eq. (3)*	*deb. + slippage Eq. (4)*	*debonding Eq. (1)*	*debonding Eq. (2)*	*deb. +slippage Eq. (3)*	*deb. + slippage Eq. (4)*
Mean	0.98	1.46	0.83	0.80	1.00	1.36	1.10	1.14
Median	0.95	0.42	0.25	0.25	1.00	1.00	0.93	1.04
Mode	0.98	0.32	-0.07	-0.03	1.00	0.70	0.80	0.87
R^2	0.89	0.17	0.31	0.40	0.90	0.54	0.76	0.90
σ	0.41	2.28	1.81	1.67	0.41	1.32	0.60	0.56
Skew	1.23	2.33	3.64	3.61	0.42	2.81	1.35	0.85
n	284	96	289	289	284	96	289	289

6. Conclusions and final remarks

The FRCMs are innovative composite materials with a promising application in the field of strengthening for both concrete and masonry structural members. Few analytical models are now available for predicting the maximum FRCM-bond strain. On the other side, the number of existing bond tests has grown considerable in the last years and, thus, a first attempt to provide a design-oriented formulation for the maximum FRCM-bond strain is proposed in this paper basing on the review of empirically-based formulations available in literature. Indeed, a new calibration is carried out herein, in order to improve the quality of the predictions for a set of formulations targeted on different failure modes and substrate (concrete or masonry) by collecting a larger database of experimental results. The comparisons of the new predictions with the experimental results evidenced:

- for concrete substrates, the new calibrated predictions have almost the same accuracy and precision of the old ones, confirming, thus, their reliability also when the database is extended;
- for masonry substrates, the available DOMs lose their accuracy when processed with a more extended database also because of the wide lacking of the experimental values of the substrate tensile strength, which, on the contrary, was diffusely available in the original database;
- for masonry substrates, the best prediction in terms of accuracy and precision is provided by the formulation depending on the axial stiffness of the FRCM reinforcement and the tensile strength of both masonry and matrix.

The availability of a more extended database of bond tests surely allowed to improve the knowledge of the bond behavior for FRCM materials applied on concrete and masonry substrates and to identify the most significant parameters, i.e. axial stiffness of the fibers, compressive and tensile strength of substrate and matrix, but, for a reliable prediction of the maximum strain, deeper investigations need about the effect of these parameters and the estimation of the tensile strength of substrate and matrix when they are not experimentally available.

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