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DESIGN RELATIONSHIPS FOR THE STRENGTHENING OF MASONRY WALLS WITH MORTAR-BASED COMPOSITES

STEFANO DE SANTIS*, PIETRO MERIGGI*, SARA FARES* AND GIANMARCO DE FELICE*

* Department of Engineering, Roma Tre University
Via Vito Volterra 62, 00146 Rome, Italy
e-mail: stefano.desantis@uniroma3.it, www.romatrestrutture.eu

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Abstract. The paper presents a design method for the strengthening of masonry walls with fabric reinforced cementitious matrix (FRCM), steel reinforced grout (SRG) and composite reinforced mortar (CRM) systems. They have proved effective for the enhancement of structural capacity and are suitable for seismic retrofitting and for applications to architectural heritage. More recently, significant research efforts have been devoted to the development of testing/certification methods and of design guidelines. For this latter purpose, analytical relationships were developed, which are consistent with Eurocodes, are suitable for engineering practice, and have been incorporated in design guides. Both the bending strengthening under out-of-plane loads and the shear strengthening under in-plane loads are dealt with in the paper. The validation of the resisting models and the calibration of partial coefficients according to the design-by-testing approach are described. Assumptions, limitations and advantages are discussed, to promote the knowledge transfer from the academia to engineering practice and the proper use of FRCM, SRG and CRM for enhancing the safety level of the built environment.

1 INTRODUCTION

The structural rehabilitation of the built environment has highly benefited of the development of mortar-based composites, which consist of high strength textiles bonded to the outer surface of structural members by means of inorganic matrices (cement, lime or geopolymer mortars). These strengthening systems are known as fabric reinforced cementitious matrix (FRCM), when comprising carbon, glass, basalt, aramid, PBO or natural fabrics [1-6], steel reinforced grout (SRG), when comprising brass or zinc coated or stainless-steel textiles [7-10], and composite reinforced mortar (CRM), when comprising pre-cured Fibre Reinforced Polymer meshes [11-13]. Although different names and acronyms actually correspond to slight differences, all these composites share the same fundamental mechanical properties.

FRCM, SRG and CRM have been engineered, investigated and analysed by several research groups in the last two decades. At the same time, industry and suppliers have made available on the market a number of products, which have been already widely applied. Their main fields of use are the seismic retrofitting, thanks to the high strength-to-weight ratio, which provides significant gain in structural capacity with negligible increase of mass and weight [3,13], and the strengthening of architectural heritage, thanks to the use of inorganic (specifically, lime-based) matrices, which ensure the compatibility with historic substrates [1].

The fast evolution of this technology has required important efforts to the academic community, institutions, practitioners and producers, to develop testing methods and certification criteria, which were needed to determine the fundamental mechanical and durability properties [14-15], as well as design guidelines, which have been conceived to make engineering calculations and assess the safety level of the strengthened structures [16-17]. Indeed, design methods represent the newest contribution to engineering practice and, at the same time, still deserve research efforts. This paper describes a design approach for the strengthening of masonry walls with mortar-based composites, under both out-of-plane and in-plane loads. Design relationships are presented, which are suitable for ultimate limit state calculations. Resisting models are validated and their partial coefficients are calibrated according to the design-by-testing approach [18], consistently with the design framework set by Eurocodes. Finally, possible lines are identified for future research, aimed at the improvement of design tools.

2 IN-PLANE SHEAR STRENGTHENING

2.1 Resisting model and design method

In order to enhance the shear strength of a masonry wall, mortar-based composites can be applied either to both wall sides (with or without transversal connectors) or to one side only. Asymmetric layouts are less effective than symmetric ones, but may be the sole option to comply with architectural limitations (e.g., paintings or fair-faced masonry) or to minimize impact. The entire wall surface is generally covered with the strengthening system (especially when this comprises bidirectional textiles), whereas a grid layout with vertical and horizontal strips can be applied with unidirectional textiles. The failure mode of the strengthened wall may be either flexure-controlled, such as rocking (Figure 1a) and toe crushing (Figure 1d), or shear-controlled, such as joint sliding (Figure 1b) and diagonal tension (Figure 1c).

The investigations performed so far have shown that the shear strength of the masonry wall is increased by mortar-based composites through three resisting mechanisms. The main one is the *strut-and-tie* mechanism, in which inclined compressed masonry trusses develop together with tensile resistant ties, which correspond to the tensile stress experienced across the cracks by the textile embedded in the externally bonded overlay. It provides a significant increase of shear strength, even if it may be fully exploited at relatively large displacements (that is, after large cracks have developed). A second mechanism relies on the enlargement of the resisting cross-section of the *compressed diagonal truss*. It depends on the thickness of the mortar matrix and on its compressive strength and is eminently brittle. Finally, transversal connectors (if present) provide some *confinement* to the masonry, limiting transversal deformations and disintegration. This mechanism is more difficult to model than the previous ones, also due to the few tests carried out so far, which allow identifying the specific contribution of connectors. To derive simple and conservative design relationships, only the first resisting mechanism (*strut-and-tie*) is considered whereas the other ones (*compressed diagonal truss* and *confinement*) are neglected.

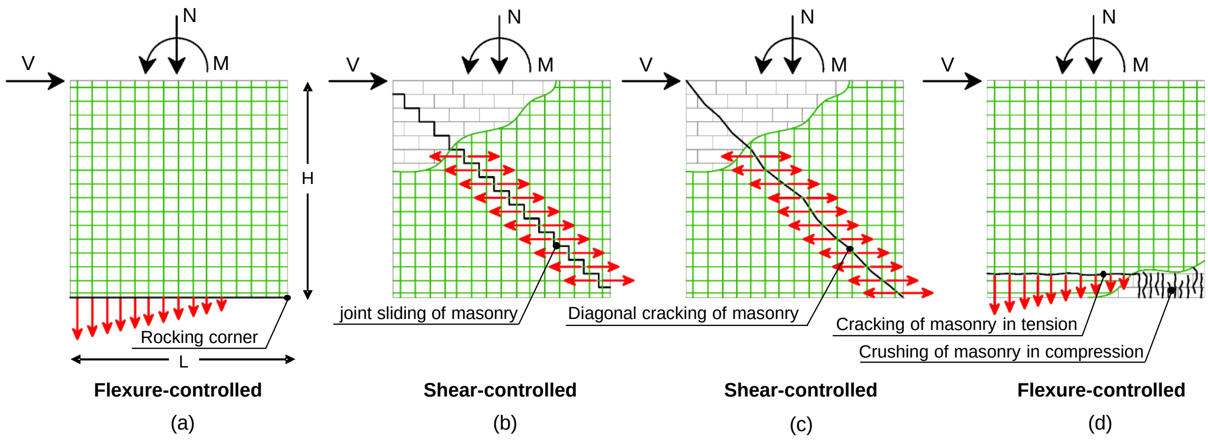


Figure 1: failure modes of a masonry wall under in-plane loads and corresponding resisting mechanisms provided by externally bonded mortar-based composites: rocking (a), joint sliding (b), diagonal tension (c) and toe-crushing (d) (failure modes are ordered for increasing vertical load)

Under these assumptions, the ultimate shear strength of a masonry wall strengthened with FRCM, SRG or CRM systems can be evaluated as that of the unstrengthened wall (V_{Rd}^{UR}), estimated with design codes, e.g. Eurocode 6 [19], plus the shear strength increase provided by the externally bonded composite (ΔV_{Rd}) multiplied by a model coefficient γ_K<1, which accounts for model errors and leads to an adequate safety level (Equation 1).

$$V_{Rd} = V_{Rd}^{UR} + \gamma_K \Delta V_{Rd} \quad (1)$$

The gain in shear strength (ΔV_{Rd}) depends on the width (L) and height (H) of the wall, on the layout of the strengthening, namely width (w_{fH}), spacing (s_{fH}) and cross-sectional area per unit width (t_{fH}) of horizontal strips, on the number of strengthened wall sides (n), and, finally, on the ultimate design strength of the composite (f_{fd}) (Equation 2).

$$\Delta V_{Rd} = \eta \, min(H;L) \, n \, t_{fH} \, w_{fH} / s_{fH} \, f_{fd} \quad (2)$$

In Equation 2, and on the base of scientific literature, η=1 if the wall is double-sided retrofitted and η=0.7 if the strengthening system is applied to one side only. As for f_{fd}, it considers the weakest failure mechanism between the tensile failure of the textile and the debonding of the strengthening system from the substrate, as per Equation 3, in which f_{bk} and f_{tk} are the characteristic (0.05-fractile) bond and tensile strengths, γ_f is a material partial coefficient (γ_f=1.5 for ultimate limit state), and α_1 and α_2 are tuning coefficients, which account for the different boundary conditions experienced by the mortar-based composite when applied in the field with respect to those of the laboratory, and are statistically calibrated on experimental basis, as described below.

$$f_{fd} = min(\alpha_1 f_{bk} \, ; \, f_{tk}/\alpha_2) / \gamma_f \qquad \alpha_1, \alpha_2, \gamma_f \geq 1 \quad (3)$$

2.2 Validation and calibration of design relationships

An experimental database was collected to validate the resistance model and calibrate its coefficients. The database is comprised of 122 tests, 66 datasets (groups of nominally identical tests) from 21 papers, and includes medium-scale bending tests on wall panels, full-scale tests on masonry walls under out-of-plane concentrated loads (with or without axial load), and full-scale air-bag tests (shake table tests were neglected), as described in detail in [20].

The design-by-testing approach recommended by Annex D of Eurocode 0 was followed [18]. First, α_1 and α_2 were tuned to match the average theoretical values of shear strength increase (ΔV_{Rm}^{th}) and the corresponding experimental outcomes (ΔV_R^{exp}). For this purpose, the tests exhibiting the tensile failure of the textile and the composite-to-substrate debonding (through any of the possible modes of failure listed in [15]) were considered separately. The resulting values are α_1=1.15 (from the subset of failures by debonding) and α_2=1.25 (form the subset of failure by tensile rupture), and a relatively good agreement between theoretical and experimental values was achieved (Figure 2a). At this stage, the average properties of the strengthening systems were taken and no partial safety factors were applied.

Then, the characteristic value of the theoretical shear strength increase was estimated to calibrate the model coefficient, which led to γ_K=1.5. The comparison between design values (ΔV_{Rd}^{th}, obtained from characteristic strengths and by applying safety factors) and experimental values (ΔV_R^{exp}) shows that the proposed design method provides a conservative estimate of the gain in shear strength, which makes it suitable for use in engineering practice (Figure 2b).

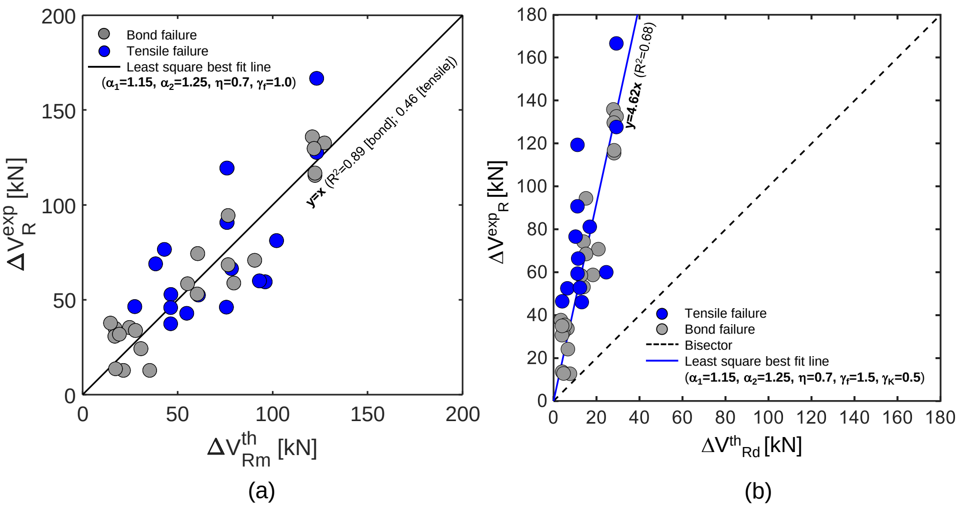


Figure 2: experimental vs. average (a) and design (b) shear strength increases

3 OUT-OF-PLANE FLEXURAL STRENGTHENING

3.1 Resisting model and design method

Externally bonded mortar-based composites can be used also to enhance the out-of-plane flexural strength of masonry walls. Reinforcement systems can be applied to the entire wall surface or in discrete vertical and horizontal strips, depending on textile arrangement (bidirectional meshes are more suitable for full covering, whilst unidirectional textiles are more commonly applied in strips), and loading conditions (vertical/horizontal bending). As for the shear strengthening, the composites can be installed either on both wall sides or on one side.

The flexural strength of a retrofitted wall can be evaluated with a cross-sectional analysis, assuming strain compatibility between mortar-based composite and masonry, plane section conservation, linear-elastic behaviour in tension and no contribution in compression of the strengthening system, and, finally, stress-block diagram in compression and no tensile strength of masonry. From the strain profile shown in Figure 3, two failure modes are considered. namely crushing of masonry (failure mode I), if the strain in the compressed masonry attains its ultimate value (ε_{mu}) or failure of the strengthening system (failure mode II), if it attains its design strain (ε_{fd}). Similar to the design strength considered for the shear strengthening discussed above, the design strain relies on those corresponding to the bond failure and to the tensile failure, which are modified through the tuning coefficients α_1 and α_2, and reduced by the partial coefficient γ_f, as per Equation 4.

$$\varepsilon_{fd} = \min(\alpha_1 \varepsilon_{bk} \ ; \ \varepsilon_{tk}/\alpha_2) \ / \ \gamma_f \qquad \alpha_1, \alpha_2, \gamma_f \geq 1 \tag{4}$$

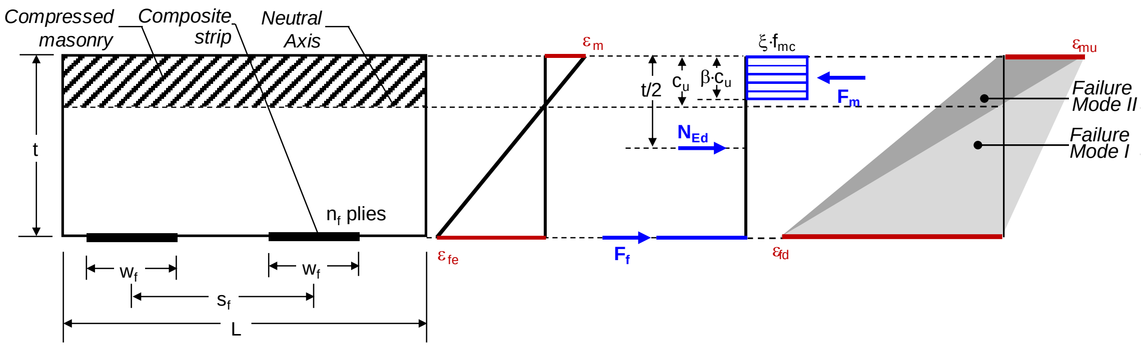


Figure 3: cross-section of the wall, strain and stress profiles, load resultants, and failure modes for a retrofitted wall under out-of-plane bending

With these assumptions, the design ultimate flexural strength is obtained as that of the unstrengthened wall (M_{Rd}^{UR}), which cab ne evaluated as recommended by Eurocode 6 [18] or other building codes, plus the gain in flexural strength provided by the mortar-based composite (ΔM_{Rd}) multiplied by a model coefficient (γ_K<1), according to Equation 5, in which M_R is the total flexural strength of the retrofitted wall net of any partial coefficients.

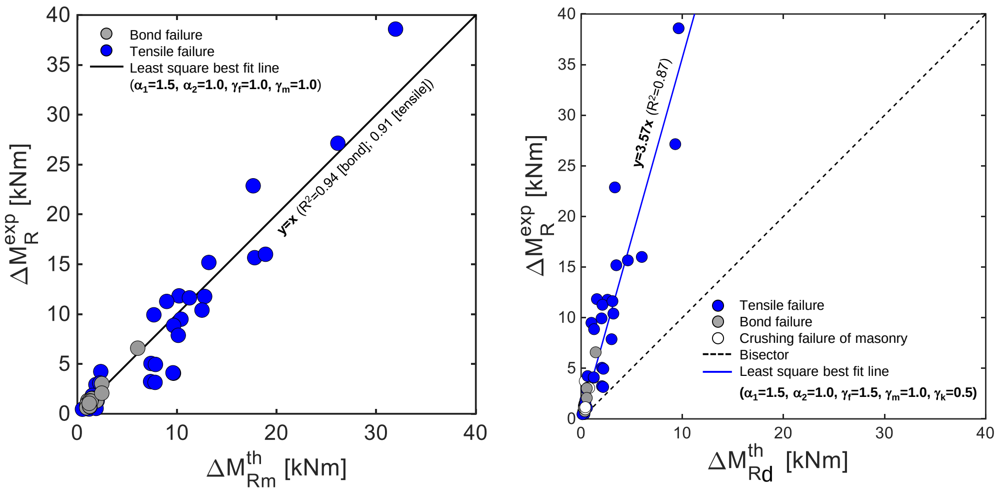
$$\begin{aligned} M_{Rd} &= M_{Rd}^{UR} + \gamma_K \, \Delta M_{Rd} \\ \Delta M_{Rd} &= (M_R - M_{Rd}^{UR}) \end{aligned} \tag{5}$$

M_R depends on the width and thickness of the wall, on the external axial load, on the number of textile layers, strips spacing, width of the single strip, design thickness of each textile layer, design axial strain (ε_{fd}) and tensile elastic modulus of the composite, and on the compressive strength of masonry. More details and all the analytical relationships are provided in [21].

3.2 Validation and calibration of design relationships

In order to validate the resistance model and calibrate its coefficients, an experimental database of 97 tests (57 datasets) extracted from 14 papers was collected [21]. Following the same procedure described above for the in-plane shear case, the values of the coefficients α_1=1.5 and α_2=1.0 were determined as those providing the Least Square best-fit between the average theoretical values of flexural strength increase (ΔM_{Rm}^{th}) and the corresponding experimental values (ΔM_R^{exp}) [19], as shown in Figure 4a. The average theoretical flexural strength increase being considered, the average properties of the strengthening systems and of masonry were taken and no safety factors were applied for this calibration.

The model coefficient γ_K=1.5 was calibrated considering the characteristic strengths of the materials (composite and masonry) and applying the corresponding partial safety factors. The estimate results adequately conservative, as demonstrated by the comparison between design (ΔM_{Rd}^{th}) and experimental values (ΔM_R^{exp}) shown in Figure 4b.



(a) (b)

Figure 4: experimental vs. average (a) and design (b) flexural strength increases

4 CONCLUSIONS

After two decades of experimental investigations and huge steps forward in the industrial development of mortar-based composites, recent research efforts have proposed design relationships for the strengthening of masonry walls under out-of-plane and in-plane loads. The overview provided by this paper shows that simple analytical formulations can be used in engineering practice for design calculations, which are consistent with the limit state framework set by Eurocodes and lead to conservative estimates of the increase of shear and bending strength provided by externally bonded strengthening systems.

An additive expression is proposed for the design shear strength, based on the strut-and-tie resisting mechanism, which activates after masonry cracking thanks to the strength of the textile embedded in the reinforcement overlay. Contributions relying on the compressive strength of the added mortar and on the confinement effect due to transversal connectors are instead neglected. Research is still ongoing on this issue and more efforts are definitely needed to gain a deeper knowledge on the compatibility between the full exploitation of the strut-and-tie contribution and the damage state in the wall and its displacement, as well as on the possible consideration of other contributions. The possible occurrence of cyclic (seismic) loads needs to be carefully considered for this purpose, and it may be worth considering the shear behavior of a cracked wall to keep formulations on the safe side.

A cross-section analysis provides the flexural strength of the retrofitted wall, starting from a compatibility-based strain profile. Simplified constitutive relationships are considered (elastic-brittle in tension for the composite, and a stress-block in compression for the masonry). Two failure modes are possible, depending on the material that attains first its design ultimate strain. Also in this case, the effect of cyclic, or even dynamic, loads should be considered to improve the design method for seismic retrofitting purposes.

In both the shear and the flexural strengthening, the weakest failure mode of the externally bonded composite, either the tensile rupture of the textile or its debonding from the substrate, is considered. The design-by-testing approach of Eurocode 0 is followed to calibrate tuning coefficients, which account for the different boundary conditions experienced by the composite when applied to large scale structural members with respect to those of small-scale laboratory tests, and a model coefficient, which includes the effects of uncertainties and variability and provides a suitable safety level.

With the aim of fostering the proper use of mortar-based composites in the rehabilitation of the built environment, more research efforts are definitely needed. Both for in-plane shear and for out-of-plane bending, the collection of further tests would allow developing improved relationships and calibrating more robust statistic coefficients. A full characterization of the strengthening materials is essential for this purpose. At the same time, from the viewpoint of real field applications, computational tools are needed for numerical simulations and structural analyses of complex layouts, with reference to loading, boundary and geometric configurations.

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REFERENCES

[1] Papanicolaou, C.G., Triantafillou T.C., Karlos K. and Papathanasiou M. Textile-reinforced mortar (TRM) versus FRP as strengthening material of URM walls: in-plane cyclic loading. *Mater. Struct.* (2007) **40**:1081-1097.

[2] Babaeidarabad, S., De Caso, F. and Nanni, A. URM walls strengthened with fabric reinforced cementitious matrix composite subjected to diagonal compression. *J. Compos. Constr.* (2014) **18**:04013045.

[3] De Santis, S., De Canio, G., de Felice, G., Meriggi, P. and Roselli, I. Out-of-plane seismic retrofitting of masonry walls with Textile Reinforced Mortar composites. *Bull. Earthq. Eng.* (2019) 17:6265-6300.

[4] De Santis, S., Roscini, F. and de Felice, G. Retrofitting of masonry vaults by basalt-textile reinforced mortar overlays. *Int. J Archit. Herit.* (2019) **13**:1061-1077.

[5] Meriggi, P., Caggegi, C., Gabor, A. and de Felice, G. Shear-compression tests on stone masonry walls strengthened with basalt textile reinforced mortar (TRM). *Constr. Build. Mater.* (2022) **316**:125804.

[6] de Carvalho Bello, C.B., Boem, I., Cecchi, A., Gattesco, N. and Oliveira, D.V. Experimental tests for the characterization of sisal fiber reinforced cementitious matrix

for strengthening masonry structures. *Constr. Build. Mater.* (2019) **219**:44-55.
[7] Borri, A., Casadei, P.¸ Castori, G. and Hammond, J. Strengthening of Brick Masonry Arches with Externally Bonded Steel Reinforced Composites. *J. Compos. Constr*. (2009) **13**:468-475.
[8] De Santis, S., AlShawa, O., de Felice, G., Gobbin, F., Roselli, I., Sangirardi, M., Sorrentino, L. and Liberatore, D. Low-impact techniques for seismic strengthening fair faced masonry walls. *Constr. Build. Mater.* (2021) **307**:124962.
[9] Fares, S., Fugger, R., De Santis, S. and de Felice, G. Strength, bond and durability of stainless Steel Reinforced Grout. *Constr. Build. Mater.* (2022) **322**:126465.
[10] Meriggi, P., de Felice, G., De Santis, S., Morganti, M. and Roscini, F. Durability of steel reinforced grout systems subjected to freezing-and-thawing conditioning. *Proc. 1st fib Italy YMG Symp. Concr. and Concr. Struct.* (2019) 47-55.
[11] Corradi, M., Borri, A., Castori, G. and Sisti, R. Shear strengthening of wall panels through jacketing with cement mortar reinforced by GFRP grids. *Compos. B Eng.* (2014) **64**:33-42.
[12] Gattesco, N., Boem, I. and Dudine, A. Diagonal compression tests on masonry walls strengthened with a GFRP mesh reinforced mortar coating. *Bull. Earthq. Eng.* (2015) **13**:1703-1726.
[13] De Santis, S. and de Felice, G. Shake table tests on a tuff masonry structure strengthened with composite reinforced mortar. *Compos. Struct.* (2021) **275**:114508.
[14] De Santis, S., Hadad, H.A., De Caso y Basalo, F., de Felice, G. and Nanni, A. Acceptance criteria for tensile characterization of Fabric Reinforced Cementitious Matrix (FRCM) systems for concrete and masonry repair. *J. Compos. Constr.* (2018) **22**:e0401804.
[15] de Felice, G., Aiello, M.A., Caggegi, C., Ceroni, F., De Santis, S., Garbin, E., Gattesco, N., Hojdys, Ł., Krajewski, P., Kwiecień, A., Leone, M., Lignola, G.P., Mazzotti, C., Oliveira, D., Papanicolaou, C., Poggi, C., Triantafillou, T., Valluzzi, M.R. and Viskovic, A. Recommendation of RILEM Technical Committee 250-CSM: Test method for Textile Reinforced Mortar to substrate bond characterization. *Mater. Struct.* (2018) **51**:1-9.
[16] ACI American Concrete Institute. *ACI 549.6R-20: Guide to Design and Construction of Externally Bonded Fabric-Reinforced Cementitious Matrix (FRCM) and Steel-Reinforced Grout (SRG) Systems for Repair and Strengthening Masonry Structures*. Farmington Hills, MI, USA (2020).
[17] National Research Council. *CNR-DT 215/2018: Guide for the design and construction of Externally Bonded Fibre Reinforced Inorganic Matrix systems for strengthening existing structures*. Rome, Italy (2020).
[18] CEN European Committee for Standardization. *EN1990. Eurocode 0: Basis of structural design*. Brussels, BE (2002).
[19] CEN European Committee for Standardization. *EN1996. Eurocode 6: Design of masonry structures*. Brussels, BE (2005).
[20] Meriggi, P., De Santis, S., Fares, S. and de Felice, G. Design of the shear strengthening of masonry walls with fabric reinforced cementitious matrix. *Constr. Build. Mater.* (2021) **279**:122452.
[21] Meriggi, P., de Felice, G. and De Santis, S. Design of the out-of-plane strengthening of masonry walls with fabric reinforced cementitious matrix composites. *Constr. Build. Mater.* (2020) **240**:117946.