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CONTRIBUTION OF FLAX-TRM SYSTEMS TO THE SHEAR RESISTANCE OF RETROFITTED MASONRY WALLS

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Abstract

This paper discusses the philosophy of current design shear models and assesses their suitability for the prediction of the shear capacity of Flax TRM-retrofitted walls based on experimental results from in plane cyclic shear tests on masonry walls retrofitted with flax-TRM. The main parameters governing the design of the retrofitting solution are identified, and the performance of the examined models is critically assessed in terms of both ultimate predicted load capacity and failure mode. Based on the strain development in the flax textiles, a shear decomposition of the resisting mechanisms is performed, and the relative contribution of the masonry, mortar overlay and textile is estimated. Finally, a new simplified design model that accounts for the contribution of the mortar and adopts a more rational effective strain limit that can be developed in the textile is proposed. The model is validated against an experimental database including both advanced and natural-fibre TRM systems.

Keywords: TRM, In-Plane Shear, Shear Strengthening, Natural Fibres, Flax, Shear Models.

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1 INTRODUCTION

Textile-reinforced mortars (TRM), comprising inorganic matrices reinforced with advanced fibre meshes, have been employed successfully as externally bonded composite systems to increase the in-plane performance of unreinforced masonry walls. More recently, textiles made from natural fibres have attracted the interest of researchers, industry and standardisation committees, as they can offer a cost-effective alternative to advanced fabrics and can help meet pressing sustainability requirements.

Considerable work has been undertaken thus far to characterize the mechanical properties of natural-fiber TRM (NTRM) systems comprising flax, jute, sisal and hemp textiles [e.g. 1-3] embedded in lime-base mortar, and to examine their interaction with masonry [e.g. 4, 5]. Although all researches have highlighted the promising potential of flax-TRM systems in strengthening applications, very limited work has examined their performance as an in-plane strengthening solution for masonry structures. To date, Ferrara et al. [6] have provided encouraging evidence that the use of two layers of Flax-TRM can increase the strength (up to 136%) and ductility of masonry panels subjected to diagonal compression. Trochoutsou et al. [7] used a similar Flax-TRM system to retrofit masonry walls subjected to in-plane cyclic shear loading, and concluded that while the mortar overlay can significantly contribute to shear strength enhancement, the flax textiles can effectively promote strain redistribution and higher ultimate drift, while ensuring structural integrity. However, these two latter studies also highlighted that no significant increase in shear capacity was achieved when using multiple layers, unlike for advanced TRM systems [8].

Evidently, there is still a lack of a comprehensive understanding on the contributions of textiles, mortar and masonry to the overall shear resistance of TRM-retrofitted elements, and the suitability of existing design models for natural-fibre TRM needs to be assessed. Current approaches estimate the contribution of TRM systems only based on their tensile or bond performance, while neglecting the contribution of the mortar [9]. Although this approach can be satisfactory when TRM with high-performance textiles are used, it might not be applicable to natural-fiber TRM, as the lower stiffness textile can undergo relatively large deformations at low stress levels and the relative contribution of the mortar can be substantial. Hence, the underlying philosophy of current design recommendations for elements strengthened with advanced TRM needs to be re-assessed to enable the development of more sustainable NTRM strengthening solutions.

This paper comments upon the philosophy adopted by available design models and examines their performance against experimental results on FTRM-retrofitted walls previously obtained by the authors. The contribution of the mortar layer and textile reinforcement are estimated based on experimental evidence, and a new design model is proposed and validated against a larger database, including both natural and advanced TRM systems.

2 SUMMARY OF EXPERIMENTAL PROGRAMME AND RESULTS

Six single-wythe unreinforced masonry walls of 1.125 m x 1.115 m were tested under concurrent in-plane cyclic shear and axial load up to their Near Collapse limit state [10]. The tested specimens comprised four walls strengthened with one and two layers of Flax-TRM on both sides (two replicates for each configuration), while the remaining two, one bare wall and one wall strengthened with only one layer of lime mortar on both sides, served as control specimens. Digital Image Correlation (DIC) was employed to obtain full-field displacement measurements and estimate crack widths and local strain in the textile.

The average values of peak loads (P_{max}), ultimate displacements (δ_{max}) at Near Collapse, maximum local strain values around the critical diagonal crack (ε_{max}), average strain values (ε_{avg}) and failure modes are summarised in Table 1. Overall, all test specimens failed predominantly in diagonal shear. Although the bare and lime-only retrofitted walls experienced significant damage at relatively low drift levels, the application of only one layer of lime mortar on both sides of the wall resulted in a notable enhancement in strength and deformability, and enabled a certain degree of strain redistribution upon masonry cracking. The use of FTRM as a retrofitting solution provided significant in-plane strength and ultimate drift enhancement (up to 118%) and promoted the development of energy dissipation mechanisms, while ensuring structural integrity, and controlled the development of brittle failure modes. Detailed results and discussion can be found in [7].

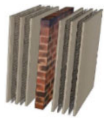
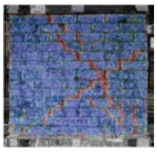
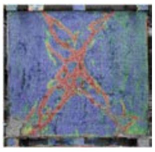
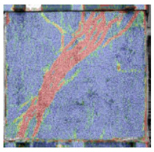
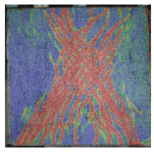
Strengthening configuration				
Specimen ID	BW	LW	FL1W	FL2W
P_{max} (kN)	46	83.7	90.1	98.2
δ_u (mm)	6.7	13.3	12.6	14.6
ε_{max} (%)	-	-	3.5	2.3
ε_{avg} (%)	-	-	2.0	0.3
Failure Mode				

Table 1: Summary of in-plane shear test results.

3 REVIEW OF CURRENT DESIGN APPROACHES

3.1 Predictive Models

Five analytical models for the estimation of the shear contribution of TRM are assessed in this paper and their main assumptions are discussed. The examined models include the model of ACI 549.4R [11], the models developed by ACI and RILEM in the latest ACI549 document [9], the model of Triantafillou [12], the model included in the Italian design recommendations [13] and the model recently developed by Thomoglou et al. [14]. The main equations are presented in Table 2, along with the relevant limiting stress/strain values and coefficients. The notation adopted here follows that used in the corresponding literature.

A limiting effective strain of 0.4% is imposed according to both approaches recommended by ACI [9,11]. However, a higher strain limit is also allowed according to the approach presented in the latest ACI document [9] if experimental evidence is provided. In contrast, the design strain recommended by RILEM is limited by the maximum tensile strain in the textile attained through bond tests and direct tensile tests on bare textiles, taken as the corresponding strength values divided by the stiffness of the bare textile and applying the experimentally calibrated coefficients α_1 and α_2, which are equal to 1.15 and 1.25, respectively. According to the model of Triantafillou [12], the stress that the TRM is allowed to develop (f_{td}) accounts for both its tensile properties and its bond performance, and is taken as the minimum of the tensile strength (f_{tk}) (from tests performed on TRM coupons) and bond stress at the onset of debonding

(f_{tbd}) (from shear bond tests performed on TRM/masonry substrate). The model proposed in the Italian standards [13] relies on the use of an effective strain, which is taken as the strain that is developed in the textile when the debonding strength is attained. Unless the resulting effective stress falls within the uncracked stage, an amplification factor α (=1.5) is also used to increase the effective strain and accounts for the higher strain that can be developed in the textile when local debonding is expected to occur at intermediate regions of an element. In any case, the tensile strength of the TRM cannot be exceeded. In addition, a reduction factor α_t is applied to the V_{TRM} (= 0.8 in the absence of experimental results) to account for the combined action of tension and shear on the textile strength. Finally, the model by Thomoglou et al. [14] is the only model that accounts separately for the shear contribution of the mortar (V_{mortar}) and the textile (V_f) and that can be used to assess the shear strength provided by the mortar overlays. The contribution of the TRM is the result of the sum of V_{mortar} and V_f, subsequently multiplied by a factor k, which is calibrated based on an experimental database and depends on the type of TRM/masonry substrate system.

Model	**ACI 549.4R**	**ACI 549.6R**	**Triantafillou**	**CNR DT 2015**	**Thomoglou et al.**
V_{TRM}	$2nA_fHf_{fv}$	$nA_fE_f\varepsilon_{fd}$	$0.9Hnt_ff_{td}$	$nt_fH\alpha_t\varepsilon_{fd}E_f$	$k(V_f+V_{mortar})$
Limits	$f_{fv}=\varepsilon_{fv}E_f$ $\varepsilon_{fv}=\min(\varepsilon_{fu},0.004)$	$\varepsilon_{fd}=min(\alpha_1\varepsilon_{fb},,\varepsilon_{tk}/\alpha_2)^*$	$f_{td}=min(f_{tk}/\gamma_t, f_{tbd})$	α (>1) α_t (<1)	$V_f=2nA_fHE_f\varepsilon_{ffd}$ $V_{mortar}=A_{mortar}E_{mortar}\varepsilon_{tm}$

*only in the RILEM approach

Table 2: Shear contribution of TRM (V_{TRM}) based on the examined predictive models.

3.2 Design parameters used in the analysis

With the exception of the models suggested by ACI 549.4R [11] and Triantafillou [12], which impose a limiting strain or stress value, respectively, the existing models followed by RILEM [9], CNR DT 215 [13] and Thomoglou et al. [14], adopt a design strain that is calculated as the ratio of the maximum stress over the stiffness of the dry textile, thus applying a linear tensile stress-strain relationship. In contrast with advanced textiles, however, the tensile behavior of natural fibers textiles is initially inelastic, and the use of the elastic stiffness E_f would result in largely underestimated strains or overestimated stress that do not represent the actual performance of natural fibre TRM systems. Hence, to obtain more representative values, the design strain values used in RILEM (ε_{fb}) and CNR DT 215 (ε_{fd}) were derived based on the constitutive law developed by the authors [4]. These were taken equal to 3.24% and 2.96% for single- and double-layer FTRM, respectively, thus falling within the stabilized cracking stage of the composite response. Although the amplification factor (α = 1.5) was implemented in the model of CNR DT 215, the resulting values exceeded the ultimate tensile strain of the dry textile, and the latter was thus used in all calculations. When assessing the performance of ACI 549.6R [9], as the effective tensile stress f_{fe}, evaluated as the product $E_f\varepsilon_{fd}$, would exceed the experimental tensile strength of the corresponding FTRM system, the latter was used and taken equal to 178 and 209 MPa for single- and double-layer FTRM, respectively. In the model of Thomoglou et al. [14], the experimental values of ε_{tm} were taken equal to 0.057% and 0.07% for one and two layers of FTRM, respectively, while the calibration factor k was taken equal to 0.55 (as suggested for glass-TRM/clay brick masonry systems, which represents more closely the stiffness of the tested FTRM system).

3.3 Assessment of predictive models for V_{TRM}

The experimental shear contribution of the FTRM systems tested by the authors, V_{TRM}, was computed as the difference between the capacity of the FTRM-retrofitted specimens and that of the bare wall (from Table 1), and is compared against the analytical results in Figure 1.

The extremely conservative predictions obtained according to the ACI549.4R approach can be attributed to the implementation of an effective strain of 0.4%, which constitutes only a fraction of the strain that the FTRM system can develop in tension (approximately 7% [1]) or before debonding (approximately 3% [4]). The newest ACI approach, however, does not rely on this conservative strain limit and results in a predicted shear capacity that better approximates the experimental value for the specimens retrofitted with a single FTRM layer.

The rest of the models also seem to estimate adequately the performance of the single-layer FTRM systems, albeit providing conservative values, but overestimate the performance of the double-layer FTRM systems. In fact, although all available models predict an increase in V_{TRM} proportional to the reinforcement ratio, the experimental evidence shows that the increase in shear capacity between the walls retrofitted with one and two FTRM layers is of only 20%.

All models failed to capture the failure mode of the Flax-TRM, as they overestimate the stress that can be developed in the textile, which is either taken at debonding or tensile failure. In this study, no textile rupture and no debonding occurred, indicating that average strains much lower that the rupture strain were developed in the flax reinforcement. In fact, the maximum strains in the flax textile, as obtained from DIC (Table 1), confirm that no rupture occurred and that ε_{max} was significantly smaller than either the ultimate textile strain (3.8%) or the strain corresponding to bond failure (4%). The maximum values of textile strain measured in the wall tests were also found to fall within the crack development stage of the composite, as derived from direct tensile tests on coupons.

The relatively good prediction obtained with the model of Thomoglou et al. for the two-layer FTRM systems (+10%) highlights the significant contribution of the mortar overlays to the overall shear resistance, as also supported by the experimental results considered in this paper (Section 2). However, further work is needed on the relative contribution of the mortar overlay and the embedded textile, as well as on the calibration factor k and its physical role.

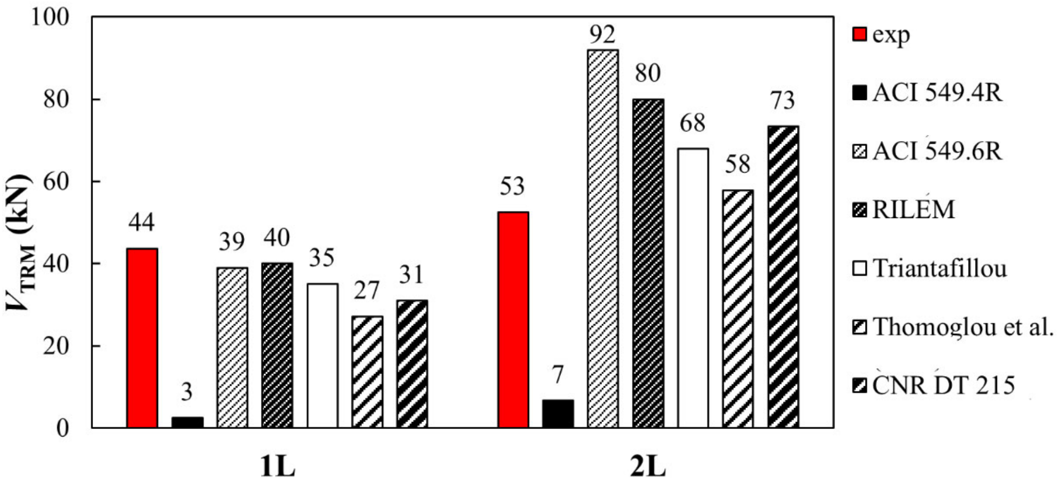


Figure 1: Experimental values and analytical predictions of the shear contribution, V_{TRM}, provided by one (1L) and two (2L) layers.

4 SHEAR DECOMPOSITION

Given the above observations, the relative contributions of the flax textile, the mortar and the masonry were estimated by examining the possible shear resisting mechanisms. The shear contribution provided by the flax textile was estimated based on the average strain values obtained from DIC analyses and the corresponding constitutive model [4]. The shear contribution of the lime-based mortar was estimated based on the corresponding equation in the model of Thomoglou et al. [14], substituting the product $E_{mortar}\varepsilon_{tm}$ with the tensile strength of the mortar, derived as the strength attained at the end of the first (uncracked) stage of the TRM axial stress-strain response. The shear contribution of the mortar overlay was estimated bason on the assumption that the mortar reaches its ultimate capacity when cracking is initiated in the retrofitted specimen; then a simple linear degradation model was adopted to account for the development of cracks and the associated loss of stress transfer. Finally, the shear contribution of the masonry was estimated by subtracting the contribution provided by the textile and the mortar from the total experimental shear capacity. The results of this analysis are shown in Figure 2, along with the response of the reference walls, and suggest that a shear resistance greater than that mobilised by the bare specimen can be developed in the masonry when it is retrofitted with Flax-TRM. This can be attributed to the fact the flax reinforcement can effectively redistribute the strain within the mortar layer and the underlying masonry, thus progressively activating undamaged areas of the wall. This highlights the need to revisit the additive nature of the individual shear contributions and to estimate the shear resisting mechanisms based on the strain level induced in the materials and the degree of strain redistribution that can be achieved.

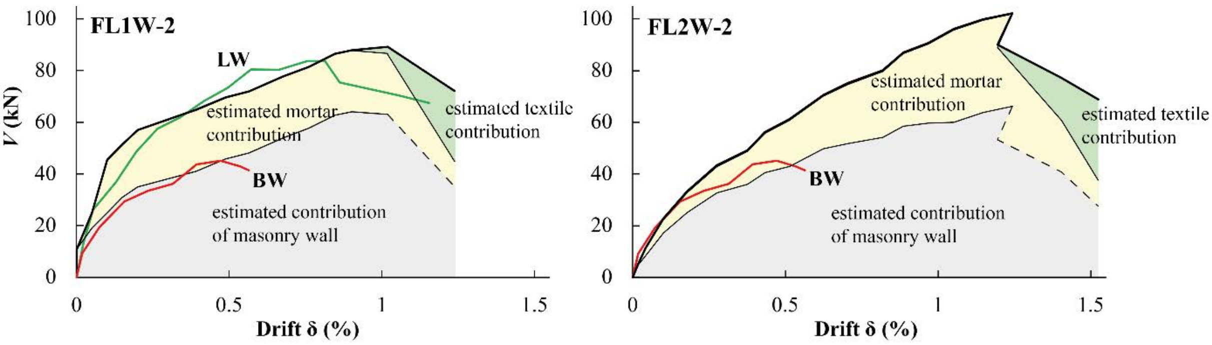


Figure 2: Shear resisting mechanisms for typical walls retrofitted with one and two FTRM layers.

5 PROPOSED DESIGN MODEL

Although the strain redistribution offered by the strengthening system can significantly enhance the capacity of the underlying masonry, current models still provide a conservative approach for the safe design of the retrofitting solution, despite overestimating the stress in the reinforcement. Given the experimental evidence obtained from this study, and keeping in mind that the adoption of a limiting reinforcement strain helps preventing excessive cracking and ensuring the integrity of the shear resisting mechanisms, a new simplified model is proposed herein. The contribution of the TRM composite is derived as the sum of the contribution of the mortar and the contribution of the fibres:

$$V_{TRM} = V_{mortar} + nt_f H \varepsilon_{II} E_{II} \tag{1}$$

where, nt_f = total thickness of TRM; and ε_{II} and E_{II} = strain at the end of the crack development stage and the elastic modulus that characterizes the same stage, respectively.

The contribution of the mortar is based on the maximum tensile stress that can be transferred before cracking, which can be derived from either direct tensile or splitting tests on the mortar or as the strength attained at the end of the first (uncracked) stage of the TRM axial stress-strain response. With respect to the contribution of the textile, an effective limiting strain equivalent to that corresponding to the end of the crack development stage is taken as an appropriate upper limit for design. This limiting strain would still enable the embedded textile to effectively control cracking in the TRM, and a good degree of composite action and strain redistribution with the masonry can still be assumed.

A database including experimental results on the in-plane shear capacity of unreinforced masonry walls strengthened with both natural-fiber and advanced TRM systems was collected and used to validate the proposed model. A total of 21 strengthened elements were considered, including single- or multiple-layer TRM systems comprising carbon, glass, steel, flax, cotton, and hemp textiles of different architectures, bonded to clay brick, tuff stone, and concrete masonry substrates.

The proposed model is easy to implement and relies only on data obtained from the mechanical characterization of the TRM system in tension. The model was found to approximate well the experimental results, yet still providing an overall level of safety (average V_{pred}/V_{exp} =0.8; absolute average error $|V_{pred} - V_{exp}|/V_{exp}$ and CoV equal to 30%) as also shown in Figure 3.

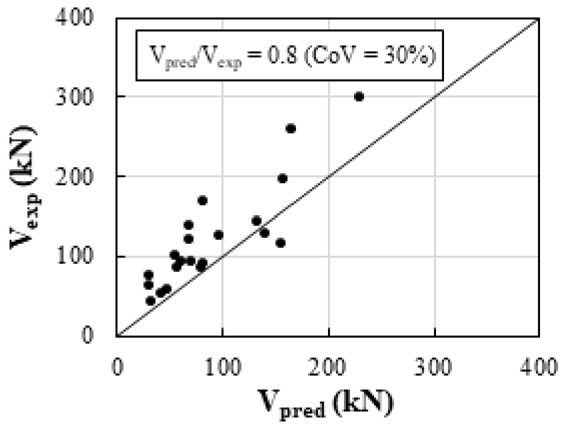


Figure 3: Experimental and predicted shear contribution of TRM according to the proposed model.

6 CONCLUSIONS

The contribution of Flax-TRM systems to the overall shear capacity of retrofitted masonry walls was examined in detail and the experimental evidence was used to assess the underlying philosophy of current shear design provisions and propose a new design model. The following conclusions can be drawn:

- Current design models overestimate the stress that can be developed in the flax textile reinforcement, as well as the shear capacity enhancement when more than one layer of FTRM is used.
- The analysis of the shear contribution of the FTRM system highlighted the complexity of the shear resisting mechanisms that develop in retrofitted masonry walls and suggests that the additive nature of the individual contributions, though adequate for design, should be revisited.
- A simplified design model adopting a more rational limiting strain value and not requiring the use of calibrated parameters was proposed and yields acceptable and safe predictions.

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