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Article

Tensile and shear bond tests on Flax-TRM systems

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Abstract. This paper presents the preliminary results of an experimental programme investigating the bond behaviour between natural fibre Textile Reinforced Mortar (TRM) composites and masonry substrates. The TRM system used in the study consisted of one and two layers of flax textile reinforcement embedded within a lime-based mortar matrix, selected due to its compatibility with historic and traditional masonry materials. The mechanical performance of the textile–matrix composite, as well as its interaction with the masonry substrate were evaluated through a series of laboratory tests. These included direct tension tests to determine the tensile capacity and behaviour of the composite, and single-lap shear bond tests to assess the bond strength and stress transfer at the TRM–masonry interface. The results obtained from both test programmes are analysed and discussed in detail, highlighting the main parameters influencing bond performance, such as textile layers, mortar properties, and interface characteristics. Particular attention is given to the stress-transfer mechanism between fibres, mortar matrix, and the parent masonry material. Based on the experimental findings, the feasibility and effectiveness of flax-based TRM systems as a sustainable and compatible strengthening technique for masonry structures are also evaluated.

Keywords: Cold-Formed Steel; Shear Buckling; Web Opening; FE Modelling; Channel Section

Introduction

The high vulnerability of unreinforced masonry structures to lateral loading (such as wind loads and earthquakes) resulted in numerous losses of human life and property, manifesting the need for structural strengthening and/or seismic retrofitting. Textile-Reinforced Mortars (TRM), which are externally bonded composite systems comprising inorganic matrices (cement-, lime- or geopolymer-based mortars) reinforced with advanced fibre meshes, offer a series of structural benefits for strengthening applications, including: high specific strength and stiffness, vapour permeability, reversibility, recyclability, compatibility with masonry substrates, ability to conduct post-earthquake damage assessment (Triantafyllou et al. 2006). Their potential in strengthening against both in-plane (Papanicolaou et al. 2015) and out-of-plane loading actions (Mordanova et al. 2016), as well as in the strengthening of vaults, arches, pillars, and lintels, has been highlighted through several case studies (Bournas 2016).

Despite the superior tensile properties of the reinforcement typically used in TRM systems (glass, carbon, aramid, PBO, steel cords), their performance is governed by the quality of the bond between the constituent materials, which often does not allow to fully exploit the fibre capacity. In parallel, these relatively high-cost fibres require a high energy input for their manufacturing and processing. The pressing need for sustainable development led to the exploration of alternative, eco-friendly reinforcing materials. Natural fibres have emerged as a potential solution for reinforcement in composites, given their excellent environmental credentials and wide availability around the world (Yan et al. 2016). Among natural fibres, flax has attracted the interest of both academia and industry due to its good specific tensile strength and stiffness, comparable to glass (Joshi et al. 2004), and deformability values suitable for strengthening applications.

However, the potential of flax-TRM (FTRM) as externally bonded systems has not yet been determined, and the mechanical properties and bond performance of such systems have not been examined in detail. Available research on the topic is still in its infancy (Olivito et al. 2014, Cevallos & Olivito 2015, Codispoti et al. 2015, Olivito et al. 2016, Olivito et al. 2018, Ferrara et al. 2019), while the complexity of the stress-transfer mechanism in already established TRM systems, which involves failure both at textile/mortar and composite/substrate interface (e.g. Alecci et al. 2016), has been well documented and is still under investigation. The complexity of the TRM bond performance is further increased when additional design parameters are taken into account, such as the number of the reinforcing layers or the textile layout, as they affect strength, failure mode and crack pattern (Misseri et al. 2019). As a result, there is a lack of in-depth understanding of the behaviour of FTRM, which in turn hinders their implementation in strengthening applications and their market acceptance.

This paper presents the preliminary results of a larger experimental programme on the bond between flax textile-reinforced lime-based mortars and unreinforced masonry prisms, with the aim of developing an effective and sustainable strengthening solution for masonry. Tensile and single-lap shear bond tests were performed on single and double-layer FTRM specimens to gain insight into the stress-transfer mechanism between fibres, matrix and parent material.

The methodology

Two types of flax textiles of different architectures (F1 and F2) were combined with the same lime-based mortar to develop sustainable composites suitable for the strengthening of masonry. The mechanical performance of the composite system was examined through:

-direct tensile tests on FTRM composites (coupons), according to AC434 provisions.

-single-lap shear bond tests on unreinforced masonry prisms, according to RILEM TC 250-CSM provisions.

The effect of the number of TRM layers on the overall performance was assessed by examining specimens comprising one and two reinforcement layers.

Each masonry prism consisted of four stack-bonded solid clay bricks of dimensions 215 x 102.5 x 65 mm and 10-mm thick mortar joints. The cement lime: sand proportions in the mortar used to bed the joints were 1:2:9, by volume, with a water-to-dry materials ratio of 0.21, by weight. The mechanical properties of the masonry substrate were experimentally determined by carrying out four compression tests perpendicular to the mortar joints, according to RILEM standards (RILEM LUMB1). The mean values of the compressive strength and elastic modulus at 28 days were found to be 30.5 MPa (CoV:2%) and 1970.5 MPa (CoV:5%), respectively.

Flax-TRM

Two types of flax textiles were investigated as reinforcement, distinguished by their geometry and physical properties. Both textiles were woven, with yarns being equally arranged in an orthogonal mesh. The textiles are shown in Figure 1, while their characteristics are summarized in Table 1.

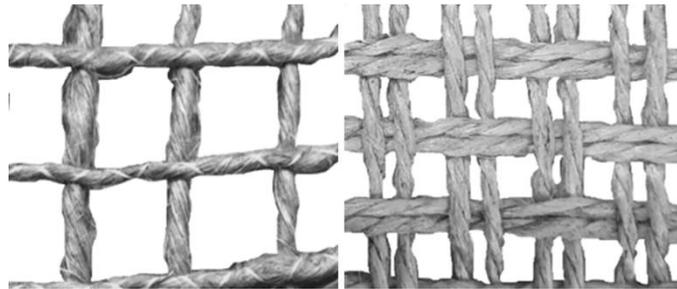


Figure 1. Textile characteristics, F1 (left) and F2 (right).

The textile mechanical properties were obtained from direct tensile tests according to EN ISO 13934:1999 (gauge length: 200 mm; grip method: epoxy-bonded aluminum tabs; loading rate: 2 mm/min; number of yarns width-wise: 3 for F1, 10 pairs for F2).

Both flax textiles were combined with a commercially available lime-based mortar, the strength of which was obtained through flexural testing on thirty-nine prisms measuring 160 x 40 x 40 mm and compression testing on the resulting halves, following EN 1015-11. The flexural and compressive strengths were 2.8 MPa and 7.7 MPa, respectively, with a CoV value of 15%.

All FTRM composites (both for tensile and shear bond tests) were prepared by applying a bottom 3-mm thick mortar layer, manually embedding the textile into the fresh mortar, and covering with a top mortar layer of the same thickness. The procedure was repeated for the specimens with two TRM layers, resulting in a total thickness of 9 mm.

For the direct tensile tests, FTRM coupons measured 600 x 50 mm and were cast in plexiglass formwork (6 replicates per configuration). Specimens were cured in a mist room for 28 days and then stored in standard laboratory conditions until testing. Width-wise, F1-TRM and F2-TRM specimens comprised 3 and 20 yarns, respectively.

For the shear bond tests, FTRM were centrally bonded across the width of the masonry prisms and 30 mm away from their front face to avoid stress concentration phenomena. A bonded area

100 mm wide and 260 mm long (3 replicates per configuration) was provided to ensure effective anchorage of the composite to the substrate (RILEM TC 250-CSM). The unbonded textile (i.e., the length of the textile projecting from the bonded area) measured 600 mm to mitigate any misalignment during testing. The specimens were cured under wet hessian cloth for 28 days and then stored in standard laboratory conditions until testing. Width-wise, F1-TRM and F2-TRM specimens comprised 7 and 40 yarns, respectively.

Table 1. Textile characteristics.

Property	F1	F2
Mesh size (mm) ^a	14	4
Yarn cross-sectional area (mm ²) ^a	1.11	0.22 ^b
Tensile Strength (MPa)	196.4	289.0
Elastic Modulus (GPa)	7.1	13.6
Strain at failure (%)	4.2	3.8

^a supplied by the manufacturer; ^b the value refers to a single yarn

A random speckle pattern was applied manually to the surface of the specimens (both coupons and masonry prisms) to enable the use of digital image correlation (DIC) and obtain full-field displacement measurements. DIC results will be presented in future publications.

Experimental Setups

To ensure a uniform stress distribution during testing, the ends of the FTRM coupons and the unbonded textile in the shear bond specimens were epoxy-bonded to aluminum tabs (150 mm long).

Direct tensile tests were performed in a universal testing machine of 10 kN capacity, in displacement control at a loading rate of 0.2 mm/min up to the occurrence of the first crack and 1 mm/min thereafter. Clevis-type grips were used, allowing for in-plane rotation of the specimens while being loaded (Fig. 2a). The specimens' ID has the form of FxLy-n, where F and L stand for Flax and Layer, respectively, x is the type of the flax textile (1 or 2 - see Fig. 1), y is the number of TRM layers (1 or 2) and n the replicate number.

Shear bond tests were performed in a servohydraulic testing machine fitted with a 50 kN load cell, in displacement control at a loading rate of 0.5 mm/min. Single-lap shear tests were performed, with the masonry prisms horizontally restrained within a rigid steel frame (Fig. 2b). A pre-tension load of 100 N was applied prior to installing the instrumentation. Four linear displacement transducers (potentiometers) of 10 mm stroke were attached on the shear bond specimens to measure the displacement relative to a thin aluminum plate glued on the textile adjacent to the loaded end: two on the substrate, on either side of the bonded area, to measure the slip between the textile and the substrate; two on either side of the bonded width, to measure the slip between the textile and the composite and derive the overall slip between the composite and the substrate (Fig. 2c). The ID of the bond specimens has the form of FxLy-260-100-n, where 260 stands for the bond length (mm) and 100 for the bond width (mm), and the rest of the notation is

the same as used for the TRM coupons.

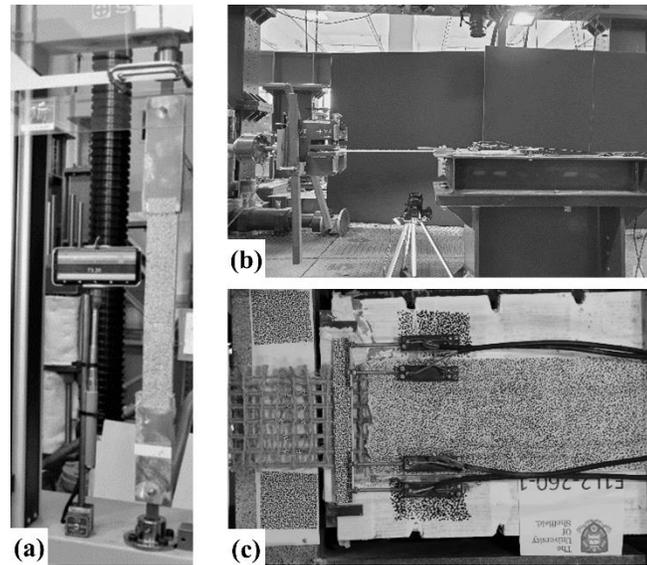


Figure 2. Experimental test setups: (a) tensile tests on FTRM coupons; (b) shear bond tests (side view); (c) shear bond tests (plan view) and arrangement of the potentiometers.

Findings/Discussion

Table 2 presents the average tensile properties of the TRM coupons (and the corresponding CoV values in parentheses) reinforced with one and two layers of the corresponding flax textiles. It can be observed that F2-TRM specimens exhibited superior mechanical properties compared to those of their F1 counterparts. The addition of an FTRM layer, however, did not increase the mechanical properties significantly.

Figure 3 shows the tensile stress-strain response curves of typical specimens grouped per flax textile type. The typical three stages that characterize the tensile behaviour of TRM systems, i.e., pre-cracked, crack development and post-cracking stage (Arboleda et al. 2016), did not always develop in the tested composites. The uncracked stage was not detectable in most of the F1L1-TRM specimens due to pre-existing microcracks formed during curing and positioning of the specimens in the testing machine. In addition, half of the F1L1-TRM specimens were characterized by the formation of one single crack with no crack development stage, while two to three cracks occurred in the remaining specimens. A telescopic failure was observed in the proximity of the cracks in all specimens, as a result of the relative slip of the inner yarn filaments. On the contrary, F2L1-TRM specimens were characterized by the formation of multiple cracks along the composite, which also provided evidence of the good bond between the textile and the mortar, resulting in a greater contribution of the matrix to the overall performance. No delamination or slippage of the reinforcement in the gripping areas were observed in any of the tested specimens. The end of the crack development stage was not always distinguishable from the post-cracking stage, with failure immediately following the formation of the last crack and initiating a softening stage triggered by the progressive tensile rupture of the yarns. This progressive failure mechanism led to the development of higher elongation capacity of the F2-TRM systems with respect to that of the bare F2 textiles.

The failure mode between the two FTRM systems did not change when an additional TRM layer was provided (telescopic failure in F1-TRM, tensile rupture in F2-TRM). However, double-layer FTRM exhibited higher ductility, developed a greater number of cracks and distinct stages of crack initiation and development.

The different textile geometry and reinforcement ratio, i.e. textile/composite cross-sectional area (Table 2), played a key role in the differentiation between the Flax-TRM systems' tensile behaviour: the large yarn cross-sectional area in F1 textiles (Table 1) may have resulted in increased moisture absorption inducing pre-existing cracks, and in a telescopic mode of failure due to uneven impregnation of all filaments, while the denser and of smaller yarn diameter F2 textile benefitted from an increased mechanical interlock with the matrix. On the other hand, the reinforcement ratio provided in F1L1-TRM composites (1.11%) was insufficient to create an effective composite system (poor stress redistribution, no appreciable increase in strength over the strength of the matrix).

Table 2. Tensile test results.

Specimen ID	Tensile strength (MPa)	Elastic modulus* (GPa)	Strain at peak load (%)	Reinforcement ratio (%)
F1L1	82.2 (15%)	2.02 (15%)	4.1 (22%)	1.11
F1L2	83.0 (11%)	2.13 (13%)	4.4 (11%)	1.48
F2L1	177.8 (12%)	2.98 (9%)	7.3 (14%)	1.44
F2L2	208.9 (8%)	3.87 (9%)	7.9 (8%)	1.92

*during cracked stage.

Shear Bond Tests

Table 3 summarizes the experimental results from bond tests in terms of i) maximum applied load, ii) maximum axial stress (load divided by the textile cross-sectional area), and iii) slip at maximum load (calculated as the average of the two transducers' measurements placed on the composite, subtracting the elastic elongation of the unbonded textile). A uniform stress distribution across the composite width and between the multiple TRM layers was assumed when determining stress values. Bond and tensile capacities were of the same order of magnitude only when the same failure mode was observed in both test series, as analysed below. The bond test

results were affected by a higher scatter than those obtained from the composites' tensile testing due to the development of different failure modes and the complex nature of the interaction between the multiple fibres/matrix interfaces. Hence, no average values are presented for identical specimens.

Table 3. Shear bond test results.

Specimen ID	Maximum load (N)	Maximum axial stress (MPa)	Slip at maximum load (mm)
F1L1-260-100-1	268	34.4	1.30
F1L1-260-100-2	360	46.3	3.86
F1L1-260-100-3*	204	26.3	1.66
F1L2-260-100-1*	583	37.5	8.24
F1L2-260-100-2	1607	103.3	4.65
F1L2-260-100-3	1030	66.2	2.36
F2L1-260-100-1	1728	200.1	6.86
F2L1-260-100-2	1193	138.1	5.98
F2L1-260-100-3	1870	216.4	9.96
F2L2-260-100-1	2753	159.3	5.87
F2L2-260-100-2	3183	184.2	7.59
F2L2-260-100-3*	1573	91.0	3.81

*different failure mode within the tested group.

The axial stress-slip relationship of all tested systems is illustrated in Figure 4, where a variety of bond performances can be observed.

The response of most F1-TRM systems exhibited an almost linear response up to the attainment of the peak stress and a post-peak softening stage, during which failure occurred progressively and was associated with an increase of slip. Specimens failed after the initiation of relative slip of the inner filaments, similarly to the behaviour obtained from direct tensile tests on composites, which was often followed by the progressive failure of individual filaments outside the bonded area, similarly to the behaviour obtained from direct tensile tests on the dry textiles. No cracking of the mortar along the bonded area occurred and no relative displacement of the top mortar layer and the substrate was recorded. Specimens F1L1-260-100-3 and F1L2-260-100-1 exhibited a different behaviour caused by a more pronounced telescopic failure mode, which resulted in reduced axial stress and increased deformation (see Table 3). The effect of non-uniform engagement of the yarn filaments within the mortar, which acts as mechanical anchorage,

triggered the slip between the yarns' filaments and resulted in higher total relative textile-to-mortar displacement and a pseudo-ductile behaviour.

F2-TRM systems developed one crack in single-reinforced specimens and one or multiple cracks in double-reinforced specimens, that widened significantly during the test. The cracks initiated as parallel to the applied load, through the thickness of the composite, and then expanded transversally to the load axis application, close to the loaded end. The peak stress was determined by the rupture of some of the F2 yarns not only in the unbonded textile but also along the bonded area and across the crack. All specimens failed due to the partial detachment of the textile from the bottom mortar layer in F2L1 series and at the two textile/mortar interfaces in F2L2 series (Fig. 5a), with the bottom mortar layer remaining always well bonded to the brick surface, indicating that the employed bond length (260 mm) was indeed sufficient. Especially for the latter series, detachment may have been facilitated by the unavoidable misalignment between the actuator and the FTRM system. As a result, along with the cracking and redistribution of stresses after the failure in one textile layer, additional bending might have been induced causing the separation of the textile from the mortar. Complete detachment of the top mortar layer was observed in specimen F2L2-260-100-3, which significantly moved with respect to the masonry support, as evidenced by the large slip values (Fig. 5b) at the composite/substrate interface (determined as the difference between the displacement measured by the potentiometers mounted on the substrate and those mounted on the composite).

Figure 6 shows the exploitation ratio of the textile, expressed by the factors η_t and η_{TRM} . The former equals to the ratio of the maximum axial stress developed during the bond test to the tensile strength of the associated textile (see Table 1); the latter equals to the ratio of the maximum axial stress to the tensile strength of the associated FTRM coupon (see Table 2). Average values are shown in this figure and were computed by excluding the specimens within the same group that exhibited a different failure mode. Overall, η_t was significantly lower than η_{TRM} , highlighting a possible degree of fibre degradation when embedded in mortar. Comparing the two FTRM systems, it can be observed that F2 textiles were likely less affected by the lime-based mortar, with both η_t and η_{TRM} values higher than those of F1-TRM.

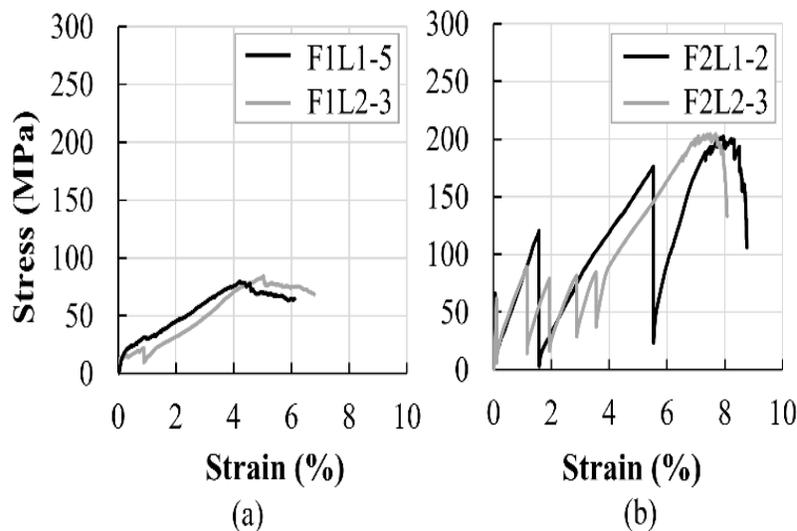


Figure 3. Tensile stress-strain response for typical single- and double-layer coupons: (a) F1-TRM and (b) F2-TRM.

Although η_t values were between 60-65% for F2-TRM systems, failure of the bond specimens occurred due to fibre tensile rupture, while all F1-TRM systems were characterized by a telescopic mode of failure, justifying values of η_t lower than 40%.

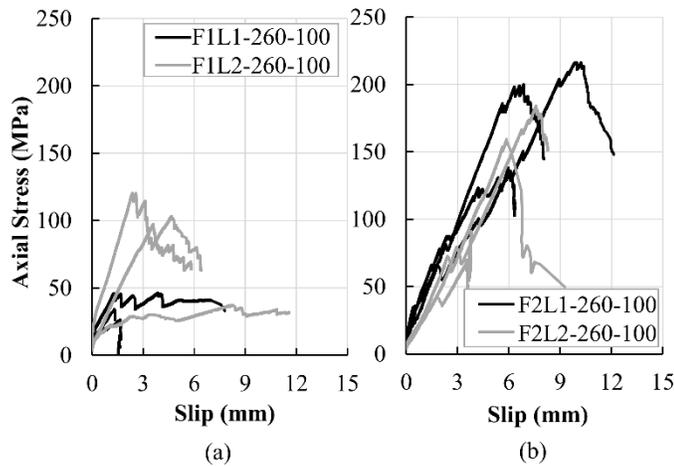


Figure 4. Axial stress-slip curves for single- and double-layer TRM-strengthened masonry prisms: (a) F1-TRM; (b) F2-TRM.

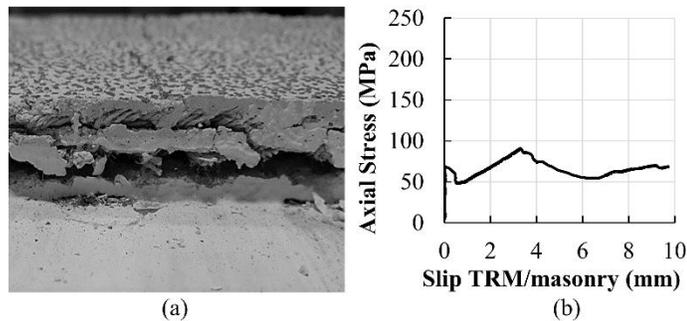


Figure 5. (a) Typical failure mode of F2-TRM bond series (side view); (b) slip of TRM to masonry for specimen F2L2-260-100-3.

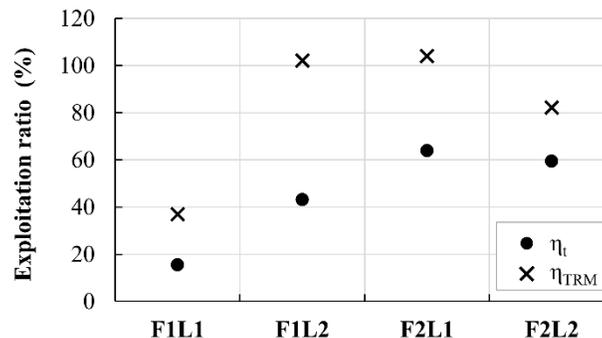


Figure 6. Exploitation ratio of the textile during the shear bond tests.

Strength values similar to those obtained for coupons under direct tension were obtained for double-layer F1-TRM ($\eta_{TRM} = 102\%$) and single-layer F2-TRM specimens ($\eta_{TRM} = 104\%$), indicating a good bond between the fibres and the mortar. The very low exploitation of F1 composites in the

case of single-layer TRM systems ($\eta_{\text{TRM}} = 37\%$) confirmed the poor fibre/mortar interaction, which was also observed in direct tensile tests on corresponding coupons. The aforementioned observations provide information for the design of the most suitable strengthening solution according to the required structural application. Provided a good fibre/matrix interaction can be achieved (e.g., F2-TRM), although the addition of an FTRM layer will not result in an increase in tensile strength, this will lead to an increase in ductility, which could be desirable in some structural applications, e.g., in-plane shear strengthening of masonry walls.

Conclusion

This study presents the preliminary results of direct tensile and shear bond tests of TRM/masonry systems reinforced with one and two layers of two different flax textiles.

Both Flax-TRM systems developed high tensile strength (80 to 200 MPa) and elongation capacity (4 to 8%).

The failure modes included telescopic failure in flax textiles with thick yarns at a large spacing (F1) and tensile fibre rupture in textiles with thin and twisted yarns at a smaller spacing (F2). Partial or full detachment between the textiles and the mortar occurred only in the latter systems when bonded to the masonry.

Overall, textiles of denser and smaller yarn cross-sectional area are more suitable for strengthening applications as they result in composites of higher ductility, with good interaction at the textile/mortar interface, evidenced by multiple cracking.

The increase in the number of FTRM layers results in a more ductile behaviour without affecting the overall mechanical performance significantly.

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Flax-TRM жүйелерінің созылу және жаншу-срез адгезиялық сынақтары

Аңдатпа. Бұл мақала табиғи талшықтарға негізделген TRM композиттері мен қалау негізі (тас, кірпіш) арасындағы адгезиялық өзара әрекеттесуін зерттеуге арналған эксперименттік бағдарламаның алдын ала нәтижелерін ұсынады. TRM жүйесі әк негізді ерітіндіге енгізілген бір немесе екі қабат зығыр талшықты текстильден құралады. «Текстиль/матрица» композиттерінің жұмыс істеу қабілеті және олардың қалау негізімен

адгезиялық байланысы тікелей созылу сынақтары мен біржақты жаншу-срез адгезиялық сынақтары арқылы зерттелді. Екі серияның нәтижелері талқыланып, күшейту жүйелерін жобалауға қажетті негізгі параметрлер анықталды. Талшықтар, матрица және негіз материал арасындағы кернеуді беру механизмі жан-жақты қарастырылып, Flax-TRM жүйелерін қалау құрылымдарын күшейту шешімі ретінде қолдану мүмкіндігі бағаланды.

Түйін сөздер: суықтай иілген болат (Cold-Formed Steel); жаншу тұрақсыздығы (Shear Buckling); қабырға ойығы (Web Opening); соңғы-элементтік модельдеу (FE Modelling); арна тектес қима (Channel Section).

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Испытания на растяжение и сдвиг на системах Flain-TRM

Аннотация. Данная статья представляет предварительные результаты экспериментальной программы, посвящённой исследованию адгезионного поведения между композитами TRM на основе природных волокон и каменной кладкой. Система TRM состояла из одного и двух слоёв льняных текстилей, внедрённых в известковый раствор. Характеристики композитов «текстиль/матрица» и их адгезионное взаимодействие с основанием из кладки были изучены с помощью прямых растягивающих испытаний и однонаправленных сдвиговых адгезионных испытаний. Обсуждаются результаты обеих серий испытаний, а также определяются ключевые параметры для проектирования усиления конструкций. Подробно рассматривается механизм передачи напряжений между волокнами, матрицей и основным материалом, а также оценивается возможность применения систем Flax-TRM в качестве решения для усиления каменной кладки.

Ключевые слова: холодногнутая сталь (Cold-Formed Steel); сдвиговая потеря устойчивости (Shear Buckling); отверстия в стенке профиля (Web Opening); конечно-элементное моделирование (FE Modelling); швеллерные профили (Channel Section)

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