Out-of-plane behaviour of TRM strengthened masonry walls

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ABSTRACT: In this work an experimental programme was carried out to investigate the out-of-plane response of medium-scale masonry walls strengthened with textile-reinforced mortar (TRM). The investigated parameters involved both the material of the fibre textile reinforcement and the amount of reinforcement utilized. Results presented, indicate significant improvement in the structural performance in terms of the out-of-plane strength, whereas key concepts of the TRM mechanical response are highlighted and discussed. A finite element simulation procedure is also suggested for the case of TRM strengthened masonry walls. Results obtained from simulation agree well with experimental results.

1 INTRODUCTION

Unreinforced masonry structures comprise a large percentage of the current building stock and in many cases involve structures of significant historical and cultural importance. Built several decades or centuries ago, these structures are currently expected to withstand operational loads that well exceed the load estimates they have been initially designed for. Furthermore, they are susceptible to the detrimental effects of damage accumulating either due to ageing or to natural hazards, i.e., extreme winds, extreme rainfalls and/ or earthquake events.

Structural retrofitting can enhance the structural properties of existing structures, eliminate unfavourable local damage effects and improve the overall structural behaviour. It thus provides a robust methodology for increasing the durability of a structure and extending its operational life. Within this setting, textile-reinforced mortar (TRM) jacketing, has been very recently established as an efficient retrofitting methodology. TRM is an innovative composite material comprising inorganic binders (e.g. cementitious mortars) in combination with open-mesh textiles fabrics (i.e. carbon, glass, basalt) impregnated within the inorganic matrix. This system is bonded externally on the masonry substrate to increase the tensile strength of the corresponding region.

Previous research studies examined the effectiveness of TRM composites in increasing the out-of-plane bending capacity of masonry walls. Investigated parameters comprised different textile materials (Kolsch, 1998, Martins et al., 2015), different number of carbon textile layers (Babaeidarabad et al., 2013) and epoxy-resin coating of glass and basalt textiles (Papanicolaou et al., 2011, Harajli et al., 2010). Kolsch (1998) concluded that the use of carbon fabric can prevent complete collapse of the wall. Additional TRM layers resulted in higher ultimate load and different failure modes (Babaeidarabad et al., 2013). Furthermore, they concluded that the epoxy-resin coating of the textile can prevent textile slippage from the mortar and demonstrated increased load capacity (Papanicolaou et al., 2011, Harajli et al., 2010).

Masonry is a composite material that consists of distinct units made of various natural or industrial materials e.g. stone, brick, and concrete. Individual units are split by joints that can be either filled with mortar or not. The mechanical properties of the units demonstrate severe anisotropy a fact that is also reflected in the mechanical properties of the composite. The latter are also influenced by the joint distribution as well as the mechanical properties of the mortar.

Three modelling approaches are identified for masonry, namely micro, macro and multiscale simulation methods, see e.g., Casolo and Milani (2010). In micro-modelling methods, a fine level of resolution is applied for each one of the constituents using either plane or solid finite elements. In macro-modelling approaches, the masonry wall is being modelled by means of properly defined and calibrated beam/ column elements or super-elements. In multiscale modelling methods, different levels of resolution are considered for each one of the masonry constituents, i.e., brick and mortar. The latter methods, i.e., homogenization methods, multiscale finite element method, and cohesive element methods enable robust and efficient analysis of masonry structure problems without hindering the accuracy of the derived analysis results.

Further to the current state-of-the-art, in this study the effect of the textile material on the out-of-plane flexural response of masonry walls is examined. Two different textile materials are investigated herein, namely the epoxy-resin coated carbon and the epoxy-resin coated glass. Additionally, the amount of strengthening reinforcement is also examined by considering the effect of 3 and 7 layers of coated glass and 1 layer of coated carbon composite material. To further highlight the mechanics involved in TRM strengthening of masonry walls, a robust and consistent finite element simulation methodology is introduced.

2 EXPERIMENTAL PROGRAMME

2.1 Test specimens and investigated parameters

Four single-wythe masonry walls specimens were tested in out-of-plane bending to examine and quantify the effectiveness of the TRM strengthening technique. Specimens were built with dimensions of 1340 x 440 x 102.5 mm, using a stretcher bond pattern. Mortar thickness of both head and bed joints was approximately 10 mm.

The examined parameters were the number of the applied TRM layers, and the textile fibre material utilized, i.e., epoxy-resin coating glass and epoxy-resin coating carbon, whereas an additional unreinforced specimen served as the control specimen. Two out of the remaining three specimens were strengthened with three and seven layers respectively of epoxy-resin coated glass fibre textile material. The final one was strengthened with one layer of epoxy-resin coated carbon fibre-textile. Given that seven layers of glass textiles are equivalent to one layer of heavy-weight carbon textile, comparison between carbon and glass was attained, in terms of their axial stiffness.

The masonry wall specimens are shown in Table 1. The notation used is TN, where T denotes the textile material, and N denotes the number of layers applied at the strengthening system. The suffix “co” denotes the textile epoxy-resin coating.

2.2 Materials

Masonry walls were built using solid clay brick units of nominal dimensions 215 x 102.5 x 65 mm. The clay brick compressive strength was obtained from compression tests applied on the bed and stretcher face of dimensions 215 x 102.5 mm and 215 x 65 mm, respectively. Its corresponding mean value obtained was 21.2 MPa. Compressive tests were also conducted on representative masonry wallettes with the resulting compressive strength being 9.3 MPa. The cement to sand mixture utilized for both head and bed joints was 1:4.

Table 1. Masonry wall specimens

Specimen	Textile material	Number of TRM layers
Control	-	-
C1_co	Carbon	1
G3_co	Coated glass with epoxy resin	3
G7_co	Coated glass with epoxy resin	7

Material properties, i.e., tensile and compressive strength of both the masonry joint mortar and the strengthening mortar were determined through three-point bending tests and uniaxial compressive tests performed on coupons at the day of test. The prisms utilized in both cases had dimensions of 40 x 40 x160 mm, per EN 1015-11 (1993). Three prims were used to perform the three-point bending tests whereas compressive tests were made on the resulting fractured parts with dimensions 40 x 40 mm. The mean values of the joint mortar compressive and tensile strength were 9.0 MPa and 2.2 MPa respectively. The corresponding values for the strengthening mortar were 38.0 MPa and 8.4 MPa, respectively.

The different composite materials used were the resin-coated carbon-fibre textile of 10 mm mesh size and the resin coated glass-fibre textile of 12 mm mesh size. Coating of both textiles was performed using a commercial two-part epoxy-resin with elastic modulus of 1.8 GPa and a tensile strength of 37 MPa (per the manufacturer datasheets). The textile material properties were defined through tensile tests on the corresponding resin-coated fibre textile used. The Young's modulus, tensile stress and ultimate strain obtained are presented in Table 2.

Table 2. Textile fibre composite material properties

Material	Weight (g/m$^{2)}$	Thickness (Nominal) (mm)	Young's modulus (GPa)	Tensile stress (MPa)	Ultimate Strain (%)	Mesh size (mm)
Coated carbon	348	0.097	217.3	3040	1.417	12
Coated glass	220	0.044	62.7	1107	1.624	10

One layer of resin-coated carbon textile, three and seven layers of resin-coated glass were utilized. The choice on number of layers was made based on the equivalence of elastic axial stiffness of the textile as discussed in Tetta et al. (2016). In particular, the axial stiffness ratio of 1 carbon fibre textile layer to that of 1 glass-fibre textile layer is evaluated as $t_C E_C / t_G E_G = (217.3 \times 0.095)/(67.2 \times 0.044) = 7$, where t_G is the glass textile thickness, E_G is the corresponding Young's modulus , t_C is the carbon textile thickness, and E_C is the resin-coated carbon fibre textile Young's modulus of the resin-coated carbon textile. Therefore, the two textile fibre materials used, namely carbon and glass, were expected to provide comparable results both in terms of effective elastic stiffness.

A high-strength cement based mortar was used to achieve bonding of the textile at the masonry substrate. This is an inorganic dry binder composed by cement and polymers at a ratio 8:1 by weight. The ratio of the water to the mortar cement utilised was 0.23 by weight.

2.3 Strengthening procedure

The implementation of the strengthening procedure comprised the following steps i) Removal of dust from the masonry wall face using air pressure; ii) Dampening of the wall surface and application of the first layer of the strengthening mortar at the entire face; iii) Implementation of the first layer of textile and impregnation into the mortar using hand pressure. iv) Application of the final layer of mortar to cover the whole surface of the textile and v) This procedure was then repeated for strengthening with more than one TRM layers. To achieve full bond between the textile and mortar, the latter should be applied while in fresh condition.

2.4 Experimental setup

The test setup involved the installation of a steel reaction frame and a servo-hydraulic actuator for the load application, as shown in Figure 2(a). Each wall was horizontally orientated with the strengthened side facing downwards. A three-point-bending test was conducted on the masonry walls with an effective span equal to 1125 mm. The load was applied monotonically at the mid-span using an actuator of 100 kN capacity at a displacement rate of 0.017 mm/s. Two potentiometers were installed at the top face, 50 mm distance from each side of the wall to monitor the vertical displacement. All data from the load cell and the potentiometers were recorded using a commercial software at a sampling frequency of 4 Hz.

2.5 Experimental results

Recorded loads versus mid-span displacements for the four specimens are presented in Figure 2(b). The experimental results are shown in Table 3 in terms of the maximum load P, the ratio of ultimate load P to the corresponding ultimate load of the control specimen P_{con} and the failure mode of each specimen. The tested specimens exhibited two different failure modes, i.e., textile rupture and shear failure (shear diagonal tension) of the masonry wall.

The control specimen, which did not receive strengthening, failed under its own weight during transportation of the specimen to the test setup. To compare the ultimate loads obtained in all specimens, the strength of the control was estimated through cross-sectional analysis. Specimen C1_co, strengthened with 1-layer of coated carbon textile failed due to textile rupture at maximum load of 35.3 kN and relative displacement of 20.1 mm. Flexural cracks propagated at the mid-span region, along the mortar joints and at the TRM surface (Figure 1 (a)).

Specimen G3_co, received 3-layers of coated glass textile, attained an ultimate load of 25.8 kN and corresponding mid-span deflection equal to 29.3 mm. Tensile cracks initiated among the mortar joints at the region of the applied load. The failure mechanism occurred when the load dropped instantly due to tensile rupture of the textile material (Figure 1 (b)). Specimen G7_co reached an ultimate load and mid-span displacement of 42.5 kN and 54.3 mm, respectively. Hairline flexural cracks initiated halfway of the linear branch of the corresponding load-deflection curve shown in Figure 2(b). Approaching the first peak load, fine diagonal cracks initiated from the right side of the specimen, which gradually propagated wider towards the mid-span region. After this point, diagonal cracks expanded and gradual debonding of the TMR composite occurred towards both supports (Figure 1 (c)).

(a) (b) (c)

Figure 1. (a) Failure of specimen C1_co due to fibres rupture, (b) Failure of specimens G3_co due to fibres rupture, (c) Failure of specimen G7_co due to shear diagonal tension.

Table 3. Experimental results

Specimen	Ultimate Load [kN]	P/P_{con}	Failure mode
Control	0.7[1]	1	Failed under its own weight
C1_co	35.3	50.4	Textile rupture
G3_co	25.8	36.9	Textile rupture
G7_co	42.5	60.7	Shear failure

2.6 Discussion

2.6.1 Effect of different number of layers

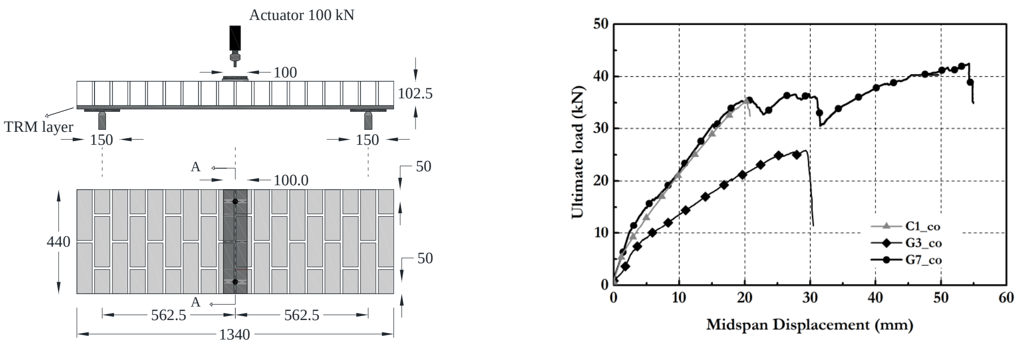
In all cases, the strengthened specimens demonstrated a substantial increase in their load bearing capacity as compared to the control specimen (Table 3). Experimental results suggest that additional TRM layers have a three-fold effect on the masonry walls specimens: (1) Increase of the specimen flexural stiffness while in the elastic regime of its response; (2) Increase of the ultimate load and (3) Change of the failure mode.

Strengthening with seven layers of coated glass fibre textile (G7_co) resulted in a 64.7% increase of the corresponding ultimate load as compared to its counterpart specimen strengthened with three layers of coated glass textile G3_co. Considering the failure mode observed, specimen G3_co failed due to textile rupture, whereas four extra coated glass TRM layers resulted in shear failure (shear diagonal tension) of the masonry in specimen G7_co. In terms of deformation capacity, G7_co, revealed increased deflection at the maximum load, namely 85.3%, compared to G3_co specimen.

2.6.2 Effect of the textile material

The load bearing capacity of G7_co specimen, was 20.4 % higher, compared to the specimen C1_co. The difference in the maximum recorded load in specimens G1_co (35.3 kN) and G7_co (42.5 kN) is attributed at the different failure mode observed in each case, namely the textile rupture and shear failure, respectively. The different failure mode observed in G7_co, suggests that 7 layers of glass fibre textile resulted in a higher tensile strength of the corresponding TRM layer as compared to 1 layer of coated carbon fibre textile and also supported by the coupon test results shown in Table 2. However, in the former case the overall thickness of the TRM layer is larger by approximately 2-2.5 times.

[1] Estimated value by means of cross-sectional analysis



(a) (b)

Figure 2. (a) Experimental setup (b) Experimental results: Load vs vertical deflection at mid-span curve

3 NUMERICAL INVESTIGATION

3.1 Finite element model

To further investigate the underlying mechanics of the TRM strengthened specimens, a set of finite element models were built using Abaqus commercial code (Abaqus, 2014). A cohesive element approach was utilised where bricks were modelled using full integration 8-noded hex-elements, whereas mortar was modelled by means of interface elements. Such a method of detailing has been found to accurately account for the meso-scale of the problem. A displacement control static analysis procedure was implemented with a maximum incremental displacement step-size equal to 0.01 m. The strengthening mortar layer was modelled using full integration quadrilateral layered shell elements with the textile fibre composite being considered as longitudinal reinforcement. The thickness of the mortar layer was identified to be equal to 2.5 mm, 2.5 mm, and 5 mm for the one layer carbon, 3 layers glass and 7 layers glass TRM configuration respectively. The mesh size was chosen to be consistent for all models and equal to 0.04 m, providing an adequate resolution both along the length of the mortar layer as well as along the height of the masonry wall.

3.2 Constitutive modelling

A concrete damage plasticity model was used to account for the inelastic constitutive behaviour of the brick masonry units. The model was calibrated using the constitutive relation introduced in Saenz (1964) and considering a brick compressive strength f_c=21.2 MPa. The dilation angle was assumed to be β=15º, whereas a zero eccentricity was assumed. A value K=0.77 was chosen for the ratio of the second stress invariant on the tensile meridian, to that on the compressive meridian. Finally, a viscosity parameter r=10^{-6} was utilized to ensure stability of the numerical solution procedure. The brick tensile strength was set to be equal to 500 KPa with the corresponding fracture energy set equal to $G=0.25$ kN/m. It should be emphasised that the value of the fracture energy utilized in this study was again chosen to ensure numerical stability of the solution procedure as in all cases the interface cohesive strength dictates the actual response of the masonry specimen under tension.

As the strengthening mortar is subjected to tensile forces only, a von-Mises plasticity model was used to model the nonlinear constitutive behaviour of the strengthening mortar layer with no hardening. The corresponding yield stress was set equal to f_{ym}=6 MPa. A von-Mises plasticity model with no hardening was used to account for the nonlinear constitutive behaviour of the textile fibre reinforcement. The corresponding material properties were E_{carbon}=190 GPa, $\sigma_{y,carbon}$=2800 MPa, E_{glass}=42.7 GPa, and $\sigma_{y,glass}$=830 MPa for the Young modulus and yield stress of the carbon and glass textile fibre composite, respectively.

The elastic and inelastic properties of the textile fibre composite materials have been identified through a curve fitting procedure based on the specimen elastic stiffness and ultimate strength capacity respectively. The nominal thickness of the textile layer was considered constant and equal to the value reported in Table 2. In both cases, i.e., glass and carbon, the identified values were smaller than the coupon test values shown in Table 2. This suggests that i) micro-sliding between the textile reinforcement and the strengthening mortar and/ or the TRM layer and the masonry wall takes place even from the elastic regime of the specimen response and ii) stress concentrations within the TRM layer locally break rovings resulting in an overall decrease of the effective textile tensile strength. The values of the maximum tensile strength of the textile material identified agree with the values evaluated from cross-sectional analysis of the masonry at peak load considering that only the textile contributes to the tensile strength of the specimen.

A cohesive modelling approach was implemented to account for the joint mortar cohesive response with the corresponding material parameters shown in Table 4. A maximum nominal stress damage initiation criterion was considered. Linear damage evolution was assumed after peak traction with the corresponding Mode-I fracture energy considered to be 0.068 kN/m. The TRM masonry interface was also modelled by means of interface elements with the corresponding cohesive properties also shown in Table 4. Mode-II fracture energy was considered in this case with a value equal to 0.068kN/m (Hordijk, 1991).

Table 4 Interface properties

Interface	Stiffness (kN/m x 10^6)			Ultimate traction (kPa)		
	K_{nn}	K_{tt}	K_{ss}	σ_{nn}	σ_{tt}	σ_{ss}
Masonry Mortar	1.51	100	100	50	1500	1500
TRM/ masonry	100	100	100	50.4	1500	1000

3.3 Results and comparisons

The numerically derived load vs deflection curves are compared against the experimental results in Figure 3 where a good fit is shown to be achieved. In particular, both the elastic and post-elastic stiffness of the masonry wall up to the peak load is accurately accounted for in all cases. Results obtained for both C1_co and G3_co provide an accurate estimate of the actual collapse load. The estimate on ultimate load displacements also agrees well with the experimental predictions. It should be highlighted that numerical simulation results have been derived on the basis of ductile behaviour been assumed for both the strengthening mortar layer and the textile composite for brevity. Clearly, a better assumption accounting for the brittle failure mode of the constituents would provide more accurate results at the cost of increasing the complexity of the numerical model. Although the finite element model considered for the case of G7_co adequately captures the specimen response up to the first peak value of the specimen, it fails to capture the actual response up to ultimate failure. This is attributed to the intriguing interlocking mechanics developing between the masonry bricks after shear failure that would call for a more detailed simulation procedure that is beyond of the scope of the current work.

4 CONCLUSIONS

An experimental programme was undertaken with the aim of identifying the effect of key design parameters on the out-of-plane flexural response of TRM strengthened masonry walls. Experimental results suggest that 7 layers of glass fibre textile resulted in the same increase in flexural capacity as in the case of 1 layer of carbon fibre textile. Increasing the number of layers of glass fibre textile from 3 to 7 resulted in an increased value of the corresponding ultimate load. A classical plasticity based finite element simulation procedure within a cohesive element approach was presented that provides accurate estimates of the specimen response both in terms of collapse load and in terms of ultimate displacement. The fidelity of the proposed simulation approach is decreased in the case of the 7 layer glass textile fibre strengthened specimen where the failure mode is developed through shear rupture of the brick masonry and debonding of the TRM layer. This calls for further development in the subject that will constitute the subject of future work.

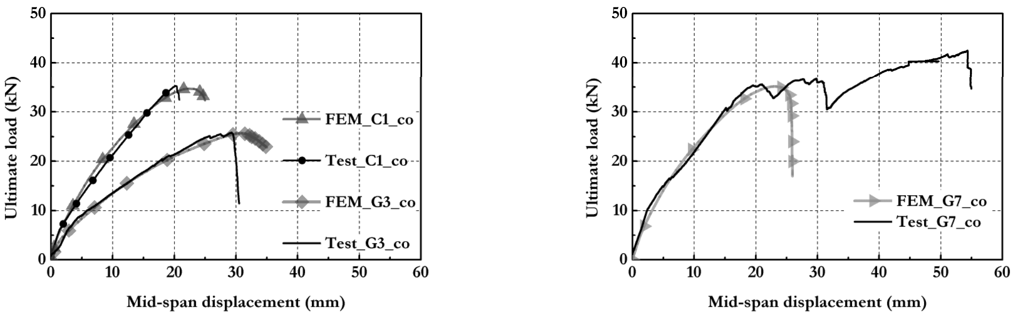


Figure 3. Finite element simulation results: Comparison against experimental results.

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