Construction and Building Materials 165 (2018) 769–781

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Out-of-plane response of masonry walls strengthened using textile-mortar system

F.A. Kariou [a], S.P. Triantafyllou [a,*], D.A. Bournas [b], L.N. Koutas [c,d]

[a] Centre for Structural Engineering and Informatics, Faculty of Engineering, The University of Nottingham, NG7 2RD Nottingham, UK
[b] European Commission, Joint Research Centre (JRC), Directorate for Space, Security and Migration, Safety and Security of Buildings Unit, Via E. Fermi 2749, I-21027 Ispra, Italy
[c] Dept. of Civil Engrg., Univ. of Thessaly, Volos GR-38221, Greece
[d] Dept. of Civil and Structural Engrg, Univ. of Sheffield, UK

HIGHLIGHTS

- The out-of-plane response of TRM strengthened walls is investigated.
- TRM effectiveness significantly depends on the wall thickness.
- Textile reinforcement coating significantly enhances the effectiveness of TRM.
- An in-house coating procedure is proposed for this purpose.

ARTICLE INFO

Article history:
Received 21 June 2017
Received in revised form 20 November 2017
Accepted 4 January 2018
Available online xxxx

Keywords:
Textile reinforced mortars
Masonry
Coated textiles

ABSTRACT

The out-of-plane response of masonry walls strengthened with textile-reinforced mortar (TRM) is experimentally investigated in this work. Medium-scale three-point bending tests were carried out on 18 specimens comprising a set of 9 single-wythe and 9 double-wythe brick masonry walls. Key investigated parameters involved the textile reinforcement ratio, the textile material, the coating of the textile reinforcement with epoxy resin, and the wall thickness. Experimental results suggest that TRM significantly increase the load bearing capacity of masonry walls. The amount of reinforcement utilised affects both the strength and deformation characteristics of the corresponding specimens, while it may alter the failure mode. Resin coating on the textile is found to be beneficial for the performance of the TRM overlays.
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1. Introduction

Unreinforced masonry is among the oldest construction systems worldwide. Masonry structures currently comprise a significant percentage of the existing building stock. Recent catastrophic events such as the earthquakes in L'Aquila (2009), Tohoku, Japan (2011), Christchurch (2011), Northern Italy (2012), and Central Italy (2016–2017) have tragically pointed out the need for restoration and strengthening of existing masonry structures. Structural strengthening interventions have been repeatedly documented as an effective method to not only preserve masonry structures but also to protect human lives, see, e.g., [1,2]. Masonry structures are also prone to ageing related structural deterioration, accelerated by the effect of adverse environmental actions, e.g., high speed winds and heavy rainfalls. Typical examples of partial collapse due to ageing include the Magdeen Tower [3] and the Feltham bridge [4] events. With the objective of mitigating such issues and also increase the durability and resilience of existing structures structural rehabilitation and strengthening techniques are employed. Structural strengthening further enables existing structure to operate under increased operational loads driven by current societal needs. Requirements for sustaining accidental events such as blast and impact, further necessitate upgrading of existing structures [5].

Due to the generic brittle response of unreinforced masonry (URM), improved structural resilience can be achieved by increasing both the strength and the ductility of the structure, thus introducing additional defence mechanisms [6–8]. To this point, several retrofitting strategies have been introduced and implemented to improve the resilience of masonry structures, e.g., grouting, post-tensioning, concrete jacketing [9] and Fibre Reinforced Polymer (FRP) composites amongst many [17]. Several researchers have

* Corresponding author.
E-mail addresses: florentia.kariou@nottingham.ac.uk (F.A. Kariou), savvas.triantafyllou@nottingham.ac.uk (S.P. Triantafyllou), dionysios.bournas@ec.europa.eu (D.A. Bournas), l.koutas@sheffield.ac.uk (L.N. Koutas).

https://doi.org/10.1016/j.conbuildmat.2018.01.026
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examined the performance of FRP strengthened masonry structures see, e.g., [10–17].

Despite their well-documented advantages (i.e. high strength and stiffness to weight ratio, corrosion resistance, ease and speed of application), the FRP strengthening technique entails several drawbacks, i.e., poor behaviour at moderate to high temperatures, combustibility, high costs, and safety-hazards for the manual workers. These are related to the properties of the organic resins used to impregnate the fibres as for example these have been reported to deteriorate for temperatures below or close to their glass transition temperature (usually in the range of 50–120 °C), see, e.g., [55,56]. Epoxy-resins furthermore decompose thermally, releasing heat, smoke, soot and toxic/ combustible volatiles for temperature between 300 and 400 °C. Compared to wet lay-up epoxy-resin applications, TRM strengthening costs can be lower due to the low-cost cement mortars utilised. Another disadvantage of FRP is that they are usually manufactured and applied in strips. This effectively results in regions of increased strength and stiffness within the retrofitted structure. In the case of brittle URM structures, this results in stress concentrations in the unreinforced regions that accelerate damage rather than mitigating it [18]. Bati and Rovero [19] demonstrated that when the distance between the FRP strips applied at the extrados is reduced, the resulting ultimate displacements increase, thus resulting in an overall increase of the pseudo-ductility of the virgin masonry wall. The advantages of global rather than stripped strengthening solutions for the case of masonry have been further examined and substantiated in the literature, see, e.g., [20,58].

In view of the aforementioned, an innovative mineral-based composite material, i.e., textile-reinforced mortar (TRM), has been proposed for structural retrofitting, addressing also cost effectiveness and durability issues. TRM comprises layers of textiles made of, e.g., high-strength carbon, glass or basalt fibres impregnated within inorganic matrices, such as cement-based mortars. The acronym 'FRCM', i.e., Fibre Reinforced Cementitious Matrix, is also used in the literature for the same material ([53,59–61]). The textiles typically consist of fibre rovings in at least two orthogonal directions, thus creating an open-mesh geometry. Due to the use of mineral-based mortars, TRM offers resistance at temperatures of up to 250 °C [21,62] or even 400 °C [63], compatibility with concrete and masonry substrates [22], ability to be applied on wet surfaces and low temperatures, and air permeability.

TRM has been used as a strengthening and seismic retrofitting material for reinforced concrete, see, e.g., [21]. A number of experimental studies have been performed to investigate the in-plane response of TRM strengthened masonry walls, see, e.g., [23–32]. Prota et al. [25] studied the in-plane response of tuff masonry panels strengthened with cementitious grid system. Papanicolaou et al. [26] tested TRM strengthened hole clay-brick masonry walls under cyclic in-plane loading and Bernat et al. [28] examined the in-plane compressive eccentric load of solid clay brick masonry walls. Increase of strength and deformability was achieved after applying the composite material in each strengthening configuration. In addition, bond between the TRM material and masonry was investigated by Faella et al. [33], D'Ambrisi et al. [34], and De Felice et al. [49]. The effectiveness of TRM, was also investigated in few experimental studies reported for strengthened masonry arches at the extrados of the arch with the TRM composite material [35,36,50]. Analytical models have also been developed to further highlight the mechanical response of TRM strengthened systems, see, e.g., [37,38].

Previous experimental studies on the out-of-plane behaviour of masonry walls highlighted the substantial gain in strength and deformability due to TRM strengthening. In particular, Kolsch [39] examined the performance of masonry walls strengthened with three layers of a unidirectional carbon fabric under cyclic loading. The author demonstrated that such an approach prevents the partial or complete collapse of the strengthened structure. Papanicolaou et al. [40] further investigated the influence of the number of carbon fibre textile layers, namely 1 and 2, on the cyclic response of masonry walls strengthened with TRM. It was observed that such a configuration resulted in a shear-flexure failure mode followed by debonding at the brick-bed joint interface. Increasing the number of layers has been found to result in a 25% increase of the maximum load. Furthermore, Papanicolaou et al. [23] demonstrated the superior performance of coated textile TRM systems by investigating the out-of-plane cyclic performance of masonry walls strengthened with one layer of coated glass, basalt, and coated basalt TRM. Both coated glass and coated basalt specimens demonstrated superior performance by avoiding textile slipping that was the predominant mode of failure in the non-coated basalt specimens.

Harajli et al. [41] studied the out-of-plane response of masonry walls strengthened with a single layer of coated glass and coated/ uncoated basalt textile TRM under both monotonic and cyclic loading. The coated glass textile TRM demonstrated improved performance in terms of load capacity due to the resulting uniform strain distribution. Conversely, in the uncoated basalt fibre textile a single predominant crack was formed leading to the local fracture of the textile. The advantages of utilizing coated textile fibres have also been highlighted in Donnini et al. [51]. In the experimental work undertaken by Tetta et al. [42] in TRM strengthening of reinforced concrete beams, it had been demonstrated that increasing the number of textile layers significantly improves the textile performance by activating a larger ratio of their corresponding tensile strength. In the present study this strategy is further enhanced and applied for the out-of-plane strengthening of masonry walls.

Babaeidarabad et al. [43] further examined the out-of-plane cyclic loading on masonry walls strengthened with one and four layers of carbon textile TRM. The authors demonstrated that for lower reinforcement ratios the dominant failure mode was textile rupture, whereas for high reinforcement ratios shear failure preceded flexural failure. Valluzzi et al. [44] also reported that their strengthening configuration utilizing basalt TRM composite resulted in shear failure mode of the examined masonry walls, whereas tensile fibre rupture was observed in the case of glass textile TRM strengthening. Very recently, Martins et al. [45] proposed an innovative textile configuration comprising either carbon or glass braided composited rods (BCR). The authors demonstrated that such an approach resulted in pure flexure failure mode of the glass BCR and a combined shear-flexure failure mode for the carbon BCR composite material.

This paper investigates for the first time in a systematic way the effect of a series of parameters on the out-of-plane response of masonry walls. In terms of textile reinforcement, both the textile material and the number of textile layers are considered as experimental parameters. Within this setting, a systematic study on the comparative effectiveness of glass, coated basalt and in addition carbon textile reinforcement is undertaken on the basis of utilizing textile layers of equivalent elastic stiffness. More specifically, the influence of 3 and 7 layers of glass and coated basalt TRM material is examined and their response is directly compared to the 1 layer of carbon fibre TRM case. To the authors' knowledge such a comparative study has not been performed. Furthermore, the effect of the resin coating on carbon and glass strengthened specimens is investigated. The behaviour of resin coated carbon textile has not been examined in the literature. Finally, both single and double-wythe walls are examined.

This work is organized as follows. In Section 2, the experimental program is thoroughly described and the properties of the materials used are presented. Next, the experimental results are presented in Section 3. Discussion of the experimental results is

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