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Modelling the nonlinear behaviour of masonry walls strengthened with textile reinforced mortars

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ABSTRACT

Textile Reinforced Mortars (TRMs) have found extensive attention for externally bonded reinforcement of masonry and historical structures. However, only few information is available regarding their mechanical properties and effectiveness in improving the seismic performance of strengthened structures. This paper presents an extensive numerical investigation on the effect of TRM composites on the nonlinear response and failure modes of masonry walls. The effect of boundary conditions and the TRM type on the performance of strengthened walls are critically discussed and presented. It is shown that the performance and failure mode of the walls can significantly change after strengthening, an important issue that should be considered at the design stage. Finally, the effect of TRM application on the nonlinear response of a large historical masonry façade in Macau is investigated and presented.

1. Introduction

Several strengthening techniques have been used and proposed for improving the seismic resistance of masonry structure [1]. Among them, Externally Bonded Reinforcement (EBR) with innovative composite materials has received extensive attention in the last years and has been the subject of several studies. Fibre Reinforced Polymers (FRPs) have been extensively used for this strengthening technique due to their high mechanical strength, low weight and ease of application. These composites, however, show a poor performance in high temperature conditions, are mechanically and thermally incompatible with poor masonry substrates and can affect the hygrothermal performance of the building due to their (relative) impermeability to moisture transfer. The use of new composite materials based on fabrics (or grids) embedded in inorganic matrices has thus recently received attention as a sustainable and a more compatible solution for application to masonry and historical structures [2–6].

These composites are referred with several terms in the literature such as Textile Reinforced Concrete (TRC), Textile Reinforced Mortar (TRM) or Fabric Reinforced Cementitious Matrix (FRCM). Two key components of TRMs are the matrix and the reinforcing mesh. The most common matrices used for strengthening applications are lime-based or cement-based. The lime-based mortars are proposed for application to masonry and historical buildings due to sustainability and compatibility issues [6]. As for the reinforcement, steel, glass, PBO (polyparaphenylene benzobisoxazole), basalt and natural fibres are among the most common materials employed [6,7]. The variety of available fibres and mortar types lead to a wide range of mechanical properties for TRMs which makes them suitable for fit for purpose design.

The mechanical behaviour of TRMs and their effectiveness in strengthening applications are highly dependent on the mechanical properties of the fibres and the mortar, as well as the bond behaviour at the fibre-to-mortar and mortar-to-substrate interfaces [6,8–10]. Mortars are usually brittle with a relatively low tensile strength (in the order of masonry tensile strength). Fibres have also a linear elastic behaviour until tensile rupture, but with a much larger deformation capacity (generally the tensile rupture strain of the fibres is much larger than mortar cracking strain). Once the mortar is cracked, fibres bridging mechanism (which is dependent on the fibre-to-mortar bond behaviour) becomes activated leading to crack propagation and a pseudo-ductile response of TRM composites [11].

Despite the recent attention on the use of TRMs for strengthening of masonry, the available information regarding the mechanical performance and effectiveness for improving the performance of

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masonry structures are still few. Although several recent studies have been devoted to mechanical characterization of TRM composites, fundamental mechanisms that govern the nonlinear response at different levels are still not well studied [12]. At the micro-level, the fibre-to-mortar bond behaviour in different strengthening systems has received few attention, see e.g. [12]. At the component level, mechanical characterization of TRMs has been mostly focused on tensile response, see e.g. [7,12–14], and the available information on flexural and shear response are very limited, see e.g. [15,16]. The bond of TRM-to-masonry has also received extensive attention, see e.g. [6,9,10,12,17–19]. The information regarding the effectiveness of TRMs in improving the seismic performance of masonry structural elements is still very limited, but the number of studies devoted to this subject have been consistently growing during the last years. Investigations at the structural level are mostly focused on the static monotonic (and very few on static cyclic) nonlinear response of strengthened walls under in-plane, see e.g. [2,5,20–27], and out-of-plane actions, see e.g. [26,28,29], as well as nonlinear response of arches, see e.g. [16,30,31].

Application of numerical modelling tools has also been limited and mostly focused on simulation of tensile response, e.g. [32,33], and bond behaviour, e.g. [18,9]. Only few studies can be found in the literature on numerical modelling of TRM-strengthened masonry at the structural level, see e.g. [34–36]. Numerical modelling of TRM-strengthened masonry, although a complex task, is an interesting approach for understanding the influencing parameters on the performance of strengthened structures and the changes of failure modes after strengthening.

Numerical simulations, depending on the desired level of accuracy and on the model size, can be performed following the micro-modelling (usually used for simulating small components) or the macro-modelling approaches (usually used for simulating structural performance) [37,38].

Micro-modelling, in which all the components and the interaction between them are simulated separately, is useful for a detailed analysis and understanding of all possible mechanisms and failure modes. In this technique, all individual components of masonry (unit, mortar and unit-to-mortar interface) and TRM layer (fibre mesh, mortar, fibre-to-mortar interface) are modelled separately. Several material parameters and suitable bond-slip laws for the interfaces are therefore necessary for a reliable simulation. This approach is time consuming (even for small scale models) and requires a fine FE mesh size to resolve the mesh dependency of the interface elements, and the analysis is computationally demanding and expensive.

On the other hand, in macro-modelling masonry and TRM are simulated as continuum elements with the nonlinearities homogenized over the elements. The average response of masonry and TRM are therefore considered in the phenomenological constitutive laws. This technique, which requires knowledge on the macro properties of each composite, is usually used for structural level investigations. The use of macro-models for structural level simulations is still at early stage for TRM-strengthened masonry, average constitutive models are not available, and the appropriateness of the existing damage/crack models is not clear yet. These two later issues require further comprehensive experimental tests on the nonlinear shear and flexural response of TRMs.

This paper presents a numerical investigation on the in-plane behaviour of TRM-strengthened masonry panels following the macro-modelling approach. The main objective is to investigate the effectiveness of different, commercially available, TRM composites on the nonlinear behaviour and failure mode of masonry walls. The nonlinear behaviour of masonry and TRM are represented by a macroscopic smeared crack approach with the assumption of perfect bond between masonry and TRM layers. Although the inclusion of interface elements between TRM and masonry is an easy task and can be considered in the same framework, the assumption of perfect bond is reasonable (and has also been made by other authors) as (i) experimental results have shown this failure is unlikely to occur, see e.g. [34] and (ii) occurrence of such a failure should be avoided at the design stage by selecting a suitable mortar type (through bond tests) to ensure the effectiveness of this strengthening system. The masonry is modelled assuming a softening anisotropic elasto-plastic continuum model [39] following the rotating smeared crack approach. The TRM layer is modelled by assuming an isotropic behaviour for the mortar (with a parabolic behaviour in compression and a tension softening law) with embedded reinforcements perfectly bonded to the mortar. This latter assumption is also reasonable as (i) the experimental results have shown that slippage of the fibres from the mortar can be avoided if the bond length is sufficiently long and (ii) even if slippage occurs, its effects can be considered in the model by modification of the mortar tension softening law and fibres' stiffness.

The accuracy of the modelling strategy is initially validated at the component level by comparing the numerical results with some experimental data taken from the literature. The model is then used for simulating the nonlinear response of TRM-strengthened masonry panels by performing static nonlinear (pushover) analysis. Finally, the effect of TRM application (considering different TRM types and strengthening schemes) on the nonlinear response of real a historical masonry façade in Macau is investigated and presented.

2. Modelling of TRM composites

This section discusses the adopted numerical modelling technique and its validation for simulating the nonlinear behaviour of TRM composites. Validation is performed by comparison of numerical results with experimental tests taken from literature. Due to the lack of available experimental data on the shear response of TRM panels, tensile tests performed by Carozzi and Poggi [14] are selected as reference. The main focus is on validation of the modelling strategy and constitutive models with particular attention to the FE mesh size and mortar tension softening law.

The total strain rotating crack model is adopted for modelling the nonlinear response of the mortar. Rotating smeared crack models seem suitable for simulating the nonlinear response of TRMs and have been used elsewhere, see e.g. [34,36]. Further comprehensive experimental tests on the TRMs behaviour under in-plane shear and out-of-plane loading conditions are however necessary for an in-depth understanding of suitable modelling approaches and development of better constitutive and damage models for these materials.

2.1. Reference experimental results

The tensile tests performed by Carozzi and Poggi [14] on TRM composites made of cementitious mortar and PBO (polyparaphenylene benzobisoxazole) fibre grids are selected as reference. The PBO fibres were organized in an unbalanced net made of 10 mm and 20 mm spaced rovings in longitudinal and transverse directions, respectively (Fig. 1a). The grid had an equivalent thickness of 0.046 mm and 0.011 mm in longitudinal and transverse directions, respectively. The materials mechanical properties, presented in Table 1, were obtained by performing tensile tests on single dry rovings and fibre grid strips (made of four rovings), and compressive and indirect tensile tests on mortar specimens (Table 1). Further details about the test methods and procedures can be found in [14].