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Modelling of the in-plane behaviour of masonry walls strengthened with polymeric grids embedded in cementitious mortar layers

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ABSTRACT

The seismic reinforcement of masonry walls needs to be carried out through appropriate and effective techniques aiming at providing both adequate strength and displacement capacity. The present research concerns experimental results about the in-plane behaviour of masonry walls strengthened through an innovative technique employing polymeric grids embedded in cementitious mortar layers applied on the wall surface. The behaviour of strengthened masonry walls subjected to cyclic shear-compression tests is examined in order to quantify the strength and displacement capacity increment provided by the reinforcement. A Finite Element Model of the unreinforced and reinforced panels has been developed and parameters defining masonry and strengthening materials have been calibrated by means of comparisons with the experimental results. The effectiveness of the strengthening system has been then numerically investigated through a wide parametric analysis varying the masonry strength, the wall shape, the axial stiffness of the strengthening grid and the strength of the mortar. Finally, a comparison of the effectiveness of the polymeric grid with a traditional steel one embedded in the same mortar layer is also reported.

1. Introduction

Existing masonry buildings generally represent one of the most vulnerable structural building typology under strong seismic actions. Unreinforced masonry structures were, indeed, normally designed for gravity loads and, taking advantage of the adequate masonry compressive strength, they behave well as long as the loads are vertical. Higher level of serviceability and safety requirements are necessary for masonry buildings, reflecting in the need of assure an upgraded seismic behaviour. The strengthening of this particular class of structures is an important issue and the adoption and design of an appropriate reinforcing system represents key aspects in order to achieve the required seismic performances in terms of energy dissipation capacity.

When a masonry structure is subjected to lateral loads induced by earthquakes, shear and flexural stresses develop in the walls. In particular, the seismic loads cause both in-plane and out-of-plane actions. If the building is characterized by good masonry quality and effective connections between vertical and horizontal elements, its global strength is mainly due to the in-plane shear strength of the masonry walls [1] and the building is able to resist to the seismic action as a whole system without activation of out-of-plane mechanisms and local collapses.

Under horizontal actions, the main in-plane failure mechanisms of unreinforced masonry walls can be summarized as shear, i.e. sliding or diagonal cracks mechanisms, and flexural, rocking or crushing mechanisms, failure modes [2]. The shear failure mode is typically found in walls with low aspect ratio and high axial loads leading to the formation of a diagonal crack, which may be stepped passing through the mortar joints according to the units/joints arrangement or involving also the units, depending on the relative strength of the masonry constituents. Sliding failure can be registered in case of low axial load and involves the formation of a horizontal sliding plane typically placed at the base of the wall. Furthermore, a masonry wall can experience a flexural failure mode in case of high aspect ratio and shear resistance. Depending on the level of axial force, the wall can fail according to a rocking motion or

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crushing of masonry. Generally, failure initiates with large flexural cracks developing at the bottom and the top of the element. As the displacement increases, the element deforms as a 'rigid body' and a rotation mechanism is activated.

The damages and cracking patterns experienced by different structural elements in masonry structures observed after seismic events require the development of new types of strengthening systems and techniques on one side and the need for quantitatively evaluating their effectiveness through experimental and numerical procedures on the other.

In this paper, among the various innovative strengthening techniques adopting FRP (Fibre Reinforced Polymers) materials, the more recent use of Cementitious Matrix-Grid (CMG) is discussed in detail. Such a strengthening technique is becoming very diffuse for masonry structures since, due to the reduced thickness of the mortar layer, it does not induces a relevant mass increase in the strengthened element that is a favourable aspect especially for seismic retrofitting. This aspect is also typical of FRP materials embedded in epoxy resin, but the CMG materials have further advantages: their bi-axial texture makes them, indeed, more suitable to strengthen masonry elements that have a 'bi-dimensional' geometry, determines a more widespread diffusion of stresses in the masonry, and make them less sensitive to debonding phenomena.

2. Innovative strengthening techniques using composite materials

Different strengthening techniques exist and have found more or less wide application in order to obtain increase of strength and/or ductility in unreinforced masonry walls. A review of retrofitting method based on the use of traditional materials can be found in Ref. [3] pointing out their disadvantages and evidencing the lack of analytical procedures for a correct evaluation of their effectiveness.

New methods based on the use of innovative materials, such as the Externally Bonded Reinforcement (EBR) made of Fibre Reinforced Polymers (FRP), have been developed in the last decades [4,5]. All the latest developed techniques take advantage of the well-known benefits proper to the FRP materials including, above all, lightweight, resistance to corrosive environment, excellent mechanical properties such as stiffness and strength, and simplicity of application. These techniques can be devoted to the improvement of the out-of-plane flexural capacity, the in-plane shear resistance and the ductility of the strengthened elements.

Several experimental or analytical researches have been carried out about the in-plane response of FRP-EBR strengthened walls.

In Ref. [6] a review of some in-plane tests configurations used to study the shear response of reinforced elements is reported. It has been noted that debonding from masonry surface, friction and dilatancy phenomena in the brick–mortar interface can influence the response of the strengthened element.

Similar experimental campaigns have been carried out by Refs. [7–14] considering CFRP and GFRP strips arranged according to diagonal cross- and grid-pattern. In particular, in Ref. [8] the combination of two repairing techniques for damaged walls has been studied, namely grout injection of mortar and application of GFRP sheets, showing that it is possible to fully recover and even upgrade the original capacity of the walls. In Ref. [12] classical diagonal compressive tests have been carried out for exploring the in-plane shear response of brick masonry panels strengthened with FRP strips applied according to diagonal and grid patterns on both sides or only at one side of the panel. The tests highlighted that the asymmetrical application of the reinforcement is associated to a limited effectiveness in terms of shear resistance improvement. Moreover, the diagonal configuration of strips resulted more efficient for enhancing the shear capacity, while the grid configuration allowed a better stress redistribution and a less brittle failure due to crack spreading, as also evidenced in Refs. [7,15]. The effectiveness of FRP laminates applied over masonry walls according to a diagonal configuration has been experimentally evidenced also in Refs. [16,17]. Most experimental tests have shown that masonry panels externally reinforced with FRP attained shear strength increase variable between 15 and 70%. Shear strength usually increases proportionally to the axial rigidity of the external reinforcement [2,7]. In addition to the shear strength, the FRP reinforcement allows improving also the displacement and the load at first crack, and the maximum displacement before the failure [7,16].

A number of experimental procedures and numerical models have been proposed for the study of the bond performances between FRP sheets and masonry elements made of natural or artificial blocks [18–23]. Such studies were aimed to explore the bond-stress-slip relationship and the maximum tensile stress in the FRP reinforcement corresponding to initiation of debonding phenomena both on the experimental and theoretical point of view by means of specific bond tests and analytical or Finite Element models. Experimental and numerical investigation evidenced that the bond behaviour is influenced by the axial stiffness of the FRP reinforcement and by the mechanical (stiffness, strength) and physical (porosity, surface consistency) properties of the masonry support [22].

A strengthening method alternative to the FRP EBR technique has been recently proposed in Refs. [24–26] for strengthening unreinforced masonry walls subjected to in-plane and out-of-plane cyclic loadings. The reinforcement consists of a Textile Reinforced Mortar (TRM) used as overlays in order to address the numerous drawbacks related to the use of the FRP EBR technique, i.e. debonding phenomena and stress concentrations, and mainly associated to the employment of inorganic binders. In addition, certain properties of masonry, such as the porosity and surface unevenness and/or roughness, which affect the epoxy-masonry bond behaviour, as well as restrictions related to intervention strategies for historic masonry buildings (e.g. requirements for reversibility), may possibly inhibit the use of FRP strengthening technique.

In Ref. [24] it has been noted that the textile-reinforced mortar system leads to an increase of the load carrying capacity of the unstrengthened panel of about 30%, which however means a reduced effectiveness compared to the FRP-EBR technique, but a larger increase of the deformability (up to about 15–30%) compared to the FRP-EBR technique. In addition, the strength generally increases with the number of layers and the axial load, at the expense of deformation capacity [26].

In Ref. [27] a similar technique has been employed in order to strengthen tuff masonry walls, which are rather common in the South of Italy as well as in the Mediterranean basin. A carbon fibre grid is placed within two layers of a cementitious-based mortar (CMG technique). The experimental diagonal compression tests showed that the strengthened walls failed for a premature debonding between the strengthening layer and the masonry substrate, even if the ultimate load was increased of 4–6 times compared with the unstrengthened walls. The evolution of stiffness observed on the load–displacement curves highlighted that the strengthening layer restrained the formation of diagonal cracks in the masonry substrate.

In Ref. [28] tuff masonry walls were externally reinforced by a CMG system externally applied on only one side or both sides of the masonry wall. A bidirectional glass grid embedded in a cementitious mortar reinforced with polymer modified glass fibres was used as CMG strengthening system. The experimental results evidenced that such a system reduces the high anisotropy of the unstrengthened panels and allows obtaining relevant increases of