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Out-of-plane behavior of reinforced masonry walls: Experimental and numerical study

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ABSTRACT

In the paper, the results of an experimental and numerical study on the out-of-plane bending effectiveness of a modern strengthening technique applied to existing masonry walls are presented. The technique consists in the application, on both wall faces, of a mortar coating reinforced with glass fiber-reinforced polymer (GFRP) meshes. Four point bending tests of full scale masonry samples (1000 width, 3000 mm height) were carried out considering three types of masonry (solid brick, 250 mm thick, rubble stone and cobblestones, 400 mm thick). The performances of plain and reinforced specimens were analysed and compared. It emerged that strengthened specimens are able to resist out-of-plane bending moments almost 4–5 times greater than those of plain specimens; moreover they can overcome deflections more than 25 times higher, due to the presence of the GFRP mesh, which contrasts the opening of cracks. The cracking and the ultimate bending moments of reinforced samples can be analytically predicted using relationships quite close to those used in the design of reinforced concrete beams subjected to combined axial and bending actions. The results of nonlinear static analyses performed on a 2D numerical model were also presented, so to comprehend the mechanical behaviour of reinforced masonry walls. Their agreement with the experimental results proved the reliability of the simulations; moreover, the extension of the 2D model to a 3D one, necessary to analyze the behavior of perforated walls, was also made.

1. Introduction

The aim to preserve ancient masonry buildings, due to their cultural and historical relevance, is often accompanied by the necessity to improve the structural safety of this architectural heritage. In particular, an important topic is to overcome to structural deficiencies related to earthquakes, as, in general, seismic provisions were not considered in the construction of these buildings. The past seismic events evidenced the poor performances of these structures (composed mainly of unreinforced masonry walls made of brick or stone units, jointed together through weak lime mortars, and wooden floors) which led to partial or global collapse due to the out-of-plane (in bending) or in-plane failure (in shear or bending) of the walls. The main critical aspects are related, on one side, to the material characteristics, such as the masonry high mass (high inertia forces) and the low masonry tensile strength and, on the other end, to structural deficiencies, such as the lack of effective connections among the resisting elements, the presence of horizontal thrust transmitted by arches, vaults and roofs, the inappropriate distribution of the walls in the two main direction and the in-plane deformability of timber horizontal diaphragms (repartition of the seismic forces proportional to the masses).

In most cases, the out-of-plane failure may be inhibited providing an adequate in-plane stiffness to the floors (e.g. by means of nailed steel plates, glued fiber reinforced polymer (FRP) strips or reinforced concrete subfloor anchored to the timber joists [1]) and an effective connection among perpendicular walls and between the walls and the horizontal diaphragms (e.g. through reinforced concrete tie beams, steel tie rods or angles [2]). Once these structural deficiencies have been amended, attaining, thus, to the so called “box behavior”, the distribution of the seismic action among the vertical resisting elements depends on their stiffness and the building failure is generally due to the in-plane collapse of the masonry walls. However, in masonry structures with high interstorey distance (4–5 m), the out-of-plane bending actions may be relevant, constituting a great problem especially in upper storeys of tall buildings, where the out-of-plane forces are higher, the axial

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load is reduced and, frequently, walls are thinner than those at lower levels.

Several techniques have been extensively applied in the past for the enhancement of both the in-plane and out of-plane performances of masonry walls, most concerning in the application of concrete coatings with steel meshes embedded (such as ferrocement [3,4], reinforced cement-based plasters [5,6] and shotcrete overlays [7,8]) or in the insertion of steel ties or strips in the mortar joints or in cuts created near the masonry surface, before repointing [9]. These reinforcements were proved as able to provide to the masonry both high strength and a properly ductile behaviour. In particular, the presence of the steel reinforcement permits the improvement of the wall deformation capacity. However, the contribution of the reinforcement can be vanished by the premature detachment of the reinforcement from the masonry [10,11], as the distribution of the seismic actions depends on the stiffness ratio between the two materials. It is thus of fundamental relevance to provide a good bond of the coating or repointing (e.g. cleaning, saturation, mechanical or chemical treatment of the masonry surface) and, if necessary, an adequate dimensioning of connectors. Moreover, severe steel corrosion problems emerged in several cases, over the time. For this reason, traditional retrofitting techniques were gradually replaced, in the last twenty years, by different reinforcement solutions based on no-corrosive materials such as FRP, based mostly on carbon, glass or aramid fibers [12,13], PBO (polybenzoxazole) [14], PP (polypropylene) [15] or stainless steel [16,17]. The fundamental benefits of the reinforcement with a composite material are strictly related to its great performances when subjected in tension.

The first application experiences in the use of FRP for the strengthening of existing masonry concerned mostly in the external bonding of thin fabrics, strips or laminates of FRP to the wall surface by impregnation with epoxy resin matrix [18–21]. Several experimental campaigns were aimed to assess the effectiveness of this technique against out-of-plane actions and to evaluate the influence on its effectiveness of different parameters as the fiber type and amount, the type of resin, the reinforcement arrangement and the boundary conditions (e.g. Refs. [22–25]). Externally bonded (EB) FRP results an effective technique and has the advantage to not increase the building mass. Typically, the benefits of the EB FRP reinforcement are related to the ability of the composite material in contrasting the opening of masonry cracks, due to the high tensile strength. However, some drawbacks have to be considered: some tests evidenced that FRP is not totally compatible with the masonry, due to the differences between stiffness, strengths and thermal coefficients. In fact, in the application on masonry surfaces, the technique frequently evidenced a poor bond to the substrate (due to the higher surface roughness and irregularity, in respect to concrete) which may induce the reinforcement delamination, reducing the effectiveness of the intervention [26–29]. In addition the epoxy resins, besides being high-costs and requiring special handling equipment and skilled installation staff, have very scarce resistance to high-temperatures and fire and are affected by ultraviolet (UV), water and alkaline degradation, needing therefore adequate protection systems [30–32]. Moreover, their application on wet surfaces or at low temperatures is not possible. Furthermore, the difficulty in removal the intervention (irreversibility of the retrofitting) lead heritage conservation authorities to avoid its application on listed historical buildings.

Thus, alternative effective rehabilitation strategies, based on the use of FRP bars or strips, mounted near the wall surface (NSM – near surface mounted) in epoxy-filled grooves created in the masonry, were developed [33–37]. In these cases, the composite is less exposed to the environment condition and fire and the visual impact of the intervention upon the structure is minimal; the premature failure of the reinforcement by pull-out may however occur [38].

Other valid reinforcement methods, able to overcome most of the limits of FRP, concern fiber-reinforced cementitious matrix (FRCM) and fiber-reinforced mortars (FRM – known also as FRG - fiber reinforced grouts - or TRM - textile reinforced mortars), where the FRP elements are embedded in an inorganic matrix [39–42]. The various proposed systems differ in the type and thickness of the matrix (ranging from high strength cement-based mixtures to natural lime mortars, from a 10 mm thin layer of scratch coat to a 30–40 mm thick layer) and in the characteristics of the FRP reinforcement (mostly textile or meshes). The installation approach is quite simple, as requires the same skills and instruments of a traditional reinforced coating intervention, such as ferrocement or steel-reinforced plasters. These strengthening systems generally exhibit a more effective bond with the substrate in respect to the epoxy glued fibers techniques and also better performances at elevated temperatures [43–45]. Inorganic matrices have a higher compatibility with historic masonry and, especially when lime-based mortars are employed, do not prejudice its water and vapour permeability (avoiding, thus, dangerous moisture accumulation at the interface) and the reversibility of the intervention.

Some experimental investigations on masonry walls strengthened through the application of a mortar coating reinforced with textiles or preformed composite meshes evidenced the capacity of these reinforcement systems to increase the out-of-plane resistance of masonry [46–49], also raising significantly the plastic deformation capacity. However, the masonry-matrix bonding performances still remain a key topic for an effective design of the material [55]. Shear bond tests [50,51] permit to evaluate the interaction between the composite material and the masonry substrate and are typically based on small masonry samples (single brick, stone units or masonry wallets) to which the reinforcement is applied on one or both sides, for a determined area. Variations in the nature and roughness of the masonry surface, in the bond area and in the characteristics of the composite material, influence the resistance and the type of collapse [52–54]. To avoid the detachment of wall coatings and to improve the reinforcement effectiveness, transversal mechanical connectors were also introduced in some applications.

The experimental investigations available in the literature on the out-of-plane behavior of masonry enhanced with these modern techniques concerned mostly quasi-static (both monotonic and loading-unloading) or cyclic procedures, so to reproduce the effects of the wall inertial load; the common test arrangements concern 3 point bending [39], 4 point bending [33] or transversal uniform loads [40]. Some dynamic, shaking table tests were also performed [25]. Besides the experimental investigations, numerical models, ranging from micro to macro modelling approaches [46–58], were developed so to simulate the behavior of reinforced masonry (RM) walls and investigate the influence of the different parameters.

A FRM strengthening technique based on the application, on both sides of the wall, of a mortar coating with GFRP meshes embedded is considered in the paper. Recent experimental and numerical investigations evidenced its effectiveness in the seismic enhancement of unreinforced masonry (URM) buildings for in-plane actions [59–61]. The study herein presented focuses to out-of-plane actions and is aimed to the evaluation of the performances of masonry reinforced with this technique and to provide methods for the analytical design and numerical modelling purposes.

At first, the results of some experimental full scale out-of-plane four-point bending tests are presented and discussed, so to evidence the improvement of the masonry performances in terms of