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Shear response of brick masonry small assemblages strengthened with bonded FRP laminates for in-plane reinforcement

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ABSTRACT

Modern composite materials are receiving increasing attention as reinforcing solutions applicable to the repair and strengthening of concrete and masonry structures. Aiming towards a better characterization of the possibilities offered by these materials, the research work reported here investigates the shear response of small masonry assemblages strengthened externally with sheets made of glass and aramid fiber reinforced polymer laminates. An alternative strengthening approach provided by microlaminated wood is also investigated.

The assemblages, consisting of masonry couplets, were subjected to combined shear and axial loading and were laid to failure through monotonic and cyclic loading processes. The efficiency of the different strengthening materials is investigated by comparison with measures obtained for unreinforced assemblages subjected to similar load conditions. The research is aimed at characterizing the contribution of the different strengthening materials and arrangements to increase both the peak shear strength and the residual (post-peak) shear strength. An attempt is made to analytically describe the strengthening effect of reinforcement. For this purpose, two different effects provided by the reinforcing laminates – the increase of friction at the brick–mortar interface and the shear strength of the laminate itself – are considered.

1. Introduction. Shear strengthening of masonry

A significant part of the building stock of many areas of the world is still constituted by historical or traditional constructions structurally consisting of brick masonry load-bearing walls. This includes both residential buildings still in use and heritage constructions of large cultural value. The evaluation and the retrofitting of the masonry shear and load-bearing walls is a key issue to ascertain the adequate safe response of these buildings under lateral actions such as hurricane winds and earthquakes. This aspect is of particular interest in the Mediterranean countries, where a massive stock of masonry buildings, erected during the 20th c. or before, coexists with very significant seismicity.

Among possible strengthening strategies, external reinforcement consisting of externally chemically bonded resistant materials, such as fiber reinforced polymers (FRP), provides an interesting possibility because it can be implemented easily, only requires minor preparation works, and preserves the material integrity of the masonry wall. However, external chemically bonded reinforcement involves complex mechanical and strength phenomena, such as: (1) the possible peeling off of the brick surface, (2) the brittle behavior of FRP both in shear and tension, (3) the effective resisting response of the reinforcement with respect to its theoretical capacity, (4) the influence of friction and dilatancy in the brick–mortar interface on the response of the strengthening and (5) the coupling of the different strength mechanisms activated by the reinforcing, which include an increase of friction due to the generation of normal anchoring forces and the contribution of the shear strength of the laminates.

A number of experimental or analytical research works have been previously carried out on in-plane response of masonry with externally bonded reinforcement (Fig. 1). Most of these works deal with FRP applications. Triantafillou [1] derived a set of analytical expressions for the prediction of the ultimate response of masonry structures using epoxy-bonded FRP laminates and compared them with experimental results obtained by testing a set of small wall specimens in out-of plane and in-plane bending (Fig. 1d). Valluzzi et al. [2,3] chose the diagonal compressive test to investigate the in-plane shear response of brick masonry panels strengthened with FRP laminates and compared the experimental results with the predictions yielded by different analytical models (Fig. 1a).

A number of investigations have been carried out on the in-plane response of walls strengthened with FRP sheets or laminates.

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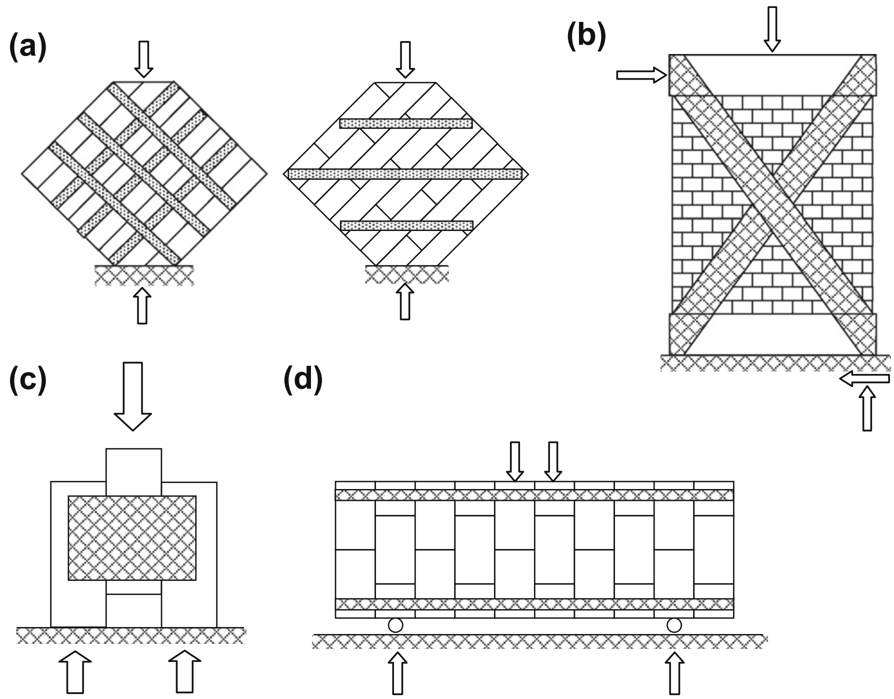

Fig. 1. Different in-plane tests configurations utilized to investigate the in-plane response of reinforced wallets and specimens: (a) Valluzzi et al. [2,3], (b) ElGawady et al. [4,5], (c) Eshani and Saadatmanesh [20], (d) Triantafillou [1].

ElGawady et al. [4,5] have investigated the response of large masonry panels strengthened with FRP laminates applied diagonally to the joints (Fig. 1b) subjected to both static and cyclic loading. Similar tests, either for monotonic or cyclic loading, have been carried out by Laursen et al. [6], Santa Maria et al. [7] using CFRP and by Fam et. al. [8], Mahmood et al. [9], Al-Salloum and Almusallam [10], Wang et al. [11] Liu et al. [12] and Stratford et al. [13], among other, using GFRP. Fam et al. [8] have specifically addressed the case of deteriorated walls repaired by means of injection and GFRP sheets; as shown by these authors, the combination of both repair measures permits to fully recover and even enhance the capacity of the walls. Marcari et al. [14] has investigated the use of FRP strengthening to improve the strength capacity of tuff masonry specimens simulating the mechanical properties of buildings in Italian historic centers. Aprile et al. [15] have investigated the influence of FRP reinforcement on the seismic reliability of ordinary masonry wall systems and have found that effective safety increment of the repaired or strengthened systems is limited due to loss of ductility. Benedetti and Steli [16] propose analytical shear-displacement curves for masonry panels, including the case of FRP reinforced ones, to be used in the evaluation of the seismic capacity of wall systems.

In lack of more specific analytical approaches, the expressions provided by the Eurocode 6 [17] or by other authors [18] for masonry conventionally reinforced with embedded steel bars, have also been used to assess externally FRP reinforced masonry. More recently, CNR-DT 200/2004 [19] has also provided an analytical approach for the estimation of the ultimate capacity of masonry walls strengthened with FRP laminates. In fact, the analytical approach given by Triantafillou [1] and CNR-DT200/2004 [19] stems from the conventional analytical treatment of shear strength of reinforced concrete using the well-known truss analogy. Because of this, these expressions can only be used for strengthened masonry members developing modes of failure equivalent to those of reinforced concrete in shear. Among the possible modes of failure shown by masonry walls subjected to in-plane forces (Fig. 2), namely overturning, sliding, brick cracking, compression and their mixed forms, only the third one (brick cracking) can be, to a certain extent, assimilated to the response of a concrete beam. The mentioned analytical expressions are only intended to assess the reinforcement of walls experiencing this third mode of failure. However, the other modes are also possible in common masonry buildings subjected to horizontal forces.

As opposed to other works, the present experimental study is carried out on elementary shear masonry assemblages rather than in entire masonry components such as large walls or panels. This is so because the study is mainly oriented to the identification of the elementary mechanisms involved in the strength response of reinforced masonry, while other studies focus on the evaluation of the overall efficiency of the strengthening. Another difference with respect to some previous research works lays on the consideration of strengthening strips applied perpendicular to the mortar joints. This type of arrangement may be necessary to provide strengthening not only in the brick cracking range but also in the sliding mode of failure (Fig. 2). A similar approach, also using simple shear assemblages strengthened by means of overlay reinforcement placed through the mortar joints, has been previously considered by Eshani and Saadatmanesh [20] (Fig. 1c). Haroun et al. [21] have also carried out shear tests on small wall strengthened transversely to the mortar joints.

Experimentation and numerical modeling at the elementary level is at present receiving increasing interest. Aiello and Sciolti [22] have proposed a test procedure for analysis of bond performance between FRP sheets and natural stones allowing evaluation of bond stress and slip values. The bond behavior of FRP reinforcement on clay bricks has been investigated by Liu et al. [23] and Willis et al. [24], among other. Numerical approaches to model the masonry-FRP interface behavior have been recently proposed by Maruccio et al. [25] and Grande et al. [26].

Certain problems or limitations of external reinforcement are not to be ignored and deserve further research. Among the possible problems is fire-resistance, especially when epoxi-based materials