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Experimental study of the in-plane cyclic behaviour of masonry walls strengthened by composite materials

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HIGHLIGHTS

- Experimental characterization of masonry walls under cyclic in-plane solicitations.
- Analyses of the damage and failure modes of the different reinforced walls.
- Comparative study based on performance parameters.

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ABSTRACT

This study presents the results of an experimental campaign on masonry walls to characterize their behaviour under in-plane solicitations. A series of five walls has been built, including one reference wall and four walls reinforced with externally bonded composites that are either FRP-composites (fibre reinforced polymer) or TRC-composites (textile reinforced mortar). In the present work, strengthening materials were not applied over the entire masonry surface: walls were reinforced only with vertical composite sheets, spaced to reduce the amount of composite materials used for the reinforcement. Each wall was tested under a vertical compression load and cyclic reversed horizontal displacements until failure. This article presents the results in terms of load displacement curves, analyses the damage and failure modes of the different walls and provides a comparative study based on performance parameters, such as load capacity, ductility, stiffness degradation, energy dissipation capacity to highlight advantages and limitations of the different strengthening materials.

1. Introduction

Strengthening of masonry structures requires the attention of a growing community of researchers because more stringent seismic design requirements have been recently adopted in many countries. Numerous (also recent) earthquakes have highlighted the vulnerability of masonry structures that show substantial damage (if not failure) when they are subjected to seismic actions. The failure modes of unreinforced masonry walls subjected to in-plane loading are diagonal cracking, sliding and toe crushing.

One of the methods most commonly used over the past several years to upgrade masonry structures is the application of externally bonded composite materials. The use of Fibre Reinforced Polymers (FRPs) has now become popular [1,2] due to their light weight and their high level of mechanical performance (which also implies significant costs). However, the potential of FRPs is usually far from being fully exploited when they are applied on masonry materials with very low tensile and shear strength. Furthermore, despite the benefits they provide, FRP materials suffer from the undesirable effects of organic binders (epoxy resins): poor behaviour at high temperatures (their maximum service temperature must be lower than the glass transition temperature of the resin), difficulties with application under wet conditions (in the absence of any special formulation, resin should not be applied to wet surfaces), strong environmental impact (non-removability, for instance) and potential health risks for persons performing their application. To this list of limits might also be added their compatibility problems with some substrates and their lack of water vapour permeability, which is likely to generate condensation problems.

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An alternative solution involves replacing the epoxy resins by inorganic matrices and focussing on Textile Reinforced Concrete (TRC). Indeed, these composite materials that resemble a fine-grained cementitious matrix with a fabric reinforcement have recently been developed [3,4,5]. Referred to as either Fibre Reinforced Cementitious Matrix (FRCM) or Textile Reinforced Mortar or Concrete/Cement (TRM or TRC), these materials overcome most of the limitations of FRPs (they are particularly compatible with masonry substrates, easy to apply – even under wet conditions, more eco-friendly,...).

Previous studies have concluded that the use of these materials can be an effective method to strengthen masonry walls subjected to in-plane actions. Diagonal compression tests have been carried out on tuff masonry panels strengthened over their whole surface and on both sides by a glass-TRC [6,7] or by a carbon-TRC [8]. In all cases, the reinforced panels exhibit a better shear strength and a better ductility: for symmetrically strengthened walls with one fabric layer, the average shear strength is amplified by a factor equal to 1.75 [6] (from 0.24 MPa for the unreinforced walls to 0.42 MPa for the strengthened walls) or 1.94 [7] (from 1.06 MPa to 2.06 MPa) with glass fabrics and 5.45 [8] (from 0.055 MPa to 0.3 MPa) with carbon fabrics. The latter author notes that TRC strengthening methods provide similar increments in shear capacity if normalized according to the calibrated reinforcement ratio. The study of Papanicolaou et al. [9] has an innovative nature for two main reasons. First, they adopted the shear-compression test to investigate the in-plane response of masonry walls. This test is more complex than the diagonal compression test, but the resulting stress state is more similar to the state created by a seismic action. Secondly, the test is conducted under cyclic reversed quasi-static loading conditions to simulate earthquake-type loading. In this study, they have analysed the behaviour of clay brick walls strengthened on both faces by a TRC made up of carbon fibre rovings connected by a polypropylene grid. When composite materials are applied only on one side, the asymmetry leads to significant out-of-plane displacements. To analyze separately the effects of in-plane and out-of-plane solicitations, it is standard experimental practice in adopting symmetric strengthening configurations even if this does not correspond to field applications. In this study, a cement-lime based matrix was used to help to regulate the internal humidity of the clay brick masonry. For size effects, authors select enough bricks to get a mechanical response of a full size specimen. TRC-reinforced walls appear to be at least 65–70% as resistant as FRP-reinforced walls with identical fibre configurations, and they are more ductile; the gain in deformability can be up to 30%. Koutas et al. [10] explored the behaviour of masonry structures with larger dimensions: nearly full-scale three-storey frames, made up of perforated fired clay bricks and retrofitted with carbon TRC over the entire surface of the infills, are loaded until failure under cyclic loading conditions. Again, the TRC-retrofitting method leads to an enhanced global response of the masonry infills both in terms of lateral strength and deformation capacity.

In all of these previous studies, TRCs are demonstrated to be effective in strengthening masonry structures when they are applied on both sides over the entire masonry surface, for all the tested substrates, for all the tested in-plane loading conditions and for all the tested textile fabrics. The aim of the present study is to reduce the amount of composite materials used in the strengthening scheme (making it more realistic) and to experimentally assess the effectiveness of these «optimized» (meaning more materials efficient) strengthening configurations. As the dimensions of composite reinforcements decrease, their efficiency is more conditioned by a correct connection with the masonry. Therefore, the addition of anchorages was performed in the present study and their contribution will be discussed.

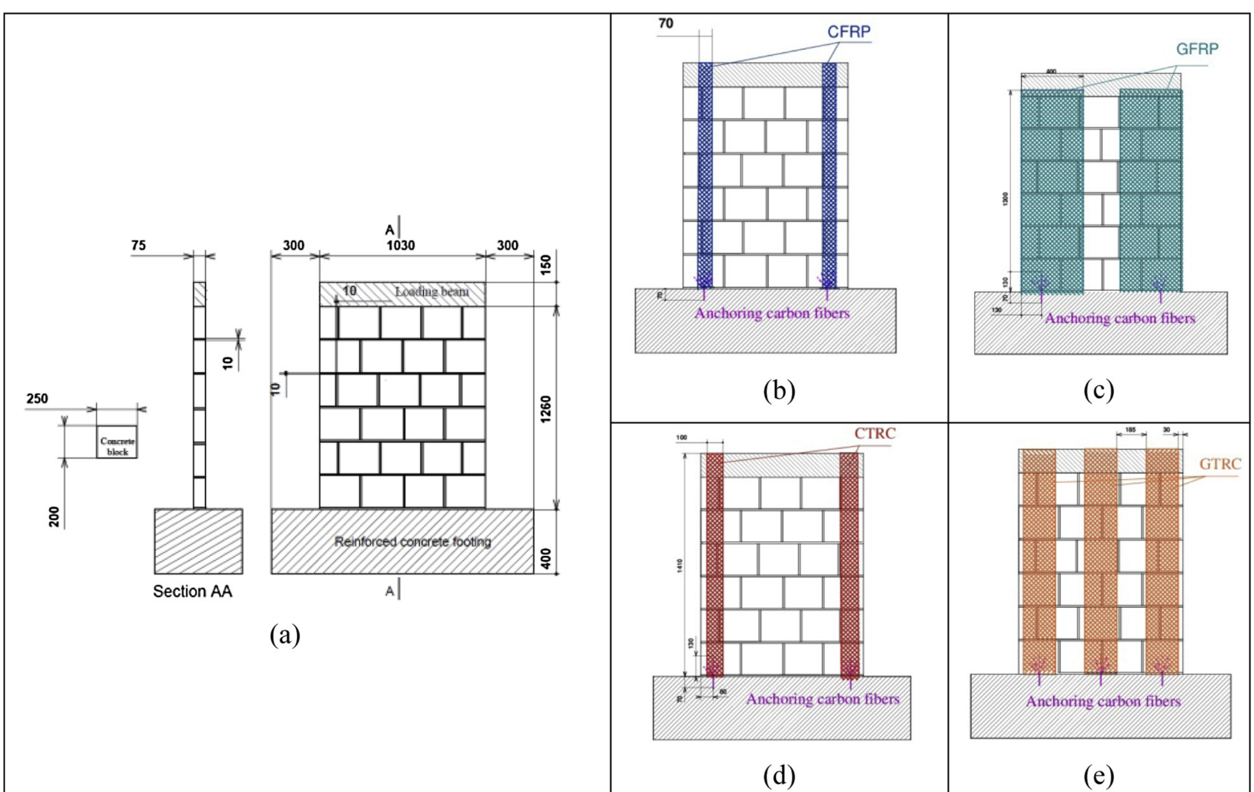

Fig. 1. Unreinforced masonry wall and strengthening schemes.