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Shear behaviour of masonry walls strengthened by external bonded FRP and TRC

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ABSTRACT

This experimental study focuses on the behaviour of hollow concrete brick masonry walls, especially walls reinforced with composite materials under in-plane loading conditions. This work is a step towards defining reliable seismic strengthening solutions. Indeed, in France, more stringent seismic design requirements for building structures have been considered with the replacement of old design codes. Thus, an experimental program has been performed at the laboratory scale. Six walls have been submitted for shear–compression tests – five walls are reinforced by (1) – fibre-reinforced polymer (FRP) strips using E-glass and carbon fabrics and/or (2) a textile-reinforced concrete (TRC), and the last wall acts as a reference. It is noted that the composite strips are mechanically anchored into the foundations of the walls to improve their efficiency. All of the walls share the same boundary and compressive loading conditions, which are representative of a seismic solicitation. Nevertheless, masonry wall performances and anchor efficiency are only evaluated under monotonic lateral loadings. A comparative study on global behaviour and on local mechanisms is performed and, in particular, highlights that the mechanical anchor systems play an important role in improving the behaviour of reinforced walls (by FRP and TRC) and that the solutions for strengthening by TRC permit the upgrade of the walls' ductility with a lower strength compared with the solutions with FRP.

1. Introduction

Masonry has a long history as a building technique. Even if reinforced concrete and steel prevail in the modern structures, masonry units are also used. In France, a significant part of buildings is erected with hollow concrete blocks. However, a relatively important manufacturing tolerance and a design with large holes give these blocks – and even more to hollow concrete block structures – a complex behaviour. Therefore, it is obvious that we should pay attention to these structures in a seismic context, particularly when a seismic hazard assessment has been revised, leading to a tightening of the safety rules in France.

Indeed, past earthquakes have revealed that unreinforced masonry structures can suffer extensive damage. Their vulnerability often lays in the weakness of mortar joints in tension and shear, which are adversely and highly subjected to shear stresses during earthquakes [1,2].

In brief, due to seismic actions, walls in a building can be subjected to shear forces both in the in-plane and out-of-plane directions. The in-plane structural walls (i.e., shear walls, subjected to lateral load along their longitudinal axis) are the primary force resisting elements [3]. Out-of-plane walls (i.e., flexural walls, subjected to lateral load transverse to their longitudinal axis) are in turn excited and if they are not resistant enough, their collapse may disrupt the stability of the building and can result in a major loss of life and property. Although these out-of-plane failures should not be overlooked, practitioners (in a broad sense, including the scientific community) tend to make the in-plane seismic response of shear walls their first priority; they indeed appear as key vertical components to bear seismic loading.

Solutions for repairing or strengthening masonry structures are many and are varied. Nevertheless, externally bonded fibre-reinforced polymer (FRP) composites are often preferentially chosen by prime contractors [4], mostly because of their lightweight and their ease of use. However, the reinforcing efficiency of FRP is rarely fully valued when they are only externally bonded to structural elements. FRP mechanical properties are limited because

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of the debonding of the composite sheets. To address this issue, an adequate mechanical anchorage system needs to be set up to enhance the bond (between a masonry structure and its foundation) performance. The benefits of this solution – in terms of the FRP efficiency and lateral load resistance of a masonry wall – have now been widely acknowledged in the case of out-of-plane actions [5].

In addition, in the context of sustainable development and health and safety conditions for workers, consideration should be given to an alternative material to FRP, which is often manufactured with highly toxic epoxy resins. The idea is to substitute these resins with cementitious materials while preserving or even improving the dissipative capacity of reinforced structures. From this perspective, textile-reinforced concrete (TRC) composites, which combine a suitable fine-grained mortar with the latest generation of textile fabrics, would benefit from promotion.

The efficiency of TRC for strengthening masonry structures has recently been investigated [6–11]. Compared with FRP, TRC composites show a nonlinear tensile behaviour with multiple matrices cracking, giving them a greater deformation capacity, a priori more suitable for seismic reinforcement [8].

Although instructive, these studies lack diversity for studied materials, reinforcement configurations, applied normal loads and slenderness ratio of walls. Sometimes, a small amount of information is known regarding damage and failure mechanisms or regarding the interaction between masonry material and reinforcements.

On the one hand, this work is aimed at further developing the existing experimental database, with special emphasis on identifying the performances of anchorage devices, particularly in the framework of a comparative study between FRP and TRC composites. This comparison will cover criteria at the global scale and, to a lesser extent, at the local scale. On the other hand, this paper tries to help identify and clarify damage dissipative mechanisms and their impact on the failure modes of the masonry walls.

To attain the aforementioned objectives, an experimental campaign has been performed, based on static monotonic shear tests, which are a simplified way to simulate stress states resulting from earthquakes. Certainly, inertial effects and the inherent cyclical nature of seismic actions are not addressed in the present study. However, this work can be regarded as a first step towards the definition of efficient reinforcement solutions. The approach is to test some strengthening configurations to have relevant and valuable information and to offer prospects that would be appropriate to assess with more realistic loadings in terms of earthquake hazards.

2. Experimental program

2.1. Masonry walls

A series of six walls has been built with the same dimension given in the Fig. 1. It should be mentioned that all of the specimens were built by a professional mason and must be considered to be in compliance with the practices. The hollow concrete block units, whose dimensions are 500 mm long, 200 mm high and 75 mm thick, belong to Group 2 according to Eurocode 6, with a strength class B40 (characteristic compression strength of 4 MPa). However, these blocks have been halved lengthwise before being assembled to make walls dimensions compatible with the limited means of the laboratory in terms of space and actuator capacity (Block work size at reduced scale: $250 \times 200 \times 75$ mm^3).

The compressive strength of the individual masonry blocks has been determined and ranges from 4 to 10 MPa (6.5 MPa on average with a standard deviation of 2.33). These blocks are assembled with a mortar composed of Portland cement (CEM I 52.5) and sand in the proportion 1:3 with a water/cement ratio equal to 0.5. Mortar test prisms of $40 \times 40 \times 160$ mm^3 were tested for compressive and flexural strengths. At 31 days, these strengths are 48 MPa and 10 MPa, respectively.

2.2. Reinforcement

2.2.1. Strengthening materials

Two types of composites have been used: the first composite is a fibre-reinforced polymer (FRP) while the latter composite is a textile-reinforced cementitious composite (TRC).

2.2.1.1. FRP composite. The fibre-reinforced composite materials consist of a two-component epoxy matrix and bi-directional fabrics made of either carbon (CFRP) or glass (GFRP). Their mechanical characteristics have been measured on six specimens according to ISO 527-1. The obtained results are listed in Table 1.

2.2.1.2. TRC composite. Knowledge on TRC composites is notably less significant than knowledge relating to FRP. However, it is

Table 1
Mechanical characteristics of composites.

Composite strengthening system	Nominal thickness (mm)	Young modulus (GPa)	Tensile strength (Mpa)	Ultimate strain (μm/m)
CFRP	0.48	105	1700	16000
GFRP	1.7	7.2	100	13.800

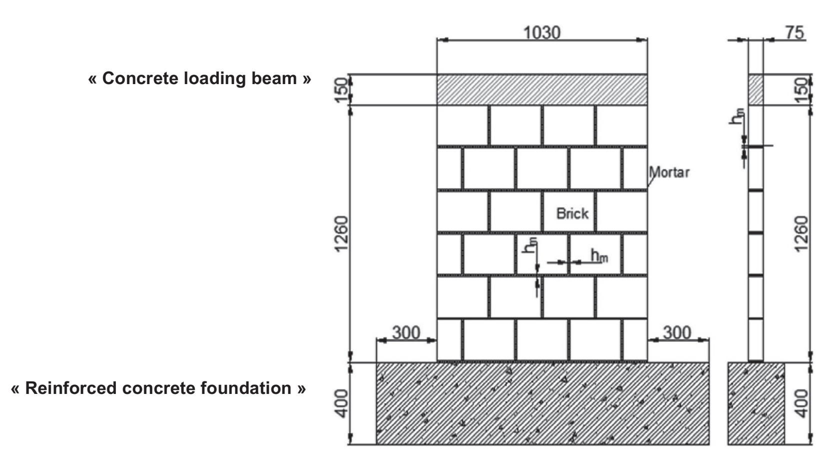

Fig. 1. Description of unreinforced masonry wall (reference).