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# Analysis of brick masonry walls strengthened with fibre reinforced polymers and subjected to eccentric compressive loads

Ernest Bernat-Maso *, Lluis Gil, Christian Escrig

*Department of Strength of Materials and Engineering Structures, Technical University of Catalonia, Colom 11, 08222 Terrassa, Spain*

## HIGHLIGHTS

- Experimental tests on real-scale FRP–strengthened brick masonry walls.
- Experimental strain analysis of the effectiveness of FRP.
- Implementing a numerical model to calculate the load-bearing capacity.
- Developing an analytical approach to calculate FPR–strengthened masonry.

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## ABSTRACT

Fibre Reinforced Polymers laminates are currently used to strengthen brick masonry walls. However, no specific evidences of the structural response of this strengthening system when brick walls are subjected to eccentric compressive loads, which might lead to second order bending effects, have been found. An experimental campaign on real-size walls has been carried out and the results have been compared with a numerical model, which predicted the observed shear/compressive masonry failure, and a new analytical approach, which has been used to accurately calculate the load-bearing capacity of the walls. Useful considerations for the strengthening design are also presented.



## 1. Introduction

Mechanism formation or shear failure are common collapse modes of masonry structures which are determined by the low tensile strength of this material. In this line, the researches by Yokel [1,2] are key pieces of the study of the bending/buckling failure of masonry. To prevent this phenomena, several strengthening technologies have been developed to improve the tensile response of the masonry. Among others, the most extended methodology might be the application of Fibre Reinforced Polymers (FRP), as presented by Ascione et al. in [3] and using Textile Reinforced Mortar (TRM), as studied by Babaeidarabad et al. [4], Harajli et al. [5] or Ortlepp et al. [6]. In particular, the use of TRM is significantly influenced by the composite response of the strengthening system, which has been studied, for example, by Larrinaga et al. [7]. Other researchers pointed out the advantages of placing plastic bands to improve the masonry tensile strength [8], studied alternative strengthening techniques (Engineered Cementitious Composites) against blast and impact loads [9] or considered the performance of Fibre Reinforced Concrete (FRC) and Mineral Based Composites (MBC) [10].

Strengthening masonry structures with FRP is a common actuation among the conservation and maintenance tasks carried out on the masonry buildings which require structural strengthening (see [11,12]). Although the drawbacks of this system (water vapour impermeability and insufficient mechanical compatibility with the masonry), which have been pointed out by several authors (see, for example the work by Baratta et al. [13], or the articles by Papanicolaou et al. [14,15]), FRP is still used for strengthening masonry structures because of its outstanding performance (justified in works like [11,12]) and the existence of consolidated guides and standards like [16,17]. In relation with the performance of the FRP, this strengthening technology is specially indicated for those interventions which require limiting the lateral deflection of the walls and look for a stiffer out-of-plane response of the structure. Moreover, it is also important to assess the second order out-of-plane response of those walls which have required an intervention using FRP in order to strengthen them against seismic events. Thus,

* Corresponding author. Tel.: +34 937398728; fax: +34 937398994.
*E-mail address:* ernest.bernat@upc.edu (E. Bernat-Maso).

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the use of FRP is justified in some specific cases although it might not be the preferable option for general masonry interventions.

One of the most studied applications of the FRP on masonry structures is to strengthen masonry walls against seismic loads [18–21]. In addition, there are comprehensive researches about the out-of-plane shear behaviour of FRP–strengthened walls [22], the in-plane shear response [23] or the out-of-plane flexural response [24]. However, it is not typically analysed how these strengthening systems might affect the response and the load-bearing capacity of the walls, in particular when vertical compressive loads are applied. Moreover, it has to be mentioned that these vertical loads are usually applied with some eccentricity, which contributes to develop sudden mechanism failure collapses [25], which are related with the second order bending effects associated with the slenderness of the walls and the eccentricity of the load. Thus, the analysis of the influence of FRP strengthening systems on the in-plane compressive load-bearing capacity is a topic that needs to be addressed to better understand these structures and assess their mechanical resistance.

There are a few experimental studies about the influence of strengthening systems on the mixed bending/buckling response which leads to a mechanism formation failure mode. Among them, the work by Dr. Garcia [26] has to be mentioned because of the novelty of strengthening multi-wythes ancient-like masonry walls subjected to eccentric load. Another research in this line [27] proved that superficial strengthening techniques might be effective at increasing the load-bearing capacity of brick masonry walls subjected to eccentric axial loads. However, the bibliographic research has not provided comprehensive experimental evidences about the performance of FRP strengthened walls subjected to this loading configuration.

On the other hand, numerical models are commonly developed on the basis of experimental results (used for calibrating and validating them) and applied to extrapolate those experimental evidences to a wider range of cases. With this purpose, the work by Cecchi et al. [28] modelled the in-plane response of FRP–strengthened masonry, the research by Milani [29] modelled the out-of-plane response and afterwards modelled the response of masonry elements strengthened with FRP grids [30] for in-plane and out-of-plane configurations. However, there have not been found specific models for studying the influence of FRP strengthening laminates on the response of eccentrically loaded brick masonry walls. Nevertheless, researches focused on other strengthening systems, like TRM (see [27]), might be considered as a starting point for the development of a numerical simulation to model this structural case.

The experimental and numerical approaches are useful to understand the structural response of materials and particular areas of a structure but easier approaches are usually preferred to deal with the design or assessment of full structures. In this line, the analytical approach presented in the codes [16,17] might be taken as a valuable reference. For more specific models, the works by Hamed et al. [24,31] are significant for addressing the out-of-plane response of FRP–strengthened masonry walls. These papers consider experimental and analytical approaches and take into account the influence of geometric parameters like the slenderness of the wall. Similarly, the recent research by Caggiano et al. [32] states an analytical approach for the bonding analysis of the FRP. However, the problem of the eccentrically loaded brick-masonry walls strengthened with FRP has not been particularly addressed from an analytical approach yet.

To sum up, it is clear that FRP is a commonly used strengthening system for masonry structures and, although it has been deeply studied for some loading configurations, there is a knowledge gap around the structural response of brick masonry walls strengthened with FRP (called FRPW in the paper) and subjected to eccentric compressive loads, which usually lead to a mechanism formation failure mode developed due to second order bending effects. In fact, experimental, numerical and analytical analyses might contribute to better understand this structural case and it is the aim of this paper to present the research carried out in this direction. Thus, experimental, numerical and analytical approaches have been used to analyse the influence of FRP on brick masonry walls subjected to eccentric vertical loads.

## 2. Methodology

The research is divided in three lines: the experimental campaign, the numerical simulation of the tested cases and the implementation of an analytical approach to calculate the load-bearing capacity of the FRPW (FRP strengthened masonry walls). The applicability of the solutions presented herein are enhanced by taking into account these three approaches simultaneously.

Each one of these activities is described with detail in this section. Then, the corresponding results are presented, compared and discussed to bring the final conclusions in the next sections.

### 2.1. Description of the walls. FRPW cases

Seventeen walls have been built and tested. Fifteen of these walls have been strengthened with carbon FRP laminates using five different configurations (see Fig. 1). Thus, there are three repetitions for each strengthening pattern and there are two control unreinforced brick masonry walls (called W#13 and W#15). The

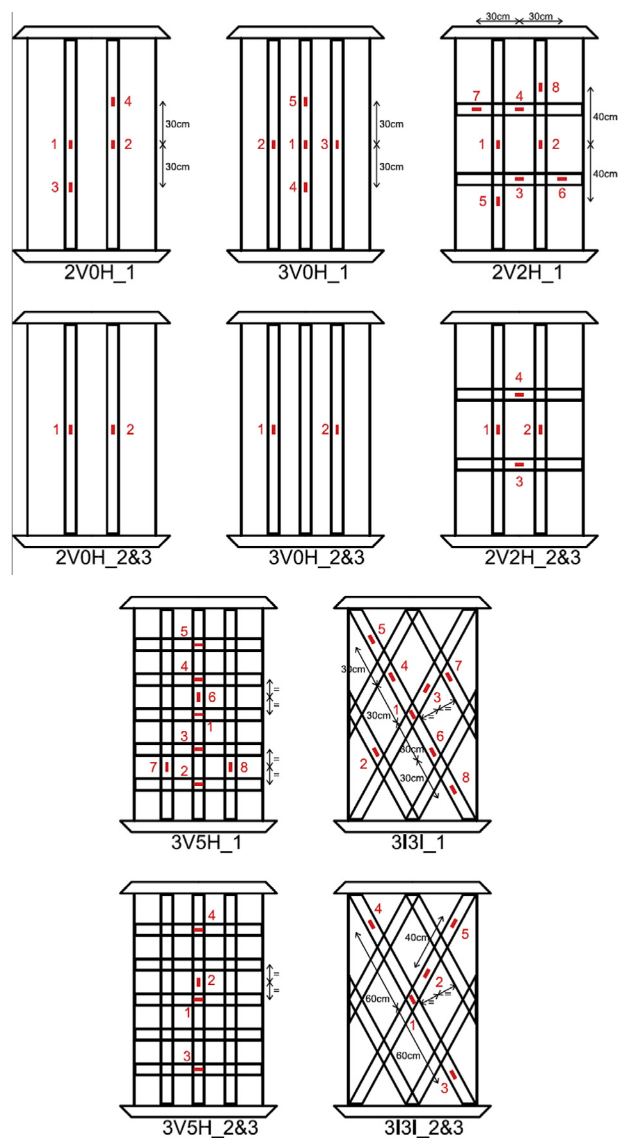


**Fig. 1.** FRP strengthening patterns and position of the strain gages.