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SHEAR STRUCTURAL RESPONSE OF STRENGTHENED UNREINFORCED MASONRY PANELS USING TRADITIONAL AND MODERN TECHNIQUES
EXPERIMENTAL SET-UP

BY

DAN ALEXANDRU GHIGA[*], **NICOLAE ŢĂRANU**, **DRAGOŞ UNGUREANU**, **DORINA NICOLINA ISOPESCU**, **MARIA CRISTINA SCUTARU** and **MIHAIL STAŞCOV**

Technical University “Gh. Asachi” of Iasi,
Faculty of Civil Engineering and Building Services

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Abstract. This paper presents the set-up needed for an experimental study regarding the shear structural behaviour of un-reinforced brick masonry walls, strengthened through both traditional and fibre reinforced polymer (FRP) based methods. Five brick masonry wall modules were designed and manufactured for this purpose. The aim of the experimental study is to quantify the effectiveness of various rehabilitation systems by comparing the structural response determined for the FRP strengthened modules with the one obtained for one module, which is left un-strengthened. In addition, a brick masonry module was strengthened through traditional methods. The advantages of the modern rehabilitation techniques may be observed by comparing the results of the FRP strengthened modules to the ones obtained for the traditionally strengthened

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[*] Corresponding author: *e-mail:* danghiga@hotmail.com

one. Important aspects regarding the behaviour of masonry strengthened walls, such as the characterization of the failure modes, the identification of the ultimate forces and the displacement and characterization of the stress-strain state may be obtained and analyzed by performing the envisaged experimental program based on the proposed set up.

Keywords: masonry; strengthening methods; traditional materials; fibre reinforced polymer (FRP) products.

1. Introduction

Masonry is one of the earliest and most widely used structural systems, mainly due to its advantageous characteristics, such as low cost, high thermal insulation, availability of materials, remarkable long-term performances and durability (Oprişan *et al.*, 2004). However, a large stock of masonry buildings is vulnerable to seismic action because of the lack of ductility, high mass and low energy absorbing capacity (Khan *et al.*, 2017). Moreover, most of the un-reinforced masonry (URM) structures have been built with little or, in some cases, no seismic requirements (National Institute of Statistics, 2017). The history of past earthquakes in Romania showed that the URM buildings had performed the worst, developing un-repairing damages and also accounted for the highest number of life losses compared to other types of constructions (Borleanu *et al.*, 2017; Berg *et al.*, 1980; Institutul Național de Cercetare-Dezvoltare pentru Fizica Pământului, 2018). Therefore, it is necessary to strengthen these structures to improve their seismic performance.

When subjected to seismic loading, the URM walls develop two possible failure modes: the in-plane failure mechanism and the out-of-plane failure mechanism. However, the researchers are generally focused on the URM walls in-plane behaviour since it provides the primary load path for the transfer of the lateral seismic force of the building to its foundation. Also, researches show that during an earthquake, the predominant failure mode is the in-plane shear failure (Khan *et al.*, 2012; Morandi *et al.*, 2018). Due to the characteristics of this failure mode, the masonry walls tend to develop diagonal cracks in two distinct patterns. The first one is specific to the URM walls made with strong masonry units and weak mortar and consists of a continuous diagonal crack along the bed and head joints. The second pattern, consisting of a crack that passes diagonally through the masonry units, is characteristic for the URM walls made with weak units and strong mortar.

Various strengthening techniques aiming to improve the in-plane behaviour of the URM walls have been developed over the last decades. These techniques focus on restoring the initial stiffness of the masonry walls, enhancing their lateral resistance and improving the in-plane inelastic deformation capacity. The classification of these techniques, considering their goals, materials and the criteria used to verify their effectiveness was presented by the authors in a recently published paper (Ghiga *et al*., 2018).

Although previous studies provided valuable information related to the methods of strengthening URM walls using fibre reinforced polymer (FRP) based systems, some parameters such as the additional bonding provided by the through-wall connectors, the effect of the anchoring method on the failure mechanisms and the interaction between reinforcements and masonry material need more investigations. The experimental program presented in this paper refers to two types of strengthening systems, a traditional jacketing and a glass fibre polymer (GFRP) integrated strengthening system. The main objective of this program is to describe the parameters that influence the failure mechanism and the shear behaviour of strengthened URM walls.

2. Overall Description of the Experimental Program

The proposed experimental program aims to assess the in-plane shear performance of the strengthened URM walls using either traditional or FRP based methods, and to compare the results to investigate any improvement of these methods. Five URM panels were conceived and, for comparison purposes, a benchmark URM wall was left un-strengthened throughout the study. The benchmark configuration is presented in Fig. 1.

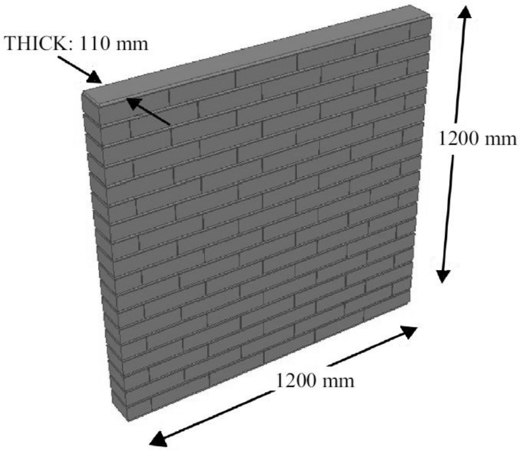

Fig. 1 – Benchmark configuration (un-strengthened URM wall).

The remaining four panels were strengthened as follows:

1° One URM panel was strengthened by traditional jacketing, which consists in the application of a self-supporting cement mortar matrix reinforced with 100 mm × 100 mm steel net of $\phi 6$, surrounding the panel. The jacketed wall surfaces were interconnected by means of through-wall $\phi 6$ steel anchors. The geometrical configuration of the traditionally strengthened URM wall is presented in Fig. 2.

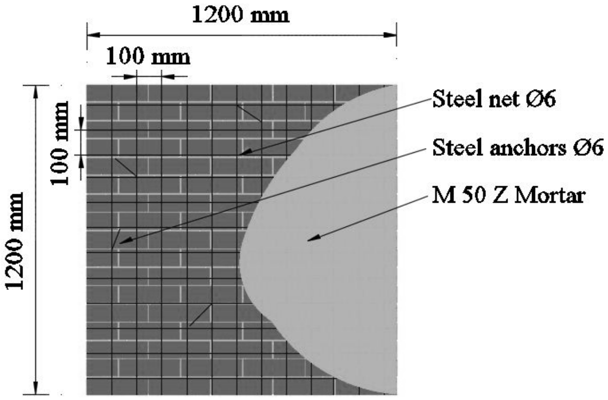

Fig. 2 – Geometrical configuration of the traditionally strengthened URM wall.

2° Three URM panels were strengthened using a pre-primed, alkali-resistant (AR) glass fibre mesh embedded in a thixotropic cement-based mortar. The geometrical configuration of the GFRP strengthened URM walls is presented in Fig. 3.

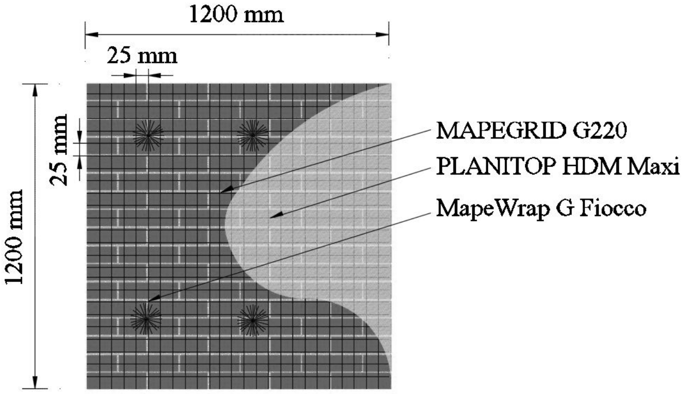

Fig. 3 – Geometrical configuration of the GFRP strengthened URM wall.

3. Materials Properties

The URM walls were made with brick units manufactured by Wienerberger. The geometry of the solid brick, clay masonry units is presented in Fig. 4 and their physical and mechanical properties, as determined and provided by the manufacturer, are listed in Table 1 (Technical data sheet, 2018).

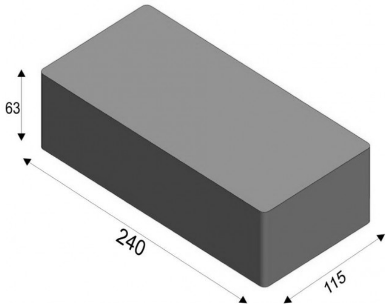

Fig. 4 – Geometry of the solid brick clay masonry units manufactured by Wienerberger (dimensions in mm), (Technical data sheet, 2018).

Table 1
Wienerberger brick units. Physical and mechanical properties
(Technical data sheet, 2018)

Characteristics	Unit	Norm
Mass	3.25 [kg]	–
Density	1,850 [kg/m^3]	–
Thermal conductivity λ10, dry unit	0.49 [W/mK]	EN 1745
No. of bricks / m^3	444 [units]	–
Mortar demand	0.22 m^3 mortar/m^3 of masonry	–
Compressive strength	15 [N/mm^2]	EN 772-1

The mortar used for the assemblage of the URM wall panels and the one used for the GFRP strengthened system are different, having distinct materials properties. The masonry panels were built with a mortar (M 50 Z) composed of Portland cement, lime and sand in the proportion and quality commonly used in the existing traditional Romanian URM buildings.

For the reinforcement overlay mortar, a high strength two-component, cement-based mortar manufactured by Mapei was selected (Planitop HDM

Maxi – Technical data sheet, 2018). The ingredient proportions are compatible to the amount and the spacings between the roving so that the penetration of the mortar through the GFRP mesh openings is easily achieved. When the two components are mixed together, they form a plastic-tixotropic blend that may be applied either by trowelling or by spraying in layers up to 25 mm thick, on both horizontal and vertical surfaces. The physical and mechanical properties of the Planitop HDM Maxi mortar are listed in Table 2.

Table 2
Planitop HDM Maxi Mortar. Physical and Mechanical Properties
(Planitop HDM Maxi – Technical data sheet, 2018)

Characteristics	Unit	Norm
Thermal conductivity	0.73 [W/mK]	EN 1745
Adhesion to masonry	2 [N/mm^2]	EN 1504-3
Density of wet mix	1850 [kg/m^3]	---
Pot life of mix	1 h	---
Compressive strength	25 [N/mm^2], 28 days	EN 12190
Tensile strength	8 [N/mm^2], 28 days	EN 196/1
Compressive modulus of elasticity	10000 [N/mm^2], 28 days	EN 13412

The mortar used for strengthening the URM modules was reinforced with a glass fibre mesh manufactured by Mapei (Mapegrid G 220 – Technical data sheet, 2018). The Mapegrid G 220 mesh and the Planitop HDM Maxi mortar are provided by the producer as an integrated strengthening system (also refer as MAPEI FRG System) that is highly compatible to the physical-chemical and elastic-mechanical properties of various masonry substrates. The Mapegrid G 220 product consists in a square mesh made from primed, alkali-resistant, glass fibres with a zirconia content of 17%. Due to the weave pattern, when this mesh is applied on masonry structures, it makes up for their lack of tensile strength and increases their overall ductility so that stresses are distributed more evenly. Also, according to the manufacturer, as a result of the high compatibility between the chemical characteristics of the mesh and of the mortar, the adhesion to the substrate is completely and appropriately developed. In most of the cases, the failure occurs in the substrate rather than at the interface level between the substrate and the strengthening system. The mechanical and physical properties of the Mapegrid G220 glass fibre mesh are listed in Table 3.

Table 3
Mapegrid G220 Glass Fibre Mesh. *Physical and Mechanical Properties*
(Mapegrid G 220 – Technical data sheet, 2018)

Characteristics	Unit
Weight	225 [g/m^2]
Mesh size	25 × 25 [mm]
Density of fibres	2.50 [g/cm^3]
Tensile strength	45 [kN/m]
Modulus of elasticity	72 [GPa]
Elongation at failure	1.8 [%]

The structural connections between the composite reinforcement layers and the faces of the URM panels were achieved by interconnecting the elements with impregnated, through-wall, glass fibre cords (MapeWrap G FIOCCO – Technical data sheet, 2018). These cords are part of the same integrated system manufactured by Mapei (also referred to as MAPEI FRG System) and provide additional anchorage for high-demanding, flexural and shear strengthening applications. The MapeWrap G FIOCCO cords eliminate the risk of corrosion when steel is used, and due to their very low weight, they can be quickly installed without the use of special lifting devices. The physical and mechanical properties of the MapeWrap G FIOCCO glass fibre cords are listed in Table 4.

Table 4
MapeWrap G FIOCCO. *Physical and Mechanical Properties*
(MapeWrap G FIOCCO – Technical data sheet, 2018)

Characteristics	Unit
Type of fibre	E-glass
Appearance	’’cord’’ formed by one-directional fibres wrapped in a protective gauze sheath
Density	2.62 [g/cm^3]
Tensile strength	2.56 [N/mm^2]
Modulus of elasticity	80.70 [N/mm^2]
Elongation at failure	3 [%]

The last component of the GFRP strengthening system is an adhesive for chemically anchoring the MapeWrap G FIOCCO cords in the holes made through the wall panels (Mapefix PE Wall – Technical data sheet, 2018). Mapefix PE Wall is a two-component, styrene-free product made from polyester resins. The latter is provided in two separate cartridges containing a resin and a catalyser. The physical and the mechanical properties of the Mapefix PE Wall adhesive are listed in Table 5.

Table 5
Mapefix PE Wall. *Physical and Mechanical Properties*
(Mapefix PE Wall – Technical data sheet, 2018)

Characteristics	Unit
Type of resin	Polyester
Appearance	Thixotropic paste
Density (mixed)	1.69 [g/cm^3]
Compressive strength	68 [N/mm^2]
Tensile strength	30 [N/mm^2]
Modulus of elasticity in compression	6105 [N/mm^2]

4. Specimens Preparation

As mentioned before, the URM panels were made of clay bricks with modular dimensions of 240 mm long, 63 mm high and 115 mm thick and mortar composed of Portland cement, sand and lime. The thickness of the bed, head and vertical joints was 10 mm, and the panels' dimensions were 1,200 × × 1,200 mm at a thickness of 115 mm. Before applying the strengthening systems, the surfaces of the panels were cleaned of dust and loose materials. After wetting the surface of the walls, the first layer of mortar was overlaid. For the traditional jacketing method, the strengthening system was conceived with the same type of mortar, while for the GFRP strengthening method, a high strength two-component, cement-based mortar was selected. The Planitop HDM Maxi mortar was prepared according to the specifications provided in the technical data sheet. The two components were mixed in clean recipients using a mortar agitator at slow speeds (starting from 400 rpm and gradually increasing up to 700 rpm), (Planitop HDM Maxi – Technical data sheet, 2018). The quantities of the components were carefully chosen according to the volumetric ratio (4 parts of Planitop HDM Maxi component A with 1 part of Planitop HDM Maxi component B and 0–0.5 parts of water) and taken into account that the workability period of the mortar is approximately 1 hour.

Once the reinforcement layers had been applied, the whole system was anchored to the masonry. In the case of the traditional system, the anchoring was performed by means of through-wall $\phi 6$ steel anchors, while for the GFRP strengthened modules, the anchorage was achieved by interconnecting both faces of the wall with impregnated glass fibre cords (MapeWrap G FIOCCO - Technical data sheet, 2018). In order to insert the glass fibre cords, holes were drilled through the URM wall panels and the loose material was removed with compressed air. The MapeWrap G FIOCCO cords were cut into 40 cm long pieces and the protective gauzes were unrolled from the centre of the cord to a length equal to the depth of the holes. The inserted parts of the cords were impregnated up to the saturation point with the Mapefix PE Wall adhesive (Mapefix PE Wall – Technical data sheet, 2018). Once the holes had been filled, the excess resin was removed with a metal trowel.

After the application of the reinforcement layers, all the URM modules were secured in specially designed fixtures and stored in laboratory conditions for 28 days, until all the components cured.

5. Experimental Procedure

After all the components had cured, the modules were prepared for the loading stage. The shear tests were performed in a PR-500 no.15 test machine (Fig. 5). In order to monitor the force applied, the testing machine was equipped with an acquisition system. The experimental tests were force controlled at a 5 kN/min loading speed. Several parameters were monitored during the application of the force: the relative displacement in horizontal and in vertical direction (measured with two linear variable displacement transducers – LVDTs that were mounted as indicated in Fig. 6), the variation of the applied force, the initiation and the development of the fracturing network.

Fig. 5 – PR-500 no.15 test machine.

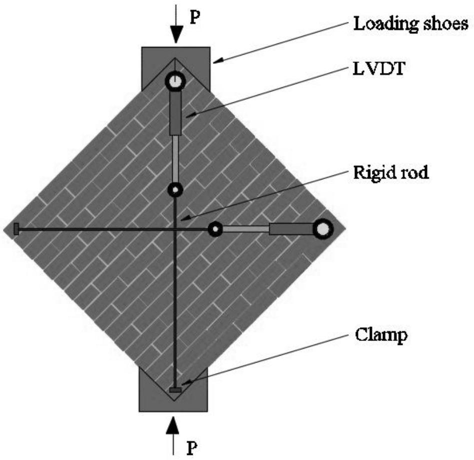

Fig. 6 – Wall panel instrumented with LVDTs.

6. Conclusions

This paper presents the experimental set-up of a study aiming to describe the shear structural behaviour of strengthened URM walls. The preparation and instrumentation of the masonry panels were extensively detailed. In order to draw reliable conclusions, the proposed experimental study was designed so as to account for the influence of different strengthening variables on the shear capacity of the masonry walls. These variables included the type of the reinforcing mesh, the type of the mortar and the type and the number of the through-wall connectors. Based on the results of this experimental program, the validity of the existing analytical and numerical models can be checked and, if necessary, corrections of the existing ones or new models can be proposed.

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RĂSPUNSUL STRUCTURAL LA FORFECARE AL PEREȚILOR DE ZIDĂRIE NEARMATĂ CONSOLIDAȚI PRIN METODE TRADIȚIONALE ŞI MODERNE

Organizarea programului experimental

(Rezumat)

Această lucrare prezintă etapele de pregătire şi instrumentare pentru un studiu experimental privind comportamentul structural la forfecare a pereților de zidărie din cărămidă nearmată, consolidați atât prin metode tradiționale, cât şi prin metode bazate pe materiale compozite polimerice armate cu fibre (CPAF). Astfel, au fost proiectate şi fabricate cinci module de pereți de zidărie din cărămidă pentru studiul experimental. Scopul studiului experimental propus este de a cuantifica eficacitatea diferitelor sisteme de reabilitare prin compararea răspunsului structural determinat pentru modulele consolidate cu materiale CPAF cu cel obținut pentru un modul, care este lăsat neconsolidat. În plus, un modul de zidărie din cărămidă a fost consolidat prin metode tradiționale. Astfel, avantajele tehnicilor moderne de reabilitare structurală pot fi emfazate prin compararea rezultatelor modulelor consolidate cu produse CPAF cu cele care vor fi obținute pentru cel consolidat prin metode tradiționale. Aspecte importante privind eficiența consolidării pereților din zidărie nearmată, pot fi obținute şi analizate prin realizarea programului experimental descries în această lucrare. Aceste aspecte fac referire la caracterizarea modurilor specifice de cedare, la identificarea forțelor capabile ultime şi la caracterizarea stării de tensiuni – deformații specifice.