IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X, Volume 21, Issue 6 Ser. 1 (Nov. – Dec. 2024), PP 53-60
www.iosrjournals.org

Experimental Analysis Of Two Unreinforced Masonry Walls Under Cyclic Loads, And Its Retrofitting Through CFRP

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Abstract
This article presents a comparative experimental study of two unreinforced masonry walls: one made of perforated bricks (285 mm x 185mm x 130 mm) and the other of threshing bricks (190 mm x 90 mm x 50 mm). The Masonry walsl were constructed with standardized Turkish bricks in a rectangular steel frame supported by pinned uprights and built over a distance of 1200mm in length by 1500mm in height. The main objectives of this work are to study the behavior of structural unreinforced masonry under seismic actions and how it can be made more resistant to these effects. To achieve this goal, lateral cyclic loads are applied to the walls in plane. This application of forces had caused damage characterized by cracking. The natural excitation of the unreinforced masonry walls is determined through Operational Modal Analysis (OMA), and the dynamic characteristics of the structures emerged in the form of vibrational modes and natural frequencies. Their data recording is made before and after the application of cyclic loading. The reinforcement to fill the cracks is carried out using layers of CFRP with epoxy resin. A comparative analysis of the natural frequencies from undamaged wall to damaged points out a decrease in damaged walls (more than 20%) and a rise of 10% of frequencies between damaged vertical brick wall compared to the damaged coated CFRP-reinforced walls. These results of laboratory tests are compiled and compared in order to evaluate the seismic effects and the solutions that the CFRP brought in the reinforcement of the walls.

Keywords*: perforated bricks, threshing bricks, unreinforced masonry wall, operational modal analysis, dynamic characteristics cyclic loading, CFRP.*

Date of Submission: 15-11-2024 Date of Acceptance: 25-11-2024

I. Introduction

Masonry structures are formed by joining elements such as stone or brick with a mortar material that acts as an adhesive. In ancient times, mortar was made from mud or clay. Today's masonry structures have roots that have left concrete traces throughout the history of mankind all over the world. Throughout history, people have always sought shelter to protect themselves from the climate and wild animals. Over the years, dwellings have evolved from caves to haystacks and from natural materials such as stones to other structures. These studies, made with more durable and useful materials, have left great traces in the history of mankind. Masonry walls of structures located in the seismic regions suffer innumerable damages due to various natural disasters such as the earthquakes. The masonry is defined as an assembly of motley materials that can be combined to acquire a unique consolidated structure. According to the use of rebar inside of the wall, masonry is divided in to two categories: unreinforced masonry and reinforced masonry wall. The materials used in these types of walls are usually blocks or stones, combined with mortar and provide an anisotropic and a nonlinear character to the masonry wall. Today, there are other innovative retrofit techniques, most notably FRPs (Fiber Reinforced Polymers). These are composite materials used in construction to strengthen structures. They consist of polymer fibers reinforced with glass, carbon or aramid. These fibers offer high tensile strength, low density and high corrosion resistance, making them ideal for a variety of civil engineering applications.

In a study conducted by Page [1], the biaxial compression fracture of the wall was investigated, with particular emphasis on its potential for predicting crushing failure in reinforcing walls. The fracture surface is dependent upon the orientation of the horizontal joints in relation to the principal stresses. In the majority of cases, rupture occurs abruptly, forming an opening in the plane parallel to the free surface of the panel and at half the thickness, regardless of the orientation of the horizontal joint. It thus appears reasonable to posit that the specific type of mortar and the mortar/brick bond do not exert any influence on this particular type of fracture. Mann and Müller [2] proposed an entirely different method through a series of simplifications with regard to the behaviour of masonry. The initial assumption was that the vertical mortar joints do not contribute to the overall resistance of the panel. Consequently, when forecasting the resistance of the panel, he took into account not only the collective resistance of the vertical joints but also the interrelationship between the horizontal and vertical stresses that occur within the wall. This simplification is based on the observation that, in general, these vertical joints were not adequately filled at the time the panel was constructed, and that there was not complete contact between the joint and the wall, due to the retraction effect of air. Sucuoglu et al. [3] considered the constructive planar model to be heterogeneous, comprising elements such as mortar, brick, layer patterns and other distinguishing features. The authors concluded that forward mixture models are not costly and proposed an isotropic symmetric model. Instead of developing a hysteretic model to capture the observed nonlinear behaviour. Mengi and McNiven [4] proposed an equivalent linear model that accounts for the nonlinear effect through a variable secant shear modulus and secant damping coefficient. This approach is not the one adopted by some researchers in this field such as Lotfi et al [5]. In their investigation of masonry joints, they introduced the fracture criterion of mortar as a means of analysing the behaviour of these structures. The authors were able to successfully simulate the initiation and evolution of cracks in masonry joints under combined normal and shear stresses in both tension-shear and compression-shear. Based on this,Mehrabi et al. [6] proposed a new interface model for the analysis of masonry structures, which is integrated with a distributed crack model developed previously for concrete, as proposed by Lofti and Shing [5]. As for Álvarez and Alcocer [7] highlighted that the reduction in oblique cracking with an increase in the aspect ratio of walls is not addressed by the current regulations in force in Latin American countries, including Mexico, Peru, Colombia, Chile and Argentina. Furthermore, they emphasised the significance of acknowledging that the calculated value may not be accurate, particularly in ground floor walls of multi-level buildings where the section can exceed one, thereby enabling resistance to inclined cracking..In a research conducted by Anthoine [8], he explored the homogenization theory of interior walls in relation to the behaviour of the constituent materials (bricks and mortar). This procedure is applied in a rigorous manner, entailing a single step and the utilisation of the actual wall geometry, encompassing finite thickness and a genuine bond pattern. A numerical implementation was conducted, and the results were compared with predictions based on existing simplified approaches. It can be seen that all the aforementioned approaches exert a slight influence on the planar elastic properties of the wall. Afterwards Mendola et al. [9] investigated the stability criteria for a masonry wall subjected to seismic transverse forces. The issue is then translated into the analysis of a fixed, free-ended prismatic column subjected to static horizontal forces equivalent to the maximum inertia. Then, Andreaus [10] proposed a new failure theory, applicable to specific scenarios such as small panels and homogeneous mortar joints. Simultaneously, he made a detailed distinction between the various crack types observed in the panel, thereby introducing intermediate failure criteria., Moreover, Lourenço [11] put forth two models to describe the nonlinear behaviour of masonry walls. One of these models is a micro model, and the other is a macro model. Among the objectives of this contribution is a comparison of the applicability of two different strategies. Along the same lines, Sánchez et al.

[12] conducted measurements that corroborated the hypothesis that deformations normal to the cross-section do not adhere to a linear law in the length of the wall. This implies that Bernoulli's kinematic hypothesis, which posits that straight sections remain straight after deformation, is not universally applicable. This is to be expected, given that the behaviour of walls is largely dominated by shear deformations. Nevertheless, the formulas used to calculate flexural compression resistance in various codes are based on the Bernoulli hypothesis (EUROCODE 6, 1995). Alcocer [13] posited that as mortar resistance declines, the contribution of mesh reinforcement also diminishes, given that the compressive strength of the mortar is inherently limited. At low levels of distortion, the wall will undergo crushing and separation, which will negate its composite section behaviour. Subsequently, the equivalent stress block in reinforced concrete is considered. The parameters employed for sizing can be applied to concrete and clay walls, and the outcomes obtained with these formulas indicate that the actual deformation distribution is nonlinear. Totoev and Nichols [14] constructed three high- stack wall prisms from seven distinct brick types. The wall panels utilized in the experiments were square panels, and the panel construction employed high-quality research-grade mortar.

In the early 2000s, a series of investigations were conducted into the modeling of masonry and concrete structures. These models, which are based on the non-linearity of these structures, also consider the interfaces in which the mortar plays a predominant role as a junction between the different elements [15,16,17,18,19,20,21]. As for Badarloo, et al [22], they conducted an experimental biaxial compression test. Failure criteria of unreinforced grouted brick masonry has been determined. Given that masonry is a composite structure, the failure of such structures depends on the properties of the materials (mortar, bricks, etc.) and the interfacial bonding properties between the various components. Accordingly, it was feasible to construct a model of the failure process occurring along the mortar interface. A two-property bonding model was used to simulate structures comprising hollow bricks. In particular, the model was employed to investigate the fracture process along the interface of a small structure comprising three hollow bricks. Further research is required to gain a deeper understanding of fracture processes in structures that cross mortar. The results demonstrated that the model accurately represented the observed behavior of the structures. In particular, the model demonstrated precise accuracy in simulating the cracking of mortar in a small masonry structure.

Furthermore, in the field of fiber reinforced structures, Hamid et al [23], Haroun et al [24] and Sayari et al [25] conducted research to investigate the in-plane behaviour of unreinforced masonry wall assemblies with mortar faced façade shells reinforced with FRP laminates. The tests included prisms loaded in compression at various joints, diagonal tension specimens and specimens loaded in joint shear.

II. Experimental Approach For Walls Construction Inside The Frame

The steel material is the standard wide flanged is a steel beam which is used as frame container of the wall. The wide-flanged beam due to its distinctive shape, is very effective in carrying weight loads. It is able to bear excessive amounts of pressure and ensure structural stability. Their property values are given in the following table:

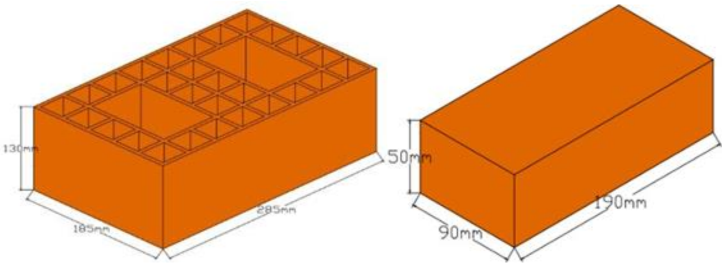
Table 1. Wide flanged beam properties

	Steel	Poisson's ratio □
Density d_1 (t/mm^3)	Young's Modulus E_1 (MPa)	
7.7E-09	2E+05	0.30

The steel frame is composed of two vertical bars with pin supports, on which are placed two other horizontal bars. A piston is put in place, in the way it can act on the horizontal upper bar of the frame (see Fig 1). The dimensions of the wall are 1.2 m long and 1.5 m high.

Figure 1. Experimental steel frame

The type of bricks used (figure 2) meets Turkish TS EN 771-1standards [26]. These bricks are vertically perforated and threshing ones with their dimensions as shown in the figure 2.



(a) Vertical perforated brick (b) Threshing bricks
Figure 2. Different types of bricks

These bricks are then assembled so that they can be contained within the steel frame.

(a) wall made of vertical perforated bricks (b) Threshing bricks wall
Figure 3. Constitutive Sample of Masonry Walls inside a steel frame

Bricks are varied and their properties also vary according to the country and the standard used. The difference in properties also depends on the content of the chemicals which constitute them. Zengin et al [27] have determined in their work that some of the properties of Turkey's materials already conform to ASTM C270 standards.

Table 1. Comparison of material properties for vertical perforated bricks

Standards or previous work	Modulus of elasticity (MPa)	Poisson's ratio	Compressive strength (MPa)
ASTM C270	3500-15000	0.20-0.213	2.35-10.1
Zengin et al [27]	1427	-----	6.38

Table 2. Comparison of material properties for threshing brick

Standards or previous work	Modulus of elasticity (MPa)	Poisson's ratio	Compressive strength (MPa)
ASTM C270	5000-37500	0.21-0.29	15-120
Zengin et al [27]	-----	-----	did not

Table 3. Comparison of material properties for mortar

Standards or previous work	Modulus of elasticity (MPa)	Poisson's ratio	Compressive strength (MPa)
ASTM C270	3500-17000	0.211-0.213	2.8-7.89
Zengin et al [27]	16723	-----	12.5

III. Operational Modal Analysis And Cyclic Loading Application

OMA identifies mode characteristics of a structure based on vibration data collected under operating conditions. The Operational Modal Analysis (OMA) method was used to obtain the mode characteristics of the walls by applying the Cyclic Vibration Method (CVM) as part of the frequency recording study. For the environmental vibration tests, 10 uniaxial accelerometers of type B&K 8340 and 1 of type B&K 4507 were used. The FEMA-461 loading protocol was applied to the frame specimens for repeated horizontal loading using a computer. The horizontal loading protocol applied to the frame specimens is given in terms of cycles of increasing displacement in two directions (push and pull). Progressive loads of up to 100 KN are transferred laterally to the vertical perforated bricks wall and up de 200 KN to the threshing bricks wall. In accordance with FEMA 461, each loading step was performed twice and the displacement amplitudes were increased by a factor of 1.4. To obtain reliable data for this test on masonry frames, cracks in the walls are observed and monitored using a variety of tools and the load and displacement at the measured location is recorded.

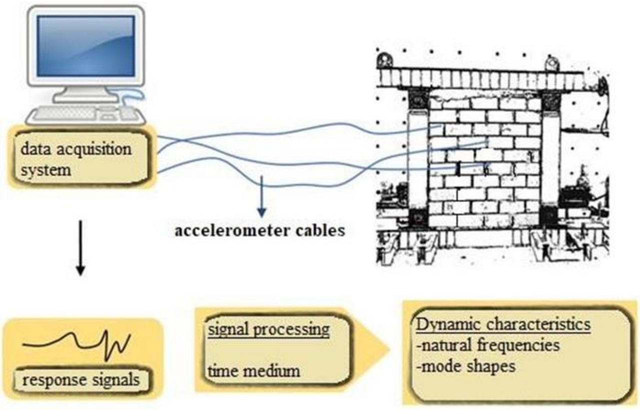


Figure 4. Process of transferring data from the wall to the computer

Figure 5. accelerometers placed on the wall and B&K type 3560-C data collection unit

This section attempts to show the procedure used to extract the results for each frequency recording, so this step is necessary. However, since the modal analyses were carried out 3 times (3 modes for each wall) in total and the mechanism is the same and repetitive, it was decided to use this procedure for only two recordings, one for the wall made of vertical perforated bricks and for the threshing one.

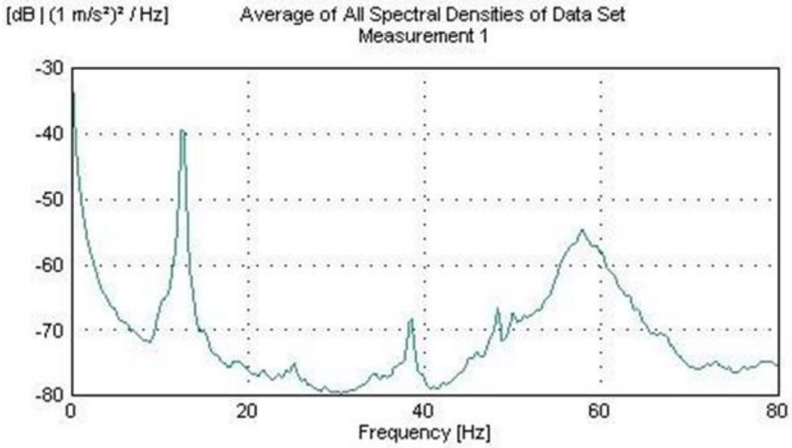


Figure 6. Spectral mean densities for undamaged wall made of vertical perforated bricks

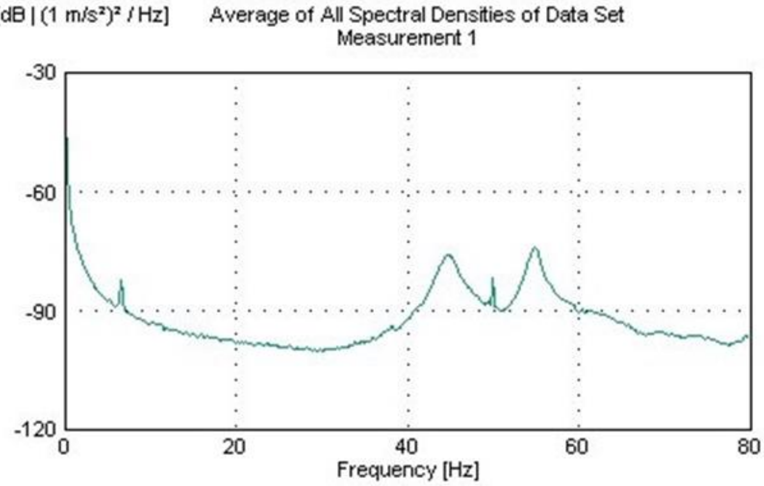


Figure 7. Spectral mean densities for undamaged threshing bricks wall

Then, frequencies are recorded for the first 3 modes before the application of cyclic forces, and are given in the following tables:

Table 4. Frequencies of the experimental undamaged wall made of vertical perforated bricks

Modes	Frequencies (Hz)
1	12.62
2	25.02
3	38.36

Table 5. Frequencies of the experimental undamaged threshing bricks wall

Modes	Frequencies (Hz)
1	6.61
2	11.98
3	44.89

Comparing the two tables, it can be seen that the wall made of perforated bricks has higher frequencies than the one composed of threshing bricks. This is because the less consolidated the material, the higher the frequencies.

After the application of cyclic forces, the masonry walls remained as follows:

(a) Perforated bricks wall **(b) Threshing bricks wall**

Figure 8. Damaged walls

Figure 6 clearly shows that the vertically perforated brick wall appears to be less resistant to cyclic loads of around 100KN, as it has surface damage. The threshing bricks wall, on the other hand, appears to suffer little damage even with loads in excess of 210 KN.

The frequencies of these walls after damage are again recorded as follows in the tables below:

Table 6. Frequencies of the experimental damaged wall made of vertical perforated bricks

Modes	Frequencies (Hz)
1	9.84
2	21.64
3	36.25

Table 7. Frequencies of the experimental damaged threshing bricks wall

Modes	Frequencies (Hz)
1	4.63
2	7.87
3	22.46

It is noticeable here that all frequencies of the two pictures have dropped in comparison to their corresponding undamaged wall. This shows that damage to a structure increases its frequency. It is also noted that the frequencies of the wall made of vertical perforated bricks are always higher than those of the threshing brick wall. This shows that the two walls do not have the same load-bearing capacity and, consequently, are not damaged in the same way.

IV. Retrofitting Of Walls With CFRP And OMA Procedure Application

Carbon Fiber Reinforced Polymer (CFRP) is a composite material composed essentially of carbon fibers and polymer. The carbon fibers provide strength and rigidity, while the polymer acts as a cohesive matrix that protects and holds the fibers together. CFRPs are generally manufactured in strip form, using various production techniques such as filament winding. These materials are highly appreciated in modern times for their high resistance to corrosion and fatigue, as well as their high ultimate deformation. To apply this material, epoxy- resin is prepared and then applied to the walls. This allows the fibers to adhere to the structures they are intended to reinforce.

(a) Application of epoxy resin **(b) CFRP applied to the wall**

Figure 9. CFRP application procedure

Damaged wall made of perforated bricks was coated with a light mortar to facilitate the application of CFRP. The installation of this resistant material is simply due to the fact that most of the cracks on the wall were observed diagonally. The cyclic loading process is repeated and this time, the forces that deteriorated the perforated bricks wall coated with CFRP was around 235 KN.

Figure 10. Damaged wall coated with CFRP

Table 8. Frequencies of the experimental damaged wall coated with CFRP

Modes	Frequencies (Hz)
1	10.91
2	23.48
3	37.15

It was noted that the frequencies for this same wall were higher than for the damaged wall without the CFRP reinforcement. This means that there has been some repair or recuperation of the material in relation to the previously damaged wall

As a matter of fact, an increase in frequencies is also seen when the undamaged wall of vertical perforated bricks is compared with damaged wall. While the mode 1 frequency for the undamaged wall is 12.62 Hz, the frequency of the damaged wall is 9.84 Hz, which corresponds to a decrease of 28 %. the same drop in frequencies can be observed in the other modes. Comparing the 2nd mode which has 21.64 Hz with the damaged coated wall with CFRP (23.48Hz), it is noted an increase of 8%. Whereas it first mode gives 10%. For the undamaged threshing bricks wall, the first mode gives 6.61 Hz and for the damaged one it gives 4.63 Hz which corresponds a decrease of 42 %.

As the threshing bricks wall remained intact and suffered very little damage, it did not require any repair through the CFRP.

V. Conclusion

Reinforcement plays a very effective role in the rigidity of the mechanical properties of structures. Masonry wall made of vertical hole bricks are less resistant than wall made of threshing bricks. After applying the cyclic loads diagonal crack was noted for the essential. Wall made of threshing bricks withstands cyclic loads of up to 200 KN without causing much damage to its surfaces, whereas the other wall almost completely collapses when loads of around 100 KN are applied. Then the natural frequencies obtained were compared with each other. Only the first three modes are considered because they are not large-scale structures. On the other hand, another comparison is made between the values of the dynamic characteristics before the application of cyclic loads and after the damage to the wall. It is found that all frequencies decreased with declining wall stiffness, and when CFRP is applied to the damaged wall, its frequency increases. However, advanced studies could conceivably make it possible to reinforce the damage structures and continue to do modal analysis with OMA procedures, and find adequate solutions to the damaged structures. Such an approach would allow to obtain shape modes and frequencies after the damage through software and to model preferably a possible repair of these structures.

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