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RESEARCH ARTICLE

DISPLACEMENT ANALYSIS ON UNREINFORCED MASONRY WALLS DUE TO LATERAL PUSHOVER IN THE PLANE LOADING

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ABSTRACT

Push-over on wall, a ubiquitous phenomenon observed in various aspects of daily life, has long been a topic of interest among Civil Engineers. Push-over analysis has emerged as a widely accepted method for assessing the seismic vulnerability of unreinforced masonry (URM) walls. Its analysis is a nonlinear static analysis technique commonly employed to evaluate the performance and seismic capacity of unreinforced masonry (URM). Despite its seemingly simple nature, the underlying mechanics of push-over on wall remain poorly understood. This study includes a review of current literature, an outline of the experimental methods, the relationships between force and structural integrity and a discussion on of the results obtained through experimentation. For this purpose, a masonry wall has been implemented under cyclic loading this aspect, shedding light on the intricate relationships between force and structural integrity. To achieve this, a masonry wall is subjected to repetitive loads that move back and forth along its upper right side. Using a FEMA protocol, the successive forces produce diagonal cracks along the entire wall, which is contained within a 1.2 m long by 1.5 m high steel frame with pinned supports as boundary conditions.

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INTRODUCTION

In recent years, researchers have endeavored to enhance their comprehension of the behavior of masonry structures when subjected to lateral loads, drawing upon the findings of numerous experimental and theoretical studies. The eccentric behavior of unreinforced masonry buildings has prompted numerous researchers to undertake a series of studies with the aim of enhancing the analytical techniques employed in the assessment of such systems. It is widely accepted that the principal weakness of unreinforced masonry buildings is in their lateral load-bearing capacity. Masonry buildings typically lack a robust lateral load-resisting system. Recently, considerable effort has been directed towards push-over analysis, which provides a means of evaluating the global response of masonry walls. In recent years, there has been a notable surge in push-over analysis, with a particular focus on simulation studies, empirical, hypothetical, and formulation studies. Push-over analysis is a static, nonlinear procedure that has been well established for the analysis of reinforced concrete and steel structures The efficacy, reliability, and versatility of push-over analysis have been demonstrated by the strong correlation between the numerical predictions and the experimental results obtained from the analysis of numerous reinforced concrete and steel structures. In the context of push-over analysis, a capacity curve is typically obtained, which details the base loads versus displacement in an idealized manner. It is essential that the correct capacity curve is obtained during experimental testing and that all critical states of the masonry structure are captured to ensure a complete understanding of the seismic performance of the structure. Unreinforced masonry (URM) walls are a common construction type in many parts of the world, particularly in regions with moderate to high seismic activity. The vulnerability of URM walls to earthquake-induced damage and collapse has been a major concern for engineers and researchers. Push-over analysis, a non-linear static analysis method, has gained popularity as a tool for assessing the seismic vulnerability of URM walls. In the 1980s, El-Refai et al. [1] tried to investigate the degree of agreement between the theoretical and measured values obtained from computer programs and experimental tests, respectively. The theoretical analyses were based on the lateral interaction between brick and mortar. It was thus concluded that the compressive strength of the wall increases as the height of the brick increases with the mortar, which is softer than the brick. As the stiffness of the mortar increased to a greater extent than that of the bricks, it imposed lateral restraints on the ends of the bricks, thereby enhancing the wall's strength. It was determined that when employing a soft mortar, the horizontal joint thickness was maintained at a minimum, given that the primary objective was to ensure wall strength. Benedetti and Benzoni [2] experimentally reproduced the resulting shear-displacement stress curves. They consisted of three superimposed linear hysteretic. The parameters forming this phenomenological hysteretic enclosure were calibrated on the basis of available experimental results. This model is derived from masonry tests. Only its applicability to general unreinforced masonry construction is included. For Priestley [3], the principal concern for a wall subjected to abrupt lateral loads is dynamic stability. He investigated the stability of a cracked wall under the influence of applied lateral loads, its own weight and inertial loads, rather than material stress levels. He examined the behavior of a one-way unreinforced wall under the influence of lateral seismic loads. The methodology was subsequently refined in 1986.Afterwards Priestley and Robinson [4] developed a methodology for calculating the resistance of an unreinforced wall

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subjected to lateral loads. Their approach was based on the assumption that the wall could be considered arched, with unidirectional action occurring between rigid boundaries at the top and bottom interfaces. The results demonstrated a notable enhancement in the wall's resistance to lateral loads. However, the objective for researchers such as Konig et al [5], was to gain insight into the dynamic cyclic behavior of unreinforced masonry (URM) shear walls after cracking. This was done with the aim of understanding the effect of axial loads on the axial loads and ductility of URM walls subjected to seismically induced planar shear forces. These authors discovered that when the axial load is low, the cracks that form at the joints in the diagonal jagged pattern along the wall can slip over each other, resulting in significant deformations and minimal strength degradation before the wall fails. In the event of elevated axial loads, the frictional resistance of the bearing joints increases in direct proportion, resulting in cracking through the masonry bricks if the principal stresses locally exceed the tensile strength of the units. Consequently, the separated portion of the masonry tends to slide downwards along more regular diagonal cracks with diminished ductility. According to Rots [6], it is necessary to add softening behavior to the interface elements. In his research, the finite element model represents the bricks as continuous linear elastic elements and the joints as nonlinear interface elements that serve as potential cracks. The interface elements have a normal stiffness and a tangential stiffness to represent the joint in the elastic phase. When the tensile strength is reached, the crack opens. The stiffness then develops according to a linear softening model and no shear stress transfer after cracking is considered. The softening pattern is controlled by three parameters: tensile stress, shape of the softening part and fracture energy. During the simulations, interface elements are placed at horizontal and vertical joints and in the center of each brick. The model shows a very brittle behavior, characterized by a sudden turn in the force-displacement curve. However, the collapse behavior of the wall loaded in compression agrees with the experimental results. As for Paulay and Priestley [7], they proposed a theory of the earthquake behaviour of a wall-filled frame and a design method for infilled frames. According to these researchers, although wall infill can increase the overall lateral load capacity, it can cause the structural response to change and asymmetric arrangement can result in force pulling on different parts of the structure. This means that wall infill can affect the structural response to earthquakes. Regarding Deodhar et al [8], they showed that mortar material and thickness of brick material are very important factors affecting the compressive strength of brick masonry prisms. In brick masonry, the greater the thickness of the brick material relative to the thickness of the mortar, the greater the strength of the masonry. A joint thickness between 5 mm and 10 mm is ideal for metric bricks and conventional bricks, and beyond 10 mm joint thickness there is a significant reduction in the strength of the brick wall. The stress-strain curve of the brick wall is similar to that of concrete. The strain corresponding to the maximum stress was always higher and the brick strength did not affect the total stress of the brick wall corresponding to the maximum stress. Nevertheless, Alfaiate et al [9] used the finite element method to study mixed mode crack propagation in concrete and masonry. A discrete approach was used: discontinuity surfaces, called imaginary cracks, were given to allow cracks to propagate. These discontinuities were modeled using: i) interface elements, in this case a numerical algorithm that avoids the need for remesh, and ii) embedding of discontinuities according to the discontinuous strongly embedded discontinuity approach.

The effect of shear stresses developed on the discontinuity surfaces was analyzed. It was found that the amount of shear stress present in the discontinuity is the most important factor affecting the structural behavior of both concrete and masonry. From all the tests analyzed, it was confirmed that the amount of shear stress present in the discontinuities is the most important factor in the mixed mode failure of both concrete and masonry. For concrete, higher shear stresses were found to result in both a stiffer post-peak response and a better approximation of the softening regime. It was also found that mixed mode failure is not significantly dependent on either Mode II fracture energy or cohesion. In masonry, when slip at mortar interfaces is allowed to fully develop, the confinement of shear stresses under high compressive stresses led to a smaller peak load as well as different failure mechanisms, which were experimentally verified. ConcerningGambarotta and Lagomarsino [10], in their workthey conceptualized the brick as a linear elastic material exhibiting brittle behavior. Subsequently, the authors examined the behavior of the mortar (sliding between joints due to internal variables) and at the interface. The model developed by Gambarotta and Lagomarsino [10] considers both mortar damage and the separation of the brick-mortar interface that occurs when it is opened and frictional sliding is activated. It is assumed that the inelastic strain components depend linearly on the mean stress and a damage variable related to the damage mechanics approach. The sliding of the units is constrained by the presence of friction at the brick-mortar interface. This model has been employed for the analysis of brick walls subjected to constant vertical loads and horizontal planar cyclic forces. Despite the fact that this approach was found to simulate the inelastic behavior of the masonry (i.e., opening and sliding of joints), it was too costly to calculate for the analysis of full-scale masonry wall panels. Moreover, other studies have focused on the homogenization of masonry, conceptualizing it as a unified entity with consistent and uniform mechanical properties across its entirety [11,12,13,14,15,16]. Nonetheless, other researchers, have focused on interface modeling, subdividing masonry into macro- and micro-modeling. In this micro-modeling, interface aspects are more emphasized [17, 18]

Bal et al. [19] described a simplified nonlinear method for identifying the fragility potential of a masonry building. This method relates the building to different limit states and compares it with the displacement demand from an overdamped displacement response spectrum during vibration of the structure Their work presents a procedure for displacement-based earthquake loss assessment for masonry buildings in the Northern Marmara Region, together with the geometrical characteristics (i.e. storey height and pier height values) of these building types. Nonlinear time history analyses were conducted on 28 case studies of buildings in the region, with 20 randomly selected acceleration records with peak ground acceleration (PGA) values ranging from 0.02g to 0.51g. The results of these analyses were used to derive period-height relationships and deflection boundary conditions for timber and reinforced concrete slab structures. Badarloo et al. [20] conducted a series of uniaxial and biaxial tests on full-scale mortar-reinforced unreinforced brick masonry square panels. The principal compressive stresses were obtained with a failure criterion oriented at 0 and 90 degrees to the bearing joints. The results demonstrated that the ratio of horizontal to vertical loading had a pronounced impact on the failure mode of clay brick and hollow clay brick layers, whereas the mortar layer exhibited minimal influence on the failure mode. The primary failure mode observed in all specimens was the separation of the mortar layer from the solid clay brick (C-brick) or F-brick layer, which corresponded to the loading ratio. The results demonstrated that the behavior of mortarless concrete brick wall panels was isotropic, and that the bearing joint orientation did not significantly influence the failure criterion. The test results indicated that the masonry strength under equal biaxial compression was, on average, approximately 36% higher than that under uniaxial compression. The effect of joint orientation was found to be very insignificant and negligible for these models. The comparison between experimental failure and the Hill criteria exhibited reasonable agreement.

Elaboration of the theoretical model of the masonry wall and its experimental materialization: To materialize the push-over, it was first necessary to design it with the required dimensions (1.2m x1.5m). Turkish standardized TS EN 771 bricks [21] measuring 28.5cm x 18.5cm x 13 cm were modeled and their layout defined. Layout is the arrangement according to which the bricks are positioned. In this work, the stretcher bond is adopted. This type of bricks arrangement, which is the most common in the world, is created when bricks are laid so that only their stretchers are visible, overlapping in the middle of the rows of bricks above and below (Figure 1). This method, which distributes block loads evenly, is the simplest way of modeling masonry structures, and consists in representing them as a combination of structural elements, such as bars, plates and beams. It is able to bear excessive amounts of pressure and ensure structural stability. Their property values are given in the following table:

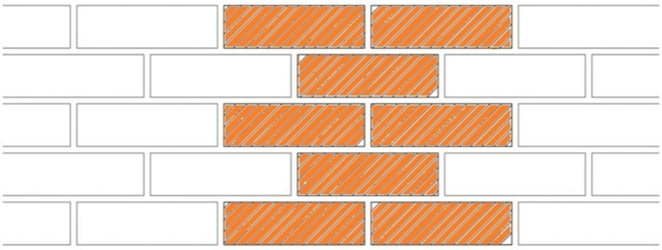

Figure 1. Stretcher bond design

A confined masonry wall is a building system in which structural masonry walls are bounded on four sides by other structural elements, such as reinforced concrete or steel [22]. This type of construction is different from a reinforced concrete frame filled with masonry. The first step is to put in place floors with vertical enclosing elements and horizontal connecting beam elements. Next, construct the structural masonry walls.

Table 1. Materials properties

Material	Modulus of elasticity (MPa)	Poisson's ratio
Steel Frame	2.00E+05	0.3
Masonry Bricks	3500	0.2

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.

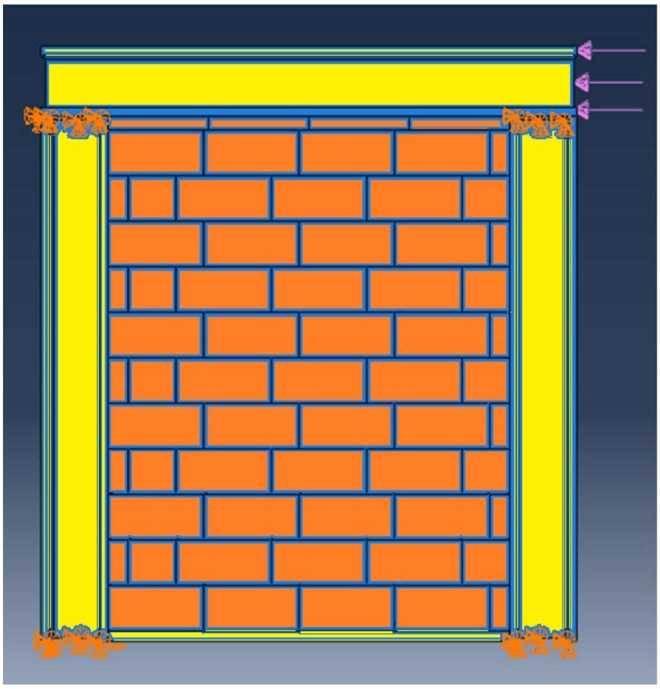

Figure 2. Boundary conditions and application of lateral cyclic forces on

This theoretical model is then materialized by building the wall in a frame, trying to respect the design criteria as much as possible.

The pinned supports are used according to the boundary conditions tools (see Figure 3). A thin layer of plaster was then placed to see cracks when lateral cyclic loads were applied.

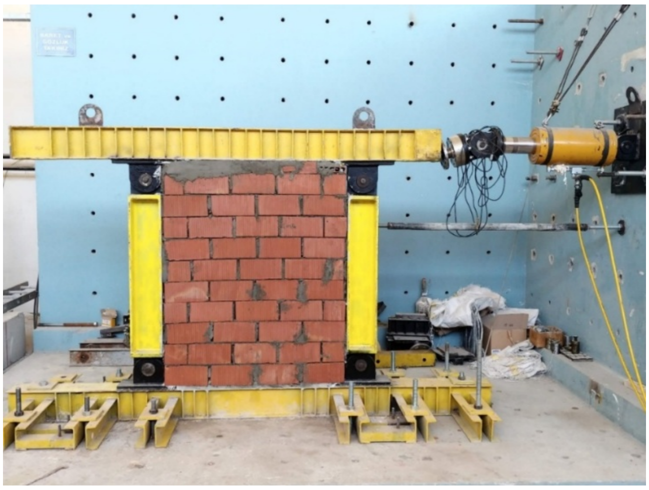

Figure 3. Masonry wall before plastering

Figure 4. Masonry wall after plastering

In situ application of the cyclic loading: The hydraulic piston was then adjusted using a control system and computer to calibrate the cyclic loads to be applied to the structure.

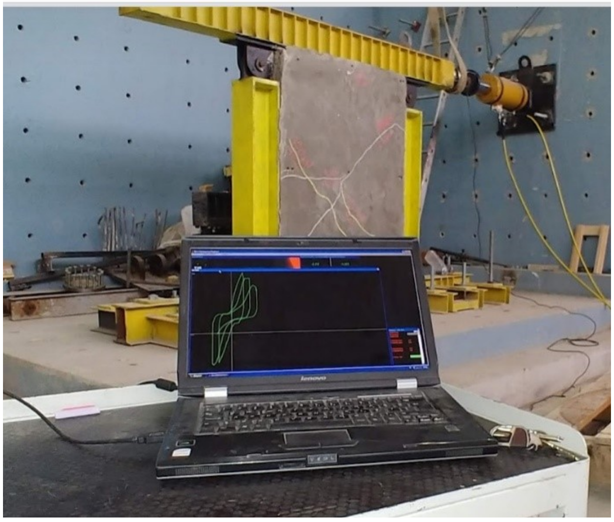

Figure 5. Computer generating cyclic loads and hysteresis curves

During application of the cyclic loading, contacts occur between the different elements, and the nonlinearity condition of the structure allow discontinuous and instantaneous change. A cyclic force which includes back and forth movement of the hydraulic piston, corresponding to the traction-compression loads. This tool is located at 1.65m from the base and consists of gradually increasing and decreasing the forces from -100 for traction to 100 for compression. The damaged masonry wall thus obtained, it is found on its surface's diagonal cracks in a zigzag form as well as displacements that oscillated between 0.7 and 9.24mm.

These damages are observed in terms of displacement of the elements, caused by the action of cyclic forces which have at the same time changed its resistance capacities. To better observe the cracks, the white chalk represents cracks caused by compression and the yellow chalk represents cracks caused by tensile forces. In fact, it was observed that a compressive load of 60 KN produced a displacement of 20 mm towards the center. If the same compressive force is increased to 95 KN or even 100 KN, a crack displacement of 10 mm is observed at the beginning of the diagonal. On the other hand, the tensile load produced a diagonal displacement of 15 mm in the opposite direction. In tests, a FEMA-461 [23] load protocol was applied to frame sample elements using a computer. The frame sample is subjected to bidirectional incremental displacement cycles (push and pull). To eliminate gaps in the setup, the first loop was set at 1.20mm. FEMA 461 states that each loading step should be performed twice, with the amplitude increasing by 1.4 times. To obtain reliable data on the masonry frame, cracks are observed, and the displacement is monitored with instruments of the Linear Variable Differential Transformer (LVDT) and the data collection system.

Figure 6. Experimental damage

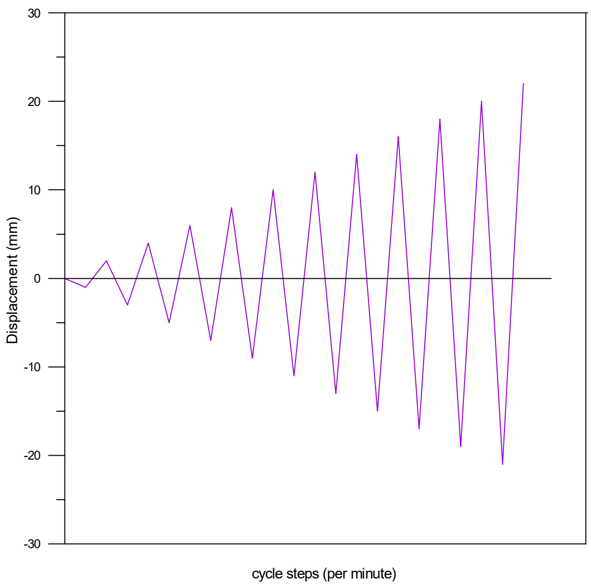

Figure 7. Protocol of cyclic loadings application

After the application of the protocol of the cyclic loadings on the masonry wall, it is noticed a long diagonal crack interspersed by two other cracks. The first crack goes in the direction of have been obtained from the analytical test of micro modeling. As for the other two cracks, they seem to come out, due to the excessive handling of the loads during the experiment. Furthermore, on the computer loads controller, a hysteresis curve is observed. This curve gives the variation of the loads and their displacements caused as the force which is applied to the wall increases or decreases.

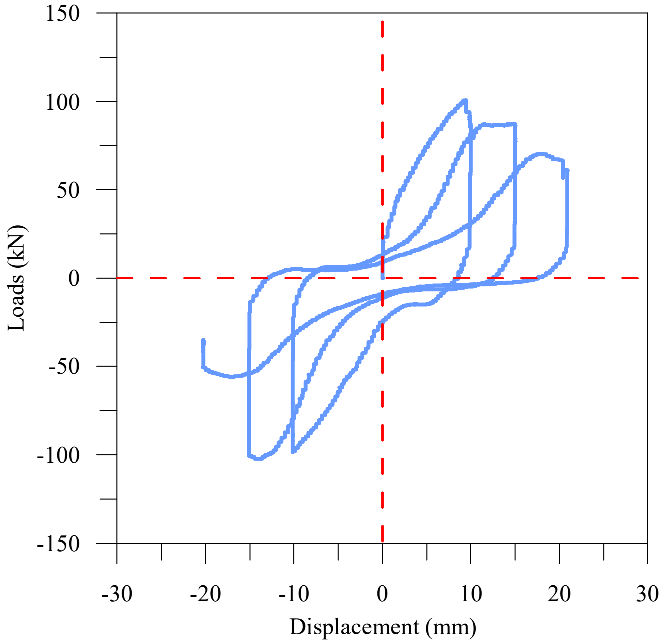

Figure 8. Hysteresis curve for damaged masonry wall

The graph shows that the maximums are 100KN and -100KN. The first peak is reached when the displacement is about 10 mm for the compression or the pushing. On the other hand, for traction, the displacement reaches a value of approximately 15 mm. On the other hand, when pulling or the traction is applied at the maximum, the displacement reaches a value of approximately -15 mm. The final compression peak occurred when, when forces were applied, the load was equal to 75 KN for a displacement of 17 mm. The final stress peak occurred when the force equals approximately 50 KN and the displacement equals 20 mm.

CONCLUSION

The push-over allowed us to first apply a FEMA-461 protocol for calibrating cyclic forces. Secondly, this process also enabled us to observe and obtain cracks in terms of displacement that can be observed on the wall. Most of this damage occurs on the diagonal of the wall. Hysteresis curves were also obtained, with maximum peaks at 100KN in both push and pull. Their peak oscillates between 15mm and 20mm. Finally, this study provides a framework for advanced structural engineering analyses that can be used for construction in seismic environments, with a view to predicting the various types of damage to masonry structures in general, and planning their possible reinforcement.

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