Macro-modeling of Adobe Piers for Seismic Analysis of Adobe Dwellings in Cuenca, Ecuador

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Abstract. Ecuador lies on the eastern rim of the seismically active area known as the Pacific Ring of Fire. In 1999, Cuenca's unique architecture and historical buildings were listed in the UNESCO World Heritage Trust sites; many of these dwellings are composed of adobe walls. The aim of this papers is to present the mechanical characteristics of adobe walls representative of Cuenca's historical buildings and a equivalent frame model to approximate the strength and vulnerability of a historical building, the behavior of masonry is represented from a macro-model approach. The properties of units and piers are obtained from experimental tests performed in the laboratories of the University of Cuenca. The numerical procedure is based on a macro-element model that is capable of reproducing flexural-rocking and shear failure modes. The macro-element is capable of representing with only one element the behavior of a whole masonry panel. The numerical results of adobe piers are compared with those of experimental tests, showing similar values for the elastic and inelastic ranges with close approximation of maximum shear strength and type of failure. This comparison allowed to estimate the mechanical properties of the macro-element model, which were used to model a historical building, Seminario San Luis. Research in this area will contribute to the conservation of historical dwellings and for future retrofitting and strengthening.

Keywords: Adobe · Historical buildings · Experimental tests
Seismic analysis · Macro-modeling

1 Introduction

In Ecuador, the main source of destructive earthquakes is the relative motion between the Nazca and South American plates. No less than 38 earthquakes of magnitude Mw7.0 or higher have been reported since 1541 causing an estimated of 80,000 casualties. A recent destructive event was the Mw7.8 Pedernales earthquake of 16 April 2016.

In the case of Cuenca, the city is located in an area with medium to high seismic hazard (PGA on bedrock of 0.25 g) [1]; the listings of earthquake events include ground motions with magnitudes ranging from Mw4.0 to Mw4.9. The little information of important seismic events and on earthquake induced structural damage in the last

R. Aguilar et al. (Eds.): *Structural Analysis of Historical Constructions*,
RILEM Bookseries 18, pp. 1328–1336, 2019.
https://doi.org/10.1007/978-3-319-99441-3_142

century, lead to a disregard against a correct design and construction process for earthquake resistant structures. In consequence, in 1999 a research group from the University of Cuenca and Red Sísmica del Austro [2, 3] conducted a research project with the aim of estimating the vulnerability analysis of Cuenca. The methodology, consisted on the Italian vulnerability index method [4]. These results were the first to present the vulnerability of the city, showing high vulnerability for all type of structures, but especially for the case of unreinforced masonry buildings, including historical buildings (see Fig. 1).

According to the 2010 census of the National Institute of Statistics and Census of Ecuador (INEC), there are 346107 buildings built with raw soil, representing 9.23% of the total construction stock. From these type of buildings, adobe constructions are the most common. However, 55% of adobe buildings are in a regular condition and 30% in a bad state of conservation.

In Azuay, province of Ecuador, the province to which Cuenca belongs, in the last ten years, according to the Annual Survey of Buildings of the INEC, 57 buildings have been built using raw soil, representing 30% of the total in the country.

Cuenca has a population of about half a million inhabitance and is the third city of importance in Ecuador. Most of the buildings located on the center area of Cuenca, have a mixture of European and own native style, making them unique. These characteristics were considered to include part of the city as a World Heritage Trust site by the UNESCO. According to this, three quarters of its historical center buildings are built with adobe.

The present paper presents a seismic vulnerability study of the Seminar San Luis building, located in the historical center next to the new cathedral the “Inmaculada Concepción”. The seminar is a three-story structure, and one of the most important historical buildings of Cuenca, constructed with masonry composed of adobes and bricks; this is a very common construction technique used in several constructions.

2 Case Study

The construction of the Seminar San Luis was planned after a Congregation of Jesuit Fathers tried to settle in Cuenca. The Order was definitively established in the city 1638, with the objective of disseminating and teaching the gospel to the population. In 1788 they began to talk about the need to create a new cathedral, a college seminary and an episcopal house. In 1802 the lifting of the Seminar in Cuenca starts; however, it was 1840 to 1856 that the construction of the Seminar was consolidated, including its two forecourt that are preserved until today [5]. From 1865 to 1874 the frontage to Benigno Malo street was rebuilt (see Fig. 2) and from 1874 to 1915 the frontage to Simon Bolivar street was also rebuilt, which are still preserved today [5].

San Luis Seminary is located in the Historic Center of Cuenca, after a restoration process opened its doors in 2017, as a public space, and it is used mainly for commerce, food services and tourism. The building is 3 story high; the story plans are shown in Fig. 3. The buildings is composed mainly of adobe walls and solid bricks; the thicknesses of walls vary between 0.30 m to 1.20 m and between 0.75 m and 0.87 m

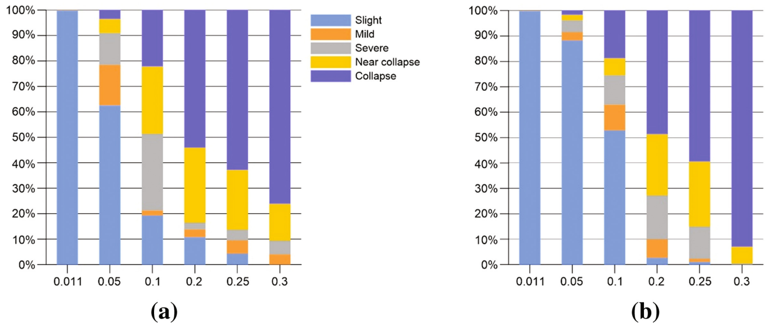

Fig. 1. Seismic vulnerability of (a) unreinforced masonry and (b) reinforced concrete buildings in Cuenca [3] as a function of PGA (Peak Ground Acceleration), adapted from Garcia and Degrande (2017) [5].

Fig. 2. San Luis Seminar, frontage to Benigno Malo Street, Cuenca, Ecuador, 2017.

respectively. Floors are supported over timber beams that lay over the walls and wooden pillars. The roof structure is timber, which supports a pitched roof composed of tile [5].

3 Pushover Analyses

3.1 Simplified Model Using an Equivalent Frame Method

The structure's strength to carry lateral inertia forces is estimated using a displacement-controlled modal pushover analysis. A 3D equivalent frame model of the building is created in the software Tremuri[1], following the methodology suggested by Lagomarsino, Galasco, Penna and Cattari [6, 7].

Figure 3 shows a representation of wall E modeled in Tremuri that is part of the Seminario San Luis building. In the program, the size of piers, spandrels and rigid

[1] TREMURI is a computer program specifically developed for the structural and seismic analysis of masonry buildings.

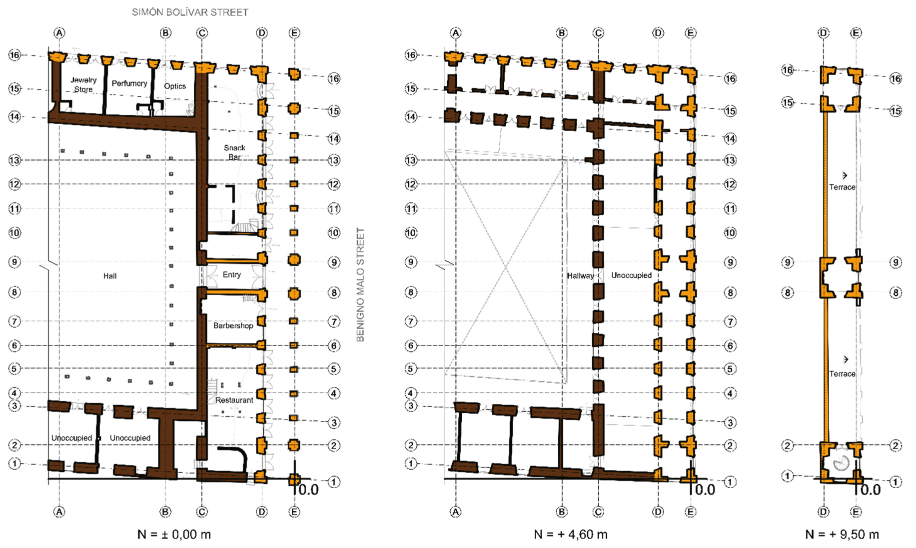

Fig. 3. Plan views and masonry composition, brick (solid orange) and adobe (solid brown), of the San Luis Seminar building: (a) ground floor, (b) first story and (c) second story (Cuenca, Ecuador, 2017).

nodes are a function of the pier effective height and size of openings; this criteria is rooted according to the formation of cracks in walls with openings under in-plane loads, and is supported from surveys of damaged buildings after earthquakes and from experimental campaigns on scaled walls [6]. Piers carry vertical and horizontal loads; while spandrels can couple piers to transfer lateral loading (Fig. 4).

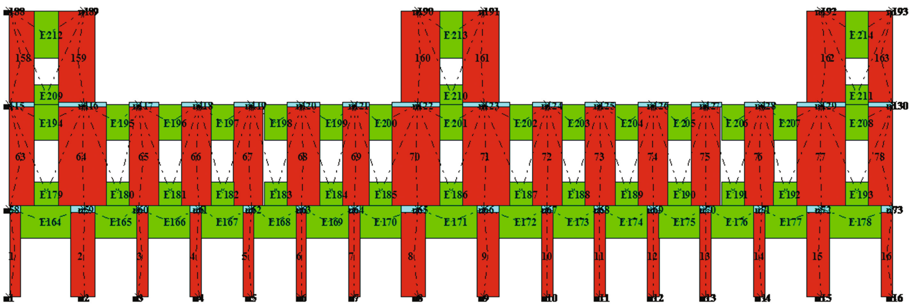

Fig. 4. Walls E modeled with Tremuri according to the floor plans of the building (Fig. 3). Piers are indicated in red, spandrels in green and rigid nodes in blue; adapted for this building from Garcia and Degrande (2017) [8].

3.2 Experimental Campaign

The mechanical characteristics of adobe material and adobe walls are obtained through tests carried out in the laboratory of the University of Cuenca [9], using adobes from 3 factories and 2 buildings, located in the historic center of Cuenca. The tests consisted of determining the compressive strength of the adobe units (see Fig. 5a), walls (see Fig. 5b), as well as diagonal compression tests in walls (see Fig. 5c) [9].

(a) (b) (c)

Fig. 5. Mechanical tests (a) compression in unit (b) pier compression (c) diagonal compression [9].

The compression strength of the adobe is defined from compression tests on 30 cube (10 cm) specimens, six from each case study; while the compression strength of the adobe piers is determined from 16 analyses. The average height and thickness of the adobe piers is 55 cm and 21 cm, respectively. These experimental tests allowed to estimate the Young's modulus of units and piers.

The diagonal compression tests (Fig. 5c) carried out on 16 piers, with an average length, height and thickness of 55 cm, 54 cm and 21 cm, respectively. The diagonal compression experiments considers a masonry panel loaded in shear and composed of three rows, each row is one and a half adobe brick. The adobes are glue using a mud mortar layer with the same composition of the units. During the experiment the panels are loaded by an incremental uni-axial load. This test defines the shear strength and cohesion of the adobe piers. Figure 6 shows the strength curve for increasing compressive loads, this curve is defined by $f_{vi} = \frac{H}{2A}$ where H is the largest shear force reached during the experiment, A is the cross-section area and f_{vi} the shear strength. The friction coefficient is defined as $\mu = \tan(\alpha)$, where α represents the intersection between the blue and dotted line in Fig. 6. The wall's cohesion is the shear strength for null compression load.

Table 1 summarizes the result of the experimental tests of adobe and brick masonry panels, and define the mean of all macroscopic properties. Piers and spandrels are modeled in the simplified equivalent frame method using a macro-element model [10]. The macro-element accurately represents the nonlinear behavior and failure modes of masonry panels, however the model needs the definition of additional parameters, a

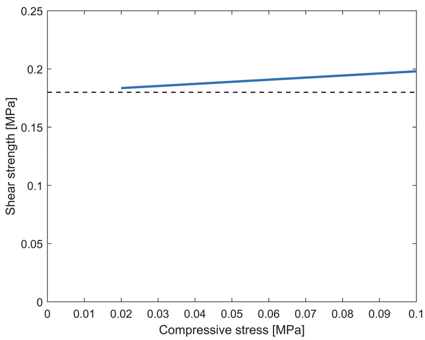

Fig. 6. Shear strength for different compression loads of an adobe pier subjected to shear forces.

dimensionless shear parameter Gc_t defined from the multiplication of the element's shear modulus G and a non-linear shear deformability parameter c_t, characterized by the tangent stiffness of masonry walls [10]. The deformability parameter is commonly obtained from experimental results [10]. Moreover, the softening behavior of masonry is defined in the macro-element model by the slope of the softening branch (obtained from experimental tests), represented by β. Finally, the energy dissipation and maximum available energy is included on a toughness function [10].

3.3 First Mode and Vibration Period of the Building

The lateral displacement of the walls participating in the *x*-direction is dominant and mobilizes approximately 80% of the total modal mass. The first eigenperiod of the building is 0.817 s and the mass participation factor for this mode is 0.85. The second mode is also lateral, in the *y*-direction, and has a period of 0.79 s. Is worth mentioning that the in-plane behavior in one direction can activate the out of plane response of the remaining walls, however in the present study the out of plane failure mode is not considered.

3.4 Non-linear Static Analysis

The Seminario San Luis shear strength is analyzed using a non-linear displacement controlled static analysis (pushover analysis). The incremental forces follow a spatial distribution that corresponds with the first lateral modes of the structure [11]. This methodology follows the same steps as presented by García and Degrande (2017) [8].

Figure 7 shows the capacity curve in the *x*-direction and the performance levels for different damage states. The control node is located at the center of gravity of the roof level. A maximum drift is imposed during the analysis, following the recommendations from ASCE-41-2006, EN-3-1998, thus the response is for drifts below 0.6%. The capacity curve is the basis to define the four limit performance levels shown in Fig. 7. The procedure follows a heuristic approach defined in Lagomarsino and Cattari (2014) [12]. The structure shows an operational performance level until 0.12 g; increasing the lateral force causes shear failure of several walls and a reduction of the overall stiffness.

Table 1. Macroscopic properties (average) of masonry panels composed of adobe and bricks, respectively.

	Young's modulus *E* [MPa]	Shear modulus *G* [MPa]	Density [kg/m^3]	Compressive strength f_{tm} [MPa]	Cohesion f_{vo} [MPa]	Friction coefficient μ [-]	Shear parameter Gc_t [-]	Softening parameter β [-]
Adobe	300	265	1566	0.85	0.18	0.075	1	0.1
Brick	2770	1111	1800	6.84	0.3	0.145	2	0.4

The building overcomes this state by redistributing the forces to the remaining walls; Fig. 7 shows these picks between the two last performance levels. Increasing the load, repeats this behavior but with increasing instability, which is why the collapse displacement is limited. The minimum PGA level for Cuenca is 0.25 g, thus the possibility of a ground motion inducing accelerations above 0.18 g is real. Only the in-plane failure mode of walls is considered in this paper. The out-plane behavior is being assessed for each wall individually following part C8 of the "The Seismic Assessment of Existing Buildings" [13].

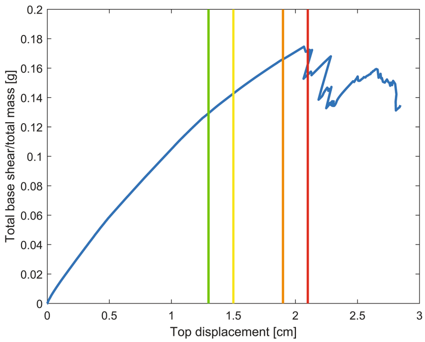

Fig. 7. Non-linear static analysis, pushover curve (blue line) and superimposed limit performance levels defined from roof displacements: fully operational (green line), operational (yellow line), life safe (orange line) and near collapse (red line); methodology adapted, for this building, from Garcia and Degrande (2017) [8]

4 Conclusions

The research was motivated due to the level of seismic hazard of Cuenca and the material composition of Cuenca's historical buildings, which makes them prone of collapse in case of the earthquake of design. The paper presented a non-linear static analysis for Seminario San Luis building, a heritage structure located in the city center of Cuenca, Ecuador.

The properties of the adobe walls were derived from compression and shear tests on adobe units and piers. The building was defined using and equivalent frame method and implemented in Tremuri; a macro-element model characterizes the behavior of masonry, represented in form of piers and spandrels. The macro-element model can reproduce the elastic and inelastic behavior of masonry, and estimate the in-plane strength of panels. The out-plane failure is not considered in this analysis and is under study.

The building was analyzed in the two principal directions; however, the paper shows only the capacity curve corresponding to the in-plane response of walls in the *x*-direction, presenting the different performance levels in function of the target node.

The capacity curve is the result of an initial study; uncertainties due to boundary conditions, structural behavior and modeling assumptions are under study. The out-of-plane behavior and additional experiments on adobe walls, units and structural components are part of a research that takes place in the University of Cuenca.

Acknowledgements. This work is carried out with the support of the University of Cuenca.

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