Seismic performance and fragility functions of confined masonry old infrastructure with handmade bricks

G H Gonzales¹, A G Aguilar¹, G Huaco² and D Garber³

¹ Bachelor, Peruvian University of Applied Sciences UPC. Lima, Peru.
² Professor, Peruvian University of Applied Sciences UPC. Lima, Peru.
³ Associate Professor, Florida International University FIU. Miami Florida, USA.

Email: u201521566@upc.edu.pe; u201517071@upc.edu.pe; pccighua@upc.edu.pe; dgarber@fiu.edu

Abstract. In several countries, confined masonry structures with handmade bricks were built for common to essential infrastructure. These bricks were made by clay using artisanal ovens; therefore, they have mechanical properties less than seismic codes currently recommend. Many of these buildings are one to three stories and were designed following past design codes or were built without considering any design codes. There is an uncertainty of the strength or ductility for these buildings to resist a severe earthquake event. For this purpose, this study aimed to develop fragility functions as a way to estimate and quantify the vulnerability of these structures. This research describes a methodology to find fragility functions based on a non-linear model with three levels of masonry handmade bricks. Experimental test data was used to validate the proposed model during the calibration process. Incremental dynamic analyses were developed for 11 pairs of seismic records for both orthogonal directions. Fragility functions reported a high probability of collapse for demand levels from a design earthquake to maximum capable earthquake.

1. Introduction
In Peru and other developing countries on the coast of South America, the most common structural system of construction is confined masonry. According to the 2017 National Censuses [1], confined masonry represents almost 56% of the total infrastructure in Peru. Due to their age, many of these structures were built with handmade bricks and were designed before the release of the first Peruvian technical standard [2] in 1970 without considering factors such as material ductility, soil type, and displacement control of the wall’s limits. Additionally, Jiménez and Moggiano [3] mentioned the sequence of twentieth and twenty-first century earthquakes: 1974 (Mw 9.0), 1966 (Mw 8.1), 1974 (Mw 8.1) and 2007 (Mw 8.1) has not released all the seismic accumulated after the occurrence of the greater 1746 Callao earthquake and tsunami (Mw 9), rather only around 20%.

Faced with this catastrophic natural disaster, Simões et al. [4] is necessary to assess the capacity of these constructions to resist a high magnitude earthquake by developing analytical fragility functions that quantify the vulnerability through the probability of equaling or exceeding a certain damage limit state based on a seismic demand. In this paper, a way to assess seismic vulnerability of structural confined masonry system is presented. Eleven (11) pairs of seismic records were selected, which were treated for later use in the application of Incremental Damage Analysis (IDA) to a 60-year-old hospital structure with 3 stories of confined masonry with handmade bricks. From this, statistical processing of
results was performed to develop fragility functions for each damage limit state, which will allow to evaluate the seismic vulnerability of the hospital under study.

2. Methodology

2.1. Description of structure analyzed
The structure studied is located in Lima, Peru. It is a hospital of confined masonry with handmade bricks that was built more than 60 years ago. It has a non-appropriate structuration to the actual NTE-030 with banked beams only one way and with insufficient joints (3cm) between adjoining buildings. Also, it has 3 stories with 3 meters of high each one. The handmade bricks had a lower axial compression ($f'_m = 4.7$ MPa) than masonry units used today. The mechanical properties of the materials were obtained from Gibu et al. [5]. Figure 1 shows the structure.

![Figure 1. (a) Analyzed infrastructure (b) Handmade bricks](image)

2.2. Seismic records
According to FEMA [6], eleven pairs of seismic records were selected from stations located in the same soil type as the structure being analyzed. The soil type was rigid soil (S1) as defined by Ministry of Housing [7]. Also, these 11 pairs of seismic records were scaled to be compatible with Peruvian target spectra based on Al et al. [8].

2.3. Nonlinear model proposed
The nonlinear model of the structure uses the experimental database of real walls of masonry handmade bricks on a real scale by Huaco [9]. The equivalent nonlinear model proposed by Gonzales et al. [10] was used in this research. This model was validated by replicating the laboratory test from Huaco [9] in SAP 2000 where parameters of the pivot hysteresis were calculated based on Ilki and Kumbasar [11]. Then, the wall was subjected to a nonlinear time history analysis inducing the history of displacement of the tested wall to compare the hysterical responses obtained from SAP 2000 and the laboratory test. Finally, an iterative process was performed by varying the previously calculated pivot parameters of the hysterical curve to obtain a better match with the experimental model comparing hysteretic responses.
2.4. Incremental dynamic analysis

The 11 pairs of seismic records were scaled to different peak ground acceleration (PGA) levels for each orthogonal direction, thus having 440 seismic records and the same number of nonlinear time history analyses. To plot the IDA curves, the intensity measure (IM) parameter was defined as the PGA and the damage measure (DM) parameter was defined as the interstory drift ratio. Figure 3 (a) and (b) show the family IDA curves highlighting 16%, 50% and 84% percentiles in each orthogonal direction.

![Figure 3](image)

**Figure 3.** (a) Percentiles 16%, 50% and 84% of the IDA curves in E-W direction (b) Percentiles 16%, 50% and 84% of the IDA curves in N-S direction.

Also, Figure 3(a) and (b) show for the same levels of demand the structure reported higher drift in N-S direction than in the E-W direction, which reflects the wall densities.

2.5. Generation of fragility Functions

2.5.1. Damage limit states. These are based on experimental test of real-scale walls for confined masonry with handmade bricks developed by Zavala et al. [12], where drifts are related to performance level: Operational (O) is 1/2500, Immediate Occupancy (IO) is 1/769, Life Safety (LS) is 1/350, Collapse Prevention (CP) is 1/286, Collapse (C) is 1/250.

2.5.2. Analysis statistical. Fragility functions were calculated with the maximum likelihood method. It mitigates non-convergence problems in adjusting fragility functions by making better predictions, which are better aligned with the damage observed in past seismic events [13].
2.5.3. Seismic demand estimation. Four levels of seismic demand were defined in this research, as indicated in ATC-40 [14], using the PGA for the Z4 zone indicated by the Ministry of Housing [7] as shown in Table 1.

| Seismic Demand                              | Description         | PGA   |
|--------------------------------------------|---------------------|-------|
| The Serviceability Earthquake (SE)         | Tr= 75 year         | 0.23g |
| The Design Earthquake (DE)                 | Tr= 500 years       | 0.45g |
| The Maximum Earthquake (ME)                | Tr=1000 years       | 0.56g |
| The Maximum Capable Earthquake (MCE)       | Tr=5000 years       | 0.68g |

3. Results
Figure 4 (a) and (b) report the fragility functions for both orthogonal directions highlighting the probability of excess of the damage limit-states for each one demand level.

![Fragility functions](image)

**Figure 4.** (a) Fragility functions in the N-S direction (b) Fragility functions in the E-W direction.

Table 2 and 3 shows probability to each damage limit state for different seismic demands. For instance, Table 3 shows for a design earthquake demand the probability of Collapse is 49.61%, the probability of Collapse Prevention is 4.68%, Life Safety is 8.64%, Immediate Occupancy is 26.76% and Operational 10%.

| Seismic Demand | Operational | Immediate Occupancy | Life Safety | Collapse Prevention | Collapse |
|----------------|-------------|---------------------|-------------|---------------------|----------|
| SE             | 6.95%       | 47.24%              | 19.24%      | 5.70%               | 20.87%   |
| DE             | 0.23%       | 10.22%              | 5.32%       | 9.49%               | 74.75%   |
| ME             | 0.05%       | 4.40%               | 1.78%       | 6.31%               | 87.45%   |
| MCE            | 0.01%       | 1.80%               | 0.42%       | 3.52%               | 94.24%   |
4. Conclusions

The results of the fragility functions show the high seismic vulnerability of the analyzed type of structure built by handmade bricks, reporting high probabilities of exceeding the limit states of immediate occupation, life safety, prevention of collapse and collapse for the different levels of demand.

The 50% percentile of the IDA curves show that in the E-W direction starting from a demand level of 0.45g, the structure would exceed the 0.5% drift limit indicated in NTP E030, while IDA curves in N-S direction this limit will be reached starting from a demand level of 0.35g. According to the damage limit states for those drift levels; the structure will already be in the collapse range, having presented considerable damage to the masonry wall with handmade bricks. These results show the need to develop policies to reinforce this type of building as the structure analyzed in this research is representative of many critical structures in Peru and other developing countries along the coast of South America.

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