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# STRUCTURAL ASSESSMENT OF CONFINED MASONRY RETROFITTING UNDER MULTI-SEISMIC SCENARIOS IN METROPOLITAN LIMA AREA

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## *Abstract*

Metropolitan Lima Area is composed by 50 districts from 2 provinces, namely Lima and Callao. This area is exposed to a seismic gap according to studies realized under SATREPS Project (Science and Technology Research Partnership for Sustainable Development between Chiba University of Japan and the National University of Engineering of Lima, Peru, 2010-2015). These studies presented that a severe earthquake (Mw8.6~8.9) may occur in Lima Region (Pulido et al., 2011) and it would result in harmful consequences. Nowadays, the population of Metropolitan Lima Area is 10.5 million (National Institute of Statistics and Informatics of Peru, 2017), and masonry structures represent 83% of total buildings in this area (Diaz, 2019). The lack of supervision resulted in the increase of non-engineered masonry dwellings. These structures are highly vulnerable to earthquakes and, consequently, most population of this area are under unacceptable very high seismic risk. In that sense, retrofitting techniques are being studied in Peru (Zavala et al., 2009), one of them consists in applied steel mesh and cement-sand mortar on one or both faces of confined masonry walls, which require low-complexity construction to improve the seismic capacity of confined masonry dwellings (Diaz et al., 2017).

In order to implement massively this retrofitting technique, a series of representative confined masonry structures of Metropolitan Lima Area are simulated under multi seismic scenarios considering simulated un-retrofitted and retrofitted conditions. Therefore, several seismic performances or damage levels are analyzed; also, quantity and distribution of retrofitting are analyzed to provide information about the effectiveness of this retrofitting technique.

Numerical simulations are carried out using nonlinear time-history analyses with mathematical models calibrated with experimental results in one-face and two-face retrofitted walls. Demand levels are characterized for metropolitan Lima area using probabilistic hazard, and soils microzonation from collected studies realized in 40 districts in Metropolitan Lima Area by the Japan Peru Center for Earthquake Engineering Research and Disaster Mitigation (CISMID) from the National University of Engineering (UNI) in the last 15 years.

Keywords: *confined masonry, retrofit, damage level, performance level*

## 1. Introduction

Peru is a country prone to earthquakes and their consequences are devastating for the inhabitants. Metropolitan Lima Area, which concentrates over 30% of population of Peru, is currently exposed to a seismic gap, according studies realized under one Project supported by the Science and Technology Research Partnership for Sustainable Development from Japan, and executed by Chiba University of Japan and the National University of Engineering of Peru [1]. A few moderated earthquakes struck Metropolitan Lima Area in twentieth century; nevertheless, expected scenarios for a severe earthquake (Mw8.6~8.9) that may occur in Lima Region are much more catastrophic. Nowadays, the population of Metropolitan Lima Area is 10.5 million (National Institute of Statistics and Informatics of Peru, 2017), and masonry structures represent 83% of total buildings in this area (Diaz, 2019).

The most representative masonry walls of these confined masonry dwellings, shown in Fig. 1, are constructed with industrial hollow bricks, handmade solid bricks and industrial tubular bricks. The last type of brick is supposed to be used for partition walls only.

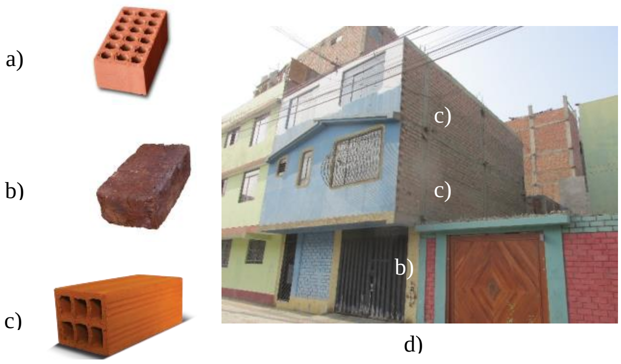



Fig. 1 – Types of bricks used in non-engineered confined masonry dwellings: a) hollow, b) solid c) tubular bricks d) Solid bricks used in first floor and tubular bricks in upper floors.

The lack of supervision resulted in the increase of non-engineered masonry dwellings. Most population of this area are under unacceptable very high seismic risk, because these structures are highly vulnerable to earthquakes. According to a study "A space for development" conducted by the Inter-American Development Bank in 2012, the housing deficit in Peru represents 72%; it means that families occupy low quality dwellings or do not count with a dwelling in Peru. In that sense, retrofitting techniques are being studied in Peru. Zavala et al. conducted a loading cyclic test in one full-scale two-story confined masonry dwelling in 2009, where masonry was rehabilitated using wire-mesh and cement-sand mortar along cracks on one face of walls. The rehabilitated two-story dwelling recovered 75% and 56% of its strength in positive and negative direction of loading, respectively [2]. Then, Diaz et al. realized a series of loading cyclic tests in retrofitted confined masonry walls in 2014, where wire mesh and cement-sand mortar were applied on both faces of confined masonry walls, including tie elements. The retrofitted confined masonry walls increased its strength by 53% and 84% in walls with handmade bricks and tubular bricks, respectively [3]. The National Training Service for the Construction Industry (SENCICO) conducted one series of experimental tests in rehabilitated confined masonry walls in 2017, where cement-sand mortar covered cracks and then wire-mesh and mortar were applied on both faces of walls [4].

The retrofitting of confined masonry walls on both faces of walls requires low-complexity construction to improve the seismic capacity of confined masonry dwellings; nevertheless, it was observed that several dwellings are not adequately separated from adjacent dwellings and the retrofitting is complicated to be applied on both faces of some walls due to electrical, water or gas installations or similar. Thus, the application of the steel mesh and mortar on two faces of walls becomes very complex. In this sense, this article analyzed the behavior of confined masonry wall when they are un-retrofitted, one-face retrofitted and two-face retrofitted.

On the other hand, the Japan Peru Center for Earthquake Engineering Research and Disaster Mitigation (CISMID) from the National University of Engineering (UNI) carried out seismic microzonation, vulnerability and risk studies realized in 40 districts of Metropolitan Lima Area. It was observed on field surveys that dwellings with similar characteristics can be grouped and represented by typical structures. In consequence, with the purpose of implementing massively this retrofitting technique, a series of representative confined masonry dwellings with handmade solid and tubular bricks of Metropolitan Lima Area are simulated under multi seismic scenarios considering un-retrofitted and retrofitted conditions in order to evaluate its feasibility.

## 2. Retrofitting Technique

This retrofitting technique is based on one experimental test conducted in Lima, Peru, by Zavala et al. in 2009 to study the behavior of a rehabilitated confined masonry dwelling [2,5]. In this study, the technique to rehabilitate this dwelling utilized wire-mesh and cement-sand mortar. The wire-mesh of 100x100mm and 4.2 mm diameter was placed and fastened to the masonry wall with wire of diameter 1.65 mm, along the crack on one face of the masonry wall. Then, the affected surface was covered by the mortar of cement-sand ratio of 1:4. Then, Diaz et al. in 2014 conducted experimental tests to study the behavior of retrofitted confined masonry walls using wire-mesh and cement-sand mortar. In this study, the technique was modified. The wire-mesh was placed and fastened to both faces of the confined masonry walls, including tie elements; and then the surface was covered by mortar of cement-sand ratio of 1:4.

This retrofitting technique consists of placing and fastening steel mesh on one-face or two-face of confined masonry walls. Tie-columns and tie-beam are included. Then, faces are covered by a cement-sand mortar until reaching 30mm of thickness, approximately. In this case, the steel mesh is made of connected rebar because it is much easier to get than the wire mesh, and its assembly is low complex.

Fig. 2 – Retrofitting of confined masonry walls

The mesh rebar is #2 (6.4mm) diameter by wire of 1.65mm diameter; separated by 150mm in both directions. The steel mesh is fastened to both faces of the wall by a wire of 1.65mm diameter that crosses the masonry. In the case of applied the retrofitting to one-face of the wall, the mesh is fastened to the wall by concrete nails of 3 inches. The steel mesh is fastened to tie elements by concrete nails of 2.5 inches. Fasteners, namely wires and concrete nails are placed at 300mm spacing in vertical and horizontal directions. The steel mesh is also fastened to existing structure, such as foundation and slabs, using rebar dowels of #2 diameter. Dowels are extended a minimum of 150 mm into the steel mesh and a minimum of 200mm into footing, slabs or beams. The mortar to cover the steel mesh is a mix cement-sand ratio of 1:3. The compressive strength of this mortar was 16 MPa in average, and the yield strength of steel bars was 420 MPa. Fig. 2 shows the construction procedure for the proposed retrofitting technique.



## 3. Experimental results

### 3.1 Specimens

Six specimens were tested under cyclic loadings, as follows:

- Three confined masonry walls using handmade solid bricks (L1): one un-retrofitted (R0), one one-face retrofitted (R1) and one two-face retrofitted (R2).
- Three confined masonry walls using tubular bricks (L2): one un-retrofitted (R0), one one-face retrofitted (R1) and one two-face retrofitted (R2).

The confined masonry walls had a total height of 2500mm and a width of 2600mm. The confinement of masonry walls consisted of reinforced concrete tie-columns and tie-beam. The length of the tie-columns was 200mm, the height of tie-beam is 300 mm, while the width of columns and beam was same as thickness of the masonry wall. Each column and beam had four longitudinal bars #3 (9.5mm), and stirrups #2(6.4mm) with the following distribution: 1@50mm, 4@100mm and then @250mm. Moreover, the specimen had a foundation in order to be connected to the reaction floor; with the cross section 900mmx300mm, and the length of 3200mm. Table 1 shows characteristics of specimens during tests.

Table 1 – Characteristics of specimens

| ID | Description of walls | Wall thickness (mm) | Wall thickness after retrofitting (mm) | Axial load in kN (average axial stress in MPa) |
|---|---|---|---|---|
| ML1R0 | Solid, un-retrofitted wall | 121 | 121 | 200 (0.64) |
| ML1R1 | Solid, one-face retrofitted wall | 121 | 147 | 200 (0.52) |
| ML1R2 | Solid, two-face retrofitted wall | 121 | 173 | 200 (0.44) |
| ML2R0 | Tubular, un-retrofitted | 110 | 110 | 200 (0.70) |
| ML2R1 | Tubular, one-face retrofitted wall | 110 | 140 | 200 (0.55) |
| ML2R2 | Tubular, two-face retrofitted wall | 110 | 170 | 200 (0.45) |

A series of six masonry prisms of each type of clay bricks were tested. The average compressive strengths were 5.7 MPa and 3.6 MPa for handmade solid and tubular bricks, respectively. Additional, diagonal tension tests of masonry assemblages were conducted. The average shear strengths of these assemblages were 0.5 MPa and 0.3 MPa for handmade solid and tubular bricks, respectively.

### 3.2 Test setup

Four hydraulic static jacks were used. Two jacks applied vertical loading to simulate the gravity load due to upper floors; and two jacks applied simultaneously lateral cyclic loading to simulate the seismic load. Jacks have 500kN loading capacity and a stroke of +/- 250 mm. The displacement protocol used in tests is shown in Fig. 3.

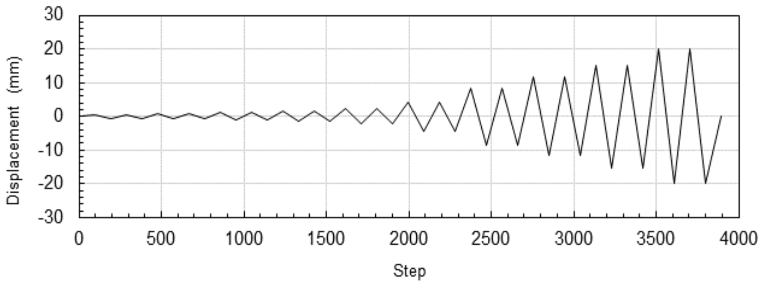


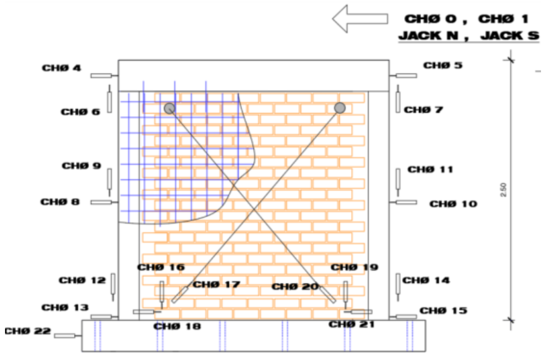

Fig. 3 – Loading displacement for lateral cyclic loading tests



Horizontal jacks were supported by the reaction wall and connected to an assemblage of steel frames for loading transfer, as shown in Fig. 4a. Vertical jacks were supported by the reaction floor and connected to the steel assemblage. The measuring system consisted of load cells in jacks (CH-00 to CH-03) and LVDTs arranged in the specimen (CH-04 to CH-22), as shown in Fig. 4b.

a) Loading system

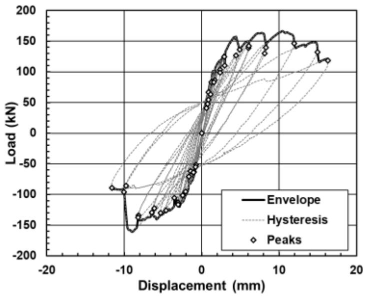



b) Measuring system

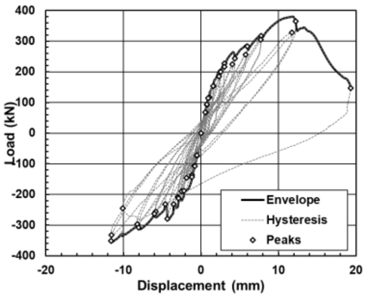
Fig. 4 – Setup of cyclic loading tests

### 3.3 Test results

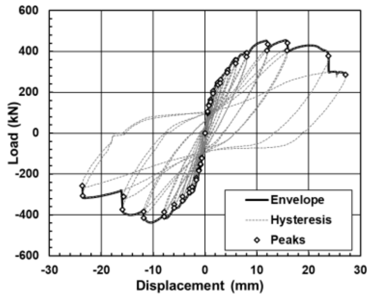
Load-displacement hysteresis curves obtained from lateral cyclic loading tests are shown in Fig. 5.



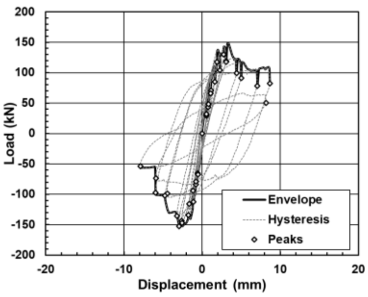

ML1R0



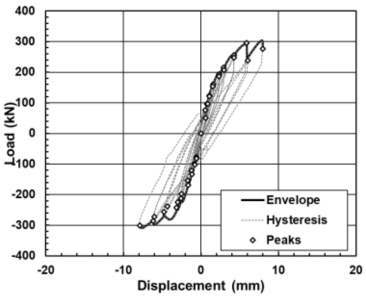

ML1R1



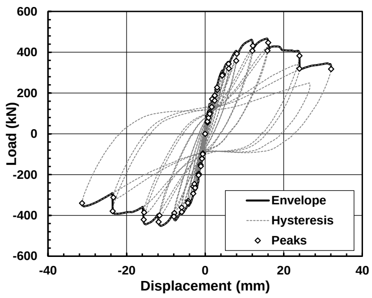

ML1R2




ML2R0



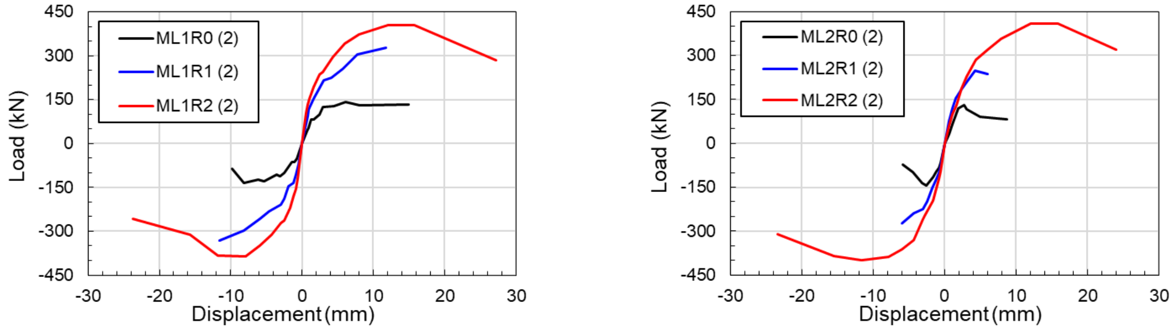

ML2R1




ML2R2

Fig. 5 – Hysteresis curves

The skeleton curves are shown in Fig. 6, and they were obtained using peaks from cycles where the target amplitude was repeated. The maximum load reached by un-retrofitted walls constructed with solid bricks and tubular bricks occurred at drift of 0.003 and 0.001, respectively; less than the limit values of 0.005, prescribed by the Peruvian Standard of Masonry Structures [6]. The maximum loads reached by one-face retrofitted and two-face retrofitted walls constructed with solid bricks occurred at same level of drift, 0.005 in average. While, the maximum loads reached by one-face retrofitted and two-face retrofitted walls constructed with tubular bricks occurred at drift of 0.002 and 0.005, respectively. It is observed that the retrofit has slight effect on ductility when masonry walls constructed by tubular bricks are retrofitted on one face. Table 2 shows values of restoring forces at the cracking (C), yielding (Y), maximum (M) and ultimate (U) state, and their corresponding displacements.



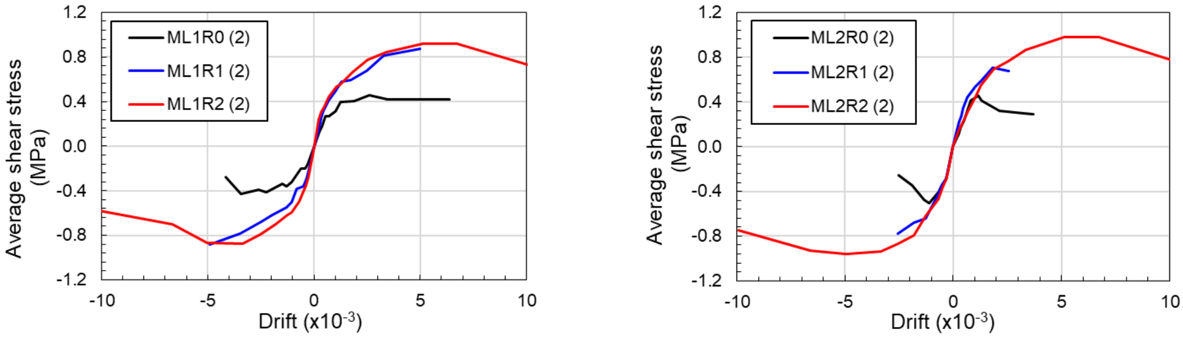

a) Handmade solid bricks walls b) Tubular bricks walls

Fig. 6 – Skeleton curves

Table 2 – Experimental results

| Specimen Id. | Displacement (mm) | | | | Load (kN) | | | |
|---|---|---|---|---|---|---|---|---|
| | (C) | (Y) | (M) | (U) | (C) | (Y) | (M) | (U) |
| ML1R0 | 1.2 | 2.6 | 7.1 | 13.0 | 72 | 120 | 138 | 110 |
| ML1R1 | 1.1 | 3.0 | 11.8 | 14.4 | 130 | 215 | 330 | 264 |
| ML1R2 | 1.8 | 3.2 | 12.0 | 20.0 | 220 | 290 | 396 | 332 |
| ML2R0 | 0.8 | 1.7 | 2.6 | 3.2 | 70 | 118 | 137 | 108 |
| ML2R1 | 1.2 | 3.0 | 4.3 | 6.0 | 130 | 225 | 260 | 240 |
| ML2R2 | 1.7 | 3.3 | 13.0 | 21.0 | 180 | 280 | 404 | 336 |

Capacity curves are also expressed in terms of average shear stress (including tie-column) and drift with the purpose of comparing un-retrofitted and retrofitted walls, as shown in Fig. 7. The average maximum shear stresses of walls constructed with solid bricks are 0.4, 0.9 and 1.0 MPa for un-retrofitted, one-face retrofitted and two-face retrofitted walls, respectively. While, the average maximum shear stresses of walls constructed with tubular bricks are 0.4, 0.7 and 1.0 MPa for un-retrofitted, one-face retrofitted and two-face retrofitted walls, respectively. Capacity of deformation is expressed in terms of ratio of deformations at maximum and yielding states named ductility factor. Here, ductility factor of walls constructed with solid bricks are 2.7 and 3.9 for un-retrofitted and one-face retrofitted walls, respectively. While ductility factor of un-retrofitted and one-face retrofitted walls constructed with tubular bricks is quite similar, 1.5 in average. Ductility factors of two-face retrofitted walls constructed with solid bricks and tubular bricks are quite similar, 3.8 in average. The increment of deformation at maximum state due to the retrofitting is slight significant in one-face retrofitted wall constructed with tubular bricks. Consequently, the proposed retrofitting technique increases ductility of the non-engineered confined masonry walls when they are constructed with solid bricks and retrofitted on one or two faces; and when they are constructed with tubular bricks and retrofitted on two faces only.




a) Handmade solid bricks walls b) Tubular bricks walls

Fig. 7 – Capacity curves in terms of average shear stress and drift

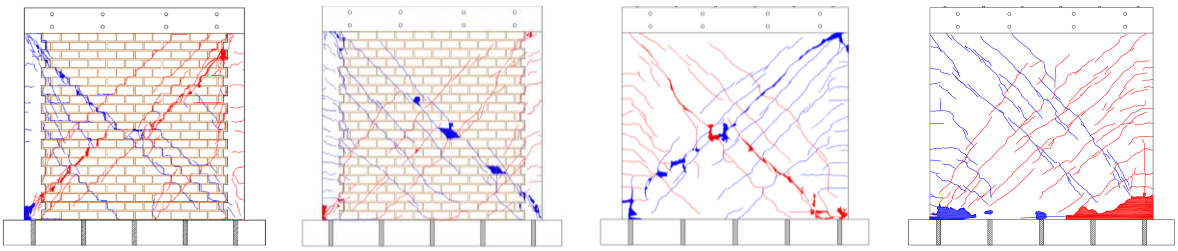


Values of strength of un-retrofitted walls constructed with solid or tubular bricks are quite similar. Nevertheless, walls constructed with solid bricks presented greater capacity of deformation; ductility factor of walls constructed with solid bricks is greater than twice the ductility factor of walls constructed with tubular bricks. Un-retrofitted walls constructed with tubular bricks dissipated less energy than those constructed with solid bricks until they reach the maximum state. Beyond this state walls constructed with tubular bricks dissipated more energy, because tie elements subjected under lateral loads behave like low ductility RC frame; however, the residual capacity of walls beyond this state is neglected, because they are unstable.

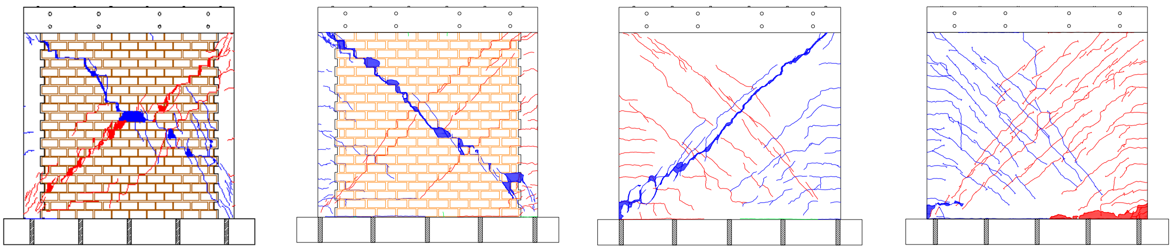
Walls constructed with solid bricks and retrofitted on one face and two faces presented quite similar strength. However, the ductility is greater when a wall constructed with solid bricks is retrofitted on two faces. Walls constructed with tubular bricks and retrofitted on two faces presented slight greater strength and ductility than those retrofitted on one face. However, the ductility is quite greater when a wall constructed with tubular bricks is retrofitted on two faces.

Fig. 8 shows the ultimate state of confined masonry walls with solid bricks and tubular bricks in un-retrofitted, one-face and two-face retrofitted conditions. Red lines represent crack patterns caused by incremental loading (pushing) and blue lines represent crack patterns caused by reversal loading (pulling). In the case of one-face retrofitted walls front and back faces are shown because crack pattern are quite different.



Un-retrofitted | One-face retrofitted (un-retrofitted face) | One-face retrofitted (retrofitted face) | two-face retrofitted

a) Walls with handmade solid bricks



Un-retrofitted | One-face retrofitted (un-retrofitted face) | One-face retrofitted (retrofitted face) | two-face retrofitted

b) Walls with tubular bricks

Fig. 8 – Ultimate state of walls with tubular bricks

Retrofitted walls on one face presented a slight increment of ductility. It can be handled for walls constructed with solid bricks; nevertheless, it keeps critical in walls constructed with tubular bricks. However, walls constructed with solid or tubular bricks retrofitted on both faces behaved quite similar until they reached their ultimate state, as shown in Fig. 6, Fig. 7 and Fig. 8; and the improvement of their strength and ductility is quite significant.



## 4. Numerical Simulations

In order to evaluate the feasibility of the retrofitting technique in non-engineered confined masonry dwellings, a series of representative structures and their corresponding retrofitted versions are simulated under earthquakes ground motions considering probabilistic seismic hazard of Metropolitan Lima Area.

### 4.1 Experimental database

In this article, experimental results of six specimens are presented. Additionally, two experimental studies on confined masonry walls where the retrofitting technique was applied of both faces of walls are complementing the experimental results in order to analyze the improvement of earthquake resistant capacity. Complementing studies consist of one series of retrofitted confined masonry walls [3] and one series of rehabilitated confined masonry where cement-sand mortar covered existing cracks [4]. In the last series of tests, walls were previously tested until they reached a drift of 0.005. All experimental results are oriented to calculate the strength of confined masonry wall when steel mesh and cement-sand mortar are applied.

Capacity curves of confined masonry structures can be represented by tetra-liner curves, which are defined by four states [7,8], which represent the cracking (C), yielding (Y), maximum (M) and ultimate (U) states. In this sense, Table 3 and Table 4 show values of average drifts and average shear stress of walls using handmade solid bricks and tubular bricks, respectively.

Table 3 – Typical behavior of retrofitted confined masonry walls using handmade solid bricks

| Wall condition | Drift ($x10^{-3}$) | | | | Average shear stress (MPa) | | | |
|---|---|---|---|---|---|---|---|---|
| | (C) | (Y) | (M) | (U) | (C) | (Y) | (M) | (U) |
| Un-retrofitted | 0.4 | 1.1 | 3.5 | 6.7 | 0.26 | 0.40 | 0.51 | 0.45 |
| One-face retrofitted | 0.5 | 1.3 | 5.0 | 6.1 | 0.34 | 0.56 | 0.86 | 0.69 |
| two-face retrofitted | 0.7 | 2.0 | 5.1 | 7.5 | 0.47 | 0.70 | 0.87 | 0.76 |

Table 4 – Typical behavior of retrofitted confined masonry walls using tubular bricks

| Wall condition | Drift ($x10^{-3}$) | | | | Average shear stress (MPa) | | | |
|---|---|---|---|---|---|---|---|---|
| | (C) | (Y) | (M) | (U) | (C) | (Y) | (M) | (U) |
| Un-retrofitted | 0.4 | 0.8 | 1.5 | 2.3 | 0.32 | 0.42 | 0.47 | 0.38 |
| One-face retrofitted | 0.5 | 1.3 | 1.8 | 2.6 | 0.36 | 0.62 | 0.72 | 0.66 |
| two-face retrofitted | 0.5 | 1.3 | 3.9 | 6.3 | 0.38 | 0.59 | 0.82 | 0.68 |

### 4.2 Representative dwellings

Technical Standard of Masonry Structures [6] establishes minimum values of wall density according seismic demand prescribed in Peruvian Earthquake Resistant Standard . Minimum values of wall density for Metropolitan Lima Area are as follows: 0.8%, 1.7%, 2.5%, 3.4% and 4.2%, corresponding to dwellings with one, two, three, four and five stories. Additionally, Technical Standard of Masonry Structures establishes that dwellings, within the highest earthquake prone zone like Metropolitan Lima Area, up to three stories may use solid bricks in first two floors, while tubular bricks must not be used at all,.

The representative dwellings consist of 14 typologies which were identified in survey from hazard, vulnerability and risk studies conducted by CISMID. These typologies present different characteristics such as, number of stories and types of bricks (one or two types in one dwelling), as described in Table 5. Besides, each typology presents 3 different plant distribution or wall density (1.7%, 2.3% and 2.9%).

The improvement of seismic capacity by the application of this retrofitting technique was demonstrated from results of numerical simulations in one calibrated mathematical model based on one full-scale two-story un-retrofitted dwelling tested under cyclic loadings [3]. In that study, the retrofitting of dwellings was simulated in the first floor only, and the damage level was reduced from collapse to moderate damage under severe seismic demand in Metropolitan Lima Area, corresponding to 475 years of average return period. In this article, studied structures simulated their retrofitting according the following criteria: (1) all walls in one face, (2) all walls in two faces, and (2.1) two faces of walls in first floors and one face of walls in higher floors, as described in Table 5. Thus, a series of 45 un-retrofitted and retrofitted structures are analyzed, each series consists of 3 values of wall density.

Table 5 – Description of target structure and retrofitting criteria

| | Target structure | Retrofitting criteria | | |
|---|---|---|---|---|
| | | a) | b) | c) |
| 1 | 1ML1 | 1ML1 R (1) | 1ML1 R (2) | - |
| 2 | 1ML2 | 1ML2 R (1) | 1ML2 R (2) | - |
| 3 | 2M2L1 | 2M2L1 R (1.1) | 2M2L1 R (2.1) | 2M2L1 R (2.2) |
| 4 | 2ML1.L2 | 2ML1.L2 R (1.1) | 2ML1.L2 R (2.1) | 2ML1.L2 R (2.2) |
| 5 | 2M2L2 | 2M2L2 R (1.1) | 2M2L2 R (2.1) | 2M2L2 R (2.2) |
| 6 | 3M2L1.L2 | 3M2L1.L2 R (2.2.1) | 3M2L1.L2 R (2.2.2) | - |
| 7 | 3ML1.2L2 | 3ML1.2L2 R (2.2.1) | 3ML1.2L2 R (2.2.2) | - |
| 8 | 3M3L2 | 3M3L2 R (2.2.1) | 3M3L2 R (2.2.2) | - |
| 9 | 4M2L1.2L2 | 4M2L1.2L2 R (2.2.2.1) | 4M2L1.2L2 R (2.2.2.2) | - |
| 10 | 4ML1.3L2 | 4ML1.3L2 R (2.2.2.1) | 4ML1.3L2 R (2.2.2.2) | - |
| 11 | 4M4L2 | 4M4L2 R (2.2.2.1) | 4M4L2 R (2.2.2.2) | - |
| 12 | 5M2L1.3L2 | 5M2L1.3L2 R (2.2.2.1.1) | 5M2L1.3L2 R (2.2.2.2.2) | - |
| 13 | 5ML1.4L2 | 5ML1.4L2 R (2.2.2.1.1) | 5ML1.4L2 R (2.2.2.2.2) | - |
| 14 | 5M5L2 | 5M5L2 R (2.2.2.1.1) | 5M5L2 R (2.2.2.2.2) | - |

Notes:

- Identification of target structure, for examples 3ML2, means a three-story dwelling using tubular bricks.
- Identification of retrofitted structure, for examples 4M2L1.2L2 R(2.2.2.1), means a four-story dwelling where two firsts floors (first and second floor) are using handmade solid bricks and two higher floors (third and fourth floor) are using tubular bricks; and they are retrofitted on two faces of walls in first, second and third floor, while it is retrofitted on one face of walls in fourth floor.

## 4.3 Numerical modeling

Simulations are performed using nonlinear time-history analysis in 3 series of 45 structures, each series consists in masonry wall density of 1.7%, 2.3% and 2.9%, resulting in 135 structures. Confined masonry walls are represented by shear springs; where primary curves and hysteresis models are represented by tetra-linear models which are calibrated using formulations based on experimental results proposed by Diaz et al. in 2019 [7] for un-retrofitted walls, and using an experimental database described above in this article.

The quake catalog used in this study consists of Lima 1966, Huaraz 1970, Lima 1974, Pisco 2007, Atico 2001 and Lagunas 2019 earthquake records and one synthetic quake for expecting scenario in a rigid soil of Lima [1]. These quakes are calibrated to reach 6 seismic demands according Table C2-1 of ASCE41-13 "Seismic Evaluation and Retrofit of Existing Buildings". In this article, these seismic demands are named as follows: very slight, slight, moderate, severe, rare and very rare, which represents an average return period of 43, 72, 225, 475, 975 and 2475 years, respectively. The probabilistic seismic hazard is proposed by Aguilar in 2017 [9]. Quakes are amplified using the response spectrum according considerations stablished in the Peruvian Earthquake Resistant Standard of 2018 [10]; it results in the following ranges of PGA: 150 to 200 gals, 200 to 250 gals, 250 to 400 gals, 400 to 550 gals, 550 to 750 gals and 750 to 1000 gals for very slight, slight, moderate, severe, rare and very rare seismic demands, respectively.



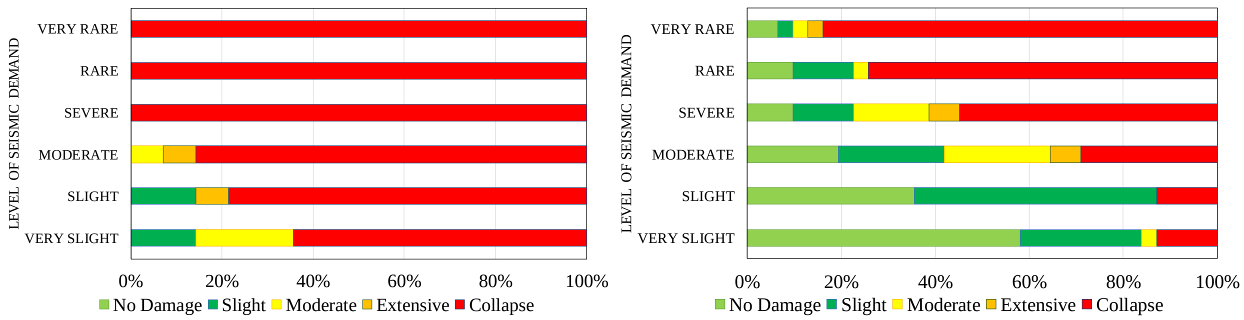
### 4.4 Results

A total of 5670 numerical simulations were performed in order to analyze the feasibility of this retrofitting technique in non-engineered confined masonry dwellings. Based on these results, the observed behavior is described as follows:

- Un-retrofitted dwellings higher than two stories, with 1.7% of wall density, collapsed under moderate seismic demand. While, un-retrofitted dwelling higher than two stories, with 2.3% and 2.9% of wall density, collapsed under severe seismic demand.
- Dwellings higher than two stories with all walls retrofitted on both faces, with 1.7% of wall density, collapsed under very rare seismic demand. Retrofitted dwellings higher than four stories with this form of retrofitting, with 1.7% of wall density, collapsed under severe seismic demand. While, this form of retrofitting applied in one-story dwellings prevented collapse under very rare seismic demand.
- Dwellings up to two stories, with 2.3 and 2.9% of wall densities, prevented collapse under very rare earthquake.
- Dwellings up to four stories with all walls retrofitted on both faces, in all cases of wall density, prevented collapse under severe seismic demand.
- Dwellings up to one story in all cases of wall density, where all walls were retrofitted on one face prevented collapse under very rare seismic demand.
- Dwellings up to four stories, in all cases of wall density, where walls were partially retrofitted on two faces in first floors and one face in upper floors prevented collapsed under severe seismic demand. These retrofitted dwellings up to two stories prevented collapsed under very rare seismic demand.
- Retrofitted dwellings present much more critical damage when walls are constructed with tubular bricks.
- In the most of cases, un-retrofitted or retrofitted dwellings presented more damages when walls with solid bricks were changed by walls with tubular bricks floor-to-floor; because it resulted in a great change of lateral resistance (stiffness, strength and ductility).

A characterization of non-engineered confined masonry dwellings in Metropolitan Lima Area to obtain a statistical distribution of each involved parameter, such as geometry of walls, wall density, distribution of types of bricks and material properties, is very complex. Since, it needs to realize thousands of inhouse technical survey of a sample which results in large consumption of resources. However, typical dwellings based on technical inhouse survey within one representative district of Metropolitan Lima Area and their corresponding retrofitted versions, shown in Table 5, are considered as taxonomy of non-engineered confined masonry walls in this study.

The damage level of un-retrofitted and retrofitted dwellings shown in Fig. 9, Fig. 10 and Fig. 11 represents a critical scenario in order to evaluated the feasibility of the massive implementation of the target retrofitting technique; since, simulated dwellings are constructed with non-engineered bricks and values of wall density taken in this study are less than minimum values established in Peruvian standards.

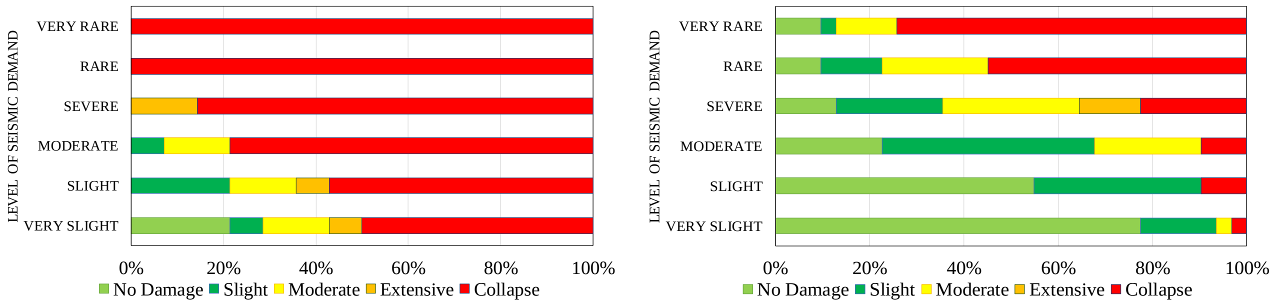



Un-retrofitted dwelling Retrofitted dwelling

Fig. 9 – Damage level in dwellings with wall density of 1.7%

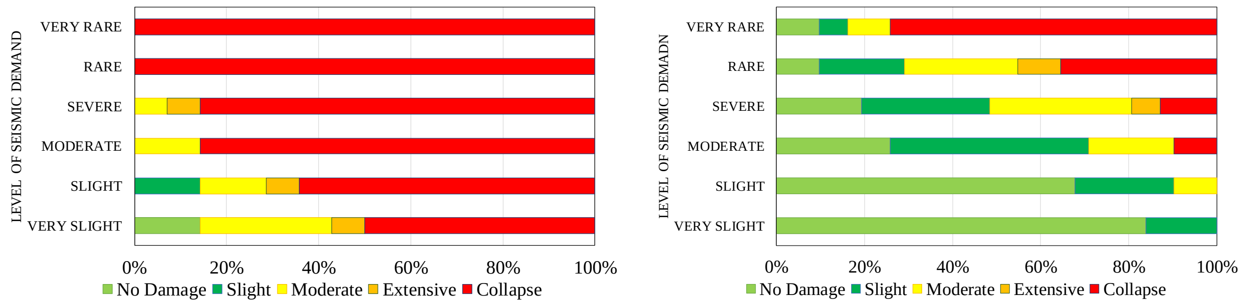





Un-retrofitted dwelling Retrofitted dwelling

Fig. 10 – Damage level in dwellings with wall density of 2.3%




Un-retrofitted dwelling Retrofitted dwelling

Fig. 11 – Damage level in dwellings with wall density of 2.9%

Retrofitted dwellings with 1.7% of wall density prevented collapse in 45% and 16% under severe and very rare demands, respectively. It is quite significant since 100% of un-retrofitted dwellings with this wall density collapsed under these demands. Moreover, retrofitted dwellings with 2.3% of wall density prevent collapsed in 77% and 26% under severe and very rare demands, respectively; and retrofitted dwellings with 2.9% of wall density prevent collapsed in 87% and 27% under severe and very rare demands, respectively.

## 5. Conclusions

One retrofitting technique is studied in this paper, which mainly uses steel-mesh and cement-sand mortar for increasing thickness of confined masonry walls on one face and two faces. Two types of masonry bricks are studied, namely handmade solid and tubular bricks.

The increment of deformation at maximum strength is slight significant in one-face retrofitted wall constructed with tubular bricks. Consequently, the proposed retrofitting technique increases ductility of the non-engineered confined masonry walls when they are constructed with solid bricks and retrofitted on one or two faces; and when they are constructed with tubular bricks and retrofitted on two faces.

Retrofitted walls on one face presented a slight increment of ductility. It can be handled for walls constructed with solid bricks; nevertheless, it keeps critical in walls constructed with tubular bricks. However, walls constructed with solid or tubular bricks retrofitted on both faces behaved quite similar until they reach their ultimate state; and the improvement of their strength and ductility is quite significant.

It was observed on numerical simulations that walls constructed with tubular bricks, even when they are one-face retrofitted, present critical damage, in this sense, retrofit of dwellings shall consider two-face retrofitting when walls with tubular bricks exist.



In the case of dwellings constructed with solid bricks, the retrofit may be applied in one and two faces of walls. Dwellings up to two stories may consider retrofitting on one face of walls. In all cases, dwellings higher than two stories may consider walls with two faces retrofitted in two firsts floors.

Un-retrofitted or retrofitted dwellings presented more damages when walls with solid bricks were changed by walls with tubular bricks floor-to-floor. In this sense, this type of irregularity must have special considerations.

Analyzed retrofitted dwellings constructed with non-engineered confined masonry walls considered 1.7%, 2.3% and 2.9% of wall density. Dwellings up to four stories retrofitted on two faces of walls behaved adequately under severe seismic demand; exceeding expectations of Peruvian Standard of Masonry Structures, because minimum values of wall density established in the standard are greater than values used in this study, even when these minimum values are supposed to be considered for dwellings with engineered confined masonry walls. However, these dwellings must increment their wall density in order to prevent collapse under very rare seismic demand.

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