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EXPERIMENTAL STUDY OF NON-ENGINEERED CONFINED MASONRY WALLS RETROFITTED WITH WIRE MESH AND CEMENT-SAND MORTAR

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Abstract

The Peruvian standards for design of earthquake resistant buildings prescribe minimum requirements to ensure safety of life of inhabitants. Nevertheless, the lack of supervision resulted in the increase of non-engineered masonry dwellings. Nowadays, non-engineered masonry represents about 60% of buildings in Lima, according to the National Institute of Statistics and Informatics of Peru (INEI). This construction system is highly vulnerable to earthquakes and, consequently, most Peruvian citizens live under unacceptable seismic risk. In that sense, it is desirable to provide low-cost retrofitting techniques which require low-complexity construction to improve seismic capacity of confined masonry dwellings for less advantaged economic sectors.

Confined masonry walls with the proposed retrofitting technique were tested for the purpose of studying its inelastic behavior by cyclic loading test. Two types of bricks are considered in this study, namely handmade solid bricks and industrial tubular bricks, both are fired clay bricks and massively used in urban areas. Experimental results are compared to study the improvement of the seismic capacity of confined masonry walls retrofitted with the proposed technique. Results showed that strength and ductility can be significantly increased by retrofitting with the proposed technique.

Also, in order to verify the improvement of the seismic capacity of non-engineered dwellings using the proposed retrofitting technique, numerical simulations are conducted using nonlinear time-history analyses. These numerical simulations are performed using analytical models calibrated with experimental results to represent the inelastic behavior of those structures under representative earthquake records.

Keywords: confined masonry, retrofitting, wire mesh

1. Introduction

Peru is located in highly seismic region on the world, called the Ring of Fire. A few severe earthquakes occurred in Lima in twentieth century, which resulted in harmful consequences. In case of dwellings, most adobe structures collapsed, while burnt-clay masonry structures remained standing. Thereafter, people accepted that burnt-brick masonry structures are stronger and more suitable for earthquake prone areas, so its use was massively extended in the country. It has been widely demonstrated during seismic events, and experimental and numerical studies that confined masonry walls can be earthquake-resistant structures [1], [2], [4], [3], [5]; and, design procedures are prescribes in standards and codes. Nevertheless, in the last decades, owners from less advantaged sectors hired nonqualified builders; consequently, masonry dwellings were built without any earthquake design criteria using low-quality materials in places with unfavorable site conditions.

The most representative masonry walls of these confined masonry dwellings, shown in Fig. 1, are made of industrial hollow bricks (less than 20% of hollow area), handmade solid bricks and industrial tubular bricks. The last type is supposed to be used for partition walls only, because of its low.

Generally, in non-engineered confined masonry dwellings, walls in first floors are composed of solid bricks, while the walls in upper floors are composed of tubular bricks. The concept of these structures is based on less weight in upper floors, considering gravity loads only. As mentioned above, Peru has several earthquake prone areas, such as its capital, Lima. Consequently, dwellings must be designed as earthquake-resistant structures. Also, there are dwellings in which structural walls are made only from tubular bricks. It is known that walls made from tubular bricks have low lateral load capacity, and their failure mode is brittle; even if it has confinement [6], [7]. For that reason, tubular bricks are not permitted for construction of structural walls according to Peruvian Standards. Besides, masonry structures shall be up to five stories high. Nevertheless, number of stories is exceeded in some areas because of the lack of control; this results in structures with high seismic vulnerability.

The Peruvian standards for earthquake resistant buildings and masonry structures, NTE-E030-2016 [8] and NTE-E070-2006 [3], respectively, prescribe minimum requirements to ensure safety of life of inhabitants, nevertheless, the lack of supervision resulted in the increase of non-engineered masonry dwellings. Nowadays, this kind of construction systems represents about 60% of buildings in Lima [9], especially in less advantaged sectors of the society who occupy the suburbs of Lima. In that sense, it is desirable to provide low-cost retrofitting techniques which require low-complexity construction, in order to improve the seismic capacity of confined masonry dwellings for less advantaged sectors.

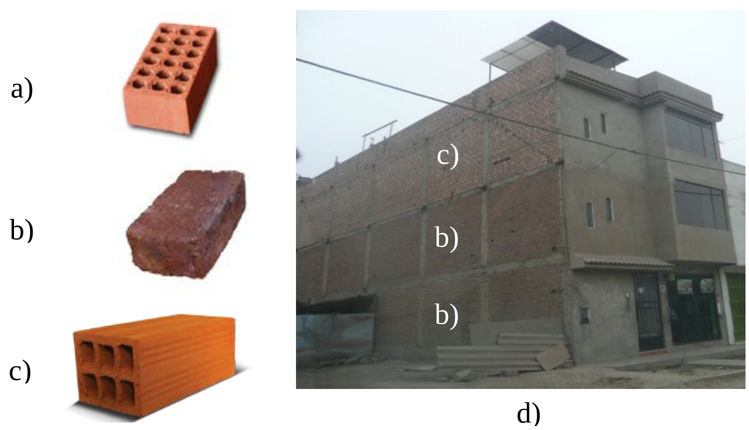


Fig. 1 – Types of bricks used in non-engineered confined masonry dwellings: a) hollow, b) solid c) tubular bricks d) Solid bricks used in first floor and tubular bricks in upper floors.

An investigation was carried out in 2003 to study the behavior of a non-engineered masonry dwelling subjected to a severe earthquake. In this study, one full-scale two-story masonry dwelling was tested under unidirectional static cyclic loading (Zavala, Kaminosono et al., 2003) [5], as shown in Fig. 2. This specimen was built using a representative handmade masonry bricks collected from rural areas. The maximum loading capacity occurred at 1.5% drift.

Before After

Fig. 2 – Full scale test of two-story non-engineered masonry dwelling (Zavala et al., 2003) [5]

Later on, another investigation was carried out in 2009 to study the behavior of a rehabilitated masonry dwelling. Thus, the specimen tested in 2003 was rehabilitated using a practical technique in order to be tested once again (Zavala et al., 2009), as shown in Fig. 3. The technique to rehabilitate this specimen utilized wire-mesh and cement-sand mortar, and it consisted of placing the wire-mesh of 100x100mm and 4.2 mm diameter along the crack on one side of the masonry wall, and then fixing it to the masonry wall with wire of diameter 1.65 mm. Finally, the wall surface was covered by a cement-sand mortar with ratio 1:4. It was observed from the experimental results that the maximum load in 2009-test (rehabilitated) was 75% and 56% of 2003-test for loading and unloading, respectively [10]. Fig. 4 shows the full-scale test of the rehabilitated dwelling. On the other hand, in the last decade, wire-mesh began to be widely used for reinforcing thin RC walls, called limited ductility wall, because of its thickness and ease of handling. Nevertheless, its usage must be limited according to some studies [11], [12].

Fig. 3 – Rehabilitation of two-story non-engineered masonry dwelling [10]

Before After

Fig. 4 – Full-scale test of two-story non-engineered masonry dwelling [10]

The technique applied in the 2009 test was improved based on the observed behavior of the rehabilitated dwelling. One of the recommendations of the previous investigation (Zavala et al., 2009) [10] was that wire mesh shall be extended to the confinement (tie-columns and tie-beam).

In this paper, a retrofitting technique is proposed that mainly uses wire-mesh and cement-sand mortar for increasing of the thickness of confined masonry walls. The proposed retrofitting technique consists of fixing the wire mesh to the foundation through dowels, and from one face to another face of the wall including the confinement. Then, the fixed wire mesh is covered by the cement-sand mortar until reaching 25 mm mortar thickness on each face, approximately.

Two types of fired clay bricks are considered in this study, namely handmade solid bricks and industrial tubular bricks. Masonry components with the proposed retrofitting technique are tested to study the behavior of retrofitted walls. Compression test of masonry prisms, diagonal tension test of masonry assemblages, and cyclic loading test on confined masonry walls were conducted [13].

Experimental results are compared to study the improvement of the seismic capacity of confined masonry walls with the proposed retrofitting technique. Also, numerical simulations are conducted in order to validate the improvement of the seismic capacity of non-engineered dwellings using the proposed retrofitting technique.

2. Proposed retrofitting technique

The proposed retrofitting technique applied in this investigation consisted of placing the wire mesh on both sides of masonry wall, including tie-columns and tie-beam as confining elements; and then covering with cement-sand mortar with mix proportion 1:4 with 22.5 mm thickness on both sides. Fig 5 shows the construction procedure for the proposed retrofitting technique.

The wire mesh of 100x100mm size and 4.2 mm diameter (commercially named Q-139) is fixed to the masonry wall through diameter 1.65 mm wire at 200 mm spacing, in horizontal and vertical directions using drill. Vertical rebar dowels of 6 mm diameter are used to connect the wall reinforcement to the existing structure. Dowels are extended a minimum of 150 mm into the wall reinforcement and be hooked to footing, slabs or beams at each 200 mm for fixing the wire mesh.

Fig. 5 – Application of retrofitting technique on confined masonry walls

3. Cyclic loading test

3.1 Specimens

Two types of clay bricks are considered for testing, as presented in Table 1, namely handmade solid bricks and industrial tubular bricks. Four wall specimen were constructed, as follows:

- Two confined masonry wall made of solid handmade bricks. Without and with retrofitting.
- Two confined masonry wall made of industrial tubular bricks. Without and with retrofitting.

The confinement of masonry walls consisted of RC tie-columns and tie-beam. The length of the tie-columns was 200mm, the height of 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, and stirrups #1 with the following distribution: 1@50mm, 4@100mm and then @250mm. Moreover, the specimen had a foundation for connecting to the reaction floor; with the cross section 900mmx300mm, and the length of 3200mm. The confined masonry walls had a total height of 2500mm and a width of 2400mm, as shown in Fig. 7. The compressive strength of concrete was 17 MPa, the compressive strength of mortar was 14 MPa, and the yield strength of steel bars was 420 MPa. Besides, a series of six masonry prisms of each type of clay bricks were tested. The average compressive strength was 3.5 MPa and 2.2 MPa for handmade solid and tubular bricks, respectively [13].

Table 1 – Characteristic of specimens

ID	Brick unit	Wall thickness mm	Wall thickness after retrofitting mm	Axial load in kN (average axial stress in MPa)
MART	Handmade solid un-retrofitted	117	117	200 (0.71)
MTUB	Industrial tubular un-retrofitted	111	111	100 (0.38)
MART-R	Handmade solid retrofitted	117	162	200 (0.51)
MTUB-R	Industrial tubular retrofitted	111	156	100 (0.27)

3.2 Test setup

The test setup consisted of four hydraulic static jacks, with the 500 kN loading capacity of each jack and a stroke of +/- 250 mm. Two jacks applied simultaneously lateral cyclic loading to simulate the seismic load, while other two jacks applied vertical loading to simulate the gravity load due to upper floors. The displacement protocol used in tests is shown in Fig. 6.

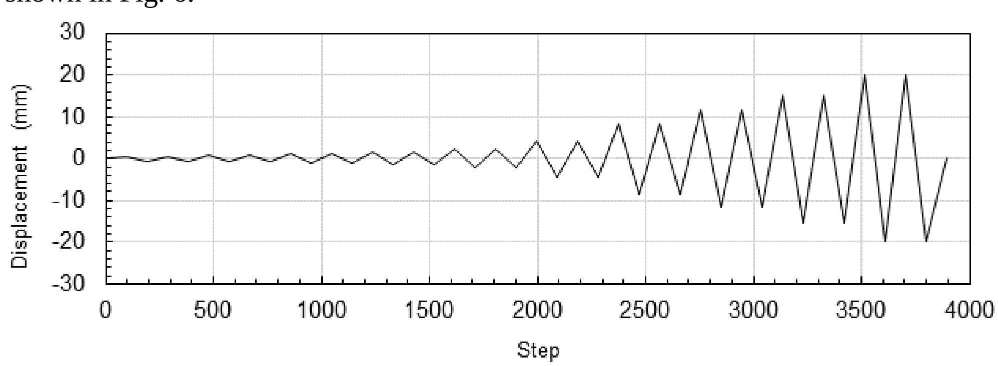
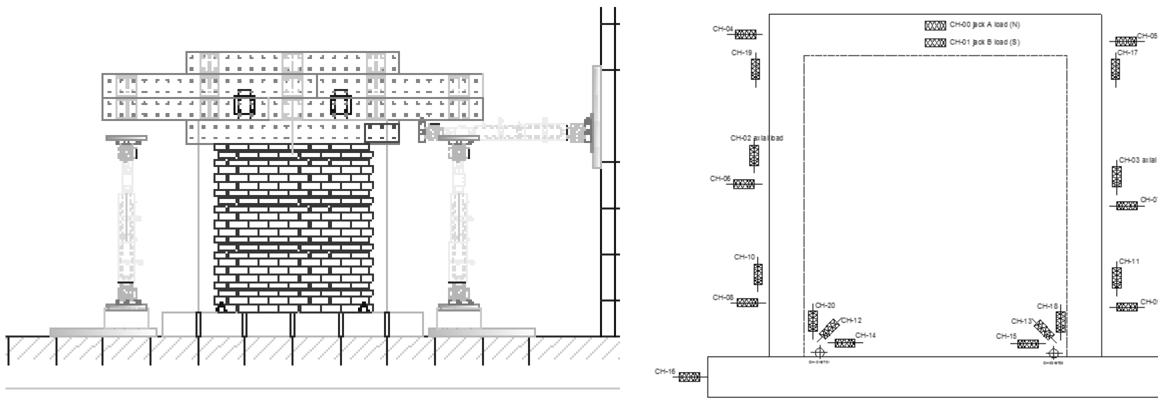


Fig. 6 – Loading displacement for lateral cyclic loading tests

Horizontal jacks were supported by the reaction wall and connected to an assemblage of steel frames for loading transfer, as shown in Fig. 7. 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-20), as shown in Fig. 7.

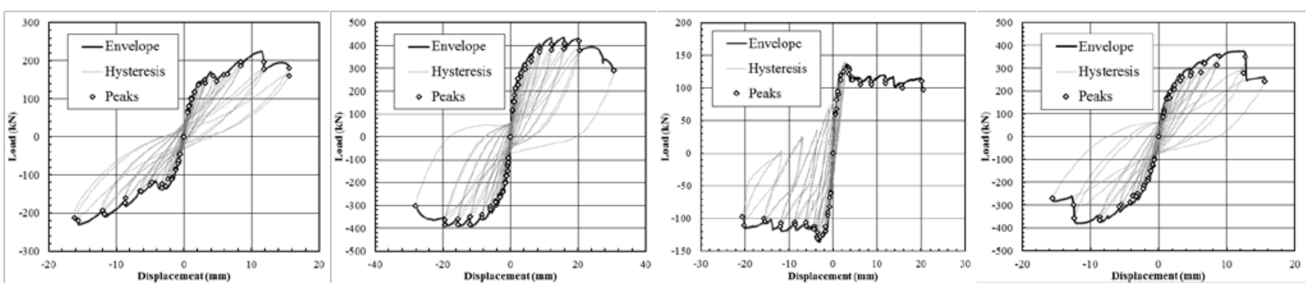


Loading system for cyclic loading tests   Measuring system for cyclic loading tests

Fig. 7 – Test setup

3.3 Test results

Fig. 8 shows load-displacement hysteresis curves from lateral cyclic loading tests for un-retrofitted specimens (MART, MTUB) and retrofitted specimens (MART-R and MTUB-R).



MART   MART-R   MTUB   MTUB-R

Fig. 8 – Hysteresis curves

The target amplitudes were reached twice, because two consecutive cycles of the same amplitude were applied. The skeleton curves were obtained using peaks of the cycles of the repeated target amplitude, as shown in Fig. 9.

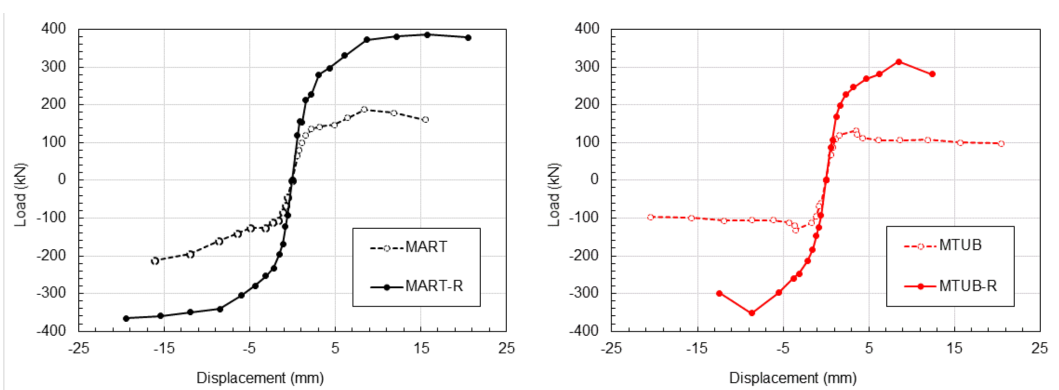


Fig. 9 – Skeleton curves

Capacity curves are expressed in terms of average shear stress (including vertical confinement) and drift for the purpose of comparing un-retrofitted and retrofitted walls, as shown in Fig. 10.

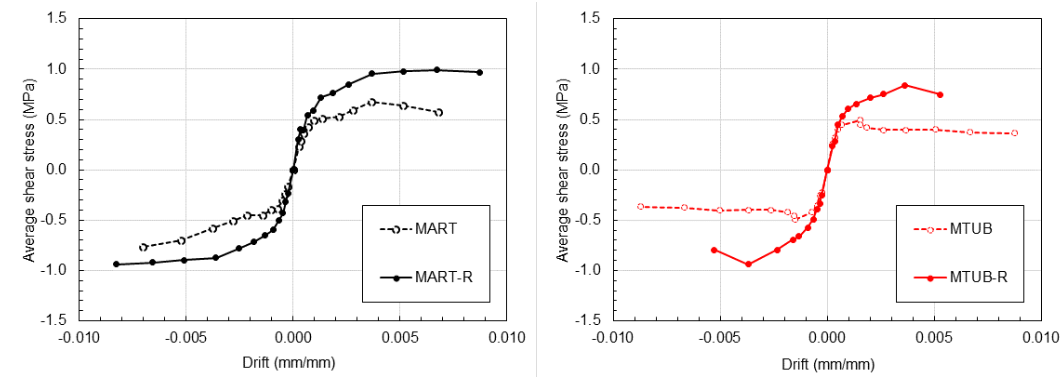


Fig. 10 – Capacity curves in terms of average shear stress and drift

Table 2 shows average values of displacement and load at cracking, yielding and maximum states. The maximum strength of un-retrofitted walls were 188 kN and 129 kN, for handmade solid and industrial tubular bricks, respectively; while maximum strength of retrofitted walls were 398 kN and 334 kN, for handmade solid and industrial tubular bricks, respectively. It is observed that the retrofit has significant effect on the strength of the masonry wall. Also, the proposed retrofitting technique increased ductility of the non-engineered confined masonry walls, even for masonry made of tubular bricks.

Table 2 – Comparison of experimental results

State	MART (F)		MART-R (F)		MTUB		MTUB-R	
	Disp. (mm)	Load (kN)	Disp. (mm)	Load (kN)	Disp. (mm)	Load (kN)	Disp. (mm)	Load (kN)
Cracking	0.8	80	2.2	255	1.1	94	1.2	169
Yielding	2.2	136	8.7	386	1.7	120	3.2	246
Maximum	8.4	188	15.8	398	3.6	129	8.5	334

Table 3 presents the maximum average shear stress for each confined masonry wall, both un-retrofitted and retrofitted, and drift at the time it is reached. The average shear stress was increased in 0.35 MPa and 0.41 MPa in walls made of handmade solid and industrial tubular bricks, respectively. It is important to note that the average shear stress for earthquake-resistant confined masonry walls is 0.5 MPa, approximately.

The increase in the average shear strength due to the retrofitting is similar for walls with handmade solid and industrial tubular bricks (0.4 MPa approximately), because the added mortar layer on each face of the confined masonry wall is the same. The maximum average shear strength was increased by 53% and 84%, in walls made of handmade solid and industrial tubular bricks, respectively. On the other hand, drift at the time of the maximum average shear stress is also significantly increased; drift ratio was increased by 88% and 136% in walls made of handmade solid and industrial tubular bricks, respectively. In the case of walls made of industrial tubular bricks, the increase in deformation capacity is critical for avoiding a severe damage. This represents the improvement of life safety conditions.

Table 3 – Comparison of maximum average shear strength

specimen	MART	MART-R	MTUB	MTUB-R
Average shear stress (MPa)	0.67	1.02	0.48	0.89
Drift ratio (%)	0.36	0.67	0.15	0.36

4. Numerical simulations

4.1 Target dwelling

The confined masonry dwelling described in Section 1 (the target dwelling) is used to conduct numerical simulations, with the purpose of verifying the improvement of the seismic capacity of non-engineered dwellings using the proposed retrofitting technique. Walls of the target dwelling are made of handmade solid bricks. The plan view of this structure is shown in Fig. 11.

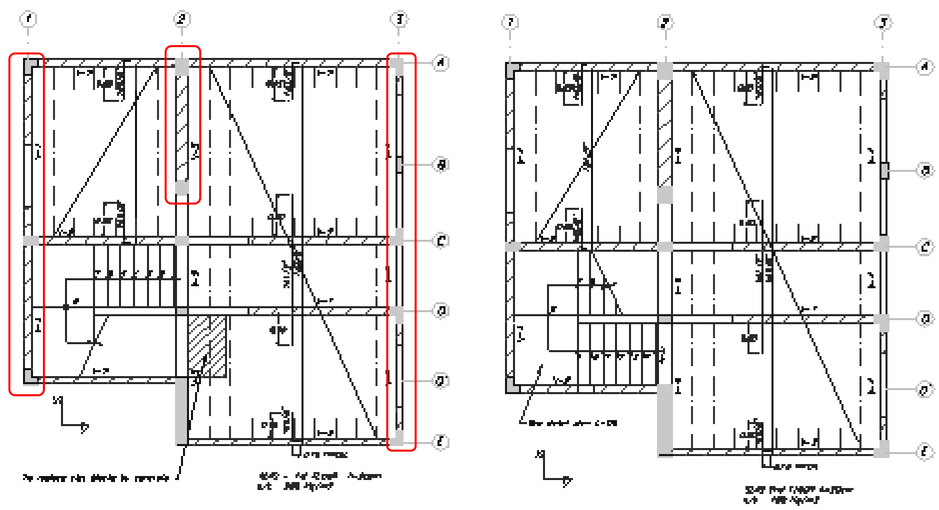
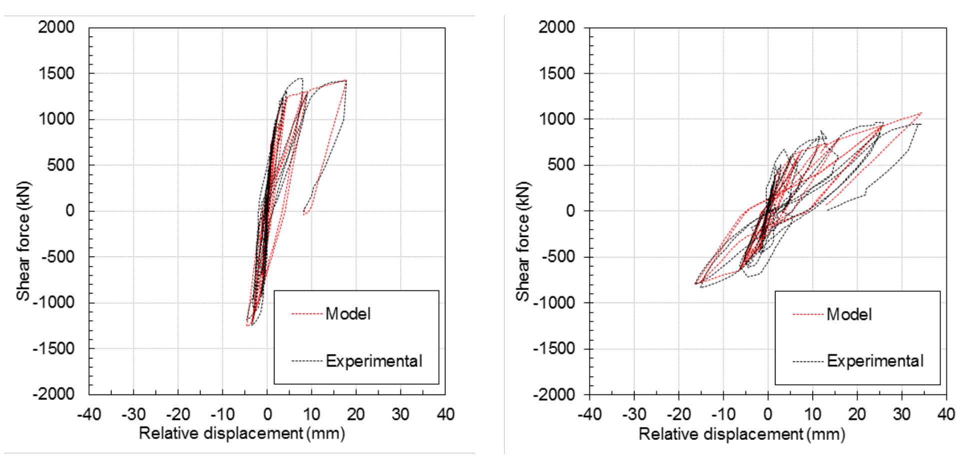


Fig. 11 – Plan view of target dwelling

The target dwelling is retrofitted using the proposed technique in Direction X, described in Section 2. Confined masonry walls along axes 1, 2 and 3 at the first floor are retrofitted (shown enclosed by rectangles in Fig. 11).

4.2 Numerical modeling

Numerical simulations are performed using nonlinear time-history analysis of the target dwelling. Shear springs were used to represent the inelastic behavior of confined masonry walls. The primary curve is trilinear and the hysteresis curve is approximated by the Modified Takeda model which considers softening and hardening. Primary curve and hysteretic parameters were set according to experimental results to calibrate the model and then approximate the actual response, as shown in Fig. 12.



Level-1 Level-2

Fig. 12 – Hysteresis curves for un-retrofitted target dwelling

Earthquake records are amplified using response spectrum according to Peruvian Standards for Earthquake-resistant Design (NTE E030-2016), which prescribe that the elastic response spectrum between 0.2 and 1.5 of natural period shall be equal or greater than the response spectrum obtained using the amplified earthquake record for horizontal components. The elastic response spectrum established for analyses corresponds to the highest seismicity zone of Peru (Z4) and a soil with shear-wave velocity between 180 m/s and 500 m/s. Four earthquake records are selected, namely: Lima 1966, Lima 1974, Atico 2001 and Pisco 2007, and one synthetic wave in intermediate soil for Lima Earthquake Scenario (Mw8.9) elaborate by Pulido [13] under SATREPS Project, as shown in Fig. 13. The maximum pseudo acceleration is 0.47g for the assumed conditions according to NTE E030-2016, and the average PGA of the amplified waves is approximately 0.55g.

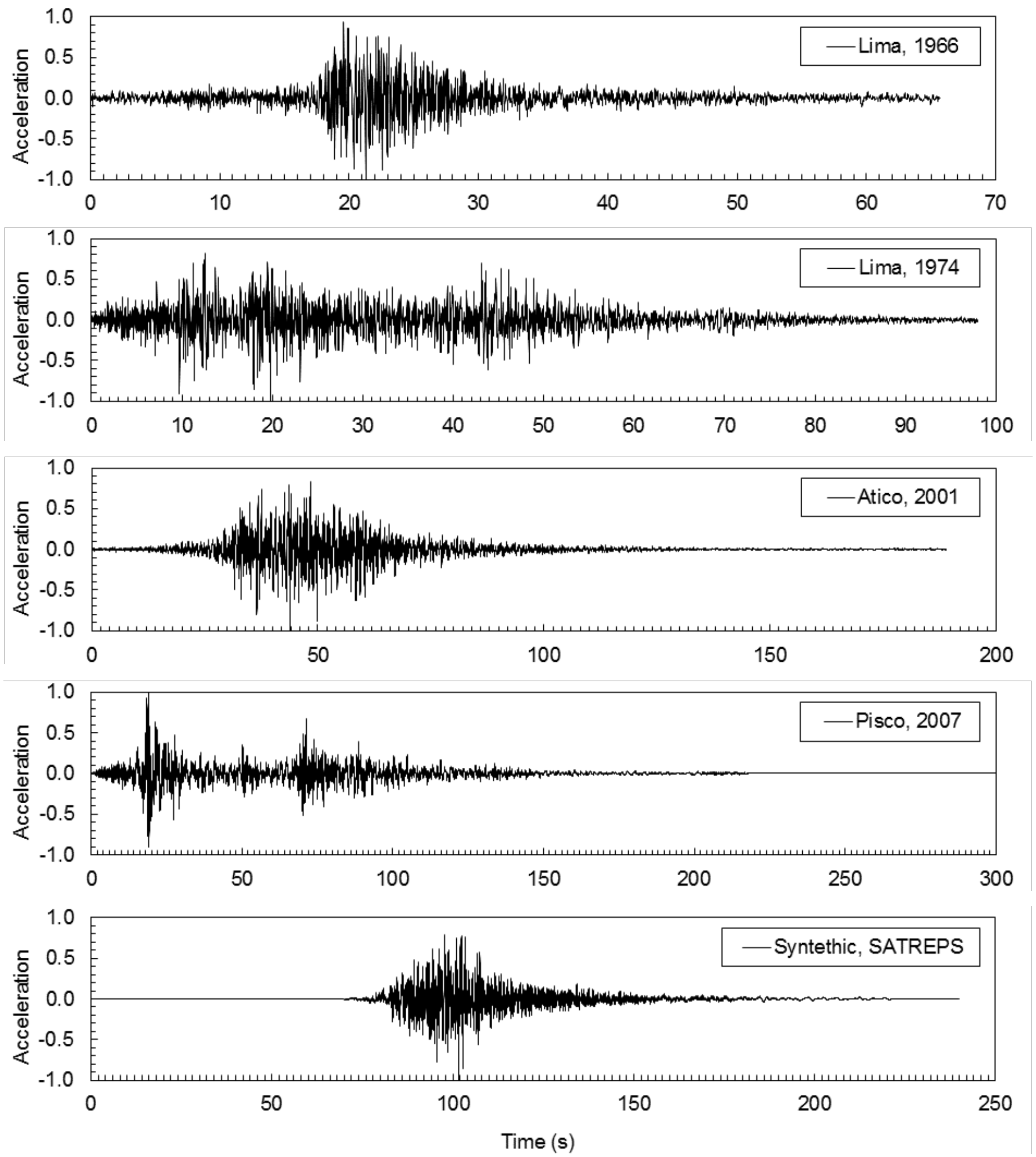


Fig. 13 – Normalized ground input motions

The total weight of the un-retrofitted target dwelling is 1170 kN and the predominant period of the direction of analysis (Direction X) is approximately 0.1 s. The area of each floor is approximately 54 m^2.

4.3 Results

Fig. 14 shows the maximum response of un-retrofitted target dwelling under the input ground motions mentioned above. The maximum drift obtained in the first and the second level is 0.66% y 0.71%, respectively. The average drift is 0.29% and 0.48% of the first and the second level, while the average base shear force is 1244 kN. The maximum drift for the un-retrofitted target dwelling exceeds the limit of 0.63% for masonry structures established in the NTE E030-2016 which corresponds to 1.25×0.5%.

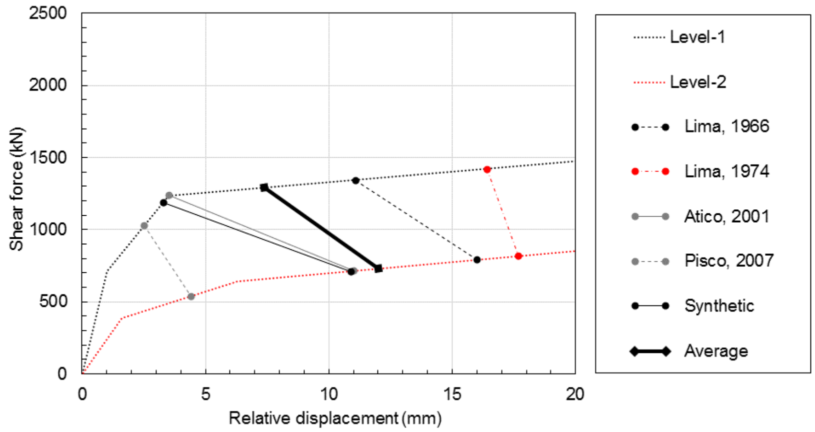


Fig. 14 – Maximum response of un-retrofitted target dwelling

Given that the target dwelling must be retrofitted under the assumed conditions described above, the proposed retrofitting technique is applied to walls of the first level only. Thus, experimental results shown in Fig. 10 were used to idealize the retrofitted walls made of handmade solid bricks. Fig. 15 shows the maximum response of the retrofitted target dwelling under the input ground motions shown in Fig. 13. The maximum drift obtained in the first and the second level is 0.06% and 0.30%, respectively. The average drift is 0.05% and 0.22% for the first and the second level, while the average base shear force is 1011 kN. The maximum drift of the un-retrofitted target dwelling is less than the limit for masonry structures established in the NTE E030-2016.

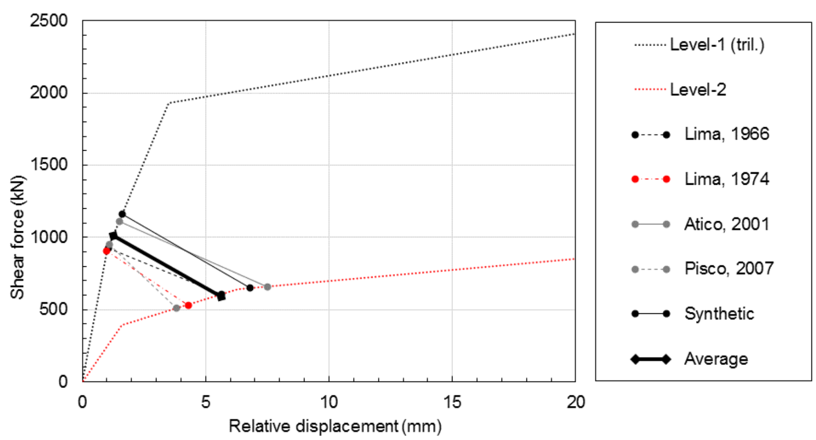


Fig. 15 – Maximum response of retrofitted target dwelling

5. Conclusions

The proposed retrofitting technique is described in the paper, which mainly uses wire-mesh and cement-sand mortar for increasing thickness of confined masonry walls.

An experimental program is shown which consists of four cyclic loading tests. Two types of bricks were used, namely handmade solid bricks and industrial tubular bricks, which are the most representative of non-engineered dwellings in Peru. The maximum shear strength is increased by 0.35 MPa and 0.41 MPa in walls made of handmade solid and industrial tubular bricks, respectively.

The increase in the average shear strength due to the proposed retrofitted technique is similar for handmade solid and industrial tubular bricks (0.4 MPa approximately), due to the same thickness of added layer on each face of the wall. The maximum average shear stress were increased by 53% and 84% for walls made of handmade solid and industrial tubular bricks, respectively. The drift at the time of the maximum average shear stress is also significantly increased; by 88% and 136% for walls made of handmade solid and industrial tubular bricks, respectively.

Numerical simulations used four earthquake records and one synthetic wave. The average PGA of amplified waves is approximately 0.55g, which corresponds to the highest seismicity zone of Peru and an intermediate soil type. The maximum drift obtained in the first and the second level of the un-retrofitted target dwelling is 0.66% and 0.71%, respectively. These values exceeded the limit for masonry structures established by the NTE E030-2016.

The target dwelling has retrofitted confined masonry walls at the first level. Numerical simulations showed that the maximum drift obtained in the first and the second level is 0.06% and 0.30%, respectively, which are less than the limit for masonry structures established by the NTE E030-2016.

The improvement of the lateral load-resisting capacity of non-engineered dwellings using the proposed retrofitting technique is shown through experimental results and numerical simulations. In walls made of industrial tubular bricks, the increment in deformation capacity avoid a severe damage which represents the improvement of life-safety conditions for the less-advantaged sectors of society who occupy non-engineered dwellings.

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