17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

ASSESSMENT OF A RETROFITTING TECHNIQUE FOR PERUVIAN CONFINED MASONRY DWELLINGS USING FRAGILITY FUNCTIONS

L. Quiroz(1), Y. Maruyama(2)

(1) *Associated Researcher, Department of Earthquake Engineering, Japan-Peru Earthquake Engineering and Disaster Mitigation Center, Faculty of Civil Engineering, National University of Engineering, Lima-Peru, lgquiroz@uni.edu.pe.*
(2) *Professor, Department of Urban Environment Systems, Chiba University, Japan, ymaruyam@faculty.chiba-u.jp.*

Abstract

A good seismic performance of dwellings in seismic-prone regions is very important because an inadequate behavior is the main cause of economic and human losses. A strategy to assess the seismic performance of structures is using fragility functions, which estimate the probable damage due to a seismic event. In Lima City, Peru, many low-rise dwellings are built with confined masonry (CM) walls because of the low cost. In our previous studies, an analytical approach was used to construct fragility functions to evaluate the seismic performance of low-rise dwellings whose vertical and lateral resistance systems consist of CM walls. It was found that two- and three-story CM dwellings are prone to high structural damage due to severe earthquakes. Based on the background, a simple retrofitting procedure used in Lima City is investigated and its effectiveness is evaluated by generating new fragility functions for the retrofitted dwellings. Because three-story CM dwellings have high probability of collapsing, it is not possible to retrofit these structures using a simple procedure. Therefore, the suggested retrofitting procedure is employed only for two-story dwellings. The procedure involves adding an electro welded wire mesh (EWWM) covered with mortar on both faces of the masonry panel. Numerical model of two-story dwellings is analyzed, and the properties of their main structural elements are defined based on the experimental results and numerical calculations. A series of nonlinear dynamic analyses are performed using simulated ground motion records for Lima City. The fragility functions for the original and retrofitted dwellings are constructed assuming that the damage ratios follow lognormal distributions. The results show that retrofitted dwellings accomplish the regulations stipulated by the E.030 Peruvian standard. Besides, the probability of damage is significantly reduced, and these structures can be constructed without gaps between adjacent dwellings.

Keywords: retrofitting, CM dwellings, nonlinear dynamic response analyses, fragility functions.

1. Introduction

In many cities of Latin America, mainly in urban areas, dwellings are built using confined masonry (CM) walls which are composed of masonry panels with vertical RC tie-columns that confine the brick walls and RC bond-beams along the walls at floor level. Past earthquakes have shown that CM dwellings are prone to structural damage. For example, the Maule Chile earthquake in 2010 (Mw = 8.8) produced diagonal cracking of masonry walls and wall failure due to the lack of confining elements around openings or poor quality of confinements [1]. In case of Peru, most residential housing units in the urban areas near the epicenter of Pisco earthquake (Mw = 8.0) were one- or two-story buildings constructed using confined brick masonry. CM dwellings with soft stories, relevant irregularities, or bad detailing collapsed or sustained severe damage but those that were modern and well-designed resisted the earthquake with little or no damage [2]. For Lima City, the capital of Peru, exist several low-rise CM dwellings and the number has been increasing because of the low cost of construction. However, Lima City has not been stricken by a strong earthquake since 1974. Therefore, the losses associated with their failure are unknown. A previous study was carried out trying to estimate the seismic assessment of CM dwellings in Lima City [3]. It was found that two- and three-story dwellings in Lima will not accomplish the requirements of the seismic design standard. In the present study, a widely used retrofitting technique for Peruvian CM dwellings is assessed through fragility functions. This technique consist of the additional electro welded wire mesh (EWWM) covered with mortar on both faces of the masonry panel [4].

Fragility functions describe the conditional probability of a structure sustaining different degrees of damage at given levels of ground motion intensity. A typical fragility function is expressed by Eq. (1):

$$P_{ik} = P\left[X \geq x_i \middle| Y = y_k\right] \tag{1}$$

where P_{ik} is the conditional probability of the degree of damage x_i at ground motion intensity level y_k. X and Y are the variables representing the damage state and ground motion intensity, respectively. Damage states have been defined in terms of interstory drift, and nonlinear dynamic analyses were performed using strong-motion records of seismic events around the world and those assumed for Lima City.

2. Derivation of fragility functions

2.1 Samples of CM dwellings and numerical modeling

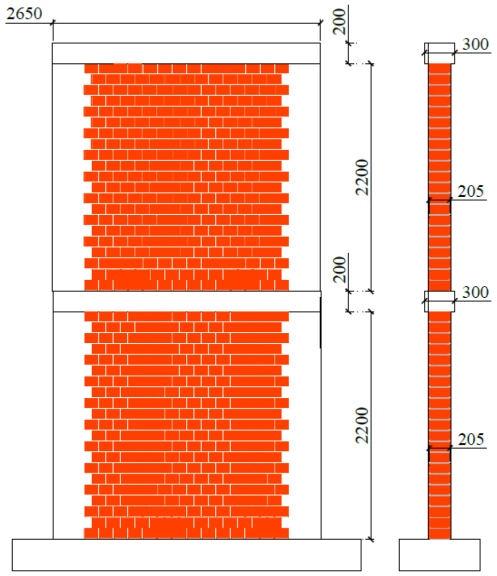

Fig. 1 – Geometrical properties of Two-story numerical model.

Table 1. Dimensions and reinforcements of confining elements in numerical models.

Tie-column				Bond-beam			
t (mm)	b (mm)	Longitudinal Reinforcement	Transverse Reinforcement	h (mm)	b (mm)	Longitudinal Reinforcement	Transverse Reinforcement
230	300	4 #4 [a]	#2: 1@5 cm, 4@10 cm, rest@25 cm	200	300	4 #3 [b]	#2: 1@5 cm, 4@10 cm, rest@25 cm

[a] 4 #4: Four conventional rebars 12.7 mm in diameter in the section of the element.

[b] 4 #3: Four conventional rebars 9.5 mm in diameter in the section of the element.

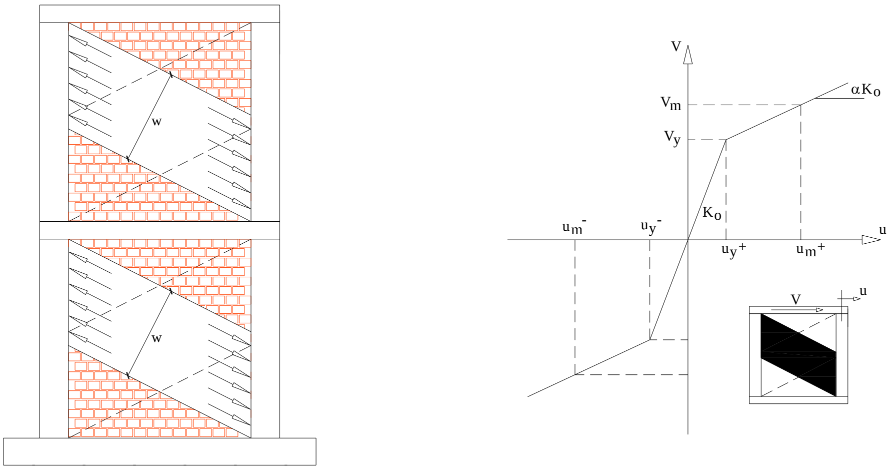

Fig. 2 – Equivalent strut model for masonry panels in numerical model and strength envelope for struts [6].

Muñoz et al. [5] presented the architectural drawings of a typical two-story CM dwelling. It can be observed that the shape of dwellings in Lima present a rectangular shape. The distribution of structural elements is usually the same in all stories. Because of the distribution of the elements, the dwellings are significantly stronger and stiffer in the longitudinal direction. In the perpendicular direction, dwellings present one or two CM walls. The present analysis was carried out in the weaker direction.

The geometrical properties are shown in Fig. 1. These dimensions and their confinement elements considered for analysis were set to be as close as possible to those of actual low-rise dwellings. In the previous study [3], the number of stories considered was 1 to 3. Reinforcements of the confining elements are listed in Table 1.

The numerical model considered the nonlinearity of the masonry panel using two diagonal compression struts per story. The struts were considered to be ineffective in tension. The curve bounded by a strength envelope is defined by an initial stiffness of the panel, a yield force Vy, a degraded stiffness and a maximum force Vm. Figure 2 show the equivalent strut model for masonry panel. For more details see [3].

2.2 Damage states and input ground motions

The damage states considered in the present study are based on interstory drift because damage to structures is directly related to local deformations based on the experimental results. Four damage states were considered based on Zavala et al. [7] and are shown in Table 2.

Table 2. Definitions of damage states based on interstory drifts.

State	Interstory Drift (%)	Description	Damage state
1	0–0.125	No damage	No damage (ND)
2	0.125–0.286	Commencement of diagonal cracking	Light (L)
3	0.286–0.5	Initial cracking of tie-columns and opening of diagonal cracks	Severe (S)
4	>0.5	Horizontal cracks along tie-columns and generalization of diagonal cracks	Collapse (C)

Table 3. Range of some seismic indices analyzed of ground motion records.

Parameter	PGA (cm/s^2)	PGV (cm/s)	AI (m/s)	Period (s)
Chibaken Toho-Oki	[39.61–455.09]	[3.07–33.70]	[0.04–1.32]	[0.25–0.83]
Northridge	[135.56–1725.51]	[10.51–342.78]	[0.28–22.58]	[0.32–2.67]
Kobe	[65.81–818.22]	[5.16–154.89]	[0.19–8.70]	[0.24–2.23]
Chi-Chi	[112.35–989.28]	[24.10–148.27]	[0.44–20.32]	[0.33–1.65]
Tohoku	[427.87–2733.78]	[16.60–107.16]	[4.59–130.17]	[0.11–0.62]
Maule	[73.35–913.26]	[5.78–58.70]	[0.16–19.87]	[0.22–1.10]
Peru-simulated	[288.14–847.70]	[14.55–101.92]	[4.09–25.90]	[0.06–0.34]

Horizontal components of ground motion records were used as input motions. Ground motion records of seismic events in Japan, USA, Taiwan, and Chile were considered in this study. The following earthquakes were used: Chibaken-Toho-Oki (1987), Kobe (1995), Northridge (1994), Chi-Chi (1999), Tohoku (2011), Maule (2010) and acceleration time histories simulated by Pulido et al. [8]. In case of retrofitted structure, only simulated records were used. The peak ground acceleration (PGA) was selected for intensity indicator because of its good correlation with structural damage. Table 3 shows the ranges of some seismic indices of ground motion records.

The acceleration response spectra for all records with the damping ratio of 5% and the design acceleration response spectrum according to the E.030 [9] were compared. The expression proposed by Iervolino et al. [10] was employed for evaluating the extent of deviation (δ) of acceleration response spectra from the design acceleration response spectrum. It was found that for the simulated records of Lima in case of one- and two-story models gave lowest value of δ, while for the three-story model, the value of δ was the smallest for the Maule earthquake records. The simulated records for Lima matched better with the Peruvian design spectra for one- and two-story dwellings [3].

2.3 Dynamic response analysis

A series of nonlinear dynamic response analyses of the numerical models was performed using a combination of Newmark-beta integration and the pseudoforce method in the IDARC program. The PGA of every record was scaled from 25 cm/s^2 until three times its original PGA [11] at an interval of 25 cm/s^2. The scaled records were applied to the numerical models to obtain the maximum interstory drift. Figure 3 shows the plot of the maximum interstory drift observed in the two-story numerical model, for different simulated input-scale ground motion records for Lima. The different maximum interstory drifts of the numerical model are observed even at the same intensity level (PGA).

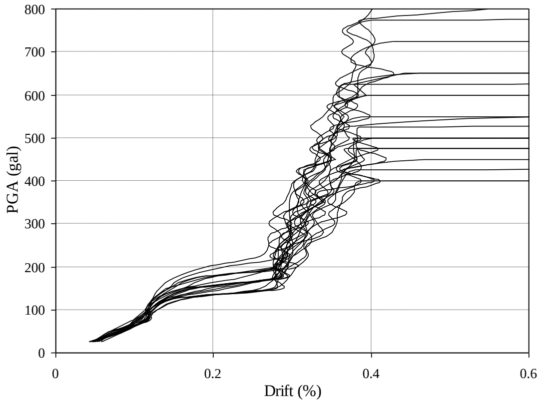

Fig. 3 – Comparison of maximum interstory drift for two-story numerical model using simulated records for Lima.

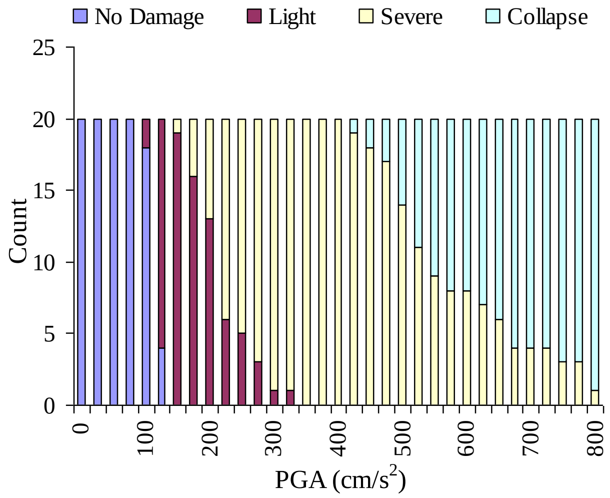

Fig. 4 – Frequencies of occurrence of each damage state based on Peruvian simulated records, for two-story numerical model.

3. Fragility Functions for CM dwellings

With the results of the dynamic response analyses, damage ratio was calculated for every damage state. Figure 4 presents the frequency of occurrence of every damage state with respect to the PGA for the numerical model for the Peruvian simulated records for the two-story numerical model. It is observed that the frequency of no-damage occurrence decreases whereas that of collapse occurrence increases with increase of the excitation level.

For constructing the fragility functions, lognormal probability distribution between the PGA and damage ratio was assumed [12]. The cumulative probability P_R of an event meeting or exceeding the condition for a particular damage state is defined by Eq. (2):

$$P_R = \Phi\left[\frac{\ln Y - \lambda}{\zeta}\right] \tag{2}$$

where Φ is the standard cumulative normal distribution function, Y is the ground motion index (PGA), and λ and ζ are the two statistical parameters of the distribution (i.e., the mean and standard deviation of ln Y, respectively) obtained by plotting ln Y against the inverse of Φ on a lognormal probability paper. The values of λ and ζ are obtained using the least-squares method as shown in Eq. (3)

$$\ln Y = \zeta \Phi^{-1} + \lambda \tag{3}$$

The statistical parameters defining the fragility functions were estimated and are presented in Table 4.

Figure 5 presents the fragility functions for light, severe and collapse damage states and every event for the two-story numerical model, respectively. In the three-story numerical model, there was no occurrence of light damage for any event. In one-story numerical model, only the light damage state occurred. It was observed that the probability of an event meeting or exceeding the condition for a damage state varies across events, particularly for the collapse damage state.

Table 4. Parameters of fragility functions for two-story numerical model for Peruvian simulated records.

Event	**Damage state**					
	DS > Light		**DS > Severe**		**DS > Collapse**	
	λ	ζ	λ	ζ	λ	ζ
Peru-simulated	4.72	0.09	5.36	0.23	6.36	0.22

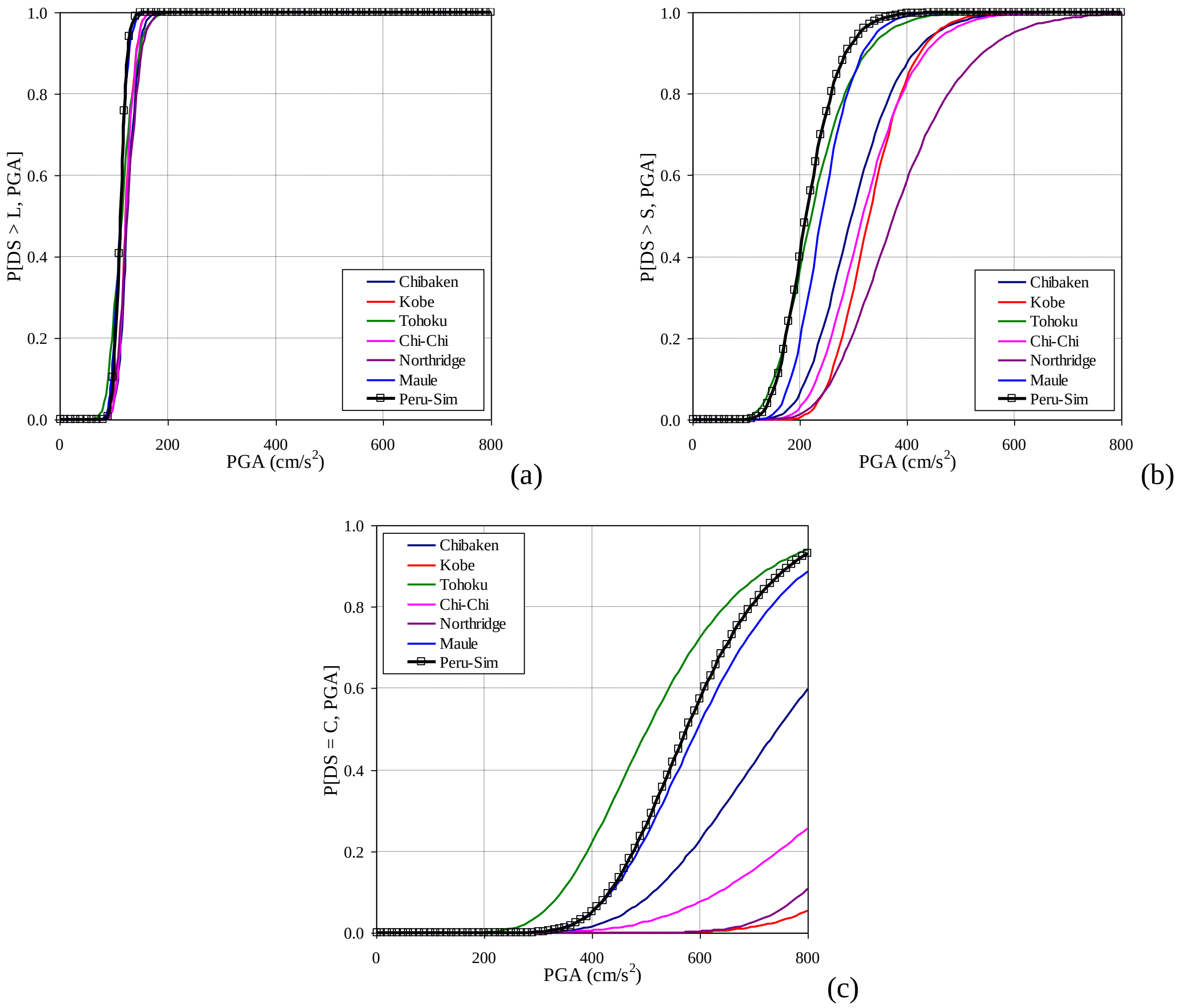

Fig. 5 – Comparison of fragility functions of various earthquake events across damage states for two-story numerical model: a) light, b) severe, and c) collapse.

In the case of three-story numerical model, the fragility functions of all events except the Kobe and Northridge earthquakes present a rapidly transition from the severe to collapse damage states, indicated by the closeness of the two damage states and steepness of their slopes. This effect could imply that the structure is susceptible to soft-story collapse.

The fragility curves estimated were validated with those presented by Matsuzaki et al. [13]. The estimations using the fragility curves in this study are a little higher than those presented by Matsuzaki et al. [13]. This is explained by the fact that adjacent dwellings in Pisco are constructed without gaps between each other and hence, their total possible displacement and the associated damage could be smaller than those estimated by numerical simulation.

4. Fragility Functions for retrofitted structure

As established in previous studies, two- and three-story CM dwellings are prone to high structural damage due to severe earthquakes. To counter the damage, a simple retrofitting procedure is presented in this section and its effectiveness is evaluated by generating new fragility functions of the retrofitted structure using the same simulated records for Lima. The seismic performance can also be evaluated by considering the same hazard levels presented in previous section. Because three-story CM dwellings have high probability of collapsing, it is difficult to retrofit these structures using a simple procedure. Therefore, the suggested retrofitting procedure was assessed only for two-story dwellings. The procedure involves adding an electro welded wire mesh (EWWM) covered with mortar on both faces of the masonry panel [4].

4.1 Retrofit material and technique

The EWWM is made of corrugated steel bars of 4.5 mm diameter separated by a distance of 15 cm. The maximum tensile strength of the bars is approximately 600 MPa. The construction does not involve any connection between the mesh and the tie-columns or foundation because its purpose is to close the diagonal cracks in the masonry panel caused by the lateral displacement. The meshes in both faces of the wall are connected using wires of 4.37 mm diameter, which pass through holes drilled in the bricks separated 45 cm. Figure 6 shows an example use of the EWWM on walls and the connector used. The drills and both sides of the wall are filled up with a liquid mortar of cement-sand. The present study assumed that this procedure is only applied on the wall of the first story.

The required reinforcement is estimated using Eq. (4):

$$As = \frac{Vy.s}{f_y.L} \tag{4}$$

(a) (b)

Fig. 6 – Example use of a) EWWM and b) connector on CM walls [4].

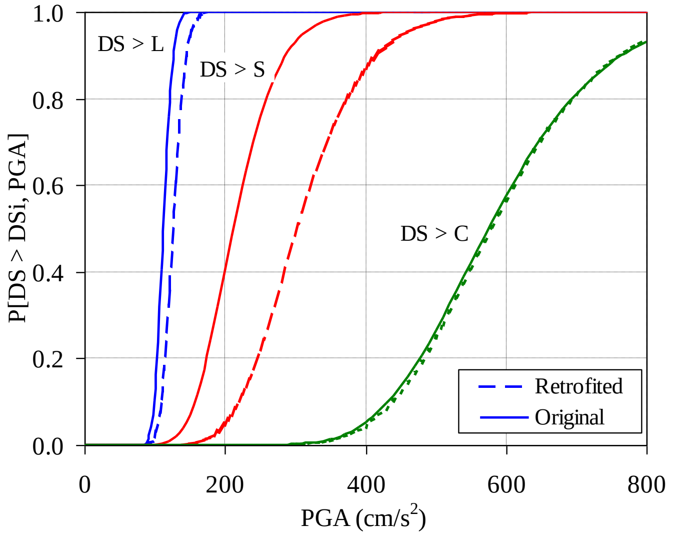

Fig. 7 – Fragility functions for two-story retrofitted dwellings using simulated records for Lima.

where *s* is the spacing between the mesh bars, *fy* is the yield stress of the bars (411.87 MPa according to [14]), and *L* is the total length of the wall. The calculation results in a required area of 22 mm^2 whereas the double mesh used for retrofitting provided a reinforcement of 32 mm^2. The parameters used to define the hysteretic model are the same as those presented in previous studies [3].

4.2 Fragility functions

Using the procedure presented in Section 3 and the simulated records for Lima, the fragility functions for the retrofit structure were constructed and are presented in Fig. 7.

Figure 7 shows reduced probabilities of light and severe damage in the retrofitted structure. The probability of each damage state at the three specific hazard levels was calculated from the curve. The probabilities of light and severe damage due to an occasional earthquake (0.2g) increased to 96% and decreased to 4%, respectively. The probability of severe damage and collapse due to a rare earthquake event (0.4g) reduced to 82% and 3%, respectively. The probabilities of severe damage and collapse due to a very rare earthquake event (0.5g) are 75% (approximately) and 22%, respectively. The reduction in the vulnerability is evident in the case of occasional earthquake, albeit not significantly for rare earthquake events because of the low increase in the thickness of the wall. Nevertheless, the retrofitted structure accomplished the regulations stipulated by the E.030 [9], considering that the new probabilities of damage states are reduced and that structures are constructed without gaps between adjacent dwellings.

5. Conclusions

Previous studies revealed that two-story dwellings in Lima will not accomplish the requirements of the E.030. The probability of collapse of these dwellings due to rare earthquakes was estimated to be less than 5%. Although the E.030 stipulates zero probability of collapse for this case, the value obtained from the analysis may be considered adequately low. The findings also indicate that three-story dwellings will suffer strong damage even under occasional earthquakes and hence, they will not accomplish the E.030 requirements. Therefore, a simple retrofitting procedure involving the addition of EWWM on both faces of the wall panel for reducing the seismic vulnerability of two-story dwellings was evaluated. The evaluation revealed that retrofitting reduces the vulnerability of the structure and facilitates its conformance to the requirements defined by the E.030.

6. References

[1] EERI (2010): The Mw 8.8 Chile Earthquake of February 27, 2010. *Special Earthquake Report — June 2010.*

[2] EERI (2007): The Pisco, Peru, Earthquake of August 15, 2007. *Special Earthquake Report — October 2007.*

[3] Quiroz L and Maruyama Y. (2017): Seismic assessment of Peruvian confined masonry dwellings using fragility functions. *17th World Conference of Earthquake Engineering 17WCEE*, Paper No. 645, 12p, Santiago, Chile.

[4] San Bartolome A., Quiun D., Barr K. and Pineda C. (2012): Seismic reinforcement of confined masonry walls made with hollow bricks using wire meshes. *15th World Conference of Earthquake Engineering 15WCEE*, Paper No. 3211, 10p, Lisbon, Portugal.

[5] Muñoz A, Blondet M, Tarque N, Carpio J and Florez A (2009): Capacity spectra of a typical confined masonry dwelling in Peru. http://www.world-housing.net/wp-content/uploads/pager/2009/08/Capacity-curves-masonry-Peru.pdf

[6] Reinhorn AM, Roh H, Sivaselvan M, Kunnath SK, Valles RE, Madan A, Li C, Lobo R and Park YJ (2009): IDARC2D version 7.0: A program for the inelastic damage analysis of structures. Technical Report, MCEER-09-0006, State University of New York at Buffalo.

[7] Zavala C, Honma C, Gibu H, Gallardo J and Huaco G (2004): Full scale on line test on two story masonry building using handmade bricks. Proceedings of 15th World Conference on Earthquake Engineering, Lisbon, Portugal. Paper No. 2885.

[8] Pulido N (2013): Earthquake rupture and slip scenarios for Central Andes Peru, and strong motion simulations for Lima (v1.0 February 7/2013). http://www.j-shis.bosai.go.jp/staff/nelson/smsimu_Central_Peru_v1p0/Lima_SMsimu_v1p0.htm.

[9] SENCICO (2003): Standard E.030 Seismic Design. National Building Regulations, Lima, Peru. (In Spanish).

[10] Iervolino I, Galasso C and Cosenza E (2010): REXEL: computer aided record selection for code-based seismic structural analysis. Bulletin of Earthquake Engineering 8, 339–362.

[11] Bommer JJ and Acevedo AB (2004): The use of real earthquake accelerograms as input to dynamic analysis. Journal of Earthquake Engineering 8 (4): 1–50.

[12] Mehanny SSF and El Howary HA (2010): Assessment of RC moment frame buildings in moderate seismic zones: Evaluation of Egyptian seismic code implications and system configuration effects. Engineering Structures 32, 2394–2406.

[13] Matsuzaki S, Pulido N, Yamanaka K, Chimoto K, Maruyama Y and Yamazaki F (2013): Vulnerability estimation of buildings using damage survey data following the 2007 Pisco, Peru, Earthquake. Journal of Social Safety 21 (In Japanese).

[14] SENCICO (2006): Standard E.070 Masonry. National Building Regulations, Lima, Peru. (In Spanish).