SISMIC RETROFITTING OF CONFINED TUBULAR MASONRY STRUCTURES THROUGH THE APPLICATION OF ELECTROWELDED MESHES
REFORZAMIENTO SÍSMICO DE ESTRUCTURAS DE ALBAÑILERÍA TUBULAR CONFINADA MEDIANTE LA APLICACIÓN DE MALLAS ELECTROSOLDADAS

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ABSTRACT

Non-engineered structures in highly seismic areas are a major cause of human and economics losses during strong earthquake in Peru. These structures are often vulnerable and do not comply with design codes. Therefore, the present study evaluates the influence of electrowelded wire meshes as seismic or structural retrofitting for confined tubular masonry walls. In this sense, dwellings of common use, of confined tubular masonry, located in the city of Lima and settled on very rigid soils, have been studied. A numerical model has been calibrated that estimates the capacity of the non-retrofitted and retrofitted confined tubular masonry walls. In addition, nonlinear static analysis has been applied to determine the capacity of the non-retrofitted and retrofitted confined tubular masonry structures, and the retrofitting cost of each structure has been calculated to determine the feasibility of the retrofitting. Finally, the retrofit improved seismic performance at a reasonable cost.

Keywords: Seismic retrofitting, seismic performance, confined tubular masonry structures, electrowelded wire mesh, tubular brick.

RESUMEN

Las estructuras no diseñadas en áreas altamente sísmicas son una de las principales causas de pérdidas humanas y económicas durante un fuerte terremoto en Perú. Estas estructuras suelen ser vulnerables y no cumplen con los códigos de diseño. Por lo tanto, el presente estudio evalúa la influencia de las mallas electrosoldadas como reforzamiento sísmico o estructural para muros de albañilería tubular confinada. En ese sentido, se han estudiado edificaciones de uso común, de albañilería tubular confinada, ubicadas en la ciudad de Lima y asentadas sobre suelos muy rígidos. Se ha calibrado un modelo numérico que estima la capacidad de muros de albañilería tubular confinada no reforzados y reforzados con mallas electrosoldadas. Además, se han aplicado análisis estáticos no lineales para determinar la capacidad de las estructuras de albañilería tubular confinada no reforzadas y reforzadas con mallas electrosoldadas, y se ha calculado el costo de refuerzo de cada estructura para determinar la factibilidad del reforzamiento. Finalmente, el reforzamiento mejoró el desempeño sísmico a un costo razonable.

Palabras Clave: Reforzamiento sísmico, desempeño sísmico, estructuras de albañilería tubular confinada, Malla electrosoldada, ladrillo tubular.

1. INTRODUCTION

Seismic retrofitting increases the resistance and ductility of new and old structures to prevent them from collapsing in the event of a strong earthquake. Retrofitting is carried out through retrofitting strategies that allow certain performance objectives to be achieved. In addition, the strategies are satisfied using appropriate retrofitting techniques [1].

In the word, the structures composed of frames have been retrofitted by technique of adding reinforced concrete walls and metal bracing, significantly increasing resistance, and the casing of the structural elements with steel purlins, carbon fiber and steel cladding, significantly increasing ductility [2]. In addition, the structures composed of masonry walls have been retrofitted by the technique of adding horizontal steel [3] and [4], electrowelded wire meshes [5] and [6] and polymer steel sheets

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reinforced with carbon fiber [7], significantly increasing resistance and ductility.

In Peru, the structures composed of frames have been retrofitted by the technique of adding reinforced concrete walls, masonry walls and steel frames with concentric bracing, significantly increasing resistance and ductility [8]. In addition, the structures of masonry walls of solid, hollow and tubular bricks have been retrofitted by the technique of adding horizontal steel, electrowelded wire meshes, fiberglass sheets and geogrids, significantly increasing resistance and ductility [9].

The walls composed of tubular bricks or confined tubular masonry walls, hereinafter referred to as wall o walls, were studied experimentally and exclusively using electrowelded wire meshes, since this retrofitting technique has significantly increased resistance and ductility at a low cost. In addition, this retrofitting technique has been evaluated for different types of connection of electrowelded wire mesh, i.e. with the mesh connected to masonry [10], connected to the masonry and confinement columns [11] and [12] and connected to masonry and all the confinement elements [13] and [14].

Peru is in an area where 80% of the world's earthquakes occur and, in addition, 83% of the dwellings in the emerging areas of its most populated city are informal masonry constructions [15] and [16]. In this sense, the technique of adding electrowelded wire meshes in masonry walls is suitable to solve this problem. Therefore, its influence on the improvement of seismic performance in masonry dwellings and the cost must be investigated to determine the feasibility of retrofitting.

2. BACKGROUND

The background is presented in two sections. In the first section, experimental studies of non-retrofitted and retrofitted walls using electrowelded wire meshes are presented. In the second section, relevant information on seismic performance is presented, i.e. information on seismic demand, capacity curve and performance point of structures.

2.1. CONFINED TUBULAR MASONRY WALLS

Unlike reinforced concrete and steel, it is inappropriate to use foreign design codes or research for masonry, as the construction procedures and materials used differ markedly from other countries [17]. In this sense, national research or experimental studies of non-retrofitted and retrofitted walls using electrowelded wire meshes are presented. The studies have been developed at the Pontifical Catholic University of Peru (PUCP) and at the National University of Engineering (UNI).

The electrowelded wire mesh has been connected in five different ways to the wall. The first three connections of the electrowelded wire mesh have occurred on both sides of the wall and the remaining two on one side of the wall. The first connection of the electrowelded wire mesh has occurred only in the masonry, the second and fourth connection in the masonry and confinement columns and the third and fifth connection in the masonry and all the confinement elements.

In the laboratory of PUCP and UNI, non-retrofitted wall [18], [10], [19], [13] and [14], retrofitted walls with electrowelded wire mesh connected only to the masonry [10] and connected to the masonry and confinement columns on both sides of the wall [11] have been studied. In addition, In the laboratory of UNI, confined tubular masonry walls reinforced with electrowelded wire mesh connected to the masonry and all the confinement elements on both sides and on one side of the wall have been studied [13] and [14]. Finally, the connection of the mesh to the masonry and the confinement columns on a single side of the wall has been studied [12].

Fig. 1 shows the bilinear capacity of one non-retrofitted wall [10] and three retrofitted walls with meshes on both sides of the wall [10], [11] and [14]. The green line represents the wall with mesh connected only to the masonry and the blue line represents the wall with the mesh connected to the masonry and all the confinement elements.

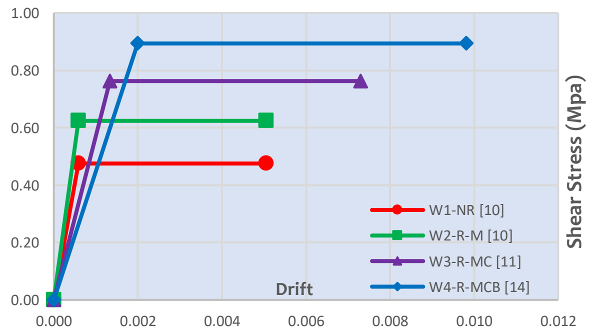

Fig. 1. Masonry walls with retrofitting on two sides

Fig. 2 shows the bilinear capacity of one non-retrofitted wall [10] and two retrofitted walls with meshes on one side of the wall [12] and [14]. The purple line represents the wall with the mesh connected to the masonry and the confinement columns and the blue line represents the wall with the mesh connected to the masonry and all the confinement elements.

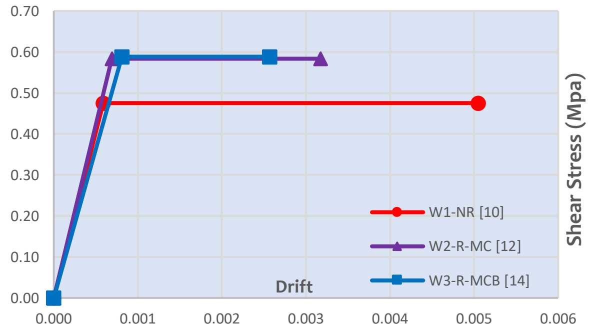

Fig. 2. Masonry walls with retrofitting on one side

It is important to highlight that the capacity of the non-retrofitted and retrofitted walls presented correspond to different authors and were made under different conditions, so comparisons are not decisive. Moreover, the bilinear capacity has been obtained using the curves of laboratory tests and applying the procedure of the American Society of Civil Engineers (ASCE 41-13) [20]. The Bilinearization is achieved mainly by considering energy equality, i.e. the area under the bilinear model was equal to the area under the experimental curve.

The wall models consider the contribution of the many parameters, such as longitudinal and transverse steel of the columns, the axial load and the compressive resistance of the masonry prism to determine the shear stress of the walls [21] and [22]. In addition, the statistical method of multiple linear regression is suitable for calibrating wall models, since it offers an acceptable coefficient of multiple determination [21], [22] and [23].

2.2. SEISMIC PERFORMANCE

Seismic performance is the behavior of a building in the face of a given seismic event. Therefore, design based on seismic performance consists of achieving a level of performance consistent with the importance of the structure. The Applied Technology Council (ATC 40) and the Structural Engineers Association of California (SEAOC 2000) provide performance levels, seismic hazard levels, and seismic performance targets [24] and [25]. In addition, a UNI study offers limit states based on drifts to quantify the level of performance of confined masonry structures [16].

Nonlinear static analysis is a method that allows the study or analysis of the capacity of a structure. In this sense, the Pushover technique is the most widely used to determine the capacity of the building by relating the basal shear to the maximum lateral displacement of the roof. The technique allows obtaining the capacity curve, which must be transformed into a capacity spectrum so that it is superimposed with the seismic demand spectrum and determines the performance point.

Seismic demand is represented by the response spectrum and the spectrum of the Seismic Resistant Design Standard (NTE E.030-2018) [26]. The elastic response spectrum is achieved using a critical damping of 7% and the inelastic response spectrum using a critical damping of 12% for masonry structures [27]. On the other hand, for the spectrum of NTE E.030, the same spectrum is considered for the elastic and inelastic ranges of the structure, since in the case of very rigid structures the reduction coefficient is equal to unity.

The capacity curve depends on the pattern of lateral loads applied to the structure. The pattern is uniform, triangular, parabolic, or it can follow the shape of the structure's first vibrating mode. In addition, the loads are increased sequentially until the structure collapses or a set limit. In programs that contain the Pushover technique, the increase in loads usually occurs in intervals of 1 kN, on the other hand, without using programs the increase usually occurs in intervals of 30 kN [28].

Fig. 3 shows the capacity of a seven-story structure of reinforced concrete in the X-X Direction for different lateral load distribution patterns. In addition, in the figure the capacity curve of the uniform load pattern differs significantly from the other two.

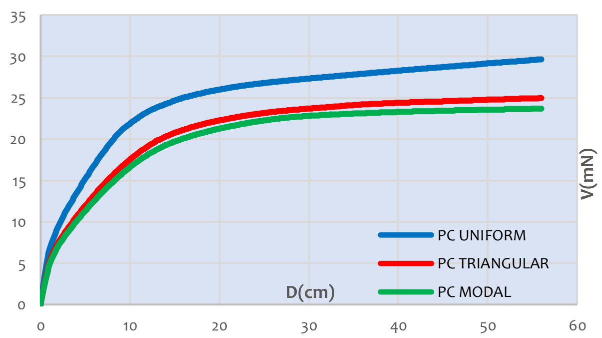

Fig. 3. Lateral load distribution patterns

The performance point is determined by the intersection or meeting of the demand spectrum and the capacity spectrum. In addition, the point represents the maximum displacement of the structure for a given level of seismic hazard. Moreover, the performance point is obtained using the Capacity-Demand Spectrum method, the Displacement Coefficient method, and the Secant method [29].

3. METHODOLOGY

The research aims to determine the influence of retrofitting through the application of electrowelded wire meshes in the improvement of seismic performance in confined tubular masonry structures.

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In this sense, a numerical model of confined tubular masonry walls must be calibrated, the performance point of the structures must be determined and the cost of retrofitting must be calculated. In addition, it is necessary to optimize the retrofitting and its cost. Fig. 4 shows research development procedure.

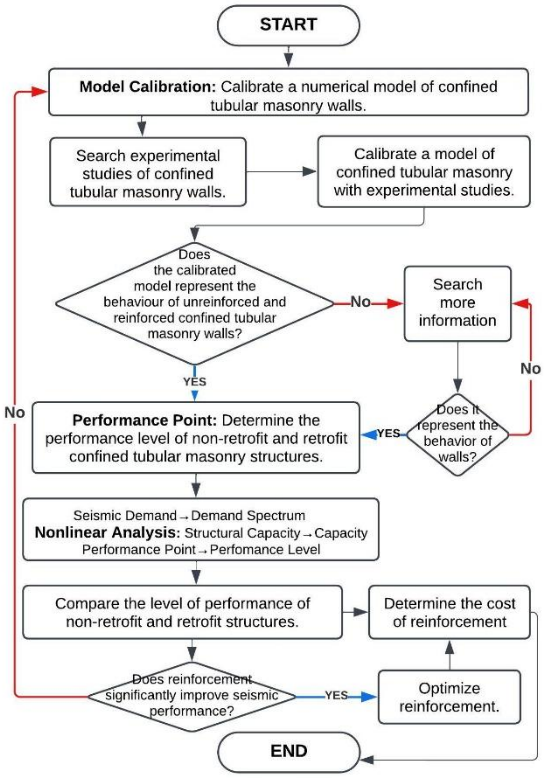

Fig. 4. Research development procedure

3.1. STUDY POPULATION AND SAMPLE

The study population consists of 16 confined tubular masonry buildings, located in the city of Lima, intended for housing and settled on very rigid soils. The buildings are of different levels and density of walls, as shown in TABLE I. In addition, the 16 buildings have an area of 91 square meters per floor.

TABLE I
Study population

Stories	Wall density (WD)				Sum
	1.4%	1.9%	2.4%	2.9%	
1	1	1	1	1	4
2	1	1	1	1	4
3	1	1	1	1	4
4	1	1	1	1	4
Sum	4	4	4	4	16

Fig. 5 presents a typical floor of the dwellings for different wall densities. In the figure the variation of wall occurs only in the horizontal direction, since in the other direction the wall density is fixed at 3.7%.

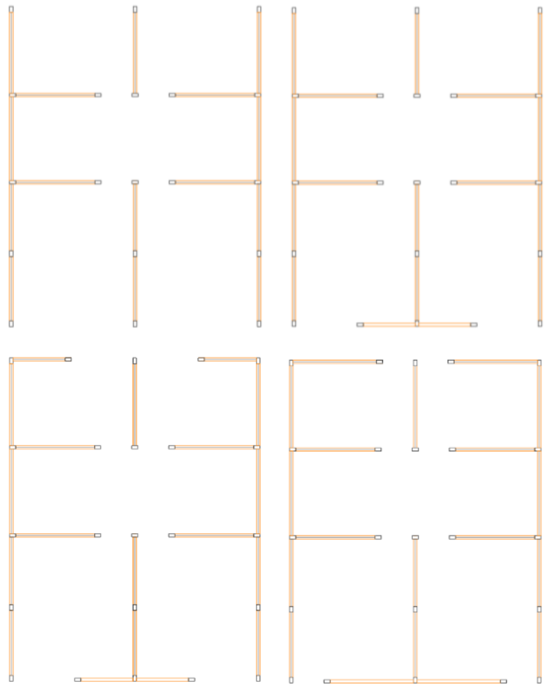

Fig. 5 Typical floors of buildings with wall density of a) 1.4%, b)1.9%, c)2.4% and d)2.9%

The study sample consists of 15 groups of non-retrofitted and retrofitted confined tubular masonry dwellings. In TABLE II, Group 1 (G1) refers to the study of 16 non-retrofitted dwellings, G2 refers to the study of 16 dwellings with retrofitted walls only in the X-X Direction and G3 refers to the study of 16 dwellings with retrofitted walls in the two main directions. In this sense, it should be noted that each group studies the 16 dwellings presented in TABLE I.

TABLE II
Study sample

G	Code	Description
1	NR	Non-retrofitted
2	Rx	Retrofitted in X-X
3	Rxy	Retrofitted in X-X and Y-Y
4	R1x	Floor 1 retrofitted in X-X
5	R1xy	Floor 1 retrofitted in X-X and Y-Y
6	R12x	Floors 1 and 2 retrofitted in X-X
7	R12xy	Floors 1 and 2 retrofitted in X-X and Y-Y
8	Ri1x	Internal walls of Floor 1 retrofitted in X-X
9	Ri1xy	Internal walls of Floor 1 retrofitted in X-X and Y-Y
10	Ri12x	Internal walls of Floor 1 and 2 retrofitted in X-X
11	Ri12xy	Internal walls of Floor 1 and 2 retrofitted in X-X and Y-Y
12	Re1x	External walls of Floor 1 retrofitted in X-X
13	Re1xy	External walls of Floor 1 retrofitted in X-X and Y-Y
14	Re12x	External walls of Floor 1 and 2 retrofitted in X-X
15	Re12xy	External walls of Floor 1 and 2 retrofitted in X-X and Y-Y

3.2. MODEL FOR CONFINED MASONRY WALLS

Models with more than two independent parameters or variables can be calibrated using multiple linear regression, multiple nonlinear regression and polynomial regression. In this sense, it can be mentioned that the multiple linear regression method is appropriate to determine the capacity of confined masonry walls [21], [22] and [23]. The multiple linear regression method is used when the dependent variable (y) is linearly related to two or more independent variables (x_1, x_2, x_3 and x_m), as shown in equation (1). The model is calibrated once the regression parameters (a_0, a_1, a_2 and a_m).

$$y = a_0 + a_1 * x_1 + a_2 * x_2 + \cdots + a_m * x_m \qquad (1)$$

The capacity of masonry walls is a function of the longitudinal and transverse steel of the columns, the axial load, the aspect ratio of the wall and the compressive strength of the masonry prims [21], [22] and [23]. In masonry walls with retrofitting, an additional parameter must be considered that represents the electrowelded wire meshes and the connection that it presents in the wall.

The dependent variable is the shear stress (τ_y) and the drift of the wall (Δ_y). The independent variables are represented by the resistance amount of longitudinal (P_t. σ_y) and transverse steel (P_{we}. σ_{wy}) of the confinement columns, the axial load (σ_o) and the resistance amount of electrowelded wire mesh (P_h. σ_{yh}). The last variables represent the compressive strength of the masonry pile (F_m) and mesh efficiency (e) as shown in equation (2) and (3).

$$\frac{\tau_y}{F_m} = a_0 + a_1 * \left(\frac{P_t * \sigma_y}{F_m}\right) + a_3 * \left(\frac{P_{we} * \sigma_{wy}}{F_m}\right) + a_4 * \left(\frac{\sigma_0}{F_m}\right) + a_5 * \left(\frac{e * P_h * \sigma_{yh}}{F_m}\right) \qquad (2)$$

$$\Delta_y = a_0 + a_1 * \left(\frac{P_t * \sigma_y}{F_m}\right) + a_3 * \left(\frac{P_{we} * \sigma_{wy}}{F_m}\right) + a_4 * \left(\frac{\sigma_0}{F_m}\right) + a_5 * \left(\frac{e * P_h * \sigma_{yh}}{F_m}\right) \qquad (3)$$

In addition, it is important to mention that the last dimensionless parameter of the last two equations represents the electrowelded wire mesh and its type of connection in the wall. The type of connection is represented by the factor e. The other dimensionless parameters were taken from studies of Sugano et al. and Diaz et al [21] and [22].

3.3. SEISMIC PERFORMANCE

Performance levels are determined by evaluating the performance point under certain limit states. In this sense, to obtain the performance point, the seismic demand spectrum and capacity spectrum of the structure must first be determined.

The magnitude of the seismic demand is a function of the return period [24] and [25]. TABLE III shows a summary of two proposals for the level of seismic hazard. The ATC-40 proposes a coefficient of 0.5 to go from a design earthquake to a service earthquake and a coefficient of 1.25 to go from a design earthquake to a maximum earthquake [24].

TABLE III
Seismic hazard levels

SEAOC-Vision 2000	ATC-40	Return period
Frequent	-	43 years
Occasional	serviceability	72 years
Rare	Design	475 years
Very rare	Maximum	970 - 975 years

In addition, for the demand spectrum to be useful, it must be transformed into spectral acceleration (s_{ai}) - spectral displacement (s_{di}) format using equation (4) must be used. The last variable is the period (T).

$$S_{di} = \left(\frac{T_i}{2\pi}\right)^2 * S_{ai} \qquad (4)$$

The capacity curve of the structure is determined by the Pushover technique and is in the format of shear at the base (V_{Bi}) and displacement at the roof (Δ). The capacity curve is transformed into a capacity spectrum using equation (5) and (6). The capacity spectrum is in spectral acceleration (S_{Ai}) - spectral displacement (S_{Di}) format. In the equations, the effective mass coefficient (α_i) and the modal participation factor (γ_i) are used, which, unlike the ATC-40, are values that vary in each step of analysis. In addition, the last variables refer to the mass of each floor (m_i) and the displacement of each floor (Δ_i) that also change in each step of analysis.

$$S_{Ai} = \frac{\sum_{i=1}^{n} m_i * \Delta_i^2}{\left(\sum_{i=1}^{n} m_i * \Delta_i\right)^2} * V_{Bi} = \frac{V_{Bi}}{\alpha_i * M_t} \qquad (5)$$

$$S_{Di} = \frac{\sum_{i=1}^{n} m_i * \Delta_i^2}{\sum_{i=1}^{n} m_i * \Delta_i} = \frac{1}{\gamma_i} \qquad (6)$$

In confined tubular masonry structures, the performance point can be evaluated based on the limit states of TABLE IV [16]. In this sense, the performance level of the structure is determined for a seismic hazard level.

TABLE IV
Limit states

Performance level	Limit state (drift)	Code
Occupancy (O)	0.0007	O
Immediate occupancy (IO)	0.001	IO
Life safety (LS)	0.0016	LS
Collapse prevention (CP)	0.0017	CP
Collapse (C)	0.0037	C

TABLE V shows the equivalence of the three performance level proposals [24], [25] and [16]. The equivalence is based on the description of damage that the structure presents after the seismic event.

TABLE V
Performance Levels

SEAOC-Vision 2000	ATC-40	Zavala et al.
Fully operational	Operational	Occupancy
Operational	Immediate occupancy	Immediate occupancy
Life safe	Life safety	Life safety
Near collapse	Structural stability	Collapse prevention
Collapse	Collapse	Collapse

Finally, it is important to present the performance objectives, as it shows the appropriate performance levels for each level of seismic hazard. In TABLE VI, two proposals are presented [24] and [25].

TABLE VI
Performance objectives

SEAOC-Vision 2000	ATC-40	Performance level
Frequent	-	Occupancy
Occasional	serviceability	Immediate occupancy
Rare	Design	Life safety
Very rare	Maximum	Collapse prevention

3.4. COST OF RETROFITTING

The cost of retrofitting depends mainly on the type of connection of the electrowelded wire mesh and the number of retrofitted faces. The mesh connection in the masonry and in all the elements of confinement is the most expensive. In this sense, the cost of retrofitting with the mesh connected to the masonry and the confinement columns is 46 dollars ($) for a single side and $ 71 for two sides per square meter. The costs were determined for the year 2023 and considered labor, materials and equipment [30]. In addition, the costs do not include value added tax.

4. RESULTS AND DISCUSSION

In this section, the results and discussions are presented in three sections. The first section presents the results and discussions of the model of the non-retrofitted and retrofitted walls of confined tubular masonry. The second section presents the seismic performance of non-retrofitted and retrofitted structures of confined tubular masonry and the retrofitting costs. The third section presents the seismic performance and costs of retrofitting of structures with optimized retrofitting.

4.1. MODEL FOR CONFINED MASONRY WALLS

The model is bilinear, and it is obtained from 14 tests, 6 corresponding to non-retrofitted walls and 8 to retrofitted walls with electrowelded wire meshes, as shown in TABLE VII. The curves of the 14 tests are converted to bilinear using the American Society of Civil Engineers (ASCE 41-13) procedure [18] based on equal energy. In addition, the model is calibrated using the multiple linear regression method.

TABLE VII
Dependent and independent variable for calibration

N°	Author	τ_y/F_m	$(P_t.\sigma_y/F_m)^{0.7}$	$P_{we}.\sigma_{we}/F_m$	σ_o/F_m	$(e.P_h.\sigma_{yh}/F_m)^{0.7}$
1	[18]	0.227	0.507	0.423	0.187	0.000
2	[18]	0.144	0.381	0.282	0.124	0.000
3	[10]	0.202	0.480	0.445	0.000	0.000
4	[19]	0.127	0.401	0.290	0.225	0.000
5	[13]	0.190	0.351	0.381	0.341	0.000
6	[14]	0.111	0.357	0.233	0.194	0.000
7	[10]	0.265	0.370	0.306	0.000	0.232
8	[11]	0.288	0.340	0.272	0.098	0.414
9	[11]	0.386	0.340	0.272	0.142	0.414
10	[13]	0.337	0.276	0.271	0.241	0.526
11	[14]	0.163	0.301	0.183	0.153	0.201
12	[14]	0.248	0.263	0.151	0.125	0.284
13	[12]	0.162	0.281	0.165	0.097	0.210
14	[12]	0.163	0.281	0.165	0.097	0.210

TABLE VIII presents the results of the calibration of the shear stress of non-retrofitted and retrofitted walls. In the table it is important to note that the coefficient of multiple determination (R^2) is close to unity, so it can be mentioned that there is a good fit.

TABLE VIII
Calibration results

Regression parameters		Standard error		Coefficient of multiple determination		Multiple correlation coefficient	
a_0	-0.049						
a_1	0.206						
a_2	0.370	Se	0.03336	R^2	0.88351	R	0.93995
a_3	0.029						
a_4	0.483						

Then, the regression parameters are replaced in equation (2) and equation (7) is obtained, which allows determining the shear stress of the non-retrofitted and retrofitted walls. The same procedure is followed to determine equation (8), which represents the drifts of the non-retrofitted and retrofitted walls of confined tubular masonry.

$$\frac{\tau_y}{F_m} = -0.049 + 0.206 * \left(\frac{P_t * \sigma_y}{F_m}\right)^{0.7} + 0.370 * \left(\frac{P_{we} * \sigma_{wy}}{F_m}\right) + 0.029 * \left(\frac{\sigma_0}{F_m}\right) + 0.483 * \left(\frac{e * P_h * \sigma_{yh}}{F_m}\right)^{0.7} \quad (7)$$

$$\Delta_y = \left[-0.454 + 6.087 * \left(\frac{P_t * \sigma_y}{F_m}\right)^{0.7} - 3.984 * \left(\frac{P_{we} * \sigma_{wy}}{F_m}\right) - 0.510 * \left(\frac{\sigma_0}{F_m}\right) + 3.183 * \left(\frac{e * P_h * \sigma_{yh}}{F_m}\right)^{0.7}\right] * 10^{-3} \quad (8)$$

Fig. 6 shows the bilinear model, which is constructed using three points. The first point is the origin, which does not require calculation. The second point is obtained using equations (7) and (8). Finally, the third point is obtained with equation (7) for the shear stress and using the drift of 0.0037 for non-retrofitted walls and 0.0050 for retrofitted walls [16] and [31]. These drift values are consistent with the average values of the ultimate drifts obtained from 14 experimental wall tests. The ultimate drift of the walls was obtained considering the ASCE 41-13 methodology, i.e. its value corresponds to 80% of the maximum resistance. Table IX shows that the average drift is 0.0041 for non-retrofitted walls. Table X shows that the average drift is 0.0062 for retrofitted walls.

TABLE IX
Confined tubular masonry walls without retrofitting

Author	Wall	Reinforcement	τ_{max} (Mpa)	Δ_{ult} (-)
[18]	1	NR	0.55	0.0049
[18]	2	NR	0.54	0.0057
[10]	3	NR	0.53	0.0051
[19]	4	NR	0.44	0.0025
[13]	5	NR	0.50	0.0050
[14]	6	NR	0.46	0.0015
Minimum	-	-	0.44	0.0015
Average	-	-	0.50	0.0041
Maximum	-	-	0.55	0.0057

TABLE X
Confined tubular masonry walls with retrofitting

Author	Wall	Reinforcement	t (Mpa)	Δ_{ult} (-)
[10]	7	R-M-2	0.69	0.0074
[11]	8	R-MC-2	0.90	0.0073
[11]	9	R-MC-2	1.03	0.0077
[13]	10	R-MCB-2	0.84	0.0053
[14]	11	R-MCB-1	0.70	0.0026
[14]	12	R-MCB-2	0.98	0.0098
[12]	13	R-MC-1	0.77	0.0032
[12]	14	R-MC-1	0.69	0.0065
Minimum	-	-	0.69	0.0026
Average	-	-	0.83	0.0062
Maximum	-	-	1.03	0.0098

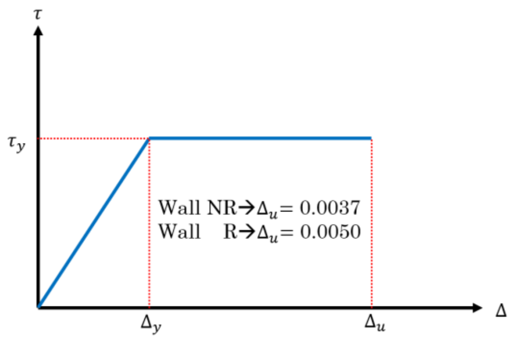

Fig. 6. Bilinear model of confined tubular masonry walls

The efficiency term (e) in equations (7) and (8) is a function of the type of connection of the electrowelded wire mesh in the wall. Therefore, its value is 0.45 when the mesh is connected only to the masonry, 0.65 when the mesh is connected to the masonry and the confinement columns and 1.00 when the mesh is connected to the masonry and all the confinement elements, since there is a study that indicates that when the mesh is connected only to the masonry, the resistance decreases to 45%, and if it is connected to the masonry and the confinement columns it decreases to 65%, with respect to the resistance of the wall with the mesh connected to the masonry and all its confinement elements [32].

The number of samples is small. For this reason, cross-validation is not applied. Moreover, the regularization method is not applied to rule out trivial independent parameters, since the parameters of the studies of Sugano et al. [21] and Diaz et al. [22], in which the method was applied, are considered.

4.2. SEISMIC PERFORMANCE AND COSTS

Seismic performance is determined based on two seismic demands. The first corresponds to the spectrum of NTE-E.030. The second corresponds to an average response spectrum plus two standard deviations of six seismic recordings. The six records correspond to the earthquakes in Lima in 1966, the Huaraz earthquake in 1970 and the Lima earthquake in 1974. In this sense, Fig. 7 is presented and using equation (4), Fig. 8 is determined.

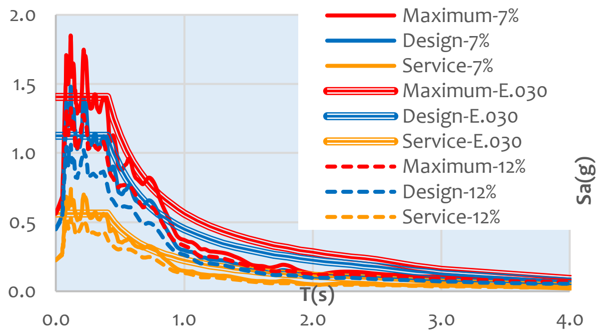

Fig. 7. Seismic demand spectrum (Sa-T)

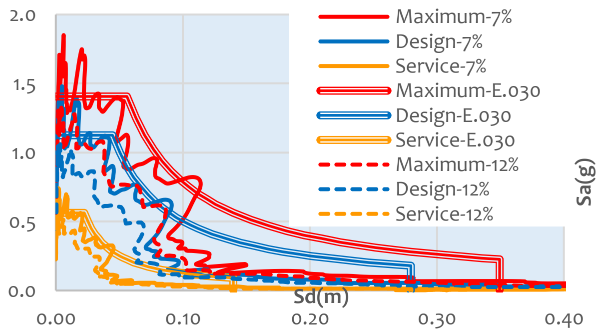

Fig. 8. Seismic demand spectrum (Sa-Sd)

Then, using the two seismic demands, the performance point and its corresponding performance level are determined. TABLE XI and TABLE XII are presented, which show the performance point and its corresponding level of performance of non-retrofitted and retrofitted structures of confined tubular masonry with a wall density of 1.4% in X-X and 3.7% in Y-Y. In addition, TABLE XIII and XVI are also presented for structures with wall density of 2.9% in X-X and 3.7% in Y-Y.

TABLE XI
Performance level of non-retrofitted structures – WD 1.4%

WD: 1.4 % in X-X and 3.7% in Y-Y			Non-retrofitted dwellings (NR)			
			1-story		3-story	
Demand	Axis	Seismic	Sa(g)	Sd(cm)	Sa(g)	Sd(cm)
NTE - E.030	X-X	Service	0.563	0.112	-	-
			Occupancy		Collapse	
		Design	-	-	-	-
			Collapse		Collapse	
		Maximum	-	-	-	-
			Collapse		Collapse	
	Y-Y	Service	0.563	0.046	0.563	0.273
			Occupancy		Occupancy	
		Design	1.125	0.091	-	-
			Occupancy		Collapse	
		Maximum	1.406	0.114	-	-
			Occupancy		Collapse	
7% y 12%	X-X	Service	0.655	0.130	-	-
			Occupancy		Collapse	
		Design	1.042	0.34	-	-
			Life safety		Collapse	
		Maximum	1.042	0.610	-	-
			Collapse		Collapse	
	Y-Y	Service	0.330	0.027	0.640	0.317
			Occupancy		Occupancy	
		Design	0.710	0.061	-	-
			Occupancy		Collapse	
		Maximum	0.880	0.072	-	-
			Occupancy		Collapse	

TABLE XII
Performance level of retrofitted structures – WD 1.4%

WD: 1.4 % in X-X and 3.7% in Y-Y			Retrofitted dwellings (Rxy)			
			1-story		3-story	
Demand	Axis	Seismic	Sa(g)	Sd(cm)	Sa(g)	Sd(cm)
NTE - E.030	X-X	Service	0.563	0.084	0.563	0.535
			Occupancy		Immediate o. (IO)	
		Design	1.125	0.168	-	-
			Occupancy		Collapse	
		Maximum	1.406	0.211	-	-
			Immediate o. (IO)		Collapse	
	Y-Y	Service	0.563	0.044	0.563	0.275
			Occupancy		Occupancy	
		Design	1.125	0.088	1.125	0.551
			Occupancy		Immediate o. (IO)	
		Maximum	1.406	0.110	1.406	0.695
			Occupancy		Life safety	
7% y 12%	X-X	Service	0.59	0.09	0.55	0.525
			Occupancy		Immediate o. (IO)	
		Design	1.200	0.18	-	-
			Immediate o. (IO)		Collapse	
		Maximum	1.510	0.230	-	-
			Immediate o. (IO)		Collapse	
	Y-Y	Service	0.320	0.027	0.640	0.310
			Occupancy		Occupancy	
		Design	0.680	0.051	1.290	0.630
			Occupancy		Immediate o. (IO)	
		Maximum	0.870	0.071	1.550	0.790
			Occupancy		Life safety	

TABLE XIII
Performance level of non-retrofitted structures – WD 2.9%

WD: 2.9% in X-X and 3.7% in Y-Y			Non-retrofitted dwellings (NR)			
			1-story		3-story	
Demand	Axis	Seismic	Sa(g)	Sd(cm)	Sa(g)	Sd(cm)
NTE - E.030	X-X	Service	0.563	0.058	0.563	0.362
			Occupancy		Occupancy	
		Design	1.125	0.116	-	-
			Occupancy		Collapse	
		Maximum	1.406	0.145	-	-
			Occupancy		Collapse	
	Y-Y	Service	0.563	0.048	0.563	0.291
			Occupancy		Occupancy	
		Design	1.125	0.096	-	-
			Occupancy		Collapse	
		Maximum	1.406	0.120	-	-
			Occupancy		Collapse	
7% y 12%	X-X	Service	0.460	0.048	0.540	0.345
			Occupancy		Occupancy	
		Design	0.930	0.100	-	-
			Occupancy		Collapse	
		Maximum	1.150	0.120	-	-
			Occupancy		Collapse	
	Y-Y	Service	0.330	0.027	0.601	0.313
			Occupancy		Occupancy	
		Design	0.710	0.061	-	-
			Occupancy		Collapse	
		Maximum	0.880	0.072	-	-
			Occupancy		Collapse	

TABLE XIV
Performance level of retrofitted structures – WD 2.9%

WD: 2.9% in X-X and 3.7% in Y-Y			Retrofitted dwellings (Rxy)			
			1-story		3-story	
Demand	Axis	Seismic	Sa(g)	Sd(cm)	Sa(g)	Sd(cm)
NTE - E.030	X-X	Service	0.563	0.053	0.563	0.336
			Occupancy		Occupancy	
		Design	1.125	0.106	1.125	0.672
			Occupancy		Immediate o. (IO)	
		Maximum	1.406	0.133	-	-
			Occupancy		Collapse	
	Y-Y	Service	0.563	0.047	0.563	0.292
			Occupancy		Occupancy	
		Design	1.125	0.093	1.125	0.585
			Occupancy		Immediate o. (IO)	
		Maximum	1.406	0.117	1.406	0.742
			Occupancy		Life safety	
7% y 12%	X-X	Service	0.410	0.040	0.550	0.335
			Occupancy		Occupancy	
		Design	0.850	0.084	1.100	0.66
			Occupancy		Immediate o. (IO)	
		Maximum	1.110	0.105	1.180	1.150
			Occupancy		Collapse p. (CP)	
	Y-Y	Service	0.320	0.027	0.605	0.315
			Occupancy		Occupancy	
		Design	0.680	0.051	1.200	0.630
			Occupancy		Immediate o. (IO)	
		Maximum	0.870	0.071	1.450	0.780
			Occupancy		Life safety	

The four tables show that increasing the density of walls improves the seismic performance of structures. The addition of retrofitting by electrowelded wire meshes improves the seismic performance of the structures. The vulnerability of structures increases when the number of levels increases. The seismic demand of the NTE-E.030 is higher than the other, since it is not considered a reduction factor because it is in the case of masonry structures that are very rigid.

TABLE XV presents the costs of retrofitting confined tubular masonry structures with wall densities of 1.4, 1.9, 2.4 and 2.9% in X-X and 3.7% in Y-Y. The cost of retrofitting increases with the amount of walls, since the retrofitting occurs in all walls.

TABLE XV
Costs of retrofitting – WD 1.4%, 1.9%, 2.4% and 2.9% in X-X

WD in X-X	Retrofitted dwellings (Rxy)			
	1Nivel	2Niveles	3Niveles	4Niveles
1.4%	$ 6309	$ 12617	$ 18925	$ 25234
1.9%	$ 6767	$ 13534	$ 20300	$ 27067
2.4%	$ 7237	$ 14473	$ 21710	$ 28946
2.9%	$ 7707	$ 15413	$ 23119	$ 30825

4.3. SEISMIC PERFORMANCE AND COSTS – OPTIMIZED RETROFITTING

In section 4.2, results of structures with all retrofitted walls have been presented and it has been noted that the retrofitting of all walls does not ensure the best performance of the confined tubular masonry structure, in addition to the excessive cost involved in reinforcing all the walls of the structure. It is important to note that for no type of retrofitting is it possible to prevent the 4-level structure from collapsing, the same happens for the 3-level structure with low wall density. Therefore, TABLE XVI is presented, which seeks to obtain the best seismic performance at the lowest cost of retrofitting.

TABLE XVI
Optimized retrofitting and costs of retrofitting

Optimized reinforcement		Wall density (WD)			
		X-X	X-X	X-X	X-X
Demand	Stories	1.40%	1.90%	2.40%	2.90%
NTE-E.030	1	Rx $ 2162	NR S/ 0	NR S/ 0	NR S/ 0
	2	R12x $ 4323	Ri1x $ 2162	Ri1x $ 2162	Re1xy $ 4034
	3	- .	- .	R12xy $ 14473	R12xy $ 15413
	4	- .	- .	- .	- .
7% y 12%	1	NR S/ 0	NR S/ 0	NR S/ 0	NR S/ 0
	2	R12x $ 4323	Ri1x $ 2162	Re1x $ 929	NR $ 0
	3	- .	- .	Ri12xy $ 7345	Ri12xy $ 7345
	4	- .	- .	- .	- .

TABLE XVII and XVIII present the performance points with their respective performance levels of the structures with optimized retrofitting. In addition, in Table XVIII only the 3-level structures with low density of wall (DM 1.4% and 1.9%) collapse in the face of the design earthquake. On the other hand, in Table XVII, for the service earthquake, it can be noted that only 3-level structures with low wall density (DM 1.4% and 1.9%) are operational or elastic state. The 4-level structures are not analyzed, since in the previous section it is determined that they do not prevent collapse for any retrofitting configuration.

TABLE XVII
Performance level of structures with optimized retrofitting-SE

WD: 3.7% in Y-Y			Wall density in X-X (Service Earthquake-SE)					
			1.40%		1.90%		2.40%	
Demand	Axis	Stories	Sa(g)	Sd(cm)	Sa(g)	Sd(cm)	Sa(g)	Sd(cm)
NTE - E.030	X-X	1	0.563	0.081	0.563	0.096	0.563	0.084
			Occupancy		Occupancy		Occupancy	
		2	0.563	0.252	0.563	0.241	0.563	0.216
			Occupancy		Occupancy		Occupancy	
		3	-	-	-	-	0.563	0.416
			Collapse		Collapse		Occupancy	
	Y-Y	1	0.563	0.046	0.563	0.046	0.563	0.047
			Occupancy		Occupancy		Occupancy	
		2	0.563	0.14	0.563	0.141	0.563	0.144
			Occupancy		Occupancy		Occupancy	
		3	-	-	-	-	0.563	0.282
			Collapse		Collapse		Occupancy	
7% y 12%	X-X	1	0.570	0.085	0.685	0.117	0.609	0.091
			Occupancy		Occupancy		Occupancy	
		2	0.660	0.300	0.650	0.280	0.660	0.300
			Occupancy		Occupancy		Occupancy	
		3	-	-	-	-	0.530	0.405
			Collapse		Collapse		Occupancy	
	Y-Y	1	0.330	0.027	0.330	0.027	0.330	0.027
			Occupancy		Occupancy		Occupancy	
		2	0.610	0.150	0.630	0.158	0.645	0.167
			Occupancy		Occupancy		Occupancy	
		3	-	-	-	-	0.650	0.310
			Collapse		Collapse		Occupancy	

TABLE XVIII
Performance level for structures with optimized retrofitting-DE

WD: 3.7% in Y-Y			Wall density in X-X (Design Earthquake-DE)					
			1.40%		1.90%		2.40%	
Demand	Axis	Stories	Sa(g)	Sd(cm)	Sa(g)	Sd(cm)	Sa(g)	Sd(cm)
NTE - E.030	X-X	1	1.125	0.161	1.125	0.192	1.125	0.168
			Occupancy		Immediate o. (IO)		Occupancy	
		2	1.125	0.503	1.125	0.638	1.125	0.478
			Life safety		Life safety		Life safety	
		3	-	-	-	-	1.125	0.965
			Collapse		Collapse		Life safety	
	Y-Y	1	1.125	0.093	1.125	0.093	1.125	0.094
			Occupancy		Occupancy		Occupancy	
		2	1.125	0.335	1.125	0.341	1.125	0.362
			Immediate o. (IO)		Immediate o. (IO)		Immediate o. (IO)	
		3	-	-	-	-	1.125	0.564
			Collapse		Collapse		Immediate o. (IO)	
7% y 12%	X-X	1	1.150	0.170	1.230	0.230	1.210	0.182
			Occupancy		Immediate o. (IO)		Immediate o. (IO)	
		2	1.180	0.620	0.970	0.473	0.825	0.510
			Life safety		Life safety		Life safety	
		3	-	-	-	-	0.970	1.015
			Collapse		Collapse		Life safety	
	Y-Y	1	0.710	0.061	0.710	0.061	0.710	0.061
			Occupancy		Occupancy		Occupancy	
		2	1.000	0.260	1.015	0.280	1.010	0.285
			Occupancy		Occupancy		Occupancy	
		3	-	-	-	-	0.895	0.484
			Collapse		Collapse		Immediate o. (IO)	

TABLE XIX and XX show the cost of retrofitting of all types or configurations of retrofitting for 3-story dwellings with different wall densities. In addition, the tables show the spectral displacement corresponding to the performance point for the design earthquake of the NTE-E.030 and the design earthquake of the response spectrum with critical damping of 7% and 12%. The value of 0.0 indicates that the capacity spectrum and the seismic demand spectrum do not intersect.

TABLE XIX
Cost of retrofitting – 3N: WD 1.9%, 2.4% and 2.9% in X-X (NTE-E.030)

G	Code	Cost ($)			Sd (cm)		
		1.90%	2.40%	2.90%	1.90%	2.40%	2.90%
1	NR	0	0	0	0.0	0.0	0.0
2	Rx	7858	9268	10677	0.0	0.0	0.654
3	Rxy	20300	21710	23119	0.0	0.0	0.672
4	R1x	2620	3090	3559	0.0	0.0	0.0
5	R1xy	6767	7237	7707	0.0	0.0	0.0
6	R12x	5239	6179	7118	0.0	0.927	0.653
7	R12xy	13534	14473	15413	0.0	0.965	0.684
8	Ri1x	2162	2162	2162	0.0	0.0	0.0
9	Ri1xy	3673	3673	3673	0.0	0.0	0.0
10	Ri12x	4323	4323	4323	0.0	0.0	0.0
11	Ri12xy	7345	7345	7345	0.0	0.0	0.0
12	Re1x	459	929	1398	0.0	0.0	0.0
13	Re1xy	3095	3565	4034	0.0	0.0	0.0
14	Re12x	917	1857	4323	0.0	0.0	0.0
15	Re12xy	6189	7129	8068	0.0	0.0	0.0

TABLE XX
Cost of retrofitting – 3N: WD 1.9%, 2.4% and 2.9% in X-X (7% and 12%)

G	Code	Cost ($)			Sd (cm)		
		1.90%	2.40%	2.90%	1.90%	2.40%	2.90%
1	NR	0	0	0	0.00	0.00	0.00
2	Rx	7858	9268	10677	0.790	0.840	0.665
3	Rxy	20300	21710	23119	1.320	0.910	0.660
4	R1x	2620	3090	3559	0.0	0.0	0.0
5	R1xy	6767	7237	7707	0.0	0.0	0.0
6	R12x	5239	6179	7118	0.935	0.815	0.665
7	R12xy	13534	14473	15413	0.0	0.835	0.660
8	Ri1x	2162	2162	2162	0.0	0.0	0.0
9	Ri1xy	3673	3673	3673	0.0	0.0	0.0
10	Ri12x	4323	4323	4323	0.965	0.0	0.515
11	Ri12xy	7345	7345	7345	0.0	1.015	0.525
12	Re1x	459	929	1398	0.0	0.0	0.0
13	Re1xy	3095	3565	4034	0.0	0.0	0.0
14	Re12x	917	1857	4323	0.0	0.0	0.0
15	Re12xy	6189	7129	8068	0.0	0.0	0.0

Retrofitting optimization occurs when a structure with some retrofitted walls presents better behavior or performance than a structure with all retrofitted walls. Moreover, it occurs when a structure with some retrofitted walls prevents structural collapse in the event of a design earthquake.

TABLE XIX shows that the best performance is presented by buildings with some retrofitted walls (R12xy), since they prevent the collapse of 3-level dwellings with wall density of 2.4% and 2.9% in the event of a design earthquake, while dwellings with all retrofitted walls (Rxy) avoid only the collapse of dwellings with a wall density of 2.9%.

TABLE XX clearly shows the optimized reinforcement, since it is evident that buildings with some reinforced walls (Ri12xy) prevent the collapse of 3-story houses with wall density of 2.4% and 2.9% in the event of a design earthquake at minimal costs, while buildings with all reinforced walls (Rxy) avoid the collapse of the same buildings. but at much higher costs.

CONCLUSIONS

- The calibrated model adequately represents the behavior of the non-retrofitted and retrofitted walls of confined tubular masonry, since the coefficient of multiple determination is close to unity.
- The seismic performance of non-retrofitted confined tubular masonry structures with low wall density is not adequate, as it does not meet the performance objectives of the SEAOC, for the two seismic demands.
- For the seismic demand of the spectrum of the NTE-E.030, it is appropriate to build non-retrofitted dwellings of one level with wall density of 1.9%, 2.4% and 2.9%, since with wall density of 1.4% with the principles of the NTE-E.030 are not met, i.e. they would collapse in the face of a rare or design earthquake.
- For the seismic demand of the response spectrum with critical damping of 7% and 12%, it is appropriate to build two-level non-retrofitted dwellings with wall density of 2.9%, since with a wall density of 1.4%, 1.9% and 2.4%, the dwellings could only be built up to one level to meet with the principles of the NTE-E.030.
- The seismic performance of the low-height, low-density retrofitted confined tubular masonry structures is adequate, since the performance objectives of the SEAOC are met for the two seismic demands.
- For the seismic demand of the spectrum of the NTE-E.030, it is appropriate to build retrofitted three-level dwellings with a wall density of 2.9%, since with wall density of 1.4%, 1.9% and 2.4%, the dwellings could only be built up to two levels to meet with the principles of the NTE-E.030.
- For the seismic demand of the response spectrum with critical damping of 7% and 12%, it is appropriate to build retrofitted three-level dwellings with wall density of 2.4% and 2.9%, since with wall density of 1.4% and 1.9%, the dwellings could only be built up to two levels to meet with the principles of the NTE-E.030.

- The optimization of the retrofitting allows that, for the seismic demand of the spectrum of the NTE-E.030, it is appropriate to build two-level dwellings with wall density of 1.4% with the retrofitted walls on the first and second levels of the X-X Direction (R2x) and 1.9% with the retrofitted internal walls on the first level of the X-X Direction (R1ix). In addition, for dwellings with wall density of 2.4% and 2.9% with the retrofitted walls on the first and second levels of the two main directions (R2xy), it is appropriate to build up to three levels, otherwise the principles of NTE-E.030 are not met.
- The optimization of the retrofitting allows that, for the seismic demand of the response spectrum with critical damping of 7% and 12%, it is appropriate to build two-level dwellings with wall density of 1.4% with the retrofitted walls on the first and second levels of the X-X Direction (R2x) and 1.9% with the retrofitted internal walls on the first level of the X-X Direction (R1ix). In addition, for dwellings with wall density of 2.4% and 2.9% with the retrofitted internal walls on the first and second levels of the two main directions (R2ixy), it is appropriate to build up to three levels, otherwise the principles of NTE-E.030 are not met.
- Non-retrofitted and retrofitted four-story dwellings of any wall density do not meet the performance objectives of the SEAOC. In addition, they do not meet with the principles of the NTE-E.030, since the dwellings would collapse in the event of a severe, rare or design earthquake.

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