PRACTICAL METHODOLOGY FOR IMPROVING SEISMIC PERFORMANCE OF MASONRY BUILDINGS IN MEXICAN TOWNS

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ABSTRACT :

In order to evaluate the structural vulnerability of masonry buildings on the basis of an earthquake disaster mitigation program, in this work a density of walls (DW) curve for Southern Mexican cities is proposed. A special methodology to compare the results with those obtained by 3D FEM models is also shown. Results shown that high damage can result on most of the studied cases as actual DW values for buildings in the shorter direction are extremely low. In order to avoid an inadequate structural behaviour, simple strategies as well as low cost retoffiting recommendations based on the obtained DW curve are proposed.

KEYWORDS: Masonry, Density of walls, Vulnerability, Building seismic performance.

1. INTRODUCTION

Masonry building construction is one of the principal economic activities in the Southern Mexican cities. This has been indeed produced by the dynamic and high increase of its population over the last twenty years. Most of the masonry buildings have reinforced concrete slabs and masonry walls confined by concrete elements; hand-made masonry clay or concrete bricks are the most extended used units for building. Unfortunately, no technical supervision is applied at their production process. Most extended type of footings are principally reinforced concrete footings, although masonry rock footings are still largely used. Most commun floor systems correspond to reinforced concrete slabs, which are continous and can be considered as good rigid diaphragms for transmitting seismic forces to the walls. Craks on walls are commonly found in this type of masonry buidings. They are produced by long term building settlements or by the seismic effect that loads have induced through the building's life. These cracks can reduce the seismic performance of walls. Masonry buildings with more of 30 years in this region have been already affected by several earthquakes. Thus, building stiffness can be strongly reduced now. In the other hand, new masonry buildings do not have been yet really tested by a strong earthquake as the last one did strike Guerrero's gap in 1907. Additionally, recent studies have detected that most of the masonry buildings have a non-adequated density of walls. Seismic evaluations of several confined masonry buildings in the Mexican State of Guerrero, built accordingly to the local and the Mexico City construcion regulations, established that most of the masonry houses had an exceptional performance during past intermediate intensity earthquakes. These researches shown that masonry building with strong damage during the 1985 Mexican earthquake was limitated to those with low density of walls (Alcocer, 1994). Cases where DW in the short direction was up to 50% or less presented strong structural damage even if excessive wall densities in the long direction were detected.

For this reason, a simple and a practical methodology to define the safety level of masonry buildings based on the density of walls is proposed. This aims to propose building retroffiting strategies in order to increase earthquake strenght of masonry buildings. In order to perform a practical home plan reviewing of the earthquake level safety for new an existing masonry buildings, a simple technical proposal for students and practical engineers, -specially for technical employes of local urban departments charged of designing, surveying and authorizing building construction-, is proposed. Structural evaluation is based on classic technical reviewing parameters, but most of all, on a density of walls (DW) curve.

2. METHODOLOGY FOR PREPARING A DW CURVE

Density of walls (DW) is an easy-obtaining adimensional parameter that allows to achieving fundamental information for earthquake performance evaluation of masonry buildings. DW is defined as the relation between the transversal area of walls, and the total built area (for a given story and direction for building). Optimal DW is that required in each of two perpendicular directions in order to withstand correctly seimic loading. DW is based on the simplified method for seismic design stated on the technical supplementary Mexican construction code for masonry buildings (NTCM, 2004). Recent obtained experiences in Mexico and other countries after the 1985 Mexican earthquake have shown the importance of this parameter in the earthquake performance of masonry buildings. Satisfactory behaviour shown by buildings during this strong earthquake and the aftershocks can be largely attributed to the prescribed seismic simplified method application. Buidings with important DW and overstrenghts were built due to this fact (Meli, 1994). Structural designing performed accordingly with the Mexican code allows obtaining satisfactory earthquake-resistant configurations. Then both, building damage or collapse can be strongly reduced. A good quality wall density in both perpendicular directions of a masonry building could be the key to provide excellent lateral load strength. Anyway, many times this recommendation is not observed for different reasons, principally limitations on building architectural configurations.

In order to apply the DW method, the same requirements of the Mexican seismic simplified method most been full filled, such as: symmetrical plants to avoiding torsional effects, excellent in-plant and elevation regularity to assuring rigid diaphragm behaviour at each building floor, total building height up to 13 m, etc. If these and some other aditional requirements are fully accomplished, building could be qualified as being appropriated to stand strong earthquakes, with only non-structural damage. Part of these requirements can be acompplished when masonry buildings have a convenable density of walls. Nevertheless, appropriated DW in both the two orthogonal directions must be verified since typical rectangular terrain configurations produce an extremely low DW in the paralel direction to the front of the masonry building. Employing the DW can be useful to improve the practical and fast structural building evaluation, so safety of masonry constructions can be quickly assessed. DW allows to define if the wall length amount is appropriated or not to stand seismic effects. After several studies performed by the UNAM (Meli, 1994), DW curves were proposed for buildings up to 5 stories (fig. 1). Anyway, this parameter is rarely used in Mexico for reviewing masonry buildings and houses. Oppositely, in several latinoamerican countries, like Peru, Ecuador and Colombia, DW curves are largely used for structural reviewing of new and existing buildings. Anyway, high DW is required by the Mexican and the local codes. This is obvious considering the high seismic coefficient used for this region, one of the most earthquake risking regions in the whole country. Another factor is the employment of an extremely conservative method of analysis to considering seismis effects. Thus, DW is also extremely high, producing undesirable non-fonctional architectural distributions and increasing building costs.

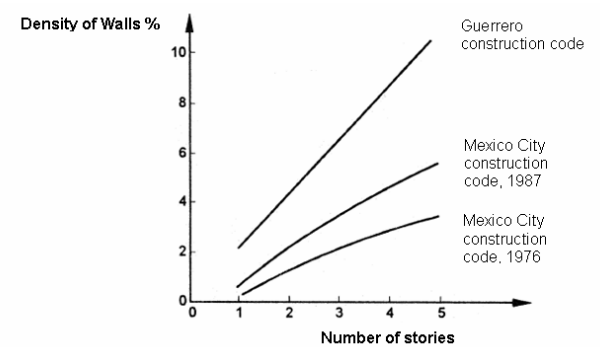


Figure 1 DW proposed by the Mexican and the Guerrero construction codes. (Meli, 1994)

For these reasons, in this work the methodology to determinate the density of walls curve for the Mexican Guerrero State is presented. In order to propose a more representative and adequated DW curve for the characteristics of the Guerrero buildings, analytical 3D models and earthquake spectra analysis were performed.

3. TYPICAL ARCHITECTURAL GEOMETRIC DISTRIBUTIONS IN GUERRERO STATE

Acapulco and Chilpancingo are two important southern Mexican cities full of contrasting types of home masonry structures. It can be found since rich residentials zones with high-cost luxury architectural designs until underprivileged homes and popular multistoried building compounds with a strong margination level. This last category does not accomplish basic safety structural conditions since it presents unfavorale earthquake resistant characteristics and a high vulnerability. So, this work deals with such a kind of construction. Most common architectural distribution for this type of buildings was determined. In order to characterize some effective strategies to reduce earthquahe damage on Guerrero common popular houses, several representative models were defined. Simple ramdom probabilistic sampling was performed to find these representative buildings. Architectural distributions and in-plant and elevation characteristics were taken into account. Extended sampling study of 302 existing buildings up to five stories in the two above mentioned cities was performed. Collecting of general data based on technical survey for structural evaluation process 1 and 2 was also performed (RGEG, 1999). Figure 2 shows, the ramdomly chosen urban zone and the selected micro-zonation area in Acapulco City. This zone was defined to perform technical and structural surveying of buildings and homes. Visual inspection facilitated registration of the basical building characteristics. Geometry, walls distribution, type of materials and the number of stories were some of the collected data. A building properties catalog was prepared with these data. Ten different types of architectural distributions and their variations were defined. Figure 3 presents a part of these data. It was found that there are basically simple quadratic and rectangular architectural plants. Important openings and irregularities were seldom found.

Figure 2 Ramdomly selected urban zone in Acapulco City, Mexico

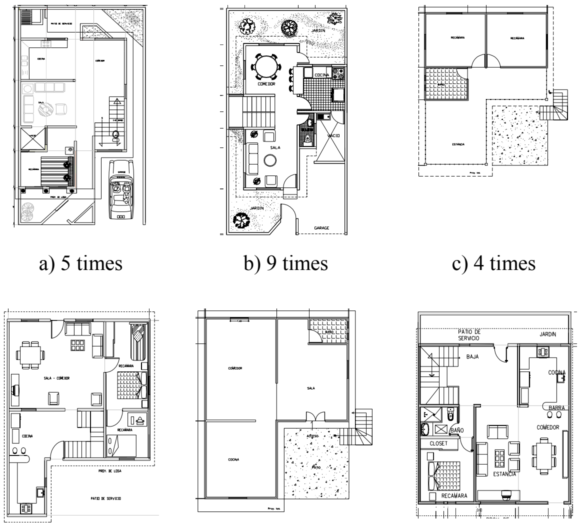
Buildings were modeled with SAP2000 analysis software. Table 1 shows typical characteristics of the studied homes and buildings. Data must be considered approximated. Only small value variations were detected. From the study it was found that at least 13% of the studied cases do not presents neither confining reinforced concrete elements on walls nor elements to strenght window and door openings. This situation must be considered of high vulnerability and risk. Table 2 shows mechanic characteristics of the structural materials. Mexican construction code specifications (NTC) were verified. For the case of concrete, Young's module was reduced in a 10% in order to obtain more conservative results. Local masonry presented a higher variability strength results compared with those obtained for concrete.

Table 1 Typical characteristics of building masonry houses

Wall thickness (cm)	Geometry (m)		Slab dimensions (m)		Confining R. C. element dimensions (cm)
	Windows	Doors	Min.	Max.	
15 -17	Width: 1 a 1.2 Height: 1 a 1.4	Width: 0.9 a 1.2 Height: 1.9 a 2.1	3	Up to 6	20 x 20, 20 x 25 y 25 x 25

Table 2 Data for numerical models

Property	Concrete	Steel	Masonry
Specific weight	0.0235 N/cm^3 (2.40 Ton / m^3)	0.077 N/cm^3 (7.849 Ton / m^3)	0.0167 N/cm^3 (1.7 Ton / m^3)
Young's module	15,504 N/mm^2 (1'581,000 Ton/m^2)	205,939 N/mm^2 (21'000,000 Ton/m^2)	588.39 ~ 882.59 N/mm^2 (60 000 ~ 90 000 Ton / m^2)
Poisson's module	0.18	0.30	0.16 ~ 0.18



a) 5 times b) 9 times c) 4 times

d) 5 times e) 6 times f) 7 times

Figure 3 Tipology of some common popular masonry houses in southern Mexican cities

Table 3 Earthquake spectra analysis parameters

Seismic zone: D, Soil type: II, Construction type: B	
Masonry type	Hand-made bricks, $f_p^* \geq 5.88$ N/mm^2 (60 kg/cm^2), mortar type I, f^*_m=1.47 N/mm^2 (15 kg/cm^2), v_m^*= 0.3432 N/mm^2 (3.5 kg/cm^2)
Reduction factors for excentricity and slenderness effects (F_E)	Interior walls. F_E = 0.7; for walls bearing lenghts with variations up to 50%. Exterior walls. F_E = 0.6; for exterior walls.
Reduction factor for axial-compresional strenght: 0.6 Reduction factor for shearing strength: 0.7	

4. NUMERICAL MODELS

Representative houses were modelled with the SAP2000 analysis software. Self-weigh loads and seismic loading were automatically generated. Thick shells up to 1 m^2 were employed to build FEM models for slabs and walls. Bending and membrane stresses in shells were activated and diaphragms constrictions were applied on concrete slabs in order to perform more accurate analyses. Frame elements of 15 x 15 cm and 15 x 20 cm were employed to simulate vertical and horizontal RC confining elements. Walls and slabs thickness were 15 and 10 cm respectively. Figure 4 shows some of the numerical models used for the static and dynamic earthquake spectra analysis.

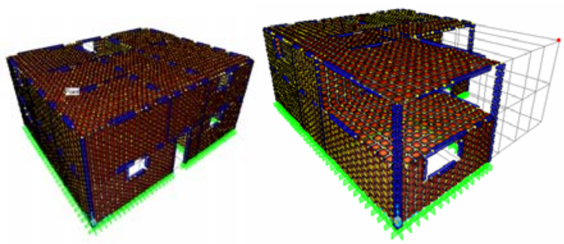


Figure 4 Numerical models of masonry representative houses and buildings for Southern Mexican cities

Optimal architectural configuration for the representative masonry buildings was determined performing sequential analysis. Total building mass was revised and taken into account each time that walls were added or eliminated in the process to find optimal wall density. In order to define the shearing force at every story for each of the modifications, additional exhaustive process was performed. Therefore, shearing resistant force was compared with the acting one obtained at each step. The shearing force for masonry, v_{mR}, was calculated with the following expression:

$$Vm_R = FR(0.5V_m * A_t + 0.3P) \leq 1.5FRV_m * At \quad (4.1)$$

Where V_m* is the diagonal compression strenght for masonry, A_T is the total cross section area of the wall and FR is a reduction factor of 0.8. In order to define the seimic acting shearing force, the following expression was used:

$$F_i = \frac{W_i(h_i)}{\sum((W_i)(h_i))} v_o \quad (4.2)$$

Where W_i is the total story weight and h_i is the effective story height. Shearing at each story (V_i) was determined with the following equation:

$$V_{(i-1)} = F_i + F_{(i-1)} \quad (4.3)$$

Ultimate shearing at each story (Vu) was determined with the following equation:

$$V_u = F.C.(earthquake) * V_{(i-1)} \quad (4.1)$$

Where F.C. is the seismic loading factor. In order to define density of walls (DW) and to build the respective curve for the Mexican Guerrero State, optimal earthquake strength for each of the studies cases were calculated. For this, the acting shearing force in a determined story (V_u), must be identical to the resistant shear force at that story (V_R). This is valid for the two building perpendicular directions:

$$V_u = V_R \quad (4.5)$$

Once the equilibrium of forces was reached (eq. 4-5), DW was calculated at each direction (x, y). Figure 5 shows the obtained results. DW curve was calculated with the following equation:

$$DW = \frac{\sum F_{AE} A_T}{A_p} \quad (4.6)$$

Where DW is the density of walls (in the x or y direction), $\Sigma F_{AE} A_T$ is the total product of the cross section area of the whole walls and the effective section factor for each one of the analysed directions. A_p is the total built area. In order to carry out this procedure, special interactive software was designed for processing the data in a fast way and to obtain the optimal values of DW for each case. In this software input with specific data of buildings was registered (including weight, wall lenght, built total area, number of stories, etc.). A non-linear regression with the Curve-Expert software was performed in order to obtain the DW best fitted curve. The following exponential fonction was chosen:

$$DWn = 1.3329\, n^{1.1721} \quad (4.7)$$

Where DW_n is the required density of walls for the n story and n is the story where the density of walls is calculated (< 5). The quadratic average of data dispersion R^2 was appropriated, with a 0.995 value. Resulting acting shearing forces were 25% smaller than those obtained with the simplified seismic method. Figure 5 shows the DW curve for the Mexican Guerrero State. This curve is also compared with that proposed in reference 5.

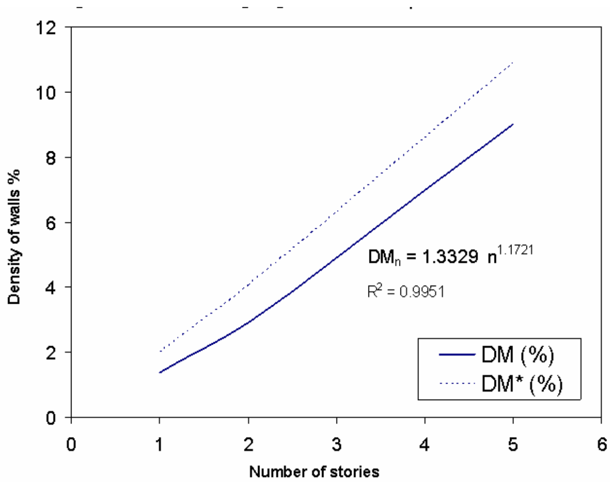


Figure 5 Comparisson between suggested DW curve and that proposed in reference (DW*) (Meli, 1994)

From the previous figure, it can be observed that the density of walls recommended in reference 5 is bigger than the one suggested in this work. Difference between the two curves is more important as the number of stories is bigger.

5. RESULTS

Application of the DW curve is very simple. All the factors concerning the service and ultimate loads have been fully considered. In this way, the curve is given exclusively in function of the number of stories. Nevertheless, use of the DW curve can be validated only if the principal requirements for the application of the seismic simplified method are fully filled. In order to show the revision process for the acting and resistant shearing force in buildings, the following example shows briefly the application to a 5 storied masonry building. The first step is to determine the total length of walls at each floor. Relation between story height (*H*) and length of wall (*L*) must be carefully verified. In order to take into account slenderness in slim walls, wall length must be reduced using the factor (F_{AE}) given in the following equations:

$$F_{AE} = 1 \; ; \; if \; \frac{H}{L} \leq 1.33 \text{, and } F_{AE} = \left(1.33\frac{L}{H}\right)^2 ; \; if \; \frac{H}{L} > 1.33 \tag{5.1}$$

Some analysis were performed without considering the wall slenderness (this process was called “fast method”). Results shown that there is not a signifative difference with those obtained with the convencional suggested method. For this reason, no significative error would be introduced if the “fast method” is used for quick structural evaluation purposes. Naturally, the requirements for applying the simplified seismic method must be fully accomplished too. Results of the structural building analysis as well as a condensed summary for determination of the DW are briefly presented in table 4.

Table 4 DW for a 5 storied masonry building

Story	Direction	Total length of walls (m)	Total wall cross section (m^2)	Existing DW (%)	Required DW (%)
1st floor	x	22.7	3.4	2.6%	9.02
	y	40.0	6.0	4.5%	9.02
Superior floors	x	22.4	3.4	2.5%	2nd floor: 7.17% 3th floor: 4.92% 4th floor: 2.80% 5th floor: 1.40%
	y	20.2	3.0	2.3%	

Figure 6 shows the strong difference between the required and the actual DW for this building. Only the 5th story has an appropriated DW, so this structure presents an eminent damage risk to big earthquakes.

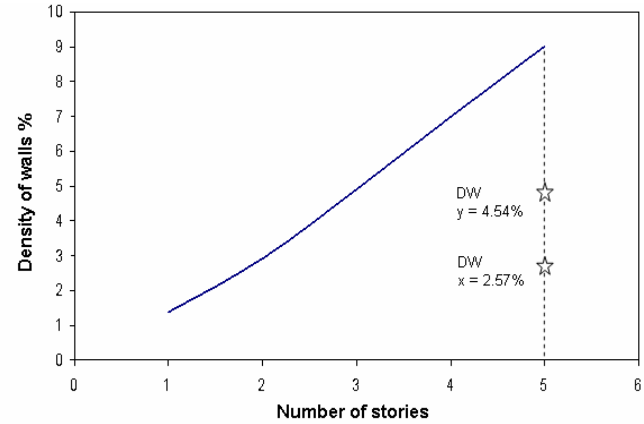


Figure 6 DW for a typical 5 storied masonry building

Total length of walls can be determined to obtain an optimal wall density (V_u = V_r) and then, required walls lenght can be distributed on the floors. Special care must be observed regarding the total weight for each story when new wall lenghts are added. Additional improtant verifications and considerations must be taken into account in order to avoid non adequated architectural spaces. In the present example, required density of walls for the 1st floor is 9.02% in direction "x", against the low existing value of 2.57%. In direction "y" the existing DW is only of 4.54%. DW requires a total wall length of 80 m for each direction in order to satisfy the local code recommendations. Such an excesive length of walls could introduce architectural problems in the building. Moreover, it will be necessary to consider additional retroffiting strategies in order to increase the building resistance to seismic loading (RC-walls and stiffening systems, etc.).

In most of the Mexican provincial municipalities, Public Urban Develepment Departments charged of the home-plans technical review do not perform any study to define the earthquake safety level of buildings. Only just non significant issues, such as ventilation and ilumination, are vaguely reviewed. In order to avoid such kind of practices and to facilitate the fast seismic evaluation of homes and buildings, a simple methodology was proposed. It consists in the following facts: Figure 7 shows the DW curve suggested for the Mexican Guerrero State. It has 4 zones which aim to help into the retroffiting and strenghtening system determination for masonry buildings and houses. Table 5, suggests economical retroffiting, stiffening and strengthenning strategies for each zone defined in figure 7. For example, zone 1 is the most critic region. Thus, recommendations in table 5 propose to increase the total wall length.

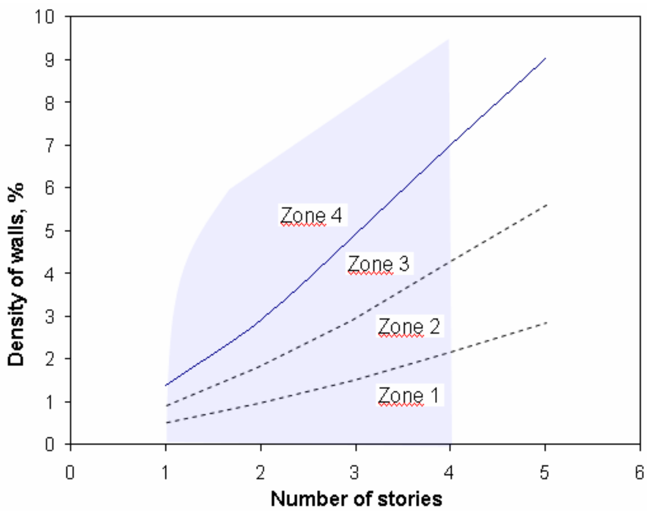


Figure 7 DW curve zones for seismic retrofitting of masonry buildings in Guerrero, Mexico

Table 5 Retrofitting strategies for masonry buildings, based on DW zones for the Mexican Guerrero State

Zone		Strategies
4	✓	No retrofitting is needed.
3	✓	Applying a layer of high quality mortar (1cm) on both the two faces of the masonry wall.
2	✓	Applying high quality layer mortar reinforced with an electric-welded mesh.
	✓	Employing steel reinforcing bars at the horizontal mortar joints between bricks (5/32" steel bars or 5/16" HR steel bars).
1	✓	Increasing the wall's length (architectural distribution reviewing is required).
	✓	Combining masonry walls with RC-walls (technical assistance is required).

6. CONCLUSIONS

From the structural analyses performed on different architectural distributions of masonry buildings, a DW curve was proposed for the Mexican Guerrero State. A simplified and a practical methodology to verify the earthquake safety of masonry buildings was consequently recommended. To apply it, both the data of architectural and the estructural building configurations are required. Acting shearing force to define the DW curve was determined employing earthquake spectra analysis. Thus, an apreciable reduction was obtained compared with the DW curve proposed by Meli (Meli, 1994). Nonetheless, the proposed DW curve still demands a wall density of around 18% for buildings up to 5 stories (9% for each one of the perpendicular directions). This could deals to an antieconomic and non-practical architectural configutrations. For this reason, using the suggested methodology is recommended only for masonry buildings up to 4 stories. Suitable zones for reviewing this type of buildings are shown in figure 7. Convenable and more appropriated architectural configurations can be obtained with the reduced DW curve. Moreover, better seismic response of masonry buildings can be achieved. This methodology offers simple and practical strategies to retroffit buildings with low actual DW. In order to assure an appropriated structural performance, these strategies must be applied only with qualifyed technical assistance. Further studies for establishing a more general DW curve that considers acceptable overstrength and in-plant and elevation excenticities are also necessary.

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