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Slenderness in Wall-frame Systems: Corrective factors for the Valley of Mexico

Esbeltez en Sistemas Marco Muro: Factores correctivos para el Valle de México

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Resumen

Introducción: Las metodologías y procedimientos utilizados en el diseño de edificaciones que muestra el Reglamento de Construcciones de la Ciudad de México 2017 están basadas en técnicas de confiabilidad y desempeño, sin embargo, los factores que se aplican en esta norma para sistemas irregulares tienen fundamento en la práctica ingenieril.
Objetivo: El objetivo de esta investigación es la obtención de factores correctivos aplicables a la normatividad de mexicana para el diseño de estructuras de concreto con características de esbeltez y con sistema marco-muro.
Metodología: Se realizó el análisis, diseño y comparativa de dos familias de edificios de concreto con sistema dual, la primera familia se caracteriza por cumplir con los requisitos de regularidad delimitadas en la normativa, la segunda familia irrumpe con el requisito de esbeltez, ambas familias están formadas por edificios de 11, 15 y 20 niveles. De cada edificio se creo una muestra con un mínimo de 50 edificios mediante el método de Montecarlo variando sus propiedades mecánicas, geométricas, cargas vivas, cargas muertas y acciones sísmicas representativas. Las muestras fueron evaluadas mediante un análisis de confiabilidad y posteriormente comparadas.
Resultados: Se dan recomendaciones para la obtención de factores basados en confiabilidad y desempeño asociadas a una aceleración específica del terreno y diferentes grados de esbeltez.

Conclusiones: El reglamento de Construcciones de la Ciudad de México contempla únicamente el factor de irregularidad por esbeltez cuando la relación altura/base es mayor a 4 y además se cuente con otra irregularidad en la edificación. Este estudio muestra que los edificios con relaciones de esbeltez mayores que 4 deben ser consideradas como irregulares y debe aplicarse un factor correctivo de acuerdo con su grado de esbeltez, esto a su vez sin haber infringido alguna otra irregularidad.

Palabras Clave

Edificios irregulars; esbeltez; confiabilidiad; sistema marco muro; marco de concreto; Opensees.

Abstract

Introduction: The methodologies and procedures used in the design of buildings shown in the Mexico City Building Regulations 2017 are based on reliability and performance techniques, however, the factors applied in this standard for irregular systems are based on engineering practice.
Objective: The aim of this research is to obtain corrective factors applicable to the Mexican standards for the design of concrete structures with slenderness characteristics and with frame-wall system.
Methodology: The analysis, design and comparison of two families of concrete buildings with dual system, the first family is characterized by complying with the requirements of regularity delimited in the regulations, the second family breaks with the requirement of slenderness, both families are formed by buildings of 11, 15 and 20 levels. For each building, a sample of at least 50 buildings was created using the Montecarlo method, varying their mechanical and geometric properties, live loads, dead loads and seismic actions. The samples were evaluated by means of a reliability analysis and then compared.
Results: Recommendations are given for obtaining reliability and performance based factors associated with specific ground acceleration and different degrees of slenderness.
Conclusions: The Mexico City Building Regulations only considers the slenderness irregularity factor when the height/base ratio is greater than 4 and there is also another irregularity in the building. This study shows that buildings with slenderness ratios greater than 4 should be considered as irregular and a corrective factor should be applied according to their degree of slenderness, this in turn without having infringed any other irregularity.

Keywords

Irregular buildings; slenderness; reliability; frame-wall system; concrete frames; Opensees.

1 Introduction

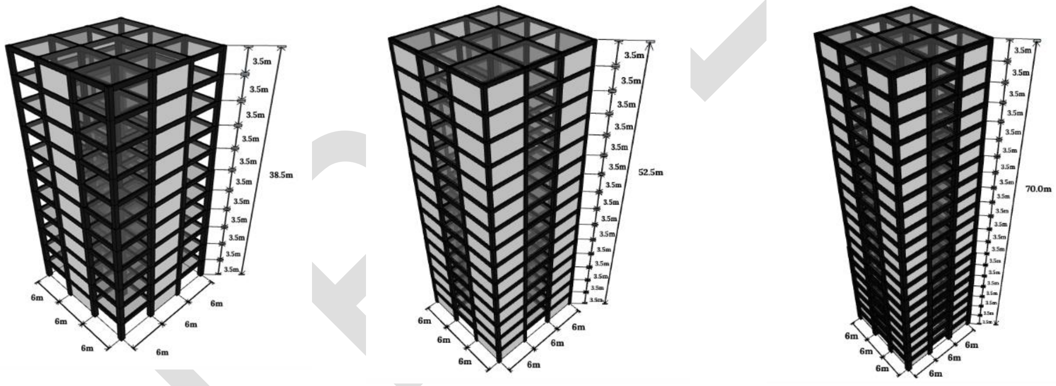
The Mexico City Building Regulations and its Complementary Technical Standards (RCCDMX and NTC respectively, in their Spanish acronyms) have been for years the basis for the design of buildings in the metropolis. These regulations go through reviews and updates when major events occur. The RCCDMX17 and its NTC17 (regulations published after the September 19th, 2017, seismic event that strongly shakes Mexico City) are based on reliability and performance of structures, however, the factors related to irregularities in buildings applied in seismic design spectrum so far are based on engineering criteria. In this research corrective factors are proposed for seismic design spectrum specifically for buildings with slenderness irregularity. Two families of buildings (11, 15 and 20 levels) with frame-wall system were analyzed. The first family conforms the regulations marked by the NTC17 to be considered regular while the second family does not satisfy slenderness condition (height-base ratio greater than or equal to 4.0).

The modelled buildings are founded at Lake zone (potent deposits of highly compressible clay strata often covered superficially by alluvial soils, dried materials and artificial fill materials) and defined with irregularity factor equal to 1.0. For prototypes with same number of levels their fundamental period must be similar (, for meaningful comparisons between them (regular building is the reference and through an iterative process the sections of the irregular building are set to get the closest fundamental period).

The software SIB (Simulation of Buildings) (Rangel and Esteva, 2015) [5] was used for obtaining the numerical framework that considers the uncertainties for live load, dead load, dimensions of the cross sections, coverings, area of the reinforcing steel and the spacing of the stirrups. A step-by-step nonlinear analysis was performed for each 3D model (of distributed plasticity) using the Opensees program (Mazzoni et. al, 2006) [6]. The input seismic records were obtained for different return periods using the hybrid method developed by Esteva and Ismael (2004) [7]. For each orthogonal directions on seismic inputs, the minimum secant stiffness reduction index ($IRRS$) and the reliability (according to the minimum value of the intensity required to produce collapse) (Esteva and Díaz, 2006) [4] of each building were obtained. A mathematical equalization of the reliability functions of the systems that share the same number of levels and fundamental period was performed. Comparing the Cornell beta (β) of a regular system with its irregular simile a corrective factor to be applied to the ordinates of the design spectrum stablished by the RCCDMX, is obtained.

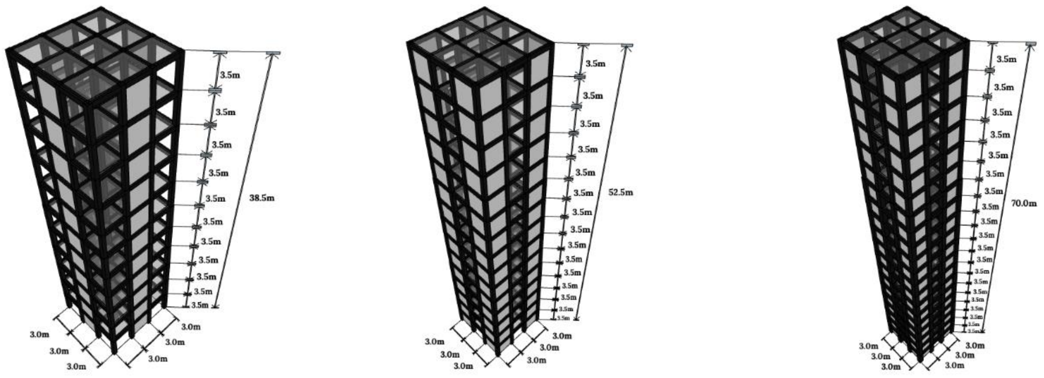
2 Description of the models

The analyzed objects are two reinforced concrete set of buildings with wall-frame system. These buildings are set in the iconic SCT site (Secretariat of Communications and Transportation) (Zone III or Lake). The first set are structures with a square base of 18 x 18 m and height-base ratio less than 4, this family is defined by the NTC17-Seism as regular buildings (Fig. 1). For the second set, the base is of 9 x 9 m with height-base ratios greater than 4, catalogued as irregular (Fig. 2). Both families were designed with a ductility factor Q = 2 and a correction factor of irregularity equal to 1. The soil-structure effects were considered by translational and rotational stiffnesses, and damping coefficients (as specified in the NTC17-Seism) using the Vásquez method (2010) [8]. The whole set of buildings were designed with f'c 250 kg/cm^2 and fy=4200 kg/cm^2, in Tables 1, 2 and 3 their cross-sections and fundamental periods are shown.



Regular Building 1 Regular Building 2 Regular Building 3

Fig. 1 3D view of a family of "Regular buildings".



Irregular Building 1 Irregular Building 2 Irregular Building 3

Fig. 2 3D family view of "Irregular buildings".

Table 1 Cross sections in Regular Buildings

Building	Floor	Column dimensions (m)	Beam dimensions (m)	Thickness slab (m)	Wall thickness (m)
Regular Building 1	1-6	0.75 x 0.75	0.32 x 0.60	0.15	0.48
	7-11	0.60 x 0.60	0.30 x 0.60	0.15	0.30
Regular Building 2	1-5	0.60 x 0.60	0.45 x 0.60	0.15	0.45
	6-10	0.55 x 0.55	0.45 x 0.60	0.15	0.40
	11-15	0.50 x 0.50	0.40 x 0.50	0.15	0.30
Regular Building 3	1-7	1.05 x 1.05	0.80 x 1.00	0.15	0.45
	8-14	0.85 x 0.85	0.60 x 0.85	0.15	0.40
	15-20	0.75 x 0.75	0.65 x 0.75	0.15	0.30

Table 2 Cross Sections in Irregular Buildings

Building	Floor	Column dimensions (m)	Beam dimensions (m)	Thickness slab (m)	Wall thickness (m)
Irregular Building 1	1-6	0.50 x 0.50	0.35 x 0.48	0.10	0.35
	7-11	0.45 x 0.45	0.35 x 0.45	0.10	0.35
Irregular Building 2	1-5	0.55 x 0.55	0.35 x 0.55	0.10	0.35
	6-10	0.50 x 0.50	0.35 x 0.50	0.10	0.35
	11-15	0.45 x 0.45	0.35 x 0.45	0.10	0.35
Irregular Building 3	1-7	0.85 x 0.85	0.60 x 0.85	0.10	0.40
	8-14	0.80 x 0.80	0.50 x 0.80	0.10	0.40
	15-20	0.65 x 0.65	0.45 x 0.65	0.10	0.40

Table 3 Periods of studied systems

Mode	Regular Building 1 (sec)	Regular Building 2 (sec)	Regular Building 3 (sec)	Irregular Building 1 (sec)	Irregular Building 2 (sec)	Irregular Building 3 (sec)
1	0.921	1.083	1.25	1.003	1.157	1.303
2	0.921	1.083	1.25	1.003	1.157	1.303
3	0.608	0.624	0.734	0.659	0.695	0.516
4	0.231	0.256	0.347	0.269	0.296	0.321
5	0.231	0.256	0.347	0.269	0.296	0.321
6	0.156	0.157	0.215	0.183	0.186	0.166
7	0.108	0.118	0.167	0.123	0.131	0.151
8	0.108	0.118	0.167	0.123	0.131	0.151
9	0.074	0.075	0.106	0.085	0.085	0.096
10	0.064	0.071	0.101	0.073	0.077	0.096
11	0.064	0.071	0.101	0.073	0.077	0.095
12	0.043	0.048	0.071	0.05	0.052	0.069

3 Building modeling

Traditional structural modeling does not explicitly express the uncertainties associated with human error in construction, design, material qualities, etc. In this investigation these uncertainties were considered through Montecarlo simulations (program "Simulation of buildings", Rangel and Esteva, (2015) [5]. Variations in live loads are simulated using the traditional load intensity model Pier and Cornell, (1973) [9] and the contributions of Soriano and Ruiz (1997) [10], while the conditions of dead loads follow the recommendations of Ellingwood, et al. (1980) [11]. Cross sections and reinforcing steel are set according to Mirza and McGregor (1979) [12, 13] and Rodríguez and Botero (1996) [14] and mechanical properties of concrete to Mendoza and Meli (1991) [15, 16].

More than 50 conditions were simulated under Montecarlo for each building. In the simulations (Opensees running) has *DispBeamColumn* elements with 5 discretizations in beams and 3 in columns (fiber type sections are under Navier-Bernoulli hypothesis). The model calibrated by Vásquez and Gallardo (2018) [17] was used for reinforced concrete walls using *TRUSS2* type elements and *ConcretewBeta* material (Stevens et al, 1991) [18], the beam and column materials used in Opensees were *Concrete01* for the unconfined concrete, *Concrete02* for the confined concrete and *Steel02* for the reinforcing steel. The soil-structure interaction was modeled using a *ZeroLength* element with a master node with the *equaldof* command.

3.1 Seismic inputs

The buildings are analyzed under the two simultaneous orthogonal seismic components representative of soils in SCT site. The intensity measure was taken as:

$$S_a(T) = \frac{S_{ax}(T) + S_{ay}(T)}{2} \quad (1)$$

where

$S_{ax}(T)$, $S_{ay}(T)$ = Pseudo-accelerations of the response spectrum associated with the fundamental period of the structure in the X and Y direction respectively.

The analyses of Esteva, Díaz and García (2010) [19] were used to obtain the seismic hazard in the site, where the accelerations associated with the fundamental period of each building under study were obtained for different return periods (Tables 4 and 5).

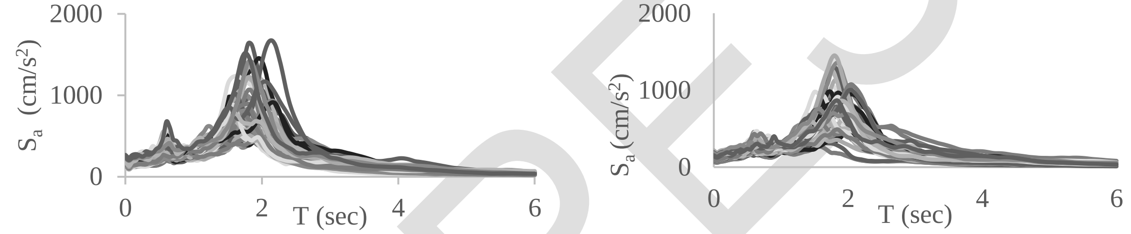
Table 4 Accelerations associated with the fundamental period of regular structures

Return period	Regular Building 1	Regular Building 2	Regular Building 3
T_r (years)	Acceleration (cm/s^2)	Acceleration (cm/s^2)	Acceleration (cm/s^2)
250	206.5	271.3	335.0
500	234.7	308.7	385.0
1000	261.5	350.7	433.5
2500	305.3	411.6	511.0
5000	339.9	458.4	575.0

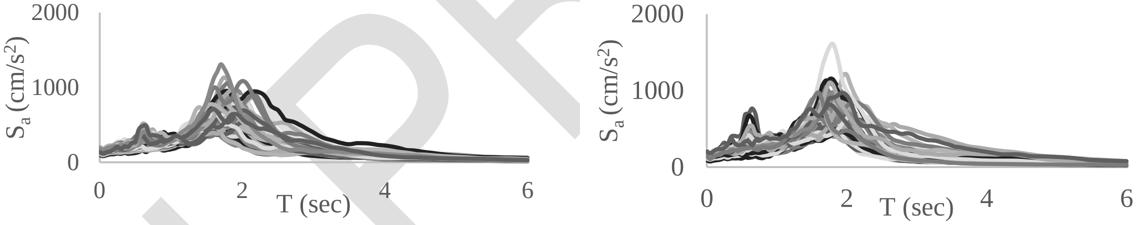
Table 5 Accelerations associated with the fundamental period of irregular structures

Return period	Irregular Building 1	Irregular Building 2	Irregular Building 3
T_r (years)	Acceleration (cm/s^2)	Acceleration (cm/s^2)	Acceleration (cm/s^2)
250	241.1	295.8	345.65
500	274.3	337.4	394.40
1000	307.5	391.2	446.99
2500	359.9	455.5	526.58
5000	399.1	506.6	592.86

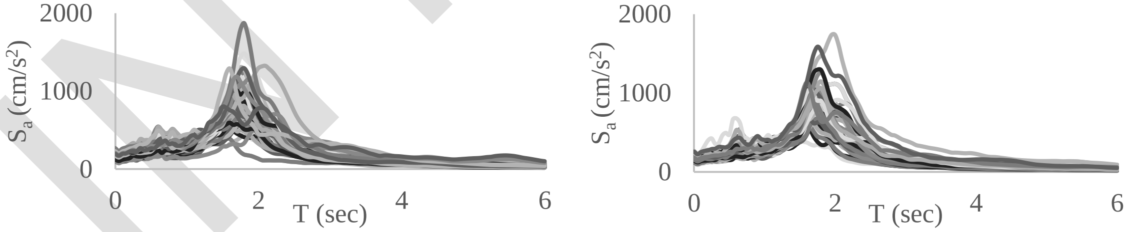
For considering extreme earthquakes, a minimum of 10 pairs of records were simulated for each return period shown in Table 4. and Table 5, obtaining 50 pairs of accelerograms for each structural system (according to Ismael and Esteva, (2006) method) [20]. The average response spectrum obtained for each pair of simulations in the X and Y directions with Eq. (1) are shown in Fig. 3.



Regular Building 1 Irregular Building 1



Regular Building 2 Irregular Building 2



Regular Building 3 Irregular Building 3

Fig. 3 Spectrum used in regular and irregular buildings

4 Results

4.1 Secant Stiffness Reduction Index

The "Secant stiffness reduction index" (I_{RRS}) proposed by Esteva and Díaz (2006) [4] was obtained. This index has the advantage of being a global indicator that generalizes the stiffness reduction of the system by taking the secant stiffness of a nonlinear dynamic analysis. I_{RRS} = 0 can be interpreted as the initial stiffness of the structure did not reduced and I_{RRS} = 1 means that the structure failed. This index is expressed as:

$$I_{RRS} = \frac{K_0 - K_S}{K_0} \tag{2}$$

where

K_0 = Initial system stiffness
K_S = Secant stiffness of the system

Both K_0 and K_s were determined for each simulated building using hysteresis curves derived from nonlinear dynamic analyses. Each simulated building underwent a nonlinear analysis with a low-intensity earthquake to obtain its initial stiffness (K_0), and subsequently, it was evaluated with medium and high-intensity earthquakes to obtain its secant stiffness (K_s) by means of the following expression:

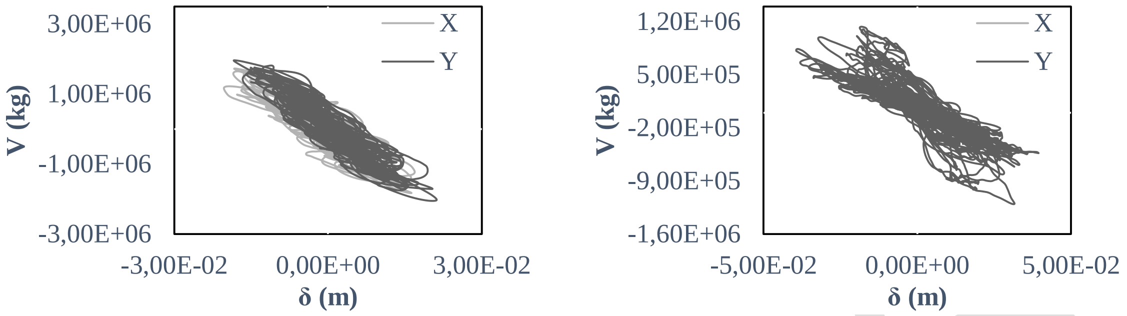
$$K_{(0,S)} = \frac{\delta_a}{V_b} \tag{3}$$

where

δ_a = Maximum displacement at the roof center of masses
V_b = Basal shear associated with the maximum displacement at the roof center of masses

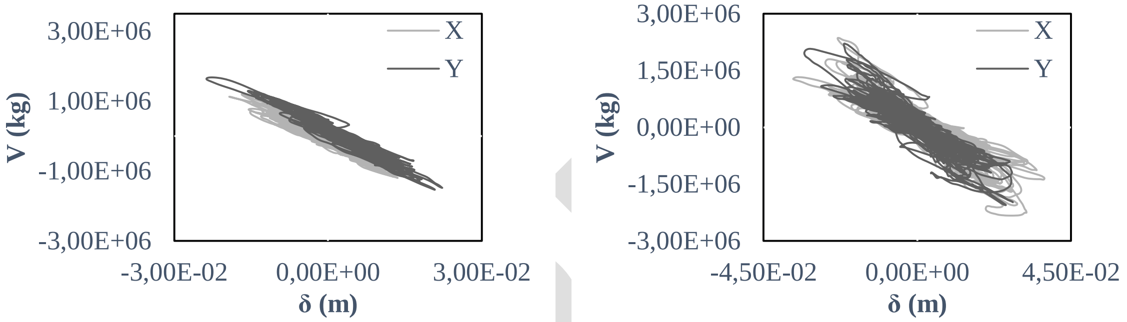
4.2 Step-by-step nonlinear dynamic analysis

The parameter K_0 is obtained from nonlinear analyses for low intensity earthquakes where the structure remains in the linear range. Analogously, K_S results of analyses with intermediate and high magnitude earthquakes where the structure is in the nonlinear range. Each analysis (for K_0 and K_S) was developed in 3D and with simultaneous earthquakes obtaining 2 hysteresis curves, one corresponding to the X direction and the other corresponding to the Y direction. The resulted I_{RRS} are for each quadrant and the largest one is selected to represent the greatest degradation of stiffness of the system (global view). Some responses for X and Y directions are shown in Fig. 4.



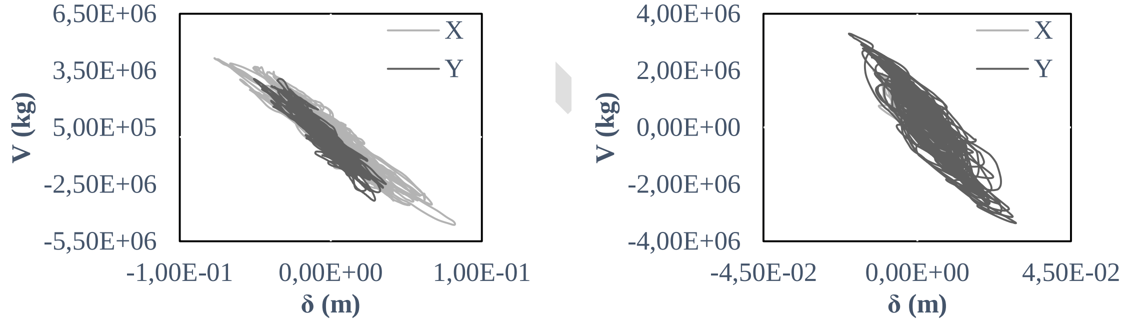
Regular Building 1 - case 1

Irregular Building 1 - case 100



Regular Building 2 - case 38

Irregular Building 2 - case 21



Regular Building 3 - case 61

Irregular Building 3 - case 19

Fig. 4 Global responses of the systems

4.3 Reliability criteria

To obtain the reliability functions, the seismic capacity of the structural systems is expressed by the minimum collapse intensity (Y_C) (Esteva and Díaz, 2006) [4] and the safety margin (Z_m):

$$Z_m = ln\frac{Y_C}{y} = ln\,Y_C - ln\,y = Z_F - Z \tag{4}$$

where

$ln\,Y_C = Z_F$ = Natural logarithm of the minimum value of the intensity required to produce collapse
$ln\,y = Z$ = Natural logarithm of the seismic intensity

The beta index (β) (Cornell, A., 1969) [21], as a reliability measurement parameter, is set by:

$$\beta(y) = \frac{E(ln\,Y_C) - ln\,y}{\sigma_z(\,ln\,Y_C)} = \frac{E(Z_F\,) - Z}{\sigma_z(\,Z_F)} \tag{5}$$

where
$E(ln\,Y_C) \quad = E(Z_F\,)$ = Expected value of the natural logarithm of minimum value of the intensity required to produce collapse
$\sigma_z(\,ln\,Y_C) = \sigma_z(\,Z_F)$ = Standard deviation of the natural logarithm of the minimum value of the intensity required to produce collapse

Let $Z = ln\,y$, we define $Z(u)$ as the natural logarithm of the random variable Y associated with a value of $I_{RRS} = u$ for a building under study. A sample of pairs of random values is required to estimate the mean and standard deviation of $Z(u)$. It is known that at the instant of failure where $I_{RRS} = 1$, the values of Z ($Z_F = ln\,Y_c$) show the intensity at which buildings fail. However, it is not possible to obtain the minimum intensity at which they would fail (Z_F). Therefore, examples from the sample that exhibit failure behavior should not be included in estimating $E\ [Z(u)]$ and $\sigma\ [Z(u)]$ through a least squares regression.
If the sample includes cases where it equals 1.0, those statistical moments E[$Z(u)$│α1] and σ[$Z(u)$│α2] and the corresponding parameters {α1, α2} should be determined using a maximum likelihood criterion employed by Ismael E and L. Esteva [20].

$$\mathrm{L}(\alpha_1, \alpha_2) = \prod_{i=1}^{m} f_Z(z_i|u_i, \alpha_1, \alpha_2)\ \prod_{j=1}^{n} [F_Z(z_j|u_j, \alpha_1, \alpha_2)]$$

where m is the number of pairs of values ($z_i,\ u_i$) for u_i < 1.0, and n is the number of pairs of values for u_j =1. f_Z and F_Z are the normal density function and cumulative distribution function respectively. The maximum likelihood criterion is used because values of u = 1 can be reached for different intensity values, and to apply the least squares fitting criterion, it is necessary to work with the minimum values of intensity that lead to u = 1.

A comparison of the reliability functions obtained for regular and irregular buildings is shown in Fig. 5.

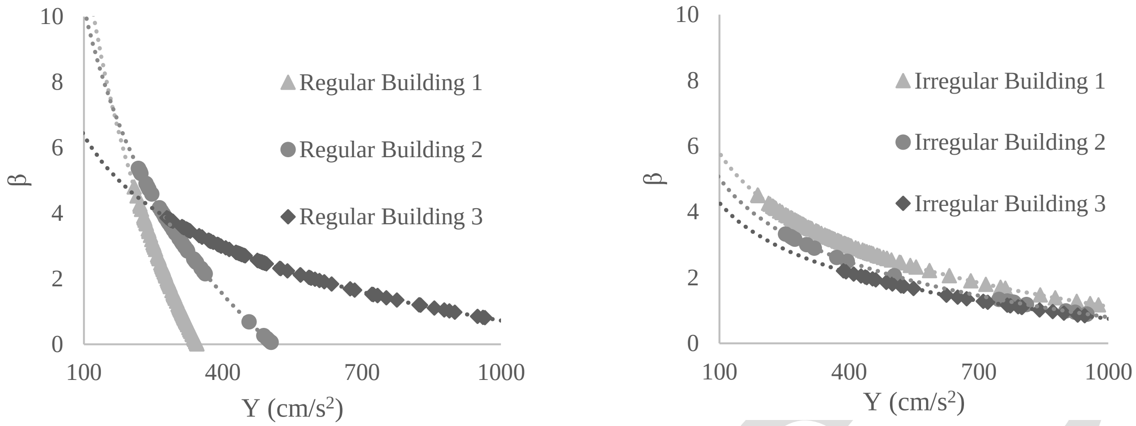


Fig. 5 Comparison of reliability functions for studied systems.

5 Corrective factors

For the determination of the corrective factors, the following assumptions were made:

i. Both families (regular and irregular) are founded on the same site.
ii. The family of regular buildings shares the same floor plan dimensions.
iii. The family of irregular buildings shares the same floor plan dimensions.
iv. Each regular building will be associated with an irregular one with the same height.
v. The comparative buildings share the same number of levels with the same mezzanine heights.
vi. The comparative buildings share the same arrangement of beams, columns, and walls.
vii. The comparative buildings share a similar fundamental period.
viii. The comparative buildings comply with the stipulations of the RCCDMX and its NTC.
ix. The comparative buildings are designed with irregularity factors equal to 1.0.
x. The comparative buildings will share the β of the regular system ($\beta_{Regular\ Building}$) associated to a representative acceleration of 250 years defined in the RCCDMX17 and its NTC17.

A graphical representation of the comparative reliability equations of a regular building versus an irregular building is shown in Fig. 6.

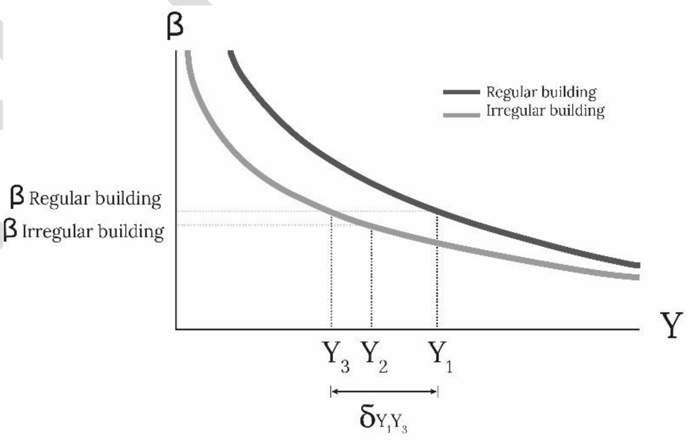


Fig. 6 Comparison of reliability equations for regular and irregular buildings.

The reliability equations of a regular building and an irregular building are expressed as:

$$\beta_{Regular\ building} = -a\, Ln(Y) + b \tag{7}$$

$$\beta_{Irregular\ building} = -c\, Ln(Y) + d \tag{8}$$

Same level of reliability between irregular and regular buildings, involves:

$$\beta_{Regular\ building} = \beta_{Irregular\ building} \tag{9}$$

The equality shown in Eq.9 defines the same level of reliability for the regular system as for the irregular system. We use the equation of the irregular system evaluated at Y_3 that equals the reliability of the regular system, as shown below:

$$-a\, Ln(Y_1) + b = -c\, Ln(Y_3) + d \tag{2}$$

Clearing Y_3 from Eq. 10:

$$Y_3 = Y_1^{\frac{a}{c}}\, e^{\frac{d}{c} - \frac{b}{c}} \tag{11}$$

The acceleration Y_1 is taken as a reference for regular systems, the difference that has with Y_3 for irregular systems is:

$$\delta_{Y_1 Y_3} = Y_1 - Y_3 \tag{12}$$

The addition of $\delta_{Y_1 Y_3}$ to the acceleration Y_2 represents the acceleration at which the irregular building must be designed.

$$Y'_2 = Y_2 + \delta_{Y_1 Y_3} \tag{13}$$

The corrective factor of the ordinates of the design spectrum of accelerations for the slender irregular system will be given by:

$$\alpha_{Y_2} = \frac{Y'_2}{Y_2} \tag{14}$$

The properties of the simulated cases are summarized in Table 6.

Table 6 Reliability equations for each system

Building	$\boldsymbol{\beta}_{Regular\ building}$	$\boldsymbol{\beta}_{Irregular\ building}$
1	β = -9.578ln(Y) + 55.959	β = -2.033ln(Y) + 15.165
2	β = -6.325ln(Y) + 39.413	β = -1.838ln(Y) + 13.496
3	β = -2.457ln(Y) + 17.698	β = -1.527ln(Y) + 11.300

Applying the equations above to the reliability functions of each building, the corrective factors that affect the ordinates of the design spectrum are show in Fig. 7.

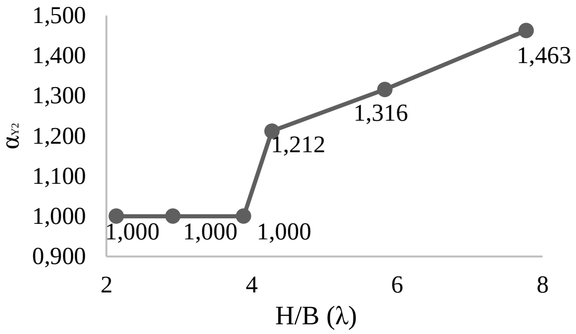


Fig. 7 Corrective factors for slenderness

Fig. 7 shows the corrective factors applicable in the design spectrum to match the reliability levels of a slender system and a regular system, these factors increase when the slenderness ratio is greater than 4.0. Finally, the inverse of these corrective factors are the irregularity factors (Fig. 8) applicable in RCCDMX17 and its NTC17.

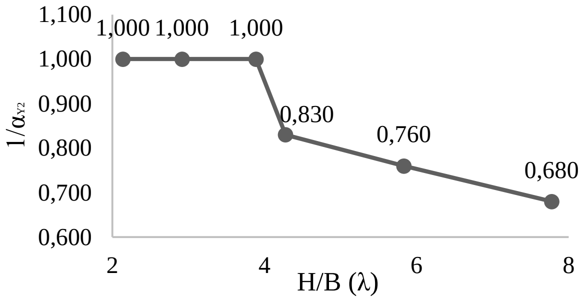


Fig. 8 Irregularity factors for slenderness

6 Conclusions

Reliability based corrective factors applicable to the seismic design spectrum marked in the RCCDMX17 and its NTC17 were obtained for buildings designed with Q=2 and classified as slender with wall-frame system founded in zone III of the lake.

NTC17-Seism specifies that to satisfies the condition of "regular building" the ratio of the height to the smallest dimension of its base must not be greater than 4, thus an irregular building is assigned an irregularity factor of 0.8, which coincides with 0.83 calculated for a slenderness of 4.28. However, the 0.8 factor specified in the regulation does not apply unless there is another irregularity in the building. Therefore, it would not meet the reliability requirements specified in this study.

Since as of 2017 the design spectrums are performed through the SASID software [3] and since this only provides the irregularity factors of 1.0, 0.8 and 0.7, the following proposal is made in the use of this tool:

To take in consideration the irregularity factor, the following conditions are recommended:

- **Irregular structure**

  A structure will be considered irregular slender if it satisfies the requirement where "The ratio of its height to the smallest dimension of its base ***is greater than 4.0 and less than 6.0****" (it is not necessary not to satisfy another requirement described in section 5.0 of the NTC17S).*

- **Very irregular structure**

  *A structure will be considered very irregular if it does not satisfy two or more of the requirements described in section 5.0 of NTC17-seismic or if the ratio of its height to the dimension of **its base is greater than 6.0 and less than 8.0.***

Table 7 Irregularity factors suggested for *SASID* tool

Structure classification	Relation (H/B)	Irregularity factor
Regular	$(H/B) < 4$	1.0
Irregular	$4 \leq (H/B) < 6$	0.8
Very Irregular	$6 \leq (H/B) < 8$	0.7

In case of using the equations of the NTC17-Seism to obtain the design spectrum, it is recommended to use the values from the Fig. 8.

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Declarations

Conflicts of interests and competing interests

- The authors have no relevant financial or non-financial interests to disclose.
- The authors have no conflicts of interest to declare that are relevant to the content of this article.
- All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.
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