SEISMIC BEHAVIOR PROFILE FROM DYNAMIC AND RESILIENCE PARAMETERS, FOR BUILDINGS DESIGNED WITH THE MEXICAN REGULATIONS

Alberto Teranishi [(1)], Octavio García [(2)], Carlos Villaseñor [(3)]

[(1)] *Adjunct Professor, Universidad Nacional Autónoma de México, aatc76@hotmail.com*
[(2)] *Professor, Universidad Nacional Autónoma de México, posgradoingcivil@ingenieria.unam.mx*
[(3)] *Adjunct Professor, Universidad Nacional Autónoma de México, cvmdiseno@gmail.com*

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Abstract

Keywords: Resilience; Bio-Seismic Profile; Structural behavior.

In this work, research is continued in which the results of the application of criteria and / or methodologies used to establish a qualification of the health and structural behavior of an important group of existing buildings in Mexico City are exposed and discussed, representative of the various types of constructions, whose analytical study and evidence of damage to recent earthquakes, allowed to redefine limits of the dynamic parameters required by the methodology to assess structural health.

Based on the concept called "Bio-Seismic Profile of Buildings", developed in Chile by the Engineers Tomás Guendelman, Mario Guendelman and Jorge Lindenberg, a qualification for the buildings is established, which considers dynamic and structural parameters related to the design philosophy seismic in Mexico, based on the ductile behavior of buildings. The methodology has been extended and characterizes the buildings through 15 indicators of seismic behavior, among which are considered the type of structuring, the mechanical properties of the elements, the parameters that govern the dynamic behavior of the structures and the response obtained before actions seismic.

The results obtained from the application of the methodology of health and structural behavior are consistent with the seismic response observed in the buildings evaluated, despite having been designed with regulations prior to the one derived from the great earthquake of September 19, 1985 occurred in Mexico City. In this work, the evaluation methodology is updated and expanded, including the structural behavior of the types of buildings that had significant damage or that collapsed as a result of the earthquake of September 19, 2017, caused by a failure mechanism other than the one generated historically the earthquakes of great destruction in Mexico. The new parameters considered in the methodology are associated with characteristics of structural resilience, such as resistance and construction materials, as well as the existence of "soft floor" in structures.

The results obtained from the application of this methodology are compared and discussed, with evidence of damage caused and / or actual response experienced during two types of intense earthquakes, one associated with a subduction phenomenon, off the southwest coast of the Mexican Pacific and another generated by a normal type intraplate failure, close to Mexico City.

1. Introduction

The resilience and / or vulnerability of a structure before or after the occurrence of an earthquake can be estimated from various methods that assume hypotheses and simplified approaches to reach analytical methods that provide more detailed information. The type of analysis method selected depends on the purpose of the evaluation, the availability or existence of data and the resources and technology available, (Aragón, 2013).

At present there are different classifications of the methods of evaluation of the seismic vulnerability of buildings, most of them are defined based on the available information of the structures to be evaluated and take into account the different types and analytical or empirical procedures, necessary to obtain a good estimate of the state of the buildings. Calvi and Pinho, (Calvi, 2006), propose a classification of these methods into 2 large groups: empirical and analytical. Empirical methods establish a relationship between the damage existing in the structure and a damage scale proposed by specialists, based on the behavior of similar characteristic buildings. For analytical methods, the damage scale is obtained from the calculation of the mechanical properties of a building for a given damage limit state, calculated from the forces induced by an earthquake, (Aragon, 2013).

This article presents the most recent results of an investigation that focuses on the estimation of the possible behavior that it could experience due to intense seismic effects, based on the concept of Bio-Seismic Profile updating the behavioral parameters established in the current regulation of Mexico City (RCDF-2017). Previous studies, (Guendelman, 2010), have shown that this approach allows to detect deficiencies of the proposed or existing structural conceptions or systems, to define possible corrections; It has been seen that the methodology can be applied to buildings constructed with other design philosophies other than those of Chile.

The Bio-Seismic Profile is a methodology or instrument that allows us to evaluate the "health" of a building, by reviewing a series of global indicators associated with its structural conception and its dynamic response, to seismic actions, which allows detecting deficiencies in the resistant structure, with the purpose of proposing possible corrections, or recommending complementary studies of greater analytical rigor.

This article presents and discusses the results of the application of the aforementioned methodology to establish a qualification of health and structural behavior for 3 selected existing buildings, one of reinforced concrete of 15 levels, another of steel of 22 levels and one of 5 levels of masonry with “soft floor” at its base, subjected to intense earthquakes and its correlation with the real response experienced before events of this nature. To determine the required behavioral parameters, dynamic modal spectral analyzes were performed on the buildings, in accordance with the Complementary Technical Standards for Earthquake Design of the RCDF-2017. In addition, there was information on the eye inspection performed on the buildings.

From the application of the methodology of health and structural behavior, it was found that the results obtained are consistent with the seismic response observed of the structural inspection of the buildings, despite having been designed with regulations prior to the one derived from the earthquake of September 19, 1985. Based on these results, it is proposed to expand the application of this methodology to evaluate other types of buildings.

2. Bio-seismic profile

The concept of Bio-Seismic Profile was presented for the first time at the VII Chilean Conference of Seismology and Earthquake Engineering, ACHISINA, by engineers Tomás Guendelman, Mario Guendelman and Jorge Lindenberg, held in 1997.

The good behavior that the buildings had before the earthquake of March 3 in Chile, suggested to the engineers to investigate and document the characteristics and dynamic parameters of these buildings, starting from a base of 585 real buildings, with which it was possible to develop a methodology of seismic qualification of reinforced concrete buildings through the evaluation of indicators, which are compared with values considered satisfactory. Initially, its field of action was limited to buildings of up to 30 floors, with its use recommended in buildings close to 20 floors, because the statistical sample of that time was concentrated in that number of levels. It is important to mention that the calculation of the indicators is carried out based on the results that come from the normative seismic analysis, (Latorre, 2010). In subsequent works, the range of application coverage has been expanded, (Henoch, 2007), including the so-called skyscrapers, which are tall buildings whose worldwide trend in their use has become extended, (Latorre, 2010).

It should be mentioned that in the indicators originally considered, there is no evidence of over-strength and the relationship of interstorey stiffnesses, which are also important for establishing the structural demand, the ductility and resilience of the structure, so they are incorporated into this work. Based on the above, the seismic indicators are grouped into three groups:

Rigidity Indicators

1. Total height / period first translational mode.
2. Effect P - Δ
3. Offset of the upper level.
4. Maximum displacement of mezzanine in center of gravity.
5. Maximum additional displacement of mezzanine at extreme points.

Coupling indicators.

6. Rotational period / translational period.
7. Coupling equivalent rotational mass / direct translational equivalent mass.
8. Dynamic Eccentricity / radius of basal rotation.
9. Coupled translational equivalent mass / direct translational equivalent mass.
10. Attached basal cut / direct basal cut.
11. Moment of coupled basal turn / moment of direct basal turn.

Indicators of Structural Redundancy and Ductility Demand.

12. Number of structural elements in seismic resistance.
13. Effective spectral reduction factor.
14. Over-resistance factor
15. List of mezzanine rigidities

In Table 1, a summary is presented with the recommended limits of each indicator, according to the regulations in force for design in Mexico (NTCDS of RCDF-2017).

Table 1 - Summary of limits for indicators of the Bio-Seismic Profile

Bio-seismic Profile Indicators	Values within normal ranges (Original)	Values within normal ranges (NTCDS)	Acceptable value slightly away from normal ranges. (Original)	Acceptable values slightly away from normal ranges. (NTCDS)
Rigidity				
1. H / T [m/s]	30 – 70		20 – 30 y 70 – 150	
2. $M_{P-\Delta} / M_{basement}$	0 – 0.1	0 – 0.08		
3. $1000\ \delta / H$	0.2 ‰ – 2 ‰	2 ‰ – 12 ‰	0 ‰ – 0.2 ‰	0 ‰ – 2 ‰
4. $1000\ \delta_{gc} / h$	0.2 ‰ – 2 ‰	2 ‰ – 12 ‰	0 ‰ – 0.2 ‰	0 ‰ – 2 ‰

5. 1000 (δ_{end} - δ_{gc}) / h	0 ‰ – 1 ‰	0 ‰ – 6 ‰		
Link translation - rotation and translation - translation				
6. T_θ / T^*	0 – 0.8 y 1.2 – 1.5		0.8 – 1.2 y 1.5 – 2.0	
7. $M_{nx\theta}$ / M_{nx}, $M_{ny\theta}$ / M_{ny}	0 – 0.2		0.2 or more	
8. e_{din} / $r_{basement}$	0 – 0.2		0.2 or more	
9. M_{nxy} / M_{nx}, M_{nyx} / Mny	0 – 0.5		0.5 or more	
10. Q_{0xy} / Q_{0xx}, Q_{0yx} / Q_{0yy}	0 – 0.5		0.5 or more	
11. M_{v0xy} / M_{v0xx}, M_{v0yx} / M_{v0yy}	0 – 0.5		0.5 or more	
Structural redundancy and ductility demand				
12. N	More than 3		2 – 3	
13. Q’	Does not apply	2 –3	Does not apply	3 – 4
14. R	Does not apply	1 – 3	Does not apply	
15. K_{i+1} / K_i	Does not apply	0 - 20	Does not apply	

3. Case studies

3.1 Building 1 (Picacho Tower).

Building 1 has office use, it is a reinforced concrete structure with 13 levels and 1 basement. Its structural system consists of columns and flat reticular slab, with a concrete core at the center of the floor, containing the elevators and internal stairs. The basement is a compensated foundation with concrete walls perimeter to the building that allows distributing the loads to the foundation. The concrete wall continues until the ground floor only in the adjoining walls that are perpendicular to the street where the building is located. In fig. 1 a view of the developed structural model is presented.

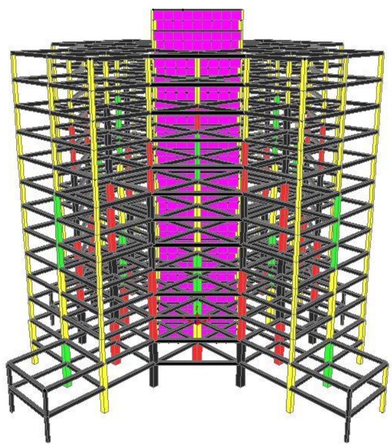

Fig. 1 – Structural model by building 1

The building is located in zone I or hills (firm ground) according to the seismic zoning that establishes the Complementary Technical Standards for Earthquake Design (NTCDS) of the RCDF and the software System of Design Seismic Actions (SASID), with a dominant soil period of approximately 0.5 seconds.

A dynamic analysis of the structure was carried out based on the design spectrum corresponding to zone I (firm ground). Gravitational and lateral loading conditions (earthquake) were considered and the corresponding combinations established by the NTCs for earthquake design were defined, including bidirectional effects, fig. 2.

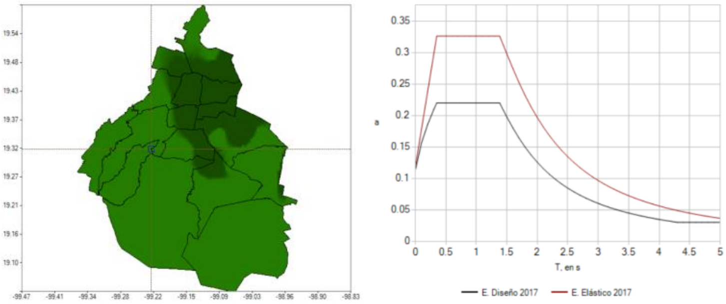

Fig. 2 – Seismic zoning and design spectrum of building 1

Based on the results of the structural analysis, the review of the resistance and service limit states was carried out, finding that the building complies reasonably, despite the fact that the building was designed and constructed before the appearance of the current regulation. (García O. and Granados R., 2007)

3.2 Building 2 (Executive Tower).

Building 2 has office use, it is a mixed foundation construction, parking basements and a core of walls in the central area of stairs and elevators solved on the basis of reinforced concrete in a square arrangement of 10 m side, while surrounding the concrete wall core, 8 metal columns located 7.5 m from the corners of the wall core are added and a tower-shaped superstructure is formed with a square plan, whose sides measure 25 m, which rises in 21 floor levels based on reinforced concrete slabs, supported by metal beams consisting of parallel and diagonal V-strings. To the 1st. Level (13.15 m), only the central core of concrete walls can be seen, lined with precasts with sculptural low-reliefs; this creates a large hall with a free height close to 12.00 m between the floor of the lobby and the plafond of the level 1 floor.

It stands out that the corners of this tower are double flown of 7.5 m. In the area of the core of concrete walls, toilets are located at medium levels with structure of reinforced concrete slabs and beams that support the walls. The stairs are based on reinforced concrete ramps loaded on standard 12” joist metal rails. The interstorey heights are uniform from Level 1 to Level 21, but as mentioned in the previous paragraph, there is a hall with an approximate height of 12 m. around the central core. From Level 21 (Roof) upwards, the core of concrete walls is continued, to structure the Machine Room of the elevators; in the outer perimeter the 8 metal columns are continued and connected to the central core on the roof of the machine room with 7.5 m metal bars, forming like a pergola. Finally, the entire external perimeter has a window and glass, protecting the roof area, from winds that, at that height, are of considerable speed, fig. 3.

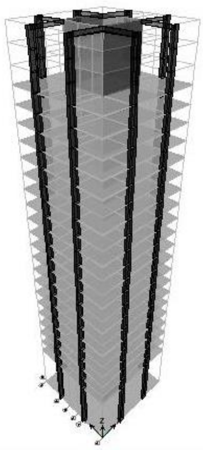

Fig. 3 – Structural model by building 2

According to the seismic zoning, the structure was located in zone II and in its analysis a Q = 2 was used, fig. 4.

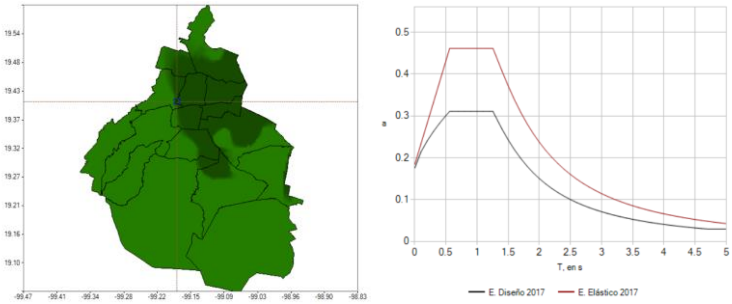

Fig. 4 – Seismic zoning and design spectrum of building 1

Based on the results obtained from the analysis, it was obtained that the existing structure does not adequately support the seismic lateral forces, which the 2004 regulation requires, whether it is considered in group B, or if it is considered in group B1 or A (Cid and Montoya, 2007). Additionally, does not comply with the regulations in force (2017). These results are presented in detail in a study carried out in the reference

3.3 Building 3 (weak ground floor).

It is a 5-level building, with residential use, built on hollow masonry walls confined in the upper levels, supported by a concrete frame in its first interstorey, typical of structures with “soft ground floor”. It is formed by 2 bodies supported on a compensated foundation; the bodies are joined by a core of stairs.

It is located on a transitional ground. Given the structural characteristics, a seismic force reduction factor Q = 1.5 was used, for which an over-resistance factor of 2.6 was obtained, according to the system that calculates the seismic actions (SASID) of the RCDF-2017.

The building showed significant damage to the earthquake on September 19, 2017 and had to be reinforced by increasing the resistance of the front walls and by adding metal cross bracing on the ground floor. In the study presented, the evaluation of the original and reinforced structural model was considered, fig. 5.

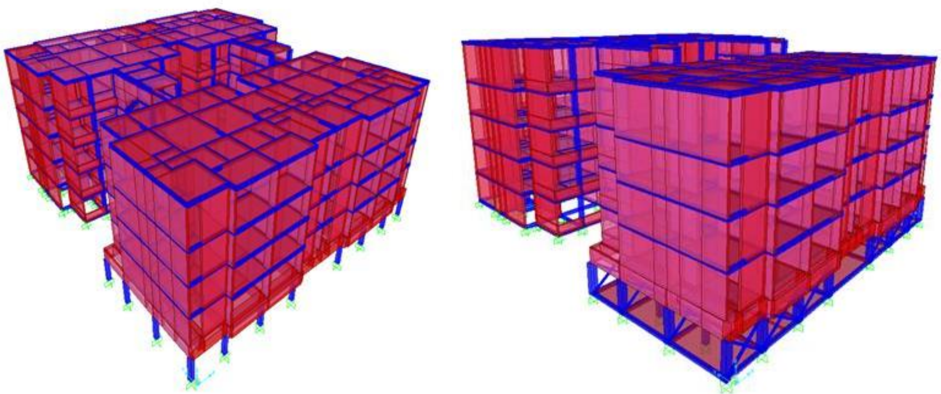

Fig. 5 – Original and reinforced structural models of building 3 with “weak ground floor”

4. Inspection results

4.1 Building 1.

A general inspection of the building was carried out, which focused on the identification of damage to structural elements and joints of beams and columns that were considered critical to detect possible anomalies in their structural work. Construction joints, floor systems, stairs, elevator cubes and in spaces where various facilities are located were inspected. Regarding the inspection of the foundation, the existence of cracking patterns in the walls and foundation slab was reviewed, without finding any evidence of damage. These results were correlated with the topographic survey which indicated that there were no differential settlements suffered by the building that evidences a bad behavior.

For this case, it was concluded that the building has a healthy structure, with adequate maintenance and no structural damage due to past earthquakes.

4.2 Building 2.

From the inspection carried out, a structure was found without apparent damage, although holes were used in the concrete walls of the central core of stairs and elevators using chisel to pass electrical and / or pipeline pipelines. They were also seen in concrete beams on elevator doors, hidden by soffits, some cracks probably due to setting contractions.

The behavior of the foundation has been magnificent, which has been evidenced not only by eye inspection but by topographic leveling. However, trying to transmit to the ground internal forces as high as those that would generate the hypothetical lateral forces required by current regulations (RCDF-2017), the foundation would require major modifications, which so far has not needed it.

From the inspection carried out on the 2 previous buildings in 2007, it was found that their behavior against intense earthquakes, including that occurred in Mexico City in 1985, has been widely satisfactory, and it is not necessary to enable any seismic protection or reinforcement system. For the 2017 earthquake, no damage was reported in these buildings.

4.3 Building 3.

From the inspection carried out, a structure with significant damage was found characterized by diagonal cracking patterns in the walls of the upper interstorey, parallel to the facade and damage to the upper part of the columns of the ground floor by combined flexo-compression effects and shear forces. The above was favored by the differences in stiffness and resistance of the first mezzanine with respect to the superior ones, characteristic of structures with "soft ground floor". Another aspect that influenced notably was the unusual characteristics of the movement experienced by the ground during the 2017 earthquake, where the vertical component of the acceleration, exceeded almost twice the maximum recorded in 1985 on firm ground and the movement of the ground was dominated by high frequencies with respect to earthquakes that are historically generated in the area. The behavior of the foundation was satisfactory.

5. Results of the Bio-Seismic Profile

Next, the results obtained for the three buildings studied are presented, in all cases the results were contrasted with the Bio-Seismic profile, see figures 6 to 14.

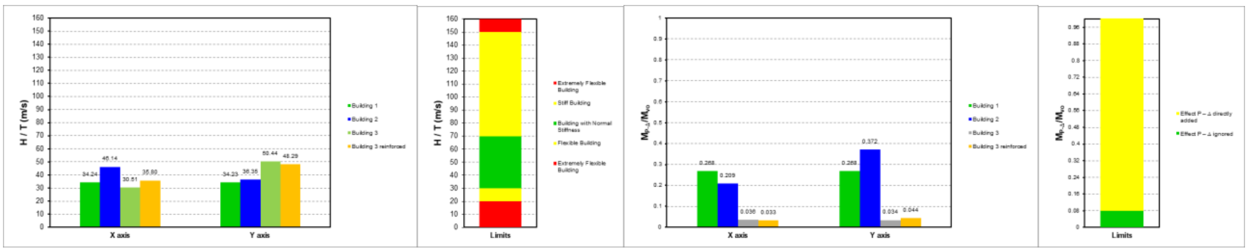

Fig. 6 – Indicator 1 Total height / period first translational mode and Indicator 2 Effect P – Δ

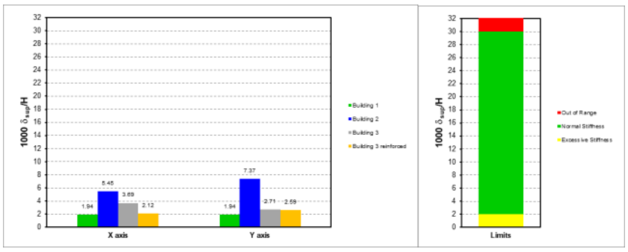

Fig. 7 – Indicator 3 Top level offset

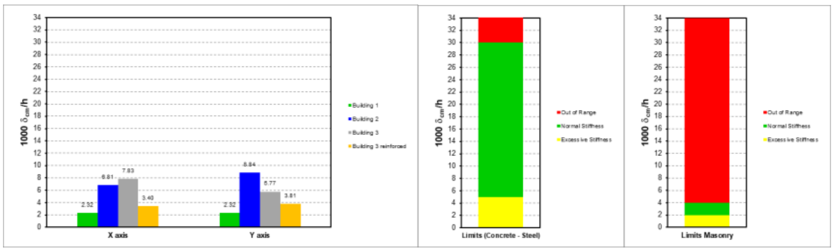

Fig. 8 – Indicator 4 Interstorey maximum displacement in center of gravity

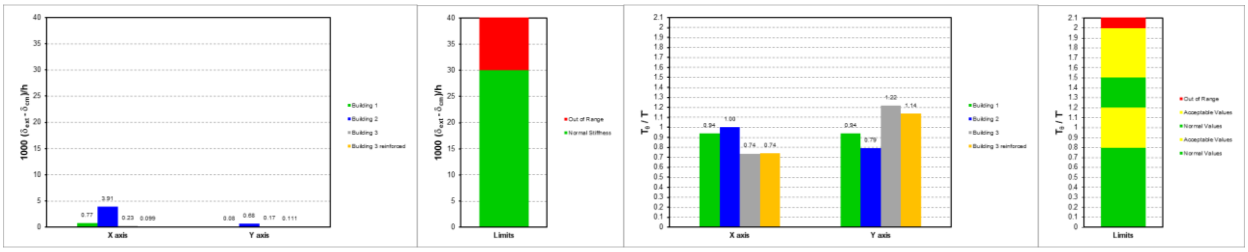

Fig. 9 – Indicator 5 Interstorey maximum additional displacement at extreme points and Indicator 6 Rotational period / translational period

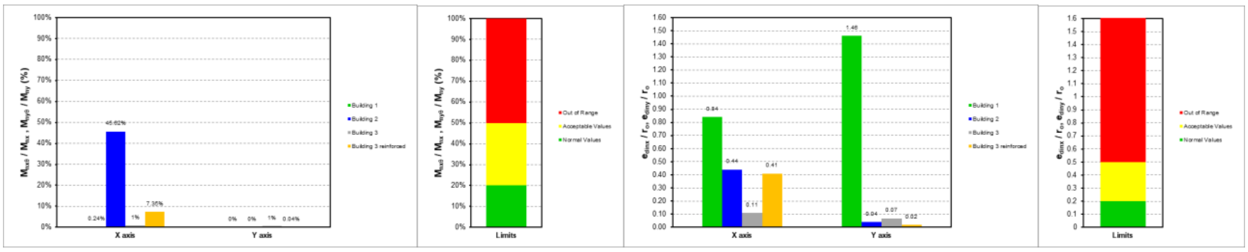

Fig. 10 – Indicator 7 Coupled equivalent rotational mass / direct translational equivalent mass and Indicator 8 Dynamic eccentricity / basal radius of gyration

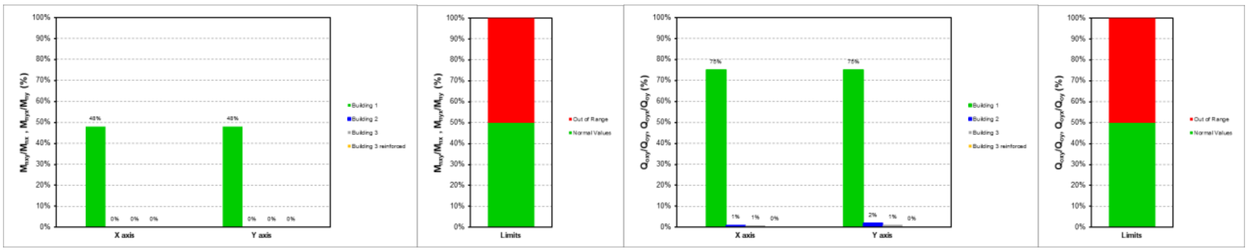

Fig. 11 – Indicator 9 Coupled translational equivalent mass / direct translational equivalent mass and Indicator 10 Coupled basal shear / direct basal shear

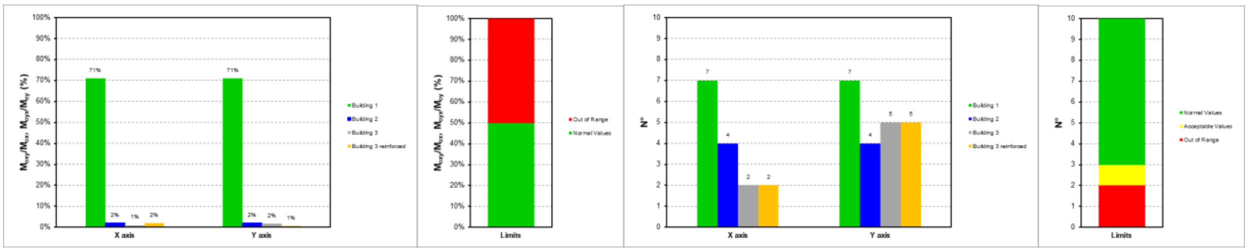

Fig. 12 – Indicator 11 Moment of coupled basal turn / moment of direct basal turn and Indicator 12 Number of seismic lateral resistance planes

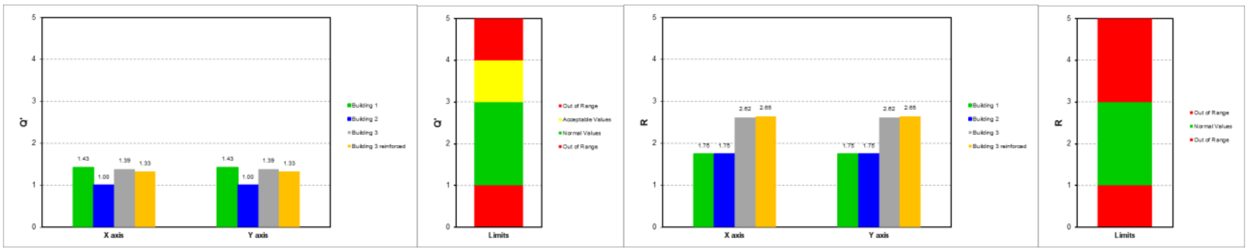

Fig. 13 – Indicator 13 Effective spectral reduction factor and Indicator 14 Over-resistance factor

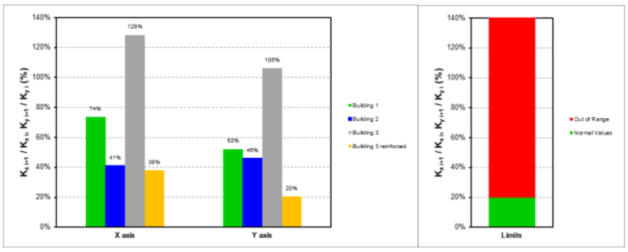

Fig. 14 – Indicator 15 Interstorey stiffness ratio

Table 2 shows the summary of the compliance of the indicators for all the models of buildings studied. It can be seen that the buildings designed with the RCDF standard exceed the limits established by indicators 2, 4, 10, 11 and 15. Particularly it can be seen that the models with asymmetric rigid distributions are those that presented the greatest seismic vulnerability.

Table 2 - Summary of limits for indicators of the Bio-Seismic Profile

Bio-seismic Profile Indicators	Building 1		Building 2		Building 3		Building 3 reinforced	
	shaft x	shaft y	shaft x	shaft y	shaft x	shaft y	shaft x	shaft y
1. H / T [m/s]	34.24	34.23	46.14	36.35	30.51	50.44	35.80	48.29
2. $M_{P\text{-}\Delta} / M_{basement}$	0.268	0.268	0.209	0.372	0.036	0034	0.33	0.044
3. $1000\ \delta / H$	1.94	1.94	5.45	7.37	3.69	2.71	2.12	2.59
4. $1000\ \delta_{gc} / h$	2.32	2.32	6.81	8.84	7.83	5.77	3.40	3.81
5. $1000\ (\delta_{end} - \delta_{gc}) / h$	0.77	0.08	3.91	0.68	0.23	0.17	0.099	0.111
6. T_θ / T^*	0.94	0.94	1.00	0.79	0.74	1.22	0.74	1.14
7. $M_{nx\theta} / M_{nx}$, $M_{ny\theta} / M_{ny}$	0.24%	0%	45.62%	0%	1%	1%	7.35%	0.04%
8. $e_{din} / r_{basement}$	0.84	1.46	0.44	0.04	0.11	0.07	0.41	0.02
9. M_{nxy} / M_{nx}, M_{nyx} / Mny	48%	48%	0%	0%	0%	0%	0%	0%
10. Q_{0xy} / Q_{0xx}, Q_{0yx} / Q_{0yy}	75%	75%	1%	2%	1%	1%	0%	0%
11. M_{v0xy} / M_{v0xx}, M_{v0yx} / M_{v0yy}	71%	71%	2%	2%	1%	2%	2%	1%
12. N	7	7	4	4	2	5	2	5

13. Q'	1.43	1.43	0.95	0.95	1.39	1.39	1.33	1.33
14. R	1.75	1.75	1.75	1.75	2.62	2.62	2.65	2.65
15. K_{i+1} / K_i	74%	52%	41%	46%	128%	106%	38%	20%

This summary table shows the values in blue as those that meet the original limits and those modified by the NTCDS-2017.

5.1 Comments on the results of the Bio-Seismic Profile.

Based on the results obtained from the global indicators presented in the previous figures, an opinion is presented on their influence on the seismic behavior experienced by the 3 buildings studied.

5.1.1 H / T.

All structures are within the parameters and have an adequate balance in their lateral stiffness according to their height.

5.1.2 Effect P - Δ.

The effects P - Δ, are important in the behavior of the first two buildings, due to their height.

5.1.3 Top level offset.

Roof displacements of all buildings do not exceed the suggested limits.

5.1.4 Maximum displacement between floors referred to the center of gravity.

The displacements between floors referred to the center of mass of the first two buildings do not exceed the suggested limits; however, there is a large displacement in building 3 as it presents problems with a soft floor.

5.1.5 Maximum displacement between floors at extreme points of the plant.

The displacements between floors at extreme points of the floor of all buildings do not exceed the suggested limits.

5.1.6 Torsional stiffness.

Based on the ratio of uncoupled periods rotational period / translational period, building 1 and 2 turn out to be torsionally rigid buildings, while building 3 with and without reinforcement is torsionally flexible on the Y axis.

5.1.7 Coupling rotational equivalent mass / direct translational equivalent mass.

It can be seen that building 2 is close to the recommended limit, which is consistent with the result obtained in indicator 6.

5.1.8 Dynamic eccentricity / radius of basal rotation.

Building 1 exceeds the recommended limits, so it may have relatively more important torsional effects than building 2 and 3.

5.1.9 Coupling translational equivalent mass / direct translational equivalent mass.

Although the recommended limits are not exceeded, according to the results obtained, building 1 presents a great coupling in its dynamic behavior.

5.1.10 Attached basal shear / direct basal shear.

The results obtained confirm what was found in indicator 9, that is to say that building 1 has a great coupling in its dynamic behavior exceeding the recommended limits.

5.1.11 Moment of coupled basal turn / moment of direct basal turn.

The results obtained indicate that building 1 exceeds the recommended values which is attributed to the relatively large mass and therefore its lateral forces, which cause a significant turning moment.

5.1.12 Number of seismic lateral resistance planes.

The first two buildings have an adequate number of resistant planes, while building 3 has the minimum number of resistant axes on one axis.

5.1.13 Effective spectral reduction factor.

In all cases, dynamic seismic forces were smaller than static forces and did not have to be increased since the minimum basal shear was met.

5.1.14 Over strength factor.

In all cases, the over-resistance is within the parameters of the profile, the highest being that of building 3.

5.1.15 Interstorey stiffness ratio factor.

In all cases there are differences in the rigidity of consecutive mezzanines, which causes problems of soft floor and irregularities of stiffness. As seen in the case of building 3 that has a weak floor.

6. Conclusions

From the analysis of the indicators of the Bio-Seismic Profile, it can be concluded that Building 1 and 2 have an adequate characteristics of rigidity and structural redundancy to satisfactorily control lateral displacements and exhibit satisfactory behavior in the face of seismic events. For Building 3, it is shown that the profile is consistent with the damages presented to the 2017 earthquake for buildings that have a structure with a soft ground floor.

For building 1 it presents torsional coupling problems, although the extension of its base in the first levels increases its good seismic behavior. In Building 1 does not exist translational-torsional coupling, so it would be expected that it does not cause major affectations since it is a torsionally stiff and symmetrical structure. Building 3 has no coupling, however, it is torsionally flexible on the Y axis.

From the detailed structural evaluations that were made to buildings 1 and 2, it was obtained that the second would not resist the level of seismic force requested by the current regulations, however, the results of the inspection carried out report that its structure is healthy. In the case of building 1, it does satisfactorily comply with current regulations and its structure also without damage. In building 3 does not resist the seismic demand and had to be reinforced for it.

It is concluded that, although the first 2 buildings were designed and constructed before the appearance of the current regulation, their structural conditions are satisfactory, indicating that they have experienced adequate seismic behavior in the face of intense earthquakes, including that occurred in Mexico in 1985 and 2017, which is consistent with the result of the application of the methodology proposed by the Bio-Seismic Profile. Building 3 had to be reinforced to satisfy the seismic demands of the current regulation and thereby improve its behavior in the face of future seismic solicitations, as it is estimated to occur due to the reduction of differences in interstorey stiffness.

From these results, the utility of this type of methodologies becomes evident, so it would be desirable to expand its application to evaluate other types of buildings not only in Mexico, which have been damaged by intense earthquakes.

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