ANALYSIS OF THE BEHAVIOR OF A FLEXIBLE BUILDING WITH SEISMIC ISOLATION IN VARIOUS INTERFACES

V. Ramirez Marquez[1], E. Guzman Lucatero[2], J. Macias Jaime[3], J. L. Almazan[4] , S. I. Reyes[5]

[1] *VIRMEX General Manager, VIRMEX Innovacion Estructural, Guadalajara, Jalisco, Mexico, victor.ramirez@virmex.com*
[2] *VIRMEX Engineer, Intelligence Department, VIRMEX Innovacion Estructural, Guadalajara, Jalisco, Mexico, erik.guzman@virmex.com*
[3] *VIRMEX Engineer, Intelligence Department, VIRMEX Innovacion Estructural, Guadalajara, Jalisco, Mexico, jesus.macias@virmex.com*
[4] *Associate professor, Department of Structural and Geotechnical Engineering Pontificia Universidad Católica de Chile, Santiago, Chile, jlalmaza@ing.puc.cl*
[5] *Research Assistant, Research Center for Integrated Disaster Risk Management (CIGIDEN), ANID/FONDAP/15110017 Pontificia Universidad Católica de Chile, Santiago, Chile, sergio.reyes@cigiden.cl*

Abstract

In previous research presented in the 16WCEE, the seismic response of a typical 19-story building for residential use in Mexico was analyzed. The structural system of the structure is based on reinforced concrete frames and walls with a fixed base. Design alternatives were proposed adding seismic isolation at one and two interfaces, presenting uplift issues in the case of one-interface isolation system due to its high slenderness. This issue was solved with the two-interface isolation system setting, installing sliding isolators at the base and the seventh level, reducing the observed uplifting. The proposed solution was considered an effective way to reducing uplifting when applying base seismic isolation to slender medium-rise buildings, however, this solution has not been studied for taller high-rise buildings with larger slenderness. In this paper, the response of the same building with the same structural settings is analyzed, but increasing to a 60-story building with a total height of 220 meters. Three configurations were studied: two 30-story block interface; three 20-story block interface; and four 15-story block interface. In each configuration the isolation interface consisted on sliding isolators. The responses of each model are analyzed to determine the optimal number (technically and economically) of stories of each rigid block that the building should be divided in order to obtain the desired performance. The response of the structure is obtained by nonlinear time-history analysis. The results obtained show a considerable energy-dissipation at each interface level, reducing seismic response, passing them from the first mode (fixed base building) to their *n*th mode according to the number of interfaces added.

Keywords: Flexible building; seismic isolation; multiple interfaces

1. Introduction

Due to nowadays tendency to build tall and slender buildings, owing to either architectural or special site conditions, a slender building response will be analyzed, modeling it at the software SAP2000 [1]. In a previous study, the seismic response of a typical 19-story building for residential use in Mexico was analyzed [2]. In this study, the same building is analyzed, but several stories were added in order to increase its slenderness. The new setting of the building counts with 60 levels and 220 meters total height. Four configurations were analyzed: one 60-story block interface, two 30-story block interface, three 20-story block interface, and four 15-story block interface, adding sliding isolators at each one of the interfaces [3]. Determining this way, the optimal (technically and economically) isolation system, guarantying an appropriate seismic performance of the structure.

Performing a fast nonlinear time-history analysis (FNA) [4], a comparative database of structural responses was obtained, which allows the correct evaluation of each system, and, at the same time, the obtainment of information to determinate the different properties to be assigned at each type of isolators, which will constitute every interface in the various considered models. In the base of the previously described study, the results obtained empower the viability of incorporating seismic isolation systems at several interfaces, in tall and slender buildings.

2. Model Description

The analyzed building model has a regular distribution, it is structured with reinforced concrete walls and frames, for residential occupancy, with a proposed location at Jalisco, Mexico, on a soil type II. The building has the following plan dimensions: 30.90 m x 20.53 m, with a total 635 m² surface, the same dimensions used at [2]. In the difference between the models studied in that occasion, this model has 60 stories. Fig. 1 shows a plan view of the building, with the structural elements distribution, that match in position with every level of the structure.

The following material properties were considered for beam, columns, and walls:

a) Concrete: 28 days design compressive strength f'c= 500 kgf/cm², specific weight γ *=2400 kg/m³.*

b) Steel: A630-420H, with an effective yield stress Fy= 4200 kf/cm², and an effective tensile stress Fu= 6300 kgf/cm², specific weight γ*=7850 kg/m³.*

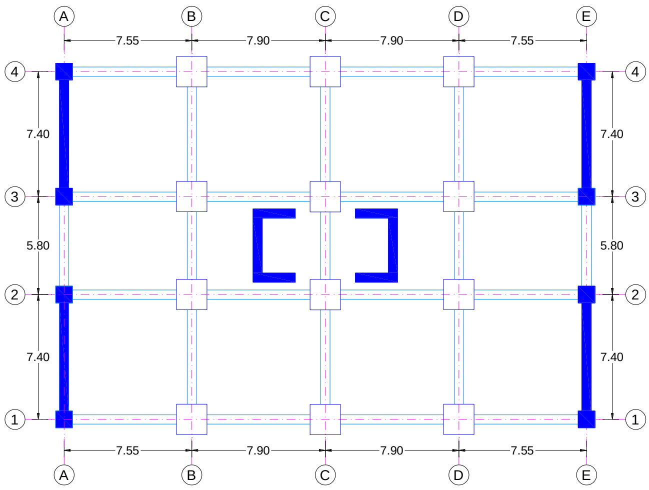


Fig. 1 – Plan View.

Concrete column, beam, and wall sections for each structure level are shown in Table 1**,** determined from a mathematical model of the studied building with a fixed base. A 20 cm thick, f'c= 350 kgf/cm² concrete slab was considered for every floor. Four isolated models were made, isolators are modeled as Frictional Isolator Links, a predefined element at the SAP2000 software [1]. Two types of isolators per interface are used, whose locations at the building are shown in Fig. 2**.**

Table 1 – Structural Elements Sections.

LEVEL	EDGE ELEMENTS A and E axis	COLUMNS B, C, and D axis	BEAMS	WALLS
	cm	cm	cm	cm
1 - 10	100 X 100	180 X 180	55 X 120	55
11 - 20	90 X 90	170 X 170	50 X 110	50
21 - 30	80 X 80	160 X 160	45 X 100	45
31 - 40	70 X 70	150 X 150	40 X 90	40
41 - 50	60 X 60	140 X 140	35 X 80	35
51 - 60	50 X 50	130 X 130	30 X70	30

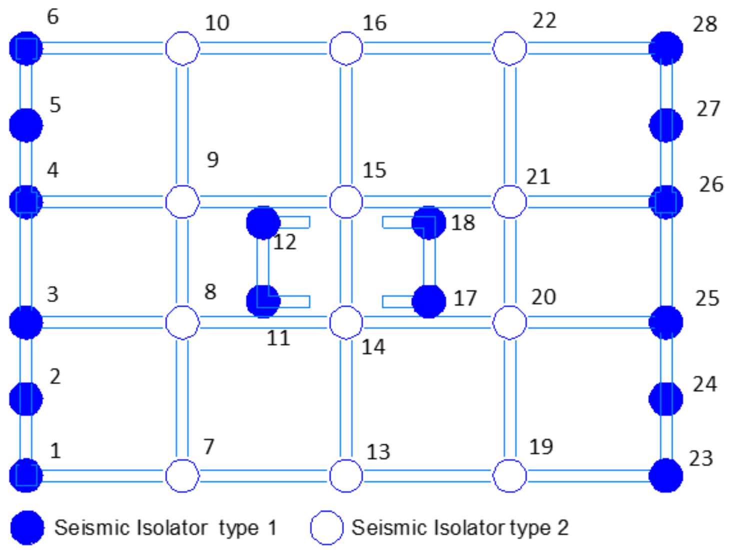


Fig. 2 – Isolator's location

At the building analysis, besides the structural elements self-weight, a dead load of 300 kg/m² was considered due to the weight of the non-structural elements, and a 350 kg/m² live load, according to the Construction and Urban Development Code of Zapopan, Jalisco [5].

The seismic analysis was performed according to [6], considering mechanical properties of the soil located at the following geographical coordinates: Latitude: 20° 41.474' N, Longitude: 103° 24.656 W. PRODISIS software [7] was used in order to obtain the seismic demand, entering the previously written coordinates, the following parameters were obtained: Seismic Zone C (second highest according to the norm); Seismic Coefficient c= *0.9 g*, Period of Soil *T=0.33 sec*, Critical Damping Factor $\zeta = 5$ %, Seismic Behavior Factor *Q*=3, Over-resistance Factor *Ro=2.5*, Redundancy Factor $\rho = 1.25$, and Irregularity Corrective Factor *α=0.90*. Due to the project's nature and the planned utilization of seismic isolators, a fast nonlinear time-history analysis was chosen to study the structure's response [8]. For the present study purposes, just one ground motion accelerogram was used, compatible with the Design Response Spectrum previously mentioned, design response spectrums and accelerograms used are shown in Fig. 3**.**

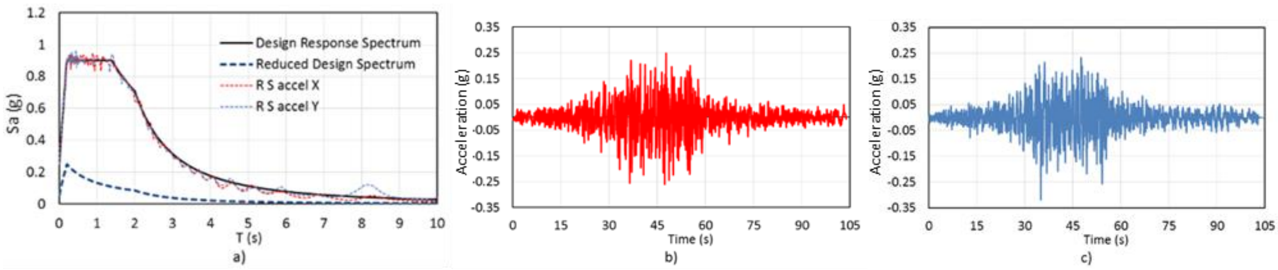


Fig. 3 – a) Design response spectrums, b) accelerogram direction X, c) accelerogram direction Y

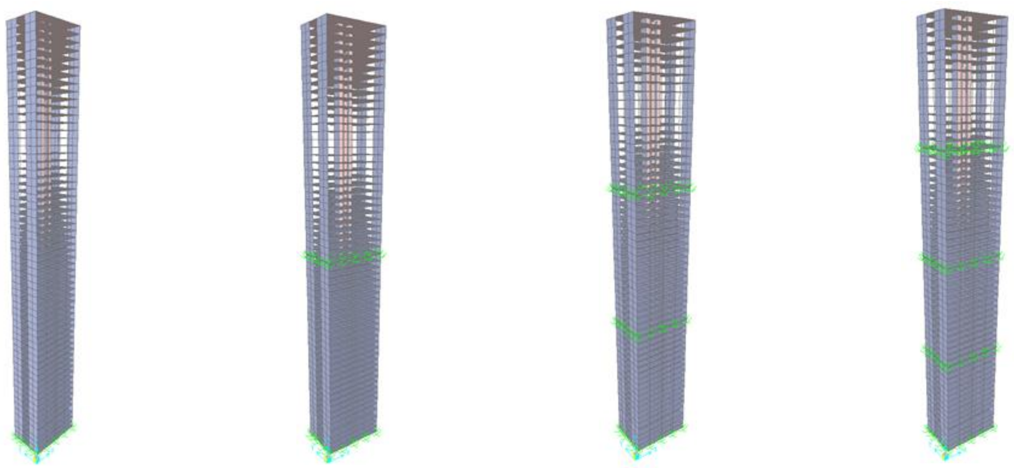
2.1 Fixed Base Model (FB)

The FB model was made in order to obtain the accurate properties for the study, making a modal-spectral analysis to define the structural sections to use, in this analysis al elements were maintained as elastic members. Once the properties shown in Table 1 are determined, the structure was subjected to nonlinear time-history analysis, in order to compare responses with the isolated system models.

2.2 Isolation System Models

Four different isolated models were considered, placing 28 seismic sliding isolators per isolation interface. The first model (1INT) counts with the isolation system at the base, the second model (2INT), besides the base isolation counts with an interface at the 30th level; the third model (3INT) counts with the isolation system at the base, and at the 20th and 40th levels; finally, the fourth model (4INT) counts with the isolation system at the base, and at 15th, 30th and 45th levels; all four models previously described are shown in Fig. 4**.**

After several tests, assigning different sliding isolator properties in each proposed model [9, 10] analyzing the respective responses, some of those properties did not accomplish the different requirements of Mexican codes, therefore, after some verifications, the following isolator properties were chosen to use during the structural analysis: Slow Frictional Coefficient: 0.04, Quick Frictional Coefficient: 0.06, Rate parameter: 0.4 sec/cm and Radius of Curvature: 304.4 cm.



a) b) c) d)

Fig. 4 – Isolation Systems Models a) 1, b) 2, c) 3, d) 4 interface

3. Structural Responses

As a result of the modal analysis, Table 2 shows the nine first vibration mode periods obtained from each model, as it can be seen, the period of the three first modes increases depending on the interface, until model 3INT, where it decreases and finally it slightly increases at the 4INT model. Fig. 5a shows the first three vibration modes of 1INT model and Fig. 5b the first six vibration modes of 2INT model, Fig. 6 shows the first nine vibration modes of 3INT model, vibration modes of 4INT model are not shown because they are the same shape of the 3INT model.

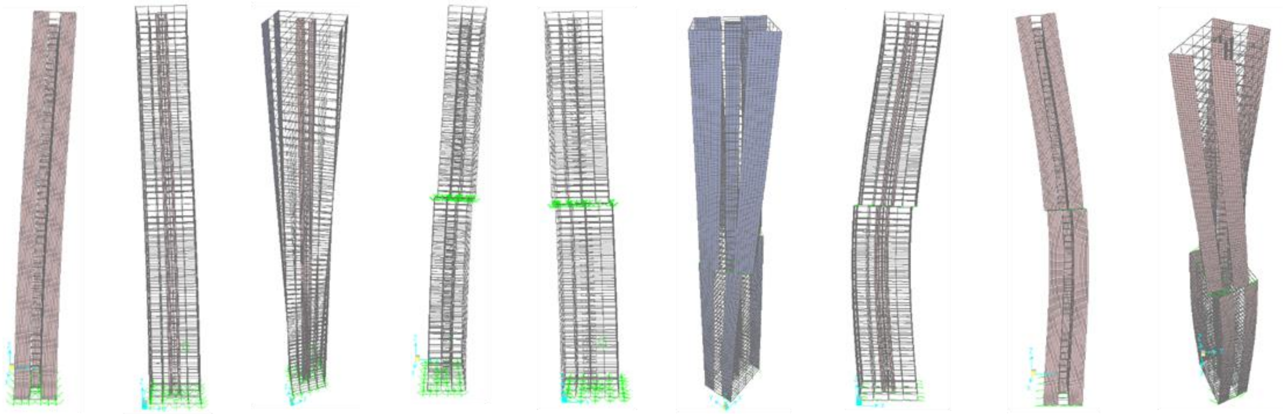


Fig. 5 – a) Three first vibration modes model 1INT, b) Six first vibration modes model 2INT

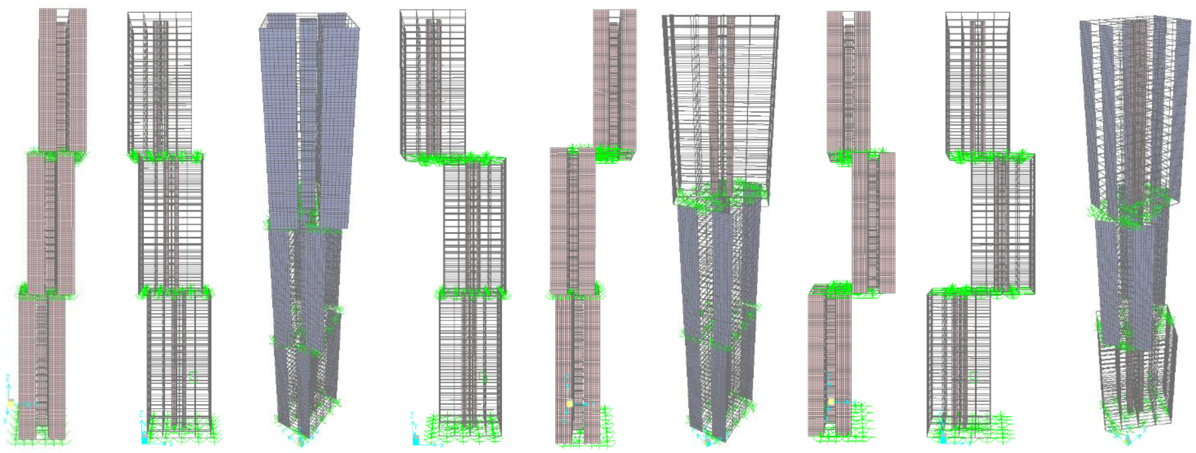


Fig. 6 – Nine first vibration modes model 3INT

Table 2 – Periods obtained from each model.

Model	T_1 (s)	T_2 (s)	T_3 (s)	T_4 (s)	T_5 (s)	T_6 (s)	T_7 (s)	T_8 (s)	T_9 (s)
FB	5.74	5.22	3.07	1.73	1.55	1.14	0.97	0.78	0.66
1INT	8.86	7.92	5.28	3.04	2.93	2.22	1.66	1.50	1.21
2INT	9.45	8.54	6.04	3.13	2.98	2.45	1.72	1.61	1.11
3INT	5.21	5.20	4.87	2.51	2.51	2.38	1.60	1.60	1.53
4INT	5.48	5.47	5.17	2.12	2.12	2.02	1.32	1.32	1.26

Due to the structural system characteristics of the building, allowed drift is 15 ‰ according to [6], Fig. 7 shows the obtained drifts. It can be seen that the FB model exceeds the previously mentioned limit, nevertheless, every isolation system model accomplishes this revision; 1INT and 2INT models presented about 40% of reduction in the obtained drift, while at the 3INT and 4INT models the drift its practically null. Fig. 8a shows roof displacements obtained from FB, 1INT and 2INT models; 3INT and 4INT models presented lower displacements, which it's appreciated with a larger scale in Fig. 8b.

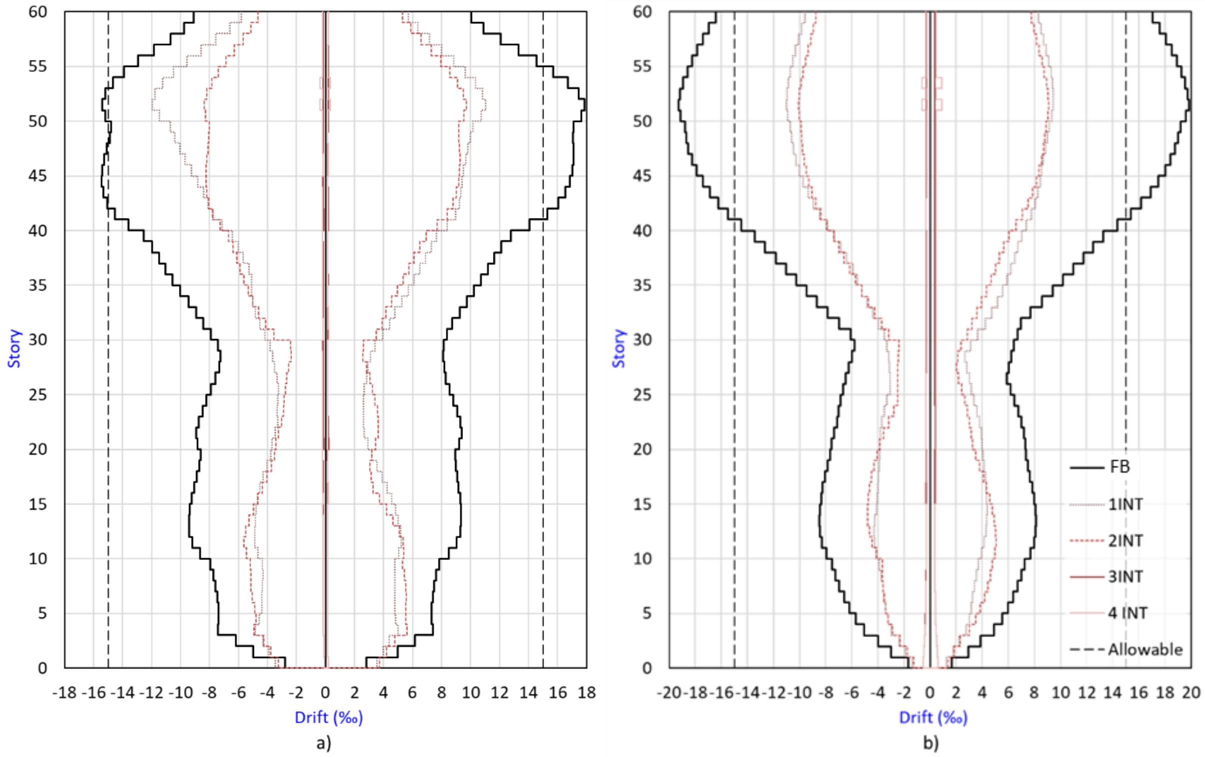


Fig. 7 –Story drifts a) X direction, b) Y direction.

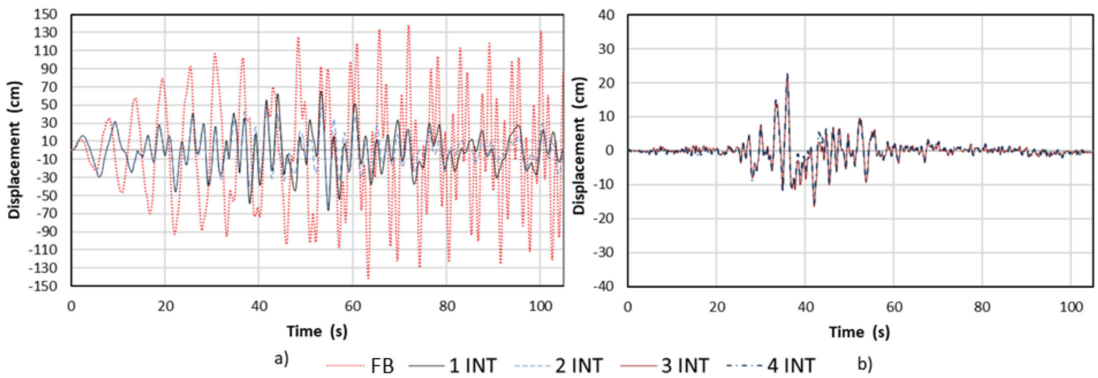


Fig. 8 – Roof displacements at models a) FB, 1INT, 2INT and, b) 3INT, 4INT

As mentioned previously, concrete sections were designed with a modal analysis using the reduced design spectrum, concrete beams and columns satisfied demands for that analysis. When the structure was subjected to the FNA analysis FB model shown to have a high demand over beams were plastic hinges formed, not the same case for columns where there were no plastic hinges. Fig. 9 shows the demand over a beam on the lower floors, as it can be seen FB, 1INT and 2 INT models experimented large moments. On the other hand, 3INT and 4 INT models resulted in lower demands, as a result no plastic hinges were formed, which maintains the elements in the elastic region. As mentioned before, there were no plastic hinges in columns, Fig. 10 shows demands on a column located at the 10th level. It is evident that the FB model is in the limit of the design, 1INT and 2INT models show a lower demand on the column, and finally, in 3INT and 4INT models column demand is unnoticeable in the plot shown. From these plots, it can be concluded that may be savings in the superstructure for 1INT and 2INT models, but in 3INT and 4INT models, there can be large savings because the concrete elements are far from maximum capacity.

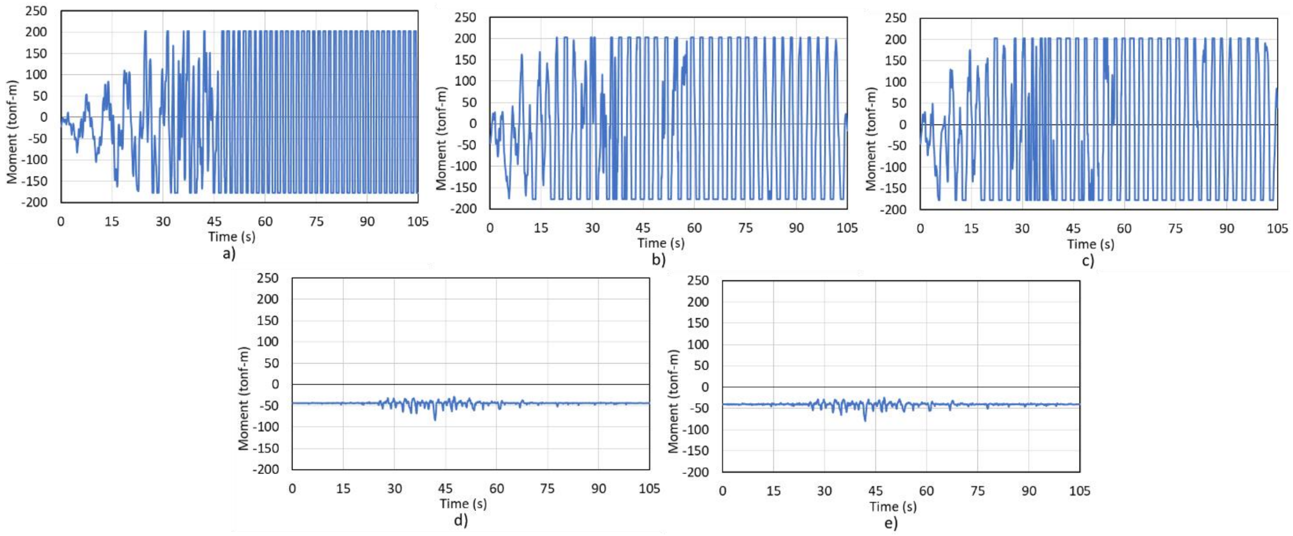


Fig. 9 – Beam demand a) FB, b) 1INT, c) 2INT, d) 3INT, e) 4INT

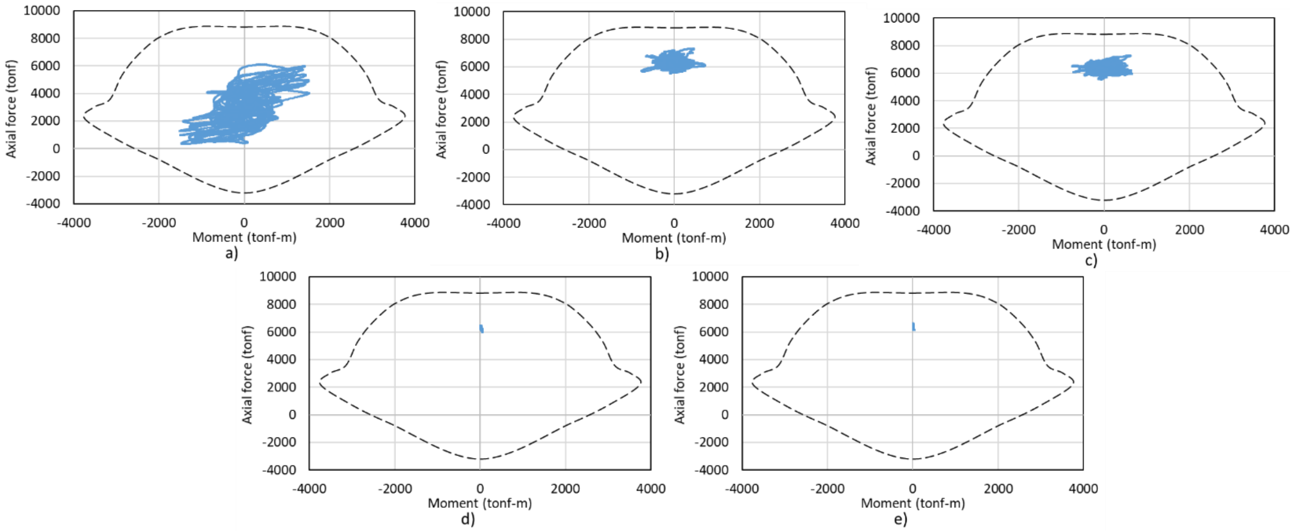


Fig. 10 – P-M interaction a) FB, b) 1INT, c) 2INT, d) 3INT e) 4INT

Comparing maximum reactions obtained from the FB model, as in regards to the isolation system models, these last ones present a remarkable 400% decrease in the acting bending moments, while axial compression force presents a 10% progressive increase in each interface. These data are shown in Table 3.

Table 3 – Obtained Reactions.

Model	Column Reactions			
	Compression	Tension	M_{X-X}	M_{Y-Y}
	tonf	tonf	tonf-m	tonf-m
FB	12166	5107	2533	4147
1INT	13825	0	542	352
2INT	14079	0	555	406
3INT	17271	0	622	471
4INT	18680	0	604	478

The maximum and minimum axial loads, for the FNA analysis are shown in Fig. 11, it can be appreciate that in the 1INT model isolators 1, 6, 23, and 28 present uplift, which are the ones located at the corners of the building, 2INT model also has uplifting on isolator 12. The problem surges in 3INT and 4INT models where 22 isolators present lifting, analyzing each model it was also observed that the models with less isolation interfaces presented lifting less times than those with more isolation interfaces. The dropback impact after uplifting may explain the increased compression forces on models 3INT and 4INT, further ensuring that measures to control impact on isolation systems may be needed.

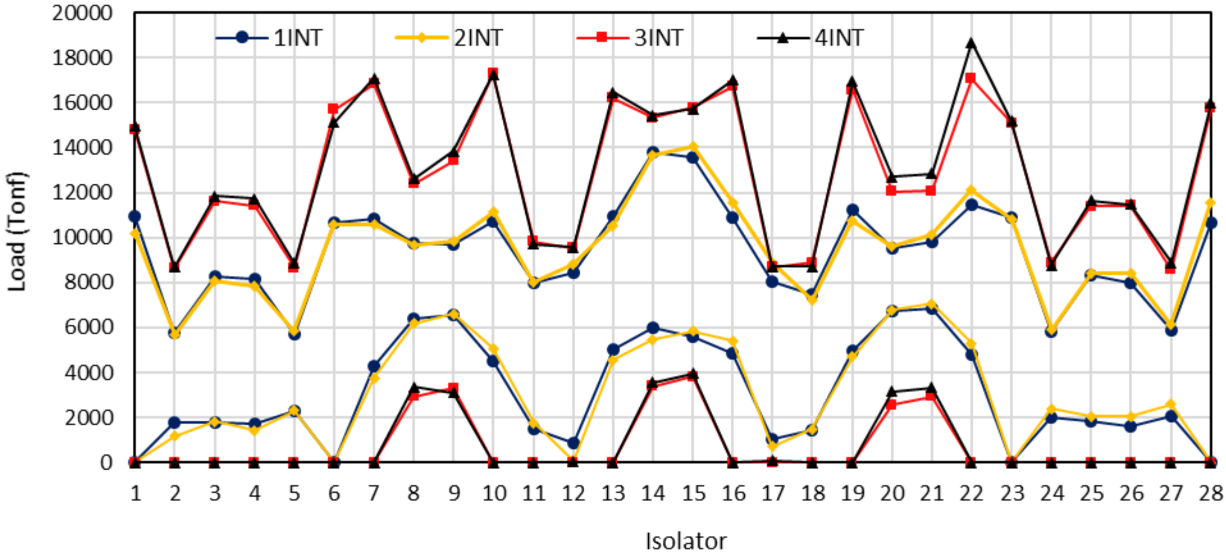


Fig. 11 – Axial loads on base isolators

Several attempts were made, testing different isolator properties, to finally determine the definitive properties previously described. Some of the proposals were not convincing, because they did not accomplish the lateral restoring force requirement established by the Mexican codes [6]. An isolator displacement over time is shown in Fig. 12 that compares the behavior of the isolator with the proposed and with the definitive properties, as it can be seen, clearly the initially proposed properties did not accomplish the requirement, so they were modified in the definitive isolators.

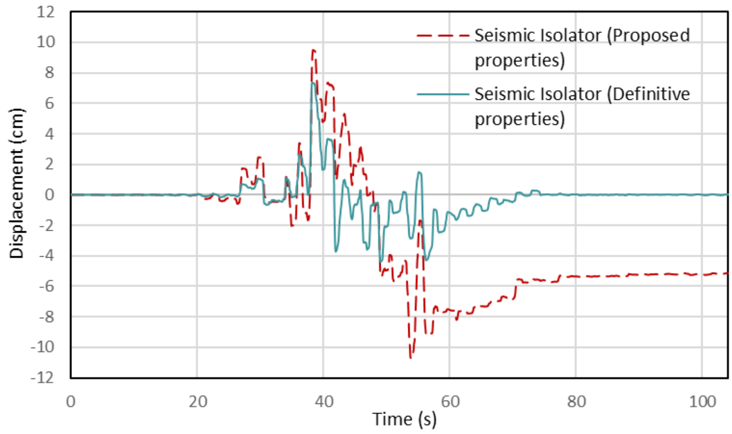


Fig. 12 – Isolator Displacement.

Hereunder, the hysterical performance of each model isolator is presented, each one located at the same position [11]. As it can be seen, 1INT and 2INT models (Fig. 13 and Fig. 14) have very similar maximum deformation and forces, in 2INT model the isolator at story 30 present low forces and deformations. 3INT and 4INT models (Fig. 15 and Fig. 16), at the base level the isolators have similar behavior, compared to de 1INT and 2INT models, and these have lower deformation despite the greater force. In the 3INT model isolators at levels 20 and 40 have large deformations but have very small forces. However, the 4INT model isolator located at level 30 has more significant deformations that the one located at level 15, while the isolator at level 45 has negligible deformation.

In almost every model the isolators of the borders presented a high reduction of the axial force when the isolators of the opposite border were more loaded. This is presented as an assymetrycal hysteresis in the plots since at one side of the of the hysteresis the forces are nearly zero. Also, for the 3INT and 4 INT models, a sudden increase of axial forces is presented, which is common after impacts due to uplifting.

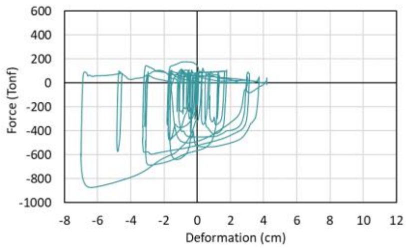


Fig. 13 – Isolator 1 force-deformation plot 1NT model

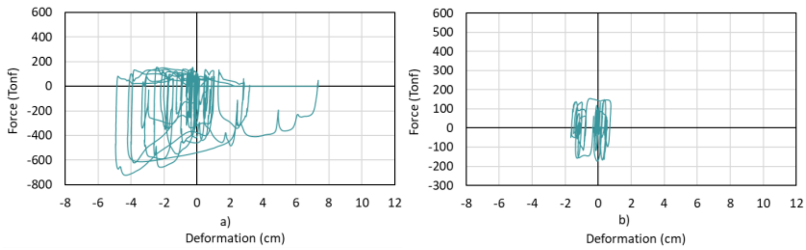


Fig. 14 – Isolator 1 force-deformation plot 2INT model a) base, b) level 30

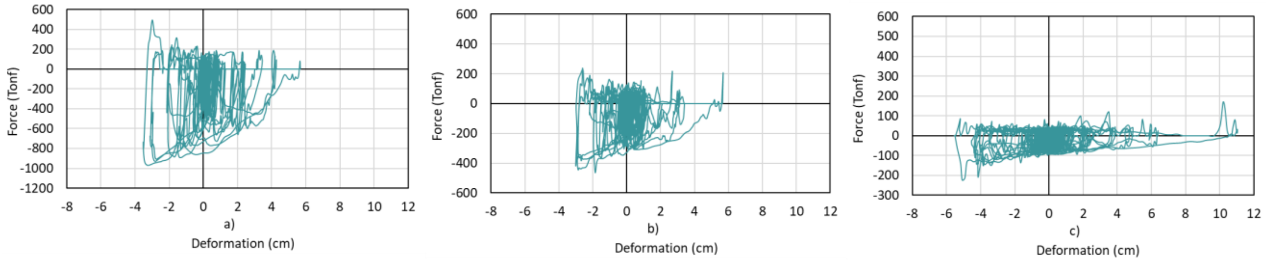


Fig. 15 – Isolator force-deformation plot 3INT model a) base, b) level 20, c) level 40

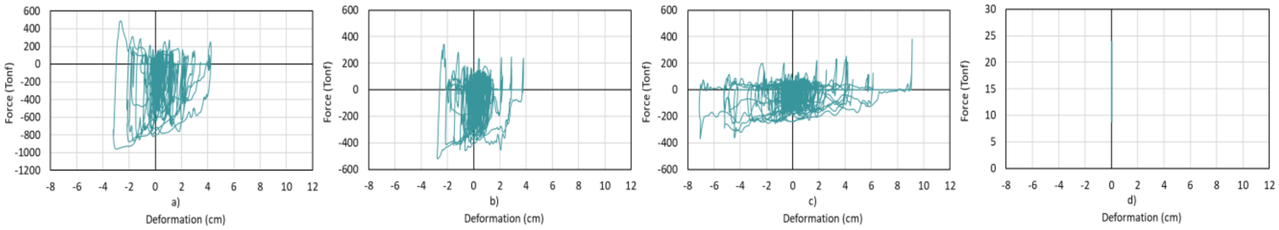


Fig. 16 – Isolator force-deformation plot 4INT model a) base, b) level 15, c) level 30, d) level 45

Maximum displacements obtained in each model were found in the first isolation interface for the 2INT model; in the second isolation interface for the 3INT model and, at the third interface for the 4INT model. Fig. 17 shows the previously described behavior, worth noting that the 3INT and the 4INT are the models that present higher displacements due to the lower frictional force compared to the 1INT and the 2INT models, these, because of the low normal force applied.

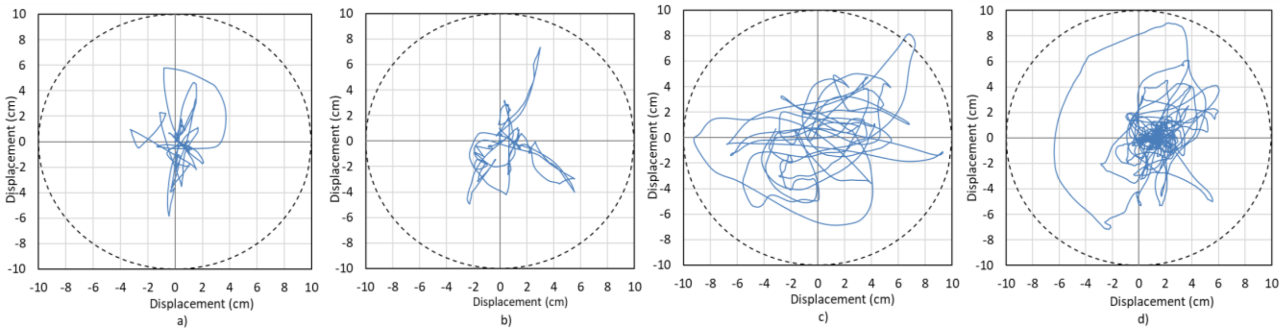


Fig. 17 – Isolator Displacements a) 1INT, b) 2INT, c) 3INT, d) 4INT

4. Conclusions

The seismic response of a slender building was analyzed in this study with the objective to encounter the best solution implementing seismic isolation interfaces in different levels of the building. The structure, for the present study purposes is located in Jalisco, Mexico and counts with 60 floors and has a 220 meters of total height; analyzing 5 different mathematical models: FB, 1INT, 2INT, 3INT and 4INT, looking through the obtained results, the following conclusions are reached:

From the FB model:

i) Presents large roof displacements, reaching about 1.5 m. ii) As to story drifts, they exceed the allowed 15‰ drift. iii) The large reactions obtained will raise the bulling cost due to required foundation. iv) The beams developed plastic hinges due to the great demand they presented.

From the 1INT Model:

v) The three first obtained vibration modes present about a 50% increase compared to the FB model. vi) With just one isolation system interface, the roof displacements decreased about 50%, the story drift showed about a 40% reduction comparing to the FB model, fulfilling this way the code requirement, but still remains high. vii) Besides, vertical force reactions present about a 10% reduction, while resultant moments present a 400% decrease. viii) As the same that in the FB model, plastic hinges were formed in beams.

From the 2INT Model:

ix) The three first vibration periods were very similar to the ones obtained in the 1INT model. x) Displacements, drifts, axial force and moment reactions present a mild variation comparing to the 1INT model. xi) Acting forces and deformations over the isolators stood the same, despite the increase in the number of isolators. xii) Also the number of isolators maintained the same behavior of beams, developing plastic hinges.

From the 3INT Model:

xiii) In the first instance, it presented the minimum fundamental period from the five considered models, xiv) Roof displacements presented about a 40% decrease compared to 1INT and 2INT models, drift happened to be practically null with a maximum value of 1‰. xv) Vertical and moment reactions had a slight increase with respect to the 2INT model, xvi) Acting forces and deformations in the isolators stood the same as the 1INT and 2INT models. xvii) With this number of isolators beams changed their demand and now they do not reach the yielding point.

From the 4INT Model:

xviii) Roof displacements, drifts, and general model behavior were significantly similar to the ones obtained in the 3INT model. xix) A 10% increase in reactions with respect to the 3INT model was obtained. xx) At the two lower interface isolators presented a reduction in deformation, isolators at level 30 had large deformations and at level 45 the deformations were null. xxi) Demand on beams and columns is the same that the one presented in the 3INT model even with the extra isolation interface.

Generally:

xvii) From the seismic isolation system models, the 3INT model fulfilled the objective of this study, since it acts as independent rigid blocks, presenting null story drifts and elastic behavior in beams and columns. xviii) 1INT and 2INT models, although presenting a 40% decrease in story drifts with respect to the FB model meeting the norm requirement, still have large displacements compared to models 3INT and 4INT. xix) The most optimal model is 3INT, as it acts as a rigid block and due to the negligible deformation of 45-story isolation interface at model 4INT, it can be concluded that a building with the characteristics of the one presented in this study requires three isolation interfaces. Although with more interfaces the drift and demand on the elemenst of the structure is reduced, the uplifting effect is increased. Further studies should be performed with non-equal rigid blocks (i.e. interfaces separated by different amounts of stories) in order to find the optimal placement of the interfaces.

5. Acknowledgments

I thank the Organization of American States OEA and the Pontificia Universidad Católica de Chile for giving me the opportunity to study the magister and for allowing me to offer the knowledge acquired for the benefit of Mexican society through the constitution of VIRMEX Innovación Estructural, in which I have offered jobs and transmitted knowledge to new generations, as well as to the clients to whom we have been able to offer solutions in their construction projects.

I also thank Ph. D. José Luis Almazán for having been my thesis supervisor and the support given to VIRMEX through his advice and feedback on various projects and in this research. I also thank in a very special way the work team of VIRMEX Innovación Estructural, that in the face of the good times that we have lived, but especially in the moments of pressure, together we have taken forward every project and challenge that has presented, learning among all and proposing always new procedures and solutions, until even presenting this research.

6. References

[1] CSI (2014): *SAP2000. Integrated Finite Element Analysis and Design of Structures*. Berkeley: Computers and Structures, Inc.

[2] Ramirez Márquez VR (2016): *Análisis del comportamiento de un edifico flexible con una y dos interfases de aislamiento*. Santiago de Chile: Tesis de Maestría. Pontificia Universidad Católica de Chile (in Spanish).

[3] Zayas VA, Low SS, Mahin SA (1990): A Simple Pendulum Technique for Achieving Seismic Isolation. *Earthquake Spectra*, **6** (2), 317-333.

[4] Wilson EL (2000): *Three-Dimensional Static and Dynamic Analysis of Structures. A Physical Approach with Emphasis on Earthquake Engineering*. Berkeley: Computers and Structures, Inc.

[5] Reglamento de Construcciones y Desarrollo Urbano del Municipio de Zapopan. (2003). Zapopan (in Spanish).

[6] Insituto de Investigaciones Eléctricas (2015): *Manual de Diseño de Obras Civiles. Diseño por Sismo*. Ciudad de México: Comisión Federal de Electricidad (in Spanish).

[7] Instituto de Investigaciones Eléctricas (2015): *Programa de Diseño Sísmico (v4.1.)*. Ciudad de México: Comisión Federal de Electricidad (in Spanish).

[8] Nagarajaiah S, Reinhorn AM, Constantinou MC (1991): 3D-BASIS - Nonlinear Dynamic Analysis of Three-Dimensional Base Isolated Structures. *Technical Report NCEER-91-0005*. University at Buffalo, State University of New York.

[9] Almazan JL, De la Llera JC (2003): Physical model for dynamic analysis of structures with FPS isolators. *Earthquake Engineering and Structural Dynamics*, **32** (8), 1157-1184.

[10] Naeim F, Kelly JM (199): *Design of Seismic Isolated Structures: From Theory to Practice*. John Wiley & Sons, Inc.

[11] Park J, Wen Y, Ang H.-S (1986): Random vibrations of hysteretic systems under bi-directional ground motions. *Earthquake Engineering and Structural Dynamics*, **14** (4), 543-557.

