SEISMIC ANALYSIS IN CORNER BUILDINGS AND ITS RELATIONSHIP WITH THE DAMAGE OBSERVED IN BUILDINGS IN MEXICO CITY DUE TO THE EARTHQUAKE OF SEPTEMBER 19, 2017.

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Abstract: *Mexico City has a well-known history of collapsed buildings under earthquake actions mainly due to soil amplification effects of seismic waves in the Mexico's Valley. On September 19, 2017, an intraplate earthquake (M=7.1) occurred, with epicenter 120 km away from Mexico City, where most of the building collapses occurred. An analysis of the collapsed buildings was carried out with the aim to identify damage patterns. Weak story buildings and torsion caused by the presence of infill walls in corner buildings were the main causes of failure. Based on the collapsed buildings, it was proposed a typology to study RC buildings from three to eight stories, two-way slabs and masonry infill walls, representative of the collapsed structures. The buildings were modelled using Perform3D and designed with the 1976 Mexico City Design Code, because most of the collapsed buildings or with severe damage were designed with regulations prior to 1985, year in which the city's regulations had significant changes due to the damages caused by the September 19th 1985 earthquake. Nonlinear time-history analyses were performed using a set of 36 accelerograms recorded in zones II, IIIa and IIIb of the Mexico City seismic zones, where most of the collapses occurred. Interstory drift ratios were assessed in order to study the damage evolution in time and to identify the causes of collapse. Results showed that infill walls had a great influence in terms of energy dissipation in lower height buildings, and, in all numerical models, the walls dissipated most of the hysteretic energy induced in the buildings during the first seconds of the earthquake action. The earthquake effect on the building corners was measured through determining the interstory drift ratios that presented important variations among the corners, exhibiting the torsional effect caused by the walls and its relation with the observed collapses.*

1. Effects of the Puebla-Morelos Earthquake on Corner Buildings

On September 19, 2017, an intraplate earthquake occurred between the states of Puebla and Morelos in Mexico (19S, 2017 earthquake), with a magnitude of 7.1 and a depth of 57 km. This earthquake was triggered by the subduction of the Cocos Plate beneath the North American Plate. Although damages were reported in areas near the epicenter, the majority of the affected structures were in Mexico City, which is 120 km away from the epicentre. These damages can be attributed to the city's high density of buildings and the wide range of building heights and structural typologies.

The soil in Mexico City is divided into three zones: hard soil (Zone I), transitional soil (Zone II), and soft soil (Zones IIIa, IIIb, IIIc, and IIId). The soft soil zones, are known to induce more severe structural damage due to the amplification effects of seismic waves (Figure 1). After the 19S, 2017 earthquake, numerous authors documented the collapse of 44 structures (Cruz-Atienza et al., 2017, Galvis et al., 2020, Hernández et al., 2019). In this study, the data obtained from post-seismic damage assessment surveys, conducted shortly after the seismic event, provided information of 40 collapsed structures. After filtering out structures that were not classified as buildings, the sample size was reduced to 31, with 11 structures identified as collapsed corner buildings (CCB).

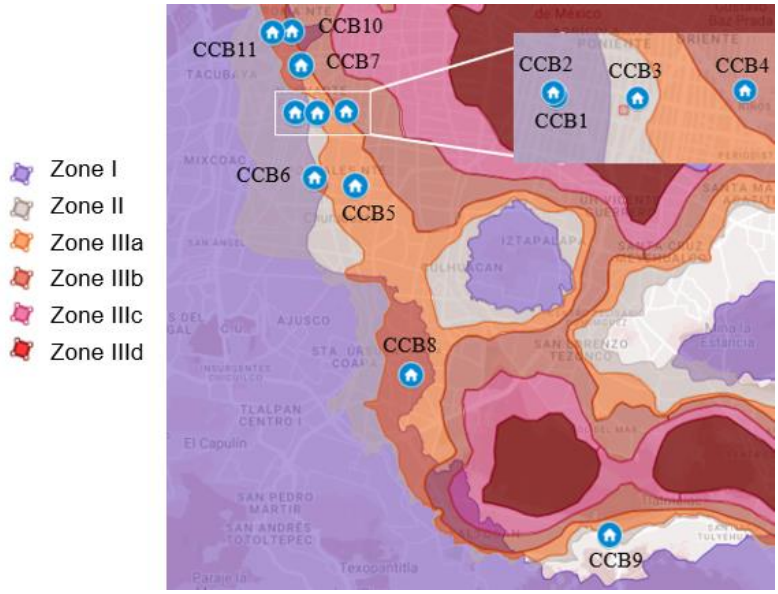

Figure 1. Location of the collapsed corner buildings due to the 19S, 2017 earthquake and seismic zonation of Mexico City

A corner building is a structure situated within a block of buildings, characterized by having two main facades that intersect at the street corner. From a structural standpoint, these primary facades often have a minimal density of walls, in contrast to the rear facades, which, due to their adjacency to neighboring buildings, have masonry infill walls. In Mexico City, mid-rise buildings are typically built employing concrete or steel rigid frames. It is also customary to seismically design these buildings without involving the infill walls. During construction stages, these walls may become attached to the frames, causing them to collaboratively work with the frames when the building is subjected to lateral loads. The structural configuration of the corner buildings that collapsed in Mexico City consisted of reinforced concrete frames with masonry infill walls situated on the two opposing perimetral sides adjacent to the building facades.

Using data from visual inspections and satellite images, it was determined that the CCB buildings were in the range of three-eight stories, the use was predominantly residential or a combination of residential and commercial use. Regarding to the floor systems, detailed information was not available, but based on the images, it was estimated that the majority of these structures had solid slabs and lightweight flat slabs. Figure 2 shows a collapsed eight-story building. 73% of the buildings experienced complete collapse, whereas 27% suffered partial collapse. All of the collapses were in seismic zones II, IIIa, and IIIb.

2. Researched Typologies

To conduct the nonlinear analyses, a representative building, typical of corner buildings that had collapsed, was selected. Based on satellite images and pre-collapse photographs, a building with floor plan dimensions of 20 m x 15 m, floor heights of 2.70 m, and column spacing of 5.0 m in both directions was proposed. The building has four bays horizontally (x) and three bays vertically (y). A total of six buildings from three to eight stories were analyzed. However, due to space limitations, the study exclusively presents the results of the three- and eight-story buildings. Figure 3 shows the floor plant where the holes at building's center correspond to the stairwell and elevator areas.

Figure 2. CCB2 building, before and after the 19S, 2017 earthquake

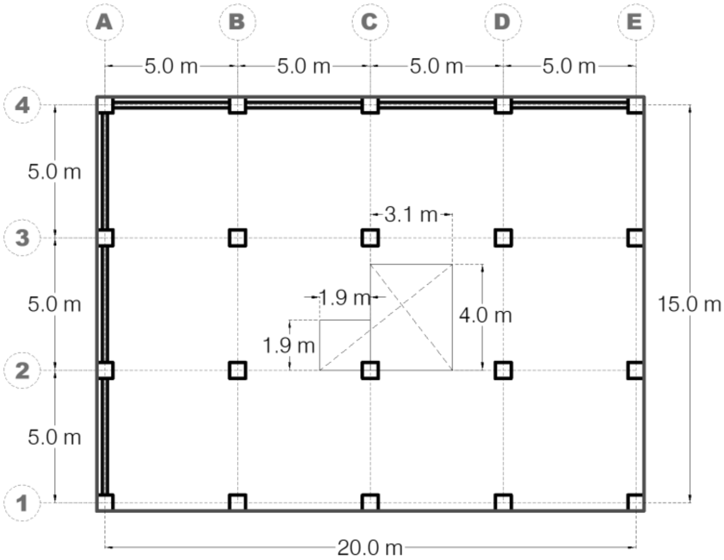

Figure 3. Typical floor plan for the analysis of corner buildings

3. Elastic Analysis and Design

The elastic models of the buildings were created using ETABS v21 software (CSI ETABS, 2023) using frame-type elements for columns and beams and four-node shell elements, with rigid diaphragms, for slabs. Masonry walls were modeled using the equivalent diagonal model (Figure 4) with the properties specified in Table 1. This approach resulted in a diagonal width (b_d) of 1.40 m and a thickness (t) equal to 0.15 m.

Table 1. Masonry wall properties

Wall thickness	t = 0.15 m
Wall height	H = 2.55 m
Modulus of elasticity	E = 1569 MPa
Compression strength	f*m = 3.92 MPa

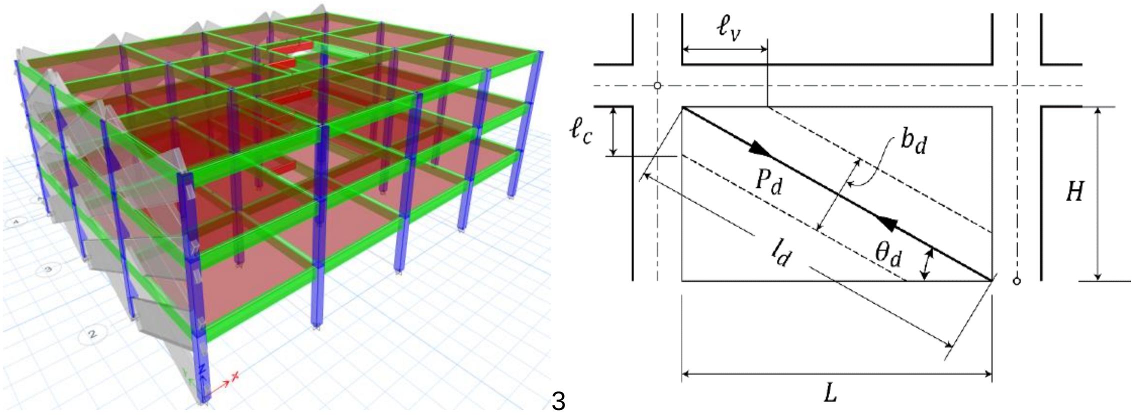

Figure 4. Numerical model of 3-story building in ETABS v21, and equivalent diagonal model for infill walls, NTC (2017)

Two numerical models were analyzed, namely: regular building (RB) without infill walls and corner building (CB) with masonry infill walls in axes "A" and "4". Table 2 displays the outcomes of the modal analysis, presenting the natural vibration periods and the modal participation factors associated with each mode. These factors reveal the degree of influence of vibration modes on the dynamic response of the building in different directions. This analysis aids in distinguishing whether the effects primarily involve translational motion, torsional motion, or a combination of both coupled motions.

The three-story RB building was more flexible than the CB building, with the fundamental period changing from 0.808 s to 0.76 s, specifically in the building's most flexible direction (y). The first mode in the CB building involves rotation around the z-axis (RZ), indicating torsional behavior, whereas in the RB building the rotational mode appears in the third mode. Similar behavior was observed for the eight-story building (Table 3), with the fundamental mode period changing from 1.33 s (RB) to 1.23 s (CB).

Table 2. Modal properties for the three-story building

Regular building (RB)					**Corner building (CB)**				
Mode	**Period (s)**	**Modal contribution factors**			**Mode**	**Period (s)**	**Modal contribution factors**		
		UX	**UY**	**RZ**			**UX**	**UY**	**RZ**
1	0.808	0.003	**0.8734**	0.0025	1	0.76	0.2236	**0.4158**	0.2396
2	0.799	**0.875**	0.0033	0.0022	2	0.369	**0.5242**	0.3626	0.0087
3	0.685	0.0024	0.0022	0.875	3	0.25	0.0251	**0.0462**	0.0271
4	0.266	0.0018	**0.0961**	0.0007	4	0.21	0.1472	0.1111	**0.6496**
5	0.264	**0.0952**	0.002	0.0004	5	0.156	0.0048	**0.0095**	0.0062
6	0.227	0.0006	0.0006	0.0969	6	0.151	0.0003	0.0004	**0.0005**

The buildings were designed following the 1976 regulations in forced for the Mexico City Building Code (RCDF, 1976). This code was used because most of the buildings were designed using this regulation in the 80's. The RCDF, 1976 established the seismic design spectra for three seismic zones. The design spectrum of Zone III (soft soil), where most of the collapses took place, was employed. Additionally, a ductility factor Q=4 was assumed since it was a common value employed for design buildings at that time (Figure 5).

Table 3. Modal properties for the eight-story building

Regular building (RB)					Corner building (CB)				
Mode	Period (s)	Modal contribution factors			Mode	Period (s)	Modal contribution factors		
		UX	UY	RZ			UX	UY	RZ
1	1.33	0.0027	**0.7484**	0.0041	1	1.234	0.1857	**0.3744**	0.195
2	1.303	**0.7501**	0.0032	0.0038	2	0.811	**0.469**	0.3074	0.0096
3	1.117	0.0042	0.0036	0.7469	3	0.504	0.1317	**0.095**	0.5872
4	0.41	0.0006	**0.1127**	0.0007	4	0.384	0.0271	0.0547	**0.0323**
5	0.404	**0.112**	0.0007	0.0006	5	0.264	0.0647	**0.0444**	0.0016
6	0.352	0.0007	0.0006	0.1132	6	0.201	0.014	0.0266	**0.0122**

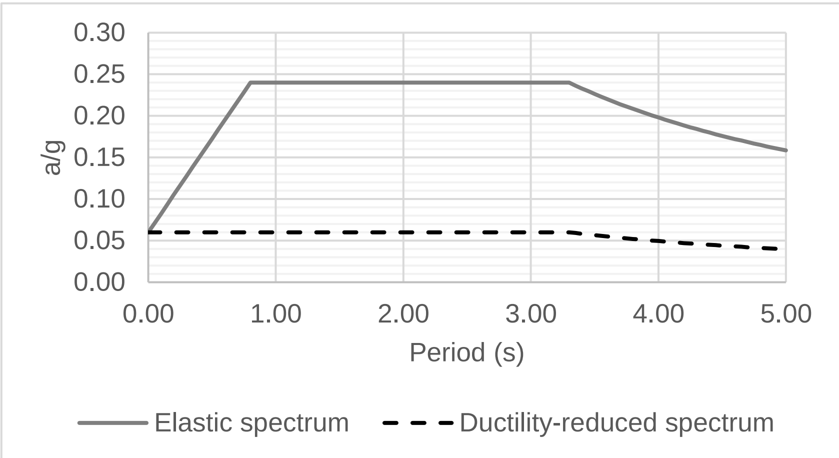

Figure 5. Elastic design spectrum and reduced spectrum according to RCDF (1976) for México City

The design process considered failure and serviceability limit states. An interstory drift limit of 0.008 was assumed as prescribed by the RCDF, 1976. This limit applied for buildings with non-structural elements separated from the primary structure, with the assumption that the walls were not included in the analysis. For the three-story building, the columns had cross section of 0.30 x 0.30 m. The eight-story building had two column sections: 0.65 x 0.65 m from floor 1 to floor 5 floors and 0.50 x 0.50 m from floor 6 to floor 8 (Figure 6). Beams had cross section of 0.20 x 0.45 m in both buildings.

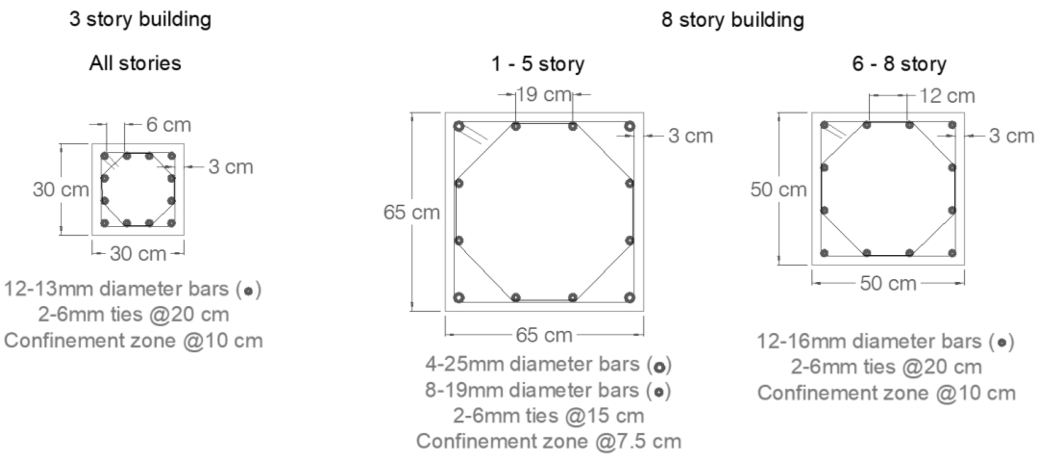

Figure 6. Columns cross sections designed according to RCDF (1976)

4. Seismic demand

Nonlinear dynamic time-history analysis was used to assess the seismic response of the buildings. The selected accelerograms to analyze de buildings were the seismic records obtained during the 19S, 2017 earthquake in Mexico City. These records were collected from a total of 68 seismic monitoring stations (Figure 7), which are part of the seismic instrumentation network operated by the Universidad Nacional Autónoma de México (UNAM) and the Seismic Instrumentation and Recording Center (CIRES). 36 seismic stations were selected in the zones of the CCB. Table 4 shows the information of the seismic stations for zone II (10 stations), zone IIIa (8 stations) and zone IIIb (18 stations).

Table 4. Seismic records used for nonlinear dynamic analysis

Seismic station	Database	Zone	Seismic station	Database	Zone
AO24	CIRES	II	AL01	CIRES	IIIb
AU46	CIRES	II	BL45	CIRES	IIIb
CO47	CIRES	II	CCCL	UNAM	IIIb
DR16	CIRES	II	CI05	CIRES	IIIb
DX37	CIRES	II	CJ03	CIRES	IIIb
EO30	CIRES	II	CJ04	CIRES	IIIb
ES57	CIRES	II	CO56	CIRES	IIIb
GR27	CIRES	II	GA62	CIRES	IIIb
LEAC	UNAM	II	GC38	CIRES	IIIb
ME52	CIRES	II	LI58	CIRES	IIIb
CH84	CIRES	IIIa	PCJR	UNAM	IIIb
IB22	CIRES	IIIa	PE10	CIRES	IIIb
JC54	CIRES	IIIa	RM48	CIRES	IIIb
LI33	CIRES	IIIa	SCT2	UNAM	IIIb
LV17	CIRES	IIIa	SP51	CIRES	IIIb
MI15	CIRES	IIIa	TL08	CIRES	IIIb
SI53	CIRES	IIIa	TL55	CIRES	IIIb
UC44	CIRES	IIIa	VG09	CIRES	IIIb

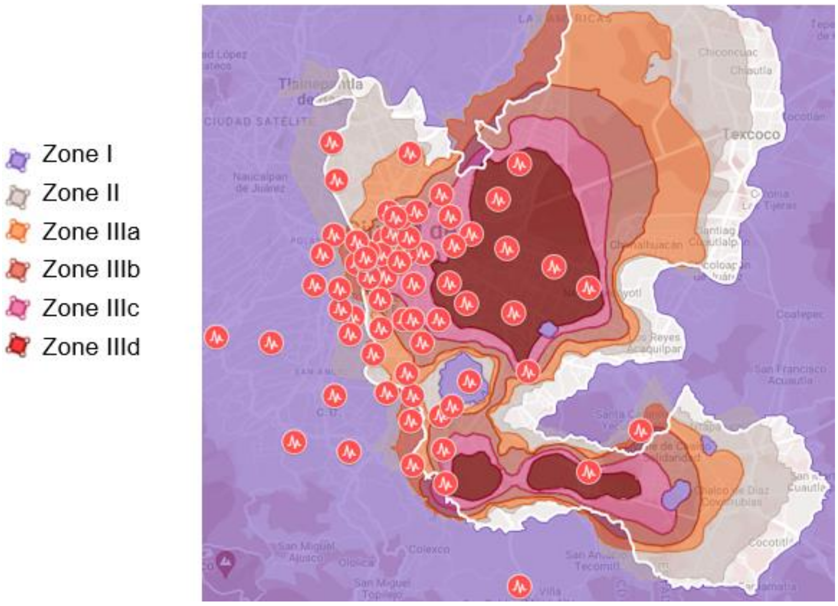

Figure 7. Seismic stations' location in Mexico City that recorded the 19S, 2017 earthquake

Before the nonlinear analysis, baseline correction was applied to all the seismic records, and the signal duration was reduced using the Arias intensity (Figure 8).

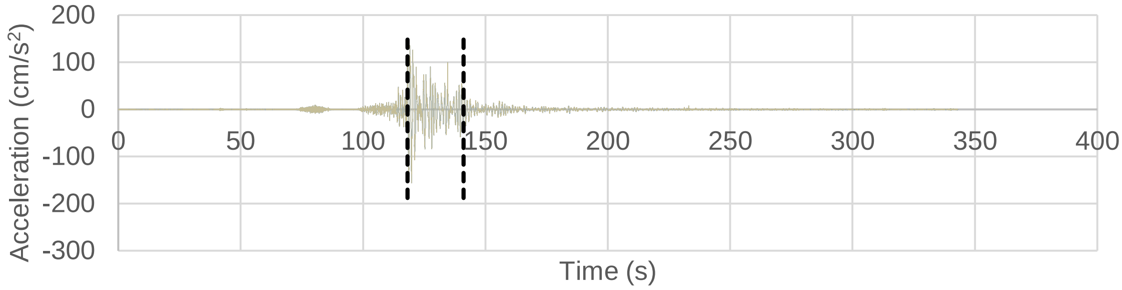

Figure 8. Signal duration (between vertical dashed lines) using the Arias intensity for the N-S component, LEAC record

5. Nonlinear analysis and seismic response of the buildings

Nonlinear analysis was performed using Perform3D v8 (CSI Perform3D, 2021), assuming a concentrated plasticity model for beams and columns. Nonlinear behavior was characterized using moment-rotation curves derived from SAP2000 software (CSI SAP2000, 2023), which were then fitted to an idealized moment-rotation curve (Figure 9).

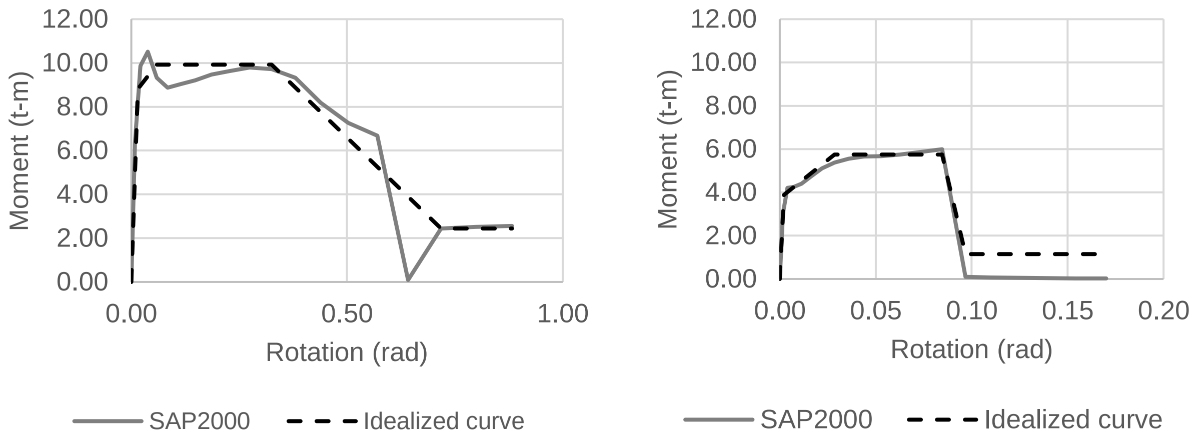

Figure 9. Moment-rotation curves for columns (left) and beams (right) of three-story building

The demand parameter selected for assessing the seismic response of the buildings was the interstory drift ratio at the building's corners (Figure 10). Figures 11-14 present the interstory drifts at corners C1 and C3 for each floor of the three-story building in zone IIIa. The regular building RB (Figure 11 and 12) shows that drifts in both corners exhibit similar amplitude values, reaching a maximum value close to 0.031, and similar demand distribution with all seismic records as well. Conversely, Figure 13 and Figure 14 show that the C1 corner of the CB building exhibits a maximum drift of 0.025, given its contact with the two walls of the rear facades, which is a lower value than the drift at corner C3 of 0.037, indicating torsional effects in the building. The C1 corner of the CB building even presents lower interstory drifts than any other of the corners of the regular building (RB). The red dashed line in the figures displays the allowable interstory drift limit according to the RCDF (1976). As observed, all records exceeded this limit, except for the C1 corner of the CB building, effect that can be attributed to the stiffness provided by the infill walls, as mentioned earlier.

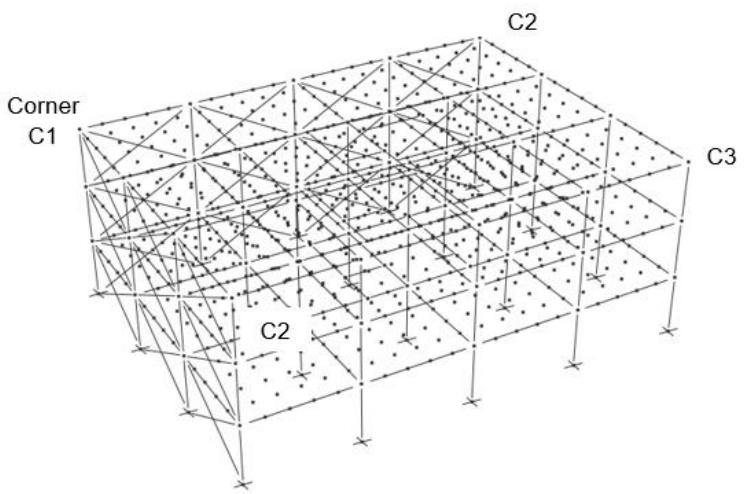

Figure 10. Nonlinear model in Perform3D and identification labels of building corners

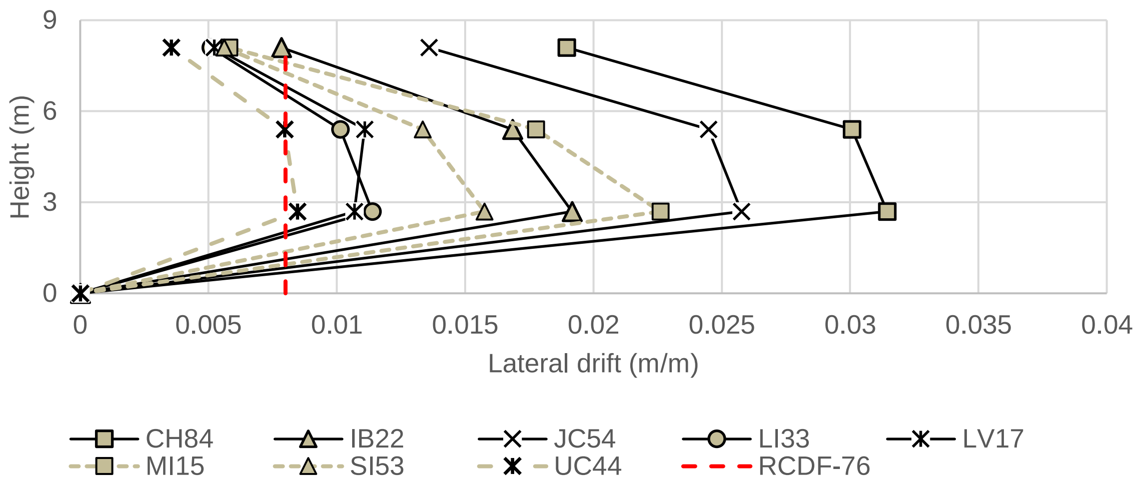

Figure 11. Interstory drift ratios in the three-story RB, corner C1-x direction, seismic records from zone IIIa

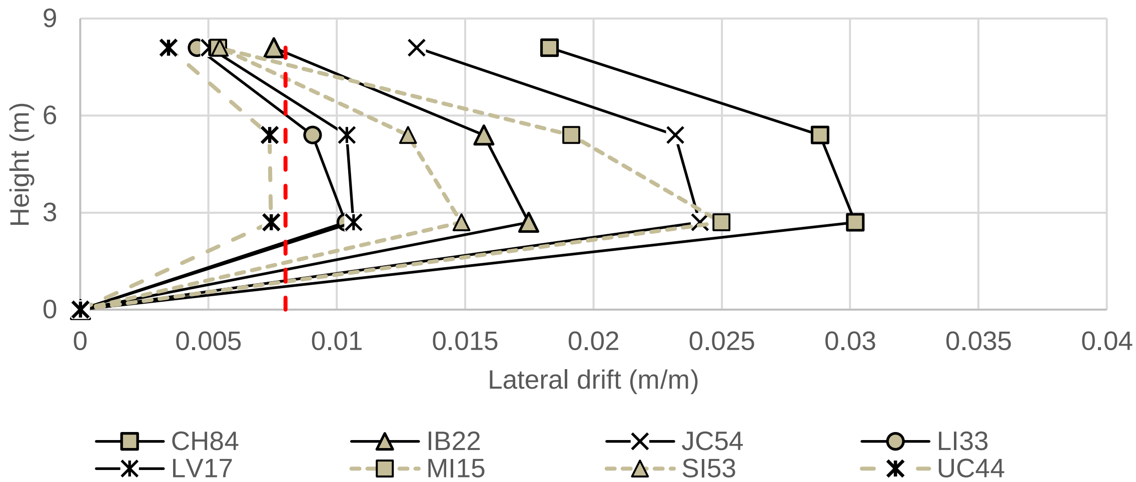

Figure 12. Interstory drift ratios in the three-story RB, corner C3-x direction, seismic records from zone IIIa

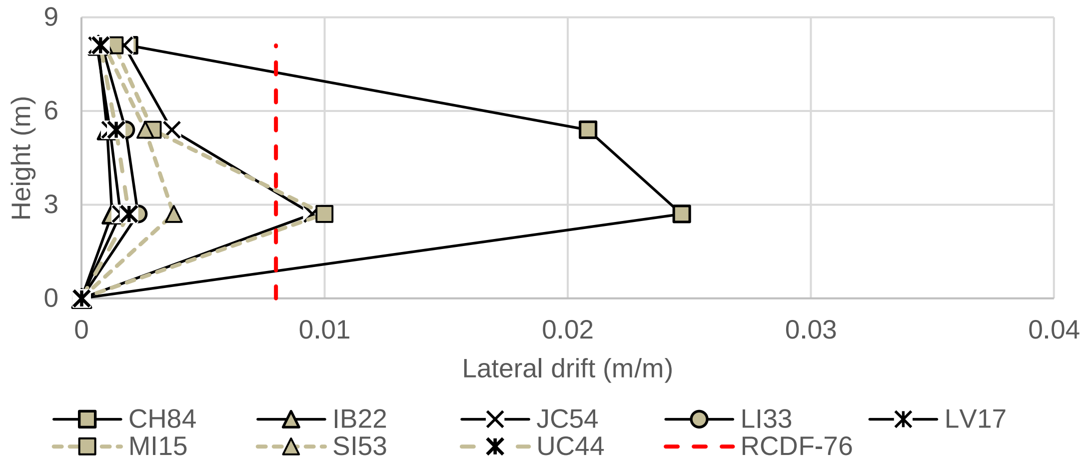

Figure 13. Interstory drift ratios in the three-story CB, corner C1-x direction, seismic records from zone IIIa

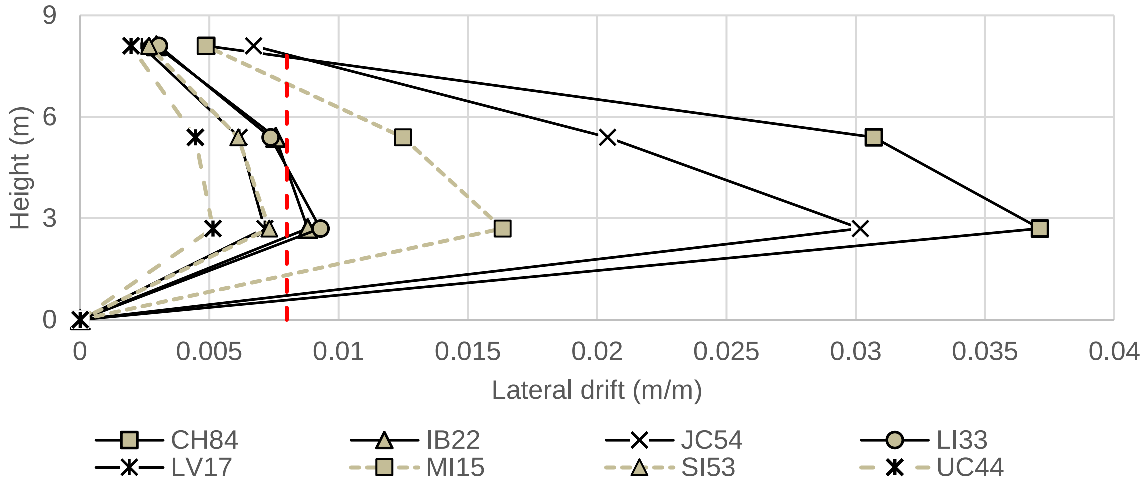

Figure 14. Interstory drift ratios in the three-story CB, corner C3-x direction, seismic records from zone IIIa

The drift limits proposed by Akbari (2012) to classified damage states were used to establish a relationship between seismic demands and potential structural damage in the buildings. The author proposes an interstory drift in the range of 0.025-0.05 for extensive damage. The buildings of this study presented seismic demands in this range, just below of the complete damage category (structural collapse). Furthermore, FEMA (2022) guidelines locate these drift values in the range of extensive-complete damage.

Figure 15-Figure 18 show that eight-story building presented a similar behavior to the three-story building regarding the interstory drifts at the corners of RB and CB buildings. C1 and C3 corners of the RB building had maximum drifts of 0.017 and 0.016, respectively, whereas these values of the CB building, changed to 0.013 and 0.018, respectively. These results suggest that the torsional effect was less pronounced in the eight-story building.

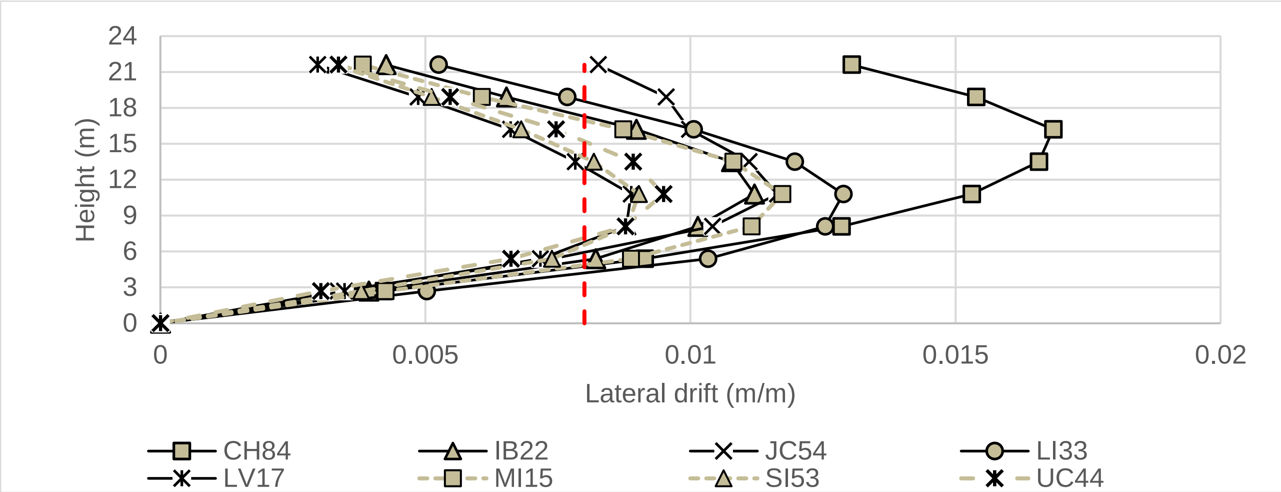

Figure 15. Interstory drift ratios in the eight-story RB, corner C1-x direction, seismic records from zone IIIa

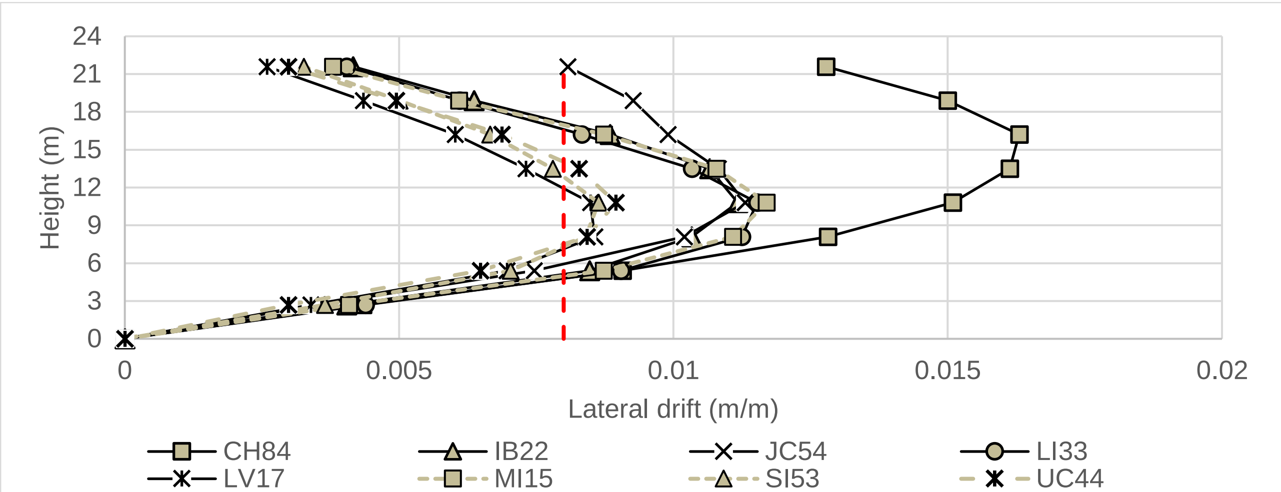

Figure 16. Interstory drift ratios in the eight-story RB, corner C3-x direction, seismic records from zone IIIa

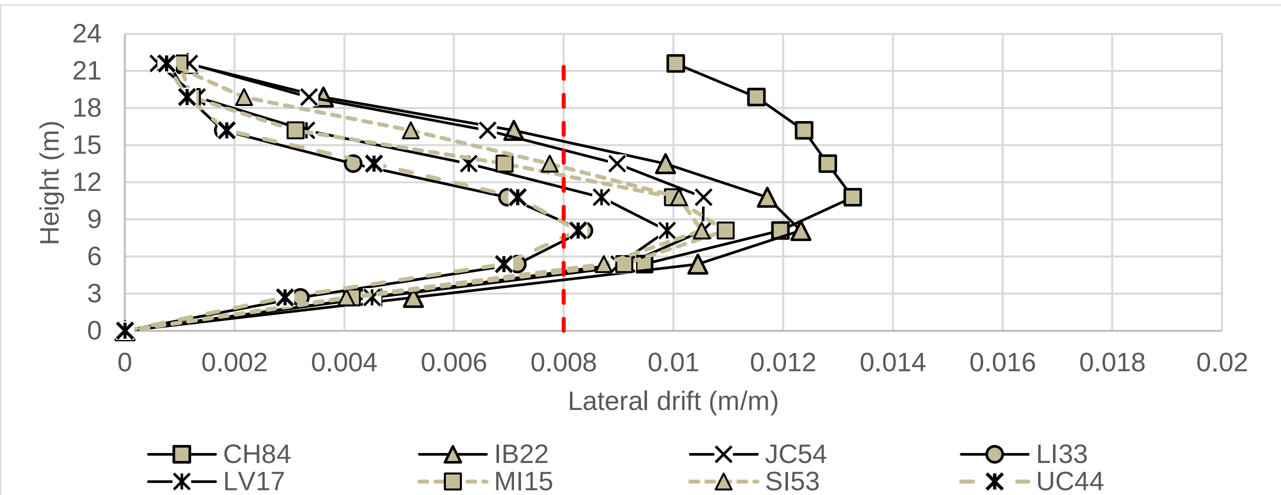

Figure 17. Interstory drift ratios in the eight-story CB, corner C1-x direction, seismic records from zone IIIa

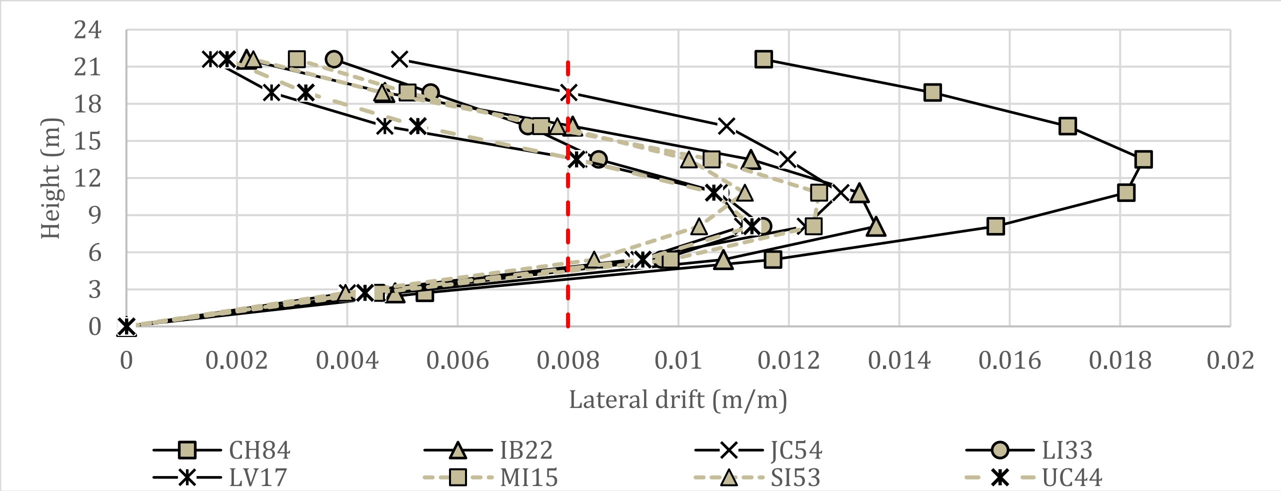

Figure 18. Interstory drift ratios in the eight-story CB, corner C3-x direction, seismic records from zone IIIa

6. Conclusions

Corner buildings experience torsional effects due to the asymmetric location of masonry infill walls on two of its perimeter sides. In this study, the torsional effects and seismic demands of a typical corner building were quantified. Initially, regular buildings (without infill walls), as control models, were analyzed and subsequently numerical models with infill walls were created to evaluate the impact of the walls in building demands. Results showed that torsion played and important effect in the interstory drift ratios at opposite building´s corners C1 (inner corner) and C3 (façade corner). In regular buildings, interstory drifts exhibited similar behavior at both corners. In contrast, buildings with infill walls decreased interstory drift demands at corner C1 due to its contact with the masonry walls, while corner C3, with no wall contact, experienced a significant increase in interstory drifts, indicating substantial torsional effects leading the buildings to a severe damage limit state.

The torsional effects were less pronounced in the eight-story building as compared with the three-story building. Consequently, low-rise buildings on soft soil areas (Zone IIIa) of Mexico City under seismic actions are particularly susceptible to be damaged when asymmetric infill walls are included. The nonlinear analysis results showed that low-rise buildings may be under substantial seismic demands yielding the structures to important damages and, in some cases, to collapse.

7. References

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