Canadian Conference - Pacific Conference on Earthquake Engineering 2023

Vancouver, British Columbia

June 25th – June 30th, 2023

Higher-mode effects on the seismic response of high-rise buildings

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ABSTRACT

The dynamic response of tall buildings is studied in this paper to evaluate the influence of higher modes. Buildings were carefully designed following capacity design principles and were virtually located in the soft soils of the lake-bed zone of Mexico City. Nonlinear dynamic analyses were carried out with *OpenSees* on 3-D models with plasticity spread along the elements. A set of accelerograms recorded during the Puebla earthquake of September 2017, in Mexico, was considered. Records were adjusted to represent the seismic hazard at the building's location. The influence of the seismic behavior based on a global shear-dominated lateral response, a bending response, and a combined shear and bending response are discussed in detail from the behavior of the studied buildings. A ratio of the spectral pseudo-accelerations corresponding to the first two vibration response modes was proposed to quantitatively anticipate conditions for which higher-mode effects unfavorably influence the structural response of tall buildings and encourage conservative decisions in the design process. The complexity of predicting the nonlinear behavior of high-rise buildings using traditional design procedures is underlined.

Keywords: Tall-building, higher mode effect, dynamic response, nonlinear analysis, earthquake

INTRODUCTION

Analysis based on the fundamental mode might underestimate the contribution of higher modes in the analysis of high- and ultra-high-rise buildings and have the potential to lead to excessive damage concentration. For this reason, a performance-based assessment is required for high-building because the critical response might not be identified based on the fundamental mode only. Despite the inelastic response affecting higher modes unequally, codes assume the same reduction factor for all modes (Maniatakis *et al.* 2013). In fact, stiffness degradation increases the contribution of higher modes (Terán *et al*. 2006), which might result in an increase in displacement and lateral demands on the upper levels.

Additionally, the relationship between the dynamic response and the soil condition might increase the higher-mode effects and, therefore, the seismic demand. In fact, Mexico City is divided into three subzones: Zone I (rock soil), Zone II (transitional soil condition), and Zone III (Lake Zone) (Rosenblueth *et al.* 1989; Singh *et al.* 2015). The Mexico City Building Code (MCBC-2020) establishes specific requirements for the performance-based assessment of high-rise buildings, similar in rigor to ASCE 41 (2017).

This paper studies the effects of higher modes in tall buildings structured with moment-resisting steel frames (MRF) and concentrically braced steel frames (CBF) and located in soft soils. The study aims at establishing quantitative measures that might contribute to anticipate conditions for which the higher modes govern the performance of the buildings.

STUDIED BUIDLINGS

Two 21-story buildings having an aspect ratio of H/B= 4.0 were considered. While one building was structured with moment-resisting frames (MRF), the other uses concentrically braced frames (CBF) as depicted in Fig. 1. The buildings were assumed to be located at a soft soil site with a soil period T_g equal to 1.10s. The structures were proposed as office buildings; so that gravity loads were also included in Fig. 1.

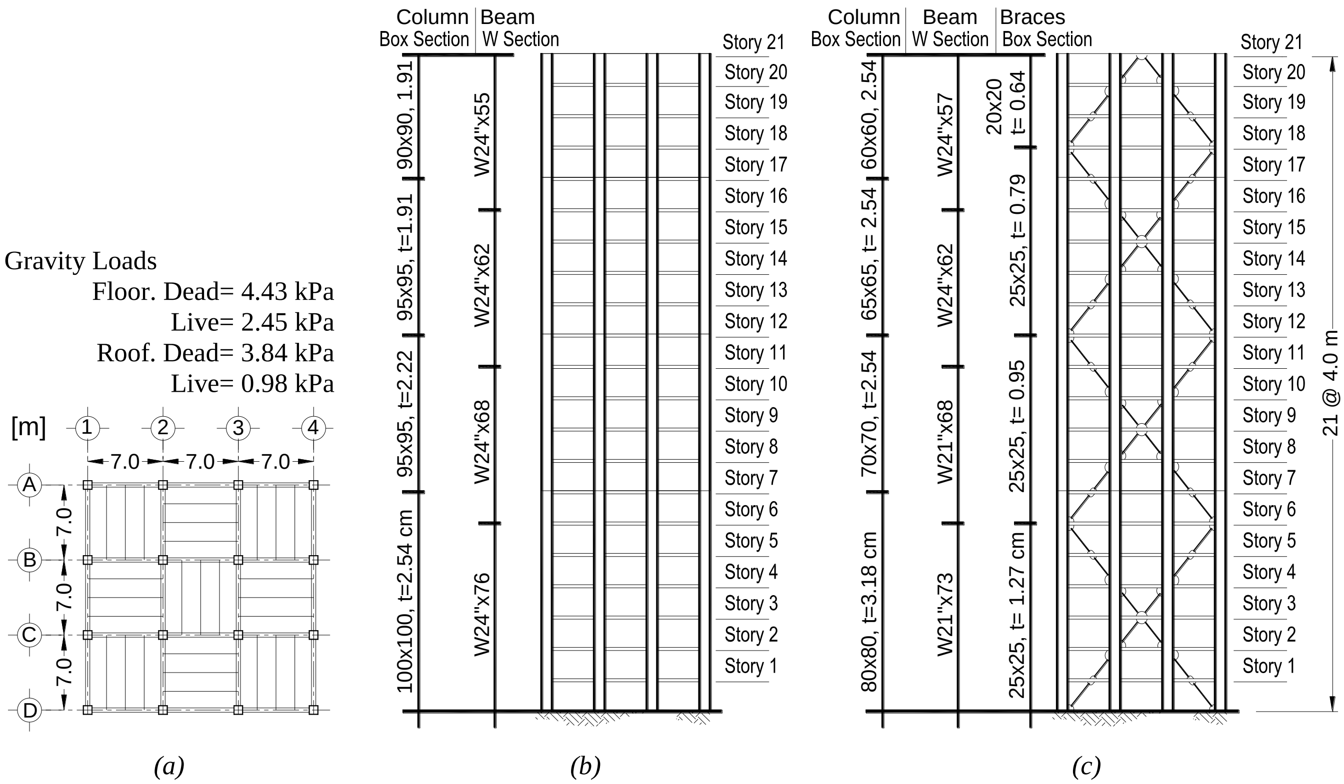


Figure 1. Analyzed buildings, (a) Plan view, (b) Moment-resisting steel frame (MRF), (c) Concentrically braced steel frame (CBF)

Buildings were designed from the results of elastic analyses of three-dimensional models following standard capacity design concepts prescribed in the local code. Local practice requires that all frames (exterior and interior) be designed to resist earthquake loading. A further discussion about this practice can be found in Tapia-Hernández and García-Carrera (2020). The characteristics of the studied buildings are summarized in Table 1 and reported in further detail in Gama-Contreras (2019).

Table 1. Modal periods of studied models

Mode	Moment – resisting frames (MRF)		Concentrically braced frames (CBF)	
	Period (s)	Frequency (rad/s)	Period (s)	Frequency (rad/s)
1	3.517	1.787	2.123	2.960
2	3.514	1.788	2.123	2.960
3	2.493	2.520	1.170	5.370

From the shape of the fundamental modes, it was concluded that the building with moment-resisting steel frames (MRFs) was dominated by a global shear response as shown in Fig. 2a; and the one structured with concentrically braced steel frames (CBFs) was dominated by a global bending-type response (Fig. 2c).

An additional building with concentrically braced steel frames was developed in such a manner as to exhibit the similar main period as the building structured with MRFs. The third model was obtained by increasing the cross-section of the perimeter columns of the building structured with CBFs and increasing its reactive mass by 30 percent. The lateral behavior of the third hypothetical building is a combined one, as is shown in Fig 2b.

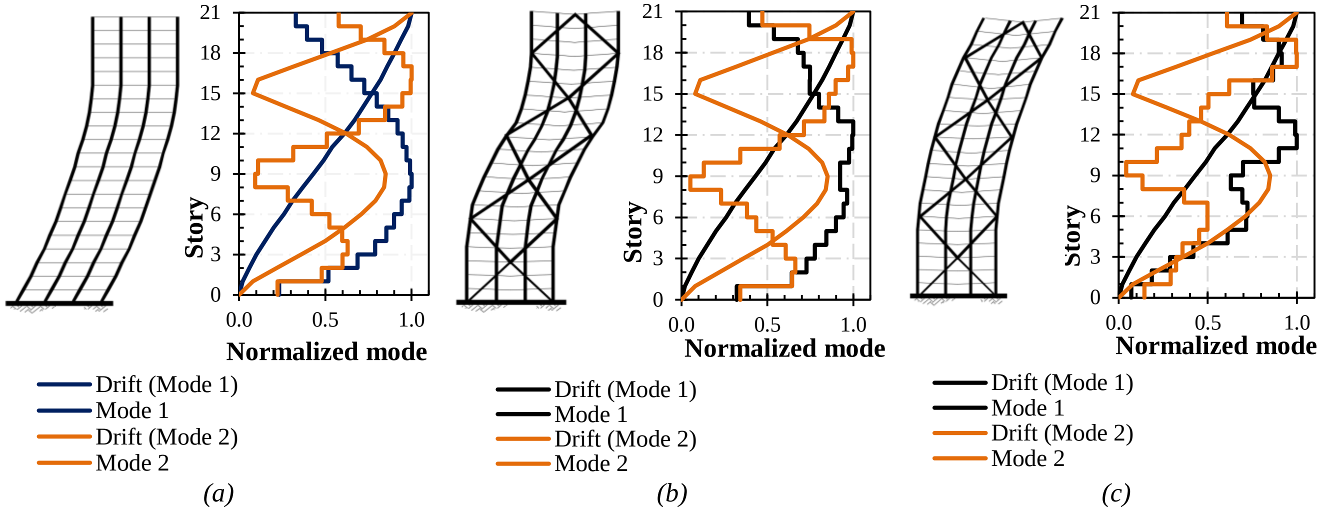


Figure 2. Lateral response of the buildings, (a) Moment resisting frame response (global shear-dominated lateral response), (b) Combined global shear and bending response, (c) Concentrically braced Frames response (global bending-dominated lateral response)

NONLINEAR MODELS

Three-dimensional analyses were performed using *OpenSees* (Mazzoni *et al*. 2006). As depicted in Fig. 3, member centerlines were considered to define the building geometry. Nonlinear beam-column elements with plasticity spread along their length were considered for columns, beams, and braces. Four rectangular patches were used for box sections in columns and the bracing system, whereas three rectangular patches were used to generate the cross-section of wide flange beams: one for the web and one for each flange. Patches were discretized into fibers with quadrilateral shapes and four integration points per element.

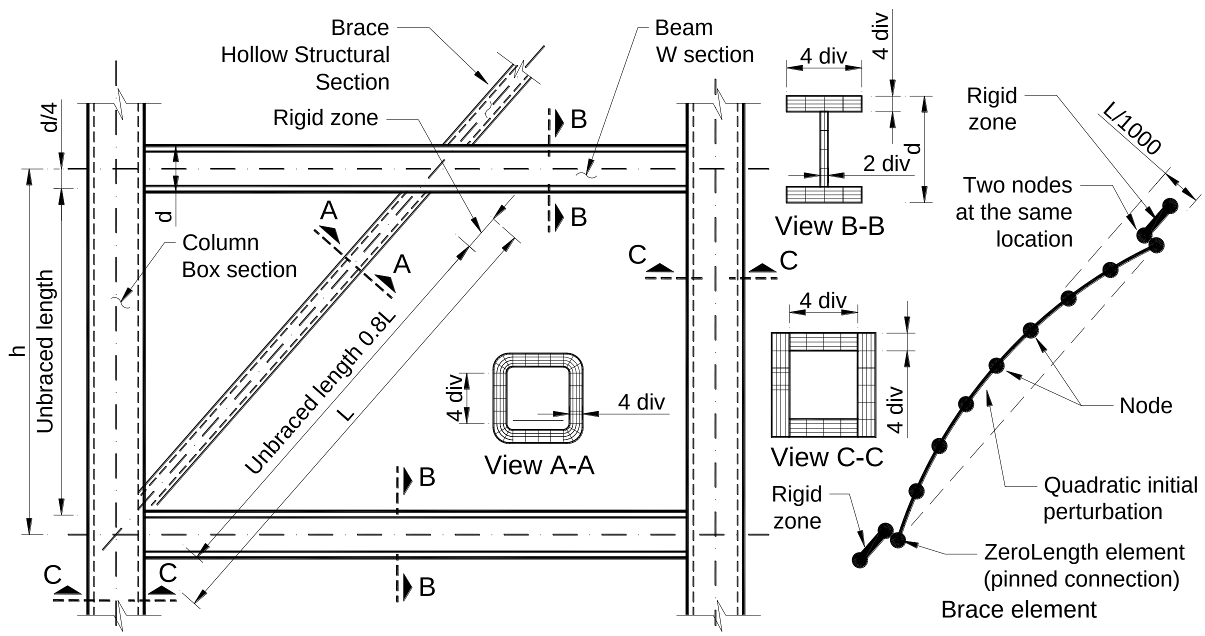


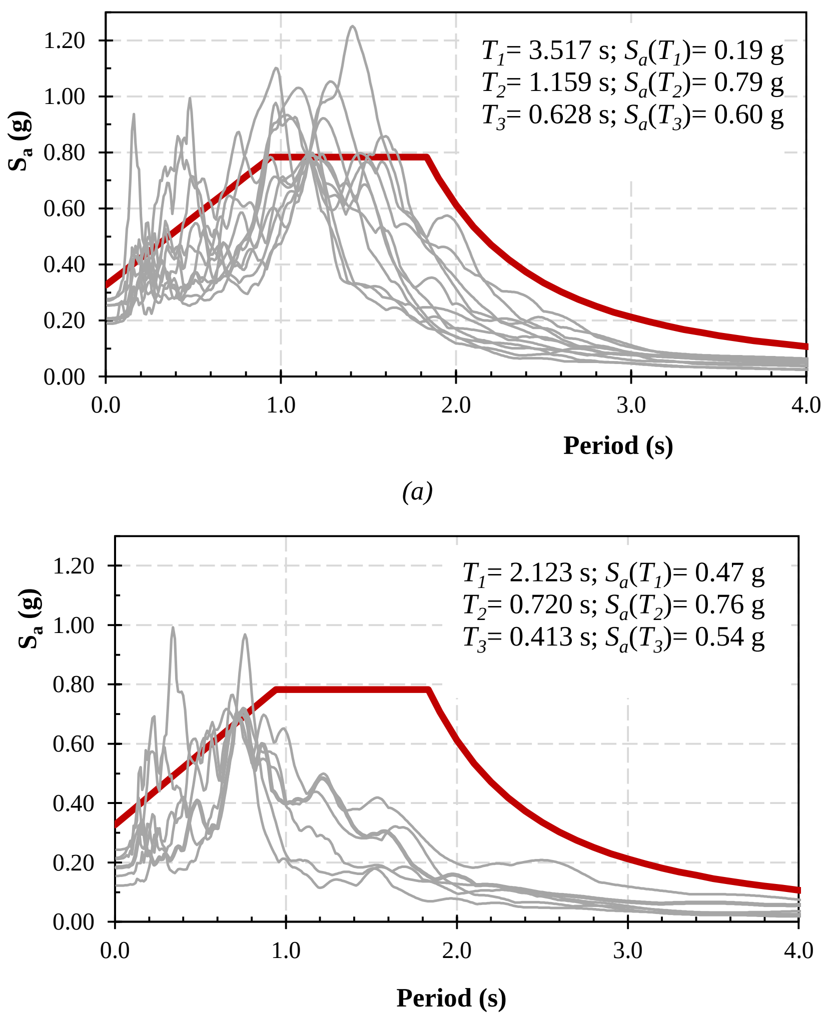
Figure 3. Analytical model

An initial camber with a quadratic shape was introduced in the centerline of the braces, as depicted in Fig. 3, to produce a perturbation to trigger buckling. The initial out-of-straightness assigned to the braces was *L*/1000, which meets the permissible tolerances in codes (MCBC-2020; AISC 360-2016). Rigid zones with ten times the original members' bending, axial, and shear stiffness were included at the ends of the elements (Fig. 3).

Steel ASTM A992 was considered for beams and columns, and steel ASTM A500 Gr. B was used for the bracing system. Strain hardening was considered equal to 0.01 following the recommendation of FEMA 355A (2000). A reasonable agreement can be found between the results of experimental tests and the proposed analytical model (Uriz and Mahin 2008; Tapia-Hernández & García-Carrera 2019). Periods and mode configurations in the *OpenSees* models were consistent with those estimated with the elastic models used for design purposes. Further information about the models can be found in Gama-Contreras (2019).

DYNAMIC ANALYSIS

On September 19th, 2017, an earthquake that struck (M_w= 7.1) Mexico City and the states of Puebla and Morelos, caused damage and building collapses (Tapia-Hernández and García Carrera 2020). A set of accelerograms recorded in Mexico City during this event was selected from those recorded by the Center for Instrumentation and Seismic Records (CIRES). The selection process favored those motions whose maximum acceleration demands occurred at a period close to the periods of the second mode of vibration of the studied structures.



(b)

Figure 4. Response spectra of selected ground motions and design spectrum, (a) Building structured with moment-resisting steel frames, MRF; (b) Building structured with concentrically braced steel frames, CBF

Nonlinear time-history analyses were conducted using *OpenSees* software (Mazzoni *et al.* 2006). Ground motions were scaled using as target the design spectrum and considering a range of periods centered around that of the second mode of vibration of the building of interest. The response spectrum of the records and the design spectrum provided by the code are compared in Fig. 4. Thus, the selected ground motions are a proper representation of the seismic hazard for the location of buildings. It is worth noting that peaks of the spectra have a proper correspondence to the second period of the buildings equal to 1.159 s and 0.72, respectivle. Namely, the ground motions achieve the purpose to overstimulate the second modes.

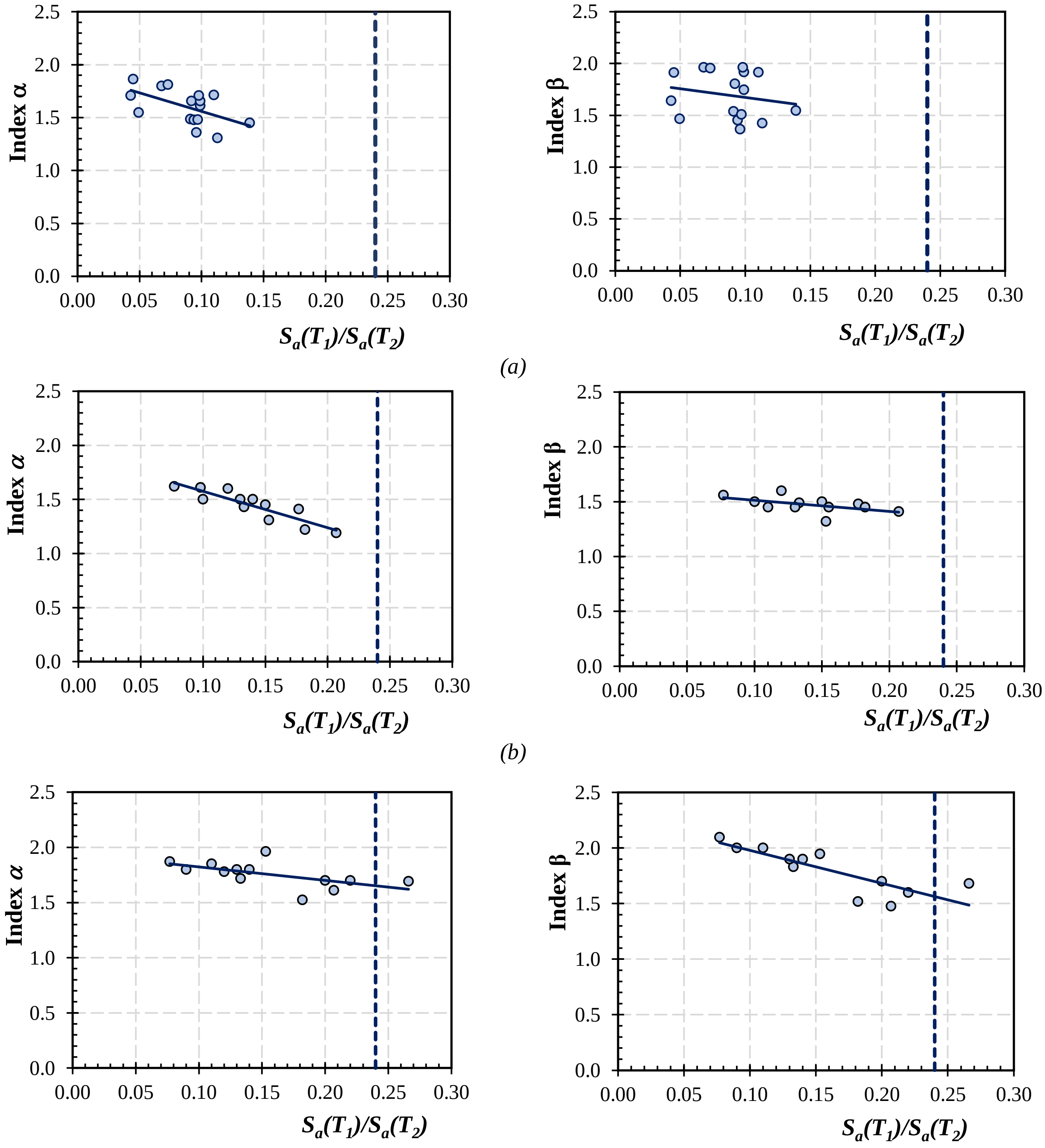
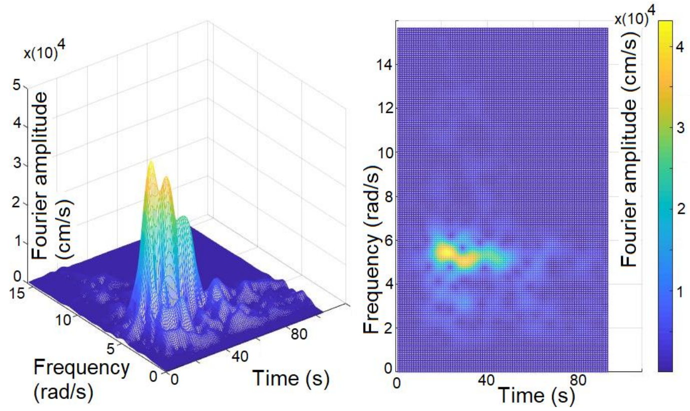
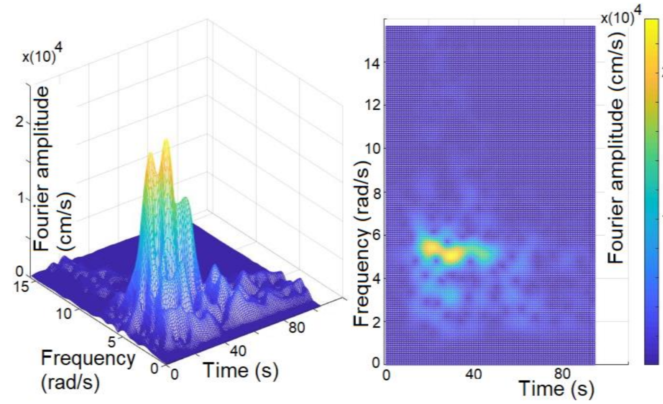


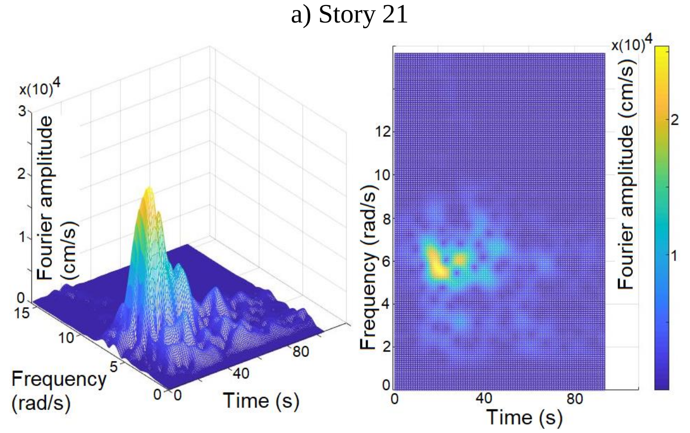
Figure 5. Indexes α and β; (a) Moment-resisting frame, MRF (global-shear dominated lateral response); (b) Concentrically braced frame (combined global shear and bending response); (c) Concentrically braced frame, CBF (global bending-dominated lateral response)



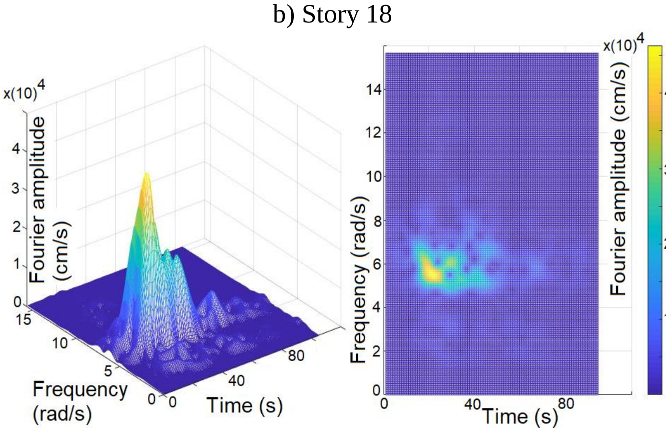
a) Story 21



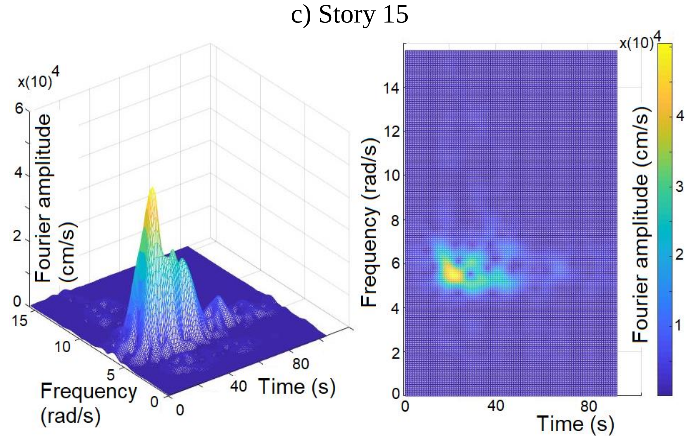
b) Story 18



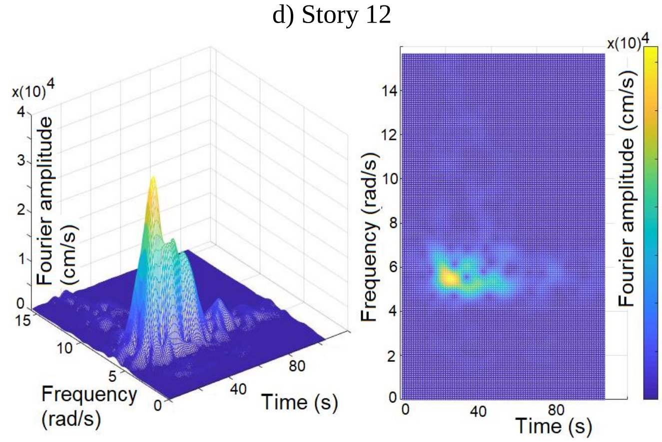
c) Story 15



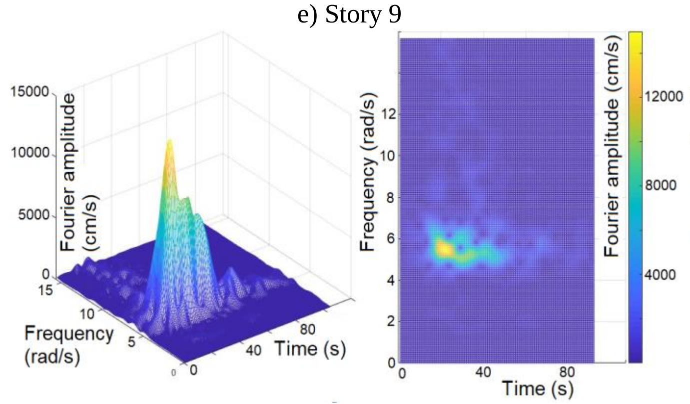
d) Story 12



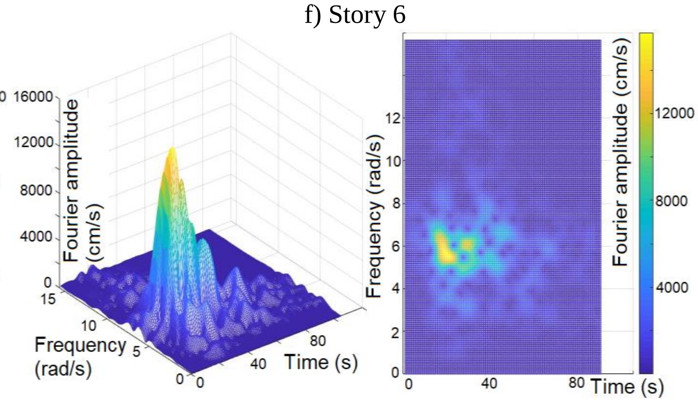
e) Story 9



f) Story 6



g) Story 3



h) Ground floor

Figure 6. Fourier amplitude spectra of output recorded accelerations under a selected record

Acceleration demands

Two indexes were considered to identify the influence of higher mode effects on the dynamic response of the studied buildings. The first index, denoted α, relates the average peak interstory drift for the ten upper stories and the average peak interstory drift corresponding to the eleven bottom interstories. The index α aims at identifying a drift concentration at the upper levels. The second index, denoted β, aims at relating the average peak interstory drift for the four upper stories and the average of the peak interstory drift corresponding to the bottom four stories. A magnitude greater than 1.0 for α or β implies larger drifts demands in the upper stories in relation to those at the bottom stories. Such condition would suggest that the higher modes of vibration have a strong influence in the dynamic response of the buildings.

The ratio of the pseudo-acceleration spectral ordinates corresponding to first and second modes of vibration, $S_a(T_1)/S_a(T_2)$, was also computed from the elastic spectrum corresponding to each of the ground motions under consideration. Fig. 5 shows the values of α and β estimated from dynamic nonlinear analyses as a function of $S_a(T_1)/S_a(T_2)$. It is worth mentioning that $S_a(T_1)/S_a(T_2)$ ratios of 0.24 and 0.61 were established from the design spectra used for the design of the MRF and CBF buildings, respectively, and that these values are far off from the actual values estimated for the ground motions. The differential between the actual $S_a(T_1)/S_a(T_2)$ ratios and the values considered during the design of the buildings highlight one of the main causes of why the structural engineer is not able to correctly assess the effects of higher modes during the design process. Note that the values of both, α and β, are significantly larger than one for all cases under consideration in this paper, indicating a drift and consequently, a damage concentration, in the upper stories of the buildings. It can be said that as the $S_a(T_1)/S_a(T_2)$ ratio increases, there is a larger influence of higher modes in the dynamic response of the buildings, situation that results in increasing damage in the upper stories relative to that established for the lower stories.

DYNAMIC CHARACTERISTICS

A frequency-domain identification technique was used to assess the effects of higher modes of vibration. Particularly, a moving-window Fourier analysis was carried out. In the technique, the acceleration record is idealized by a model in which a single input *x(t)* and output *y(t)* are characterized by an impulse response function *h(t)* that follows Eq. 1.

$$y(t) = \int_0^{\omega} h(\tau)x\,(t-\tau)d\tau \qquad (1)$$

The parameters, which describe the input-output relation of the building, were chosen to minimize the difference between the smoothed Fourier transform of the recorded acceleration time-histories and the Fourier transform of the response. Further details on the technique based on vibration experimental tests can be found in McVerry (1979). The process is studied mode by mode by comparing the computed and recorded response only over a specified frequency band, including the significant responses due to each mode.

Fig. 6 shows the variation of the dynamic response of the MRF building for a selected ground motion. The response, quantified in terms of Fourier amplitude spectra (in cm/s), is illustrated in 3D as a function of the time (in seconds) and frequency ω (in rad/s). The Fourier amplitude spectra consistently peak at around 5.4 rad/s, frequency that closely corresponds to the second mode of vibration of the building (T_2= 1.159 s; f_2= 0.863 Hz; ω_2= 5.421 s). There is a slight response at the 15th, 18th, and 21st floors at a frequency of 1.8 rad/s, which is related to the first mode of vibration (T_1= 3.517 s; f_1= 0.284 Hz; ω_1= 1.787 s). Additionally, a perceptible structural response at a frequency around 10 rad/s is noticed at the 3rd and 6th stories, which is related to the 3rd mode (T_3= 0.628 s; f_3= 1.592 Hz; ω_3= 10.005 rad/s).

The results shown in Fig. 6 clearly demonstrate that the technic properly estimates the dominant frequencies of motion, and that the selected ground motions overly excite the higher modes of vibration of the building in such a manner as to maximize the contribution of the second mode to its dynamic response. As a result, much larger drift and acceleration demands result in the upper stories of the building with respect to those estimated for the lower stories. This leads to an excessive damage concentration in the upper stories that cannot be properly identified by the structural engineer during the design process and highlights the need to establish design parameters capable of properly informing the dynamic response of the building for design purposes.

CONCLUSIONS

The higher-mode effects on the seismic response of high-rise buildings is studied to establish recommendations to encourage conservative decisions in the analysis and design process. Two 21-story buildings were designed following the capacity design principles. Buildings were structured with moment resisting frames and concentrically braced frames, and were located in a soft soil condition.

Nonlinear dynamic analyses were performed using *OpenSees*. Beam-column elements with plasticity spread along the element length were considered for structural elements, including a detailed bracing system model to capture the buckling and a connection model at the ends of brace elements with springs. The influence in the seismic response of buildings based on a global shear-dominated lateral response, a bending response, and a combined shear and bending response are discussed from the behavior of the studied structures.

Quantitative measures are offered to anticipate cases and conditions in which the effect of the higher modes would be dominated the response. The proposal is based on the proportion of pseudo-accelerations between the first and second modes, defined as a quantitative index. A tendency was identified that demonstrates that the greater the pseudo-acceleration ratio, the second mode would develop a relevant influence in the dynamic response.

A frequency-domain system identification technique was considered to recognize the dynamic characteristics through a moving-window Fourier analysis. Based on the obtained results, the selected records achieve the target to excite the higher modes under inelastic dynamic analyses. The tendency demonstrate that the second mode has a non-negligible contribution to the seismic response.

REFERENCES

[1] AISC 360-16 (2016), “Specification for structural steel buildings”, American Institute of Steel Construction, Chicago, IL.
[2] ASCE/SEI 41-17 (2017). Seismic evaluation and retrofit of existing buildings. American Society of Civil Engineers.
[3] FEMA 355A (2000), “State of the art report on base metals and fracture”, Program to Reduce the Earthquake hazards of Steel Moment-Frames Structures, Federal Emergency Management Agency September.7 9 135 7 9 13 1 4
[4] Gama-Contreras C. (2019), “Higher-modes effects in the analysis and design of Tall Buildings in Soft Soils”, Master Thesis, Universidad Autónoma Metropolitana, Mexico (in Spanish).
[5] Maniatakis, C., Psycharis, N. and Spyrakos, C., (2013) Effect of higher modes on the seismic response and design of moment-resisting RC frame structures. Engineering Structures. 56, 417-430.
[6] Mazzoni, S., McKenna, F., Scott, M. y Fenves, G. (2006). Open system for earthquake engineering simulation, user command-language manual, Report NEES grid-TR 2004-21. Pacific Earthquake Engineering Research, University of California, Berkeley, CA. http://opensees.berkeley.edu.
[7] MCBC-2020 (2020), Mexico City Building Code, Gaceta Oficial del Departamento del Distrito Federal (in Spanish).
[8] McVerry, G. H. (1979), “Frequency Domain Identification of Structural Models from Earthquake Records”, Report EERL 79-02, Earthquake Engineering Research Laboratory, Caltech, Pasadena, California.
[9] Rosenblueth E, Ordaz M, Sánchez-Sesma F.J., et al. (1989) The Mexico Earthquake of September 19, 1985—Design Spectra for Mexico’s Federal District. Earthquake Spectra 5(1): 273–291
[10] Singh S.K., Ordaz M., Pérez-Campos X., et al. (2015) Intraslab versus interplate earthquakes as recorded in Mexico City: Implications for seismic hazard. Earthquake Spectra 31(2): 795–812.
[11] Tapia-Hernández E. and García-Carrera J.S. (2019), “Inelastic response of ductile eccentrically braced frames in soft soils”, Journal of Building Engineering. Vol. 26.
[12] Tapia-Hernández E. and García-Carrera J.S. (2020), “Damage assessment and Seismic behavior of Steel Buildings during the Mexico Earthquake of September 19, 2017”. Earthquake Spectra. Vol. 36, Issue 1.
[13] Terán, A., Arroyo, D. and León, J., (2006). Effect of the degradation of rigidity in the seismic performance of the upper levels of buildings located in the lake zone of Mexico City., Proceedings, XV Mexican Conference on Earthquake Engineering, Puerto Vallarta, Jalisco, México (In Spanish).
[14] Uriz P. and Mahin, S. (2008), Toward Earthquake-Resistant Design of Concentrically Braced Steel-Frames Structures, Report of Pacific Earthquake Engineering Research Center, PEER 2008/08, November.Copyrights (do not include in the paper)