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INFLUENCE OF EARTHQUAKE MECHANISMS TO THE SEISMIC RESPONSE OF STEEL MOMENT FRAMES

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Abstract

Recent studies conducted on Steel Moment Frames (SMFs) highlight the importance of considering the effect of certain characteristics of earthquake ground motions (GMs) such as duration and spectral shape in their seismic response. Although their acceleration response spectra have mainly characterized ground motions in seismic standards, these studies indicate that the probability of collapse is sensitive to the GMs' duration. This represents a concern in areas with a different tectonic mechanism, such as South-America, and Pacific Northwest U.S., where subduction processes mainly generate GMs. It is well-known that the duration and spectral shape of subductions earthquakes are quite different from crustal earthquakes. Motivated by these issues, this research presents a parametric study to assess building height sensitivity to metrics such as inter-story drift ratios and floor accelerations, considering GMs records from subduction and crustal earthquakes carefully selected and scaled.
The scientific basis of this research is a series of nonlinear dynamic analyses conducted on SMFs (varying in height) at different seismic hazard levels. Two hazard levels are considered in this study: a) Life safety and b) Collapse prevention. The paper intends to understand the sensitivity of engineering demand parameters (i.e., drifts and floor accelerations) of SMFs to different earthquake mechanisms (i.e., crustal earthquakes vs. subduction earthquakes). The GMs records of subduction earthquakes consist of a set of GMs representative of South America and Japan's seismicity. The GMs records set of crustal earthquakes collects large magnitude-long distance events representative of Southern California.

Keywords: Steel Moment Frames, EDPs, Floor Accelerations, Megathrust Earthquakes.

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1 INTRODUCTION

Steel Moment Frames (SMFs) are among the most popular systems to resist lateral forces, chiefly due to their architectural versatility. When appropriately designed and detailed, SMFs are among the most ductile available systems for seismic regions [1]. Because of these reasons, these systems have been extensively studied in the past. Early studies on the topic concentrated their attention on the response modes, ending up in the design philosophies [2]. After the 1994 Northridge and 1995 Kobe earthquakes, the focus was on the study of beam-column connections [3]. More recently, with the advances in computational capabilities, SMFs have been studied under the framework of Performance-Based Earthquake Engineering (PBEE). In this manner, extreme limit states such as the collapse probability have been introduced as performance metrics (e.g., [4,5]).

The PBEE approach has enabled researchers to explore profoundly different aspects of SMF response. For instance, the effect of column base behavior on the seismic performance of SMFs has been addressed by several studies (e.g., [6-9]). The influence of the gravity framing system on their collapse probability has been investigated by [10,11]. The soil-structure interaction effects on the response of buildings subjected to earthquakes were assessed by [12,13]. More recently, several researchers have focused on loss estimation after earthquake events [14,15]. Besides, different models have been proposed to predict the behavior of nonstructural elements [16-18]. The technological advances have permitted monitoring buildings entailing the development of new fields such as structural health monitoring [19,20].

The preceding discussion highlights the importance that SMFs have received during the last decades. Besides, it is worldwide accepted that ground motion (GM) parameters such as amplitude, duration, and frequent content, are the most influential on buildings' response. However, practitioner engineers typically carry out their structural designs based on the building codes (e.g., ASCE 7-16), which characterize GMs with the design spectrum. As per this concept, the design spectrum quantifies GMs' amplitude and frequency content, neglecting the influence of duration. Recent studies such as [21-24] have investigated the influence of duration on the collapse probability of buildings by subjecting archetype frames to short and long duration GMs. Results of these studies indicate that duration and spectral shape play a significant influence on the collapse probability of buildings.

Medalla et al. 2020 [25] studied the response of SMFs (i.e., 40 in total) subjected to megathrust earthquakes by performing a hazard-consist analysis and a comparative collapse evaluation. The authors showed that the collapse probability of SMFs is higher when these systems are subjected to megathrust earthquakes rather than crustal earthquakes. Thus, the seismic demands for the design of buildings located in countries with high seismic activity (e.g., Ecuador) where the GMs are mainly caused by megathrust earthquakes and adopt the US steel design standards may be underestimated, resulting in potentially nonconservative designs.

Motivated by the preceding discussion, this paper presents an evaluation of the earthquake mechanisms' influence, i.e., crustal earthquakes vs. subduction earthquakes on Engineering Demand Parameters (EDPs) such as inter-story drift ratios (IDR) and floor accelerations (FA). For this purpose, a total of 5 archetype frames (varying in height) were subjected to two sets of GMs. The first set represents GMs associated with subductive mechanisms, while the second set contains GMs from crustal earthquakes. Those GMs were carefully selected and scaled to represent two hazard levels a) Life safety and b) Collapse prevention. Thus, the sensitivity of the SMFs to EDPs is assessed through this investigation. In this manner, new insights about SMFs behavior are given. The paper starts by describing the problem in this introductory section. Next, the details of the nonlinear models are described. Then, in a subsequent section of the paper, the results are presented and discussed, and finally, conclusions, limitations of the current work, and lines for future work are provided.

2 METHODOLOGY OF THE PAPER

For the purposes of this paper, i.e., to assess the sensitivity of EDPs to earthquake mechanisms, a total of five archetype frames are developed. The difference among these frames lies in their height (varying from 8.50m to 79.85m). Thus, this investigation's scientific basis consists of a series of Nonlinear Time History (NTH) simulations conducted on the mathematical models developed herein. These archetype frames are part of the study by NIST [26], have been adopted in several studies about SMFs' behavior (e.g., [27-29]), and their salient features are described next.

2.1 Mathematical Models

Figure 1a illustrates the typical plan view of all buildings. The SMFs are located at the perimeter of the building, while the rest of the components are part of the gravity framing system. All SMFs are three-bay frames, with a width of 6.10m. The first story's height is 4.50m, while the rest of the stories are 3.90m. The buildings were designed as per ASCE 7-05. On all the floors it was applied a dead load of 4.78 kN/m^2, and an unreduced live load of 2.38 kN/m^2, with the exception of the roof, where a live load of 0.95 kN/m^2 was applied. The weight of the cladding was considered with a perimeter load of 1.20 kN/m2. For the seismic design of the SMFs it was assumed a Response Coefficient Factor R=Cd=8, and site class "D" conditions under the seismic design category $D_{max,}$ which is consistent with the far-field conditions of Los Angeles. The beam-column connections are detailed as RBS connections based con ASIC 341 [30] and AISC 358 [x]. For more details about these SMFs, refer to [31].

Concentrated plasticity models have been adopted for this investigation since this approach has been broadly used for studies on SMFs (e.g., [27, 28, 29, 32, 33]). Thus, beams and columns are idealized as linear-elastic elements with rotational springs (hinges) at their ends. Beam members consist of three linear elastic elements with two hinges located each at the RBS, while column members consist of one linear elastic element with two rotational springs at the ends. These rotational springs are simulated with the well-known Ibarra-Medina-Krawinkler (IMK) bilinear model [34]. This model consists of a trilinear backbone curve with rules that capture cyclic strength and stiffness deterioration. These rules were initially proposed by Ibarra et al. [34] and then modified by Lignos and Krawinkler [35]. The spring properties were calculated by the methodology detailed at NIST [36].

The IMK bilinear models, as all uni-axial plasticity models, are not able to capture the Moment-Axial Load (M&P) interaction. For the springs located at the columns, this phenomenon is capture in an approximate manner. Thus, a reduced bending strength is calculated with the interactive equations from AISC [37] under the presence of an average gravity load (i.e., 1.05 P_D+0.5P_L). This approach has been adopted in other studies related to the assessment of SMFs behavior (e.g., [27, 28, 29, 32, 33]) mainly because SMFs are drift-controlled rather than force-controlled, and consequently, the columns are lightly loaded. Moreover, studies such as [38] show good agreement between experimental results and this approach. Panel zones are modeled as a parallelogram assembly with rigid elements and with a nonlinear spring placed at one corner to simulate shear distortions in the parallelogram. Column bases were modeled with the rotational springs suggested by Torres-Rodas et al., 2016 [39] for the low-rise buildings (i.e., 2-, 4- story) and with the models by Torres-Rodas et al., 2018 [40] in the case of taller buildings (i.e., 8-, 12-,20- story). P-Delta effects were captured using a leaning column connected to the SMFs through rigid elements and loaded with the gravity load equivalent to half of the building at each floor plant.

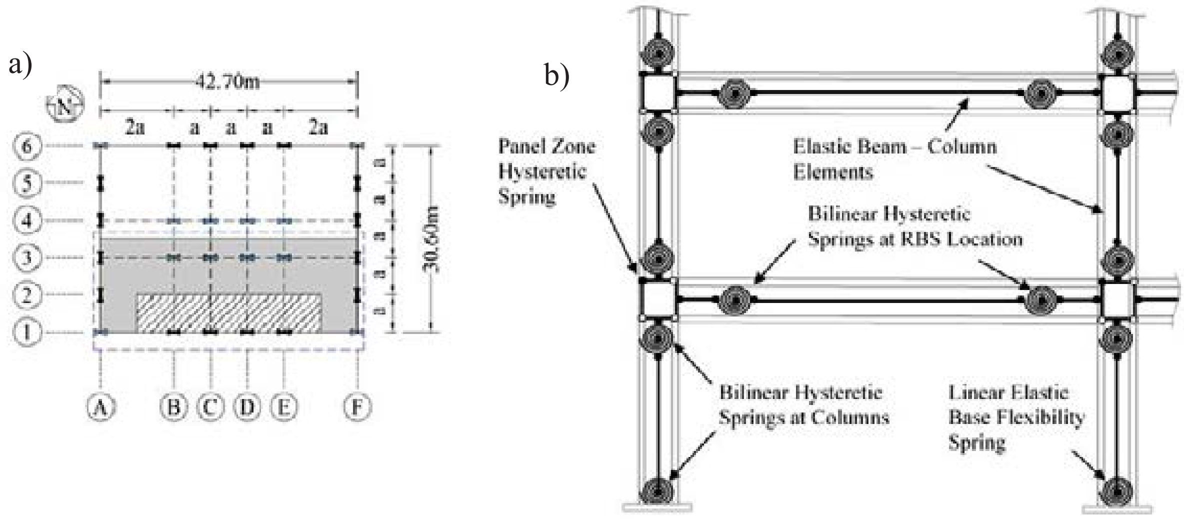

Figure 1: a) Typical plan view of all frames (from [9]), b) Mathematical models of the SMFs (from [32])

2.2 Ground Motions Selected

The seismic demands were analyzed using two criteria. On the one hand, several intense ground motions recorded worldwide were analyzed, including both subduction and crustal earthquakes. The earthquakes are shown in Table 1. These earthquakes were scaled linearly so that their intensities cover the accelerations reported in the MCE and DE spectrum of ASCE7-16 [41].

ID	Earthquake	Country	Year	Mw
1	Valparaiso	Chile	1985	7.9
2	Chi-Chi	Taiwan	1999	7.6
3	Sur Peru	Chile	2001	8.4
4	Tokachi-Oki	Japan	2003	8
5	Tocopilla	Chile	2007	7.7
6	Maule	Chile	2010	8.8
7	Tohoku	Japan	2011	9
8	Iquique	Chile	2014	8.1
9	Manabi	Ecuador	2016	7.8
10	Loma Prieta	USA	1989	6.9
11	Landers	USA	1992	7.3
12	Northridge	USA	1994	6.7
13	Kobe	Japan	1995	6.9
14	Duzce	Turkey	1999	7.1
15	Hector	USA	1999	8.1

Table 1: Megathrust earthquakes used for seismic simulation

On the other hand, as mentioned within this research's objectives, the aim is to analyze records of subduction and crustal ground motions representing the tectonic behavior of South America. For this, subduction earthquakes in Chile and Ecuador and crustal earthquakes recorded in Colombia's central region were analyzed. In the seismic accelerometric network of the mentioned countries, there are few records generated during high-intensity ground motions associated with return periods of more than 250 years. Due to this lack of information, seismic simulation was used for analyzes carried out in this study.

The seismic simulations were carried out in two phases. On the one hand, seismological simulation techniques using Green's functions were applied. When it was not possible to reach the design intensities, linear scaling was used to reach the objective thresholds. Linear scaling factors were always lower than 1.8. The simulation technique used is proposed by Kohrs-Sansorny et al. [2005][42]. This methodology uses a two-stages stochastic summation of low-intensity motions (seed motions) that work as empirical Green's functions. Likewise, the simulation employed considers a seismic source point and requires the characterization of two parameters: a) the seismic moment (M_0) and b) the stress drop (Δ_σ). This methodology considers the variation of frequency and energy contents. This technique incorporates wave propagation and site effects in such a way as to eliminate geological uncertainties from the problem when using the same site where the record was obtained [43]. The seed motions for crustal earthquakes used in this paper were recorded during the events under consideration in Table 2 for the Colombian network.

Date	M_w	M_0 (dyne-cm)	$\Delta\sigma$
25/01/1999	6.3	2.54E+25	40
08/03/2005	5.2	7.94E+23	50
06/02/2017	5.4	1.58E+24	50

Table 2: Seismic parameters for the seeds used in seismic simulations for crustal earthquakes

2.3 Nonlinear Time History Simulations

All the mathematical models developed herein were subjected to the two sets (i.e., crustal and megathrust) of GMs detailed in this paper's previous subsection. The software OpenSees is used for all the simulations since it has been extensively verified for NTH analysis [44], and all the modeling features earlier described can be applied. Moreover, several researchers have used this platform to study the behavior of SMFs with the use of NTH analysis [25-29]. Thus, the effect of the earthquake mechanisms (i.e., crustal vs. subductive) in the buildings' seismic performance (i.e., EDPs) is assessed. A total of five mathematical models representing the archetype frames (2-, 4-, 8-, 12- and 20- story) illustrated in Figure 1b have been developed for this investigation. Table 3 summarizes the fundamental periods of each frame. Two seismic hazard levels are considered in this study a) Life safety and b) Collapse prevention. For each simulation, two response metrics are recorded a) Maximum Floor Accelerations (FA) and b) Peak Interstory Drift Ratios (IDR). In this manner, the median values of the EDPs from each set (i.e., crustal vs. subduction) are compared.

Story Frame	First Period (s)
2-	0.69
4-	1.86
8-	2.42
12-	318
20-	4.44

Table 3: First Period of the frames

3 DISCUSSION OF RESULTS

The results from the NTH simulations of all the mathematical models are discussed in this section of the paper. Table 4 summarizes the results from the median IDR of all the SMFs at the two seismic hazard levels (i.e., DE and MCE level of shaking) analyzed herein, while Table 5 summarizes the results from the peak floor accelerations. As per Table 4, results from the simulations indicate that the IDRs of the low and mid-rise buildings (i.e., 2-, 4-, 8- and 12-stories) are relatively insensitive to the earthquake mechanism (i.e., crustal vs. subduction). The median values of the maximum IDRs associated with each earthquake mechanism are relatively similar, with the only exception in the tall building, i.e., the 20-story building. For this frame, the IDRs tend to be increased by 25% for the subductive earthquakes compared with the GMs' crustal set. This observation might indicate that the earthquake mechanism's influence is associated with the building height (and consequently the first vibration mode).

In contrast to IDRs, Table 5 indicates that the peak floor accelerations (FA) of all the frames are sensitive to the earthquake mechanism. As per Table 5, the subductive GMs entail higher FA than crustal earthquakes. At the Design seismic hazard level, the FA are amplified on average by 35% in the subductive earthquakes, while at MCE level of shaking, the FA are amplified (on average) by 50%. Results from the simulations indicate that the building height does not play an important role in the sensitivity of earthquake mechanisms to FA as apparently it does in IDRs.

Floor accelerations play an essential role in the behavior of nonstructural components. It is worldwide accepted that these components may be divided into two broad groups: the first one, sensitive to IDRs, while the second one, sensitive to floor accelerations [45,46]. Components such as masonry and partition walls fall in the first category, while ducts, parapets, or tanks are examples of the second group [46]. The components from this latter category must carry the forces coming from the building motion. Typically, the acceleration demands acting on these elements are evaluated from the floor response spectrum criteria, where the spectrum is calculated based on the floor accelerations at the desired level. Results from this investigation indicate that the earthquake mechanism (crustal vs. megathrust) profoundly influences the building response in terms of peak floor accelerations, which might affect the anchorage detailing of nonstructural components sensitive to this EDP.

Summary of Results median (I.D.R.) (%)					
Hazard Level	# Stories				
	2	4	8	12	20
M.C.E. with Crustal	3.00	3.12	3.44	3.37	3.46
M.C.E. with Megatrust	3.07	3.82	3.37	3.92	4.79
D.E. with Crustal	2.31	2.44	2.39	2.25	2.79

D.E. with Megatrust	1.97	2.80	2.48	2.48	3.75

Table 4: Summary of Results median (I.D.R.) (%) including collapses.

Summary of Results median Floor Accelerations					
Hazard Level	# Stories				
	2	4	8	12	20
M.C.E. with Crustal	458.68	509.30	572.36	760.84	1018.11
M.C.E. with Megatrust	580.19	763.09	1112.76	1203.07	1746.92
D.E. with Crustal	325.75	379.15	515.21	568.22	640.69
D.E. with Megatrust	440.50	614.40	880.75	880.76	1211.87

Table 5: Summary of Results median floor Accelerations including collapses.

4 SUMMARY, CONCLUSIONS, AND LIMITATIONS

This paper presents the results from NTH simulations conducted on five archetype frames varying in height (i.e., 2-, 4-. 8-, 12- and 20-story) with the intention to evaluate the influence of the earthquake mechanisms (i.e., crustal vs. subduction) on building's metrics such as maximum IDRs and peak floor accelerations. For this purpose, ground motions from both mechanisms were carefully selected and scaled. Two criteria were used for the selecting and scaling process. The first one consists of a linear scaling to the GMs selected with the DE and MCE spectrums from ASCE 7-16 [41], while the second approach uses seismological techniques to simulate GMs.

The results from the NTH simulations conducted in this paper indicate that GMs (scaled at a defined intensity) from megathrust earthquakes cause higher peak floor accelerations than GMs (scaled at the same intensity as the megathrust ones) from crustal earthquakes. On average, the amplification is around 50% when the GMs are scaled to the MCE level of shaking, while it is close to 35% at DE level. This finding might be important in the context of detailing the anchorage of nonstructural components sensitive to accelerations. On the other hand, the IDRs seem to be less sensitive to the earthquake mechanism. Only the 20-story SMF shows an amplification due to the subductive process, which might indicate a potential influence of the building height.

The results of this paper are subjected to limitations that must be addressed appropriately to generalized the findings. First, a limited number of frames is considered (five in total); second, the bias due to ground motion effects, including the GMs' vertical component; third, the modeling assumptions might affect the results (e.g., concentrated plasticity models vs. distributed plasticity models). Finally, this research does not address the soil-structure interaction effects.

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