Effect of Ground Motion Duration on Seismic Response of Archetype SCBFs Buildings

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Abstract

Several long duration and subduction earthquakes took place in the last decade in different locations around the world, e.g. Chile in 2010, Japan in 2011, etc.. These earthquakes motivate the need to prepare for not only large-magnitude, but also possible long-duration earthquakes in the Cascadia subduction zone along the Pacific Northwest Coast of the United States. In this paper, two multi-story archetype buildings were selected in Seattle, WA: three-story and nine-story special concentric braced frames (SCBFs). The two SCBFs were modeled and analyzed using OpenSees under 88 short and long duration ground motions that were scaled to two hazard levels for a deterministic nonlinear time history analysis: 10% exceedance in 50 years and 2% exceedance in 50 years. The results show that at the 10%/50 years hazard level, very limited deformation and little concentration of inelastic deformation over the building height in both buildings are observed. However, at the 2%/50 years hazard level, both archetype SCBFs experienced relatively more damage under the long duration ground motions. The damage included severe brace buckling and complete brace ruptures in many cases. In some cases, soft story mechanism was observed where all the braces within a certain floor were ruptured. In the case of the nine-story SCBF, about 50% higher drift demands and larger number of soft story mechanisms were reported in the case of long duration earthquakes as opposed to short duration ones.

Keywords: Cascadia subduction zone; Long Duration Earthquakes; steel braced frames; low-cycle fatigue

1 Introduction

Special concentrically braced frames (SCBFs) are widely used in seismic design. Their strength and stiffness result in an economical system that easily meets serviceability limit states and ideally work for performance-based seismic design (PBSD). During large earthquakes, SCBFs exhibit a nonlinear behavior and must provide sufficient ductility to assure the life safety and collapse prevention performance states. The desired inelastic nonlinear behavior is dominated by braces extensive yielding, buckling, and low-cycle fatigue induced fracture, which need to be accurately captured by analytical models for reliable PBSD and collapse risk assessment. Current analytical approaches used in practice might not be well-suited for modeling low-cycle fatigue associated with very long duration earthquakes. The reason is that many of the commonly used low-cycle fatigue models are not physics-based models, and are typically statistical or regression models determined from previous experimental data that is mostly from cyclic tests and lacks dynamic or realistic seismic tests. Thus, it might not be possible to accurately predict and assess the post-yield mechanisms, failure modes, and structural collapse risk of SCBF buildings in urban areas located in the Cascadia Subduction zones (e.g. Seattle, WA or Portland, OR) using current approaches.

Several long duration earthquakes have recently taken place such as the 2014 M8.2 Iquique, Chile earthquake, the 2011 M9.0 Tohoku, Japan earthquake, and the 2010 M8.8 Maule, Chile earthquake. The size of the faults rupture controls the durations of the ground motions where a rupture over 500 km during the 2010 Chile earthquake for instance led to many sites across Chile experiencing ground motions lasting for up to 90 seconds. Similar scenarios of long duration earthquakes potential risk can occur in the United States especially at the Cascadia Subduction zone in the Pacific Northwest. A subduction event at the Cascadia may produce earthquakes with extended durations and affect several states and metropolitan areas such as Seattle. This triggered national or maybe international initiatives to potentially consider the duration as a mapped parameter for next generation national seismic hazard maps and in turn, be considered in building codes. Several analytical projects studied the effect of long duration earthquakes on steel and reinforced concrete buildings as briefly discussed in next paragraph. However, most of these studies did not verify existing models against proper experimental tests or consider special modeling to account for damage-accumulation and deterioration as it relates to the earthquake duration, and especially long duration events. Accordingly, he duration issue is not planned to be part of the scope of upcoming NEHRP Recommended Provisions for New Buildings and Other Structures, but the duration remains an active “long-term” issue for consideration as more research and test data become available.

Recent studies used such records but even before then, older studies considered synthetic ground motions and other methods to study earthquake duration effects. The next few lines presents some of the old and more recent previous studies that considered ground motion durations but with focus only on those studies that investigated duration effects on structural response. Fewer studies analyzed the duration effects on steel structures. As for studies that specifically related earthquake duration and steel CBFs or SCBFs, few studies were found in the literature and only two examples are shown here for brevity. Foschaar et al. [1] investigated the effect of ground motion duration on the collapse capacity of a 3-story steel braced frame. They used two record sets, one with long duration records and the other with spectrally equivalent short duration records. This approach was useful in isolating the effect of the ground motion duration from other ground motion characteristics. They found that the duration affects the collapse capacity significantly. Next, Tirca et al. [2] studied the effect of mega-thrust subduction records versus crustal records by analyzing the nonlinear response of 4-story, 8-story and 12-story moderately ductile-CBF (MD–CBF) office buildings located in Canada. They found that in the case of the 8-story and 12-story MD–CBF buildings, the largest demand occurred mostly at the same floors; dominant at the bottom two floors under both crustal and subduction record sets. However, in the case of the 4-story MD–CBF building the largest demand occurred at the top floor under the subduction record set and at the bottom two floors under the crustal record set. They concluded that subduction records characterized by longer Trifunac duration did not affect the peak interstory drift or the peak residual interstory drift. Also the damage was concentrated at floors characterized by lower brace over strength. To avoid the occurrence of brace fracture when subjected to ground motions scaled to match the design spectrum, it is recommended to provide a sufficient safety margin when the size of bottom floor braces is selected.

In a recent study by the authors [3, 4], detailed modeling and extensive shake table testing was conducted to investigate the effect of longer earthquake durations on behavior of SCBFs, but was mostly limited to single-story frames. The main objective of this paper is to extend the previous work and further expand the calibrated models used in [3,4] to full SCBFs archetype buildings to study the effect of ground motion duration on realistic structures. Two buildings, three-story and nine-story, that resembled original SAC buildings but modified to have SCBFs as lateral support system instead of moment resisting frames, are modeled in OpenSees [5]. Two planer frames are adopted from the two buildings and used for the analysis. 44 spectrally-matched pairs are used to conduct nonlinear time history analysis and study the effect of duration. All the ground motions are scaled to two hazard levels for a deterministic time history analysis: 10% exceedance in 50 years and 2% exceedance in 50 years. All analysis results are interpreted in a comparative way to isolate the ground motions duration effects and conclude this study.

2 Archetype Buildings

Two archetype buildings were used in this study. The three- and nine-story buildings were adopted and based on the model buildings used as part of the SAC Steel project [6]. These designs adopted the basic floor plan, story height, and gravity loads. Appropriate modifications were made to transform the buildings from special moment resisting frames to SCBFs. The new design details were taken after Hsiao et al. [7]. The buildings were designed using the equivalent lateral force procedure [8,9]. Figs. 1 and 2 show the typical floor plan and elevation of the three-story and the nine-story buildings, respectively.

A brief discussion of the design basis of the archetype buildings is presented next but the reader is referred to [7] for more details. The basic design R value used to adjust the design spectrum was 6. All the buildings were designed for a location in Seattle, WA, using Seismic Design Category D with soil Site Class C. The three-story buildings had 4-by-6 bays with identical story height, while the nine-story building have 5-by-5 and with a taller bottom story to reflect typical midrise construction. The braced bays were placed on the perimeter of the buildings in a symmetric plan configuration using a multi-level X-bracing configuration. According to Hsiao et al. [7], Table 1 gives the resulting design member sizes of the three- and nine-story buildings. Rectangular HSS were used for all brace sections. The fundamental periods of the resulting frames were 0.38 and 0.87 seconds for the three- and nine-story buildings, respectively.

Table 1 - Member sizes of the three- and nine-story archetype buildings representative SCBFs used for the analysis in this study

Building	Story	Brace	Beam	Exterior Col.	Interior Col.
3-story	1	HSS 6x6x5/8	W21x93	W14x90	W14x90
	2	HSS 6x6x1/2	W21x93	W14x90	W14x90
	3	HSS 5x5x1/2	W24x104	W14x90	W14x90
9-story	1	HSS 8x8x1/2	W21x93	W14x283	W14x283
	2	HSS 7x7x1/2	W21x83	W14x283	W14x283
	3	HSS 7x7x1/2	W21x83	W14x283	W14x283
	4	HSS 7x7x1/2	W21x83	W14x193	W14x193
	5	HSS 6x6x5/8	W21x83	W14x193	W14x193
	6	HSS 6x6x1/2	W21x83	W14x120	W14x120
	7	HSS 6x6x3/8	W21x83	W14x120	W14x120
	8	HSS 5x5x1/2	W21x83	W14x74	W14x74
	9	HSS 5x5x5/16	W24x104	W14x74	W14x74

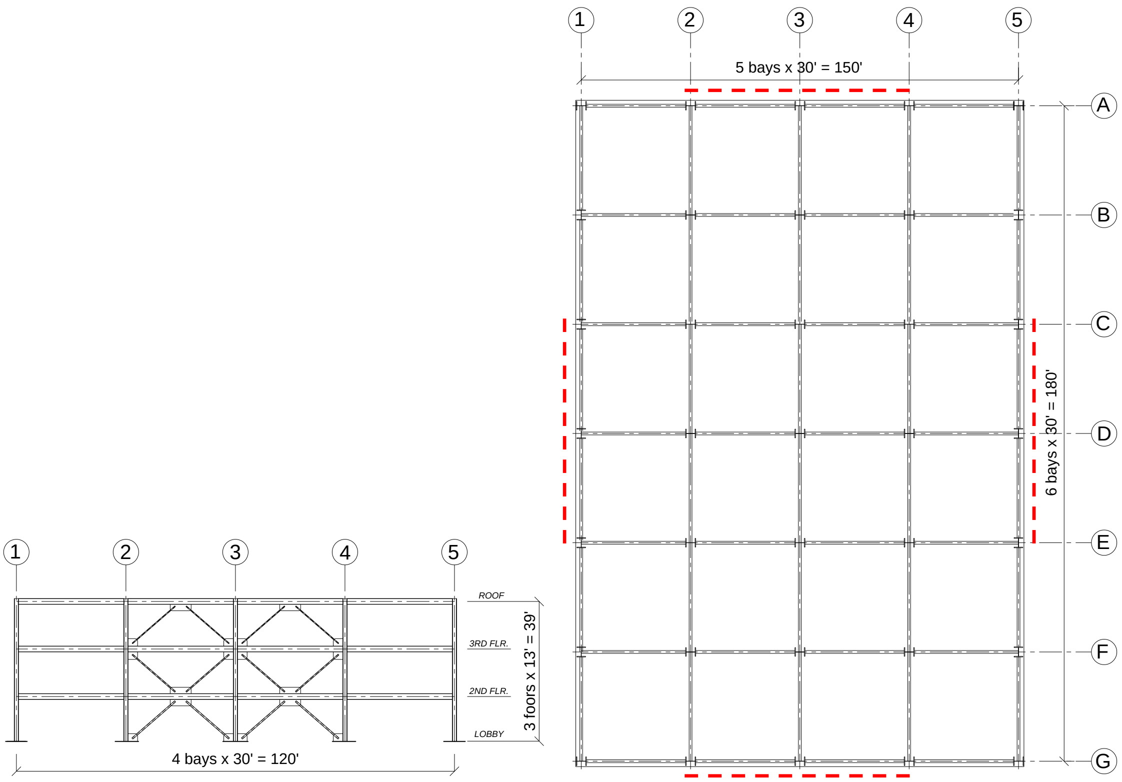

Fig. 1 – Plan and Elevation of the three-story archetype building

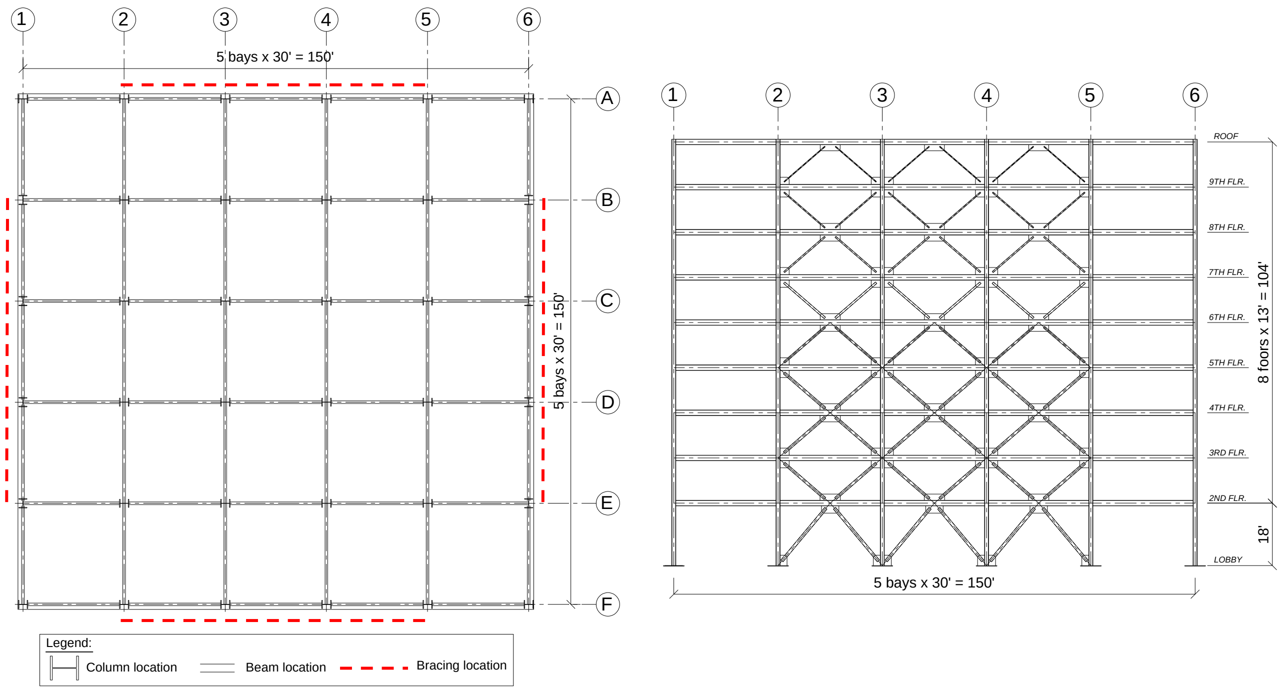

Fig. 2 – Plan and Elevation of the nine-story archetype building

3 System Modeling

To assess the seismic performance of SCBFs under long duration ground motions, comprehensive nonlinear dynamic analyses are needed especially that full system testing is not feasible or possible. The models needed for such purposes must include every yield mechanism and failure mode that impacts the seismic response of the overall frame and must be capable of simulating the response beyond initial fracture. These requirements could be met by incorporating the various modeling techniques used in literature [3,4,7]. The gravity loads and second order (P-delta) effects were included in the simulation by employing a leaning column connected to the frame by rigid links, as illustrated in Fig. 3. The gravity frame was modeled using shear-connection springs simulating the total rotational strength and stiffness of gravity beam-column connections (shear-tab connections), which were located between the rigid link and the leaning column. The gravity loads at each floor level were placed on the gravity frame. The technique used herein was similar to what was adopted in [7].

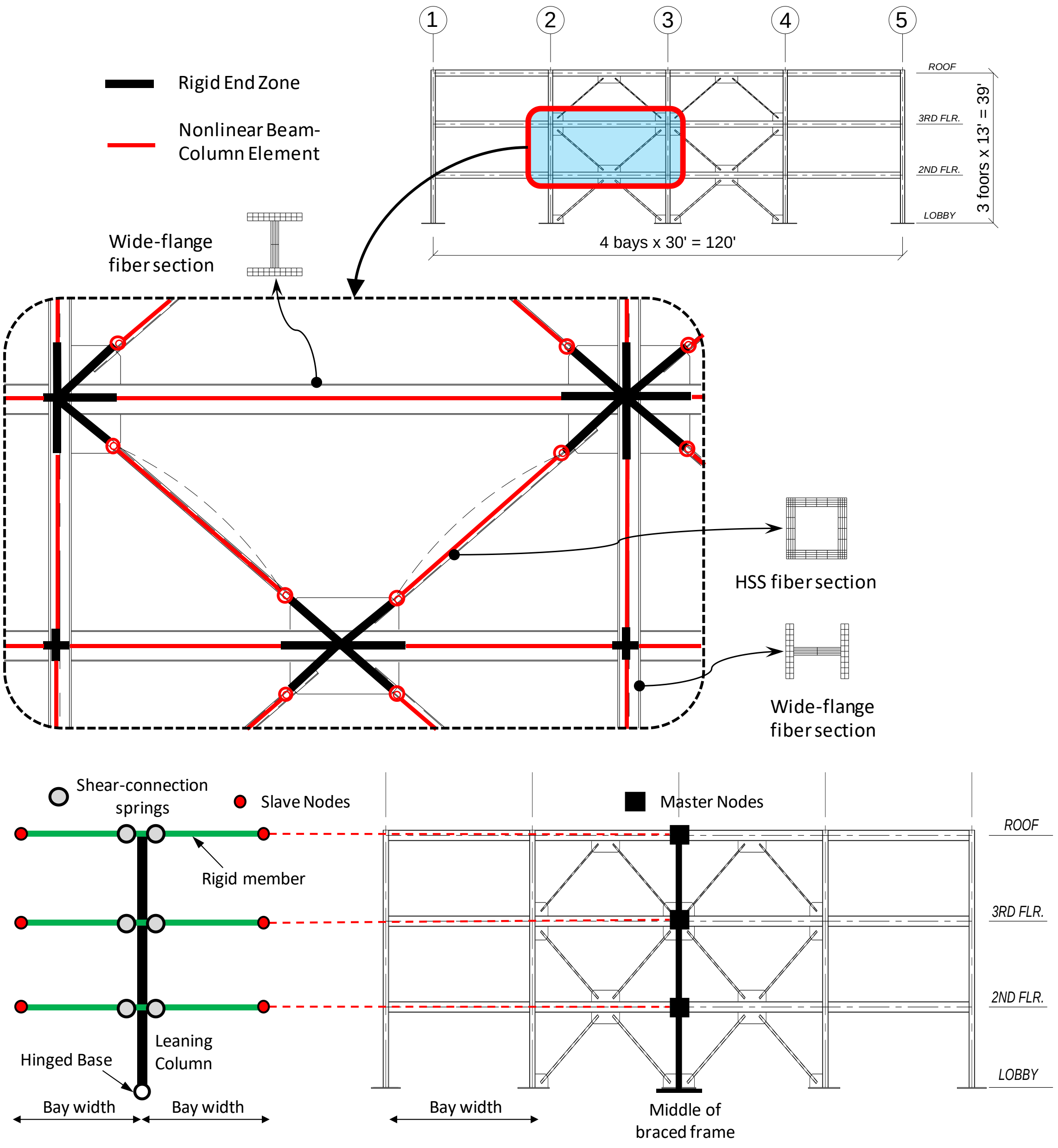

Fig. 3 – Model Details and Leaning column modeling

Force beam elements were used for columns, beams and braces. Twenty nonlinear force-based elements were used to model the braces with five integration points. Corotational geometric transformation was used for the braces as large out-of-plane displacements are expected. Fiber sections were implemented for all the nonlinear frame elements in the model. While all the geometric modeling assumptions, e.g. for gusset plates, were previously verified against the University of Washington experimental program as explained in [4]. The fatigue parameters m and ε_0 used for the model were implemented from [10]. The properties of the shear-connection springs were based upon Liu's model of shear tab connections with composite slabs [11]. The springs were simulated using the Pinching4 material model in OpenSees [5]. Each spring element had a stiffness and strength that were equivalent to the number of the gravity bays contributing to the seismic weight. The rigid beams used in the gravity frame model, which had the same length of the gravity bay, were supported by rollers. The nodes at the end of the rigid beams were slaved to the nodes at the middle of the braced frame in horizontal translation at each level as illustrated in Fig. 3. The base of the leaning column was pinned. Wide-flange sections W10x49 and W12x65 were used for the gravity columns of the three- and nine-story buildings throughout the height, respectively. To represent the overall contributions, such as initial axial and bending stiffness and strength, of the gravity columns to the lateral-load resisting system, a particular cross section of the leaning column was adopted with a cross-sectional area, moment of inertia and plastic moment capacity equal to the total of the gravity columns contributing to the seismic weight.

4 Ground Motions Selection

In order to study the duration effect on the two frames adopted from the archetype buildings described above, nonlinear dynamic analysis was considered under large number of ground motions. A generic set of 88 recorded ground motions was selected to analyze the structure, which was adopted from the previous work by [12]. The selected motions do not represent the hazard at any specific site. The 88 records comprise two suites of ground motions, first, 44 of these ground motions were taken from the FEMA P695 [13] far-field set, which contains relatively short duration ground motions (with $Ds_{5\text{-}75}$<25s), recorded from shallow crustal earthquakes. The second set or the remaining 44 records were selected from long duration ground motions (with $Ds_{5\text{-}75}$>25s) recorded from both large magnitude interface earthquakes like the 2011 Tohoku (Japan), 2010 Maule (Chile), and 1985 Michoacan (Mexico) earthquakes, and large magnitude crustal earthquakes like the 2008 Wenchaun (China) and 2002 Denali (USA) earthquakes.

The ground motion selection done was done so that the 88 selected records have a wide range of $Ds_{5\text{-}75}$ values that covers the broad range of ground motion durations anticipated in Seattle, for instance. Seattle is one of the places or potential locations at risk of a large magnitude and long duration earthquake from the Cascadia subduction zone. In addition, each of the 44 long duration ground motions was selected to have a similar response spectrum to one of the short duration ground motions. Readers are referred to [12] for details of selection and scaling procedure along with full information on the selected records response spectra and time series. A deterministic analysis was used in this study. For this purpose, the mean of each suite of ground motion was linearly scaled to represent a specific hazard level for analysis. Fig. 4 shows all response spectra after scaling to represent a 10%/50 years and 2%/50 years hazard levels response spectra. The linear scaling used for each desired hazard level considered mainly a range of periods around the fundamental periods of the two frames of interest.

5 Results and Discussions

This section presents the results obtained from two sets of nonlinear time history analysis conducted for both the three- and nine-story archetype SCBFs. Each set included analysis under 88 ground motions (44 short duration records and 44 long duration records) that were scaled to a specific hazard level, i.e. 10% in 50 years and 2% in 50 years. The presented results include maximum story drift % and inter-story drift %. The results are all shown comparatively where each demand parameter is presented for the individual and mean of 44 short versus 44 long duration ground motions.

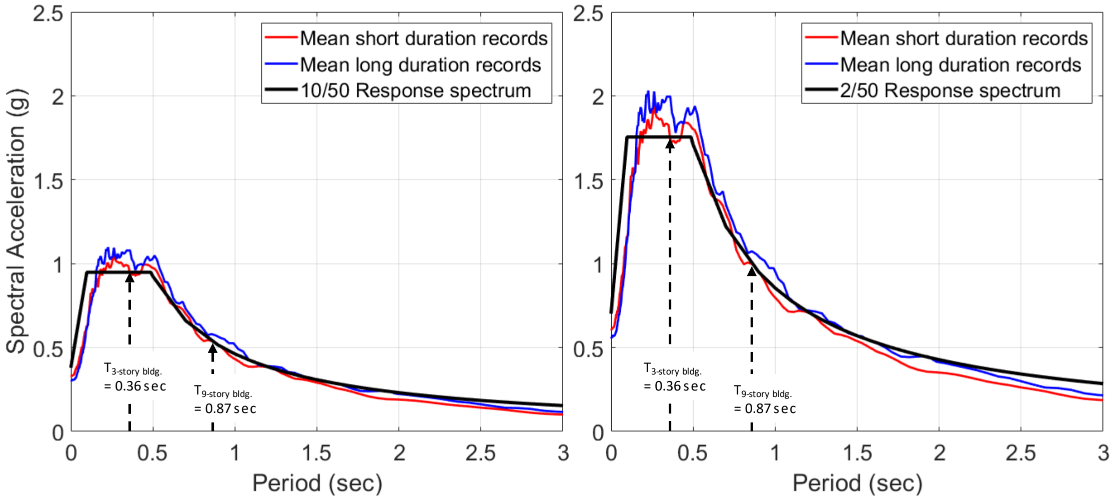

Fig. 4 Short and Long duration ground motion mean compared to both 10%/50 years and 2%/50 years

5.1 Three-Story Building Results

Fig. 5 (left-hand side) shows the average maximum story drifts (MSD) and Inter-Story Drift computed for the 3-story SCBF for both hazard levels under short and long duration ground motions. The average MSDs over the frame height varied between 0.3% and 0.4% for both suits of ground motions for the 10%/50 years hazard level. The results show that both suits of earthquakes at this hazard level cause very limited deformation and little concentration of inelastic deformation over the building height. The ground motion duration also does not have any specific adverse effects on MSD which is attributed to the fact that the duration sensitive effects, i.e. low-cycle fatigue induced brace rupture, did not occur at this intensity level. The interstory drift distribution along the frame height for the 3-story building is shown in Fig.5 from short and long duration earthquakes. The figure shows that no large interstory demands are expected as this hazard level, which is less than the typical hazard level for design. All interstory values obtained from the analysis satisfy the ASCE 7-16 drift% limits [8]. However, at this low intensity hazard level, the long duration records show slightly higher demands compared to those resulted from the short duration motions.

For the 2/50 level analyses, the average MSD values increased significantly, and severe concentration of deformation occurred in most cases. Fig. 5 (right-hand side) shows the individual records results and the average MSD computed for the 3-story SCBF for the 2/50 hazard level. The long duration suite of ground motions has caused relatively more damage compared to short duration ground motions. The damage included severe brace buckling that exceeded three times the brace width and complete brace ruptures in many cases. In some cases, soft story mechanism was reported where all the braces within a certain floor were ruptured. The same figure shows the interstory drift for the same building type. It is clear that the values increased significantly for this hazard level compared to the 10%/50 years hazard level. Some values were noted to be high which resulted from those cases when soft story mechanisms were reported.

5.2 Nine-Story Building Results

Similar to the three-story SCBF analysis, two hazard levels, i.e. 10% and 2% in 50 year (2/50 and 10/50), were used to scale the two suites of ground motions for nonlinear time history analysis of the 9-story SCBF model. Fig. 6 (left-hand side) shows the average maximum story drifts computed for the 9-story SCBF for the 10/50 under both short and long duration earthquakes. The difference between the response of the 9-story SCBF under both suites of ground motions was not significant at that hazard level. This is because none or only few number of ground motions caused failure in both cases. However, it can be still noticed that the long duration suite caused an average higher drift % concentrated at the first floor. The variation between the average results from both suites of ground motions is around 25% higher in case of long duration records.

Fig. 6 shows as well the maximum story displacement for the same building type. It is worth mentioning that at this hazard level, no damage has been reported and only limited brace buckling was observed in some braces, which did not exceed three times the brace width.

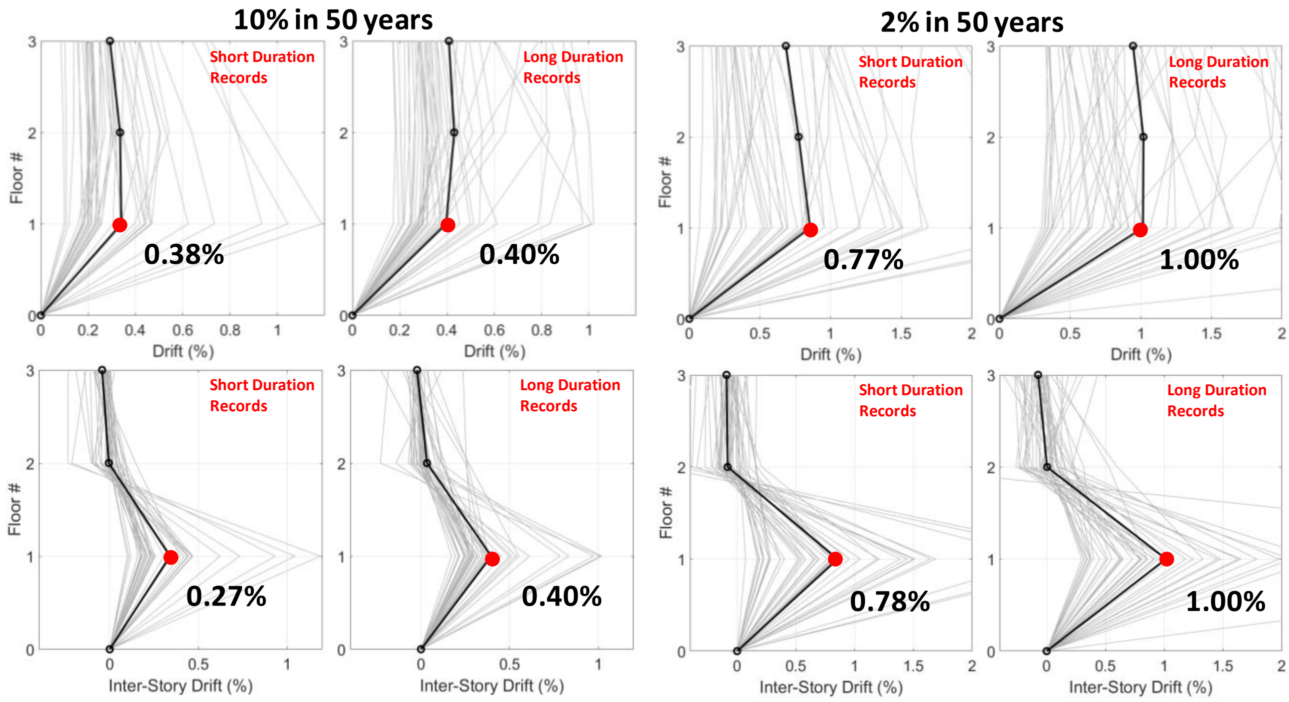

Fig. 5 Distribution of maximum story drift and Inter-Story Drift along 3-story SCBF height at the 10%/50 years and 2%/50 years hazard level as compared for short and long duration earthquakes

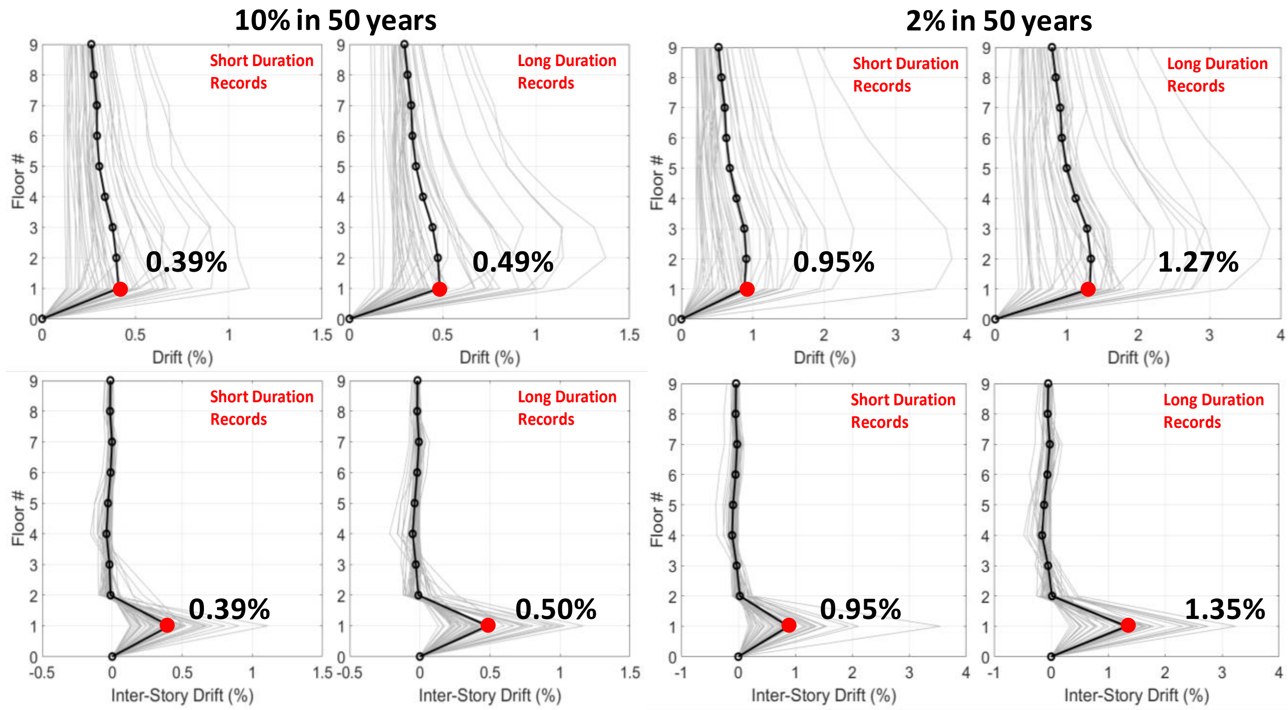

Fig. 6 Distribution of maximum story drift and Inter-Story Drift along 9-story SCBF height at the 10%/50 years and 2%/50 years hazard level as compared for short and long duration earthquakes

Fig. 6 (right-hand side) shows the average maximum story drifts computed for the 9-story SCBF for the 2/50 hazard level. It can be observed from the figure that a significant difference is observed between the average results from the short and long duration suites at this hazard level. Although both suites comprised spectrally-matched pairs, yet longer duration records led to more accumulation of damage. The observed difference is around 50% in the case of maximum drift ratios, which is a significant difference, especially when noting that larger number of soft story mechanisms were reported in the case of long duration earthquakes. More details about brace ruptures and mechanisms are presented in the next section on limit states. Fig. 6 shows the interstory drift for the SCBF under both suites of ground motions. The difference is again around 50% more in case of long duration ground motions. The analysis showed concentration of damage in the first story as before.

6 Limit States

Four performance limit states were considered to further evaluate the duration effect on SCBFs based on comparisons of the results obtained in previous section for both short and long duration ground motions. These limit states were selected to reflect the significant key stages in SCBF nonlinear response as obtained and progressed through the analysis. These limit states were adopted in part after the study in [7] and with some modifications proposed by the author. A brief description of the four different limit states used to interpret the archetype SCBFs analysis results is as follows.

- Initial brace buckling: Brace buckling was reported for each brace in the SCBFs in every analysis case. Following prior experiments, initial brace buckling typically occurs at approximately 0.3% story drift [1], which is the value used to report brace buckling in this study.
- Excessive brace buckling requiring replacement of the brace: Requirements for possible replacement of the brace are defined as: (a) the maximum out-of-plane displacement of the brace exceeded three times the brace depth, or (b) prediction of brace fracture. These damage states related to definitions developed in a prior study for developing fragility curves for concentric braced frames (ATC-58 2009).
- Brace fracture: The fracture was predicted by the OpenSees analysis model as interpreted from reported damage index values.
- Soft Story: This limit state is introduced by the author and refers to the case when all braces at a given floor ruptured in an analysis case. This case can be considered to possibly lead to forming a soft story mechanism if the residual floor lateral stiffness and force resistance from columns and beams are significantly lower than the braced frame before brace rupture.

All results from the extensive conducted analysis, previously discussed in section 5 before, were compiled together to determine the probability of occurrence for each of the four performance limit states defined above. The probability of meeting a certain limit state is expressed in a simplified way through the percentage of the braces that experienced a given limit state relative to total number of braces in the analyzed SCBF. Fig. 7 shows such percentages for the 3-story building at the 10%/50 years and 2%/50 (MCE level) years hazard levels as obtained from the short and long duration analyses separately. For the 10%/50 years hazard level, almost all braces buckled but no damage was reported according to the limit states defined above. On the other hand, for the case of the 2%/50 years hazard level, the long duration ground motions caused more damage than the short duration ones in the case of the 3-story building. This is clear when the possible brace replacements, brace rupture, and soft story mechanism are considered. However, the difference between short and long duration cases was not significantly large. This might be attributed in part to the fact that because of the short period of the three-story building, high force demands were expected in the frame regardless of the duration effect.

Fig. 8 shows similar damage level comparisons for the 10%/50 years and 2%/50 years hazard levels for the 9-story building. Again, for the 10%/50 years hazard level, results show that brace buckling occurred at 100% of the analysis cases, but no additional damage was observed at this hazard level. However, for the

2%/50 years hazard level, the long duration earthquakes are shown to cause more significant damage either for excessive brace buckling (expressed as possible replacement limit state) or brace fracture. The soft story mechanism was reported only in the case of long duration records.

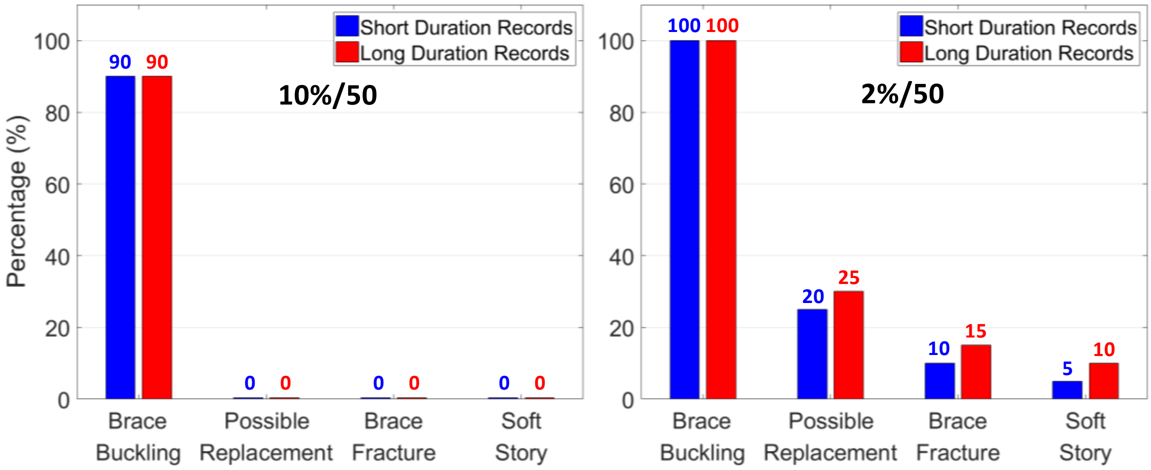

Fig. 7 Percentage of braces meeting a given limit state as related to total number of braces in the 3-sotry SCBF as obtained from analysis results under the short and long duration ground motions scaled at 10/50 and 2/50 hazard levels

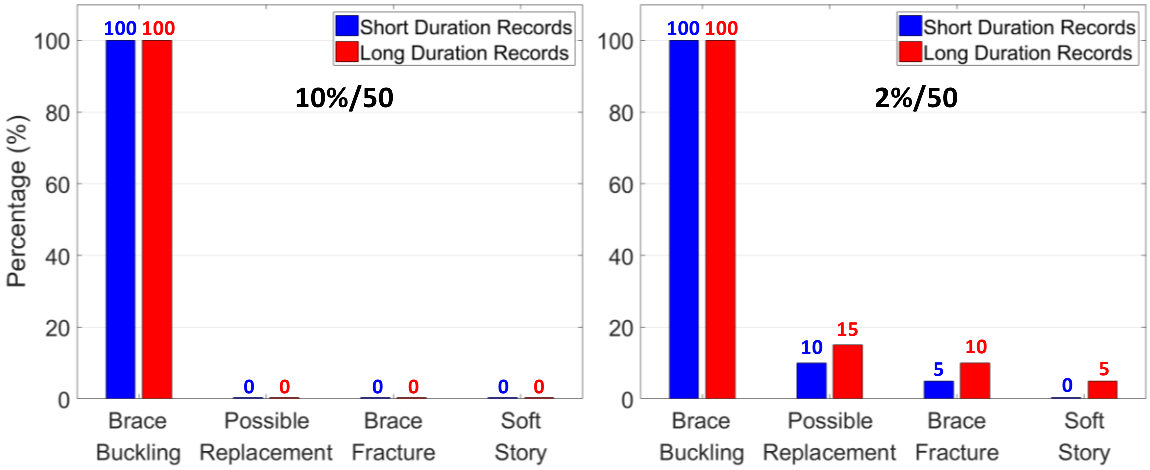

Fig. 8 Percentage of braces meeting a given limit state as related to total number of braces in the 9-sotry SCBF as obtained from analysis results under the short and long duration ground motions scaled at 10/50 and 2/50 hazard levels

The presented results from the archetype SCBFs analysis especially what pertain to the story mechanisms or possible brace ruptures are yet another means of highlighting the importance of considering ground motion duration in future designs or performance-based assessment. Overall, it was shown and demonstrated in different analysis cases throughout this study that severe structural damage or even full collapse might have a larger probability of occurrence only because the larger damage accumulation in SCBF braces associated with longer duration effects.

7 Summary and Conclusions

The goal of this study was to investigate the influence of earthquake duration on the structural response of SCBFs. A calibrated model was used to simulate full SCBF archetype buildings to study the effect of ground motion duration on full structures. Two buildings, three-story and nine-story, that resembled original SAC buildings but modified to have SCBFs as lateral support system were used. Two planer frames were adopted from the two buildings and used for nonlinear time history analysis under 44 spectrally-matched pairs of short and long duration ground motions to study the effect of duration. All the ground motions were scaled to two hazard levels for the deterministic time history analysis: 10% exceedance in 50 years and 2% exceedance in 50 years. All analysis results were interpreted in a comparative way to isolate the ground motions duration effects, which was the main variable in the ground motion pairs. Several concluding remarks can be drawn from the analysis results as follows:

- From the archetype buildings analysis at the 10%/50 years hazard level, the results showed very limited deformation and little concentration of inelastic deformation over the buildings height. In the 3-story building, the ground motion duration did not have any specific adverse effects. However, for the 9-story case, the long duration suite of ground motions caused an average higher drift % concentrated at the first floor and about 25% higher than the average results from short duration ground motions.
- At 2%/50 years hazard level, both archetype SCBFs experienced relatively more damage under the long duration ground motions. The damage included severe brace buckling that exceeded three times the brace width and complete brace ruptures in many cases. In some cases, soft story mechanism was reported where all the braces within a certain floor were ruptured. In the case of the 9-story SCBF, about 50% higher maximum drift ratios and larger number of soft story mechanisms were reported in the case of long duration earthquakes.
- The presented results from the archetype SCBFs analysis especially what pertain to the story mechanisms or possible brace ruptures are yet another means of highlighting the importance of considering ground motion duration in future designs or performance-based assessment.
- Overall, it was shown that severe structural damage or even full collapse might have a larger probability of occurrence only because the larger damage accumulation in SCBF braces associated with longer duration effects. The ground motion duration can significantly affect the displacement, and ductility, capacity of SCBFs.

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