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PHYSICAL MECHANISMS UNDERLYING THE INFLUENCE OF GROUND MOTION DURATION ON STRUCTURAL COLLAPSE CAPACITY

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Abstract

This study explores the physical mechanisms by which the duration of strong ground motion influences structural response. While a number of previous studies have found that ground motion duration influences only cumulative damage indices, and not peak structural deformations, a few recent studies that employed realistic, deteriorating structural models were able to demonstrate the effect of duration on peak deformations and structural collapse capacity. These recent studies were, however, empirical in nature and did not fully explore the reasons behind the observed effects of duration. Many of the previous studies qualitatively attributed the effects to the cyclic deterioration of strength and stiffness of the structural components, which represents just one mechanism by which duration exerts its influence. In contrast, the present study shows that the gradual ratcheting of drifts, accentuated by the destabilizing $P-\Delta$ effect, is an equally important mechanism by which duration influences structural response. The relative contributions of the two mechanisms—cyclic deterioration and ratcheting—to the observed influence of duration on the collapse capacity of a five-story steel moment frame building, are quantified by conducting incremental dynamic analysis (IDA) using spectrally equivalent sets of long and short duration ground motions. The use of spectrally equivalent ground motions allows controlling for the effect of response spectral shape. A response parameter called the ratcheting interval is defined and used to explain the larger potential for a long duration ground motion to cause structural collapse, when compared to a spectrally equivalent short duration ground motion scaled to the same intensity level. These findings shed light on the interaction between structural model characteristics and the observed influence of ground motion duration on structural response. In addition, they highlight the importance of using models that capture both cyclic deterioration and the $P-\Delta$ effect to reliably account for the effect of ground motion duration when assessing structural collapse risk.

Keywords: ground motion duration; cyclic deterioration; ratcheting; collapse capacity; nonlinear dynamic analysis

1. Introduction

A number of past and recent research efforts have focused on analyzing the influence of ground motion duration on structural response [1]. As expected, many of them found duration to be strongly correlated to cumulative damage metrics like total dissipated hysteretic energy and accumulated plastic strain. Since a number of these studies employed simplistic, non-deteriorating structural models, however, they did not observe any effect of duration on peak structural deformations [e.g., 2–10]. In light of these findings, and the prevalent use of acceptance criteria for structural design and assessment based on peak structural deformations, ground motion duration is not explicitly considered in current structural design and assessment standards [e.g., 11–13].

Recent studies by the authors and others, using more realistic structural models that simulate structural behavior at large nonlinear deformations more accurately, have, however, demonstrated that duration does influence peak structural deformations [e.g., 7, 14]. This effect of duration was observed at ground motion intensities large enough to produce significant inelastic deformations, thereby manifesting itself as a reduction in the collapse capacity of a structure when analyzed under long duration ground motions. These observations are, however, empirical in nature, and do not examine the physical mechanisms underlying the observed effect of duration. While most studies qualitatively attribute the effect of duration to the deterioration in strength and stiffness of structural components under cyclic loading [e.g., 3, 14–16], few have examined the contributions of other mechanisms or attempted to quantify their relative contributions.

The objective of this study is to obtain a deeper understanding of the reasons underlying the observed influence of ground motion duration on structural collapse capacity, i.e., the physical mechanisms that enable long duration ground motions to cause structural collapse at lower intensity levels than short duration ground motions. While structural deterioration is definitely expected to be an important factor, the gradual ratcheting of drifts, exacerbated by the destabilizing $P-\Delta$ effect of gravity loads [17], has also been observed to play a significant role. The potential of the $P-\Delta$ effect to amplify deformations and induce dynamic instability has been previously highlighted by a number of studies, notably [18–20]. Studies like [1, 14, 18, 21, 22, p. 2-34, 23, p. 98] have further suggested that the impact of the $P-\Delta$ effect may be more pronounced under long duration ground motions. The actual mechanism by which long duration ground motions induce structural collapse by ratcheting has, however, not yet been investigated. This study quantifies the relative contributions of deterioration and ratcheting to the sensitivity of a ductile five-story steel moment frame building to ground motion duration. The effect of duration on the collapse capacity of the structure is quantified using sets of spectrally equivalent long and short duration ground motions, which help control for the effect of response spectral shape [14]. The relative contribution of each physical mechanism is evaluated by analyzing a series of different permutations of the original structural model. A response parameter called the *ratcheting interval*, computed from a smoothed story drift ratio (SDR) time history, is introduced and employed to explain the larger potential for a long duration ground motion to cause structural collapse by ratcheting, when compared to a spectrally equivalent short duration ground motion scaled to the same intensity level.

2. Steel moment frame model

A ductile five-story steel moment frame building located in San Francisco, and previously analyzed in [14, 24], was chosen to demonstrate the contributions of the deterioration and ratcheting mechanisms to the observed effect of duration on structural collapse capacity. The frame was designed with strong columns and relatively weak beams with reduced beam section (RBS) hinges, as illustrated in Figure 1. The large strong-column-weak-beam ratio ensures sufficient engagement of all stories under earthquake excitation, without forming any story mechanisms, i.e., without any localization of plastic deformation at only a few stories. Consequently, structural collapse always occurs in the same sidesway collapse mechanism involving all stories, irrespective of whether it is caused by a short or long duration ground motion. Controlling the collapse mechanism in this manner helped prevent any differences in the collapse mechanism when analyzing the structure under long and short duration ground motions, from confounding the results. Results obtained using this structure are also expected to be representative of other modern, code-conforming structures.

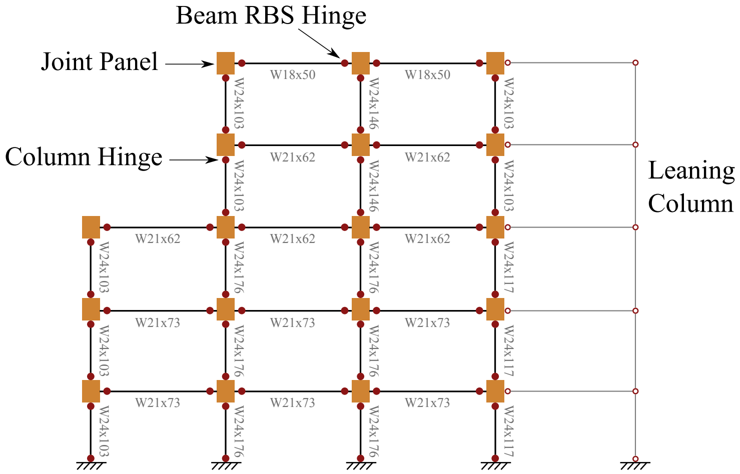


Figure 1: Schematic of the numerical model of the five-story steel special moment frame building.

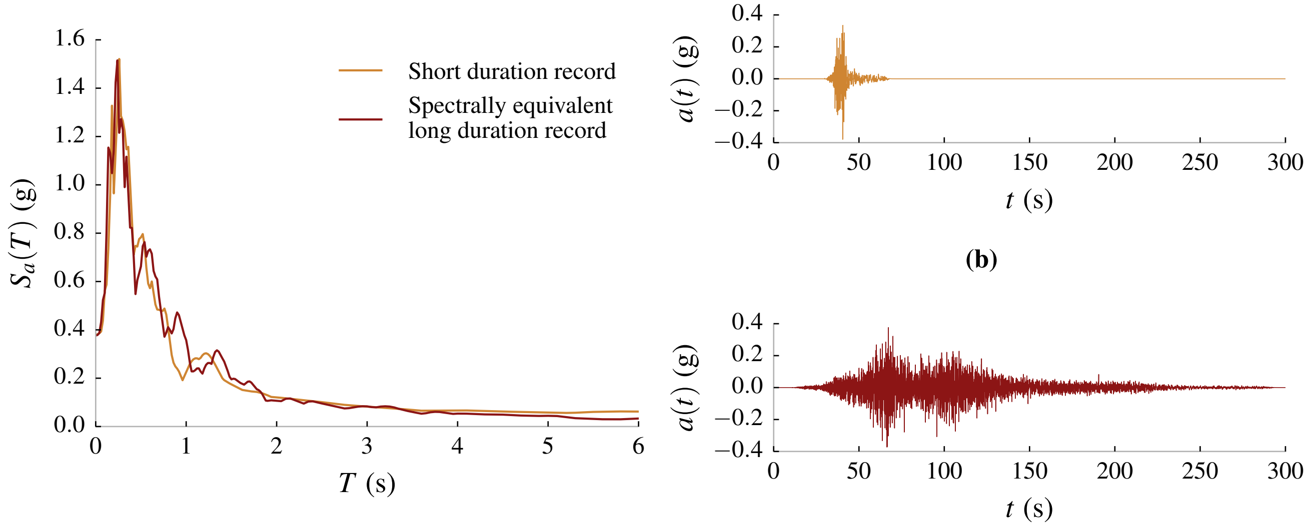
A two-dimensional centerline model of the structure was created and analyzed using OpenSees rev. 5184 [25]. A schematic of this model is illustrated in Figure 1. Each story of the structure is 3.96 m tall, and each bay is 8.84 m wide. The beams and columns were modeled using linear elastic elements, with all the inelastic deformation concentrated in zero-length plastic hinges located at the RBS hinges on each beam, and at the ends of each column. The hysteretic behavior of the plastic hinges was modeled using the bilinear Ibarra-Medina-Krawinkler hysteretic model [26], modified as per the recommendations of Lignos and Krawinkler [27]. This model incorporates (*i*) a post-capping negative stiffness branch of the backbone curve to capture in-cycle deterioration; and (*ii*) an algorithm to cyclically deteriorate both strength and stiffness based on the cumulative hysteretic energy dissipated. The parameters of the model were computed using the equations proposed by Lignos and Krawinkler [28]. The hysteretic shear behavior of the finite panel zones was modeled using a trilinear backbone curve, whose parameters were computed using the equations described in FEMA [29]. Geometric nonlinearity was modeled using a small-displacement, linear $P-\Delta$ formulation, and the contribution of the adjacent gravity frame to the destabilizing $P-\Delta$ effect was captured using a pin-connected leaning column. A linear viscous damping ratio of 2 % of critical was assigned to the linear elastic elements only, as recommended by Charney [30]. The elastic fundamental period of the structure is 1.64 s. All response history analyses of the structure were carried out using the explicit central difference time integration scheme, since it was found to be more robust and efficient than implicit time integration schemes, which sometimes failed to converge [31, Chapter 7].

3. Spectrally equivalent long and short duration record sets

This study employs 5–75 % significant duration (Ds_{5-75}) [32] to quantify the duration of strong shaking contained in an accelerogram. It is defined as the time interval over which 5 % to 75 % of the integral $\int_0^{t_{max}} a^2(t)dt$ is accumulated, where $a(t)$ represents the ground acceleration at time t, and t_{max} represents the length of the accelerogram. Ds_{5-75} was shown to be better suited than other duration metrics to guide the selection of ground motions for structural collapse capacity estimation, in a previous study by the authors [14]. Ds_{5-95}, another commonly employed definition of significant duration, which was shown in [14] to perform equivalent to Ds_{5-75}, was not used in this study.

The FEMA P695 [33] far-field record set consists of 22 orthogonal pairs of horizontal ground motions (44 individual components) recorded from shallow crustal earthquakes. Since all 44 records in this set are of relatively short duration (with $Ds_{5-75} < 25$ s), it will henceforth be referred to as the short duration set. Corresponding to each individual ground motion in the short duration set, a companion long duration ground motion (with $Ds_{5-75} > 25$ s) with a closely matching response spectral shape was selected to form a spectrally equivalent long duration set.

These long duration ground motions were selected from a database consisting of more than 4000 ground motions recorded from large magnitude earthquakes like 2010 Maule (Chile), 2011 Tohoku (Japan), and 2008 Wenchuan (China). A procedure similar to the one described in Chandramohan et al. [14] was followed to find the long duration record from the database with the closest matching response spectral shape. An upper limit of 5.0 was imposed on the factor by which a long duration record could be scaled in the matching procedure, to avoid scaling low intensity records by inordinately large factors. The response spectra and acceleration time histories of one of the spectrally equivalent long and short duration record pairs are plotted in Figure 2; histograms of the durations of the ground motions in the two sets are plotted in Figure 3. Since the records in the two sets are selected to have equivalent response spectra, it is assumed that any observed differences in the response of a structure analyzed using them can be attributed to the difference in their durations. It was shown in Chandramohan et al. [14] that this record selection procedure does not introduce any significant biases with respect to other ground motion characteristics that may influence structural response.



(a)

(b)

(c)

Figure 2: Comparison of the (a) response spectra and acceleration time histories of the (b) short and (c) long duration ground motions constituting one of the 44 spectrally equivalent record pairs. The short duration ground motion is from the 1979 Imperial Valley (USA) earthquake, recorded at the El Centro Array #11 station, and has a Ds_{5-75} of 5 s. The long duration ground motion is from the 2011 Tohoku (Japan) earthquake, recorded at the Nagawa (AOMH17) station, scaled by a factor of 2.76, and has a Ds_{5-75} of 53 s.

4. Relative contributions of cyclic deterioration and the $P-\Delta$ effect to the observed influence of duration

The long and short duration record sets were each used to estimate the median collapse capacity of the steel moment frame building by conducting incremental dynamic analysis (IDA) [34]. This entails incrementally scaling each ground motion to higher intensity levels until it causes structural collapse, which is indicated by the unbounded increase in the story drift ratio (SDR) at any story above a threshold of 0.10. The lowest $S_a(1.64\,\mathrm{s})$ value that a ground motion needs to be scaled to, to cause structural collapse, is called its *collapse intensity*; where $S_a(1.64\,\mathrm{s})$ represents the 5 % damped pseudo spectral acceleration at the elastic fundamental period of the structure. The median collapse capacity of the structure is then estimated as the geometric mean of the collapse intensities of all the ground motions in a set, assuming the structural collapse capacity follows a lognormal distribution. The median collapse capacity of the structure was estimated as 0.98 g using the short duration set and 0.71 g using the long duration set. The lower median collapse capacity estimated the long duration records implies that they

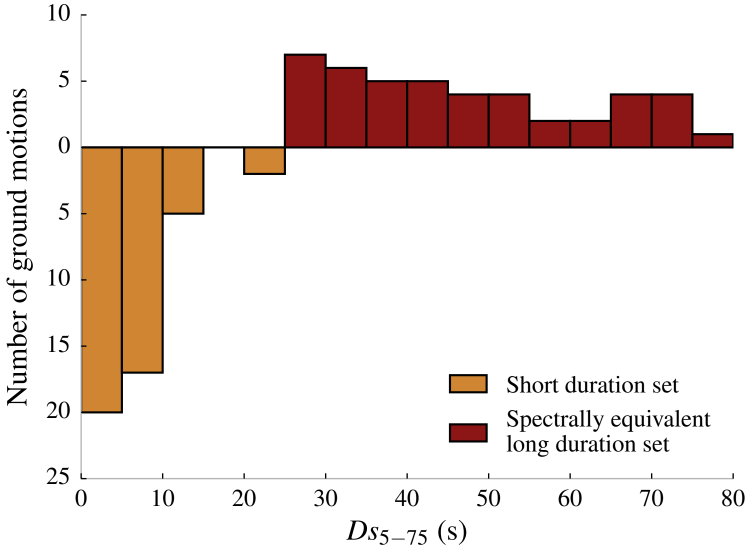


Figure 3: Histograms of the 5–75 % significant durations (Ds_{5-75}) of the ground motions in the spectrally equivalent long and short duration record sets.

are inherently more damaging than the short duration records. Since the two sets are spectrally equivalent, the 28 % difference in estimated median collapse capacity is a measure of the influence of ground motion duration on structural collapse capacity.

The characteristics of the structural model that enabled the effect of duration to be observed were identified by repeating the analysis using various permutations of the structural model. To assess the contribution of cyclic deterioration to the observed effect of duration, a modified version of the structural model, with the cyclic deterioration of the strength and stiffness of all the plastic hinges disabled, was re-analyzed. The effect of duration on structural collapse capacity in these analyses was reduced to 18 % from the original 28 %. This residual effect of duration alludes to the existence of mechanisms other than cyclic deterioration by which duration influences structural response. The contribution of the $P-\Delta$ effect was investigated next by repeating the analysis using a version of the structural model with cyclic deterioration enabled, but the $P-\Delta$ effect disabled. The influence of duration on structural collapse capacity was computed to be 17 % in this case, which is nearly equal to the value obtained when only cyclic deterioration was disabled, implying that both cyclic deterioration and the $P-\Delta$ effect contribute nearly equally to the observed influence of duration on the steel moment frame building. Finally, when both cyclic deterioration and the $P-\Delta$ effect are disabled, the effect of duration is reduced to −1 %, which is very close to zero. This implies that cyclic deterioration and the $P-\Delta$ effect are the two major contributors to the observed effect of duration, and that both their contributions are equally significant. Ignoring either of the two characteristics when modeling a structure could, therefore, result in inaccurate structural collapse risk estimates. It is worth noting that for the analyses conducted on structural models with the $P-\Delta$ effect disabled, the IDA curves do not become completely horizontal, i.e., collapse by dynamic instability is not simulated at or below a peak SDR of 0.10. Nonetheless, the collapse peak SDR threshold of 0.10 is still enforced to maintain consistency with the other cases. The median collapse capacities computed using each record set for all four structural model permutations discussed above, are summarized in Table 1. The reason why the deterioration in component strength and stiffness over subsequent inelastic cycles could enable longer duration ground motions to cause structural collapse when scaled to lower intensities, is fairly obvious. The reason why modeling the $P-\Delta$ effect should produce a similar result is, however, not as intuitive. It is hypothesized that the $P-\Delta$ effect enables long duration ground motions to cause structural collapse by ratcheting; this hypothesis is examined in the following section.

Table 1: Summary of the median collapse capacities of the steel moment frame building estimated using the two spectrally equivalent record sets for all considered structural model permutations. The effect of duration is computed for each case as the percentage decrease in the median collapse capacity estimated using the long duration set, with respect to the short duration set.

Structural model incorporates		**Median collapse capacity estimated using**		**Percentage decrease in median collapse capacity**
Deterioration	$\boldsymbol{P-\Delta}$ **effect**	**Short duration set** (g)	**Long duration set** (g)	
✓	✓	0.98	0.71	28
	✓	1.02	0.84	18
✓		1.15	0.95	17
		1.23	1.24	−1

5. Effect of duration explained by the ratcheting collapse mechanism

Ratcheting is a mode of sidesway collapse observed in ductile structures, whereby an initial inelastic excursion in one direction, concentrated in one or more stories, produces amplified $P-\Delta$ moments in that direction. These $P-\Delta$ moments encourage further inelastic deformation to occur in the same direction under continued ground excitation, thereby producing even larger $P-\Delta$ moments, which finally lead to dynamic instability and sidesway collapse. Structural collapse by ratcheting can, therefore, be broadly viewed as a two-stage process: (*i*) the creation of an initial inelastic excursion, whose magnitude is primarily a function of the ground motion intensity; and (*ii*) the subsequent gradual amplification of drifts due to the $P-\Delta$ moments, which is primarily a function of the duration of strong shaking following the initial excursion. Short duration ground motions cause structural collapse at relatively large ground motion intensities since they rely on large initial inelastic excursions to cause dynamic instability. Long duration ground motions, on the other hand, are able to cause structural collapse at lower ground motion intensities since the smaller initial inelastic excursions produced at these lower intensities are gradually amplified by ratcheting until the eventual onset of dynamic instability later in the time series. A response parameter called the *ratcheting interval* is defined below and used to illustrate this phenomenon.

The ratcheting interval is computed from the SDR time history at the story where the collapse threshold is first exceeded. Hence, it is computable only when the ground motion is scaled at or above its collapse intensity. The SDR time history is first smoothed using the locally weighted scatterplot smoothing (LOWESS) [35] technique as demonstrated in Figures 4a, 4b, and 4c. The ratcheting interval is then computed as the time elapsed from the last point where the smoothed SDR time history exceeds a threshold of 0.01 until the first point where the actual SDR time history exceeds the collapse threshold of 0.10. It is an approximate measure of the time interval over which drifts are amplified by ratcheting before sidesway collapse due to dynamic instability occurs. Smoothed and thresholded SDR time histories computed from all the long and short duration ground motions, scaled to their respective collapse intensities, are plotted in Figure 5a. Histograms of the ratcheting intervals computed from these smoothed time histories are plotted in Figure 5b. The long duration ground motions are observed to exhibit longer ratcheting intervals (median of 22 s) on average, when compared to the short duration ground motions (median of 8 s), implying that the ratcheting collapse mode is more dominant under the long duration ground motions when they are each scaled to their respective collapse intensities. It is worth noting that the ground motion collapse intensities were estimated to a precision of 0.01 g when conducting IDA, and longer ratcheting intervals may have been computed for some ground motions if their collapse intensities were estimated to a finer precision. This is not, however, expected to significantly influence the obtained results.

As demonstrated in Figure 4, when the long duration ground motions are scaled above their respective collapse intensities, the ratcheting intervals they produce tend to decrease. Therefore, as they are incrementally scaled above their collapse intensities, the mode of collapse they trigger transitions closer to what was observed under the short duration ground motions. The decreasing trend in the median ratcheting intervals produced by the long and short duration records as they are scaled above their collapse intensities, is evident from Figure 6. The reason why the median ratcheting interval produced by the long duration records oscillates and saturates beyond a geometric mean $S_a(1.64\,\mathrm{s})$ of about 1.00 g, is discussed later. The median was chosen over the geometric mean to summarize

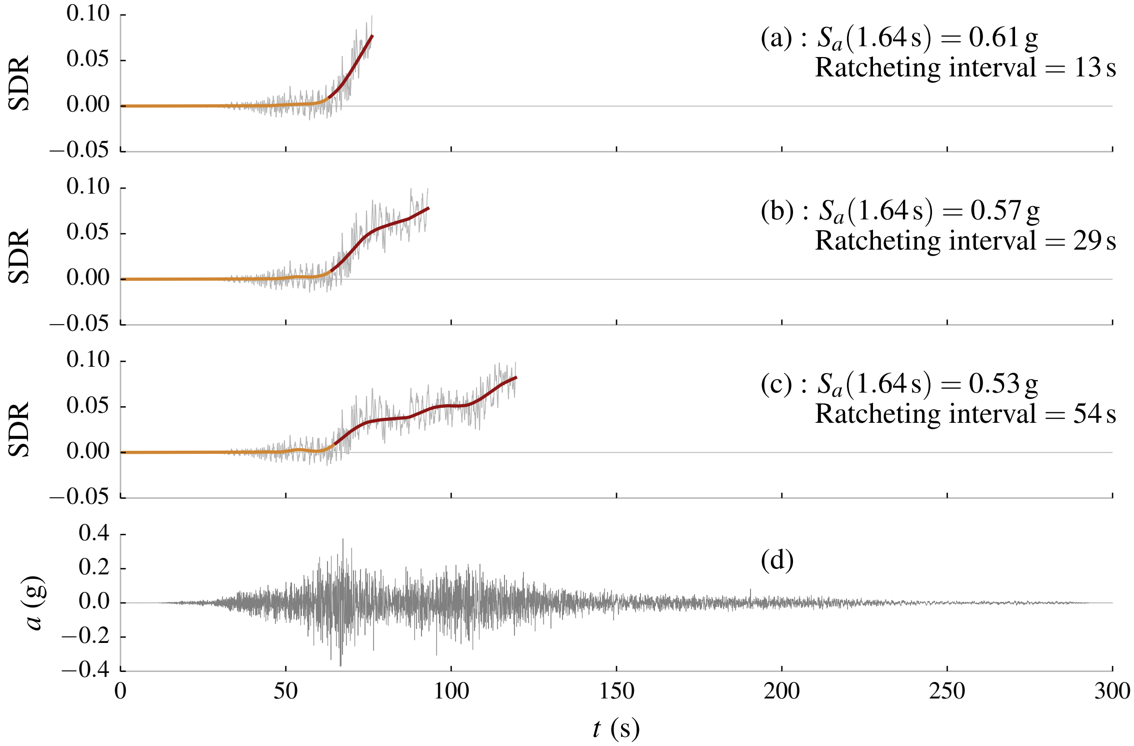
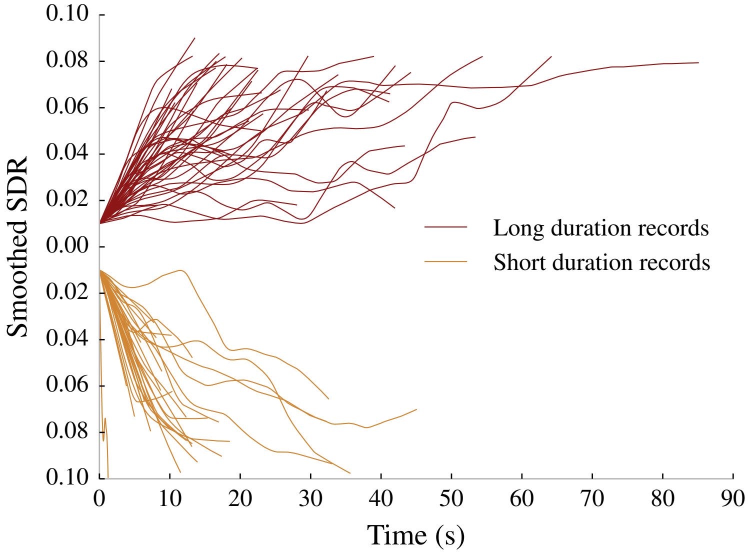


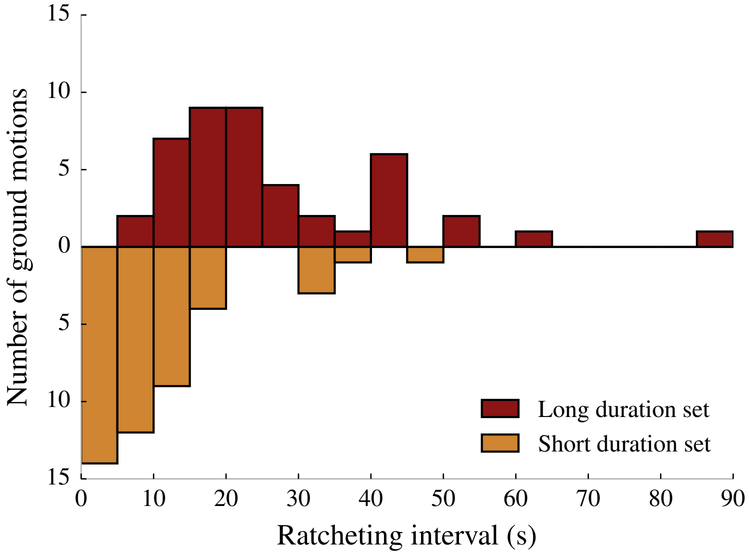
Figure 4: Smoothed time histories of the SDR at the fifth story, under the long duration ground motion from the 2011 Tohoku (Japan) earthquake, recorded at the Nagawa (AOMH17) station, scaled to (c) its collapse intensity level: $S_a(1.64\,\text{s}) = 0.53\,\text{g}$, and two higher intensity levels: (b) 0.57 g and (a) 0.61 g. The parts of the smoothed SDR time histories used to compute the ratcheting interval are plotted in red. The original accelerogram, scaled by a factor of 2.76 (the scale factor used during record selection), is plotted in (d).

the ratcheting intervals, since it is not affected in instances when ground motions produce a ratcheting interval of 0 s. Ground motions that did not cause structural collapse when scaled to certain intensity levels above their collapse intensities, by a phenomenon called resurrection [34], were excluded from the computation of the median ratcheting interval at that intensity level. When the long duration records are scaled such that their geometric mean $S_a(1.64\,\text{s})$ value is close to 0.98 g: the geometric mean collapse intensity of the short duration records, they produce a median ratcheting interval almost equal to that produced by the short duration records scaled to their respective collapse intensities. In other words, at this intensity level, both long and short duration ground motions trigger similar modes of collapse. Therefore, as the long duration records are scaled above their collapse intensities, the initial inelastic excursions they produce become large enough to cause structural collapse due to dynamic instability earlier in the time series, in a manner similar to the short duration ground motions. The remaining duration of strong shaking contained in the long duration accelerograms represents their unused, redundant potential to cause structural collapse by ratcheting. This helps explain why a long duration ground motion is more likely to cause structural collapse than a short duration ground motion with a similar response spectral shape, scaled to the same intensity level, as observed previously in [14, 36].

The reason why the median ratcheting interval produced by the long duration ground motions oscillates and saturates beyond a geometric mean $S_a(1.64\,\text{s})$ of about 1.00 g, is demonstrated using a representative long duration ground motion in Figure 7. The expected decrease in ratcheting interval is observed as it is scaled from its collapse intensity of $S_a(1.64\,\text{s}) = 0.76\,\text{g}$ to 0.96 g. When scaled up to 1.18 g though, the ratcheting interval increases since an earlier inelastic excursion has now grown large enough to initiate the ratcheting of drifts until eventual collapse. This phenomenon is responsible for the oscillations in the median ratcheting interval produced by the long duration ground motions, observed in Figure 6. As the ground motion is scaled up to 1.52 g, which



(a)



(b)

Figure 5: (a) Smoothed SDR time histories at the controlling story under all ground motion from the two sets scaled to their respective collapse intensities, plotted from the last point the smoothed time history exceeds a threshold of 0.01, until the first point the actual SDR time history exceeds the collapse threshold of 0.10; and (b) histograms of the ratcheting intervals computed from these smoothed and thresholded SDR time histories.

is twice the collapse intensity level, the ratcheting interval decreases again, as expected. The ratcheting interval does not decrease much below 18 s as it is scaled further above 1.52 g, however, because of the unique nature of the initial portion of the long duration accelerogram, depicted in Figure 7e. The gradual ramp in the amplitude of successive ground acceleration cycles over a duration of about 20 s ensures that the smaller initial cycles are not capable of producing inelastic excursions large enough to initiate ratcheting. This is the reason why the median ratcheting interval of the long duration ground motions saturate at around 10 s, and do not approach 0 s like the short duration ground motions.

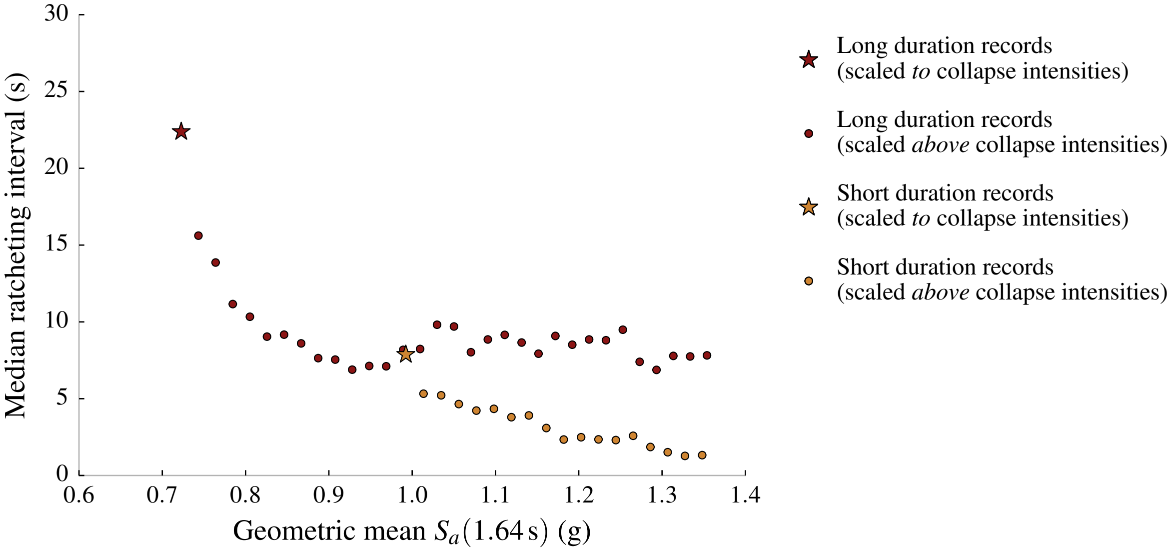


Figure 6: The median ratcheting intervals produced by the long and short duration records are plotted against their respective geometric mean collapse intensities as stars. The median ratcheting intervals produced by the records in both sets as they are incrementally scaled above their collapse intensities, are plotted as circles.

6. Conclusion

The cyclic deterioration in strength and stiffness of structural components and the ratcheting of drifts due to the $P-\Delta$ effect were shown to be the two major mechanisms by which ground motion duration exerts an influence on the collapse capacity of a ductile five-story steel moment frame building. The relative contributions of these two mechanisms to the total observed effect of duration were quantified by conducting incremental dynamic analysis on several permutations of a numerical model of the steel moment frame building, using spectrally equivalent long and short duration record sets. These record sets allowed assessing the influence of duration on structural collapse capacity while controlling for the effect of response spectral shape. The analysis revealed that both mechanisms contributed almost equally to the observed effect of duration. A response parameter called the ratcheting interval was defined and used to describe how the gradual ratcheting of drifts due to $P-\Delta$ moments can enable a long duration ground motion to cause structural collapse when scaled to a lower intensity level, compared to a short duration ground motion with a similar response spectral shape.

These findings highlight the importance of using structural models that incorporate both cyclic deterioration and the $P-\Delta$ effect, in conjunction with ground motions of durations that closely represent the seismic hazard at the site, to accurately estimate structural collapse risk. While modeling the $P-\Delta$ effect is relatively straightforward and fairly commonplace, accounting for cyclic deterioration poses a few additional challenges. The modified Ibarra-Medina-Krawinkler hysteretic model employed in this study adopts a phenomenological approach to modeling the strength and stiffness deterioration of structural components. For the analyzed steel moment frame, this entails simulating a number of deterioration modes like local flange and web buckling, lateral-torsional buckling, and crack initiation and propagation until fracture [37, 38], using a phenomenological deterioration algorithm. Owing to the complexity of this behavior, the model parameters controlling component deterioration are associated with a relatively large degree of uncertainty [28]. This motivates the need to develop and use more realistic physics-based models that explicitly simulate the dominant modes of deterioration. Efforts to calibrate the Ibarra-Medina-Krawinkler hysteretic model, undertaken by Lignos and Krawinkler [28], used measurements from experimental tests that employed cyclic loading protocols derived predominantly from short duration ground motions [39]. Structural components are, however, expected to exhibit different hysteretic behavior under loading protocols developed to simulate long duration ground motions [39–41]. The observation that structural collapse under long duration ground motions occurs predominantly by the gradual, unidirectional ratcheting of drifts, also suggests

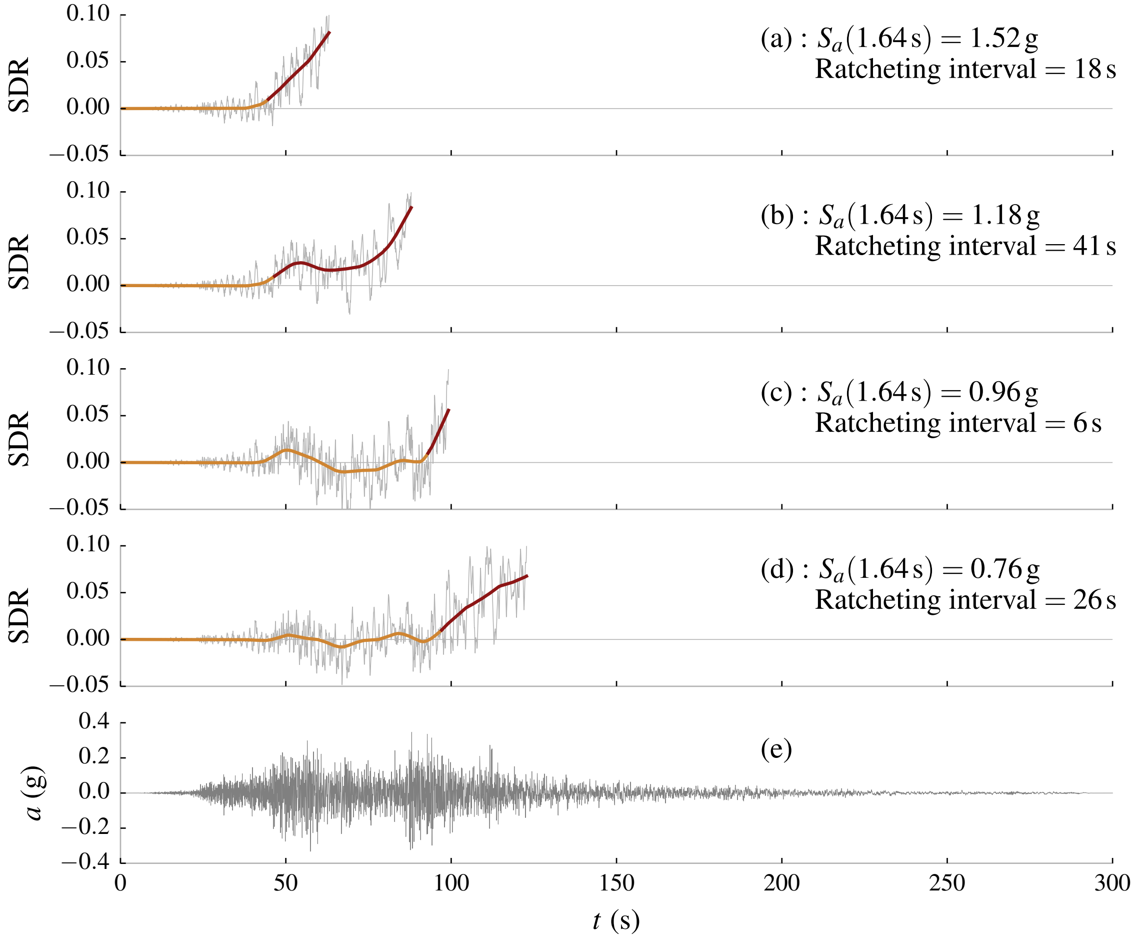


Figure 7: Smoothed time histories of the SDR at the fifth story, under the long duration ground motion from the 2011 Tohoku (Japan) earthquake, recorded at the Kakunodate (AKT014) station, scaled to (d) its collapse intensity level: $S_a(1.64\,\text{s}) = 0.76\,\text{g}$, and three higher intensity levels: (c) 0.96 g, (b) 1.18 g and (a) 1.52 g. The parts of the smoothed SDR time histories used to compute the ratcheting interval are plotted in red. The original accelerogram, scaled by a factor of 5.00 (the scale factor used during record selection), is plotted in (e).

that long duration cyclic loading protocols used to calibrate and validate analysis models should consider unsymmetrical loading response. Hence, the applicability of the equations developed to predict median model parameters as functions of member characteristics, when simulating structural response under long duration ground motions, requires further investigation.

7. Acknowledgements

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References

[1] Hancock J and Bommer JJ (2006). "A State-of-Knowledge Review of the Influence of Strong-Motion Duration on Structural Damage". *Earthquake Spectra* **22** (3), pp. 827–845. DOI: 10.1193/1.2220576.

[2] Cornell CA (1997). "Does Duration Really Matter?" *FHWA/NCEER Workshop on the National Representation of Seismic Ground Motion for New and Existing Highway Facilities*. National Center for Earthquake Engineering Research, Burlingame, CA, pp. 125–133.

[3] Bommer JJ, Magenes G, Hancock J, and Penazzo P (2004). "The Influence of Strong-Motion Duration on the Seismic Response of Masonry Structures". *Bulletin of Earthquake Engineering* **2** (1), pp. 1–26. DOI: 10.1023/B:BEEE.0000038948.95616.bf.

[4] Iervolino I, Manfredi G, and Cosenza E (2006). "Ground motion duration effects on nonlinear seismic response". *Earthquake Engineering & Structural Dynamics* **35** (1), pp. 21–38. DOI: 10.1002/eqe.529.

[5] Hancock J and Bommer JJ (2007). "Using spectral matched records to explore the influence of strong-motion duration on inelastic structural response". *Soil Dynamics and Earthquake Engineering* **27** (4), pp. 291–299. DOI: 10.1016/j.soildyn.2006.09.004.

[6] Oyarzo-Vera C and Chouw N (2008). "Effect of earthquake duration and sequences of ground motions on structural responses". *10th International Symposium on Structural Engineering for Young Experts*. Changsha, China.

[7] Raghunandan M and Liel AB (2013). "Effect of ground motion duration on earthquake-induced structural collapse". *Structural Safety* **41**, pp. 119–133. DOI: 10.1016/j.strusafe.2012.12.002.

[8] Barbosa AR, Ribeiro FLA, and Neves LC (2014). "Effects of ground-motion duration on the response of a 9-story steel frame building". *10th U.S. National Conference on Earthquake Engineering*. Anchorage, AK.

[9] Hou H and Qu B (2015). "Duration effect of spectrally matched ground motions on seismic demands of elastic perfectly plastic SDOFs". *Engineering Structures* **90**, pp. 48–60. DOI: 10.1016/j.engstruct.2015.02.013.

[10] Mantawy A and Anderson J (2015). "Assessment of Low-Cycle Fatigue Damage in R.C. Frame Buildings Under Long-Duration Earthquakes". *SECED 2015 Conference: Earthquake Risk and Engineering towards a Resilient World*. Cambridge, UK.

[11] PEER TBI (2010). *Guidelines for Performance-Based Seismic Design of Tall Buildings*. Tech. rep. PEER 2010/05. Pacific Earthquake Engineering Research Center, Berkeley, CA.

[12] NIST (2011). *Selecting and Scaling Earthquake Ground Motions for Performing Response-History Analyses*. Tech. rep. NIST GCR 11-917-15. National Institute of Standards and Technology, Gaithersburg, MD.

[13] ASCE (2016). *Minimum Design Loads for Buildings and Other Structures*. Tech. rep. ASCE/SEI 7-16. American Society of Civil Engineers, Reston, VA.

[14] Chandramohan R, Baker JW, and Deierlein GG (2016a). "Quantifying the Influence of Ground Motion Duration on Structural Collapse Capacity Using Spectrally Equivalent Records". *Earthquake Spectra* **32** (2), pp. 927–950. DOI: 10.1193/122813EQS298MR2.

[15] Beyer K and Bommer JJ (2007). "Selection and Scaling of Real Accelerograms for Bi-Directional Loading: A Review of Current Practice and Code Provisions". *Journal of Earthquake Engineering* **11** (S1), pp. 13–45. DOI: 10.1080/13632460701280013.

[16] Marafi NA, Berman JW, and Eberhard MO (2016). "Ductility-dependent intensity measure that accounts for ground-motion spectral shape and duration". *Earthquake Engineering & Structural Dynamics* **45** (4), pp. 653–672. DOI: 10.1002/eqe.2678.

[17] Gupta A and Krawinkler H (2000). "Dynamic P-Delta Effects for Flexible Inelastic Steel Structures". *Journal of Structural Engineering* **126** (1), pp. 145–154. DOI: 10.1061/(ASCE)0733-9445(2000)126:1(145).

[18] Takizawa H and Jennings PC (1980). "Collapse of a model for ductile reinforced concrete frames under extreme earthquake motions". *Earthquake Engineering & Structural Dynamics* **8** (2), pp. 117–144. DOI: 10.1002/eqe.4290080204.

[19] Mahin SA and Bertero VV (1981). "An Evaluation of Inelastic Seismic Design Spectra". *Journal of the Structural Division, Proceedings of the American Society of Civil Engineers* **107** (ST9), pp. 1777–1795.

[20] Bernal D (1987). “Amplification factors for inelastic dynamic p–Δ effects in earthquake analysis”. *Earthquake Engineering & Structural Dynamics* **15** (5), pp. 635–651. DOI: 10.1002/eqe.4290150508.

[21] Mahin SA (1980). “Effects of duration and aftershocks on inelastic design earthquakes”. *7th World Conference on Earthquake Engineering*. Istanbul, Turkey, pp. 677–680.

[22] PEER (2010). *Modeling and acceptance criteria for seismic design and analysis of tall buildings*. Tech. rep. PEER/ATC-72-1. Pacific Earthquake Engineering Research Center, Berkeley, CA.

[23] ASCE (2013). *Seismic Evaluation and Retrofit of Existing Buildings*. Tech. rep. ASCE/SEI 41-13. American Society of Civil Engineers, Reston, VA. DOI: 10.1061/9780784412855.

[24] FEMA (2014). *Seismic Performance Assessment of Buildings, Volume 5 - Use of Seismic Performance Assessment Methodologies to Evaluate Code Performance*. Tech. rep. FEMA P-58-5. Federal Emergency Management Agency, Washington, D.C.

[25] McKenna F, Fenves GL, and Scott MH (2006). *OpenSees: Open system for earthquake engineering simulation*. Berkeley, CA. URL: http://opensees.berkeley.edu (visited on 2016-07-26).

[26] Ibarra LF, Medina RA, and Krawinkler H (2005). “Hysteretic models that incorporate strength and stiffness deterioration”. *Earthquake Engineering & Structural Dynamics* **34** (12), pp. 1489–1511. DOI: 10.1002/eqe.495.

[27] Lignos DG and Krawinkler H (2012). *Sidesway collapse of deteriorating structural systems under seismic excitations*. Tech. rep. 177. John A. Blume Earthquake Engineering Research Center, Stanford University, Stanford, CA.

[28] Lignos DG and Krawinkler H (2011). “Deterioration Modeling of Steel Components in Support of Collapse Prediction of Steel Moment Frames under Earthquake Loading”. *Journal of Structural Engineering* **137** (11), pp. 1291–1302. DOI: 10.1061/(ASCE)ST.1943-541X.0000376.

[29] FEMA (2000). *State of the art report on systems performance of steel moment frames subject to earthquake ground shaking*. Tech. rep. FEMA 335C. Federal Emergency Management Agency, Stanford, CA.

[30] Charney FA (2008). “Unintended Consequences of Modeling Damping in Structures”. *Journal of Structural Engineering* **134** (4), pp. 581–592. DOI: 10.1061/(ASCE)0733-9445(2008)134:4(581).

[31] Chandramohan R (2016). “Duration of earthquake ground motion: Influence on structural collapse risk and integration in design and assessment practice”. PhD thesis. Stanford University, Stanford, CA.

[32] Trifunac MD and Brady AG (1975). “A study on the duration of strong earthquake ground motion”. *Bulletin of the Seismological Society of America* **65** (3), pp. 581–626.

[33] FEMA (2009a). *Quantification of Building Seismic Performance Factors*. Tech. rep. FEMA P695. Federal Emergency Management Agency, Washington, D.C.

[34] Vamvatsikos D and Cornell CA (2002). “Incremental dynamic analysis”. *Earthquake Engineering & Structural Dynamics* **31** (3), pp. 491–514. DOI: 10.1002/eqe.141.

[35] Cleveland WS (1979). “Robust Locally Weighted Regression and Smoothing Scatterplots”. *Journal of the American Statistical Association* **74** (368), pp. 829–836. DOI: 10.1080/01621459.1979.10481038.

[36] Chandramohan R, Baker JW, and Deierlein GG (2016b). “Impact of hazard-consistent ground motion duration in structural collapse risk assessment”. *Earthquake Engineering & Structural Dynamics* **45** (8), pp. 1357–1379. DOI: 10.1002/eqe.2711.

[37] Krawinkler H and Zohrei M (1983). “Cumulative damage in steel structures subjected to earthquake ground motions”. *Computers & Structures* **16** (1-4), pp. 531–541. DOI: 10.1016/0045-7949(83)90193-1.

[38] Deierlein GG, Reinhorn AM, and Willford MR (2010). *Nonlinear structural analysis for seismic design*. Tech. rep. NEHRP Seismic Design Technical Brief No. 4. National Institute of Standards and Technology, Gaithersburg, MD.

[39] Bazaez R and Dusicka P (2016). “Cyclic Loading for RC Bridge Columns Considering Subduction Megathrust Earthquakes”. *Journal of Bridge Engineering* **21** (5), p. 04016009. DOI: 10.1061/(ASCE)BE.1943-5592.0000891.

[40] Krawinkler H (2009). “Loading Histories for Cyclic Tests in Support of Performance Assessment of Structural Components”. *3rd International Conference on Advances in Experimental Structural Engineering*. San Francisco, CA.

[41] FEMA (2009b). *Effects of Strength and Stiffness Degradation on Seismic Response*. Tech. rep. FEMA P440A. Federal Emergency Management Agency, Washington, D.C.