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Research Paper

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Influence of ground motion duration on the dynamic deformation capacity of reinforced concrete frame structures

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Abstract

This study investigates the influence of ground motion duration on the dynamic deformation capacity of a suite of 10 modern reinforced concrete moment frame buildings. A robust numerical algorithm is proposed to estimate the dynamic deformation capacity of a structure by conducting incremental dynamic analysis. The geometric mean dynamic deformation capacity of the considered buildings was, on average, found to be 26% lower under long duration ground motions, compared to spectrally equivalent short duration ground motions. A consistent effect of duration on dynamic deformation capacity was observed over a broad range of structural periods considered in this study. Response spectral shape, however, was found to not significantly influence dynamic deformation capacity. These results indicate that the effect of duration could be explicitly considered in seismic design codes by modifying the deformation capacities of structures.

Keywords

Ground motion duration, reinforced concrete, dynamic deformation capacity, incremental dynamic analysis, moment frame structure, collapse simulation

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Introduction

Data recorded from recent large magnitude earthquakes, such as 2008 Wenchuan, China (M_W 7.9); 2010 Maule, Chile (M_W 8.8); and 2011 Tohoku, Japan (M_W 9.0), have spurred a number of research efforts into the influence of ground motion duration on structural response. These studies have investigated the influence of ground motion duration on peak and cumulative structural demand parameters (e.g. Barbosa et al., 2017; Raghunandan and Liel, 2013), including structural collapse capacity (e.g. Chandramohan et al., 2016; Raghunandan et al., 2015). A few of these studies have translated their findings into proposals to account for duration in design by adjusting the design strength of structures to compensate for their increased likelihood of collapse under long duration ground motions (e.g. Chandramohan et al., 2018; Liel et al., 2015). This study investigates the influence of ground motion duration on the deformation capacity of reinforced concrete (RC) framed structures. The aim of this study is to lay the foundation for an alternative and more natural means to incorporate the effect of duration in contemporary seismic design codes that do not specify an explicit collapse performance objective (e.g. NZS 1170.5, 2004), by adjusting the deformation capacities of structures instead.

The potential significance of duration on the seismic response of structures has been recognized for some time (Hancock and Bommer, 2006; Liddell et al., 2000). Previous studies have employed both numerical simulations and experimental tests to investigate the influence of duration on structural response. Studies that employed numerical simulations include Raghunandan and Liel (2013), Raghunandan et al. (2015), Chandramohan et al. (2016), Barbosa et al. (2017), and Bravo-Haro and Elghazouli (2018), which analyzed steel and RC moment frame buildings; Fairhurst et al. (2019), which analyzed RC wall buildings; Li et al. (2019), and Hammad and Moustafa (2020), which analyzed special concentrically braced steel frames, and Pan et al. (2018), which looked at timber frame buildings. These studies have consistently highlighted the need to use numerical models that incorporate the in-cycle and cyclic degradation of strength and stiffness of structural components (Ibarra et al., 2005), and the destabilizing P-Δ effect of gravity loads (Gupta and Krawinkler, 2000), to adequately capture the effect of duration on structural response.

Although most numerical studies found no significant influence of ground motion duration on peak structural *deformation demands* (e.g. Fairhurst et al., 2019; Raghunandan and Liel, 2013), some experimental studies have observed an effect of duration on structural *deformation capacity*. Laboratory tests have consistently reported correlations between the number of loading cycles and the ultimate deformation capacities of RC and steel structural components (Hancock and Bommer, 2006; Liddell et al., 2000; Ou et al., 2013; Pujol et al., 2006). Liddell et al. (2000) reported a 40% reduction in the ductility capacity of RC beams, and Ou et al. (2013) reported a 24% reduction in the ductility capacity of RC columns, under long duration psuedo-static loading protocols, compared to conventional short duration loading protocols. These differences in deformation capacity are typically attributed to the larger degradation in structural strength and stiffness associated with an increase in the number of loading cycles (Ou et al., 2013). Mohammed et al. (2015) reported a 45% reduction in the deformation capacity of an RC column specimen subjected to a long duration ground motion on a shake table, compared to a spectrally equivalent short duration ground motion. The scope of these experimental studies was, however, limited to evaluating the effect of duration at the component level. Raghunandan and Liel (2013) observed a slight decrease in maximum story drifts recorded at intensity levels just below collapse, with duration, for a range of modern ductile and older non-ductile RC frames. Pan et al. (2018) employed incremental dynamic analysis (IDA) to analyze timber frame structures and also found them to collapse at 12%–20% lower peak story drift ratios (SDRs) under long duration ground motions, compared to short duration ground motions.

This study develops a robust procedure to numerically determine what will be referred to as the *dynamic* deformation capacity of a structure by conducting IDA. This procedure is then used to evaluate the dynamic deformation capacities of 10 archetype RC framed structures designed using modern building codes (International Code Council (ICC), 2003, 2012) at three sites in Western USA. Spectrally equivalent short and long duration record sets are employed to assess the influence of ground motion duration on dynamic deformation capacity, while controlling for any effect of response spectral shape.

Estimating structural dynamic deformation capacity

The *dynamic* deformation capacity of a structure is defined as the largest SDR it can safely withstand without collapsing due to dynamic instability. It can be estimated as the largest SDR simulated when conducting IDA (Vamvatsikos and Cornell, 2002), at ground motion intensity levels lower than or equal to the collapse intensity. The computation procedure described below is a refined version of methods previously employed by Liel et al. (2011) and Haselton et al. (2010) to relate story and roof drifts at the onset of collapse, to system ductility.

IDA is conducted by scaling each ground motion in a set to incrementally higher intensity levels until the peak SDR exceeds a pre-defined threshold. A relatively high peak SDR threshold of 20% was employed for the ductile RC frames analyzed in this study, to help minimize any dependence of the computed dynamic deformation capacity on the chosen threshold. Suitable alternative thresholds may, however, be used when analyzing other types of structural models. The 5% damped pseudo-spectral acceleration at the fundamental modal period of the building, $S_a(T_1)$, is used to quantify ground motion intensity, in line with current design and assessment practice. An IDA curve is a piecewise linear plot of the simulated peak SDR (over all stories and the entire duration of response) against the intensity, $S_a(T_1)$, of a single ground motion. The last line segment of the IDA curve is drawn horizontally from the highest intensity level at which a peak SDR lower than the threshold was observed, to indicate global dynamic instability.

Since the value of the dynamic deformation capacity as defined above is sensitive to the precise definition of the structural collapse point along the IDA curve, it was considered necessary to develop a robust definition of the collapse intensity. The definition of collapse intensity proposed in this study is the intensity corresponding to the starting point of the first line segment whose slope is either greater than 5% of the initial elastic slope (k_e) of the IDA curve or negative, when tracing the IDA curve backwards from the horizontal segment. k_e refers to the slope of the first line segment when tracing the IDA curve forwards from the origin. The dynamic deformation capacity is now computed as the largest peak SDR value observed at ground motion intensities equal to or lower than the collapse intensity. This method of identifying the collapse intensity and dynamic deformation capacity is illustrated in Figure 1a for a 20-story RC frame with a fundamental modal period of 2.3 s. The method was developed to be robust against the hardening of IDA curves, which refers to the phenomenon of observing negative IDA curve slopes, or a structure exhibiting lower peak deformations at higher ground motion intensities (Vamvatsikos and Cornell, 2002). The computation of dynamic deformation capacity for IDA curves exhibiting hardening behavior is illustrated in Figure 1b.

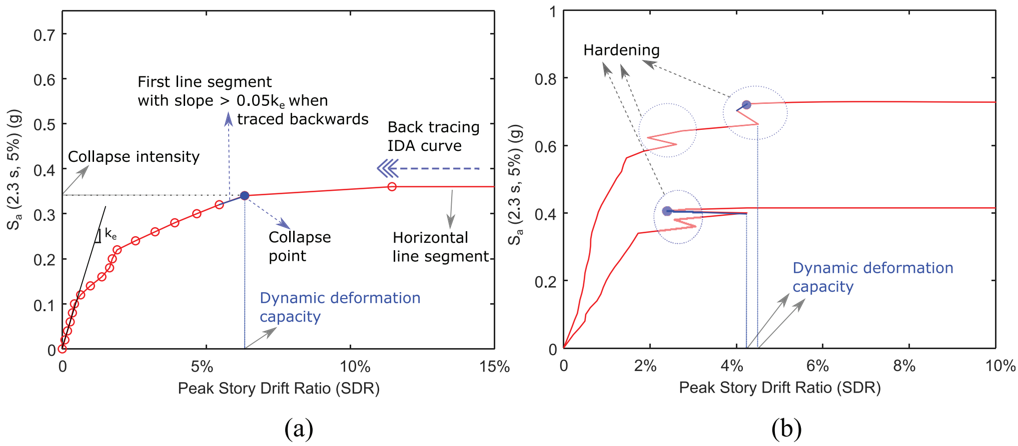

Figure 1. Procedure to compute the dynamic deformation capacity of a structure from an IDA curve for (a) a regular case, and (b) cases with hardening.

Table 1. Seismic design characteristics of the archetype RC moment frame buildings used in this study, previously designed by Raghunandan et al. (2015) and Haselton et al. (2010)

Site	Design MCE_R[a] ordinates	No. of stories	ID	Fundamental modal period (s)[b]
Los Angeles	S_s = 2.40 g	2	LA02	0.53
	S_1 = 0.84 g	4	LA04	0.84
		8	LA08	1.53
	S_s = 1.50 g	12	LA12	2.09
	S_1 = 0.60 g	20	LA20	2.31
Seattle	S_s = 1.37 g	2	ST02	0.57
	S_1 = 0.53 g	4	ST04	0.98
		8	ST08	1.76
Portland	S_s = 0.98 g	2	PL02	0.61
	S_1 = 0.42 g	8	PL08	1.93

[a]Risk-targeted Maximum Considered Earthquake (MCE_R) spectral ordinates at T = 0.2 s (S_s) and T = 1 s (S_1) (American Society of Civil Engineers (ASCE), 2010).
[b]Computed from eigenvalue analysis, considering cracked concrete sections.

The accuracy of the dynamic deformation capacity estimated using the described procedure typically improves by reducing the $S_a(T_1)$ increments used to conduct IDA. Specifically, the first $S_a(T_1)$ increment should correspond to the elastic response of the structure to accurately estimate k_e. Therefore, the peak drift response at the first scaling increment should be equal to or lower than the yield drift from a pushover analysis. The accuracy of the estimated collapse intensity (and consequently the dynamic deformation capacity) can be improved further by using fine $S_a(T_1)$ increments near the intensity level at which the peak deformations exceed the defined threshold.

Archetype RC frame structures

The structures analyzed in this study are RC special moment resisting frames, representative of modern seismic design practice in Western USA, previously designed and analyzed

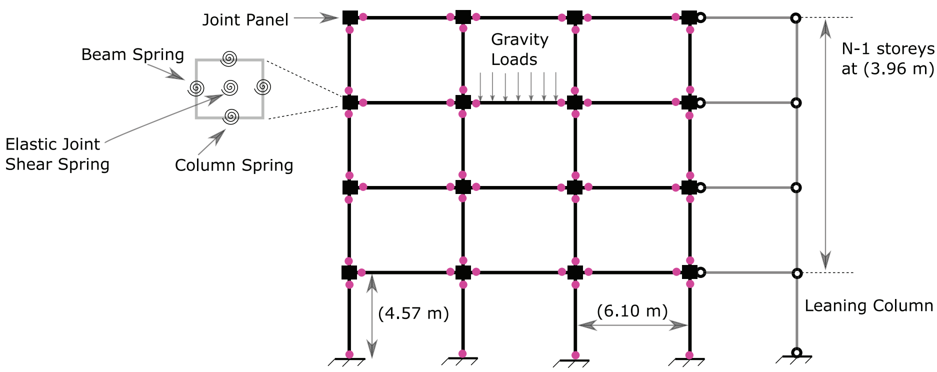

Figure 2. Schematic of the reinforced concrete frame models used to analyse the archetype structures ranging in height from 2 to 20 storeys.
N refers to the total number of storeys in the frame.

by Raghunandan et al. (2015) and Haselton et al. (2010). Ten buildings were considered, ranging in height from 2 to 20 stories. These buildings were designed as space frames, at sites in Los Angeles, Seattle, and Portland; their properties are summarized in Table 1. All buildings were designed for site class D, according to the provisions of the current 2012 International Building Code (IBC) (ICC, 2012), except for the 12- and 20-story buildings, which were designed as per the 2003 IBC (ICC, 2003). The two different versions of the same design code used here, IBC 2003 and IBC 2012, are considered to be comparable and any minor differences between the two are not expected to have a significant effect on the results of this study. The designs incorporated capacity design requirements to prevent column shear failure and encourage strong column-weak beam mechanisms, and detailing requirements for transverse reinforcement and lap slices. All buildings have three bays, 6.10 m (20 ft) wide, and story heights of 4.57 m (15 ft) (first story) and 3.96 m (13 ft) (upper stories), as shown in Figure 2.

Two-dimensional concentrated plastic hinge models of the archetype buildings were developed in OpenSees (McKenna et al., 2006), one of which is schematically illustrated in Figure 2. The hysteretic behavior of the plastic hinges was modeled using the Ibarra-Medina-Krawinkler peak-oriented model, which incorporates the in-cycle and cyclic deterioration of strength and stiffness. An updated version of this material model in OpenSees was employed in this study, which was observed to produce noticeably different results compared to previous studies (Haselton et al., 2010; Raghunandan et al., 2015) that analyzed the same numerical models. P-Δ effects were modeled, and the destabilizing effect of the adjacent gravity frame was captured using a pin-connected leaning column. Both these model characteristics are essential to simulate dynamic instability, and thereby compute dynamic deformation capacity. They have also been demonstrated to be necessary by previous studies such as Raghunandan et al. (2015) and Chandramohan et al. (2017), to adequately capture the effect of ground motion duration on structural response. The shear deformation of the finite joint panels was modeled using elastic shear springs. 5% Rayleigh damping was assigned to the periods corresponding to the first and third modes of the structures. Although the limitations of the Rayleigh damping model in simulating structural response have been highlighted by studies such as Priestley and Grant (2005) and Petrini et al. (2008), it is assumed here that such limitations will uniformly affect the results from the two ground motion sets. Therefore, they are not expected to significantly

Table 2. Summary of the number of records from each earthquake in the long duration record set

Earthquake	Magnitude (M_W)	No. of records
Valparaiso (Chile)	7.8	3
Michoacan (Mexico)	8.0	1
Chi-Chi (Taiwan)	7.6	2
Denali (USA)	7.9	1
Hokkaido (Japan)	8.3	1
Chuetsu-oki (Japan)	6.6	1
Wenchuan (China)	7.9	2
Maule (Chile)	8.8	1
El Mayor-Cucapah (USA)	7.2	1
Tohoku (Japan)	9.0	31

influence the conclusions of this study. The fundamental modal periods of the structures are indicated in Table 1.

Ground motion sets

The ground motions used in this study comprise 44 short duration ground motions from the FEMA P695 (Federal Emergency Management Agency (FEMA), 2009) far field set and 44 long duration ground motions previously selected and used in Chandramohan (2016). The short duration (SD) set consists of ground motions recorded from moderate magnitude shallow crustal earthquakes, while the long duration (LD) set consists of ground motions produced by large magnitude crustal and subduction earthquakes, selected to have an equivalent mean response spectrum as the SD set, as described in Chandramohan (2016) and illustrated in Figure 3a. A few additional details regarding the LD set are provided in Table 2; further details can be found in Chandramohan (2016).

Duration is quantified using 5–75% significant duration (Ds_{5-75}) (Trifunac and Brady, 1975), which was shown by Chandramohan et al. (2016) to be an efficient metric for structural response prediction. The records in the SD set have Ds_{5-75} values shorter than 25 s, while those in the LD set have Ds_{5-75} values longer than 25 s. The distribution of the Ds_{5-75} values of the ground motions in the two sets is shown in Figure 3b. The geometric mean Ds_{5-75} values of the ground motions in the SD and LD sets are 5.4 s and 42 s respectively. Since the two sets are spectrally equivalent, any differences observed in the simulated response of the buildings can be attributed to the difference in their durations. The potential effects of other ground motion characteristics, such as velocity pulses, Arias intensity, cumulative absolute velocity, and so on, are expected to be either insignificant or included through their correlation with duration and spectral shape. Hence, such characteristics are not explicitly considered in this study.

Influence of duration on dynamic deformation capacity

IDA was conducted to estimate the dynamic deformation capacities of the 10 RC frame models using the ground motions from the SD and LD sets. To ensure the accurate computation of collapse intensities and dynamic deformation capacities, a fine $S_a(T_1)$ increment of 0.10 g was used to conduct IDA for the shorter period 2-, 4-, and 8-story frames. This $S_a(T_1)$ increment was further reduced to 0.01 g near the collapse intensity. For the longer period 12- and 20-story frames, an $S_a(T_1)$ increment of 0.02 g was used, which was

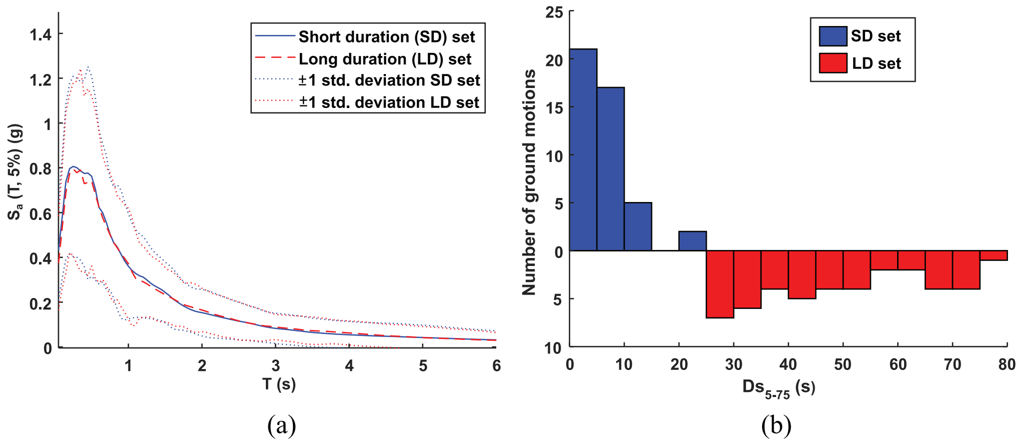

Figure 3. Comparison of the (a) mean and ± 1 standard deviation response spectra of the long and short duration record sets; and (b) distribution of the Ds_{5-75} of their records.

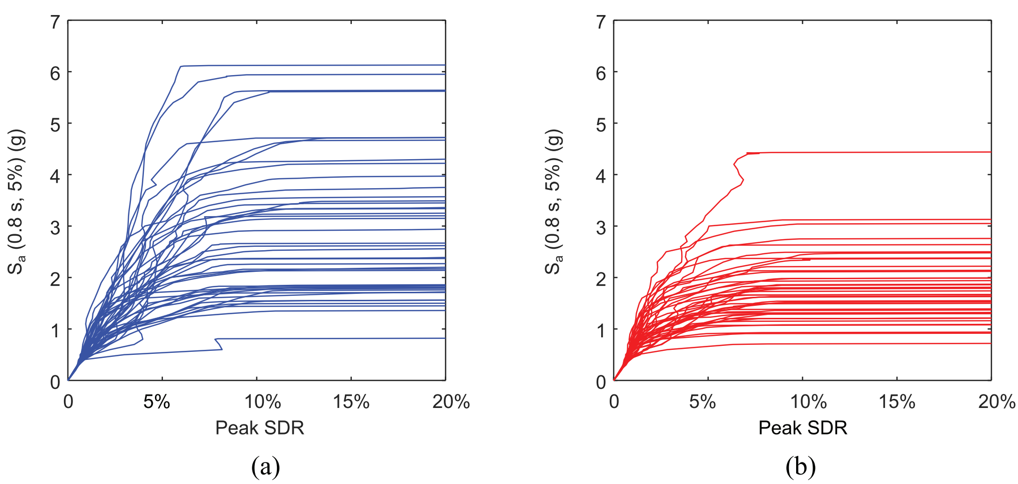

Figure 4. IDA curves from the analysis of the LA04 RC frame (T_1 = 0.8 s) using (a) the short duration set and (b) the long duration set.

reduced to 0.005 g near the collapse intensity. The explicit central difference time integration scheme was used to conduct all analyses to ensure the results are unaffected by numerical non-convergence (Danielson et al., 2008), which has been shown to be responsible for the premature declaration of structural collapse in some instances (Chandramohan, 2016).

The IDA curves for the 4-story Los Angeles frame (LA04) are plotted in Figure 4. The building is observed to collapse at lower intensity levels under the long duration records than the short duration records. On average, the geometric mean collapse capacity of the 10 considered buildings is found to be 31% lower under the LD set as compared to the SD set. These results are generally consistent with the findings of previous studies on the topic (Bravo-Haro and Elghazouli, 2018; Chandramohan et al., 2016; Raghunandan et al., 2015).

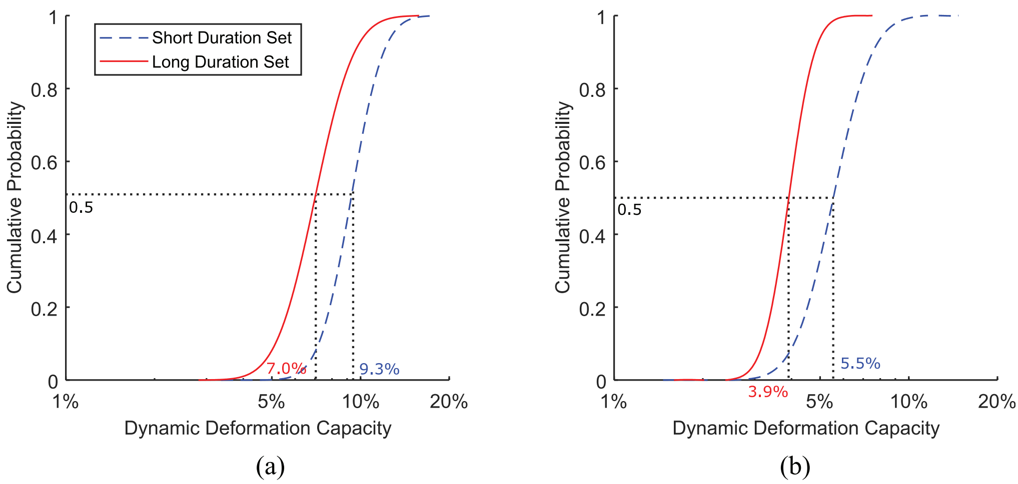

Figure 5. Lognormal cumulative probability distributions of the dynamic deformation capacities of the (a) LA02 and (b) LA20 RC frames.

Following the procedure defined earlier, the dynamic deformation capacities of the structural models are computed using the ground motions from the SD and LD sets. The lognormal probability distribution was found to represent the computed dynamic deformation capacities well, as verified by visually inspecting the quantile–quantile (QQ) plot. The fitted lognormal cumulative probability distribution functions for the LA02 and LA20 RC frames are shown in Figure 5. The median dynamic deformation capacities of the structures corresponding to a cumulative probability of 50% are clearly observed to be lower under the long duration ground motions, compared to the short duration ground motions.

Table 3 summarizes the median deformation capacities for the 10 frames, which are observed to be in the range 5.5%–9.3% for the SD set and 3.9%–7.0% for the LD set. The hysteretic model employed in this study was calibrated against experimental data from 255 RC column tests (Haselton et al., 2008), wherein 35% of the recorded $\theta_{cap,pl}$ (plastic rotation capacity) values were in the range 5%–10%. In addition, the static deformation capacity, defined as the peak SDR recorded at the point of 20% loss in strength during a nonlinear static pushover analysis (FEMA, 2009), was computed for all 10 frames and found to lie in the range 6.1%–8.3%. Hence, the dynamic deformation capacities listed in Table 3 are considered to lie within the range of experimental observations and accepted definitions of structural deformation capacity.

The median dynamic deformation capacity of the 2-story LA02 frame is estimated to be 7.0% and 9.3% using the LD and SD sets respectively. For the 20-story LA20 frame, it is estimated to be 3.9% and 5.5%, respectively. Since the two record sets are spectrally equivalent, the reduction in median dynamic deformation capacity of 25% and 29% under the long duration ground motions, for the 2- and 20-story RC frames respectively, can be characterized as the effect of duration. Similar reductions in median deformation capacity are also observed for the other structures, as indicated in Table 3. The decrease in deformation capacity under long duration ground motions can likely be attributed to the same reasons cited by previous studies for the decrease in structural collapse capacity under long duration ground motions: (1) cyclic deterioration in strength and stiffness; and (2) the ratcheting collapse mechanism (Chandramohan et al., 2017). Preliminary investigation by the

Table 3. Median dynamic deformation capacities of the RC frames subjected to the short (SD) and the long duration (LD) record sets

ID	Median dynamic deformation capacity estimated using the		Percentage decrease in median dynamic deformation capacity	*a* (slope)
	SD set	LD set		
LA02	9.3%	7.0%	25%	–0.14
LA04	8.9%	6.9%	23%	−0.15
LA08	6.9%	5.4%	22%	−0.14
LA12	5.8%	4.2%	28%	−0.22
LA20	5.5%	3.9%	29%	−0.24
ST02	8.7%	6.2%	28%	−0.16
ST04	8.1%	6.1%	24%	−0.15
ST08	6.4%	4.6%	29%	−0.22
PL02	8.7%	6.6%	25%	−0.14
PL08	6.2%	4.4%	29%	−0.23

The percentage decrease in the median dynamic deformation capacity under the LD set is computed with respect to the SD set. *a* refers to the slope of the least squares regression line for the dynamic deformation capacity versus Ds_{5-75} relationship plotted in Figure 6.

authors found that long duration ground motions can also influence the distribution of story drifts over frame height causing collapse in different mechanisms compared to short duration ground motions. It would be of interest to explore this point further as another possible explanation of the observed effect of duration.

On average, the median dynamic deformation capacity under the LD set is observed to be 26% lower than the SD set. The effect of duration on the deformation capacities of the RC frames analyzed in this study is slightly higher than the 12%–20% reduction in peak SDR at collapse observed by Pan et al. (2018) for low-rise timber structures. The two studies are, however, not directly comparable because they employ different record sets and procedures to estimate deformation capacity.

To further investigate the variation in dynamic deformation capacity with duration, deformation capacity is plotted against Ds_{5-75} for all the analyzed buildings in Figure 6. The plots are presented on logarithmic axes since the durations of anticipated ground motions conditional on a rupture are typically lognormally distributed (Abrahamson and Silva, 1996; Bommer et al., 2009; Kempton and Stewart, 2006), and dynamic deformation capacity has also been found to follow a lognormal distribution. A decreasing trend in deformation capacity with Ds_{5-75} is evident from the plots and is in agreement with preliminary findings by Raghunandan and Liel (2013).

A bilinear regression model is fit to the data points on logarithmic scales to reconcile the fact that deformation capacity is not expected to increase indefinitely under extremely short duration ground motions. Specifically, the deformation capacity is expected to be finite under monotonic loading. The bilinear regression model, described by Equation 1, is constant for durations shorter than a critical value and varies linearly for longer durations, indicating that deformation capacity is not influenced by ground motion durations lower than the critical value. This critical duration value is expected to be related to the fundamental modal period of the structure, since the period determines the number and range of deformation cycles experienced, which in turn controls the influence of duration on structural response. In this study, the critical duration value is selected as $5T_1$ as this provides

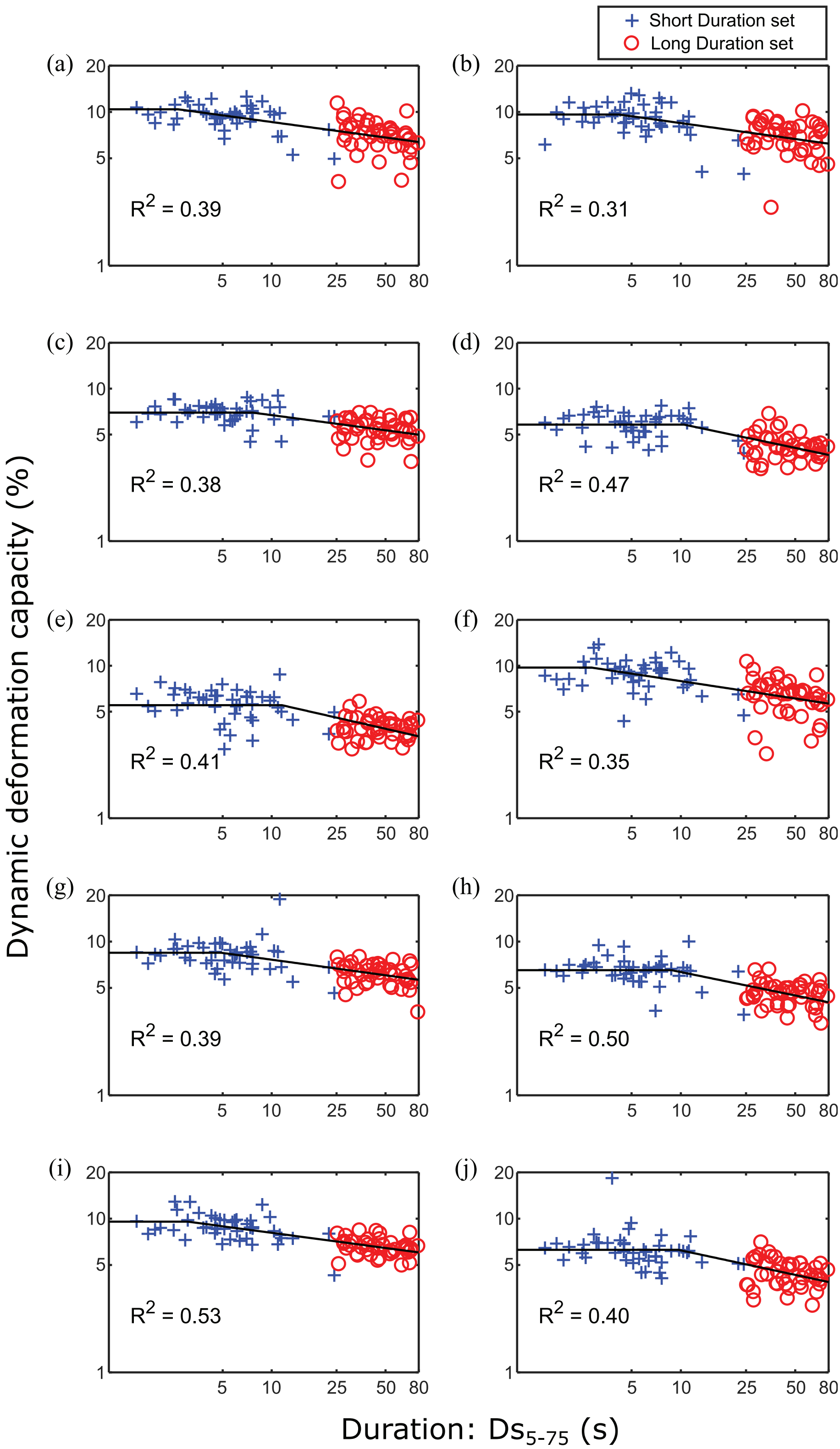

Figure 6. Log-log plot of dynamic deformation capacity vs Ds_{5-75} with the bilinear regression model for (a) LA02, (b) LA04, (c) LA08, (d) LA12, (e) LA20, (f) ST02, (g) ST04, (h) ST08, (i) PL02, and (j) PL08 RC frames.

R^2 refers to the coefficient of determination of the model fit.

the best coefficient of determination (R^2) values, on average, for the regression model. Comparable R^2 are also obtained by choosing period-independent critical duration values of 4s or 5s, suggesting that further research is necessary to characterize this quantity more precisely:

$$\ln \text{ Dynamic Deformation Capacity} = \begin{cases} c_0 + \epsilon; & \text{if } Ds_{5-75} \leq 5T_1 \\ a(\ln Ds_{5-75}) + c_1 + \epsilon; & \text{if } Ds_{5-75} > 5T_1 \end{cases} \quad (1)$$

where c_0, c_1, and a are regression coefficients, and ϵ is the residual error term. The decreasing trend in dynamic deformation capacity with durations longer than the critical value is consistent with the decrease in median dynamic deformation capacity under the LD set, compared to the SD set, indicated in Table 3. The p-value of the coefficient a characterizing the slope of the linear segment is found to be lower than 2.3×10^{-8} for all the structures, indicating that the observed influence of duration on dynamic deformation capacity is statistically significant. The coefficient of determination (R^2) from the regression analysis falls in the range of 0.31–0.53 for all structures, indicating a moderate correlation between the two parameters.

Considering the example of the LA04 frame from Figure 6b, a 10-fold increase in Ds_{5-75} (from 5 to 50 s) reduces the dynamic deformation capacity by 29% (from 9.4% to 6.7%) on average. This implies that structures designed as per contemporary building codes, which have been historically calibrated to short duration ground motions, are likely to exhibit lower deformation capacities than expected under longer duration ground motions. This short duration bias is evidenced in NZS 1170.5 (2004), which defines structural ductility as the level of deformation that can be sustained for at least 4 cycles without excessive degradation, a value representative of response under short duration ground motions.

Figures 7a and b, plot the reduction in median dynamic deformation capacity and collapse capacity respectively, under the LD set, against the fundamental modal period, T_1, of the structures. While Figure 7b shows a decreasing trend in the effect of duration on collapse capacity with increasing structural period, Figure 7a does not indicate any clear trend for reduction in deformation capacity, which is observed to be rather consistent over the range of periods. The observation for collapse capacity is similar to that reported by Raghunandan et al. (2015) and can be explained by the fact that shorter period buildings typically experience a larger number of deformation cycles, and consequently, faster rates of degradation, thereby increasing their sensitivity to duration. It is interesting to note that this effect is not seen with dynamic deformation capacity, for which the longer period 8-, 12-, and 20-story frames have reported the same or slightly higher levels of reductions as compared to the shorter period frames. A possible explanation for this could be the ratcheting effect caused by P-Δ forces, which has been shown previously to enable long duration ground motions to cause structural collapse at lower intensities (Chandramohan et al., 2017). Taller frames are more likely to exhibit a ratcheting form of collapse. While it is possible that this phenomenon affects deformation capacity more than collapse capacity, additional research is needed to verify this hypothesis. The fairly consistent effect of duration observed for all 10 considered frames makes it hard to evaluate the relationship between the observed effect and various seismic design parameters such as site hazard, and design base shear coefficient. While these results suggest that the effect of duration on dynamic deformation capacity is independent of such parameters, there is not enough evidence to support this assumption.

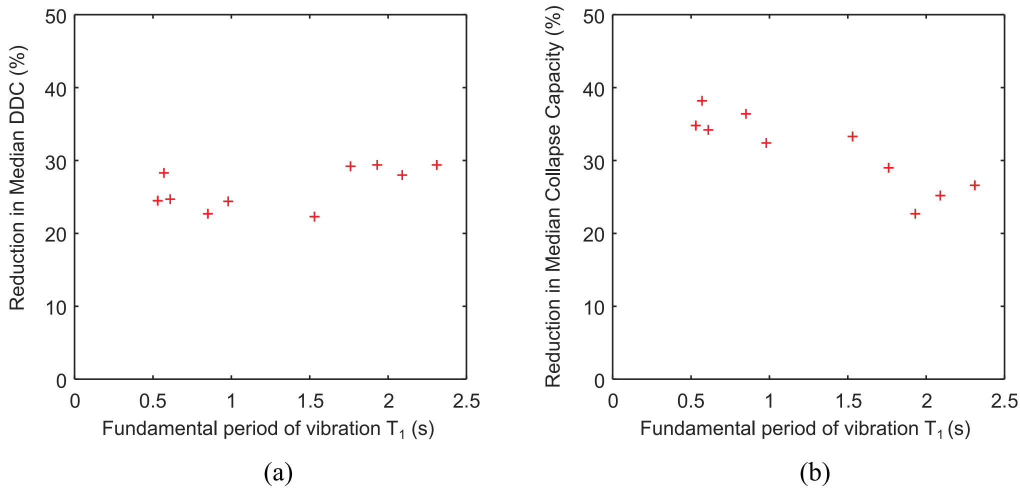

Figure 7. The observed reduction in estimated median (a) dynamic deformation capacity and (b) collapse capacity, computed using the LD set with respect to the SD set, plotted against the fundamental period of vibration of the respective RC frames.

Previous studies investigating the influence of ground motion characteristics on structural response have found response spectral shape to be an important predictor of structural collapse capacity, in addition to duration (Chandramohan, 2016; Haselton et al., 2011). Hence, the effect of response spectral shape on dynamic deformation capacity was investigated, in an attempt to explain the scatter in the data points in Figure 6. Response spectral shape is quantified in this study by $S_aRatio(T_1, 0.2T_1, 3.0T_1)$ (Eads et al., 2016). As described by Equation 2, $S_aRatio(T_1, 0.2T_1, 3.0T_1)$ is computed as the ratio of the spectral acceleration at the fundamental modal period, $S_a(T_1)$, and the geometric mean of the portion of the response spectrum lying between the periods $0.2T_1$ and $3.0T_1$, denoted by $S_{a,avg}(0.2T_1, 3.0T_1)$:

$$S_aRatio(T_1, 0.2T_1, 3.0T_1) = \frac{S_a(T_1)}{S_{a,avg}(0.2T_1, 3.0T_1)} \qquad (2)$$

The variation of dynamic deformation capacity and collapse capacity of the LA08 frame with S_aRatio, is plotted in Figures 8a and b, respectively. In agreement with the findings of previous studies, collapse capacity is observed to increase with S_aRatio. The effect of S_aRatio on dynamic deformation capacity is, however, found to be relatively small. The p-value of the slope of the least-squares regression line is 0.08, which is relatively large, indicating that the relation is statistically insignificant. Similar results were also observed for the other analyzed structures, where little to no correlation was found between dynamic deformation capacity and S_aRatio. This result implies that the conclusions of this study would not have been affected even if the SD and LD sets were not selected to be spectrally equivalent to each other. These results indicate that unlike collapse intensity, the drift at which second-order moments exceed the structure's lateral strength capacity is not dependent on spectral shape. Also, the dynamic deformation capacity is expected to be more strongly influenced by cumulative demand measures such as duration than peak demand measures like spectral shape.

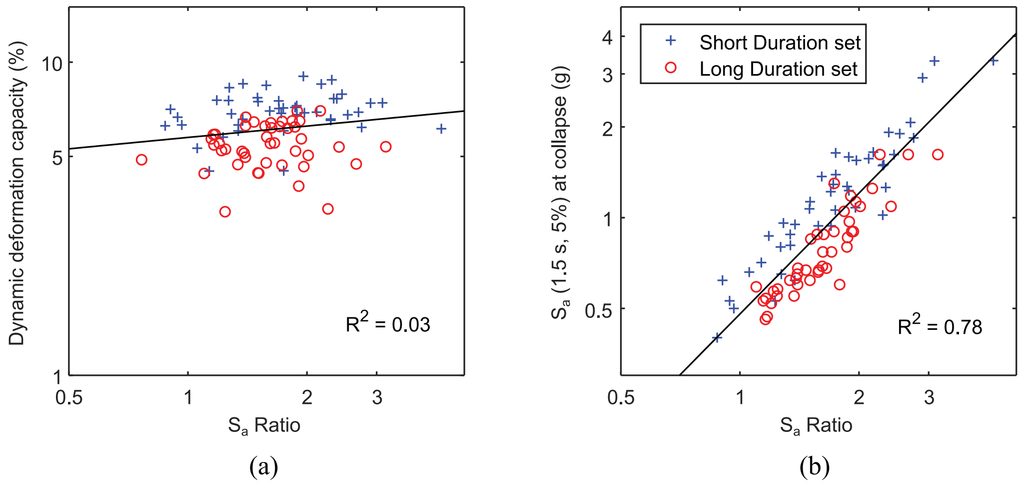

Figure 8. Log-log plot of (a) dynamic deformation capacity vs S_aRatio and (b) collapse intensity vs S_aRatio for the for LA08 RC frame (T_1 = 1.5 s).

An important caveat is that the dynamic deformation capacities presented in this study are intended to inform the design of lateral load resisting systems of buildings only. The numerical simulations employed in this study do not explicitly model gravity systems. Hence, buildings whose deformation capacities are controlled by components in the gravity system, such as gravity columns and precast diaphragms, could possess significantly different dynamic deformation capacities. Other limitations of this study include the fact that the numerical models do not capture component axial-flexure interaction and foundation soil-structure interaction. The conclusions are finally limited by the range of considered moment frame configurations.

Conclusion

The influence of ground motion duration on the *dynamic* deformation capacity of a suite of modern ductile RC frame buildings was assessed using two sets of ground motions: a short duration (SD) set and a spectrally equivalent long duration (LD) set. The dynamic deformation capacity of a building is defined as the largest SDR it can safely withstand without collapsing due to dynamic instability. A robust numerical algorithm was developed to compute the dynamic deformation capacity of a structure using IDA.

The dynamic deformation capacities of the analyzed structures estimated using the LD set were found to be 26% lower than those estimated using the SD set, on average. A consistent decreasing trend in deformation capacity with durations (longer than a critical duration) was also observed from regression models fit to the data. In general, the effect of duration on dynamic deformation capacity, considered to be largely due to the cyclic deterioration and P-Δ effects, was observed to be fairly uniform over a range of structural periods. Unlike collapse capacity, dynamic deformation capacity was not found to be strongly influenced by ground motion response spectral shape, quantified here by S_aRatio.

Previous numerical studies have focussed on characterizing the effect of duration on structural collapse capacity and incorporating this effect in building codes via modifications to the design strength. This study employs nonlinear dynamic analyses to demonstrate and quantify the effect of duration on structural deformation capacity instead. The findings of this study suggest that current structural design and assessment guidelines, which are implicitly tailored to short duration ground motions, might underestimate the seismic collapse risk of RC frame structures at sites susceptible to long duration ground motions. This study provides the motivation and basis for an alternative method to account for the effect of duration by modifying the deformation capacity of a structure as a function of the average duration of ground motion it is likely to experience.

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