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Investigating the influence of ground motion duration on the dynamic deformation capacity of reinforced concrete framed structures

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ABSTRACT

Recent studies have demonstrated the effect of earthquake ground motion duration on structural collapse capacity. They have also proposed methods to explicitly account for this effect of duration in structural design and assessment procedures via an adjustment to the design ground motion intensity. The objective of this study is to explore an alternative method to account for the effect of duration by adjusting the permissible peak deformations instead. This paper describes preliminary investigations into the effect of ground motion duration on the dynamic deformation capacity of ductile reinforced concrete framed structures. The dynamic deformation capacities of the structures under short and long duration ground motions are estimated by conducting incremental dynamic analysis (IDA) on realistic, deteriorating nonlinear structural models. Sets of spectrally equivalent short and long duration ground motions are employed to control for the effect of response spectral shape. Preliminary results indicate a reduction in the dynamic deformation capacity of the analysed structures under the increased cyclic demands imposed by long duration ground motions. These results will be assimilated to propose a modification to the peak deformation acceptance criteria employed by seismic design and assessment procedures to explicitly account for the effect of duration.

1 INTRODUCTION

The influence of ground motion duration on cumulative damage indices has been documented by a number of studies in the last couple of decades (Hancock & Bommer 2006). More recently, studies employing realistic, deteriorating structural models that capture the in-cycle and cyclic degradation of structural

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components and the destabilising *P*-Δ effect of gravity loads have demonstrated the effect of duration on structural collapse capacity (Raghunandan & Liel 2013; Raghunandan et al. 2015; Chandramohan et al. 2016; Bravo-Haro & Elghazouli 2018). These studies have highlighted the importance of explicitly considering ground motion duration, in addition to response spectra, in structural design and assessment practice. The consideration of duration was shown to be especially important at sites susceptible to long duration ground motions from large magnitude earthquakes occurring in subduction zones such as the Hikurangi subduction zone (Chandramohan et al. 2018).

Most methods that have been proposed to explicitly consider the effect of duration in structural design and assessment have translated the observed effect of duration on structural collapse capacity into recommendations to adjust the design ground motion intensity (Chandramohan et al. 2018). This study highlights recent proposals from Bhanu et al. (2019) for an alternative method to capture the effect of duration by adjusting the peak permissible deformations in structures instead. The development of this method is motivated by the observation that the *dynamic deformation capacity* of the analysed reinforced concrete framed structures is smaller under longer duration ground motions. The influence of duration on the dynamic deformation capacity of a two and eight-story reinforced concrete frame is assessed by conducting incremental dynamic analyss (IDA) using spectrally equivalent sets of short and long duration ground motions.

2 INCREMENTAL DYNAMIC ANALYSIS UNDER LONG AND SHORT DURATION GROUND MOTION SETS

This study investigates the dynamic response of a two and eight-story modern, ductile reinforced concrete (RC) moment frame building. The buildings are designed according to the 2012 IBC (ICC 2012) for a site in Los Angeles, USA, and were previously analysed by Raghunandan et al. 2015. Two-dimensional concentrated plastic hinge models of the moment frames were developed in OpenSees (McKenna et al. 2006) (Figure 1). The models were designed to capture the in-cycle and cyclic deterioration of the strength and stiffness of structural components, as well as the destabilising *P*-Δ effect of gravity loads, to adequately capture the effect of ground motion duration. The hysteretic behaviour of the plastic hinges placed at the ends of the beams and columns was modelled using the Ibarra-Medina-Krawinkler peak-oriented model (Ibarra et al. 2005). Shear deformation of the finite joint panels was modelled using elastic shear springs. 5% Rayleigh damping was assigned to the first and third modes of structures. The fundamental periods of the two and eight-story structures are 0.5 s and 1.5 s respectively.

5-75% significant duration ($Ds_{5\text{-}75}$) (Trifunac and Brady 1975) was previously shown to be an efficient duration metric in predicting structural collapse capacity (Chandramohan et al. 2016), and is therefore used in this study to quantify the duration of strong ground motion. Two sets of long and short duration ground motions containing 44 records each were selected for the study. The long duration set consists of ground motions recorded from recent large magnitude events such as the 2008 Wenchuan (M_w 7.9), 2010 Maule (M_w 8.8), and 2011 Tohoku (M_w 9.0), with $Ds_{5\text{-}75}$ greater than 25 s. The short duration consists of records from the FEMA P695 (FEMA 2009) far-field record set, which are from shallow crustal events with $Ds_{5\text{-}75}$ smaller than 25 s. The records in the two sets were selected to have equivalent response spectra, so that any difference in simulated response under the two sets can be attributed to duration effects. The median $Ds_{5\text{-}75}$ values for the short and long duration record sets are 5 s and 42 s, respectively. Detailed information regarding the record sets and the selection procedure can be found in Chandramohan 2016 and Chandramohan et al. 2017.

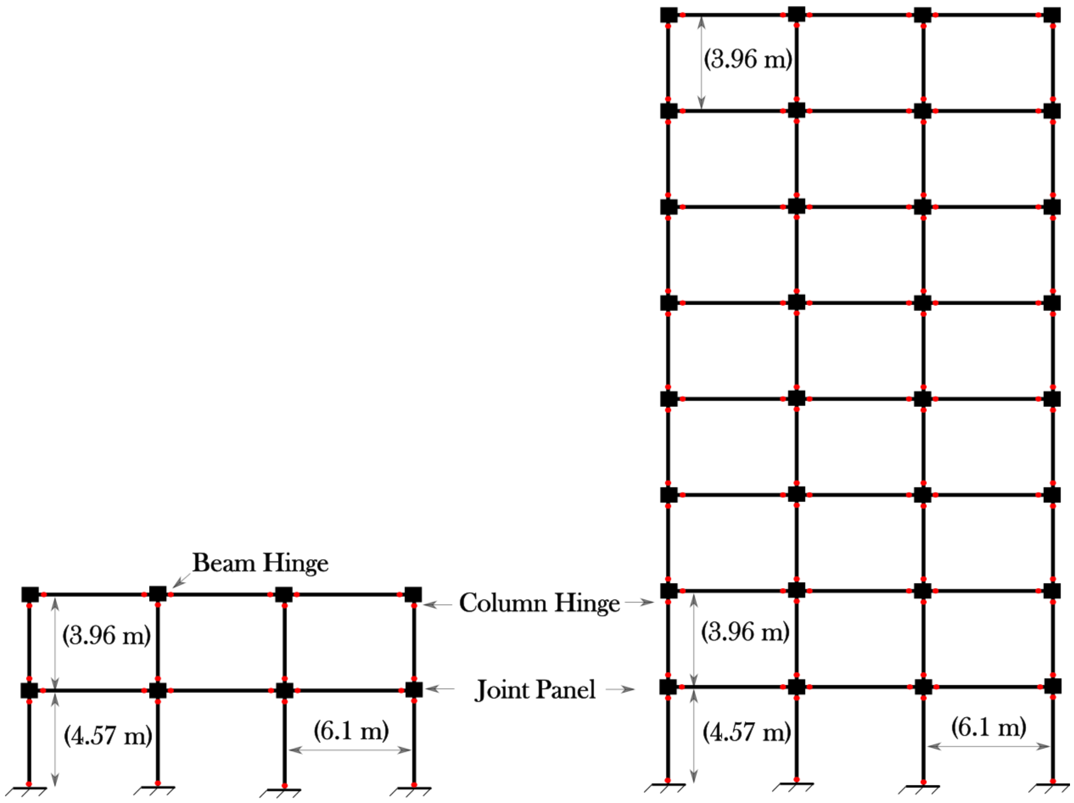

Figure 1: Schematic of the numerical models of the: (left) two-story RC frame and (right) eight-story RC frame buildings.

Incremental dynamic analyses (IDAs) (Vamvatsikos and Cornell 2002) are conducted on both structural models by incrementally scaling each ground motion until it causes structural collapse. Structural collapse is identified by a large story drift ratio (SDR) exceeding a threshold of 0.20. The explicit central difference time integration scheme is to conduct all the analyses since it was found to be more robust and efficient against numerical non-convergence (Chandramohan 2016). The intensity measure (IM) chosen to quantify the ground motion intensity is the 5% damped pseudo-spectral acceleration at the building's elastic fundamental period, $S_a(T_1)$, in line with current design and assessment practice. The collapse intensity of a structure is defined as the lowest $S_a(T_1)$ value to which the ground motion must be scaled to cause structural collapse. An IDA curve is a plot of the variation in the peak story drift ratio (SDR) with the intensity, $S_a(T_1)$, of a ground motion. The IDA curves for the two RC frame models are presented in Figure 2.

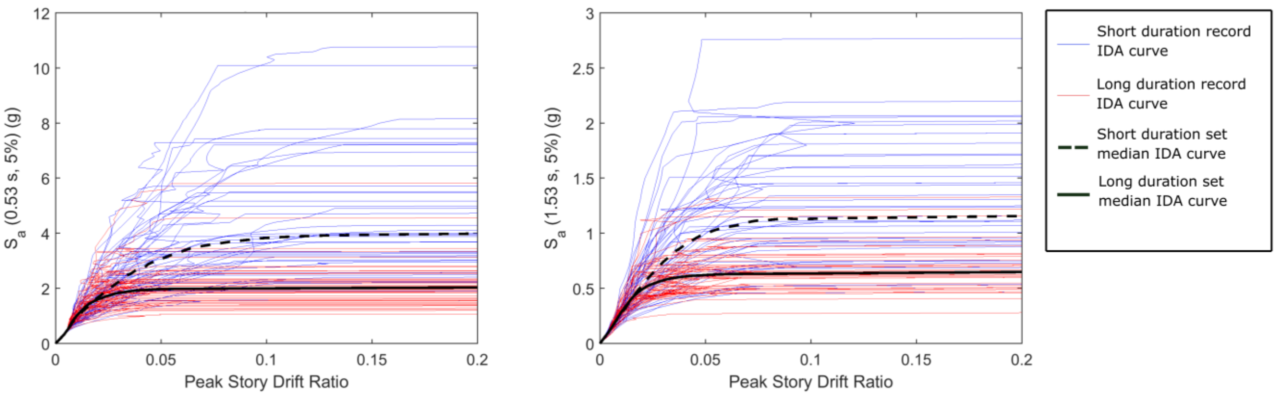

Figure 2: IDA Curves for the (left) two-story RC frame and (right) eight-story RC frame.

It can be observed from Figure 2 that both structures collapse at lower intensities under the long duration records compared to the short duration records. This observation is consistent with the findings of recent studies on this topic (Raghunandan et al. 2015; Chandramohan et al. 2016; Bravo-Haro & Elghazouli 2018). The median collapse capacities, computed as the ground motion intensity corresponding to a 50% collapse probability, are reported in Table 1. The median collapse capacities are observed to be significantly lower under the long duration set compared to the short duration set (by 49% and 44% for the two and eight-story frames respectively). Since the two record sets are spectrally equivalent, this reduction in collapse capacities can be attributed to the effect of duration.

Table 1: Summary of Median Collapse Capacities

Model	Median Collapse Capacity from Short Duration Set (g)	Median Collapse Capacity from Long Duration Set (g)	% Decrease
2 Story RC Frame	3.98	2.03	49%
8 Story RC Frame	1.15	0.64	44%

Plots of collapse intensity versus *Ds*$_{5\text{-}75}$, for all the 88 ground motions are presented in Figure 3. The decreasing trend in collapse intensity with increasing duration is consistent with the findings of Chandramohan et al. 2016. For a five-fold increase in duration (from 5 s to 25 s), the collapse intensities are reduced by approximately 40% (from 4.10 g to 2.40 g) and 35% (from 1.15 g to 0.75 g) on average for the two and eight-story RC frames respectively.

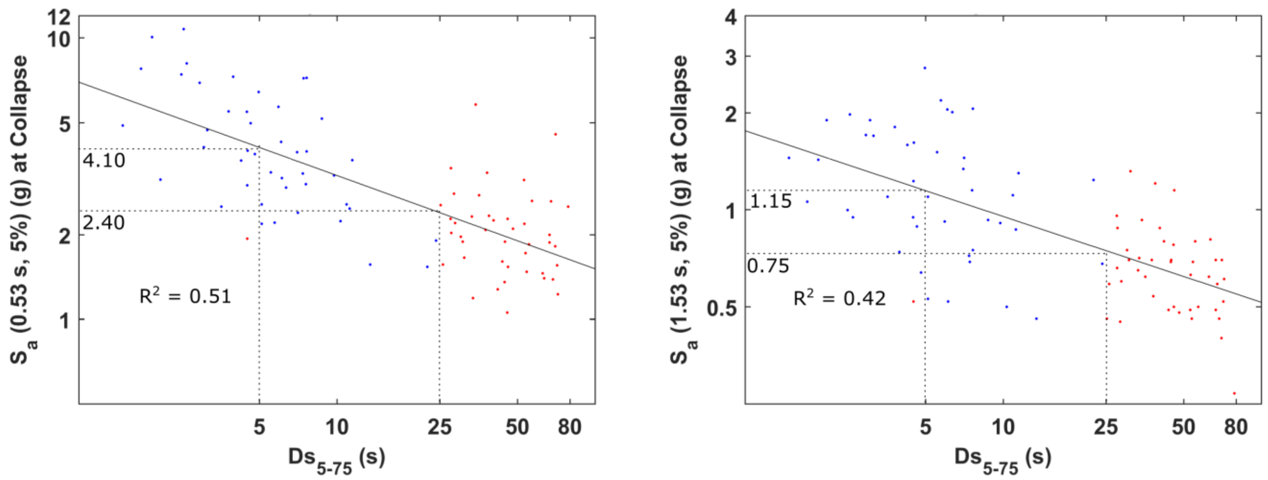

Figure 3: Log-log plot of Collapse Intensity vs. Ds$_{5\text{-}75}$ *with the least squares regression line for the (left) two-story RC frame and (right) eight-story RC frame.*

3 EFFECT OF DURATION ON DYNAMIC DEFORMATION CAPACITY

The IDA procedure employed assumes structural collapse to have occurred when the peak SDR exceeds a threshold of 0.20. Through the IDA process, Bhanu et al. (2019) propose that the dynamic deformation capacity of a structure can be evaluated as the peak deformation demand (peak SDR) associated with the largest ground motion intensity that the structure can withstand successfully without collapse.

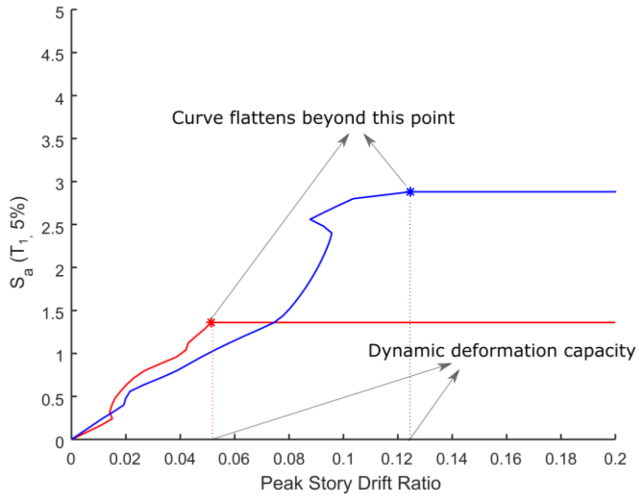

Figure 4: Identifying dynamic deformation capacity through IDA Curves.

From the IDA curves, this dynamic deformation capacity can be identified as the peak SDR just before collapse, corresponding to the point where the curve starts to flatten out horizontally, as shown in Figure 4. This concept was previously employed in Haselton et al. 2010 and Liel et al. 2010 to relate story and roof drifts at the onset of collapse with overall system ductility.

In Figure 5, all such points, where the IDA curves initiate to flatten out horizontally, are plotted to identify the dynamic deformation capacities of the considered structures under each individual ground motion, along with the median values from each set. It can be observed that the dynamic deformation capacities are relatively lower under the long duration records as compared to the short duration records. The median dynamic deformation capacities from the long duration set are 0.031 and 0.040 for the two and eight-story RC frames respectively, as compared to 0.073 and 0.066 from the short duration set. Since the two sets are spectrally equivalent, this reduction of 57% and 40% in dynamic deformation capacities of the two and eight-story RC frames respectively, can be attributed to the effect of duration. The use of the explicit time integration scheme ensures that these results are unaffected by numerical non-convergence, which may have otherwise caused the premature declaration of structural collapse in some instance and consequently, an underestimation of the collapse intensities and dynamic deformation capacities (Chandramohan 2016).

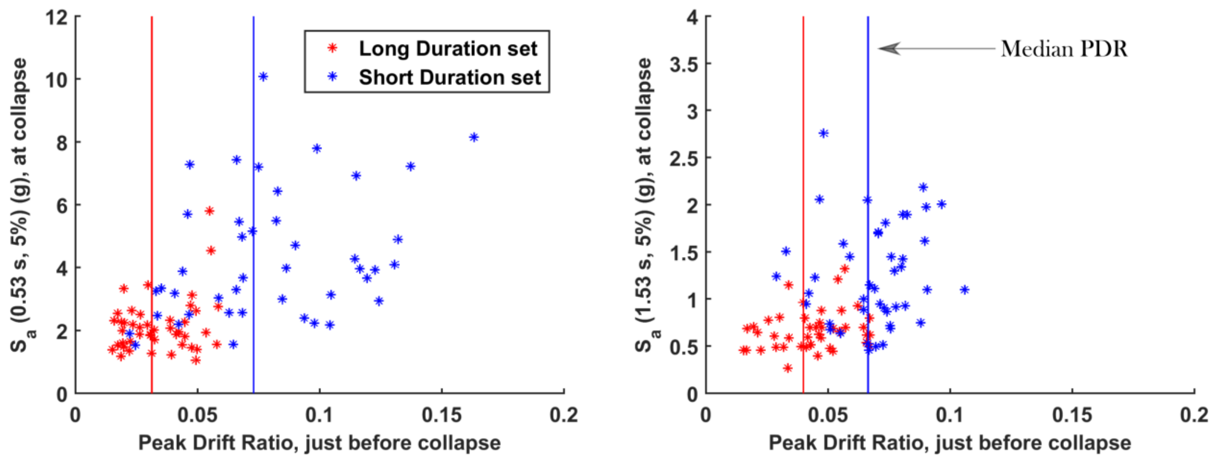

Figure 5: Plots of Collapse Intensity vs. Peak SDR, just before collapse (dynamic deformation capacity) for the (left) two-story RC frame and (right) eight-story RC frame along with the median deformation capacity for each set.

To analyse the relation between ground motion duration and the dynamic deformation capacity of the considered structures more closely, plots of peak SDR just before collapse (dynamic deformation capacity) versus $Ds_{5\text{-}75}$, for all the 88 ground motions are presented in Figure 6. The least squares regression lines highlight the decreasing trend in dynamic deformation capacity with increasing ground motion duration. According to the regression line, a five-fold increase in duration (from 5 s to 25 s) reduces the dynamic deformation capacity of the structure by 46% (from 0.074 to 0.040) and 28% (from 0.065 to 0.047) on average for the two and eight-story RC frames respectively.

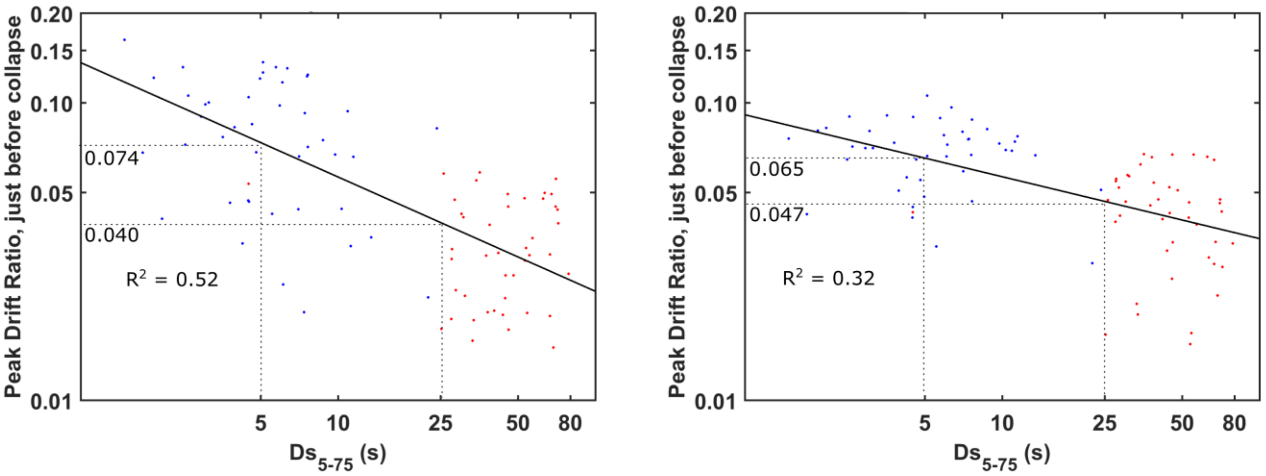

Figure 6: Log-log plot of Peak SDR, just before collapse (dynamic deformation capacity) vs. $Ds_{5\text{-}75}$ *with the least squares regression line for the (left) two-story RC frame and (right) eight-story RC frame.*

Evident from the slopes of the least squares regression lines, the effect of duration on the dynamic deformation capacity of the two-story frame is higher than that for the relatively taller eight-story frame. Moreover, the observed influence of duration on dynamic deformation capacity is confirmed to be statistically significant for both structures. The p-values (of the slopes of the regression lines) are 1.5×10^{-15} and 5.1×10^{-9}, and the associated coefficients of determination (R^2) are 0.52 and 0.32 respectively, for the two and eight-story RC frames respectively.

Most of the previous studies investigating the relation between ground motion duration and peak structural deformations either did not look at the deformation capacity close to collapse or employed non-degrading structural models that do not capture the effect of duration accurately. The results of this study, however, clearly demonstrate the influence of ground motion duration on the dynamic deformation capacity of structures. The observations made here (and in Bhanu et al. 2019) should motivate the need to explicitly account for the effect of duration in seismic design and assessment guidelines by modifying the permissible peak deformations in structures.

4 CONCLUSIONS

This paper presented the results of a numerical study to investigate the effects of earthquake ground motion duration on structural response, in terms of the dynamic deformation capacities of two and eight-story ductile reinforced concrete moment frames. The conclusions of the study are summarised in the points below:

- In accordance with the findings of previous studies, the collapse capacities of the analysed structures were found to be 49% and 44% lower for the two and eight-story frames, respectively under a long duration record set, compared to a spectrally equivalent short duration record set.
- A relatively novel approach, detailed further in Bhanu et al. (2019), has been employed to study the effect of duration on structural dynamic deformation capacity by recording the peak SDR values, just before collapse. These values, interpreted as structural dynamic deformation capacities, are observed to reduce with increasing ground motion duration. The median dynamic deformation capacities under the long duration record set are found to be 57% and 40% lower as compared to the short duration set, for the two and eight-story RC frames respectively.
- The results of this study indicate that the dynamic deformation capacities reduce with increasing duration (defined using $Ds_{5\text{-}75}$). A five-fold increase in duration is seen to reduce the dynamic deformation capacity of the two and eight-story RC frames by 46% and 28% on average respectively.

- The effect of ground motion duration on structural dynamic deformation capacity is observed to be higher for the two-story RC frame as compared to the more flexible and taller eight-story RC frame.

The findings of this study suggest that current structural design and assessment guidelines, which do not explicitly consider the effect of duration and assume a constant structural dynamic deformation capacity, might underestimate the collapse risk of reinforced concrete framed structures at sites susceptible to long duration ground motions from large magnitude subduction earthquakes. These results motivate the need to develop a method to explicitly account for the effect of duration in seismic design and assessment guidelines by adjusting the peak permissible deformations in structures. Further efforts are currently underway to extend this study to a wider range of reinforced concrete structures, and to investigate the physical phenomena causing the observed effects of duration.

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