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INFLUENCE OF GROUND MOTION DURATION ON THE DYNAMIC DEFORMATION CAPACITY OF STEEL FRAME BUILDINGS

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Abstract

This study investigates the influence of ground motion duration on the dynamic deformation capacity of modern ductile steel moment resisting frame buildings. A number of recent studies have demonstrated the lower collapse capacities of structures under long duration ground motions. This effect of duration is not explicitly considered in the seismic design process. Although numerical studies to date have generally found no significant influence of ground motion duration on peak structural *deformation demands*, except for intensities close to collapse, experimental tests have consistently reported lower *deformation capacities* of structural components under loading protocols containing a larger number of cycles. In agreement with these experimental tests, recent numerical studies on reinforced concrete and timber structures have also reported collapse at lower peak story drift ratios under long duration ground motions, compared to short duration motions. This study employs a robust numerical algorithm to determine the dynamic deformation capacities of two modern ductile steel frame buildings – a four and a twelve-storey frame, by post-processing the results of incremental dynamic analysis. Concentrated plastic hinge models of the steel frame buildings are developed in OpenSees using the modified Ibarra-Krawinkler deterioration model with bilinear response to represent the hysteretic behaviour of the plastic hinges. A suite of 88 short and long duration ground motions are employed to investigate the influence of ground motion duration on dynamic deformation capacity. The 5-75% significant durations ($Ds_{5\text{-}75}$) of the selected ground motions range from 1 s to 80 s. Results indicate a 42% and 30% reduction in the dynamic deformation capacity of the four and twelve-storey frames respectively, under the long duration record set. This suggests that current structural design and assessment guidelines might underestimate the seismic collapse and damage risk of steel structures at sites susceptible to long duration ground motions. The findings of this study will, therefore, lay the foundation for a procedure to incorporate the effect of duration in contemporary seismic design codes by adjusting structural deformation capacities based on the durations of the anticipated ground motions.

Keywords: ground motion duration, dynamic deformation capacity, incremental dynamic analysis, steel moment frames

1. Introduction

A number of recent studies have clearly demonstrated the adverse effects of earthquake ground motion duration on structural response for a wide range of structures [e.g., 1–5], including steel moment resisting frames (MRFs) [e.g., 6–8]. While modern seismic design codes do not explicitly consider duration in the design and assessment process, these studies have found that code-conforming structures have lower than expected performance when subjected to long duration ground motions. Duration is found to be strongly correlated to cumulative damage [1] and this correlation translates into structural collapse at lower intensities with increasing ground motion duration [3, 8, 9]. Though a couple of studies have proposed methods to account for duration in design by adjusting the design strength of structures [e.g., 10, 11], alternative methods to do so need to be explored to incorporate this effect in contemporary seismic design codes that do not specify an explicit collapse performance objective.

In addition to collapse capacity, another parameter of relevance to design is structural deformation demands for non-collapse conditions. Results from numerical studies indicate that the peak deformation demands are largely unaffected by ground motion duration for intensities lower than design values [e.g., 2, 5]. At higher intensity levels though, long duration motions are observed to cause dynamic instability [6, 7] due to the in-cycle and cyclic degradation of strength and stiffness of structural components [12] and the destabilising P-Δ effect of gravity loads [13]. As the structures are observed to perform in a relatively stable manner under short duration ground motions even at these higher intensity levels and deformation demands, this phenomenon can be interpreted as a total loss in the structural deformation capacity due to the large number of cycles associated with long duration motions. While many past experimental studies have demonstrated the effect of duration or the number of loading cycles on the ultimate deformation capacities of reinforced concrete (RC) and steel components [e.g., 1, 14–17], this effect has been noticed at a whole system level through numerical dynamic analyses by the authors and others only recently [4, 18, 19].

The objective of this study is to quantify the effect of ground motion duration on the dynamic deformation capacity of modern ductile steel MRFs. To this end, a robust numerical algorithm, previously developed by the authors in [19], is employed to determine the dynamic deformation capacities of two steel MRFs by post-processing the results of incremental dynamic analysis (IDA) conducted using a short and a spectrally equivalent long duration ground motion set. The results of this study are expected to lay the foundation for a novel method to account for the effect of duration in contemporary seismic design codes by adjusting the deformation capacities of structures. Furthermore, dynamic deformation capacity can be used as a parameter to quantify structural capacity against cumulative damage induced due to earthquake ground motion for applications in post-event damage and repairability assessment procedures.

2. Steel moment resisting frame models

The structures analysed in this study are a four-storey and twelve-storey steel MRF systems, designed by [20] as office buildings for a site in Wellington and in accordance with New Zealand standards NZS 1170.0 [21] and NZS 1170.5 [22]. Beam-column connections were designed as reduced beam section (RBS) hinges to incorporate capacity design requirements compatible with New Zealand detailing [23] and to ensure ductile behaviour. Steel member sizes and connections were defined following the Steel Structures Standard [24]. The two buildings have first storeys of 4.5 m height and upper storeys are 3.6 m tall.

For numerical analysis purpose, two-dimensional concentrated plastic hinge models of the buildings were developed in OpenSees [25] by [26], as illustrated in Fig. 1. The four-storey and twelve-storey buildings were modelled with three and four bays respectively, each of 8 m width. Linear elastic elements were used to model the beams and columns and masses were lumped at the beam-column joints. Zero-length plastic hinges were modelled at the ends of columns and at the RBS hinges on beams. To incorporate the in-cycle and cyclic deterioration of strength and stiffness, the hysteretic behaviour of the plastic hinges was modelled using the modified Ibarra-Krawinkler deterioration model with bilinear response [27]. A pin-connected leaning column that simulates the behaviour of a number of gravity columns was modelled to capture the destabilising effect of gravity loads on the gravity frame. The joint panel zone shear flexibility was modelled using a quadrilinear spring to account for the full range of panel zone behaviour from the elastic range to strain hardening range [28]. Rayleigh damping used with 2% critical damping was assigned to the periods corresponding to the first and third modes of the structures and to the linear elastic elements only [29]. The fundamental model periods (T_1) of the four and twelve-storey structures are 1.15 s and 2.10 s respectively.

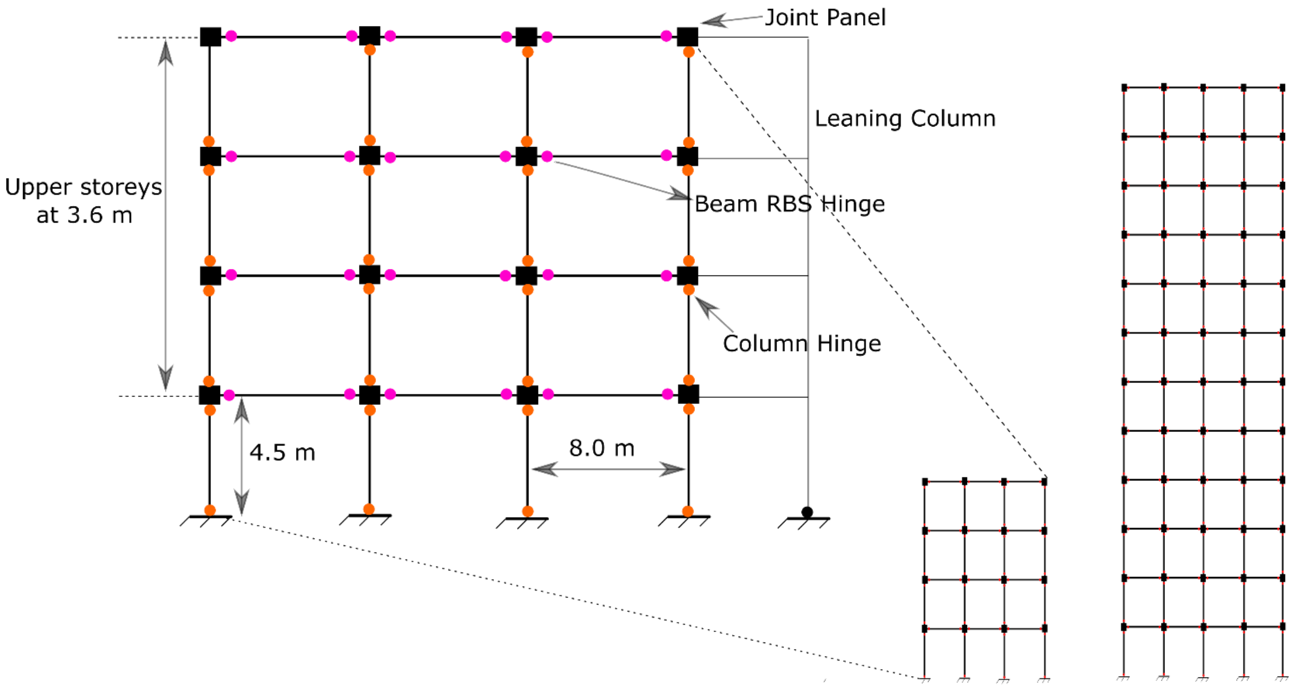

Fig. 1 - Schematic of the numerical models of the four-storey and twelve-storey steel frame buildings analysed.

3. Incremental dynamic analysis for dynamic deformation capacity estimation

As previously proposed by the authors in [18, 19], the *dynamic* deformation capacity of a structure is defined as the largest story drift ratio (SDR) it can safely withstand without collapsing due to dynamic instability. Incremental dynamic analysis (IDA) [30] was employed to estimate the dynamic deformation capacities of the case-study structures as the largest SDR simulated at ground motion intensity levels lower than or equal to the collapse intensity.

To study the effect of duration, two spectrally equivalent sets of short (SD set) and long duration (LD set) ground motions were employed in this study. Duration was quantified using 5-75% significant duration ($Ds_{5\text{-}75}$) [31] as it has been shown to be an efficient duration metric in predicting structural response [3]. The SD set has 44 short duration ground motions from the FEMA P695 far field set [32], with $Ds_{5\text{-}75}$ shorter than 25 s and a geometric mean of 5 s. The LD 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 and a geometric mean of 42 s.

IDAs were conducted on the two structural models by incrementally scaling each ground motion from the two ground motions sets, until structural collapse was identified by a large SDR exceeding a threshold of 20%. The 5% damped pseudo-spectral acceleration at the building's elastic fundamental period, $S_a(T_1)$, was used to quantify ground motion intensity. Fine $S_a(T_1)$ increments of 0.04 g were used to conduct IDA and these increments were further reduced near the collapse intensity following the hunt and bracket approach [30] to ensure the accurate computation of collapse intensities and consequently the dynamic deformation capacities.

To avoid any numerical non-convergence, the explicit central difference time integration scheme was used to conduct all the analyses [11].

The IDA curves for the four and twelve-storey frames are plotted in Fig. 2(a) and Fig. 2(b) respectively. It can be observed from Fig. 2 that the analysed frames collapse at lower intensities under long duration records compared to short duration records. There is a reduction of 37% in the estimated median collapse capacity of the two frames, when subjected to the LD set as compared to the SD set. These results are consistent with the findings of previous studies on steel MRFs [e.g., 6, 8].

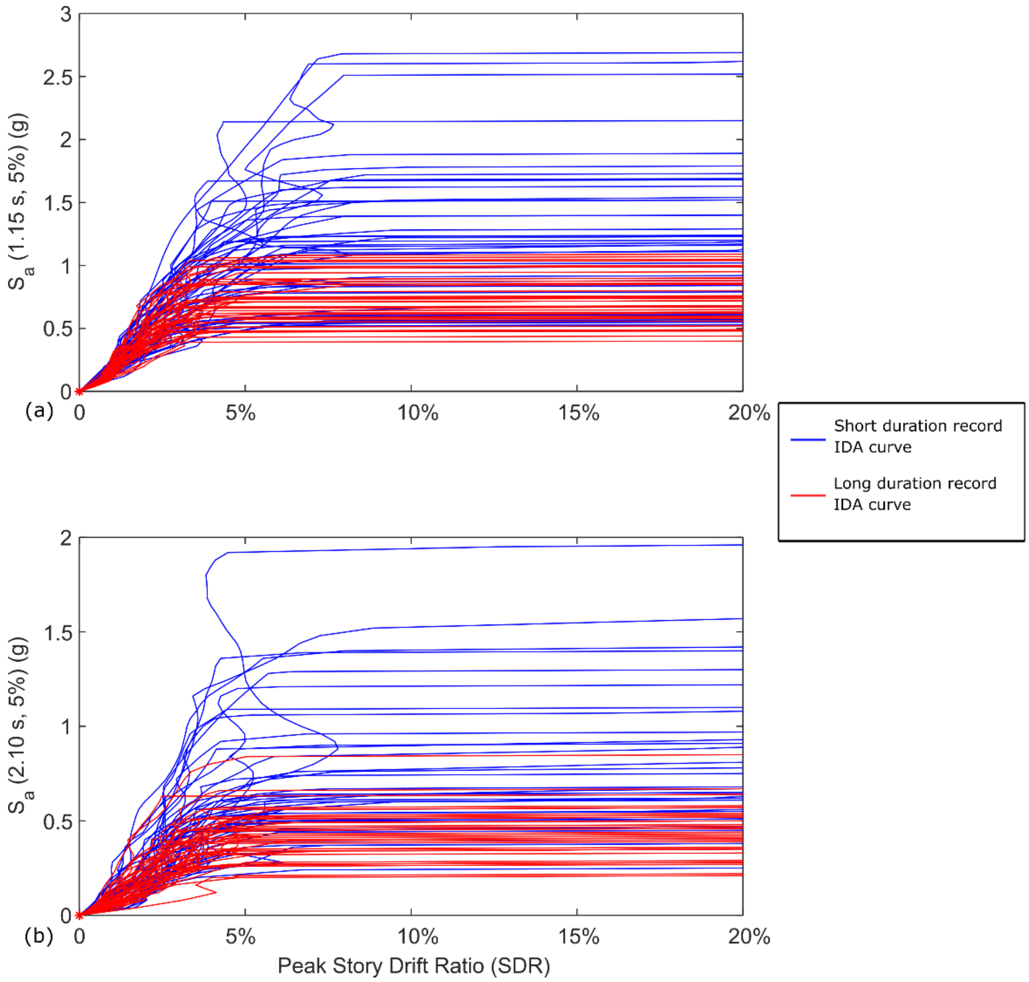

Fig. 2 – IDA curves for the (a) four-storey frame (T_1 = 1.15 s), and (b) twelve-storey frame (T_1 = 2.10 s), indicating the points used to record the dynamic deformation capacities.

The dynamic deformation capacities of the two frames were computed from the IDA curves using the methodology illustrated in Fig. 3. Firstly, the IDA curve was traced backwards from the collapse threshold to identify the collapse intensity as the intensity corresponding to the starting point of the first line segment whose slope is greater than 5% of the initial elastic slope, k_e, of the IDA curve. The dynamic deformation capacity was then recorded as the largest peak SDR value observed at ground motion intensities equal to or lower than the collapse intensity. This method of computing deformation capacities is robust against the hardening of IDA curves, which refers to the phenomenon of a structure exhibiting lower peak deformations at higher ground motion intensities [33], as shown in Fig. 3(b).

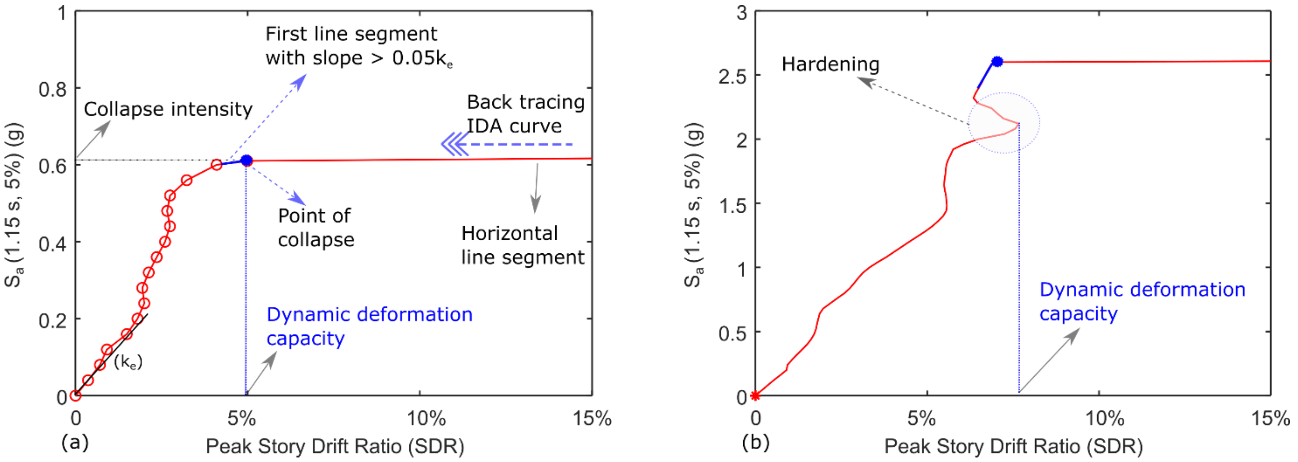

Fig. 3 – Procedure to compute dynamic deformation capacity of a structure from an IDA curve.

4. Effect of duration on dynamic deformation capacity

The computed dynamic deformation capacities of the structural models are fitted to lognormal cumulative probability distribution functions, presented in Fig. 4. As observed from the IDA curves in Fig. 2 and reiterated by the plots in Fig. 4, both steel frames can withstand larger deformations before collapse under the SD set of ground motions. These results indicate that the analysed frames have lower dynamic deformation capacities when subjected to long duration ground motions as compared to short duration motions. The median dynamic deformation capacities of the structures are summarised in Table 1 and illustrated in Fig. 4. These median deformation capacities are observed to reduce by 42% and 30% under the LD set compared to the SD set, for the four and twelve-storey frames respectively. The observed reduction in the dynamic deformation capacities under the LD set in this study can be attributed to the effect of duration, since the two record sets are spectrally equivalent and it is assumed that other intensity measures do not significantly influence the paired experiment.

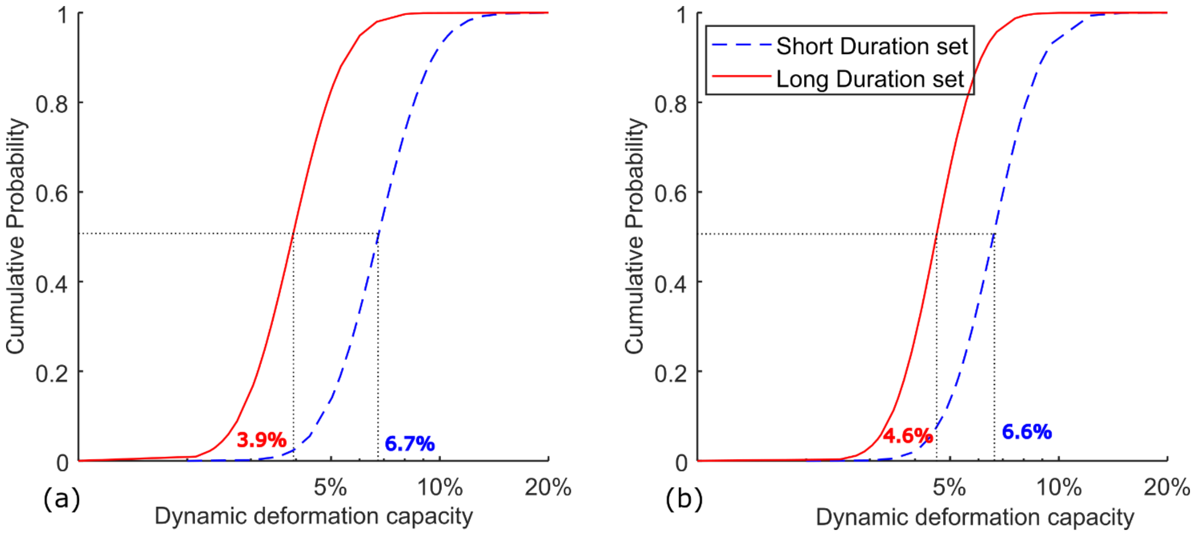

Fig. 4 – Lognormal probability distributions of the dynamic deformation capacities of the (a) four-storey, and (b) twelve-storey frames.

Table 1 – Summary of Median Dynamic Deformation Capacities

Model	**Median Dynamic Deformation Capacity from the SD Set**	**Median Dynamic Deformation Capacity from the LD Set**	**% Decrease**
4 Storey	6.7%	3.9%	42%
12 Storey	6.6%	4.6%	30%

Shown in Fig. 5 are the log-log plots of the dynamic deformation capacity against duration, $Ds_{5\text{-}75}$, for each ground motion. The plots are presented on logarithmic axes since the durations of anticipated ground motions conditional on a rupture are typically lognormally distributed [34], and dynamic deformation capacity has also been found to follow a lognormal distribution in this study (as shown in Fig. 4). The ground motions used in this study were, however, not selected to follow a distribution conditional on a rupture. A decreasing trend in deformation capacity with $Ds_{5\text{-}75}$ is evident from Fig. 5. To further investigate this trend, a bilinear regression model, described by Eq. (1), is fit to the data points in Fig. 5.

$$\ln \text{Dynamic Deformation Capacity} = \begin{cases} \mathrm{c}_o + \varepsilon & \text{if } Ds_{5-75} \leq 2T_1 \\ a(\ln Ds_{5-75}) + \mathrm{c}_1 + \varepsilon & \text{if } Ds_{5-75} > 2T_1 \end{cases} \tag{1}$$

where c_o, c_1, and a are regression coefficients, and ε is the residual error term. The coefficient c_o can be related to the deformation capacity of the structure under monotonic loading. The coefficient a, characterising the slope of the linear segment, indicates the extent of influence of duration on the dynamic deformation capacity of the analysed structure.

As dynamic deformation capacity physically cannot increase indefinitely under extremely short duration ground motions and should ideally be capped at structure's static deformation capacity, the regression model, described by Eq. (1), is constant for durations shorter than a critical value and varies linearly for longer durations. This critical duration value is expected to be related to the fundamental modal period of the structure T_1, since the period determines the number of loading cycles experienced, which in turn controls the effect of duration. The critical duration value chosen in this study is $2T_1$, although it remains to be confirmed by future studies.

As observed from Fig. 5, the deformation capacity of the four-storey frame (a = -0.26) is affected more by ground motion duration than the twelve-storey frame (a = -0.17). This can be due to the smaller fundamental period of vibration of the four-storey frame as similar results have been observed previously in the literature for RC frames [e.g., 9, 19] demonstrating a decrease in the effect of duration with increasing structural period. The coefficients of determination (R^2) from the regression analysis are 0.53 and 0.27 for the four and twelve-storey frames respectively. The p-value of the coefficient a is lower than 1×10^{-6} for both frames, indicating that the observed relationship between $Ds_{5\text{-}75}$ and dynamic deformation capacity is statistically significant.

The observations made here are in agreement with the findings of (i) previous experimental studies that reported reduced ductility capacities of structural components under long duration ground motions [17] and loading protocols [14, 16], and (ii) a recent numerical study by the authors that demonstrated similar relationship between ground motion duration and dynamic deformation capacity for RC frames [19]. These results imply that structures designed in accordance with modern seismic design codes are likely to display inferior performance under long duration ground motions as compared to similar intensity short duration ground motions. Therefore, it is deemed important to consider the "duration" factor, along with intensity and frequency, when designing structures for sites susceptible to long duration ground motions. This can be achieved by modifying the target deformation capacities of structures according to the anticipated ground motion duration at the site.

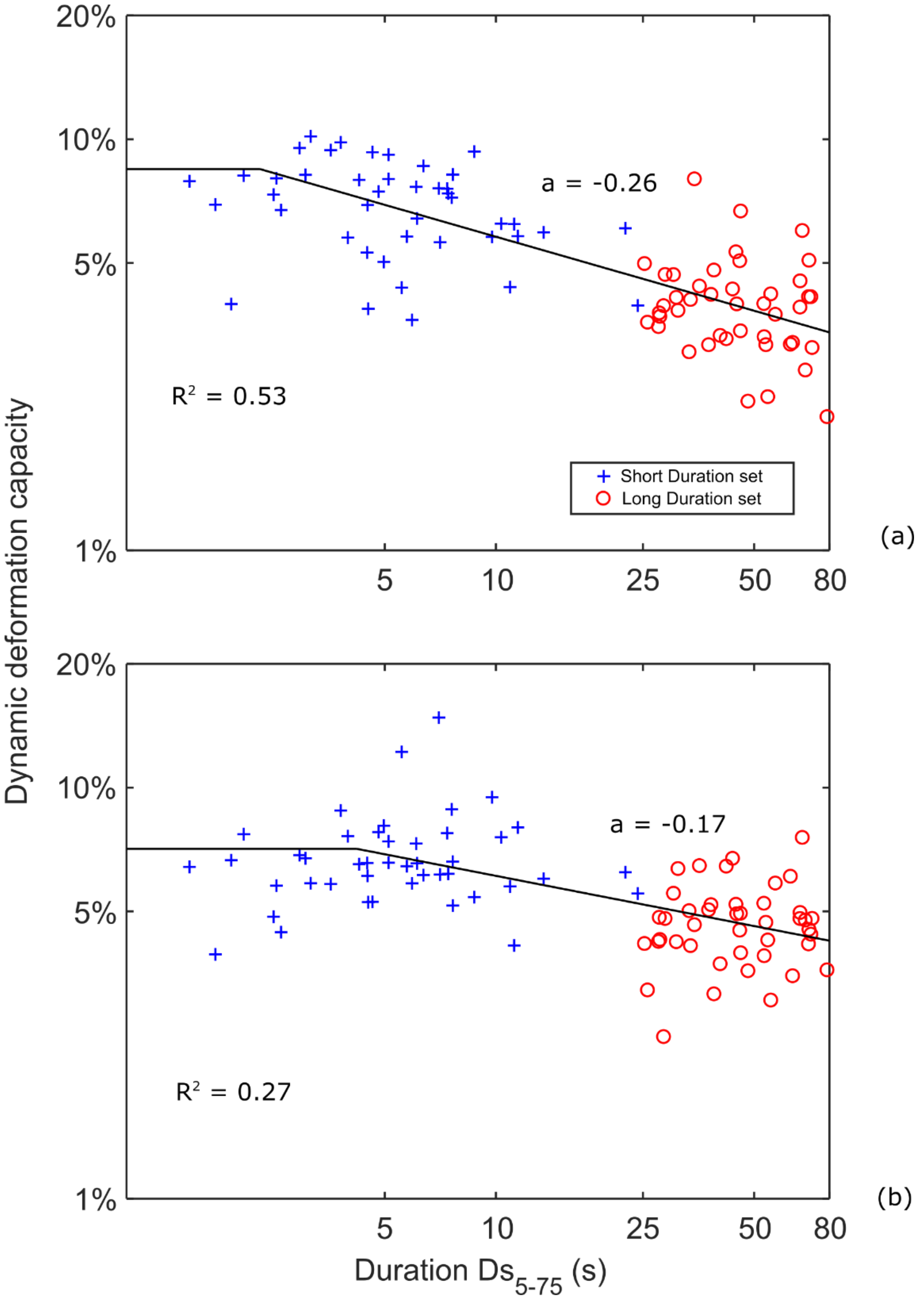

Fig. 5 - Log-log plot of dynamic deformation capacity vs. $Ds_{5\text{-}75}$ with the bilinear regression model for the (a) four-storey, and (b) twelve-storey frames. " R^2 " refers to the coefficient of determination of the model fit and " a " refers to the slope of the linear segment.

5. Conclusions and Discussions

This study is an extension of previous work by the authors on RC frames. A robust numerical procedure to estimate dynamic deformation capacity was utilised to investigate its correlation with ground motion duration for two modern ductile steel moment resisting frame buildings. The dynamic deformation capacities of the four and twelve-storey steel frames subjected to a long duration record set were found to be 42% and 30% lower respectively, as compared to a short duration set. For ground motion durations longer than a critical duration value, a consistent decreasing trend in deformation capacity with duration was observed from regression models fit to the data. The observed effect of duration was larger for the four-storey frame as compared to the longer period twelve-storey frame, which can be attributed to the larger number of deformation cycles experienced by the shorter period structure leading to a faster rate of deterioration. 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 and damage risk of reinforced concrete framed structures at sites susceptible to long duration ground motions, especially from large magnitude subduction earthquakes. These results provide the basis to develop an alternate method to explicitly account for the effect of duration in seismic design and assessment guidelines by adjusting the peak permissible deformations in structures.

Furthermore, dynamic deformation capacity can be interpreted as a parameter that quantifies structural capacity against cumulative damage induced due to a particular earthquake ground motion. As observed from the results in this study, this capacity for a structure reduces with increasing ground motion duration. Therefore, even if collapse is not reached, the post-event residual capacity of a structure is expected to be smaller after being subjected to a long duration motion as compared to a similar intensity short duration one. This concept can be further explored to account for duration in post-event repairability and residual capacity assessment procedures.

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