Incorporating the influence of duration on dynamic deformation capacity in seismic assessment

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ABSTRACT

The dynamic deformation capacity of a structure is the peak storey drift ratio it can safely withstand without collapsing due to dynamic instability. In a previous study, the authors developed a robust procedure to compute this quantity by conducting incremental dynamic analysis and demonstrated that structures, on average, possess lower dynamic deformation capacities under longer duration ground motions. This paper proposes a method to explicitly consider this effect of ground motion duration in seismic assessment of existing buildings. Preliminary results indicate that the dynamic deformation capacity of a structure at short durations compares well with its static deformation capacity computed via nonlinear static pushover analysis. These results are used to develop a relationship to adjust the static deformation capacity of a reinforced concrete structure based on the mean duration of anticipated ground motions.

1 INTRODUCTION

Seismic design codes and assessment guidelines around the world do not explicitly consider the effect of ground motion duration. For example, NZS 1170.5 Supplement (Standards NZ 2004) mentions the use of a "magnitude-weighting" approach to account for the increase in damage-potential from longer duration shakings associated with large magnitude events. Tarbali and Bradley (2016), however, demonstrated that implicit consideration of duration and cumulative effects via causal parameters such as magnitude is not a reliable approach. A number of studies in the past decade have demonstrated and quantified the effect of duration on structural collapse capacity for a wide range of structures (e.g. Raghunandan et al. 2015; Chandramohan et al. 2016; Bravo-Haro & Elghazouli 2018; Pan et al. 2018; Fairhurst et al. 2019). A few studies have proposed methods to incorporate this effect by increasing the design ground motion intensity levels at sites expected to experience longer duration ground motions, in proportion to the effect that duration is expected to have on structural collapse capacity (e.g. Liel et al. 2015; Chandramohan 2016). These methods are based on the premise that buildings designed using a seismic design code are expected to achieve a specific collapse performance. Since specifying an explicit collapse performance objective is not a uniform practice in seismic design codes employed around the world, e.g. NZS 1170.5 (Standards NZ 2004), alternate methods to incorporate duration in design and assessment guidelines need to be explored.

Recent studies by the authors have quantified the effect of ground motion duration on the dynamic deformation capacity of structures, a quantity related to the deformations at incipient structural collapse (Bhanu et al. 2020; Bhanu et al. 2021). These studies analysed 10 RC and 2 steel frames to reveal a decreasing trend in dynamic deformation capacity with ground motion duration. This implies that under longer duration ground motions, structures not only collapse at lower ground motion intensities on average, but are also able to withstand smaller deformations before the onset of collapse. Raghunandan & Liel (2013) and Pan et. al (2018) have previously reported this phenomenon for RC frames and timber frames respectively. This reduction in structural deformation capacity is attributed to the larger number of deformation cycles induced by longer duration motions.

The objective of this study is to propose recommendations to incorporate the effect of duration in seismic assessment guidelines by exploiting the observed relationship between dynamic deformation capacity and ground motion duration. To this end, nonlinear static pushover analyses are conducted to compute the "static deformation capacities" of 10 RC frames, in accordance with FEMA P695 (FEMA 2009). These quantities are compared to the dynamic deformation capacities recorded in Bhanu et al. 2021, to establish a relationship between static deformation capacity and duration. This relationship is proposed as the basis for explicitly considering the effect of duration in seismic assessment of existing buildings.

2 DYNAMIC VS. STATIC DEFORMATION CAPACITY

The dynamic deformation capacity (DDC) of a structure is defined as the largest storey drift ratio (SDR) it can safely withstand without collapsing due to dynamic instability. It can be estimated as the largest SDR simulated when conducting incremental dynamic analysis (IDA) (Vamvatsikos & Cornell 2002), at ground motion intensity levels lower than or equal to the collapse intensity. Bhanu et al. (2021) describes this quantity in further detail and develops a robust numerical algorithm to compute it.

In Bhanu et al. (2021), the authors fitted a bilinear regression model to predict structural dynamic deformation capacity using ground motion duration for 10 modern RC frames with a wide range of structural periods (0.5 s – 2.3 s), varying in height from 2 to 20 storeys. Equation 1 describes the least-squares regression line characterising the decreasing trend in deformation capacity with Ds_{5-75}.

$$ln\ DDC = \begin{cases} ln\ DDC_{max} & ; Ds_{5-75} \leq D_c \\ a(ln\ Ds_{5-75}) + c_1 & ; Ds_{5-75} > D_c \end{cases} \quad (1)$$

where D_c is a critical duration, which is assumed to be equal to 5 T_1 (T_1 is the fundamental modal period of the structure), and Ds_{5-75} is the 5-75% significant duration of the ground motion (Trifunac & Brady 1975). This bilinear regression model is plotted in Figure 1 for the two-storey (LA02) and the twenty-storey (LA20) Los Angeles frames. The model suggests that the dynamic deformation capacity of a structure assumes a maximum and constant value, DDC_{max}, for durations shorter than D_c and decreases linearly under longer durations. For example, it can be observed in Figure 1(a) for the LA02 frame with T_1 = 0.53 s, that the predicted DDC_{max} is 10.4%, which decreases linearly on a logarithmic scale for durations longer than 2.7 s. Similarly, for the LA20 frame (T_1 = 2.31 s), the model predicts a DDC_{max} of 5.5%, which decreases linearly for durations longer than 11.6 s.

The trend described above is analogous to the reduction in deformation capacity commonly observed with the increasing number of loading cycles in experimental tests (Liddell et al. 2000; Pujol et al. 2006; Ou et al. 2013). The maximum deformation capacity of a structural component is typically observed under a pseudo-static monotonic test; the deformation capacity is observed to be lower under a cyclic test, and to decrease further as the number of cycles is increased. This trend of decreasing deformation capacity with number of cycles is expected to translate from the component-level to the building-level. The numerical equivalent of a pseudo-static monotonic test is a nonlinear static pushover analysis. Hence, this study investigates the relationship between the maximum dynamic deformation capacity computed using Equation 1 (DDC_{max}), and the static deformation capacity estimated from a pushover analysis.

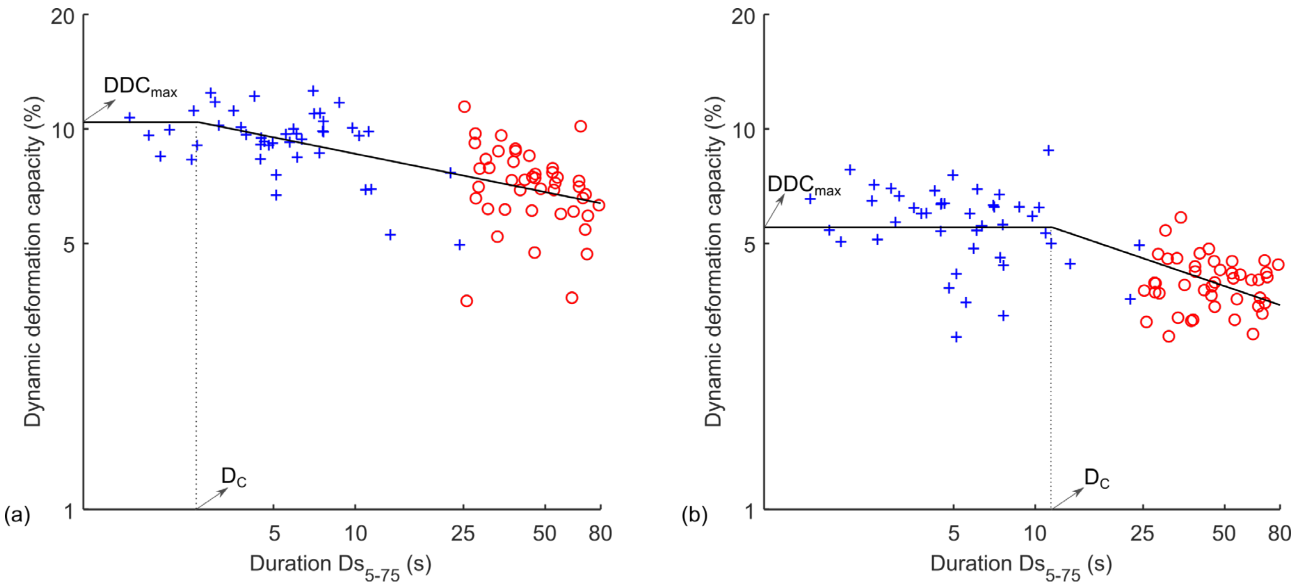

Figure 1: Least-squares regression lines for (a) the two-storey LA02 frame, and (b) the twenty-storey LA20 Los Angeles frame (Bhanu et al. 2021).

FEMA P695 (FEMA 2009) proposes a method to use the results of a nonlinear static pushover analysis (ASCE 2017) to quantify building seismic performance factors like the shear strength (V_{max}), the ultimate displacement (δ_u), and ductility (μ). The ultimate displacement capacity, δ_u, is estimated as the roof displacement at the point corresponding to 20% strength loss ($0.8V_{max}$). Figure 2 shows an idealised pushover curve and demonstrates the computation of δ_u. This study adapts the FEMA P695 method to compute the static deformation capacity (SDC) of a structure in terms of storey drift ratio rather than roof displacement. The SDC of a structure is defined herein, as the peak SDR recorded amongst all storeys at the point corresponding to 20% loss in strength in a nonlinear static pushover curve.

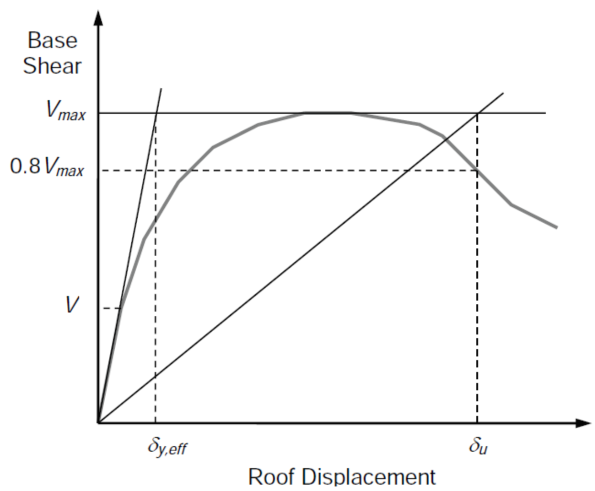

Figure 2: FEMA P695 method to compute the ultimate displacement capacity, δ_u, from a nonlinear static pushover curve (FEMA 2009).

The SDC is computed according to this definition for the 10 RC frames previously analysed in Bhanu et al. (2021). Other than the twenty-storey frame, LA20, all the analysed buildings exhibited maximum drift response at the first storey, corresponding to the $0.8V_{max}$ point. For the LA20 frame, the largest SDR corresponding to $0.8V_{max}$ was recorded at the third storey. Figure 3 presents the pushover curves for the LA02 and LA20 RC frames. Table 1 presents the DDC_{max} and SDC values for the 10 RC frames. The deformation capacities in Table 1 indicate that shorter period frames are generally able to sustain larger deformations compared to the longer period frames. This can be attributed to the fact these taller frames are designed with lower base shear coefficients in comparison with the shorter frames and could have higher P-Δ effects. The SDC values are observed to be 10-20% lower than DDC_{max} for the two- and four-storey frames (LA02, ST02, PL02, LA04, and ST04), and 15% higher for the twenty-storey frame (LA20). For the eight- and twelve-storey frames (LA08, ST08, PL08, and LA12), the SDC values are within ± 5% of DDC_{max}.

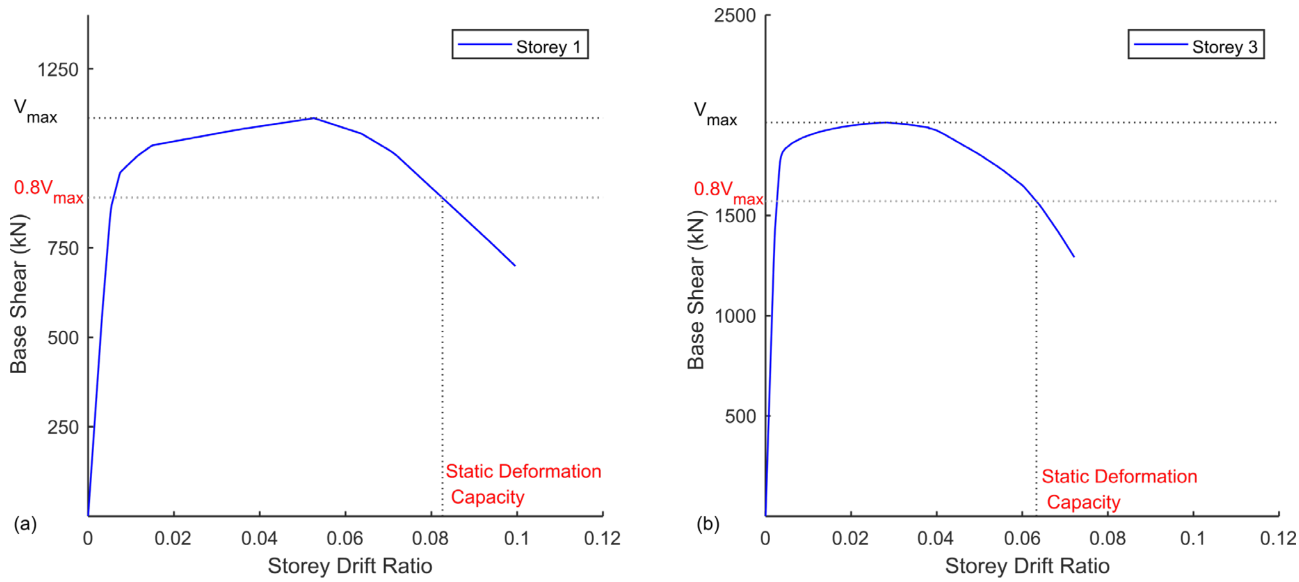

Figure 3: Computation of the static deformation capacities from pushover curves of the storey with the largest drift response for the (a) LA02 and (b) LA20 RC frames.

3 INCORPORATING THE EFFECT OF DURATION IN SEISMIC DESIGN AND ASSESSMENT

Previous studies have demonstrated and quantified the effect of duration on collapse capacity and dynamic deformation capacity; computation of these quantities, however, requires a large number of time-history analyses and significant post-processing. Hence, the use of these parameters is not considered feasible for practical applications. Nonlinear static pushover analysis is, on the other hand, widely used in seismic assessment practice because of the relatively lower computational effort entailed. A close relationship is also observed between SDC computed from pushover analyses and DDC_{max} computed from time-history analyses, in Table 1. Hence, assuming that SDC ~ DDC_{max}, the authors propose that the effect of duration on dynamic deformation capacity, quantified through Equation 1, can be exploited in seismic design and assessment by adjusting the static deformation capacity, as presented in Equation 2.

$$In\,SDC_{adj} = \begin{cases} \ln SDC & if\ Ds_{5-75} \leq D_c \\ a(\ln Ds_{5-75}) + c_1 & if\ Ds_{5-75} > D_c \end{cases} \qquad (2)$$

where SDC_{adj} is the static deformation capacity adjusted for duration effects under a ground motion duration of Ds_{5-75}. The coefficients a and c_1 are assumed to be the same as in Equation 1 from Bhanu et al. 2021.

Table 1: Comparison of the maximum dynamic deformation capacity (DDC_{max}) and the static deformation capacity (SDC) computed for the 10 RC frames.

Frame ID*	**Fundamental Modal Period (s)**	DDC_{max}	**SDC**	$\frac{SDC}{DDC_{max}}$
LA02	0.53	10.4%	8.3%	0.79
ST02	0.57	9.7%	8.3%	0.85
PL02	0.61	9.6%	8.0%	0.84
LA04	0.84	9.6%	7.8%	0.81
ST04	0.98	8.5%	7.6%	0.90
LA08	1.53	7.0%	6.6%	0.95
ST08	1.76	6.5%	6.4%	0.98
PL08	1.93	6.3%	6.3%	1.00
LA12	2.09	5.8%	6.1%	1.04
LA20	2.31	5.5%	6.3%	1.15

*More information regarding the design characteristics of the RC frames can be found in Bhanu et al. 2021.

Equation 2 implies that for any duration d s, SDC_{max} is equal to SDC evaluated from nonlinear pushover analysis if d is shorter than D_c, and decreases linearly on a logarithmic scale for d greater than D_c. Consequently, this also implies a reduced ductility for durations d greater than D_c, since deformations at yield are not affected by ground motion duration. Based on these observations, the authors propose that seismic assessment guidelines, such as ASCE 41 (ASCE 2017), can possibly incorporate the effect of duration by adjusting the expected deformation capacity limits. For example, in ASCE 41 method of seismic evaluation and retrofit of existing buildings, seismic demands computed from nonlinear static or dynamic procedures are compared with the plastic rotational capacities outlined in the acceptance criteria corresponding to different performance levels of Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). These capacity limits are related to the deformations corresponding with certain points on the force-deformation curve from experiment, which is similar to a pushover curve as mentioned earlier in this paper. Specifically, the CP performance limit can be considered to be the same as the SDC, assuming that SDC also corresponds to the point where hinge strength drops by 20% from the peak. Therefore, to account for the reduction in deformation capacity based on the anticipated duration, the total rotational capacity limits can be adjusted by multiplying with a factor "k", where k is defined through Equation 3.

$$k = \frac{SDC_{adj}}{SDC} \quad (3)$$

The total rotational capacity here refers to the sum of the plastic rotational capacity for CP and the yield rotation. It is to be further explored if similar adjustments can be made for other limit states of IP and LS.

It should be noted that Equation 2 is a preliminary approximation of the effect of duration on static deformation capacity. Currently, the authors are working on refining this relationship further by exploring the following points observed in this paper and in Bhanu et al. 2021:

1. There is a trend in SDC and DDC_{max} ratio with structural period, as observed in Table 1.
2. The average effect of duration on dynamic deformation capacity is consistent over a range of periods and frames.
3. The critical duration, below which the dynamic deformation capacity is the maximum (DDC_{max}) for a structure and is constant, is expected to be a function of the fundamental modal period of the structure but requires further research.

4 CONCLUSION

This paper is an extension of previous work by the authors demonstrating a decreasing trend in dynamic deformation capacity (DDC) with ground motion duration for 10 RC frames. Modifying the FEMA P695 method, the static deformation capacities (SDC) of the analysed structures were estimated as the peak SDR recorded amongst all storeys at the point of 20% loss in strength in nonlinear static pushover analysis. The SDC of the analysed structures were found within ±20% error range of the DDC values predicted at short durations lower than a critical duration. A preliminary relationship was proposed to adjust static deformation capacity based on anticipated ground motion duration. It was further proposed that the effect of duration on deformation capacity can be incorporated in seismic assessment and retrofit process for existing buildings by adjusting the acceptable capacity limits. By doing so, structures assessed at different sites, likely to experience ground motions of different duration, will approximately have the same margins of safety against collapse. Further efforts are currently underway to refine these methods.

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