Response of tall Steel Moment Resisting Frames (SMRF) to near-fault pulse-like ground motion

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SUMMARY:
This contribution describes a study on the elastic response of tall buildings subjected to near-fault pulse-like ground motions, with special emphasis on the relative importance of different vibration modes, and their dependence on the predominant period of such ground motion. Generic elastic Steel Moment Resisting Frames (SMRF) are analyzed using a set of ground motion records. It is found that the peak inter-storey drift demands of the SMRF models increase as the fundamental period of the SMRF approaches the dominant pulse period. Higher mode contributions to peak inter-storey drifts are found to be significant at the upper storeys of the frames, more so for the taller ones. Equivalent pulses, which have been suggested in the literature to represent near-fault ground motion are found to be inapt to simulate the higher mode response— deficient in predicting both the peak inter-storey drift as well as its distribution along the height of the frames.

Keywords: near-fault ground motion, inter-storey drift, higher mode response, tall moment resisting frames

1. INTRODUCTION

Near-fault ground motions recorded in the forward directivity region contain strong velocity pulses. The concentration of seismic energy in one or a few cycles of strong pulses has an impulsive impact on structures, potentially causing severe damage. This potentially impulsive behaviour became evident after strong earthquakes in the past, for example, the 1994 Northridge, the 1995 Kobe, and the 1999 Chi-Chi earthquakes. Evidence of near-fault related damages to engineering structures have been documented since over 60 years. Benioff (1955), for example, reported strong seismological evidence of near-fault phenomenon in explaining the intensity patterns observed after the 1952 Kern County, California, earthquake. Some other studies concerning damaging effects of near-fault ground motions are those of Westergaard (1933), Mahin et al. (1976), Bertero et al. (1978), Anderson and Bertero (1987), and Hall et al. (1995).

Due to the impulsive nature of near-fault ground motions, researchers have used simple mathematical pulses to model them. The use of simple pulses in studying the dynamic response of structures has a long history, for example, Biggs (1964) used one-sided pulses of rectangular, triangular, and ramp-like shapes to evaluate elastic as well as inelastic response of single degree of freedom (SDOF) systems. Biggs found that the pulse amplitude and duration relative to the period of vibration of SDOF system are the two important parameters controlling the peak elastic response. Several mathematical models of simple pulses intended to represent salient features of near-fault ground motions has since been used in the literature (see Rupakhety 2010 for an overview of different models).

Simple pulse models are mostly capable of simulating the peak response of SDOF systems at long periods— in general, at periods larger than about 0.7 times the period of dominant ground-motion pulse. At shorter periods, equivalent pulse models fitted to recorded ground motion typically underestimate the response. The satisfactory behaviour at long periods has led some researchers to the conclusion that seismic response of building structures can be characterized by using simple pulse models (Mavroeidis and Papageorgiou 2003, Mavroeidis et al. 2004). Alavi and Krawinkler (2004) conclude that a reasonable equivalence between a near-fault ground motion and a pulse can be established in a range of T_1 / T_p from 0.375-3.0, where T_1 is the fundamental period of a building, and T_p is the dominant pulse period.

The general notion that simple pulses may adequately represent seismic response of SDOF systems is often extrapolated to seismic response of multiple degree of freedom (MDOF) structures. The main argument behind such extrapolation is that a pulse model that sufficiently simulates the fundamental mode response is adequate (Alavi and Krawinkler 2004). Whereas this might be a reasonable hypothesis for low-rise structures predominantly responding in the first mode of vibration, its validity for tall buildings with significant response contribution from higher vibration modes is questionable. This is because simple pulse models lack in describing high-frequency components of ground motion, and are therefore inadequate to simulate response of higher vibration modes. It is therefore important to study, in a systematic manner, how biased simple pulse models are in describing response of tall buildings subjected to actual near-field ground motion records. This study focuses on this task with special emphasis on the relative importance of higher vibration modes and to what degree they might influence the suitability of surrogating an actual ground motion by a mathematical pulse. In the following sections, the structural models used, the ground motion database, the computational procedure, and an overall analysis of the results are presented in sequence.

2. STRUCTURAL MODEL

Structural models used in this study are single-bay generic steel moment resisting frames (SMRFs). Four different frames with 9, 12, 15, and 18 stories are considered. A lumped mass equal to 889.6 kN (200 kips) is assigned to each storey. The second moment of inertia of beam in a storey is kept equal to that of the columns supporting it. With this assumption, the relative stiffness of beams and columns are tuned to obtain a constant drift along the height when subjected to the lateral forces specified in IBC (2003). Their stiffnesses are then scaled to obtain a first mode vibration period of $0.071H^{0.8}$ (Goel and Chopra 1997), where H is the total height of the frame measured in meters. Classical damping model is assumed, and other details including the modal periods, mode shapes, and modal damping ratios can be found in Rupakhety (2008).

3. GROUND-MOTION RECORDS

The set of ground-motion records used in this study is a subset of the database described in Rupakhety (2010). Only those records which contain a clear and dominant pulse in their velocity time series are considered. In addition, only forward-directivity affected records are used. The pulse model of Mavroeidis and Papageorgiou (2003) is fitted to each of the selected records. The fitted pulses are called equivalent pulses hereafter and serve to quantify the response due to the impulsive part of ground motion. Each of the 9-, 12-, 15-, and 18-storey frames is subjected to those ground motions which satisfy the criteria $T_1 > 0.7T_p$. This results in 35, 43, 50, and 56 being used in structural analysis of the 9-, 12-, 15-, and 18-storey frame, respectively. The selected records are identified in Table 1 by their waveform identification numbers (WID) which can be found in Rupakhety (2010).

Table 1. Ground-motion records used in this study

Number of storeys	List of WIDs
9	1, 2, 3, 4, 17, 24, 25, 26, 28, 29, 30, 32, 34, 65, 67, 68, 69, 70, 75, 76, 77, 80, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 99, 100, 106
12	Same as above and 7, 18, 38, 42, 45, 46, 66, 78
15	Same as above and 5, 11, 12, 13, 15, 74, 79
18	Same as above and 6, 8, 10, 14, 16, 71

4. STRUCTURAL ANALYSIS

The response of the SMRFs subjected to ground motions listed in Table 1 is computed by using modal superposition method to be able to identify the contribution from individual modes. The response parameter of interest is selected as inter-storey drift ratio IDR as it is related to the story shears and serves as an important damage indicator of building structures subjected to strong ground motions. This response parameter is able to describe local damage at the story level. If $u_i(j,t)$ represents the lateral displacement of storey j due to mode i as a function of time, the i th mode contribution of IDR is computed as

$$IDR_i(j,t) = \frac{u_i(j,t)}{h} \times 100 \tag{4.1}$$

where h is the storey height. By modal superposition, the total interstory drift at story j can be obtained as

$$IDR(j,t) = \sum_{i=1}^{ns} IDR_i(j,t) \tag{4.2}$$

where ns is the number of storeys, which is also equal to the number of vibration modes ignoring the rotational inertia. The maximum IDR is obtained as

$$IDR_{\max}(j) = \max\left|IDR(j,t)\right| \tag{4.3}$$

The time when the IDR is maximum at storey j is denoted as t_j, and the contribution of mode i to $IDR_{\max}(j)$ at storey j is given by

$$\delta_{i,j} = \begin{cases} \left|IDR_i(j,t_j)\right| & \text{if } i = 1 \\ \operatorname{sgn}\left[IDR_1(j,t_j)\right] IDR_i(j,t_j) & \text{if } i > 1 \end{cases} \tag{4.4}$$

where the $\operatorname{sgn}[\bullet]$ operator represents signum function. The first mode contribution is always taken as positive, and the contribution of higher modes is taken as positive if it is in the same direction as the first mode contribution and vice versa.

5. RESULTS

In this section, we present some examples of the results that highlight the contribution of higher vibration modes, and their relative importance depending on the frequency content of ground motion. The results for a typical ground motion are presented first, followed by an analysis of average results.

5.1. Response to a typical pulse-like ground motion

The ground motion being considered is the strike-normal component of the 1987 Superstition Hills, USA, earthquake recorded at the PTS station. A comparison between the recorded ground motion and the equivalent pulse is presented in Fig. 1 showing ground velocity, pseudo spectral velocity (PSV), and spectral displacement (SD). The first mode periods of the 9-, 12-, 15-, and 18-story SMRFs are shown with vertical lines from left to right respectively. The period of the equivalent pulse is 2.25 s. This record is selected because the pulse fitted to this record sufficiently simulates the peak response of SDOF systems having vibration period equal to the first mode period of all the four SMRFs. The total interstory drifts and the contributions of the first three modes of the 12-storey SMRF computed using the actual record and the equivalent pulse are presented in Fig. 2.

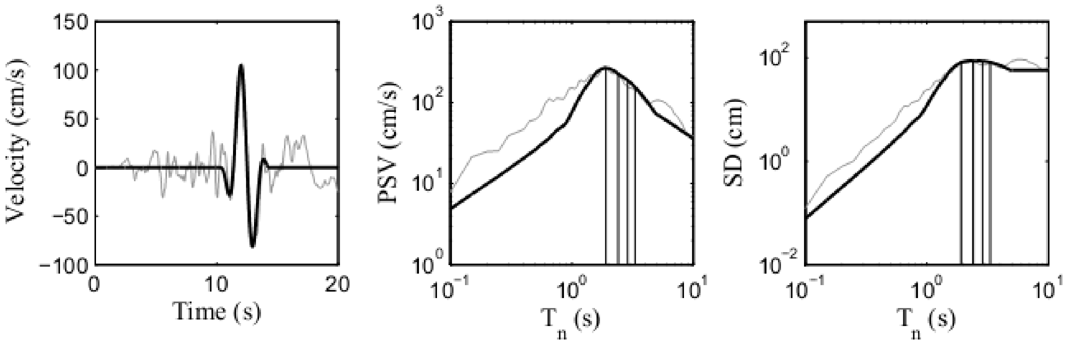

Figure 1. Strike-normal component of the 1987 Superstition Hills, USA, earthquake recorded at the PTS station. The grey and black lines represent the actual record and the equivalent pulse, respectively. The vertical lines from left to right represent the fundamental periods of 9-, 12-, 15-, and 18-story SMRFs.

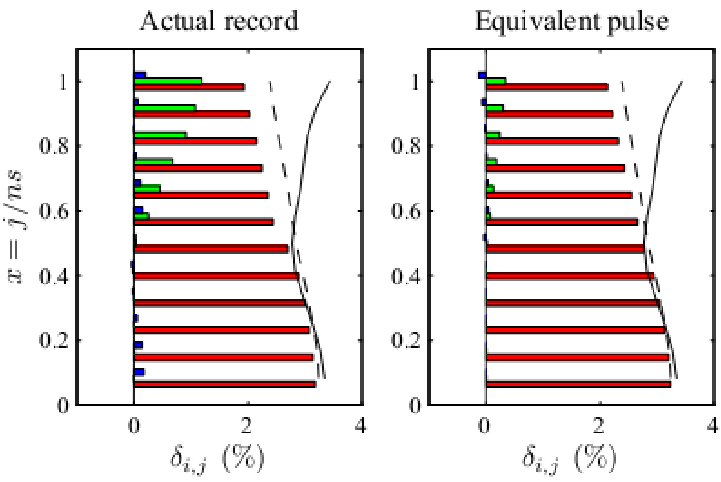

Figure 2. *IDR* along the dimensionless height of the 12-story SMRF subjected to the ground motion and its equivalent pulse shown in Fig. 1. The red, green, and blue bars represent the contributions of the first, second, and third modes respectively. Maximum interstory drifts considering all modes of vibration are shown with the solid (for actual record) and dashed (for equivalent pulse) lines.

Figure 2 shows that the contribution of second mode is significant. The second mode period of the 12-storey frame is 0.9s where the record PSV is as high as it is at its first mode period of 2.4s (see Fig. 1). The effect of second mode causes the maximum interstory drift to migrate to the top floor. The pulse is able to capture the first mode response of the frame and therefore the total drift computed by using the record and the pulse match each other in the lower half of the frame where the response is dominated by the first mode. The pulse underestimates the second mode response of the frame, and therefore underestimates the maximum drifts in the upper half of the frame. Similar results were observed for other frames, which can be found in Rupakhety and Sigbjörnsson (2011).

5.2. IDR at the roof

In this section, the accuracy with which simple pulses can predict the peak IDR at the roof of the 9-, 12-, 15-, and 18-story frames is investigated. Each frame is subjected to the above mentioned ground motion records. For each frame, the maximum interstory drift at the roof $IDR_{\max}(ns)$ is computed from Eqn. 4.3 by substituting $j = ns$. The maximum interstory drift at the roof corresponding to a ground motion record k and its equivalent pulse are denoted by $IDR_{\max}^{k,r}(ns)$ and $IDR_{\max}^{k,p}(ns)$ respectively. The ability of the equivalent pulse to represent a ground motion k is evaluated by computing an error term(E_k), which is defined as:

$$E_k = \frac{IDR_{\max}^{k,r}(ns)}{IDR_{\max}^{k,p}(ns)} \tag{5.1}$$

A value of E greater than 1 indicates that the pulse is predicting smaller interstory drift than the record. The errors introduced in IDR by using an equivalent pulse instead of an actual record are indicated in Fig. 3. The errors are plotted against the normalized period. The results indicate that the IDR at the roof computed by using an equivalent pulse is, on average, 1.4 times smaller than that computed by using an actual record. The errors display a decreasing trend with increasing values of T_1/T_p. This can be explained by the fact that as the value of T_1/T_p increases, the higher mode periods get closer to the pulse period where the pulse can adequately represent the actual ground motion. The figure shows that the performance of an equivalent pulse is satisfactory if the fundamental period of the frame is about 1.5 times larger than the pulse period. For the 9-, 12-, and 15-story frames considered here, this implies that an equivalent pulse can adequately represent an actual ground motion if the pulse period is smaller than 1.26s, 1.6s, and 1.91s respectively. Considering the relationship between moment magnitude and pulse period presented in Mavroeidis and Papageorgiou (2003), these pulse periods correspond to moment magnitudes of 6.0, 6.2, 6.4, and 6.5 respectively. This observation leads to the conclusion that simple pulse models cannot adequately represent recorded ground motions of large earthquakes in the period range of the frames considered in this study, i.e., those having first mode periods less than 3.3s. This also indicates the importance of high-frequency components of near-fault ground motion in the total response of tall buildings.

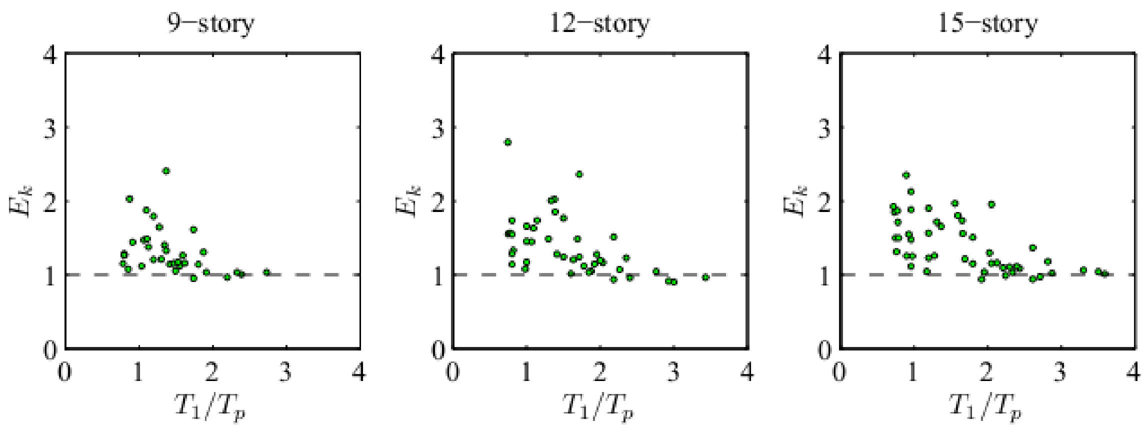

Figure 3. Errors in the computation of interstory drift ratio at the roof of 9-, 12-, and 15-story SMRF due to the use of an equivalent pulse instead of an actual ground-motion record.

5.3. Height-wise distribution of inter-storey drifts

In this section, the height-wise distribution of inter-storey drifts of SMRFs and its dependence on the fundamental period of the frame relative to the pulse period is investigated. For each frame, maximum inter-storey drift at each storey is computed for the corresponding records and their equivalent pulses. These results are divided into three groups satisfying the conditions $0.7T_p \le T_1 < 1.3T_p$, $1.3T_p \le T_1 < 2.0T_p$, and $2.0T_p \le T_1$, respectively. The mean value of the maximum interstory drift is denoted by $\bar{\delta}$. The results are presented in Fig. 4.

It is observed that the inter-storey drift is the largest for the first group of ground motions where the fundamental period of the frame is within 0.7-1.3 times the pulse period. This case is shown with blue lines in Fig. 4. For this case, the drift demand along the height of the frame remains almost constant except at the top 30% of its height where higher mode contributions become important. Because the higher mode periods in this case lie in the region where the pulse PSV is much smaller than the record PSV, the inter-storey drift demands predicted by the pulses are dominated by the first mode. This explains why the pulses underestimate inter-storey drift demands at the higher stories of the frames. As the fundamental period of the frame is increased to 1.3-2 times the pulse period, the first modes of the frames are excited by ground-motion components with smaller amplitudes and therefore the drift demands decrease. On further increasing the fundamental period of the frames relative to the pulse period, drift demands reduce further. It can also be observed that the location of maximum inter-storey drift along the height of the frame migrates towards the top of the frame if T_1 is relatively larger than T_p. This happens due to larger contributions from higher modes; when the first mode period is much larger than the pulse period, the higher mode period approaches the pulse period where the ground motion is characterized by larger amplitudes. The differences between the inter-storey drifts predicted by an actual records and their equivalent pulses are the smallest for the third group of ground motions with $T_1 > 2.0T_p$.

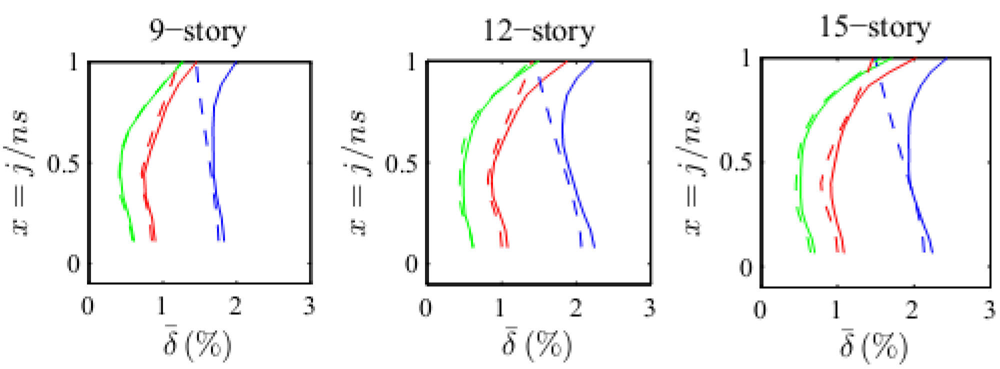

Figure 4. Mean interstory drifts of the 9-, 12-, and 15 -story SMRF. The solid and the dashed lines represent the results obtained by using the actual records and their equivalent pulses respectively. Blue, red, and green lines correspond to $0.7T_p \le T_1 < 1.3T_p$, $1.3T_p \le T_1 < 2.0T_p$, and $2.0T_p \le T_1$, respectively.

6. CONCLUSIONS

It is found that the higher mode contributions to maximum interstory drifts of tall frames subjected to near-fault ground motions are important. The importance of higher modes is larger at the upper portions of the frame and increases as the height of the frame increases. Maximum interstory drifts depend strongly on the ratio of the fundamental period of vibration of the frame and the pulse period. When the fundamental period of the frame is close to the pulse period, interstory drift demands are larger than when it is much larger or much smaller than the pulse period. Simple pulse models as the one used in this study are not capable of simulating the higher mode response of tall structures. It is found that the accuracy with which a simple pulse model can represent an actual ground motion depends on the fundamental period of the frame relative to the pulse period. On average, simple pulses result in elastic interstory drift demand 1.4 times smaller than actual near-fault ground motions. For a simple pulse to adequately simulate the elastic interstory drift demands of a tall frame, the fundamental period of vibration of the frame has be to at least 1.5 times larger than the pulse period. However, the most severely affected structures are those whose fundamental period is close to the pulse period. These results indicate that simple pulse models might not be an adequate replacement for pulse-like ground motions to predict the elastic seismic response of tall buildings in the near-fault region. These results, obtained for elastic structures, should not be extended to inelastic structures. Development of ductility in structural members, and the lengthening of vibration period due to inelasticity might result in the relative importance of different modes of vibration that are different than those for elastic structures. In such cases, the initial elastic period of the building relative to the pulse period and the maximum ductility allowed in the structure will both play an important role in determining the relative importance of different modes of vibration. A systematic study of such systems with different models of inelasticity and their distribution in the structural system is currently being undertaken in order to extend the results presented here to inelastic building models.

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