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RESPONSE OF MULTI-STORY STRUCTURES TO NEAR-FAULT GROUND MOTIONS AND EQUIVALENT PULSES

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ABSTRACT

The response of multi-story structures to near-fault ground motions were investigated to find the most predictive Intensity Measure for these kinds of motions utilizing Incremental Dynamic Analysis. Three different generic multi-story shear buildings were subjected to fifty four near-fault ground motions including ordinary and forward-directivity records. The Maximum Story Displacement Ductility Demand was selected as the Engineering Demand Parameter. Results showed that the only intensity measure that appears to be valid for both ordinary and forward-directivity ground motions is the peak ground velocity. The structural response to the forward directivity ground motions was reproduced using an equivalent pulse model based on the modified Gabor Wavelet pulse. It is shown that when the ratio of pulse period to the fundamental structural period falls in a range of 0.5 to 2.5, the equivalent pulse model appropriately represents structural response to forward-directivity ground motions. The simplified pulse parameters can be predicted using existing relationships and can be incorporated into probabilistic seismic hazard analysis to develop a seismic reliability analysis. Finally, P-Δ was investigated for forward-directivity ground motions. Results showed that P-Δ effects on the ductility demand are significant.

Introduction

Most of the energy in forward-directivity ground motions is concentrated in a narrow frequency band and is seen as a distinct, high intensity velocity pulse at the beginning of time history records. These pulses, in turn, may result in high seismic demands for buildings. Recent research has addressed the seismological aspects of fault mechanisms leading to forward-directivity, the characteristics of forward-directivity ground motions (Somerville 1997, Spudich 2008), and structural response to these motions (Hall 1998, Mylonakis 2001, Zhang 2002). However, designers still lack specific guidelines as how to account for forward-directivity effects when determining the seismic hazard for a given structure. In the current state-of-the-practice, forward-directivity effects are introduced in seismic hazard analyses by modifying the ground motion elastic response spectra (Somerville 1997, Abrahamson 2000) and using spectral-based intensity measures (IM) to capture structural response (Baker 2008). Nevertheless, forward-

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directivity ground motions typically have large intensities and tend to drive structures into the nonlinear range. For these cases, a linear response spectrum, and in particular the spectral acceleration at the first-mode period of the structure, $S_a(T_1)$, no longer serves as an effective intensity measure (Baker 2008).

The paper first presents a description of the ground motion database used in this study, along with the methodology employed to extract forward-directivity pulses from the recorded ground motions. The structural models are then described, and their responses to ordinary and forward-directivity ground motion are compared. The selected equivalent pulse model based on the modified Gabor wavelet pulse (Gabor 1946, Mavroeidis 2003) is explained. The parameters of the Gabor wavelet pulses are then calibrated such that the equivalent pulses render a similar structural response to that of the recorded forward-directivity records. These parameters are compared to parameters of forward-directivity pulses extracted directly from the recorded ground motions, and cases in which structural response can be predicted with the simplified pulses are identified. Finally, the response of the structures to pulse-type ground motions is summarized in terms of a response surface. Twenty-seven forward-directivity ground motions and twenty-seven ordinary ground motions from six earthquakes with moment magnitude greater than 6.5 were used in this study. All records were taken from Loma Prieta, Erzincan, Northridge, Kocaeli, and Chi-Chi events from stations within 20 km of the fault rupture. Baker's automated procedure (Baker 2008) was used to extract the forward-directivity pulses and obtain their period and amplitude for each of the forward-directivity motions. For brevity, details about the records and extracted pulses are omitted from this paper; one can refer to the author's Ph.D. dissertation (Sehhati 2008) for more information.

Multi-Story Systems

Three generic buildings were considered. The buildings are seven, fourteen, and twenty one-stories high. The buildings were designed as regular structures, both in plan and in height, with fundamental periods of exactly 1, 2, and 3 seconds, for the seven, fourteen, and twenty one-story buildings respectively. The structures were designed to have the same base shear coefficient (defined as the base shear that causes yielding in the structure divided by the total weight of the structure). The base shear coefficient was arbitrarily selected to be 0.07. The seismic resisting system, in the weak direction, consists of four moment resisting steel frames. Each frame has three 6.1 m long by 3.81 m high spans. Details of the building in the strong direction are irrelevant in this study because the structures were only loaded along their weak axis. To reduce computational efforts, the structures were simplified as shear building models.

A MATLAB program was written for conducting 2D nonlinear dynamic analyses of the frames. The step-by-step integration method with the Wilson-Theta modification (Chopra 1995) was used for time integration and the Modified Newton-Raphson Method (Chopra 1995) was used to iterate within each time step. Steel material nonlinearity was modeled by an elastoplastic kinematic hardening relationship, having identical properties in tension and compression. The frames were assumed to have a viscous damping ratio equal to 5%. Plastic hinge properties of each member were modeled with a bilinear non-degrading moment-curvature model with a range of strain hardening from 2.5% to 3.5%. P-Δ effects, which can have a significant role in the response of near-fault structures with an excessive drift, were considered by adding geometric stiffness to the first order stiffness matrix (see author's Ph.D. dissertation (Sehhati 2008) for details).

Analysis Results

Structural analyses were preformed for each of the three structures described in the previous paragraph using forward-directivity and ordinary ground motions. Only the fault normal component of each record was applied to the structures and it was assumed that the weak axes of the structures are perpendicular to the fault. The maximum story displacement ductility demand (MSDD) was selected to describe the inelastic response of the structures. The MSDD becomes greater than 1.0 when the relative displacement in any story is larger than the story yield displacement. The maximum inter-story ductility demand (MIDD) was defined as the maximum value of the MSDD over all the stories. The results of the structural analyses for the ordinary and the forward-directivity ground motion sets are shown in Fig. 1. The maximum standard deviation of the MSDD for all stories (σ_{max}) is shown for each structure. Observe that the mean structural response is consistently higher for the forward-directivity ground motion set (Fig. 1b). Even though the ordinary and the forward-directivity ground motion sets have approximately the same mean PGA (0.49g and 0.48g, respectively), their PGVs are distinctly different due to the presence of the initial velocity pulse (the mean PGV of the forward-directivity set is 81.7 cm/s compared to 42.0 cm/s for the ordinary ground motion set). The forward-directivity pulse leads to larger nonlinearities in the system, and thus to a larger structural demand. Moreover, since the structural response appears to be controlled by the initial pulse, and this pulse varies widely from one ground motion to another, the dispersion in the structural response is larger for the forward-directivity set as evidenced by the larger values of σ_{max} of MSDD when the structure is subject to forward-directivity ground motions (Fig. 1b) as opposed to ordinary ground motions (Fig. 1a).

Performance-based design requires the use of ground motion parameters (e.g., Intensity Measures) for predicting structural response. The response of the three structures in terms of MIDD as a function of three different intensity measures (PGA, $S_a(T_1)$, and PGV) are presented in Fig. 2. The standard deviation parameter, σ, computed separately for forward directivity and ordinary ground motions are shown in Fig. 2. A small σ value implies that the considered IM is a good predictor of MIDD. In Fig. 2a, the poor correlation between MIDD and PGA indicates that PGA is a poor predictor of structural response for both ordinary and forward-directivity ground motions. Also observe that $S_a(T_1)$ is a better predictor of MIDD for ordinary ground motions than for forward-directivity ground motions (Fig. 2b). This variability in standard deviations can be important when using traditional hazard analyses for forward directivity ground motions. PGV is a better predictor of MIDD than $S_a(T_1)$ for all the cases studied (Fig. 2c). The above results highlight the need to search for alternative ways to determine structural demand for structures subjected to forward directivity ground motions. In the next sections, an alternative approach using simplified pulse representations of forward-directivity motions is explored.

Equivalent Pulse Model

The Modified Gabor wavelet which is defined by three parameters (A, f_p, and γ) was used as equivalent pulse model. A, f_p, and γ are amplitude, frequency, and the oscillatory character (i.e., zero crossings) of the Gabor wavelet pulse. A minimization methodology was developed to constrain the parameters of the Gabor pulse such that the structural response to the pulses was similar to the structural response to recorded forward-directivity ground motions.

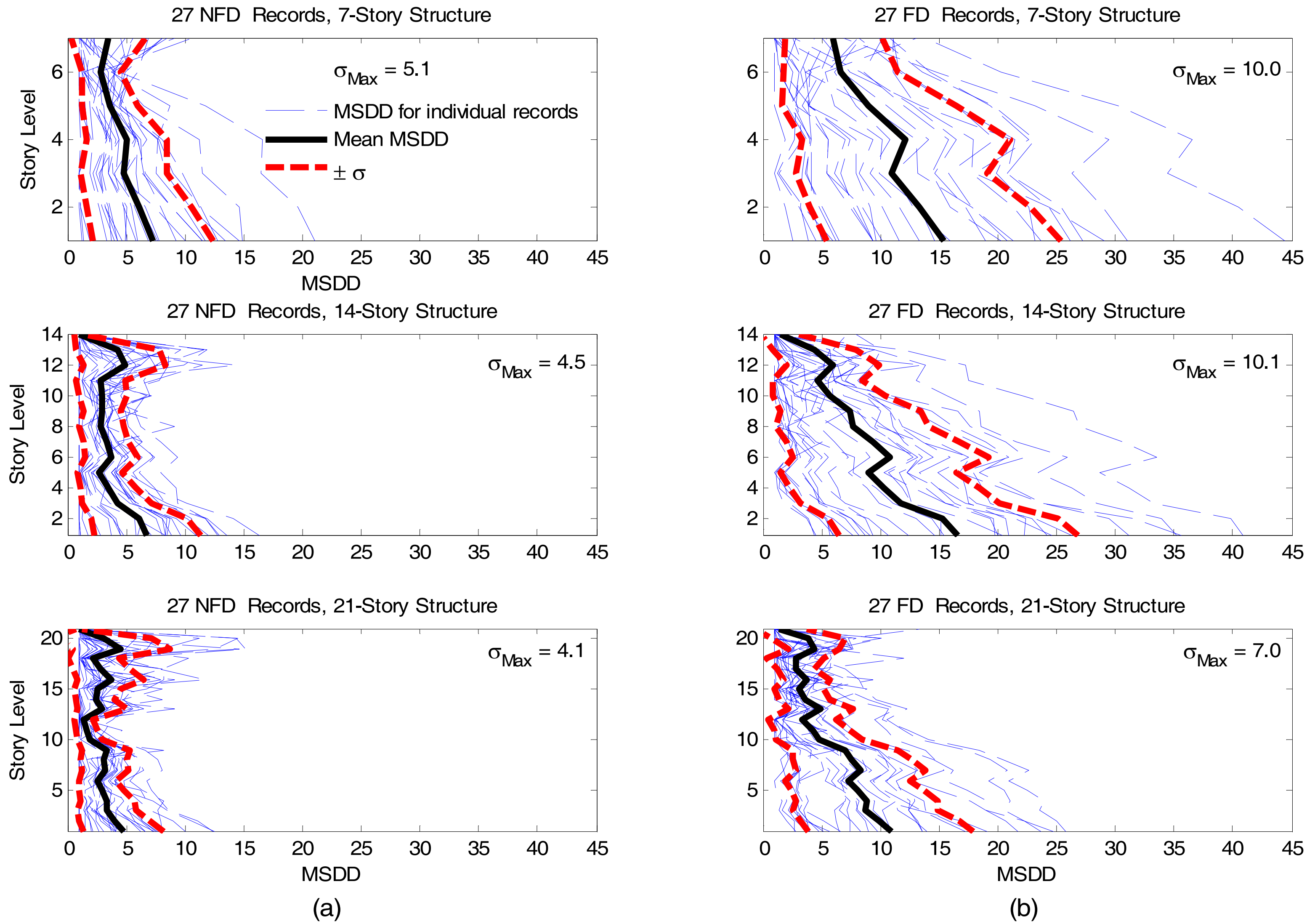

Figure 1. Maximum story ductility demand for (a) 27 non forward-directivity (NFD) records and (b) 27 forward-directivity (FD).

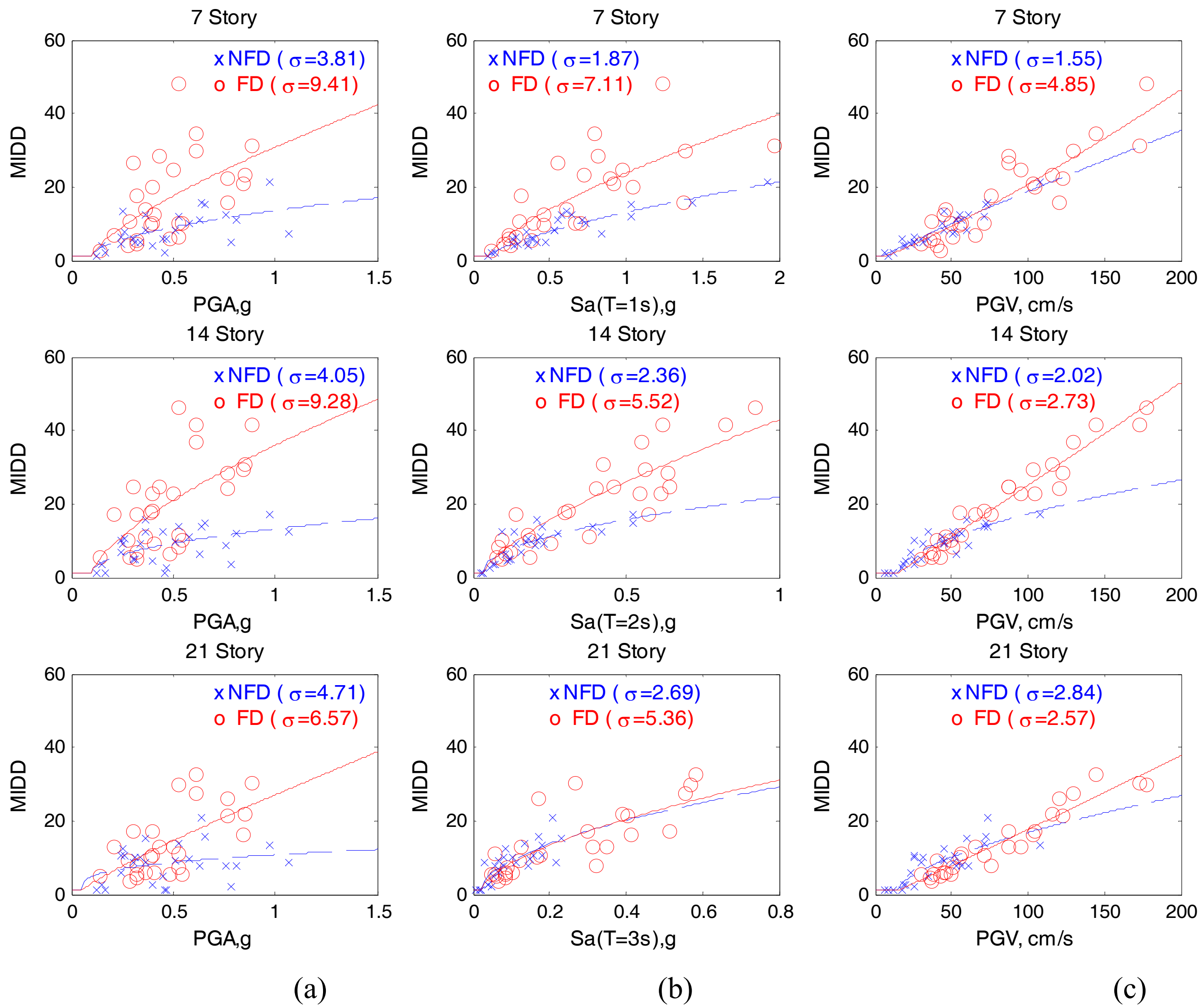

Figure 2. Maximum inter-story ductility demand for the 7, 14, and 21 story structures subjected to the forward-directivity (FD) and non forward-directivity (NFD) ground motions plotted versus different Intensity Measures: (a) PGA; (b) spectral acceleration at the first-mode; (c) PGV. Dashed and continuous lines represent the median response for the NFD and FD ground motion ensembles, respectively.

The parameter γ was selected based on the number of peaks and troughs of the forward-directivity pulse extracted using Baker's procedure. Parameters A and f_p were obtained by minimizing the differences between the MSDD due to the recorded forward-directivity ground motions and the MSDD values due to the Gabor wavelet pulses. The MSDD due to the Gabor pulses were compared to the MSDD due to the pulse-like ground motions for cases in which the period of the forward-directivity pulses are roughly equal to the period of the structures and cases in which the periods are significantly different. There was a close agreement between the displacement ductility demand due to the simplified pulses and the recorded forward-directivity ground motions. More details are available in the author's Ph.D. dissertation (Sehhati 2008).

Discussion

The parameters of the Gabor pulses (pulse period and pulse amplitude) were obtained by matching the structural response of the multi-story structures such that the response to the Gabor pulse was similar to the response of recorded forward-directivity pulses. Where the pulse parameters match those extracted directly from the velocity time histories of recorded ground motions (using Wavelet Analysis (Baker 2008)), the implication is that structural response is controlled by the forward-directivity pulses; for the structures studied herein, this is the case when the ratio of pulse period to the fundamental period of the structure falls in a range between 0.5 and 2.5 (Fig. 3). In this range of pulse periods, 85% of the Gabor pulse periods are within 20% of the pulse period of the extracted forward-directivity pulses. Therefore, in this range of periods the response is controlled by the forward-directivity pulse and the Gabor wavelet pulses are capable of both reproducing structural response to forward-directivity ground motions and accurately resembling the recorded motions. Outside of this range, additional analyses indicated that structural response is controlled by the higher frequency content of the ground motions that either overrides or follows after the forward-directivity pulse. The higher frequency contents elicit contribution of higher structural modes. In these cases, the pulse parameters are not adequate IM. Although, the Gabor pulses are still able to mimic structural response to recorded ground motions, but in these cases those pulses have no resemblance to the recorded ground motions and have no predictive value. The amplitude of the Gabor pulses obtained using the minimization procedure is on average 73% of the PGV (with a standard deviation of 0.22). Hence, attenuation relationships for PGV can be used to predict the amplitude of the pulses.

The distribution of the MSDD changes depending on the value of the pulse parameters. The critical story shifts from the base of the structure to higher stories with a decrease of the period of the pulse. However, the value of the ductility demand decreases as the period of the pulse decreases. In general, the distribution of the MSDD may be classified into three groups (Fig. 4). For example, if we consider the 14-story structure, for pulses with long periods ($T_p > 0.7$ sec), the critical story is at the base. For pulses in the intermediate period range ($0.4 < T_p \leq 0.7$ sec), the critical story moves to higher stories. For pulses with shorter periods ($T_p \leq 0.4$ sec), the distribution of the MSDD tends toward a uniform shape over the height of the structure. These period ranges change from structure to structure. This distribution of the MSDD cannot be captured by an elastic or spectral analysis which is based on $S_a(T_1)$.

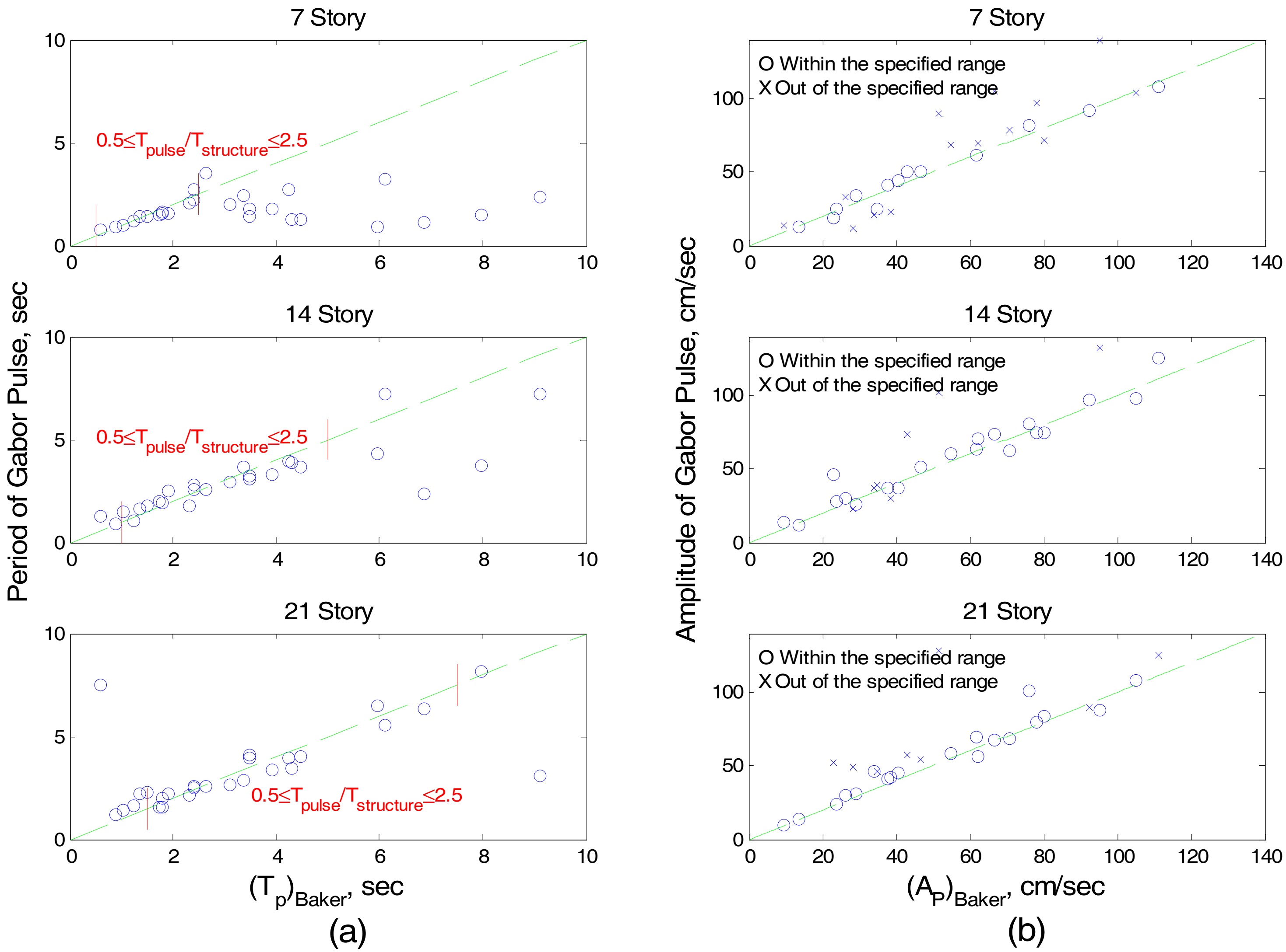

Figure 3. Comparison of (a) the periods and (b) the amplitudes of the Gabor pulses and the parameters of the forward directivity pulses.

Given that Gabor wavelet pulses can reasonably represent near-fault ground motions when their pulse period is in the neighborhood of the fundamental period of the structure ($0.5 \leq T_{pulse}/T_{structure} \leq 2.5$ for the structures studied herein), multiple runs can be used to predict the inelastic response of the structure for pulses with all possible amplitudes and periods in this range. Thus, the inelastic response of structures can be predicted for a range of forward-directivity pulses with realistic amplitudes and frequencies (Fig. 5). The short period region of the response surface in Fig. 5 is less smooth than the response at other period ranges, indicating that there are no clearly defined trends in the response of the structure in this region. This likely happens because the contribution of higher modes becomes predominant. A response surface such as that shown in Fig. 5 can be coupled with Probabilistic Seismic Hazard Analyses to predict structural response (Sehhati 2008). When $T_{pulse}/T_{structure}$ is outside of the defined range, the forward-directivity pulse may not control response and other IMs must be selected for predicting structural response.

Analyses were repeated without consideration of P-Δ effects. It was found that the P-Δ effect decreases the stiffness of the system, elongates the fundamental period of the structure, and imposes more demand to the base of the structure. P-Δ effects are more significant for records that cause more drift to the structure. For example, when P-Δ effects are considered, the mean value of MSDD computed at the base of the 7, 14, and 21-story structures increased by 6%, 16%, and 22%, respectively, for the forward directivity ground motion data set. For all the cases when the critical story occurs at the base, P-Δ effects increased MIDD and the critical story remained at the base. On the other hand, no consistent trend was observed when the critical story was one of the middle stories. On 75% of these cases, P-Δ effects increased the value of MIDD and the critical story either stayed in the same floor, moved to the base, or shifted to other stories. In the remaining 25% of the cases, the critical story location either remained or shifted to other floors, but the value of MIDD decreased.

Conclusions

The spectral acceleration at the first-mode period of vibration is not the ideal IM to capture structural response to pulse-like ground motions. On the other hand, dynamic analyses using an equivalent pulse model renders similar structural response to that computed for forward-directivity pulses when $0.5 \leq T_{pulse}/T_{structure} \leq 2.5$. In this period range, the response of the structures is controlled by forward-directivity pulses and equivalent pulses can be used to predict structural response. Outside of this range, the response of the structures is not controlled by the forward-directivity pulse. The shape of the MSDD distribution and location of the critical story are influenced heavily by the period and amplitude of the forward-directivity pulse. The MSDD is higher at the base when ground motions contain forward-directivity pulses with longer periods (e.g., for larger magnitude earthquakes). The critical story shifts up when the pulse period is shorter. This distribution of the MSDD has not been considered in building codes such as the IBC which assume that the maximum demand occurs at the base. Therefore, revisions for the codes to consider this issue are recommended. P-Δ effects can be significant for structures subject to forward-directivity ground motions and should be accounted for in design. This study was based on the response of three generic buildings, hence care must be exercised when generalizing the results presented herein. Moreover, only the response of the buildings to the fault-normal component of all ground motions was considered.

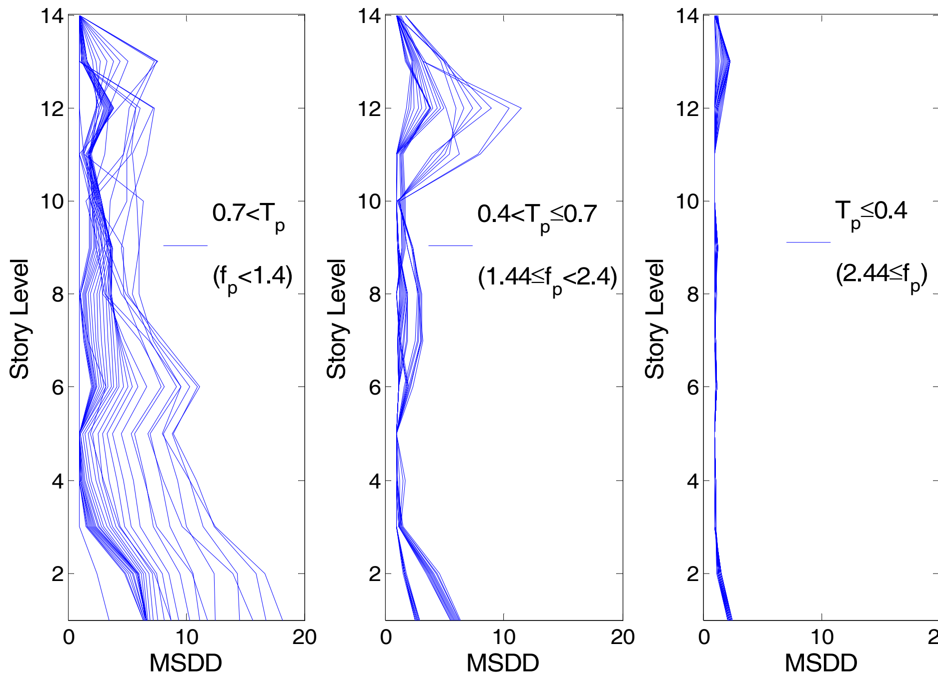

Figure 4. Distribution of maximum story ductility demand of the 14-story building for Gabor wavelet pulses with long ($T_p > 0.7$ sec), intermediate ($0.4 < T_p \leq 0.7$ sec), and short periods ($T_p \leq 0.4$ sec). Results for other buildings are qualitatively similar.

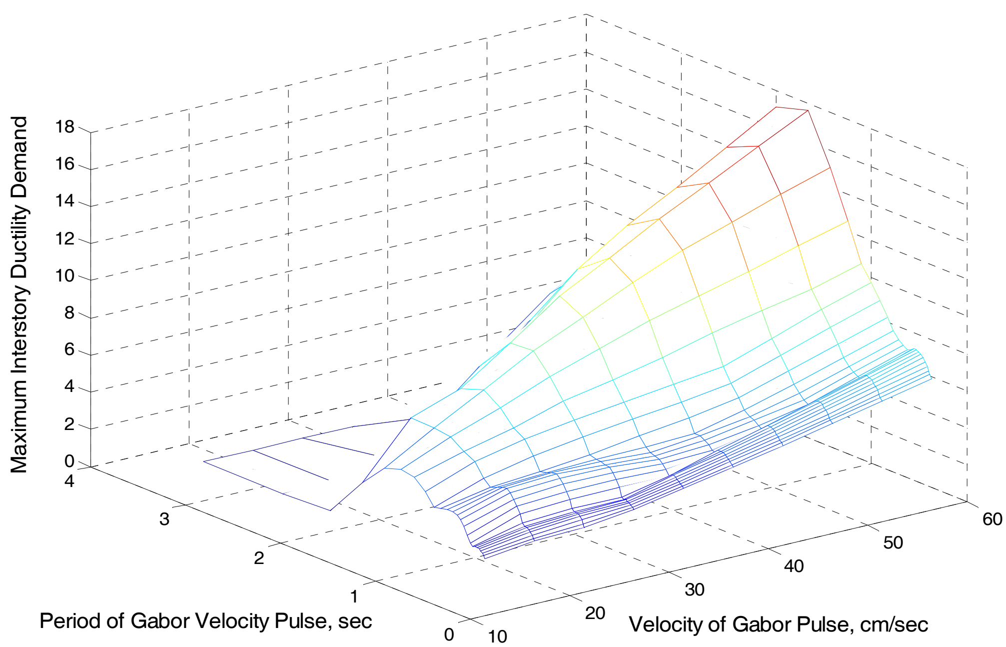

Figure 5. Maximum inter-story ductility demand of the 7-story structure for Gabor pulses with parameters $\gamma = 3$, $15 < A < 60$ cm/s, and $0.37 < T_p < 3.33$ s.

Acknowledgments

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