Effect of Arrival Time of Velocity Pulse on Seismic Response of Structures

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SUMMARY:

From past ground motion records, it has been observed that a forward directivity pulse may arrive at a relatively latter part of a time-history. However, the effect of such late arrival of pulse on seismic response of structures has not been investigated so far. In this study, the arrival time of a velocity pulse with respect to the strong motion duration has been defined through a parameter, normalized arrival time (*NAT*). Considering a large number of previously identified pulse-type motions, it is found that NAT correlates well with the associated pulse period and source-to-site distance for ground motions originating from dip-slip faults. The influence of *NAT* on the response of structures with varying properties are then studied by classifying these motions into early and late arriving pulse motions based on a limiting *NAT* value of 0.2. Results indicate that *NAT* may affect the response of a structure significantly depending on its dynamic properties.

Keywords: Forward directivity pulse, pulse arrival time, nonlinear response.

1. INTRODUCTION

After several structural damage incidents during the 1994 Northridge, 1995 Kobe, and 1999 Chi-Chi earthquakes, a large number of studies (Hall et al., 1995; Liao et al., 2001; Krawinkler et al., 2003; Tirca et al., 2003; Mavroeidis et al., 2004; Akkar et al., 2005) have been directed towards the prediction of displacement and strength demand under the near-field pulse-type ground motions. Malhotra (1999) and Chopra and Chintanapakdee (2001) found that the presence of wide acceleration sensitive region in the response spectra of the pulse-type motions is responsible for their higher strength demand compared to that of far-field motions. It has also been observed that a large displacement/ductility demand is imposed on structures under the pulse-type motions due to a huge amount of energy dissipation in a relatively fewer cycles of motion (Bertero et al., 1978; Kalkan and Kunnath, 2006). Previous studies have also predicted that the pulse period (T_p) and the pulse amplitude (A_p) are the two pulse parameters that typically influence the displacement demand on structures.

None of the studies conducted so far have considered the arrival time of velocity pulse as a parameter that might influence the response of structures. This might be due to a common perception that the velocity pulses arrive at the beginning of the time-history records. However, the velocity pulses do not always arrive at the beginning of a record. Fig. 1.1 depicts the velocity time histories of ground motions recorded at the Pacoima Dam (upper left abutment) and the TCU029 stations during the 1971 San Fernando earthquake and 1999 Chi-Chi earthquake, respectively. It may be observed from this figure that the velocity pulse arrives at the very beginning of the record at the Pacoima Dam site whereas for the TCU029 station, the pulse arrival is relatively late. Such variation in arrival time of the velocity pulse may affect the response of structures as a significant amount of input energy is associated with the velocity pulses. Focusing on this aspect, in this study a systematic investigation has been carried out to (1) identify the various parameters that are responsible for variation in arrival time of velocity pulses and (2) assess the influence of arrival time of velocity pulse on the nonlinear response of single-degree-of-freedom (SDOF) systems.

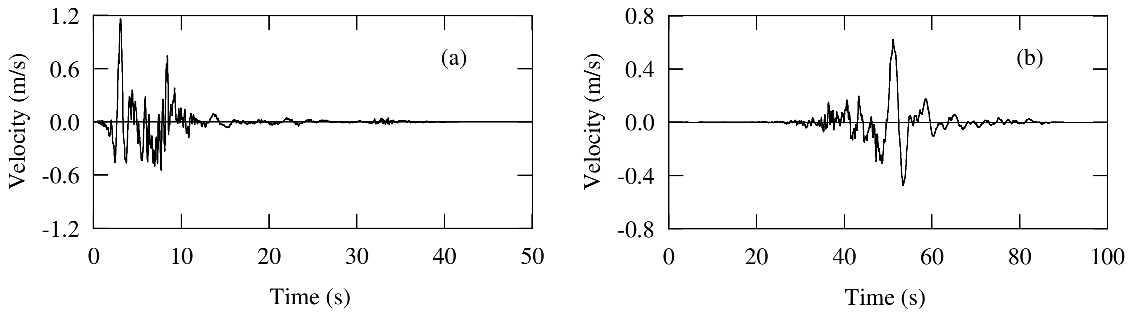

Figure 1.1: Velocity time histories of ground motions recorded at (a) Pacoima Dam (upper left abutment) recording station during the 1971 San Fernando earthquake (NGA no. 77) and (b) TCU029 recording station during the 1999 Chi-Chi earthquake (NGA no. 1476).

2. CLASSIFICATION OF NEAR-FAULT PULSE-TYPE MOTIONS

To study the effect of pulse arrival on seismic response of structures, a suit of 84 motions (fault-normal component) have been selected that are identified as pulse-type motions by Baker (2007). These motions are representative of free field motions as documented in the PEER-NGA database (Pacific Earthquake Engineering Research Center, 2011) and are recorded within a distance of 60 km from the fault rupture plane. The distance criterion has been chosen on the basis of the maximum value of upper limit for closest distance of recording sites from the fault proposed by Stewart et al. (2001).

In order to define the arrival time of the dominant velocity pulse, a parameter, normalized arrival time (*NAT*) has been introduced in the present study. *NAT* is defined as the ratio of the occurrence time (*a*) of peak ground velocity (*PGV*) from the starting of the strong motion duration as defined by Trifunac-Brady (Trifunac and Brady, 1975) to the total strong motion duration (*b*) considering an acceleration time-history. The reason behind adopting such definition is the fact that for a near-fault pulse-type motion, *PGV* occurs due to a pulse. Fig. 2.1 provides a pictorial representation of *NAT* (= a/b).

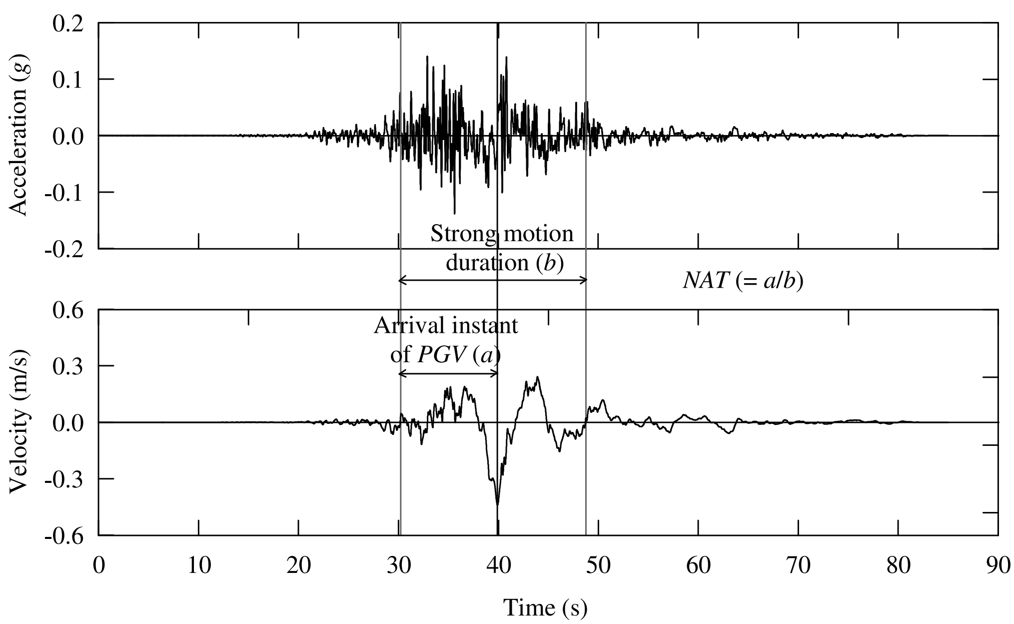

Figure 2.1: Illustration of *NAT* using acceleration and velocity time-histories of ground motion recorded at TCU046 recording station during the 1999 Chi-Chi earthquake (NGA no. 1486).

To study the correlation of a few seismological and pulse parameters with *NAT*, the pulse-type motions are divided into two categories depending on the fault type (i.e., whether they have originated from a dip-slip fault or a strike-slip fault). Fig. 2.2 shows the variation of *NAT* with closest distance from site to fault rupture plane (R) for the two fault types. As observed from Fig. 2.2(a), *NAT* of pulse-type motions originated from the dip-slip faults are correlated well (correlation coefficient ρ = 0.620) with R. Fig. 2.3 provides variation of *NAT* with T_p. One can observe from Fig. 2.3(a) that for motions originated from dip-slip faults, there is a increasing trend between *NAT* and T_p upto T_p = 6.5 s (approximately), followed by a decreasing trend. Further, to study the correlation of *NAT* with T_p for motions originated from the dip-slip faults, the increasing and decreasing branches are plotted separately in Figs. 2.3(b) and 2.3(c), respectively. The values of ρ for increasing and decreasing branches are found to be 0.545 and 0.577, respectively, indicating that a good correlation exists between the two parameters (i.e., *NAT* and T_p). No proper trend exists, however, between *NAT* and R (see Fig. 2.2(b)) and *NAT* and T_p (see Fig. 2.3(d)) for pulse-type motions resulting from the strike-slip faults.

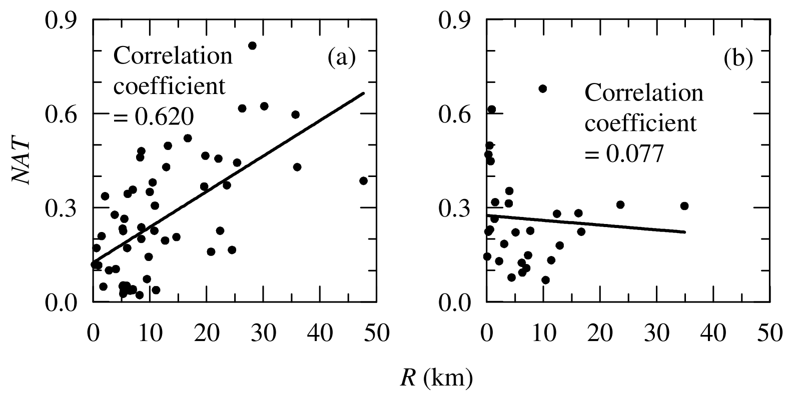

Figure 2.2: *NAT* versus R plot for motions originated from (a) dip-slip faults and (b) strike-slip faults.

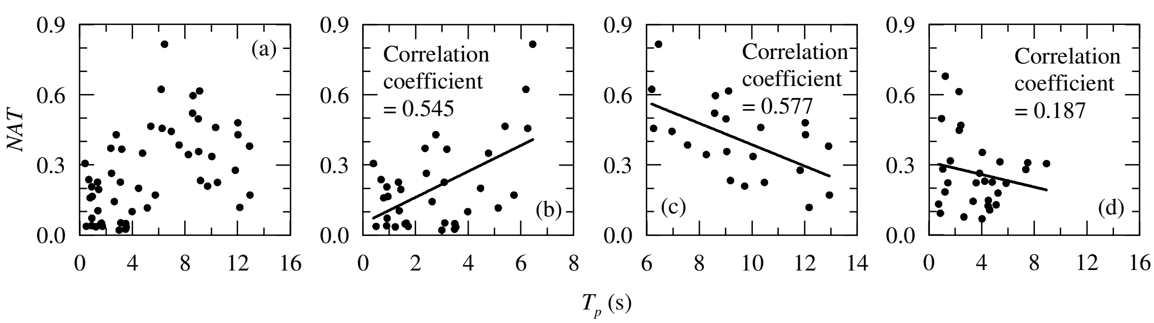

Figure 2.3: *NAT* versus T_p plot for motions originated from (a) dip-slip faults, (b) dip-slip faults and having pulse period less than 6.5 s, (c) dip-slip faults and having pulse period more than 6.0 s, and (d) strike-slip faults.

To categorize the pulse-type motions on the basis of pulse arrival, 54 pulse-type motions originated from dip-slip faults have been considered as they show good correlation for *NAT* with R and T_p. Fig. 2.4 shows the plot of normalized cumulative number of motions with *NAT*. As observed from Fig. 2.4, 50% of the motions considered possess a *NAT* value less than 0.225. In the present study, a value of 0.2 has been chosen as a limiting value for *NAT* that divides the 54 motions in the ratio of 23:31. Thus the pulse-type motions are classified into two groups: 23 early arriving pulse motions for which $NAT \leq 0.2$ and 31 late arriving pulse motions for which $NAT > 0.2$.

The distribution of motions with the R and T_p have been shown in Figs. 2.5(a)-2.5(b) and 2.5(c)-2.5(d) for the early arriving and the late arriving pulse motions, respectively. Also shown in these plots are the middle values of the corresponding quantities. Figs. 2.5(a)-(b) indicate that the majority of the early arriving pulse motions are expected at a distance of 5-10 km from the fault with pulse period ranging from 0.5 to 4.0 s. The late arriving pulse motions may be observed up to a distance of 50 km from the fault (see Fig. 2.5(c)). However, the majority of the late arriving pulse motions are expected to arrive at a distance of 0-30 km from the fault. The majority of pulse period for the late arriving pulse motions may lie in period regions ranging from 0.4s to 12 s.

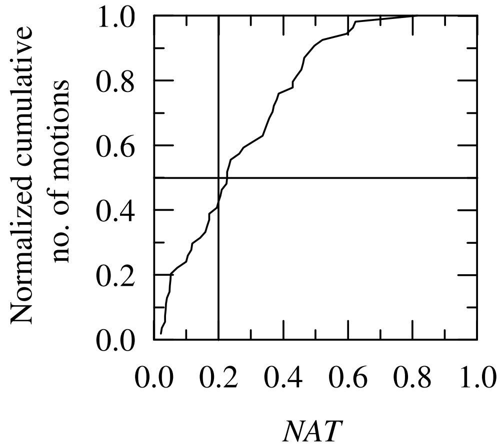

Figure 2.4: Plot of normalized cumulative number of motions with *NAT*.

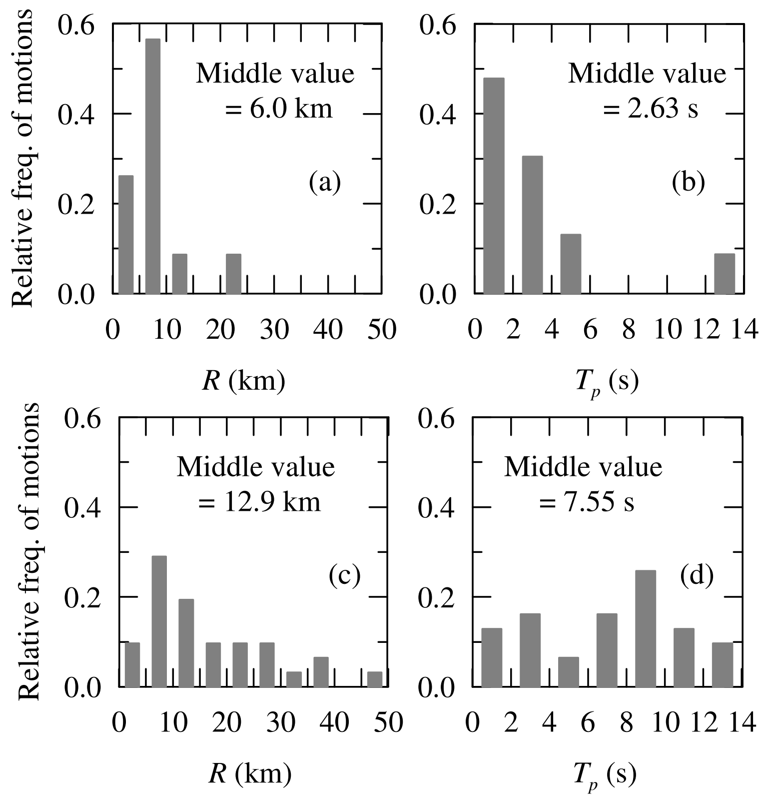

Figure 2.5: distribution of motions with the R and T_p for 2.5(a)-2.5(b) for the early arriving and 2.5(c)-2.5(d) the late arriving pulse motions.

3. DESCRIPTION OF OSCILLATORS

A series of SDOF oscillators with period ranging from 0.4 to 2.0 s at an interval of 0.1 s are considered to investigate the effect of pulse arrival on seismic response of structures. Such a period range is chosen as most of the moderate height framed structures lie within this range. For all the oscillators, 5% damping has been assumed. For nonlinear behaviour, each oscillator is modelled alternatively as elastic perfectly plastic (EPP), stiffness degrading (SD), and strength and stiffness degrading (SSD) oscillators. For better understanding of the inelastic response exhibited by the oscillators under pulse-type motions, two ductility levels viz. 2 and 4, indicating low and medium ductility, have been considered. In order to achieve the target ductility level, elastic strength of an oscillator is reduced to yield strength using strength reduction factor as proposed by Miranda (1993) for alluvium soil sites. This is because about three-fifth of the pulse-type motions considered (i.e., 34 out of 54) are recorded in sites that conform to site class 'D' of ASCE/SEI 7-05 (American Society of Civil Engineers, 2005) and the range of the shear wave velocity for this site class matches with that of the alluvium soils. The modeling and nonlinear time-history analyses of SDOF oscillators have been carried out using a finite element based open-source software, OpenSees (OpenSees, 2010).

4. SELECTION AND SCALING OF GROUND MOTIONS

To investigate the influence of pulse arrival on seismic response of SDOF systems in a systematic manner, only the 54 pulse-type motions originated from dip-slip faults are considered. The scaling of the ground motions is done in such a way that all of them impose the same amount of demand on the elastically responding oscillator of a particular period. The value of scale factor for a particular motion is obtained by taking the ratio of spectral acceleration demand under that motion to the design spectral acceleration, both evaluated at a particular period. For this purpose, the design acceleration response spectrum for 5% damping and PGA = 0.40 g has been considered as per ASCE/SEI 7-05. Such a high PGA is chosen because the expected hazard level is high at sites near to faults. Fig. 4.1(a) depicts the 5% damped design acceleration spectrum (SA_D) along with the mean spectrum of 23 early arriving pulse motions (SA_{EP}) and 31 late arriving pulse motions (SA_{LP}). To illustrate the effect of scaling, the acceleration spectrum of the pulse-type motions scaled at periods 0.5 s, 1.0 s, and 1.5 s are shown in Figs. 4.1(b)-4.1(d). As observed, the scaled pulse motions, especially the late arriving pulse motions, impose higher demands compared to the design spectrum at periods beyond the period at which they are scaled.

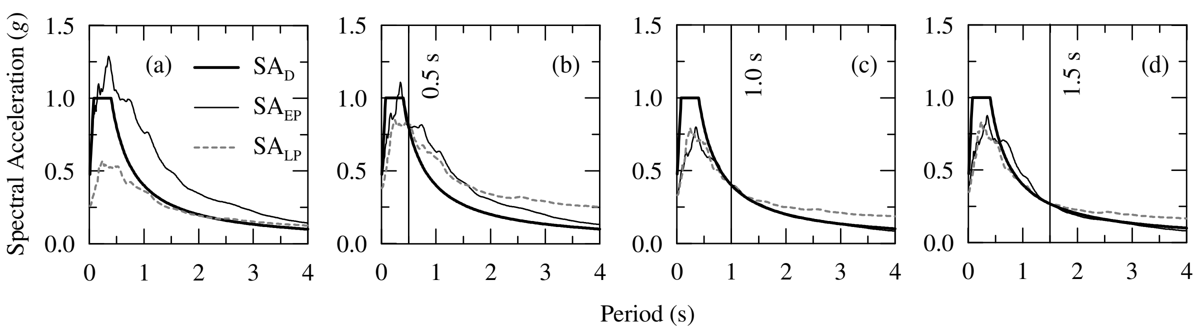

Figure 4.1: Design acceleration spectrum (SA_D) and mean acceleration spectrum of the early arriving pulse (SA_{EP}) and the late arriving pulse (SA_{LP}) motions (a) unscaled, (b) scaled at 0.5 s, (c) scaled at 1.0 s, and (d) scaled at 1.5 s.

5. RESULTS AND DISCUSSION

To quantify the amount of damage incurred by a non-linear system under the pulse-type motions, ductility demand has been chosen as the parameter under investigation. For all types of oscillators and the two target ductility levels, variation of the mean ductility demand with oscillator period for the early arriving pulse and the late arriving pulse motions are shown in Fig. 5.1. One can observe from Fig. 5.1 that for all types of oscillators and both ductility values, the mean ductility demand of the late arriving pulse motions is higher compared to the mean demand of the early arriving pulse motions for the period range considered except around a period of 0.5 s for ductility 2 and below 0.6 s for ductility 4. One can also notice that the ductility demand under the early arriving pulse motions shows a decreasing trend with increasing period with the ductility demand approaching the target ductility at long periods. This trend is not clearly observed for the late arriving pulse motions. It can be observed from Fig. 5.1 that the mean ductility demand under both the early and late arriving pulse motions is the maximum for strength and stiffness degrading oscillators. One can also observe that the mean values of ductility demand are always higher than the target ductility values for the pulse-type motions. The mean ductility demand for the late arriving pulse motions can even exceed twice the target ductility for moderate ductility. This is because the formulation of strength reduction factor used was originally developed considering far-field motions only and not these sets of early and late arriving pulse motions.

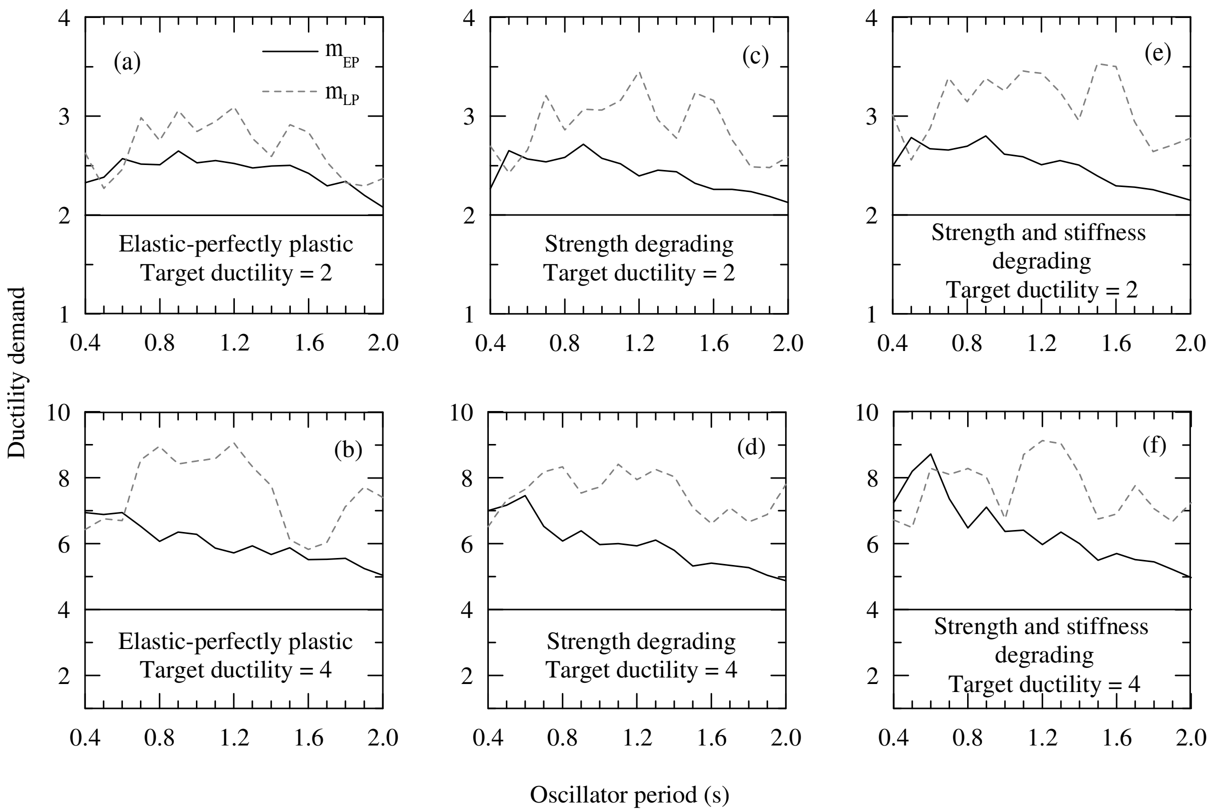

Figure 5.1: Mean ductility demand versus oscillator period for the early arriving pulse (m_{EP}) and the late arriving pulse (m_{LP}) motions for (a, b) elastic-perfectly plastic oscillators, (c, d) strength degrading oscillators, and (e, f) strength and stiffness degrading oscillators for target ductility 2 and 4.

The mean plus one standard deviation values of ductility demand with oscillator period considering the early arriving pulse and the late arriving pulse motions are shown in Fig. 5.2 for all types of oscillators and the two target ductility levels. It can be observed from Figs. 5.1 and 5.2 that the variation of mean values and mean plus one standard deviation values of ductility demand with oscillator period is similar. It is important to note that, for moderate ductility, the mean plus one standard deviation values of ductility demand of the late arriving pulse motions exceed three times the target ductility. For both the target ductility, the mean plus one standard deviation values of ductility demand is the maximum for strength and stiffness degrading oscillators.

To quantify the effect of pulse arrival on ductility demand, the ratio of the mean ductility demand under the late arriving pulse motions to the mean ductility demand under the early arriving pulse motions for both the target ductility have been plotted in Fig. 5.3. One can observe from Fig. 5.3 that, for both the target ductility levels, the late arriving pulse motions impose higher demand compared to the early arriving pulse motions over the period range considered except around 0.5 s for ductility 2 and below 0.6 s for ductility 4. It is important to note that, for strength and stiffness degrading oscillators, the increase in mean ductility demand under the late arriving pulse motions compared to the mean ductility demand under the early arriving pulse motions can be as high as 55% for low ductility and 60% for moderate ductility in the long period range. It can be observed from Fig. 5.3(b) that, depending upon the oscillator type, the mean ductility demand under the early arriving pulse motions may increase upto 30% in comparison to the mean demand under the late arriving pulse motions when the oscillator period is 0.5 s and the ductility is moderate.

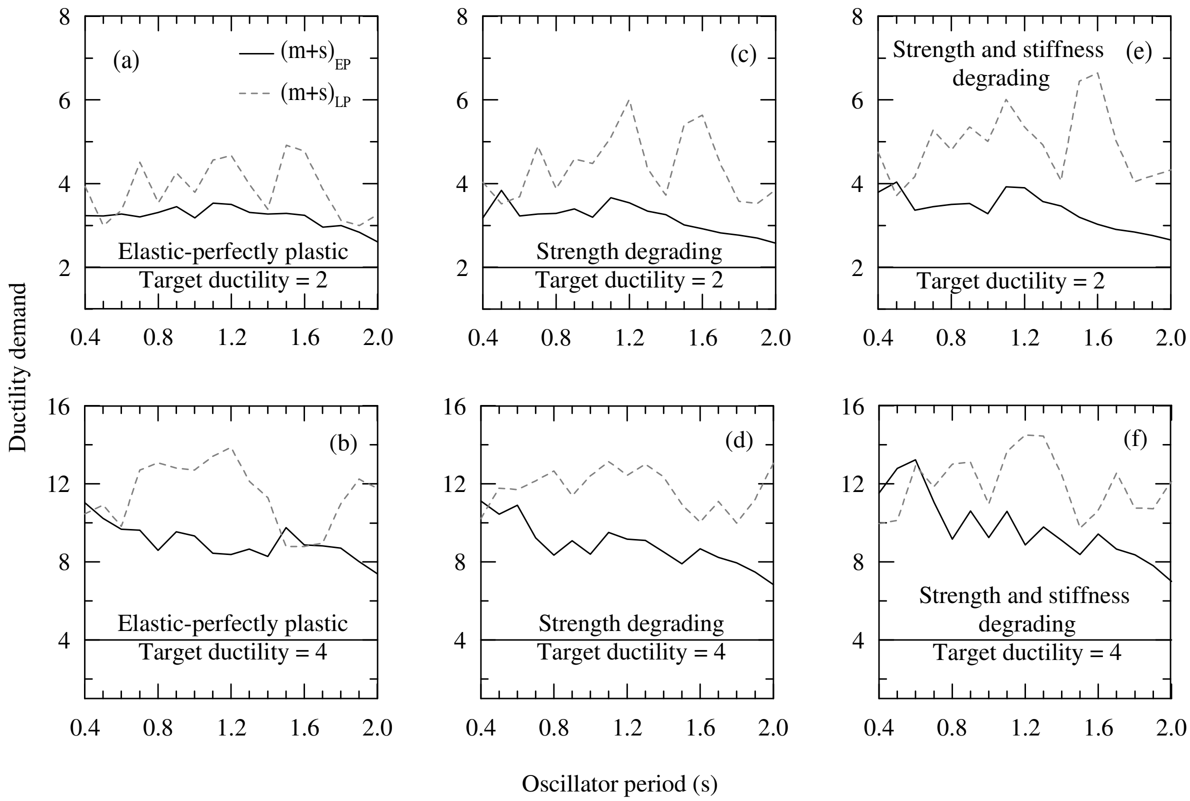

Figure 5.2: Mean plus one standard deviation ductility demand versus oscillator period for the early arriving pulse ($(m+s)_{EP}$) and the late arriving pulse ($(m+s)_{LP}$) motions for (a, b) elastic-perfectly plastic oscillators, (c, d) strength degrading oscillators, and (e, f) strength and stiffness degrading oscillators for target ductility 2 and 4.

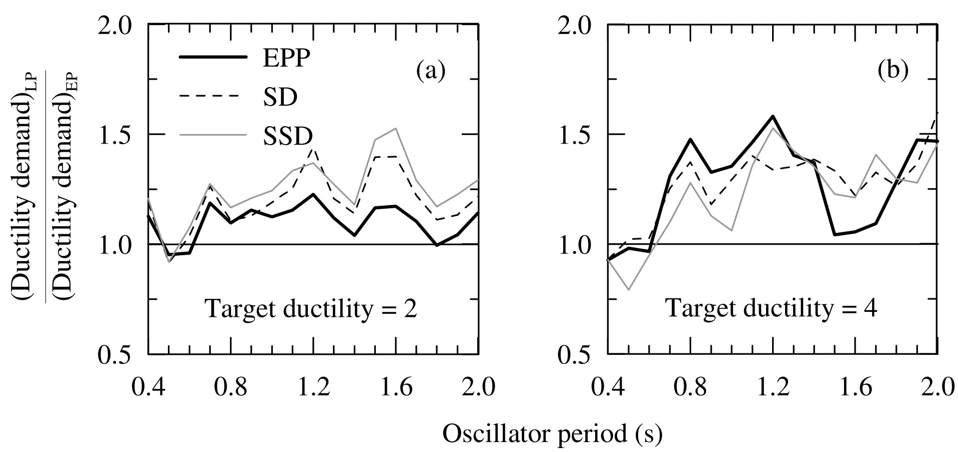

Figure 5.3: Ratio of mean ductility demand for the late arriving pulse motions to mean ductility demand for the early arriving pulse motions versus oscillator period for elastic-perfectly plastic (EPP), strength degrading (SD), and strength and stiffness degrading (SSD) oscillators for (a) target ductility 2 and (b) target ductility 4.

To study the influence of arrival instant of velocity pulse on the increase in mean ductility demand, two oscillator periods viz. 0.5 s and 1.2 s have been considered. These two period values have been considered because the increase in mean ductility demand is very high at these periods. The ratio of the mean acceleration spectrum of the late arriving pulse motions to the mean acceleration spectrum of the early arriving pulse motions are shown in Fig. 5.4 for motions scaled at and in the vicinity of periods 0.5 s and 1.2 s. The vertical lines in these plots indicate the period at which the motions are scaled. It can be observed from Figs. 5.4(a)-5.4(c) that the elastic strength demand of the late arriving pulse motions is slightly lower (with a minimum value of 0.8) than the elastic strength demand of the early arriving pulse motions upto certain period beyond 0.5 s, when the motions are scaled at and in the vicinity of 0.5 s. This indicates the reason behind the increase in mean ductility demand of the early arriving pulse motions over the mean ductility demand of the late arriving pulse motions at 0.5 s (see Fig. 5.3). When the motions are scaled at relatively long periods (i.e., in the vicinity of 1.2 s), the elastic strength demand of the late arriving pulse motions is much higher than the elastic strength demand of the early arriving pulse motions beyond the periods at which the motions are scaled (see Figs. 5.4(d)-5.4(f)). It is also observed from Figs. 5.4(d)-5.4(f) that the mean elastic demand of the late arriving pulse motions increases with respect to the mean elastic demand of the early arriving pulse motions with period. Such increase in elastic strength demand of the late arriving pulse motions results in 55-60% increase in the mean ductility demand under these motions (see Fig. 5.3).

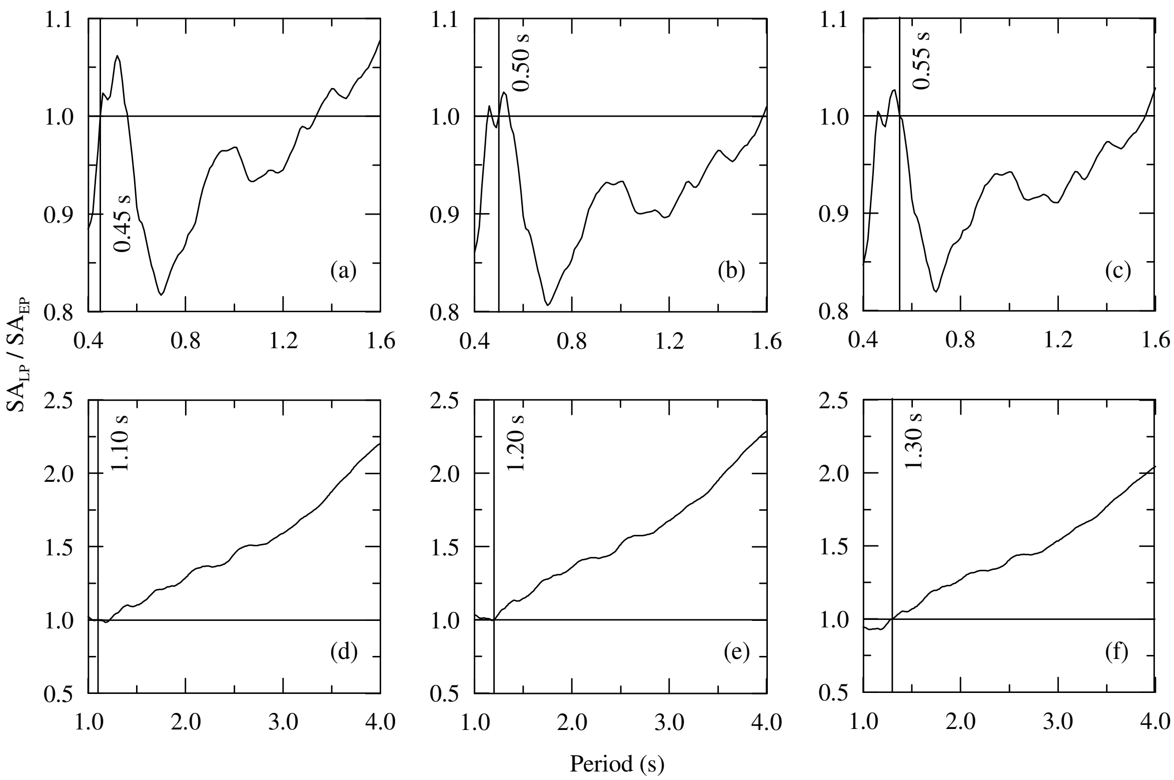

Figure 5.4: Ratio of mean acceleration spectrum of the late arriving pulse motions (SA_{LP}) to mean acceleration spectrum of the early arriving pulse motions (SA_{EP}) versus period for motions (a) scaled at 0.45 s, (b) scaled at 0.50 s, (c) scaled at 0.55 s, (d) scaled at 1.10 s, (e) scaled at 1.20 s, and (f) scaled at 1.30 s.

6. CONCLUSIONS

For systematic evaluation of the influence of the arrival time of velocity pulse on seismic response of structures, a parameter *NAT* has been defined in the present study. An attempt has been made to correlate *NAT* with *R* and T_p. *NAT* is well correlated with *R* and T_p for motions originating from dip-slip faults. As a next step, the pulse-type motions originated from dip-slip faults have been classified into early and late arriving pulse motions based on a *NAT* value of 0.2. Further, nonlinear analyses of a series of SDOF oscillators with various hysteresis rules and periods representing natural period of medium rise frame buildings have been carried out under the early arriving pulse and the late arriving pulse motions. Some of the important observations made from the present study are listed as follows:

(1) *NAT* for pulse-type motions originated from dip-slip faults increases linearly with the increase in *R*.

(2) *NAT* for pulse-type motions originated from dip-slip faults shows a linear increase with T_p upto approximately 6.5 s beyond which it shows a decreasing trend.

(3) The mean ductility demand of pulse-type motions is quite high compared to the target ductility values (75% and 125% for target ductility 2 and 4, respectively).

(4) At long periods, the mean ductility demand of the early arriving pulse motions is only about 10-30% higher compared to the target ductility.

(5) The increase in the mean ductility demand of the late arriving pulse motions can be as high as 55-60% compared to the mean ductility demand of the early arriving pulse motions at long periods.

(6) The mean ductility demand of the early arriving pulse motions slightly exceed the mean ductility demand of the late arriving pulse motions around 0.5 s for ductility 2 and below 0.6 s for ductility 4.

It is important to note that the observations related to nonlinear response are based on the response of SDOF oscillators and hence, apply to only those structures that behave in the similar way as SDOF systems behave.

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