The influences of seismic sequence on the inelastic SDOF systems

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SUMMARY:
Structures located in seismic region may be subjected to multiple ground motions due to the seismic sequence. This paper focuses on the mainshock-aftershock sequence-type ground motions characterized by the presence of strong aftershock ground motions after the mainshock and separated by short intervals of time. Strong aftershocks may increase the damage state of structure for the damage accumulation. This paper investigates the response time histories (acceleration, velocity and displacement) of inelastic single-degree-of-freedom (SDOF) structures under the mainshock-aftershock sequence-type ground motions. It is found that peak responses (e.g. peak acceleration, peak velocity and peak displacement) of structure due to the aftershock are comparable with the corresponding values due to the mainshock. Aftershock may increase or decrease the residual displacement of structure with respect to mainshock alone, and the change of residual displacement can reflect the damage accumulation (e.g. additional damage) of structures due to the aftershock.

Keywords: mainshock-aftershock sequence-type ground motions, inelastic SDOF systems, damage accumulation

1. INTRODUCTION

Historical earthquakes have shown that many aftershocks often follow a large mainshock. Mainshock-aftershock sequence-type ground motions characterized by the repetition of medium-strong earthquake ground motions and separated by short intervals of time have been observed in several areas [CENC, 2008; NIED, 2009; Decanini *et al.*, 2000]. For example, after the mainshock on May 12, 2008 (Mw=8.0) that struck the Sichuan province of China, five aftershocks with magnitudes greater than 6.0 were recorded before May 31 [CENC, 2008]. Therefore, structures located in seismic regions may be subjected to mainshock-aftershock sequence-type ground motions. However, it is impossible for the most structures that damaged by mainshock to be repaired before the presence of subsequent aftershocks due to the short intervals of time. In such cases, strong aftershocks may increase the damage levels of the structures due to the damage accumulation characterized by the additional structural damage induced by aftershock, which has been confirmed in the post-earthquake field reconnaissance [Priestley, 1988; EQE Engineering, 1990]. Nonetheless, almost all the seismic design codes in the world are based on the single ‘design earthquake’ without taking into account the influence of mainshock-aftershock sequence. Consequently, there is a need to investigate the effects of mainshock–aftershock sequence-type ground motions on existing structures.

The original investigation about the seismic sequence can be traced to the end of 19th century, which is conducted by Omori [1894]. In his work, Omori concluded that the rate of aftershocks decays inversely with time after the mainshock. For the effects of mainshock-aftershock sequence-type ground motions on structures, however, it was till 1980 that one of the pioneering studies by Mahin [1980] appeared. Mahin found that strong aftershocks may double the displacement ductility demands of many elastoplastic single-degree-of-freedom (SDOF) systems. Except for the Mahin’s work, there have been several investigations aimed to research the seismic performance of inelastic SDOF systems under the mainshock-aftershock sequence-type ground motions or multiple ground motions [Elnashai *et al.*, 1998; Sunasaka and Kiremidjian, 2002; Amadio *et al.*, 2003; Das *et al.*, 2007; Iancovici, 2007; Hatzigeorgiou, 2009,2010a,2010b; Moustafa and Takewaki, 2011].

From the literature survey, it should be noted that most authors researched the effect of earthquake sequence on the inelastic SDOF systems through the different inelastic response spectra, such as inelastic displacement ratio spectra, behavior factor spectra, etc. However, few of them focused their attention on the characteristic of response time histories of inelastic SDOF structures under the mainshock-aftershock sequence-type ground motions. It should be noted that response spectra values can only provide the maximum seismic response of structure and can't reflect the response evolution of structures under mainshock-aftershock sequence-type ground motions. Unfortunately, to the author's best knowledge, only Moustafa and Takewaki [2011] investigated the response time histories of inelastic SDOF systems with the artificial ground motion sequences. No quantitative information about the acceleration, velocity and residual displacement of systems were provided in these investigations.

In light of the above discussions, this paper studies the response time histories of inelastic SDOF systems under the recorded mainshock-aftershock sequence-type ground motions. Various response demand parameters of structure due to the aftershock, such as peak acceleration, peak velocity, peak displacement and residual displacement are compared with the corresponding values due to mainshock.

2. STRUCTURAL MODEL AND GROUND MOTIONS

The periods of vibration of the inelastic SDOF systems in this paper are set at 0.5s and 2s， as the representative periods of short and medium-long period structures, respectively. The viscous damping ratio is assumed to be 5%. Elastic-Perfectly-Plastic (EPP) hysteretic model is utilized here for its simple form of force-displacement relation. The relative lateral strength of system is measured by the strength reduction factor R, which is defined as the ratio between the strength demand on an infinitely elastic SDOF system during the ground motion and the yield strength of the corresponding inelastic SDOF system with the same mass and initial stiffness. Four values of R are considered (i.e. R=2, 3, 4 and 5) to study the influence of different yield strength. It should be noted that the P-Delta effect is not included in this paper.

Large numbers of mainshock-aftershock sequence-type ground motions were recorded in the Chi-chi earthquake (Mw=7.6), which struck the central area of Taiwan on September 21, 1999. Two records of sequence-type ground motions are selected from the Chi-chi earthquake, as shown in Table 2.1. It is well known that there is a time gap between mainshock and aftershock for most seismic sequences. After the excitation of the mainshock, the vibration of structure will cease gradually due to damping, and then structure begins to move when the aftershock presents. Therefore, a time gap of 100s is applied between two consecutive seismic ground motions to accommodate the real situation, and this time gap is considered sufficient to cease the vibrating of any civil structures because of damping [Hatzigeorgiou, 2011a]. The time histories of the sequence-type ground motions used in this paper are presented in Figure 2.1.

Table 2.1. List of mainshock and aftershock ground motions in the Chi-Chi Earthquake.

Earthquake	Station	Direction	Shock Type	Date/Time	*M*	*PGA*(g)	Record Name
Chi-chi	CHY015	W-E	mainshock	1999-9-20	7.6	0.145	CHY015-W
			aftershock	1999-9-25 23:52	6.3	0.121	
	CHY029	W-E	mainshock	1999-9-20	7.6	0.277	CHY029-E
			aftershock	1999-9-25 23:52	6.3	0.241	

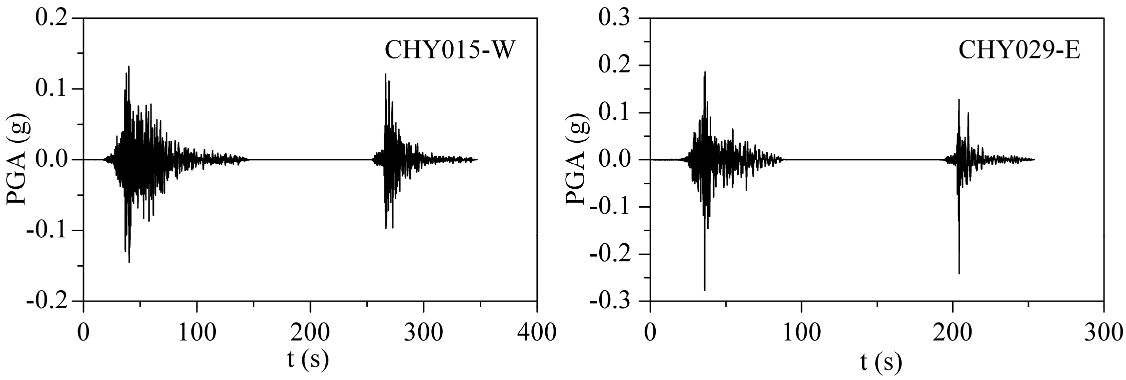
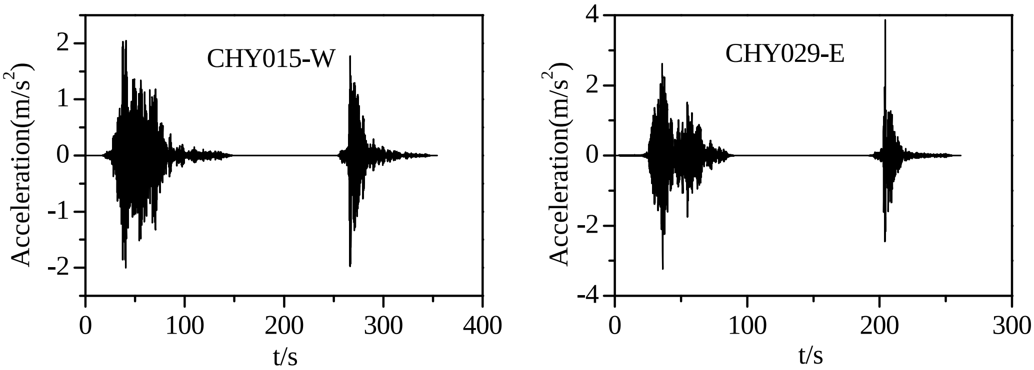


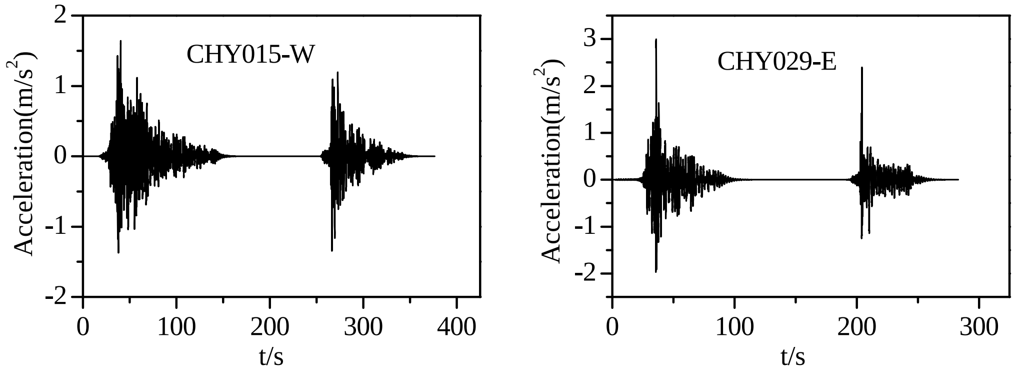
Figure 2.1. Time histories of sequence-type ground motions with a time gap of 100s added between two motions.

3. ACCELERATION

Figure 3.1 shows the acceleration response time histories of inelastic SDOF systems corresponding to *R*= 5. There is the obvious time range where acceleration responses of structures keep the constant of zero, which also confirm that the time gap of 100s between two consecutive seismic ground motions is enough to cease the vibrating of structure due to the damping. The peak acceleration (PA) of structure due to the aftershock is comparable with or even larger than the one due to the corresponding mainshock.



(a) *T*=0.5s

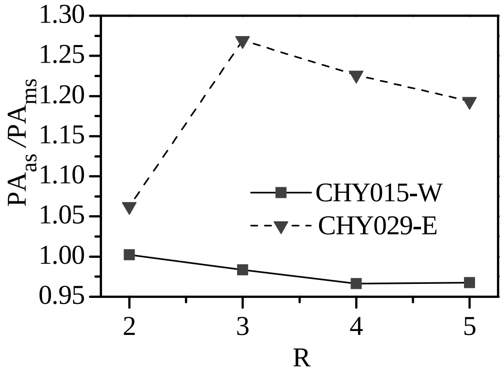


(b) *T*=2s

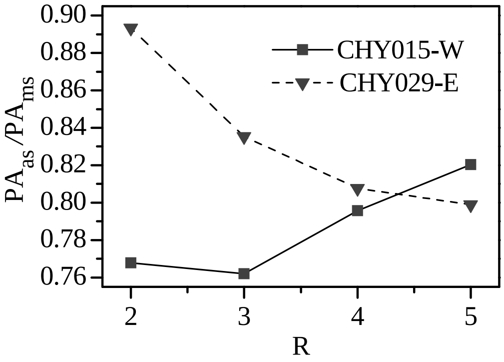
Figure 3.1. Time histories of acceleration response of systems for strength reduction factor *R*=5

To illustrate the effect of aftershock on the acceleration response of inelastic SDOF system more clearly, the ratios of peak accelerations of structures under aftershock ground motions to peak accelerations of structures under mainshock ground motions are presented in Figure 3.2. It is obvious from Figure 3.2 that aftershocks have the significant influence on the acceleration response of inelastic

SDOF system. All the ratios presented in Figure 3.2 are larger than 70%, which means that the peak acceleration of system due to the aftershock should not be ignored. Furthermore, the ratios of peak accelerations of structures (*T*=0.5s) under the ground motion CHY029-E, as shown in Figure 3.2(a), are greater than 1.0, and the peak value of these ratios is 1.27. These results indicate that the mainshock-aftershock sequence-type ground motions have the potential to increase the peak acceleration of structure with respect to the mainshock ground motion alone.



(a) *T*=0.5s



(b) *T*=2s

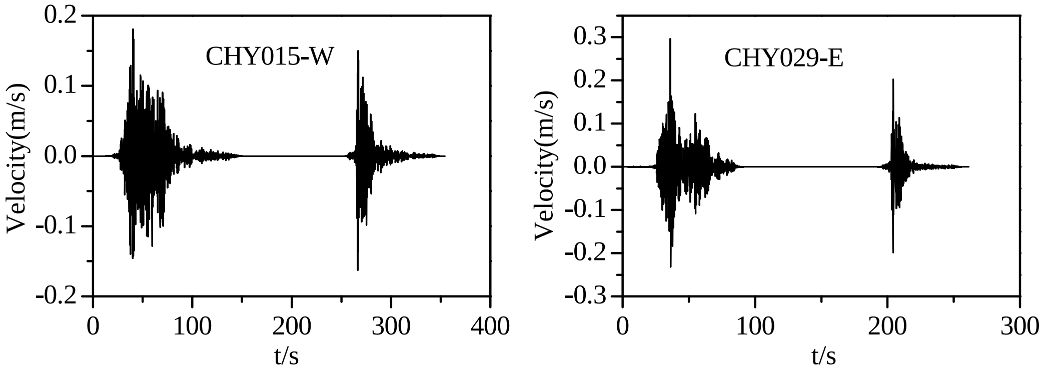
Figure 3.2. Ratios of peak accelerations of structures under aftershock to peak accelerations of structures under mainshock

4. VELOCITY

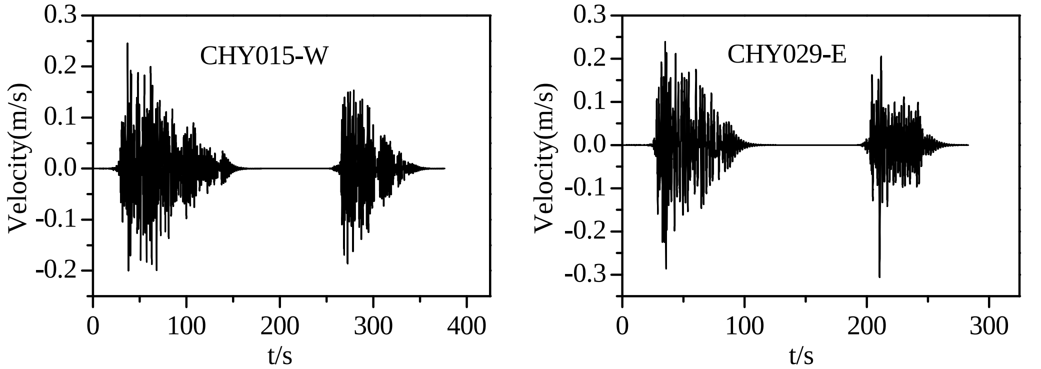
The velocity response time histories of inelastic SDOF systems corresponding to *R*= 5 are presented in Figure 4.1. The results in Figure 4.1 indicate that, in general, the velocity response time histories of inelastic SDOF systems exhibit the similar trend with the acceleration response time histories. The peak velocity (PV) of structure due to the aftershock is comparable with or even larger than the one due to the corresponding mainshock.

Figure 4.2 shows the ratios of peak velocities of structures under aftershock to peak velocities of structures under mainshock, for demonstrating the influence of aftershock on the velocity response of inelastic SDOF system. It is obvious that all ratios presented in Figure 4.2 are greater than 65%, which means that the peak velocity of system due to the aftershock should not be neglected. Moreover, the ratios corresponding to structures (*T*=2s) under the ground motion CHY029-E, as shown in Figure 4.2(b), are greater than 1.0, and the peak value of these ratios is 1.33. These results imply that the mainshock-aftershock sequence-type ground motions may increase the peak velocity of structure with respect to the mainshock ground motion alone. Therefore, the conclusion that aftershock has the significant effect on the velocity response of inelastic SDOF system should be reasonable.

However, we observe that the aftershock can’t always enhance both of peak acceleration and peak velocity of the same structure. For example, for the structure (*T*=0.5s) corresponding to *R*=4 under the ground motion CHY029-E, the peak acceleration of structure due to the aftershock is larger than corresponding value due to the mainshock, as shown in Figure 3.2, but the size relation between the peak velocities of structure due to the aftershock and mainshock is just in reverse, as shown in Figure 4.2.

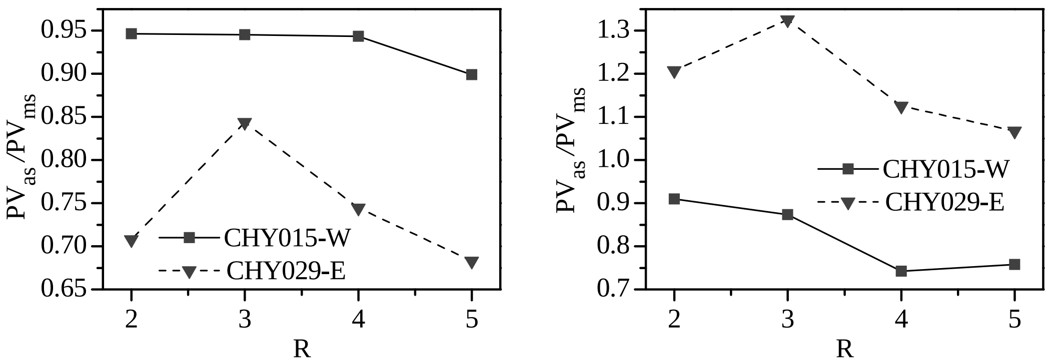


(a) *T*=0.5s



(b) *T*=2s

Figure 4.1. Time histories of velocity response of systems for strength reduction factor *R*=5

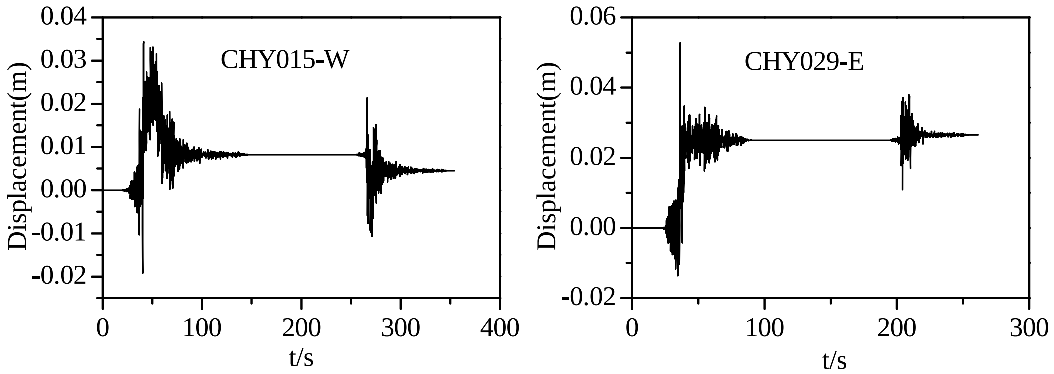


(a) *T*=0.5s (b) *T*=2s

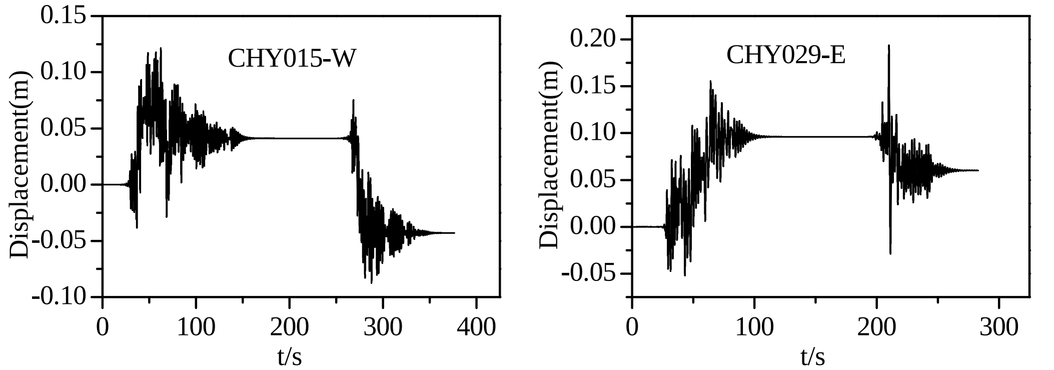
Figure 4.2. Ratios of peak velocities of structures under aftershock to peak velocities of structures under mainshock

5. DISPLACEMENT

Figure 5.1 presents the displacement response time histories of inelastic SDOF systems corresponding to *R*=5. There is the notable residual displacement after the mainshock, which means that the structure will cease the moving on the new balance position before the presence of aftershock. The results in these figures show that aftershock may increase the peak displacement of structure or change the residual displacement of structure. Another interesting phenomenon is that the aftershock may alter the direction of residual displacement, as shown in Figure 5.1(b) corresponding to ground motion CHY015-W.



(a) T=0.5s

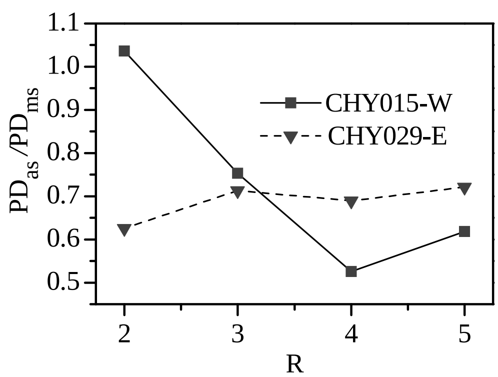


(b) T=2s

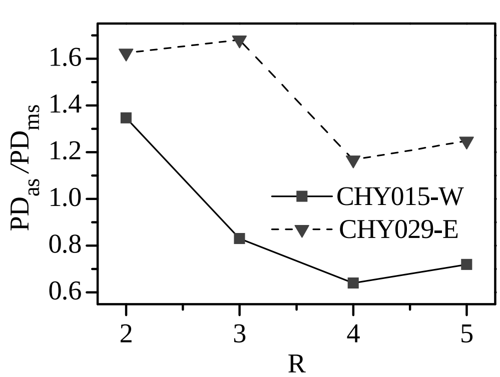
Figure 5.1. Time histories of displacement response of systems for strength reduction factor R=5

The ratios of peak displacements of structures under aftershock to peak displacements of structures under mainshock are presented in Figure 5.2. Most ratios in Figure 5.2 are larger than 60%, which means that aftershock can cause the comparable peak displacement with the mainshock. Furthermore, the ratios corresponding to structures (T=2s) under the ground motion CHY029-E are greater than 1.1, and the peak value of these ratios is 1.68. These results quantitatively show that mainshock-aftershock sequence-type ground motions have the potential to increase the ductility demand of structures with respect to mainshock ground motion alone.

Nevertheless, the results in Figure 5.2 also indicate that mainshock-aftershock sequence-type ground motions can't elevate the ductility demand for all structures, even for the structures with the same period of vibration. For instance, whether the ratios corresponding to the structures (T=0.5s) under the ground motion CHY015-W are greater than 1.0 depends on the relative lateral strength (measured by strength reduction factor R), as presented in Figure 5.2(a).



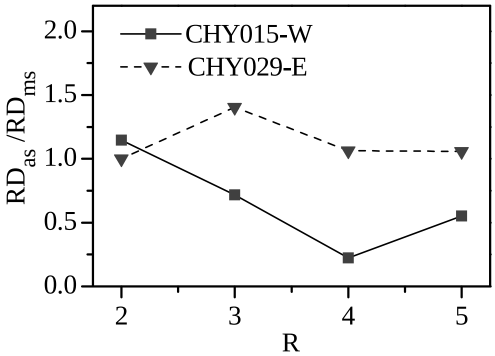
(a) T=0.5s



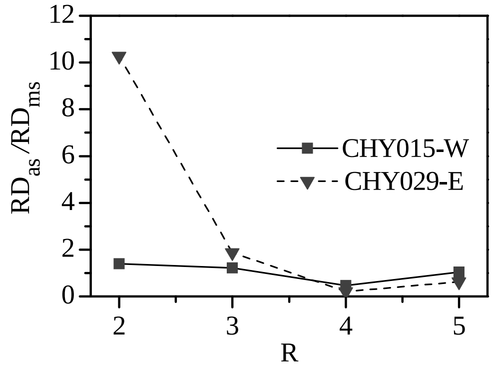
(b) T=2s

Figure 5.2. Ratios of peak displacements of structures under aftershock to peak displacements of structures under mainshock

The ratios of residual displacements of structures under aftershock to residual displacements of structures under mainshock are illustrated in Figure 5.3. The ratio being greater than 1.0 means that aftershock increase the residual displacement of system with respect to mainshock, while the ratio being smaller than 1.0 means that aftershock decrease the residual displacement of structure. It is obvious that the aftershock may increase or decrease the residual displacement of systems, because the ratios in Figure 5.3 are greater or smaller than 1.0. Residual displacement means that the structure undergoes the inelastic deformation during the ground motion. The change of the residual displacement due to the aftershock means that the structure undergoes the inelastic deformation during the aftershock ground motion. So the damage of structure will increase with the change of residual displacement.



(a) T=0.5s



(b) T=2s

Figure 5.3. Ratios of residual displacements of structures under aftershock to residual displacements of structures under mainshock

6. CONCLUSIONS

The main purpose of this paper is to study the response time histories of inelastic SDOF systems under the mainshock-aftershock sequence-type ground motions. For those purposes, the time histories of acceleration, velocity and displacement response of inelastic SDOF systems under the mainshock-aftershock sequence-type ground motions are analyzed. Various response demand parameters of structure due to the aftershocks are compared with the corresponding values due to the mainshocks. The following conclusions are drawn from this investigation:

(1) The peak acceleration, velocity, displacement of structure due to the aftershock are comparable with the corresponding values due to the mainshock, and in particular aftershock has the potential to increase the response of structure. In addition, it should be noted that the aftershock can’t always enhance both of peak acceleration, peak velocity of the same structure, which means that for a fixed structure, aftershock may increase the peak acceleration while not increase the peak velocity.

(2) Aftershock may increase or decrease the residual displacement of structure with respect to mainshock alone, and the change of residual displacement can reflect the damage accumulation of structures. However, it is difficult to detect the change of residual displacement just from the final residual displacement of structure at the end of seismic sequence. In addition, aftershock has the potential to change the direction of residual displacement.

It should be noted that the results in this paper are based on Elastic-perfectly plastic (EPP) hysteretic model, and the deterioration and pinching effect of structure are not included. However, the results and conclusions in this paper are suitable for most of the existing structures, and the effects of different hysteretic models which can consider the deterioration and pinching effect of structure will be further studied in our future work.

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