Damage Assessment of RC Frame Structures under Mainshock-Aftershock Seismic Sequences

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SUMMARY:
This paper presents a numerical investigation on the cumulative damage of structures subjected to mainshock-aftershock seismic sequences. For this purpose, a three-storey RC frame model structure was built and subjected to repeating mainshock-aftershock ground motions and mainshock earthquake only. The damage state of the frame model was measured by the Park and Ang's damage index. It was found that, unlike previous results based on the peak and residual drift demands, aftershock does significantly increase the damage state of the structure. Furthermore, the damage state of the structure may be strongly dependent on the cumulated damage caused by previous earthquake. The residual displacement of structure under a strong mainshock will become the new balance axis for the follow-up earthquakes, and have to be taken into consideration in calculating the Park and Ang's damage index.

Keywords: mianshock-aftershock earthquake, RC frame structure, residual displacement, cumulative damage

1. INTRODUCTION

In modern seismic design code of different countries, the structure is designed to behave linear-elastically without damage under a moderate single earthquake (Ghobara, 2001). However, historical events indicate that aftershocks usually happen after mainshock earthquake which brings about the cumulative damage effect to the structures. For example, in May 12, 2008, Wenchuan earthquake (M=8.0), there were 86403 aftershocks including 8 with magnitude greater than 6.0, and 40 with magnitude greater than 5.0. Many buildings were severely damaged and even collapsed in aftershock earthquakes (Zhao, Taucer, and Rossetto, 2009). Similarly, in March 11, 2011, the Great East Japan earthquake (M=9.0), there were more than 600 aftershocks bigger than magnitude 4.5, including a 7.7M aftershock happened 30 minutes following the mainshock earthquake (Takewaki, 2011). In particular, earthquakes followed by strong aftershocks have caused extensive structural damage, and induced huge losses of human lives and property. For example, the Luanhe river bridge collapsed in the 7.1 magnitude aftershock which took place 15 hours after Tangshan earthquake (M=7.8), in July 28, 1976 (Wu and Li, 1995). Similarly, it was reported that an aftershock (M=5.3) of the 1987 Whitter Narrows earthquake (M=5.9) increased the damage of the I-5/I-605 separator which had been caused by the mainshock (Priestley 1988). It is clear that aftershocks are crucial to structural safety in the event of earthquakes. Therefore, it is necessary to further understand the effects of mainshock-aftershock seismic sequences in the seismic response of the structure.

There are several investigations aimed at studying the effect of different seismic sequences on the response of single-degree-of-freedom (SDOF) and multiple-degree-of-freedom (MDOF) systems. Earthquake events are typically composed of mainshock and aftershock sequences. The mainshock earthquake in most cases releases the largest amount of energy and thus causes the detrimental damage and destruction. Generally, the maximum magnitude sequence is regarded as the mainshock sequence. Yoshio and Anne (1993) studied the safety evaluation of the structure under mainshock-aftershock earthquake sequences, and found that the large magnitude of the aftershocks could cause significant cumulative damage effect of structures. So the mainshock-aftershock earthquake sequence consists of the mainshock sequence and the largest magnitude of the aftershock earthquake, or the largest and the second largest magnitude of the aftershock earthquake in one earthquake event. The mainshock-aftershock earthquake sequence can be divided into two groups according to what the aftershock sequence accounts for: a) as-recorded seismic sequence; b) artificial seismic sequence. As-recorded seismic sequence can reflect the real characteristics of the mainshock and aftershock sequences. Mahin (1980) studied the response of nonlinear SDOF systems which were subjected to mainshock–aftershock acceleration time histories recorded during the 1972 Managua earthquake. He employed that the displacement ductility demand of elastoplastic SDOF systems slightly increased at the end of the main aftershock with respect to the mainshock. Similarly, a numerical study of nine existing Mexican highway bridges under as-recorded mainshock-aftershock seismic sequences was carried out by Ruiz-Garcia, *et al* (2008). They observed that there was a slight increase in maximum lateral drift peak. George and Asterios (2010) studied the inelastic response of eight RC frames which were subjected to five real seismic sequences, and they were recorded by the same station, in the same direction and in a short period of time, up to three days. In such cases, there was a significant damage accumulation as a result of multiplicity of earthquakes. However, there are few seismic records of the mainshock-aftershock earthquake, and they strictly dependent on types of site. Moreover, successive real events present different characteristics, making the study more complex to perform, and a probabilistic approach is required to solve the problem.

A few studies deal with the effect of artificial seismic sequence on the response of the structure. Li and Ellingwood (2007) studied the response and damage state of two steel moment resisting frame models subjected to artificial seismic sequences by scaling the mainshock by a factor derived from the aftershock hazard near Eureka, California. The damage ratio for beam-to-column connections is defined as the ratio of the number of fractured connections to the total number of connections. It was demonstrated that the damage pattern might change during the aftershocks. It depended on the period shift caused by damage due to the mainshock and the frequency characteristics of the aftershock ground motion. Ruiz-Garcia and Juan (2011) studied the response displacement of the structure under artificial sequences, which are based on the randomized, back-to-back approach, and as-recorded seismic sequences as well. It found that the artificial seismic sequence might lead to an overestimation of the maximum lateral drift peak and residual drift demands compared to the as-recorded ones. But their lateral drift demands would increase when aftershock is considered. And an examination of the as-recorded seismic sequences showed that the frequency content of the mainshock and the main aftershock were weakly correlated. This back-to-back approach neglected the different characteristics of the mainshock and aftershock sequences, but it can to some extent reflect the response and the cumulative damage state of the structures under aftershock.

It should be noted that although previous studies provided information for the effect of seismic sequences on the response of structures, most of the previous studies employed the lateral displacement demands to evaluate the seismic response. However, Shunsuke and Sozen (1972) indicated that the maximum peak lateral displacement caused by the second earthquake sequence was the same as that by the first one, when small scale RC frames was subjected to a repeating earthquake sequence. It seems that the peak lateral displacement does not appropriately represent the cumulative damage of structures under mainshock-aftershock seismic sequences, and the damage index might be a more reasonable parameter to characterize the performance of structures under multi-impacting earthquakes.

The main objective of this study is to gain further understanding on the effects of mainshock–aftershock seismic sequences in the cumulative damage of RC frame structure. For this purpose, nonlinear dynamic analyses were conducted for the three-storey RC frame with different repeating mainshock-aftershock earthquake sequences.

2. STRUCTURE AND MODELING

As an example, a three-storey RC frame building shown in Fig.1, was chosen for demonstration. The columns had dimensions: 300*mm*×300*mm*. All the beams had rectangular cross-sections, with the width of 250*mm* and height of 500*mm*. The typical reinforcement of column and beam was given in Fig.1. The slabs had a thickness of 100*mm*.

The structure was designed according to Code for Seismic Design of Buildings in China (GB 50011-2010) for a fortification intensity of 7, soil type Ⅳ. A permanent load of 8kN/m^2 and a live load of 2kN/m^2 were adopted in the design of the structure. The only exception was the roof, which had a permanent load of 9kN/m^2 and a live load of 0.5kN/m^2. Concrete with quality C30 and Q335 longitudinal reinforcement (yield strength of normalized value amounts to 335*MPa*) were used for the construction of described building. The transverse reinforcement type was Q235, whose yield strength of normalized value was 235*MPa*.

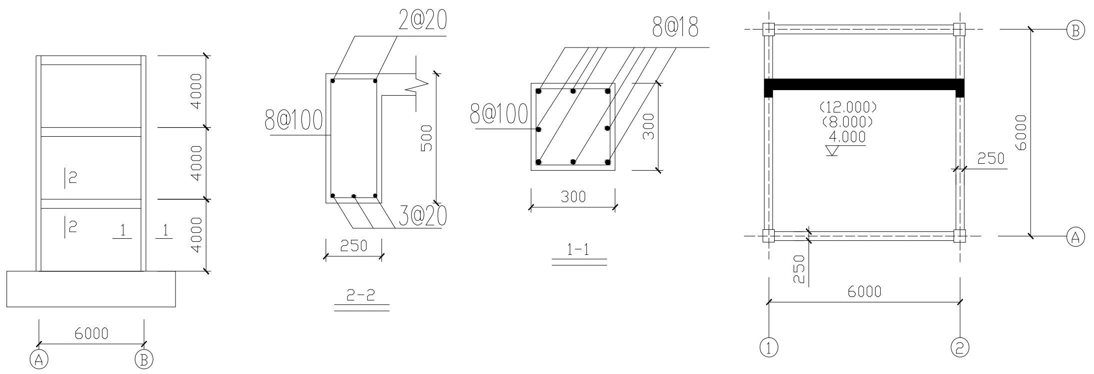


Figure 1. Dimensions of the three-story frame building

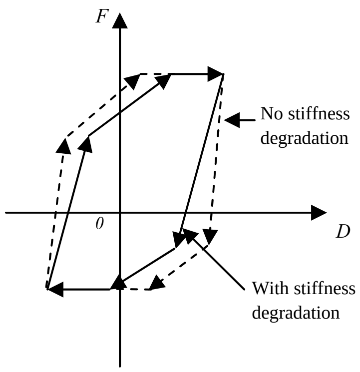


Figure 2. Hysteretic loop with stiffness degradation

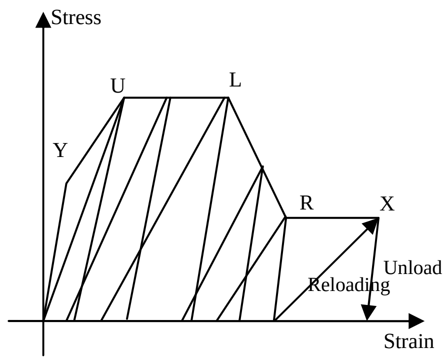
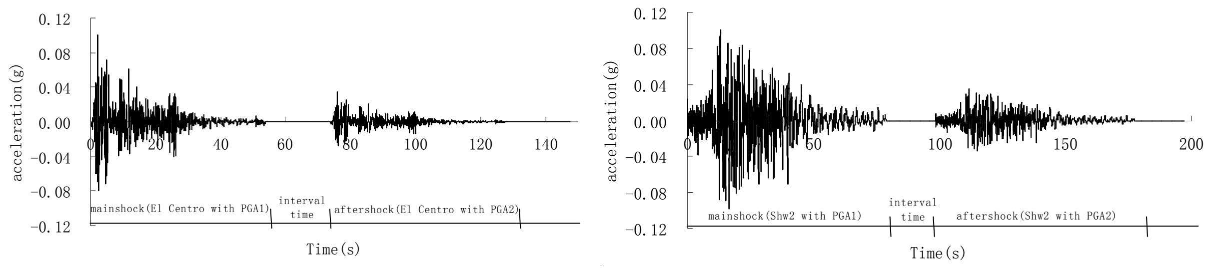


Figure 3. Hysteretic model

Nonlinear dynamic analyses were conducted for the three-storey RC frame with different mianshock-aftershock earthquake ground motions. The computer software PERFORM-3D was selected for the analyses. The beams and columns were modeled by fiber beam element based on the material characteristics. In the PERFORM-3D, the amount of energy degradation was related to the amount of stiffness degradation. Fig.2 shows the hysteresis loop with stiffness degradation. The hysteretic rules were given in Fig.3. The degradation factor at each of the Y, U, L, R and X points was 1, 0.9, 0.7, 0.4 and 0.3 respectively.

3. DYNAMIC ANALYSIS

In this study, attention is focused on the cumulative damage in the RC frame subjected to aftershocks with different magnitude. For this purpose, the El Centro (NS component) sequence and the Shanghai artificial seismic wave 2 (Shw2) were selected as a seed for simulating repeating mainshock-aftershock earthquake sequences with back-to-back approach. The ground motion's features such as frequency content, and strong motion duration of the mainshock and aftershock sequences are similar, but the magnitudes are different. And a 20s silent time interval was added between the mainshock and aftershock sequences shown in Fig.4. Ten mainshock-aftershock sequences with different intensity were prepared as listed in Table.1 for structural analysis.



(1) The El Centro (NS component) Sequence

(2) The Shw2 Sequence

Figure 4. The mainshock-aftershock earthquake sequence

Table.1. List of the Amplitude of Mainshock Only and Mainshock-Aftershock Sequences

Sequence	PGA(g) of mainshock only sequence	Mainshock-aftershock sequence	
		PGA1(g) of mainshock	PGA2(g) of aftershock
El Centro (NS component)	0.1	0.5	0.1
	0.2	0.5	0.2
	0.3	0.5	0.3
	0.4	0.5	0.4
	0.5	0.5	0.5
Shw2	0.1	0.5	0.1
	0.2	0.5	0.2
	0.3	0.5	0.3
	0.4	0.5	0.4
	0.5	0.5	0.5

4. RESULTS

4.1 Displacement time-history response

Fig.5 shows the response displacement of three-story RC frame structure subjected to the different mainshock-aftershock earthquake. It is found that there is a significantly residual displacement after a strong mianshock. The residual displacement under the Shw2 mianshock earthquake sequence is larger than that of the El Centro sequence, due to the difference in spectral characteristics of the two earthquake sequences. In addition, the cumulative residual displacement under Shw2 is gradually increased with the magnitude of the aftershock sequence increasing, while that under EI Centro earthquake sequence is uncertain. A possible explanation could be that the change of the residual displacement under mainshock earthquake may be influenced by the characteristic of the next seismic sequence. This reveals that the lateral drift as a single index for measuring the structural global performance is not sufficient to reflect the damage state of the structures.

Fig.6 shows the response displacement of the three-story RC frame structure during aftershocks of different intensity as well as mainshock earthquake only. In all cases, the intensity of the mainshock earthquakes is the same and is taken to be 0.5*g*. It is found that the residual displacement of the structure after a strong mianshock sequence will become the new balance axis for the response of the structure under aftershock. And it is not significantly increased in the maximum displacement of the structure under aftershock sequence, comparing with that by the mainshock earthquake only. In addition, the change of cumulative residual displacement may be not sure, because the spectral characteristics and magnitude of the aftershocks are different. The aftershock influences the residual displacement of the structure and mainshock-aftershock seismic phenomena should be taken into account to achieve reliable estimation of the residual displacement.

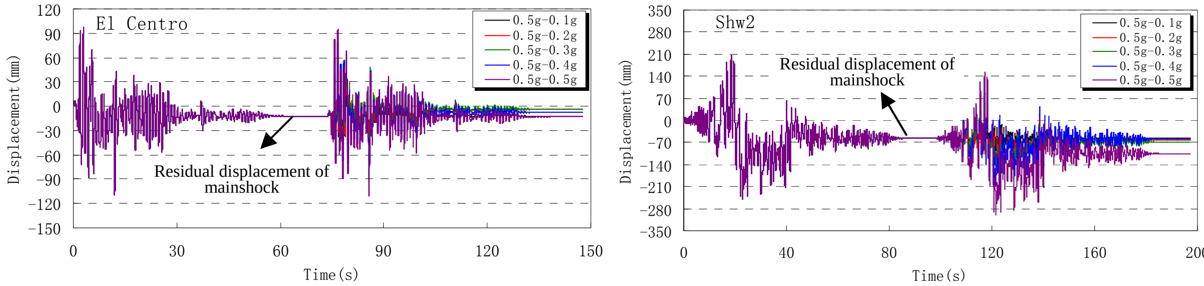


Figure 5. The response displacement of three-story RC frame structure under mainshock-aftershock sequence

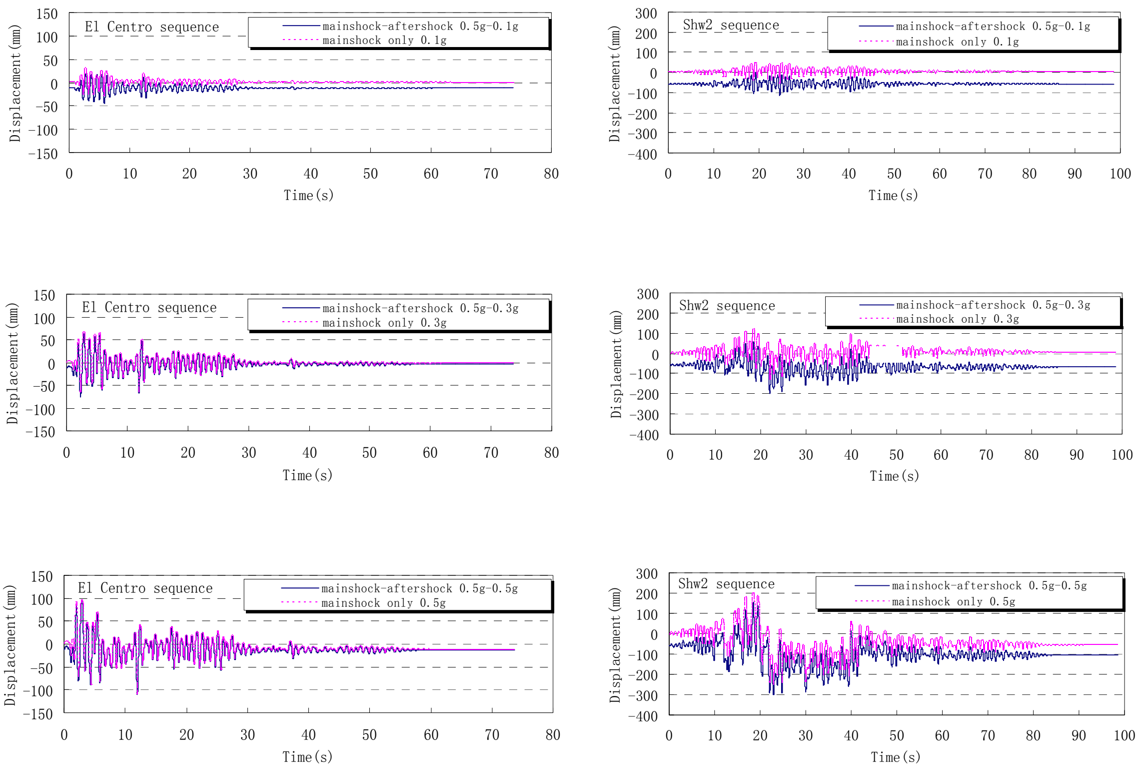


Figure 6. The response displacement of aftershock and mainshock only

4.2 Results of damage analysis

Park and Ang's global damage index (Park and Ang, 1985) is one of the best known and most widely used damage index. It is based on scaled values of ductility and dissipated energy of the local element during the seismic ground shaking. The damage index (*DI*) is defined as a combination of maximum deformation and hysteretic energy:

$$DI = \frac{\delta_m}{\delta_u} + \frac{\beta}{P_y \delta_u} \int dE_h \tag{4.1}$$

Where δ_m is the maximum deformation of the element, δ_μ the ultimate deformation, β a model constant parameter (usually, β=0.05–0.20) to control strength deterioration, $\int dE_h$ the hysteretic energy absorbed by the element during the earthquake and P_y is the yield strength of the element.

First, the damage state of the structure was estimated by taking the mainshock-aftershock earthquake sequences as a single event using Eqn. 4.1. The ultimate rotations used in calculating Park and Ang's index is 5. And β is taken as 0.15 according to Park, *et al* (1987) for nominal strength deterioration. Fig.7 shows the damage index versus PGA for the structure subjected to mainshock-aftershock sequences as well as mainshock earthquake only. In all cases, the intensity of the mainshock earthquake are the same and are taken to be 0.5*g*. There is an obvious correlation between the PGA of the aftershock earthquake and the damage state of the structure, the damage index increases with the magnitude of the aftershock earthquake rising. In Fig.7, it can be found that, after a strong earthquake, the structural damage index well become sensitive to the aftershock earthquake. It increases obviously even under a minor aftershock sequence. It is true both El Centro and Shw2 sequence as shown in Fig.7(1) and Fig.7(2). This suggests that the damage state of the structure would be aggravated after subjected to a strong aftershock earthquake, and may be strongly dependent to the cumulated damage caused by previous earthquake.

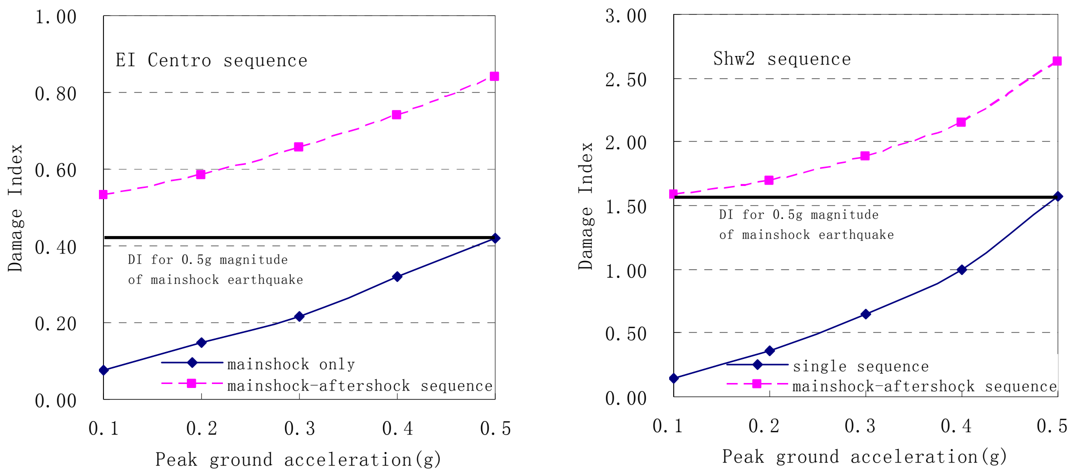


Figure.7 Park and Ang's damage index under mainshock-aftershock and mainshock only

For a thorough understanding of the cumulated damage caused by previous earthquakes, the damage state of the structure was again estimated by taking the aftershock earthquake as a single event and comparing to cases of mainshock earthquake only with different intensity. Fig.8 shows the hysteretic relationship between displacement and base shear of aftershock earthquake and mainshock only with different magnitude. It is found that the residual displacement of the structure after a strong mianshock sequence will become the new balance axis for the response of the structure under aftershock. So the residual displacement after mainshock earthquake should be considered for calculating the Park and Ang's damage index of aftershock earthquake. Fig.9 shows the ratio of Park and Ang's damage index of the aftershock earthquake divided by that of the mainshock only ($DI_{aftershock}$ / DI_{only}) with the different magnitude. In order to calculate the Park and Ang's damage index of aftershock earthquake, it has to consider the residual displacement of the structure after mianshock earthquake. It is found that the ratio is larger than one ($DI_{aftershock} > DI_{only}$), and it gradually reduces with the increasing magnitude of the aftershock earthquake. There is an obvious damage of the structure after mainshock earthquake, and the damage state of the structure will be significantly cumulated under slight magnitude of aftershock, comparing with the unimpaired structures. The Park and Ang's index which is based on scaled values of ductility and dissipated energy of the structure during the seismic ground shaking can qualitatively and quantitatively account for the cumulative damage of structure under aftershock sequence.

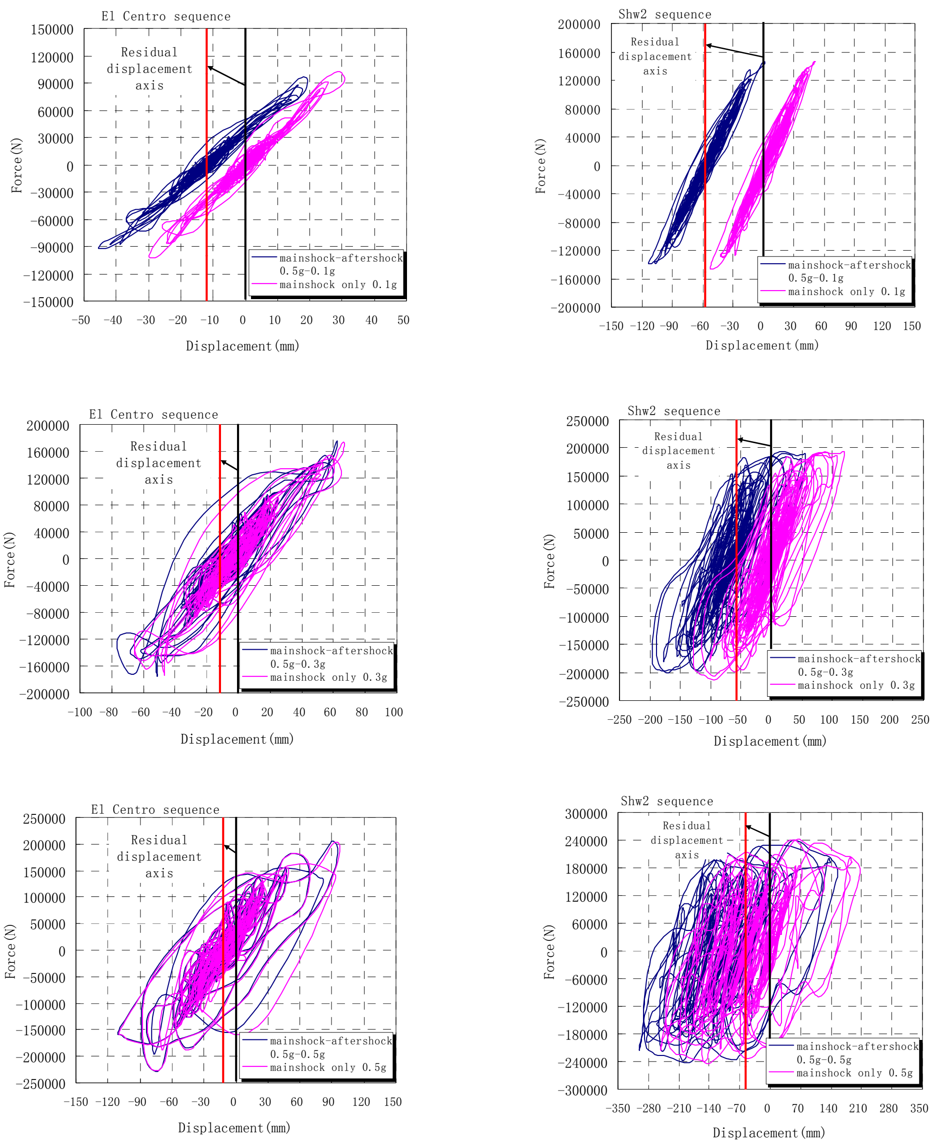


Figure.8 Hysteretic relationship with aftershock sequence and mainshock only

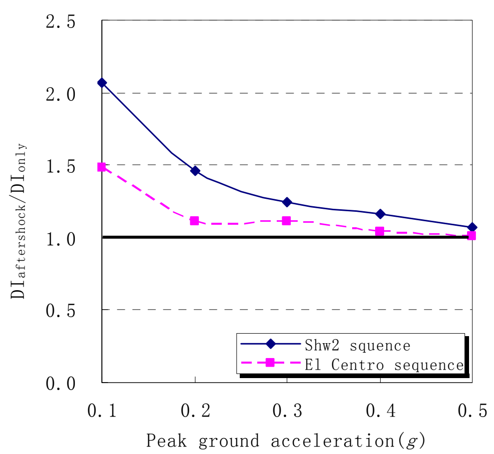


Figure.9 The ratio of Park and Ang's index of aftershock and mainshock only with PGA

5. CONCLUSIONS

This paper presents the results of an analytical investigation aimed at evaluating the cumulative damage of a three-storey RC frame structure subject to different repeating mainshock-aftershock earthquake sequences. From the results obtained in this investigation, the conclusions are drawn as follows:

- The seismic damage for mainshock-aftershock earthquake is higher than that for single ground motion. But aftershock sequences do not significantly increase the large lateral drift demands. A possible explanation would be that the lateral drift as a single index for measuring the structural global performance is not sufficient to reflect the damage state of the structure.
- The residual displacement of structure after a strong mianshock earthquake would become a new balance axis for next earthquake. Due to the difference between spectral characteristics and magnitude of the aftershock earthquake, the changes of cumulative residual displacement may not be sure under aftershock sequence.
- There is an obvious correlation between the PGA of the aftershock earthquake and the damage state of the structure. The damage index gradually increases with the magnitude of the aftershock earthquake rising.
- The damage state of the structure may strongly dependent on the cumulated damage caused by previous earthquake. The mainshock-aftershock seismic phenomena should be taken into account to reliably estimate the performance of the structure.
- The damage index based on the Park and Ang's model can qualitatively and quantitatively ascertain the cumulative damage state of the structure under aftershock earthquake. It suggested that the residual displacement of the structure caused by a strong mianshock earthquake should be taken into considering when using Park and Ang's model to calculate the damage state of the structure under aftershock earthquake.

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