*Proceedings of the $2^{nd}$ International Conference on Civil, Structural and Transportation Engineering (ICCSTE'16)*
*Ottawa, Canada – May 5 – 6, 2016*
*Paper No. 117*

# Influencing Factors of Incremental Damage Evolution of Reinforced Concrete Structures Subjected to Aftershocks

**Jingjing Xu*, Zheng He**
Department of Civil Engineering / Dalian University of Technology
No.2 Linggong Road, High-tech District, Dalian 116024, China
xujingjing1116@126.com; hezheng1971@126.com

***Abstract*** - An endeavour is made to study the potential of strong aftershock to worsen the damage state of a structure as its damage accumulates. A method for the calculation of incremental damage due to aftershocks, with the structural damage imposed by mainshock considered, is proposed based on the modified Park-Ang damage model. The influences on aftershock incremental damage of concerned factors, e.g. the aftershocks frequency content described by the mean period $T_m$, the structural damage state after mainshock and the structural dynamic characteristics, are then studied. A case study is performed with a 4-story and a 12-story RC frame. Several as-recorded ground motion sequences whose aftershocks have their aforementioned concerned factors varying are used in subsequent incremental dynamic analyses. The results indicate that incremental damage due to aftershocks with long $T_m$ is much more serious while incremental damage induced by aftershocks with short $T_m$ is smaller, relatively. Moreover, the location of weak story of structure subjected to different aftershocks varies: structure subjected to aftershocks with long $T_m$ has its weak story in the bottom part of the building which is more favourable for structural damage evolution, and vice versa. These imply that the practice of taking repeated mainshock as aftershock may overrate the influence of aftershock, aggravating the structural damage state of weak story at the action of mainshock. The damage states of mainshock have a significant influence on the evolution of structural damage state when the intensities of aftershocks are quite low, however, the impact of the damage states due to mainshock on the evolution of structural damage state decreases when the intensities of aftershocks increase gradually. The structural damage increases obviously when the $T_m$ of aftershock is included in the variation range of $T_1$ during the ground motions attacking.

***Keywords*:** Mainshock-aftershock sequences; frequency content; incremental damage of aftershocks; damage evolution; reinforced concrete.

## 1. Introduction

In many historical earthquakes, a series of aftershocks often followed the occurrence of the strong mainshock. Strong aftershocks may worsen the damage state of structures and even lead to collapse, by reason of damage accumulation.

At present, most of the studies focus on how the intensity of aftershock influences the evolution of structural damage state. However, the frequency content of aftershocks has influence on the incremental damage evolution of structure [1]. Garcia and Manriquez [2] indicated that the incremental damage due to aftershocks is obvious when the predominant period of aftershock and period of damaged structure approaches. Actually, only in a small number of cases, the predominant period of aftershock and period of damaged structure approaches. Therefore, the study is not comprehensive.

In the studies of aftershocks, the researchers mainly investigate the damage accumulation caused by aftershocks from three directions, i.e. the maximum displacement response of structures subjected to the aftershocks [3], the number and distribution of failure sections [4] and the damage indices of structures [5]. When the intensity of aftershocks is relatively small than that of the mainshock, structural displacement response to aftershocks is far less than that to the mainshock. As a result, it is unreasonable to use structural maximum displacement response to describe the additional damage caused by aftershocks. The change of number of failure sections is not obvious [4], though it does increase slightly with aftershock intensifying, so it cannot describe the damage accumulation caused by aftershocks. The modified Park-Ang damage index, considering both the maximum deformation and the accumulated dissipated hysteretic energy, can reflect the damage accumulation effect caused by aftershocks of small intensity [6]. Zhai, Wen and Chen [5], in consideration of effects of the mainshock, took a structure with the residual displacement from the mainshock in its initial equilibrium position for aftershock and then calculated the modified Park-Ang damage index to describe additional damage caused by aftershocks. However, comparing with the intact ones, the characteristics of damaged components change which makes the modified Park-Ang damage index of damaged components large when the intensity of aftershock is quite low. Therefore, it is not feasible to consider the residual displacement from the mainshock only. A new method for the computation of the incremental damage due to aftershocks should be proposed considering the damage states of post-mainshok structures.

In this paper, a new method of computing the incremental damage index subjected to aftershock is proposed to describe the damage accumulation effect of mainshock-aftershock sequences. The impact of frequency content on evolution of incremental aftershock damage of different RC frames with various damage states due to mainshock is analysed in this paper.

## 2. The Incremental Damage Index Due to Aftershock

### 2.1. The modified Park-Ang damage model

The Park-Ang damage model considers the first time excess destruction and the fatigue destruction of component by the displacement item and the energy item respectively [6]. The modified Park-Ang damage model, based on the Park-Ang damage model, substitutes the maximum unrecoverable displacement for the maximum displacement [7], which describes the first time excess destruction more reasonably. The modified Park-Ang damage index of section can be calculated as Eqs. (1):

$$\mathrm{D} = \frac{\varphi_m - \varphi_r}{\varphi_u - \varphi_r} + \beta \frac{E_H}{M_y \varphi_u} \tag{1}$$

where, $\varphi_m$ is the maximum curvature of structural members through earthquake ground motions; $\varphi_r$ is the recoverable curvature when unloading; $(\varphi_m - \varphi_r)$ is the maximum unrecoverable curvature; $\varphi_u$ is the ultimate deformation capacity of structural members under monotonic loading; $M_y$ is the yield moment; $E_H$ is the hysteretic energy dissipation of structure under earthquake ground motions; $\beta$ is a positive dimensionless parameter to scale the effect of hysteretic energy dissipation on the final damage of structure.

### 2.2. The aftershock incremental damage index of sections

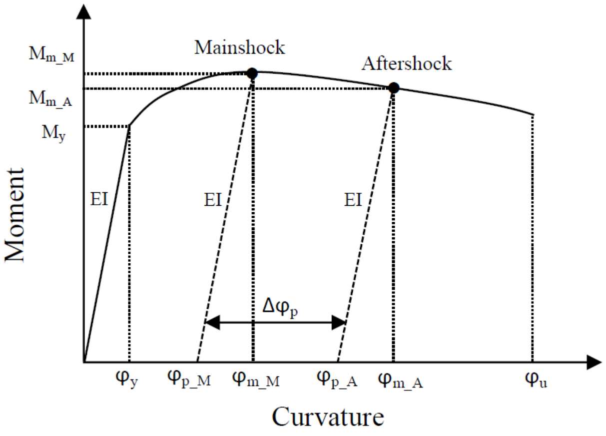

Fig. 1: Maximum unrecoverable curvature $\Delta\varphi_p$ subjected to aftershock.

Fig. 1 shows the skeleton curve of a section of a reinforced concrete component. $\varphi_y$ and $\varphi_u$ are the yield curvature and the ultimate curvature of section. EI is the initial bending stiffness of section. It is assumed that the section is unloaded at the initial stiffness after entering the plastic phase. Therefore, the recoverable curvature of maximum response point can be computed as Eqs. (2).

$$\varphi_r = \frac{M_m}{EI} \tag{2}$$

The two points on the skeleton curve in Fig. 1 represent the maximum response points subjected to mainshock and aftershock whose maximum curvatures and maximum moments are $\varphi_{m\_M}$ , $\varphi_{m\_A}$ ,$M_{m\_M}$ and $M_{m\_A}$. Thus the maximum unrecoverable curvatures of mainshock and aftershock can be computed as Eqs. (3) and Eqs. (4).

$$\varphi_{p\_M} = \varphi_{m\_M} - \frac{M_{m\_M}}{EI} \tag{3}$$

$$\varphi_{p\_A} = \varphi_{m\_A} - \frac{M_{m\_A}}{EI} \tag{4}$$

When $\varphi_{p\_A}$ is small than $\varphi_{p\_M}$, aftershock leads to fatigue destruction only, whereas aftershock leads to both first time excess destruction and fatigue destruction of components. Therefore, the incremental damage index due to aftershock can be calculated as Eqs. (5):

$$\Delta D_a = \beta \frac{E_{H\_A}}{M_y \varphi_u} \ , \qquad (\varphi_{p\_A} \le \varphi_{p\_M}) \tag{5-1}$$

$$\Delta D_a = \frac{\varphi_{p\_A} - \varphi_{p\_M}}{\varphi_u - \varphi_r'} + \beta \frac{E_{H\_A}}{M_y \varphi_u} \ , \qquad (\varphi_{p\_A} > \varphi_{p\_M}) \tag{5-2}$$

where, $E_{H\_A}$ is the hysteretic energy dissipation under aftershock.

The total damage under the mainshock-aftershock sequences $\mathrm{D_{seq}}$, considering the mainshock damage index $\mathrm{D_m}$ and the incremental damage index $\Delta\mathrm{D_a}$ , can be calculated as Eqs. (6):

$$\mathrm{D_{seq}} = \mathrm{D_m} + \Delta\mathrm{D_a} \tag{6}$$

### 2.3. The global damage model of structure

The damage index models mentioned above are mainly aimed at the local damage of components. However, the local damage states cannot reflect the global damage state of structures. The structural global damage state can be described from the component level and the structure level. The global damage index described from structure level is based on the stiffness or periods of structures. However, the structural damage state described from structure level may be incredible when the distribution of damage is not uniform [8]. While the global damage index described from component level, which provides specific information of damaged structure, is calculated by the weighted combination of damage indices of all components.

The most widely used global damage model proposed by Park et al. [9] is calculated by Eqs. (7):

$$\mathrm{D} = \sum \lambda_i D_i \tag{7}$$

where, i is the number of component or story; $\lambda_i = E_i / \sum E_i$ is the weight coefficient; $E_i$ is the hysteretic energy dissipation of component or story; $D_i$ is the damage index of component or story.

The global damage model proposed by Park et al., whose calculation process is simple, emphasizes the damage degree of the weak-layer by a lager weight coefficient. While the damage indices of some severely damaged components, especially the beams, may be much greater than 1. This phenomenon leads to the result that the global damage index achieves 1 which represents collapsing of the structure, when the structure is slightly damaged, actually.

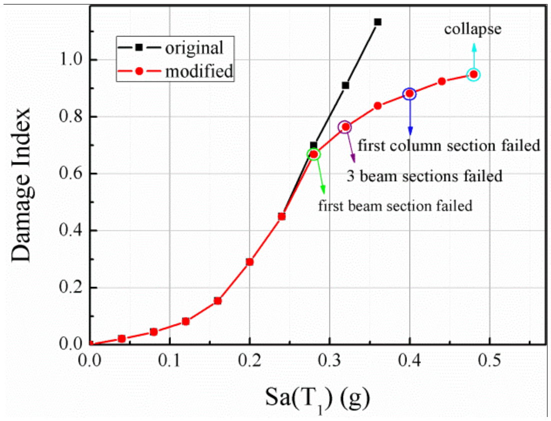

Fig. 2: Evolution curve of global damage index (12-story frame).

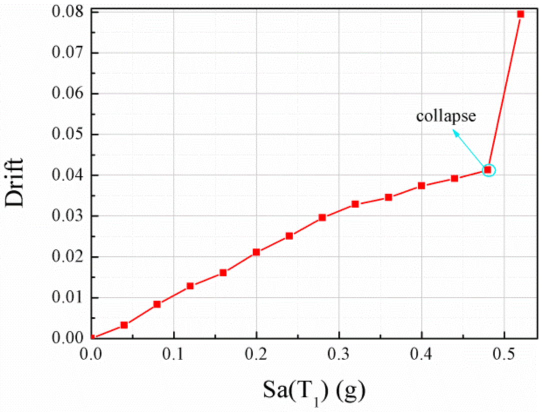

Fig. 3: Maximum inter-story drift (12-story frame).

Park et al. provided that the component is completely damaged when its damage index achieves 1 based on [6]. Therefore, a component whose damage index is equal to 1 or greater than 1 has no contribution to the seismic resistance of the structure similarly. So make the damage index of component equal to 1 when the damage index is greater than 1 during the weighted combination of damage indices of all components. Fig. 2 presents the evolution of global damage index of a 12-story RC frame calculated by the original and modified way of combination. The global damage index, calculated in the original way of combination, develops rapidly when the structure is almost collapsed and achieves 1 when only 3 beams sections of the structure failed. It is not feasible obviously. However, the damage index, calculated by the modified way of combination, develops slowly when the structure is slightly damaged (damage index between 0 and 0.2) [10] and almost collapsed. When the structure is moderately damaged (damage index between 0.2 and 0.5) [10], the damage index develops rapidly. Fig. 3 shows the maximum inter-story drift of structure under earthquakes of different intensities. Based on [11], the structure collapses when is maximum inter-story drift is greater than 4%. Therefore, the global damage index of structure is 0.95 when the structure collapses which is acceptable.

## 3. Influencing factors of Incremental Damage Evolution

### 3.1. Indices of frequency content

At present, the indices of frequency content mainly based on the ground motion itself, e.g. the mean period $T_m$, or the response spectrum of the ground motion, e.g. the predominant period $T_p$. $T_p$ is the most widely used index, however, it considers the most prominent frequency content only and has weak correlation with the shape of the response spectrum. In another words, a ground motion with small $T_p$ may have a rich component of low frequency. The mean period, originally proposed by Rathje et al. [12], is calculated by the weighted mean periods of the Fourier amplitude spectrum in a specific range of frequency and has strong correlation with the shape of the response spectrum [13]. $T_m$ can be mathematically expressed as:

$$T_m = \frac{\sum C_i^2/f_i}{\sum C_i^2}\ , 0.25\text{Hz} \le f_i \le 20Hz \tag{8}$$

$T_m$ is chosen as the index of frequency content in this paper. The ground motion is divided into short $T_m$ ground motions ($T_m \le 0.5$s) and long $T_m$ ground motions ($T_m > 0.5$s) according to $T_m$ [14].

### 3.2. Seismic sequences

Previous studies repeat the mainshock as aftershock or adjust the aftershock ground motion to make its predominant period equal to the predominant period of the site [15]. However, the two methods, to some degree, neglect the influence of frequency content which results in inaccurate estimate of the aftershock incremental damage. Therefore, as-recorded seismic sequences are used in this paper as is shown in Table 1 [16]. The frequency content of the two aftershocks in Chi-Chi earthquake (1999) is distinct. The $T_m$ of the Mw 5.9 aftershock is about 1s whereas the $T_m$ of the Mw 5.9 aftershock is less than 0.5s. In the Tohoku earthquake (2011), the aftershock ground motions (Mw=7.5) recorded by two stations (MYG004 and MYG010) are quite different. The $T_m$ of aftershock in Nepal (2015) is about 1.4s which represents the typical long $T_m$ seismic sequences.

Table 1: Seismic sequences.

| **Earthquake** | **Station name** | **Date** | **Magnitude** | **$T_m$(s)** | **Component** |
|---|---|---|---|---|---|
| Chi-Chi | CHY024 | **1999.9.20** | **7.62** | **0.890** | **NGA_no_1193_CHY024-E** |
| | | 1999.9.20 | 5.9 | 1.270 | ath.CHICHI03.CHY024-E |
| | | 1999.9.20 | 6.2 | 0.360 | ath.CHICHI02.CHY024-E |
| | CHY035 | **1999.9.20** | **7.62** | **0.842** | **NGA_no_1202_CHY035-E** |
| | | 1999.9.20 | 5.9 | 0.963 | ath.CHICHI03.CHY035-E |
| | | 1999.9.20 | 6.2 | 0.409 | ath.CHICHI02.CHY035-E |
| | CHY029 | **1999.9.20** | **7.62** | **0.885** | **NGA_no_1198_CHY029-E** |
| | | 1999.9.20 | 5.9 | 1.271 | ath.CHICHI03.CHY029-E |
| | | 1999.9.20 | 6.2 | 0.320 | ath.CHICHI02.CHY029-E |
| Tohoku, Japan | MYG004 | **2011.3.11** | **9.0** | **0.200** | **MYG0041103111446.NS** |
| | | 2011.3.11 | 7.5 | 0.180 | MYG0041103111526.NS |
| | MYG010 | **2011.3.11** | **9.0** | **0.457** | **MYG0101103111446.NS** |
| | | 2011.3.11 | 7.5 | 0.821 | MYG0101103111526.NS |
| Nepal | Kanti Path | **2015.4.25** | **7.8** | **1.440** | **KATNP.HNE.NQ.01_A** |
| | Kanti Path | 2015.5.12 | 7.3 | 1.450 | KATNP.HNE.NQ.01_A |

## 3.3. Case study

A 4-story and a 12-story reinforced concrete frames are designed, with seismic fortification intensity 8 degree, site class II and seismic design classification I. Concrete grade C30 is used for beams, slabs and columns. The longitudinal bars of beams and columns are HRB335 and the stirrups are HPB300. The OpenSEES platform was used to simulate the frames. The first three vibration periods of 4-story frame are 0.98s, 0.31s and 0.17s. The first three vibration periods of 12-story frame are 2.06s, 0.70s and 0.41s.

Table 2: The global damage indices of different damage states subjected to mainshock.

| Damage states | Damage index | Damage index range of [10] |
|---|---|---|
| Intact $DS_1$ | 0.0 | - |
| Minor $DS_2$ | 0.2 | 0.0~0.2 |
| Moderate $DS_3$ | 0.4 | 0.2~0.5 |
| Severe $DS_4$ | 0.6 | 0.5~1.0 |

Table. 2 presents the global damage indices of different damage states subjected to mainshock [10]. The mainshock ground motion intensities of the four damage states are obtained through the IDA analysis and calculation of the structural damage indices. In order to investigate the effect of various damage states from mainshocks on the aftershock incremental damage, the IDA analysis is carried out using the seismic sequences mentioned in 3.2 whose intensities of mainshocks are scaled as the intensities calculated above.

Fig. 4 shows the IDA curves of aftershocks of long $T_m$ and short $T_m$ on the 12-story frame of different damage states subjected to mainshock. It can be seen that, whether the aftershock is of long $T_m$ or short $T_m$, the incremental damage of damaged structures ($DS_2$~$DS_4$) is very small when the intensities of aftershocks are low which indicates that aftershocks of low intensities has little influence on damaged structures. However, the incremental damage increases rapidly when the aftershock become stronger. The incremental damage index is smaller when the structural damage state is worse under the same intensity of aftershock.

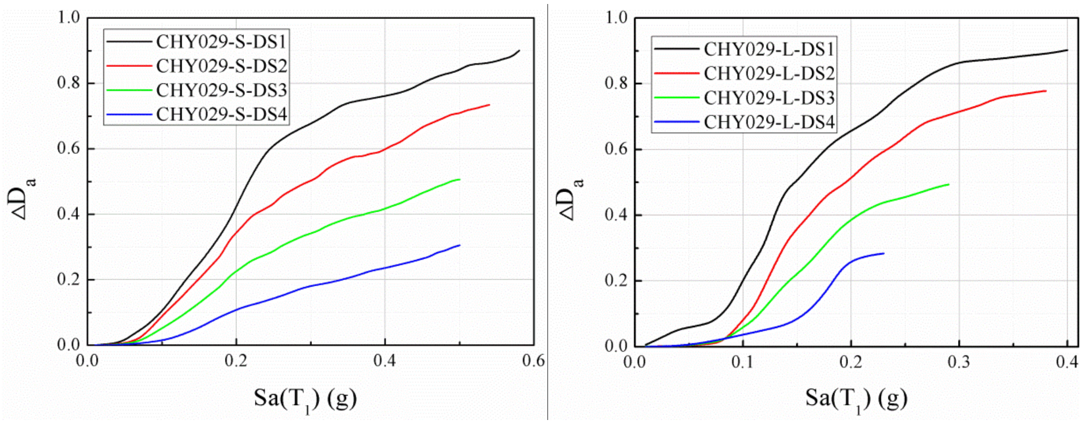

Fig. 4: IDA curves of aftershocks of short $T_m$ (-S) and long $T_m$ (-L) on the 12-story frame of different damage states.

Fig. 5 presents the comparison between the incremental damage evolution curves of aftershock with short $T_m$ and long $T_m$. It can be seen that aftershocks of long $T_m$ result in larger incremental damage than aftershocks of short $T_m$ especially when the damage state subject to mainshock is severe.

The global damage index can describe the structural damage state easily, however, the story damage distribution of damaged structure subjected to aftershocks has an important influence on the structural damage evolution. To investigate the impact of mainshocks on the incremental story damage distribution due to aftershocks, the mainshocks and aftershocks in Table 1 are combined into seismic sequences randomly and then the IDA analysis is carried out using these seismic sequences. The result indicates that the story damage distribution subjected to a certain aftershock is similar whatever the mainshock is. Therefore the practice of taking repeated mainshock as aftershock may overrate the influence of aftershock, aggravating the structural damage state of weak story at the action of mainshock.

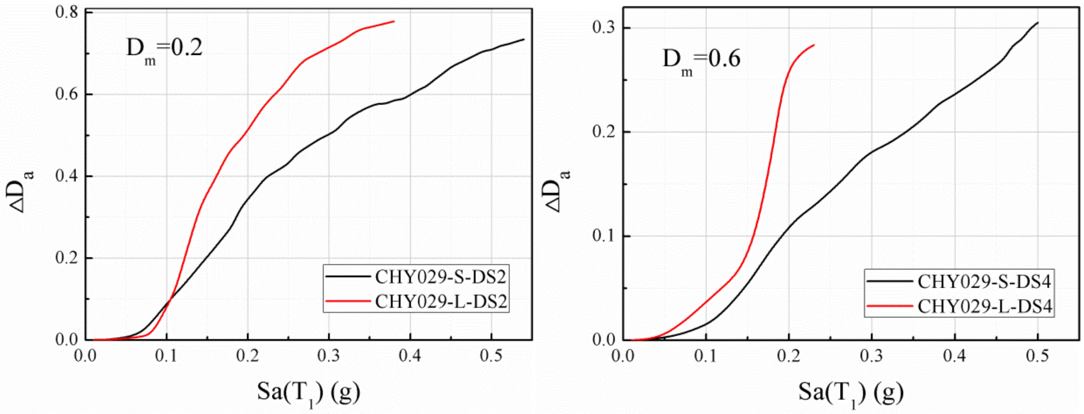

Fig. 5: The evolution curves of incremental damage due to aftershocks with short $T_m$ (-S) and long $T_m$ (-L) (12-story frame).

Fig. 6 shows the incremental story damage distribution of slightly ($DS_2$) and severely ($DS_4$) damaged structures due to aftershocks of short $T_m$ and long $T_m$ when the $Sa(T_1)$s of aftershocks are 0.2g. It can be seen that the characteristics of aftershocks have a great influence on the incremental story damage distribution. Structure subjected to aftershocks with long $T_m$ has its damage weak story in the bottom part of the building which is more favourable for structural damage evolution while structure subjected to aftershocks with short $T_m$ has its damage weak story in the upper part of the building.

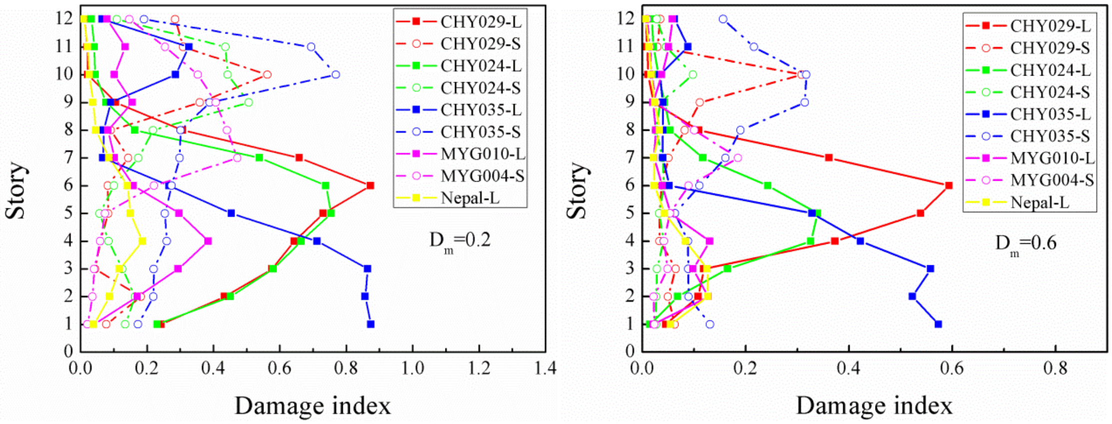

Fig. 6: The incremental story damage index due to aftershocks of slightly ($D_m$=0.2) and severely ($D_m$=0.6) damaged structures with Sa($T_1$) equal to 0.2g (12-story frame).

Fig. 7 and Fig. 8 present the total damage indices $D_{seq}$ of the 12-story and 4-story frames subjected to the seismic sequences. From Fig.7, it can be seen that $D_{seq}$ is similar to $D_m$ when the intensity of aftershock is low and the $D_{seq}$ of a severe damaged structure is larger than that of a slightly damaged structure. However, the difference between them is decreasing gradually with the intensity of aftershock growing. When the structures almost collapse, the $D_{seq}$ of structures of various damage states are close to each other. This phenomenon indicates that, when the aftershock is of low intensity, the damage index of post-mainshock structure is mainly determined by the damage state subjected to mainshock. With the intensity of aftershock growing, $D_{seq}$ is determined by both the damage state of mainshock and the characteristics of aftershock. When the structure almost collapses, the damage state is mainly determined by the characteristics of aftershock.

The trend in Fig. 8 is similar to that in Fig. 7 in the case of short $T_m$ aftershock. However, in the case of aftershock with long $T_m$ ($T_m$=1.27s), $D_{seq}$ of intact structure ($DS_1$) exceeds that of slightly damaged structure ($DS_2$) distinctly in Fig. 8 when the Sa($T_1$) of aftershock is between 0.3g and 0.45g. The variation of the first structural period ($T_1$) in this intensity rang is analysed. It finds that, when the damage state of structure is $DS_1$, the first period ($T_1$) of the 4-story frame varies between 0.98s and 1.33s which is just around the mean period of the long $T_m$ aftershock. But the first period ($T_1$) of the slightly damaged 4-story frame is between 1.4s and 1.58s which is far from the mean period of the long $T_m$ aftershock, relatively. This phenomenon shows that the structural dynamic characteristics have an effect on the evolution of damage states. The structural damage indices increase obviously when the $T_m$ of aftershock is included in the variation range of $T_1$ during the ground motion attacking.

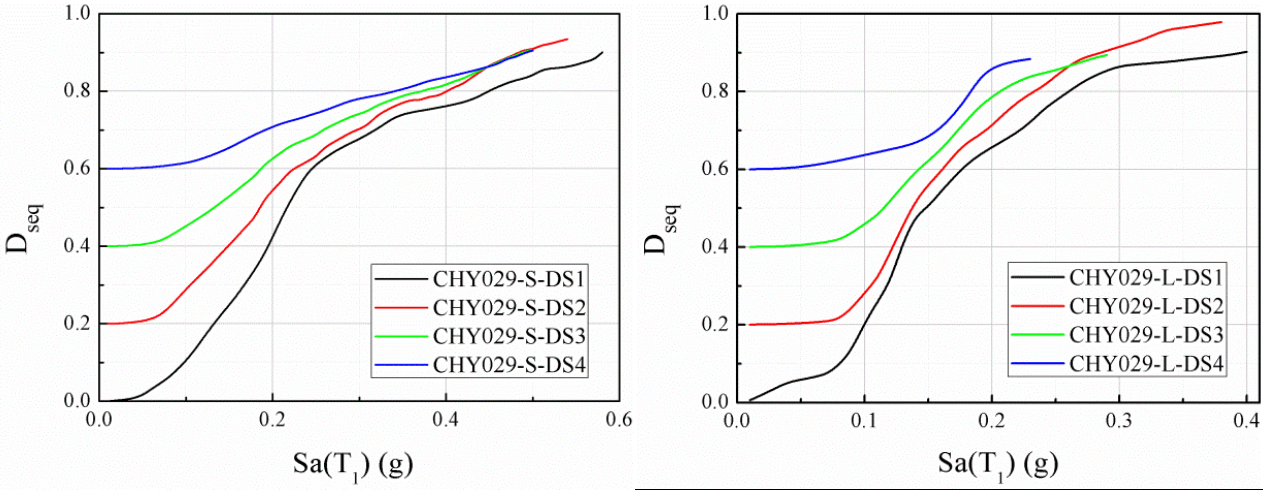

Fig. 7: The evolution of $D_{seq}$ due to Chi-Chi-CHY029 seismic sequences (12-story frame).

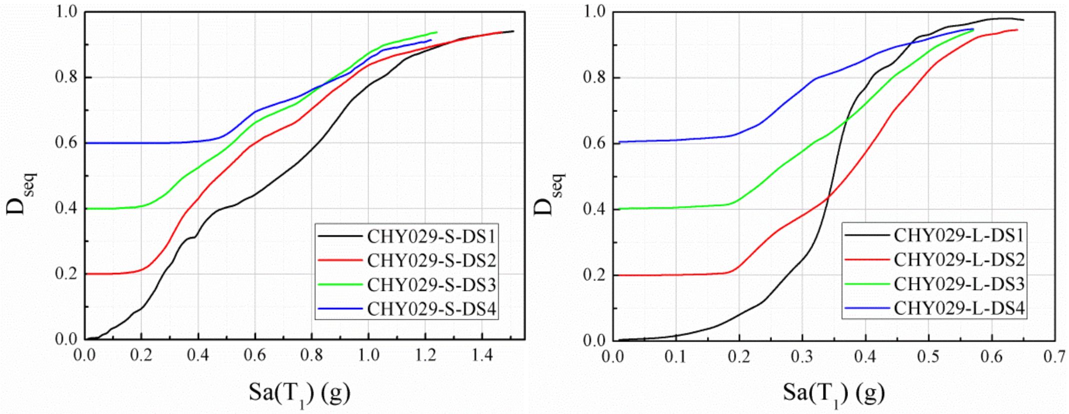

Fig. 8: The evolution of $D_{seq}$ due to Chi-Chi-CHY029 seismic sequences (4-story frame).

## 4. Conclusions

A method for the calculation of incremental damage of structures due to aftershocks is proposed to describe the damage accumulation effect of mainshock-aftershock sequences, based on which, the effects of frequency content of aftershocks, structural damage states and dynamic characteristics of structures on the evolution of incremental damage due to aftershock are studied. The following conclusions are drawn from this research:

(1) The frequency content of aftershocks has a significant influence on the evolution of incremental damage due to aftershocks: incremental damage due to aftershocks with long $T_m$ is much more serious while incremental damage induced by aftershocks with short $T_m$ is smaller, relatively. Moreover, the location of weak story of structure subjected to different aftershocks varies: structure subjected to aftershocks with long $T_m$ has its weak story in the bottom part of the building which is more favourable for structural damage evolution, and vice versa. These imply that the practice of taking repeated mainshock as aftershock may overrate the influence of aftershock, aggravating the structural damage state of weak story at the action of mainshock.

(2) The damage state of mainshock has a significant effect on the structural damage state when the intensities of aftershocks are quite low. However, when the intensities of aftershocks increase gradually, the impact of the damage state due to mainshock on the structural damage state decreases and the characteristics of aftershock begin to play an important role in the evolution of structural damage state. When the structure almost collapses, the damage state of the structure is mainly determined by the characteristics of aftershock.

(3) The structural dynamic characteristics have an effect on the evolution of damage states. The structural damage increases obviously when the $T_m$ of aftershock is included in the variation range of $T_1$ during the ground motion attacking.

## References

[1] Q. W. Li and B. R. Ellingwood, "Performance evaluation and damage assessment of steel frame buildings under main shock–aftershock earthquake sequences," *Earthquake Engineering and Structural Dynamic*, vol. 36, pp. 405-427, 2007.

[2] J. Ruiz-García and J. C. Negrete-Manriquez, "Evaluation of drift demands in existing steel frames under as-recorded far-field and near-fault mainshock-aftershock seismic sequences," *Engineering Structures*, vol. 33, pp. 621-634, 2011.

[3] Y. Li, R. Song, and J. W. Van De Lindt, "Collapse fragility of steel structures subjected to earthquake mainshock-aftershock sequences," *J. Structural Eng.*, vol. 140, no. 12, pp. 04014095, 2014.

[4] Z. He and Y. L. Liu, "Probabilistic damage analysis of mainshock-aftershock with the consideration of next generation attenuation relationship," *J. Harbin institute of technology*, vol. 46, no. 6, pp. 86-92, 2014.

[5] C. H. Zhai, W. P. Wen, Z. Q. Chen, et al, "Damage spectra for the mainshock–aftershock sequence-type ground motions," *Soil Dynamics and Earthquake Engineering*, vol. 45, pp. 1-12, 2013.

[6] Y. J. Park and A. H. S. Ang, "Mechanistic seismic damage model for reinforced concrete," *J. Structural Eng.*, vol. 111, no. 4, pp. 722-739, 1985.

[7] S. K. Kunnath, A. M. Reinhorn, and J. F. Abel, "A computational tool for seismic performance of reinforced concrete buildings," *Computers and Structures*, vol.41, no. 1, pp. 157-173, 1992.

[8] G. H. Powell and R. Allahabadi, “Seismic damage prediction by deterministic methods: concepts and procedures,” *Earthquake Engineering and Structural Dynamics*, vol. 16, no. 5, pp. 719-734, 1988.

[9] Y. J. Park, A. H. S. Ang, and Y. K. Wen, “Seismic damage model for reinforced concrete buildings,” *J. Structural Eng.*, vol. 111, no. 4, pp. 740-757, 1985.

[10] Y. J. Park, A. H. S. Ang, and Y. K. Wen, “Damage-limiting aseismic design of buildings,” *Earthquake spectra*, vol. 3, no. 1, pp. 1-26, 1987.

[11] FEMA-356, Prestandard and Commentary for the Seismic Rehabilitation of Buildings, Federal Emergency Management Agency, Washington D.C, USA, 2000.

[12] E. M. Rathje, N. A. Abrahamson, and J. D. Bray, “Simplified frequency content estimates of earthquake ground motions,” *J. Geotechnical and Geoenvironmental Eng*., vol. 124, no. 2, pp. 150-159, 1998.

[13] M. Kumar, J. M. Castro, P. J. Stafford, et al. “Influence of the mean period of ground motion on the inelastic dynamic response of single and multi degree of freedom systems,” *Earthquake Engineering and Structural Dynamics*, vol. 40, no. 3, pp. 237-256, 2011.

[14] R. Song, Y Li and J. W. Van de Lindt, “Impact of earthquake ground motion characteristics on collapse risk of post-mainshock buildings considering aftershocks,” *Engineering Structures*, vol. 81, pp. 349-361, 2014.

[15] B. Wu and J. P. Ou, “Statistical relationship between magnitudes of mainshock and aftershock and parameters of earthquake ground motion,” *Earthquake Engineering and Engineering Vibration*, vol. 13, no. 3, pp. 28-35, 1993.

[16] Pacific Earthquake Engineering Research Center. Peer Strong Ground Motion Database [Online]. Available: http://peer.berkeley.edu/products/strong_ground_motion_db.html.