EVALUATION OF MAXIMUM INELASTIC DISPLACEMENTS OF SDOF STRUCTURES SUBJECTED TO AFTERSHOCKS

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ABSTRACT

Earthquake sequences, commonly consisting of a mainshock event and several aftershocks, are frequently recorded in recent earthquakes. It is impossible to repair mainshock-damaged structures before the occurrence of the subsequent aftershocks due to a short interval between two consecutive seismic ground motions. The damage, which is caused by the mainshocks, might be rapidly aggravated by the subsequent strong aftershocks. Thus, it is particularly important to know the structural capacity and seismic performance of mainshock-damaged structures when subjected to the subsequent aftershocks. For this purpose, the objective of this paper is to predict the maximum inelastic displacement of mainshock-damaged structures when subjected to the subsequent aftershocks via an index that is defined as the ratio of the residual displacement of a structure under mainshock to the maximum inelastic displacement of the structure under the subsequent aftershock. The aftershocks are scaled to maintain different relative intensities. The index is computed by performing response history analyses of inelastic single degree of freedom systems with varying vibration periods. Four different hysteretic models are considered while five levels of lateral strength ratio, \( R \), are adopted herein to account for the inelasticity. The influence of the vibration period, lateral strength ratio, the relative intensity of aftershock as well as the hysteretic model is studied. The analysis results show that this index can be used to predict the maximum inelastic displacement of structures subjected to aftershocks.

Keywords: Mainshock-aftershock sequences; Maximum inelastic displacement; SDOF structures; Residual displacement; Lateral strength ratio

1. INTRODUCTION

Earthquake sequences are frequently recorded in recent large earthquakes, such as 2010 New Zealand earthquake(Bradley et al. 2014), 2011 Tohoku earthquake(Hirose et al. 2011). It is impossible to repair mainshock-damaged structures before the occurrence of the subsequent aftershocks due to a short interval between two consecutive seismic ground motions. Unfortunately, no efforts focus on predicting the performance levels of post-earthquake buildings when subjected to the future earthquakes. This is important because the damage, which is caused by mainshock, might be rapidly aggravated by the subsequent strong aftershocks (Zhai et al. 2014, 2015a, 2016, 2017). This phenomenon has been confirmed in the post-earthquake field reconnaissance(Ceci et al. 2010; Augenti and Parisi 2010; Di Sarno et al. 2013). For example, no modern engineered structure collapsed, and no lives were lost in the New Zealand mainshock on the 4th September 2010; however, the subsequent aftershock on the 22nd February 2011 resulted in widespread structural damage, collapse of buildings, and the loss of 182 lives and a further 164 serious injury (Wilkinson et al. 2013; Lambie et al. 2017).

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Thus, a fast safety evaluation for the performance levels of structures when subjected to the future aftershocks is an interesting and important topic that contains a lot of technical challenges.

Structures excited by earthquake-induced strong ground motion may experience deterioration both in strength and stiffness, which may exhibit significant residual displacements at the end of the earthquake. The residual displacements can be measured in-situ using various methods such as the digital image correlation method (Quan et al. 2004), the Robotic Total Station (RTS) (Psimoulis and Stiros 2007) and the satellite Global Positioning System (GPS) (Nikitopoulou et al. 2006; Cheloni et al. 2017). Thus, the residual displacements can be easily obtained from post-earthquake structures.

Structures under the subsequent earthquake begin to vibrate based on the residual displacements caused by the preceding earthquake. The residual displacements will have an impact on the maximum inelastic displacements of structures under the subsequent earthquake. Thus, a reliable maximum inelastic displacement of structures under the subsequent earthquake can be predicted by considering the residual displacements caused by the preceding earthquake.

The novelty of the study is to propose a simple and robust method to predict the maximum inelastic displacement of post-earthquake structures subjected to the subsequent aftershocks by considering the residual displacement of the post-earthquake structures. It is very important for informed decision-making during the post-earthquake response, recovery and mitigation phases. Among these, an index, γ, defined as the ratio of structural residual displacement under the preceding earthquake to structural maximum inelastic displacement under the subsequent aftershock, was introduced herein. 218 recorded mainshock-aftershock (MSAS) sequences are carefully selected as the earthquake input, and the aftershock is scaled to different relative intensities to simulate the action of different intensities of the future aftershocks. Three degrading hysteretic models, simulating the behavior of RC structures, are selected, and an elastic-perfect-plastic (EPP) that can represent the behavior of steel structures is also adopted as a comparison model.

2. PARAMETERS AND HYSTERETIC MODELS

2.1 Parameters

The index, γ, considered herein, is defined as the ratio of the residual displacement demand, \( x_{r,ms} \), of an inelastic SDOF system under a mainshock to the maximum inelastic displacement demand, \( x_{\text{max,as}} \), of the inelastic SDOF system under the subsequent aftershock. The analytical expression of the γ is provided as follows:

\[
\gamma = \frac{x_{r,ms}}{x_{\text{max,as}}} \quad (1)
\]

In this study, the residual displacement demand, \( x_{r,ms} \), was calculated for a SDOF system with a specific lateral strength, defined herein as the lateral strength ratio, \( R \), on the basis of the following equation:

\[
R = \frac{F_e}{F_y} \quad (2)
\]

where \( F_e \) is the minimum yield strength required for a system to remain in the elastic regime of the structural response under the earthquake loading, while \( F_y \) is the yield strength of the corresponding inelastic SDOF system with the same mass and initial stiffness.

Five lateral strength ratios, \( R = [2,3,4,5,6] \) are chosen deliberately to consider various levels of inelasticity that the structural systems are anticipated to experience during the earthquake-induced strong ground motions.
The aftershocks were scaled to different intensities to consider the effects of aftershocks on the $\gamma$. The notation $\nabla PGA$ is introduced and defined as the ratio of the $PGA$ of the aftershock, $PGA_{as}$, to that of the corresponding mainshock, $PGA_{ms}$, as follows:

$$\nabla PGA = \frac{PGA_{as}}{PGA_{ms}}$$

(3)

2.2 Hysteretic models

The present study selected four hysteretic models (Zhai et al. 2016): (i) Elastic-Perfectly-Plastic (EPP) model that represents a non-degrading system; (ii) Modified-Clough (MC) model that simulates the flexural behavior and exhibits stiffness degradation upon reloading; (iii) Pinching (PH) model that simulates the rc structures with open or closed cracks; (iv) Stiffness-Strength-Degradation (SSD) model based on the three-parameter model, which represents the global behavior of systems that exhibit stiffness degradation and strength deterioration during reloading branches. Moreover, Figure 1 presents the force-displacement loops for these four models, which were obtained from the time history analysis of a SDOF structure subjected to a MSAS sequence with one aftershock ($M_w = 5.9$) that was recorded in the Chi-Chi earthquake (TCU067 N-S). It should be noted that a unit mass was assumed herein.

![Force-displacement loops for four models](image1)

Figure 1. Hysteretic response of a SDOF system ($T=1.0$ s, $R=5$, $\nabla PGA = 0.5$) under the MSAS ground motion (TCU067 N-S) (a) EPP; (b) MC; (c) PH; (d) SSD.

![Time history response](image2)

Figure 2. Time history response of a SDOF system ($T=1.0$ s, $R=5$, $\nabla PGA = 0.5$) under the MSAS ground motion (TCU067 N-S).

3. GROUND MOTIONS

In this study, a total of 218 MSAS sequences, including 116 MSAS sequences recorded on soil C and
102 MSAS sequences recorded on soil D, were selected. Complete information of all earthquake sequences can be found in references (e.g. Zhai et al. 2016). The results in reference (Zhai et al. 2014) indicate that the aftershock ground motion with $\overline{VPGA} \leq 0.5$ has minor influences on the structural response, thus the $\overline{VPGA} = 0.5$ was used as the smallest relative intensity. Besides, $\overline{VPGA} = 1.0$ was employed to simulate the extreme case, while $\overline{VPGA} = 0.8$ was considered as a moderate intensity aftershock.

4. STATISTICAL RESULTS

4.1 Mean spectra and COV

Figure 3 shows the mean $\gamma$ for EPP system under MSAS sequences ($\overline{VPGA} = 0.5$) by considering two different soil types. It can be observed that the mean $\gamma$ shows the same general trends regardless of site conditions. In the short-period region, the mean $\gamma$ is significantly dependent on the vibration period, decreasing sharply with the increase of the vibration period. The mean $\gamma$ fluctuates within a narrow range in the medium-long period region, which is independent of the vibration period.

In the whole period region, the mean $\gamma$ increases with the increase of $R$. For structures located on soil C, the mean $\gamma$ increases from 0.47 to 0.69 as $R$ increases from 2 to 6 when the vibration period $T = 0.5$ s, as shown in Figure 3 (left).

Figure 3. Mean $\gamma$ for EPP system under MSAS sequences ($\overline{VPGA} = 0.5$) by considering two different soil types.

Figure 4 illustrates the COVs of $\gamma$ for EPP system under MSAS sequences ($\overline{VPGA} = 0.5$) by considering two different soil types. In the whole period region, the COVs are significantly dependent on the variation period. All the COVs in Figure 4 are within a range of 0.3 to 0.7 on site class C and D. The COVs are moderately dependent on $R$, decreasing with the increase of $R$. In general, the trends of COVs are similar, but the COVs on class C are slightly higher than that on class D.

Figure 4. COVs of $\gamma$ for EPP system under MSAS sequences ($\overline{VPGA} = 0.5$) by considering two different soil types.

4.2 Effects of aftershocks
To investigate the effects of aftershocks on the $\gamma$, a series of nonlinear dynamic analyses was calculated by considering various combinations of $R$ and $V\text{PGA}$. The obtained results for EPP system, under a set of given conditions (site class C and $R = 2, 4, 5,$ and $6$), are shown in Figure 5. It can be seen that all the curves decrease as the $V\text{PGA}$ increases, indicating that the structural maximum displacement under aftershocks increases as the $V\text{PGA}$ increases. The relative intensity of aftershock exerted minor influence on the mean $\gamma$ especially for structures with higher lateral strength ratios (e.g. $R = 6$), meaning that the relative intensity of aftershock has a minor effect on structural maximum displacements under aftershocks. The existing literature has also reported the minor effect of aftershock on several displacement-based metrics (i.e., inelastic displacement ratios (Hatzigeorgiou and Beskos 2009; Zhai et al. 2015b) and ductility demand (Hatzigeorgiou 2010; Goda 2012; Goda and Taylor 2012)).

Figure 5. Mean $\gamma$ for EPP system under MSAS sequences by considering three different relative intensities.

4.3 Effects of models

To compare the effects of models on the $\gamma$, the mean $\gamma$ for EPP, MC, PH and SSD systems was calculated by considering various combinations of $R$ and $T$, as shown in Figure 6. It can be observed that the EPP systems experience, on average, higher $\gamma$ values compared to the ones corresponding to the systems modeled with the MC, PH and SSD hysteresis laws. This is because residual displacements for degrading systems are smaller than residual displacements for EPP systems. Such a reduction in residual displacement values for the degrading systems, being already reported elsewhere (Ruiz-García and Miranda 2006; Liossatou and Fardis 2015), is associated to their narrower and self-centering hysteresis loops compared to the EPP-related ones (Figure 1) that are representative of steel buckling restrained braces or eccentrically braced frames when they are subjected to earthquake excitations. Furthermore, the simplified systems, modelled herein with the three degrading hysteresis laws (MC, PH and SSD), led to quite similar $\gamma$ values that, in turn, can be primarily attributed to the identical unloading stiffness that has been defined for the MC, PH and SSD models.

5. CONCLUSIONS

The study presented herein was conducted to quantify the maximum displacements that structural systems of varying strength and hysteretic behaviour experience when subjected to aftershocks. Numerous SDOF systems, modelled with different lateral strength ratios (i.e., $R=[2,3,4,5,6]$) to represent both strong and weak structural realizations, were excited by 218 MSAS sequences selected on the basis of a multi-criterion strategy. The performance of response history analyses enabled
calculating the structural residual displacement under mainshock to the structural maximum inelastic displacement under the subsequent aftershock, $\gamma$, while a thorough statistical analysis enabled evaluating its relationship with the seismological parameter, i.e., relative intensity of aftershock, as well as structural characteristics, i.e., lateral strength ratio, vibration period and hysteretic models. The results were presented in the form of constant strength inelastic spectrum, in which the mean $\gamma$ values are plotted against the vibration periods. The main conclusions drawn can be summarized as follows:

i. The mean $\gamma$ values were found to be marginally influenced by the lateral strength ratio and lower mean $\gamma$ values were found for the stronger EPP systems (i.e., $R<4$) compared to the weaker ones. Relatively higher sensitivity in the varying lateral strength of the systems was identified for the dispersion of $\gamma$ quantified herein by the COV, which was calculated higher for systems with $T>0.50$.

ii. Irrespective of the systems' lateral strength, the relative intensity of aftershock exerted marginal influence on the $\gamma$.

iii. The EPP systems experienced, on average, higher $\gamma$ values than ones corresponding to the systems modelled with the degrading hysteresis rules considered herein (MC, PH and SSD). The latter is related to the wider hysteresis loops that the EPP systems are associated to.

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Figure 6. Comparison of the mean $\gamma$ for EPP system and three degrading models by considering four different lateral strength ratios.

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7. REFERENCES


