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Framework for the vulnerability assessment of structure under mainshock-aftershock sequences

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ABSTRACT

Many earthquakes have indicated that the mainshock-damaged structures may be more vulnerable to severe damage and collapse during the subsequent aftershocks. This manuscript presents a framework for the vulnerability assessment of structure under the mainshock-aftershock sequences. In this framework, the engineering demand parameter (*EDP*) which can more effectively characterized the additional damage of structure induced by aftershock, and the intensity measure (*IM*) having the higher correlation with the additional damage of structure are selected and used. The versatility of the proposed framework is demonstrated on a case-study reinforced concrete (RC) frame structure with 5 stories. The influences of aftershocks on the fragility of structure are studied for different limit states. The effects of aftershocks on the fragility of structure are more obvious for the case that mainshock fragility changes from 30% to 60%, and the maximum influence of aftershock can exceed 15%. The results in this study can be used to evaluate the vulnerability of structure under the seismic sequence in the pre-earthquake environment.

1. Introduction

The past earthquakes (e.g. the Wenchuan, China earthquake in 2008, and the Tohoku, Japan earthquake in 2011) have shown that the strong mainshocks are always followed by lots of aftershocks, which have smaller magnitudes but often produce the moderate-strong ground motions in the mainshock-damaged region. Thus, the buildings in the earthquake active region are generally subjected to mainshock-aftershock sequence (i.e. a sequence of multiple earthquakes), while current seismic design codes in the world are based on the single “event”. The short time intervals between mainshock and aftershocks leave the mainshock-damaged structure no time to be repaired in the post-mainshock environment. The fact that current seismic design codes allow the structures to experience the damage during design earthquake (i.e. mainshock) makes the aftershocks cause the additional damage to mainshock-damaged structure even though they are not as strong as mainshock. The cumulative damage, consisting of damage induced by mainshock and additional damage induced by aftershocks, must be properly quantified and incorporated in the performance evaluation and design.

During the last ten years, many investigations have been conducted to study the influences of aftershocks on the responses of various structures [1–40], and have provided the useful results to incorporate the aftershock into the seismic design. Many researchers [1–13] studied the influences of aftershocks on the inelastic response spectra with single-degree-of-freedom (SDOF) systems, aiming to provide the simple tools to include the aftershock into the seismic design and structural performance evaluation. The various multiple-degree-of-freedom (MDOF) structures were also employed in many other studies [14–40]. Although the different kinds of structures and different mainshock-aftershock sequences database (i.e. recorded or simulated earthquakes sequences) are employed in the above investigations, the common conclusion is still obtained that the moderate-strong aftershocks would increase the damage of structure.

Fragility assessment has been a popular tool to evaluate the seismic performance of structures [41,42], thus the vulnerability of structure under seismic sequences has been studied by many researchers [20–24,28–39], and frameworks for the vulnerability assessment considering the effects of aftershocks have also been proposed for different aims by several studies [20,35,37,38]. In these studies, the peak inter-story drift ratio or peak roof drift ratio [20–24,29–36,38,39] is widely used as the *EDP* to quantify the cumulative damage of the structure induced by mainshock-aftershock sequence. Zhai et al. [10] studied the responses of SDOF systems under the mainshock-aftershock sequences,

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and concluded that the hysteretic energy and modified Park-Ang damage index (energy-based *EDP*) can more effectively reflect the aftershock-induced additional damage than the ductility demand (peak-deformation-based *EDP*). When the mainshock-damaged structure is subjected to the subsequent aftershocks, it may experience the inelastic deformation (i.e. hysteretic energy is dissipated and the damage is increased) while its peak value is smaller than that of the intact structure under the mainshock. Thus the energy-based *EDP* can more clearly characterize the additional damage induced by aftershock. However, just Ghosh et al. [37] built the seismic demand model of seismic sequence with Park-Ang damage index for highway bridges. It is important to study the fragility of structure under mainshock-aftershock sequence with damage index.

Besides, for the seismic risk analysis in the pre-earthquake environment, the intensities of mainshock and aftershock can be firstly obtained by the seismic hazard analysis. The fragility results of structure are generally used by the engineers to compute the probability of structural damage exceed a given damage status. References [20–24,28–39] provide the aftershock fragility as a function of damage extent (which is induced by mainshock) and intensity of aftershock ground motion. However, because intensity of mainshock ground motion is not contained in the aftershock fragility function, it is not applicable to use the aftershock fragility function to directly assess the seismic performance of intact structure (defined as the structure experiencing no damage from earthquake) in the pre-earthquake environment where just the intensities of mainshock and aftershock ground motions can be predicted by seismic hazard analysis. Thus this manuscript also aims to provide the fragility of intact structure under the mainshock-aftershock sequences, in which the damage exceeding probability of structure directly related to the intensities of mainshock and aftershock. This tool is convenient and consistent for the engineers to compute the damage exceeding probability of intact structure under the mainshock-aftershock sequences.

In light of the above discussions, this study proposes the framework for vulnerability assessment of structure under mainshock-aftershock sequences. The formulation of framework is firstly presented in Section 2, and then this framework is applied to a 5-story reinforced concrete (RC) frame structure in Section 3. The effect of aftershock on the fragility of structure is quantitatively studied.

2. Formulation of vulnerability assessment framework

This section presents the formulation of framework for the development of seismic sequence fragility curves for the intact structures before the seismic sequence.

2.1. Mainshock fragility analysis methodology

Following the classical seismic fragility analysis methodology, mainshock fragility can be explicitly expressed as a conditional probability that a structure will reach or exceed a specified level of damage for a given mainshock ground intensity measure IM_{ms}. Mainshock fragility curves $F_{ms}(x)$ can be computed with following equation:

$$F_{ms}(x) = P\,[EDP_{ms} \geq EDP_{LSi}|IM_{ms} = x] \tag{1}$$

where EDP_{ms} is the engineering demand parameter of structure under the mainshock, LSi is the *i*th limit state of structure, EDP_{LSi} is the threshold of engineering demand parameter for LSi.

To derive the fragility function, the probabilistic seismic demand model (PSDM) that relates the median *EDP* of the structure to the *IM* has been widely calibrated and used in fragility analysis. For the mainshock case, the relationship between the *EDP* and *IM* can be expressed in the power form [43]

$$\lambda(EDP_{ms}|IM_{ms}) = a \cdot IM_{ms}{}^{b} \tag{2}$$

where $\lambda(EDP_{ms}|IM_{ms})$ is the median value of the EDP_{ms} on the structure as a function of an IM_{ms}, regression coefficients a and b can be computed by a linear regression analysis of $\ln(EDP_{ms})$ on $\ln(IM_{ms})$ computed by numerical simulations. The dispersion $\beta(EDP_{ms}|IM_{ms})$ accounting for the uncertainty in the relation is estimated:

$$\beta(EDP_{ms}|IM_{ms}) = \sqrt{\frac{\sum[\ln(edp_{ms,i}) - \ln(\lambda(EDP_{ms}|IM_{ms}))]^2}{N-2}} \tag{3}$$

where N is the number of simulations and $edp_{ms,\,i}$ is the mainshock demand at *i*th simulation.

Following the lognormal distribution assumption of response of structure, probability that EDP_{ms} exceeds EDP_{LSi} conditioned on the IM_{ms} can be computed by:

$$P(EDP_{ms} \geq EDP_{LSi}|IM_{ms}) = 1 - \Phi\left[\frac{\ln(EDP_{LSi}) - \ln(\lambda(EDP_{ms}|IM_{ms}))}{\beta(EDP_{ms}|IM_{ms})}\right] \tag{4}$$

where $\Phi[\cdot]$ is the cumulative normal distribution function.

2.2. Mainshock-aftershock fragility analysis methodology

Similar with the method in the above section, mainshock-aftershock sequence fragility curves $F_{seq}(x_1, x_2)$ can be computed with following equation:

$$F_{seq}(x_1, x_2) = P\,[EDP_{seq} \geq EDP_{LSi}|IM_{ms} = x_1, IM_{as} = x_2] \tag{5}$$

where EDP_{seq} is the engineering demand parameter of structure under the mainshock-aftershock sequence, IM_{as} is the aftershock ground motion intensity measure.

For the response of structure under the mainshock-aftershock sequences, the *EDP* is dependent on the *IM*s of mainshock ground motion (i.e. IM_{ms}) and aftershock ground motion (i.e. IM_{as}). In order to build the seismic demand model following the mainshock fragility analysis methodology, mainshock-aftershock sequences can be considered as discrete cases that include the aftershock ground motion with a given relative intensity. The relative intensity measure of aftershock ground motion ∇IM is introduced and defined as:

$$\nabla IM = IM_{as}/IM_{ms} \tag{6}$$

For the seismic sequences including aftershock ground motion with given ∇IM, the mainshock-aftershock sequence fragility curves $F_{seq}(x_1, x_2)$ can be simplified into:

$$F_{seq}(x_1, \nabla IM) = P\,[EDP_{seq} \geq EDP_{LSi}|IM_{ms} = x_1, \nabla IM] \tag{7}$$

where ∇IM is a constant.

The relationship between EDP_{seq} and IM_{ms} can be expressed as:

$$\lambda(EDP_{seq}|IM_{ms}, \nabla IM = i) = a \cdot IM_{ms}{}^{b} \tag{8}$$

where $\lambda(EDP_{seq}|IM_{ms}, \nabla IM = i)$ is the median value of the EDP_{seq} on the structure as a function of an IM_{ms}, regression coefficients a and b can be computed by a linear regression analysis of $\ln(EDP_{seq})$ on $\ln(IM_{ms})$ computed by numerical simulations. The dispersion $\beta(EDP_{seq}|IM_{ms}, \nabla IM = i)$ accounting for the uncertainty in the relation is estimated:

$$\beta(EDP_{seq}|IM_{ms}, \nabla IM = i) = \sqrt{\frac{\sum[\ln(edp_{seq,i}) - \ln(\lambda(EDP_{seq}|IM_{ms}, \nabla IM = i))]^2}{N-2}} \tag{9}$$

where N is the number of simulations and $edp_{seq,\,i}$ is the mainshock-aftershock sequence demand at *i*th simulation.

Following the lognormal distribution assumption of response of structure under the mainshock-aftershock sequence, probability that EDP_{seq} exceeds EDP_{LSi} conditioned on the IM_{ms} can be computed by: