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Impact of earthquake ground motion characteristics on collapse risk of post-mainshock buildings considering aftershocks

Ruiqiang Song [a,*], Yue Li [a], John W. van de Lindt [b]

[a] Department of Civil and Environmental Engineering, Michigan Technological University, Houghton, USA
[b] Department of Civil and Environmental Engineering, Colorado State University, Fort Collins, USA

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ABSTRACT

This paper investigates the influence of duration and frequency content of earthquakes on the collapse risk of post-mainshock buildings accounting for four damage states. The 5–95% significant duration D_s and the mean period T_m are selected as the index parameters to represent the duration and frequency content of ground motions, respectively. The modified Ibarra–Krawinkler hysteretic model is used in the structural models to capture strength and stiffness degradation associated with structural damages. The ground motion intensity is measured by inelastic spectral displacement (S_{di}) to implicitly capture the spectral shape effect. Structural collapse capacities are determined using a suite of 62 records with a broad range of earthquake ground motion characteristics. The results demonstrate that both the duration and frequency content of ground motion play a significant role in structural collapse capacity. The degree of influence of aftershock characteristics on post-mainshock building collapse capacities becomes more significant as the structural damage level from the mainshock increases. As a result, post-mainshock structures with more serious damage states may be more fragile when subjected to the aftershocks with longer duration and lower frequency. Aftershocks are usually characterized by shorter duration and higher frequency than those of the corresponding mainshocks, thus the collapse risk of post-mainshock buildings may not be properly estimated using seeding scaled mainshock record as an aftershock compared to those using as-recorded mainshock–aftershock sequences.

1. Introduction

Recent earthquakes show the potential risk from aftershock hazards [1,2]. Due to the complex stress interaction of tectonic plates around the displaced fault plane after a mainshock, numerous aftershocks may be triggered posing a significant risk to life safety, causing further structural damage, hampering reoccupation and restoration of buildings, and increasing financial loss. The 2010 M8.8 Chile earthquake on February 27 triggered approximately 90 aftershocks with magnitudes 5.0 or greater in the 24 h recorded by the USGS [3]. About 588 aftershocks with moment magnitudes of 5.0 or greater were recorded after the March 11, 2011, Great Tohoku earthquake in Japan [4]. The M8.6 Indonesia earthquake on April 11, 2012, was followed by many strong aftershocks with the largest measured at M8.2 just over two hours later [5]. Because of the difference in occurrence mechanisms between the mainshock and aftershocks, the characteristics of the mainshock may be remarkably different from its aftershocks. Therefore, the aftershock hazard and its characteristics must be accounted for to assure accurate evaluation of seismic behavior of structures.

The ground motion characteristics have an important influence on the seismic behavior of buildings, including ground motion intensity [2,6,7], spectral shape [8,9], duration [10–12], frequency content [13,14], near-fault [15,16], etc. In order to accurately predict the structural response and minimize the dispersion of analytical behavior of buildings, the ground motion characteristics need to be taken into account in the procedure of ground motion selection.

Although it is well known that ground motion duration has an important effect on soil liquefaction and slope instability [17,18], the influence of ground motion duration on structural response is still a topic worth further investigation [19]. The degree of influence of the duration depends on many factors, such as the definition of duration, the seismic demand parameter, damage metric, and the structural nonlinear property [20]. Experimental testing results of reinforced concrete and steel frames have typically demonstrated that the duration of ground motion or the number of

* Corresponding author at: Department of Civil and Environmental Engineering, 212 Dillman Hall, Michigan Technological University, Houghton, MI 49931, USA. Tel.: +1 (906)2818097.

E-mail address: rsong1@mtu.edu (R. Song).

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loading cycles is positively correlated to structural damage. The damage of the connections of steel moment-resisting frames observed in the Northridge and Kobe earthquakes was associated with low cycle fatigue and hence the duration of ground motion had a significant influence on structural behavior [19]. Analytical studies using the cumulative damage measures usually find a positive correlation between duration and structural damage. However, when the damage measures related to maximum response are used, some analytical studies show that the correlation between duration and damage is very weak except that the degradation characteristics of structural components and destabilizing effects of gravity loads are taken into account [12]. van de Lindt and Goh [21] found that seismic duration greatly affects structural reliability and proposed a duration effect factor to measure the effect of duration on reliability. Iervolino et al. [11] concluded that ground motion duration is not statistically significant to the displacement ductility demand. Ruiz-Garcia [22] suggested that the ground motion duration does not remarkably affect the peak residual drift demands in SDOF and multiple degrees of freedom (MDOF) systems. Raghunandan and Liel [12] examined the effect of duration on the collapse of reinforced concrete buildings with different structural properties and concluded that the ground motion duration had a significant influence on the collapse capacity of concrete structures with high deterioration and less deterioration.

Frequency content of ground motion may have a significant effect on the dynamic response of buildings subjected to earthquake excitation. When the frequency content of earthquake ground motions closely matches the natural periods of buildings [23], the structural dynamic response and seismic forces can be significantly enhanced and the buildings may suffer severe damage. From an engineering practice perspective, it is more convenient to characterize frequency content by a scalar parameter, compared with a response spectrum, which provides the comprehensive information of ground motion frequency content.

Past studies have proposed several scalar frequency content parameters to investigate the influence of ground motion frequency content on the seismic behavior of buildings, such as the predominant velocity period T_g, the characteristic period T_c, and the mean period T_m. T_g represents the period of the maximum 5% damped relative velocity spectrum for an elastic SDOF system. T_g was adopted by Uang and Maarouf [24], Ruiz-García and Miranda [25], and Chakraborti and Gupta [26] to characterize seismic deformation demands of buildings. Ruiz-García [27] investigated the features of mainshock–aftershock and presented that the T_g of aftershocks tends to be shorter than that of the mainshocks, and may significantly impact the seismic behavior of post-mainshock buildings. T_c is defined as the period corresponding to the interaction ordinate of two straight lines which represents an idealized acceleration response spectrum. Chopra and Chintanapakdee [28] studied the ratio of structural period T_1 to T_c to characterize the difference in the inelastic response of SDOF systems, and recommended T_c values for near-fault and far-fault ground motions of 0.79 and 0.42 s, respectively. T_m is defined as the mean period of the Fourier amplitude spectrum (FAS) in a specified frequency range and is adopted in this study. Rathje et al. [29] and Rathje et al. [30] recommended that T_m should be used due to its relation with FAS and its superior performance to distinguish the frequency content of strong ground motions. Kumar et al. [14] demonstrated that the seismic displacement of SDOF systems is amplified when the ratio of T_1 to T_m is lower than one, and that the base shear and maximum story drift profile of MDOF systems are remarkably influenced by higher modes of the building when T_m approaches the higher mode periods of buildings. Kumar et al. [31] found that the ratio of T_1 to T_m and the behavior factor have a remarkable influence on the global drift. The behavior factor is defined as "an approximation of the ratio of the seismic forces that the structure would experience if its response was completely elastic with 5% viscous damping, to the seismic forces that may be used in the design, with a conventional elastic analysis model, still ensuring a satisfactory response of the structure" [32].

The effect of characteristics of ground motion records on the structural behavior is not well understood, especially the effect on collapse risk of post-mainshock buildings. This study investigates the influence of aftershock characteristics on the collapse risk for both post-mainshock SDOF and MDOF steel building models. Incremental dynamic analysis was carried out on a set of 62 aftershock records with varying characteristics. The analysis is based on a nonlinear SDOF system and a typical 4-story steel framed building using deterioration models, which are capable of capturing the key properties of strength and stiffness degradation associated with structural damage, along with destabilizing effects of gravity loads. A generalized linear modeling regression technique was used to predict the structural collapse capacity measured in terms of inelastic spectral displacement. In addition, the relationship of the characteristics between the mainshock and aftershocks are investigated. This research will facilitate selection of the aftershock records in seismic behavior analysis, and reduce the variation of structural collapse capacity, as well as improve the assessment of collapse risk of post-mainshock buildings.

2. Duration of ground motion and frequency content

2.1. Duration

Many definitions for ground motion duration are available in the literature, such as the bracketed duration and the significant duration. The bracketed duration is defined as the time elapsed between the first and last excursion of the absolute accelerogram exceeding a specified threshold value. The significant duration are based on the length of the time between which specified proportions of the total energy of the ground motion record are accumulated. The duration of ground motion record in this study is measured by the 5–95% significant duration (D_s) since it has been used and recommended in a number of past studies [33]. D_s is defined as the interval of the times at which 5 and 95 percent of the Arias intensity of the ground motion are accumulated. The Arias intensity (AI) represents the integral over the recorded time of the square of the acceleration time history, which can be expressed as:

$$AI = \frac{\pi}{2g}\int_0^T a^2(t)\,dt \tag{1}$$

where T is the total recorded time of a ground motion, $a(t)$ is the recorded acceleration history, and g is the acceleration due to gravity. D_s accounts for the time length of the strongest part of ground motion since it represents the duration over which 90% of the total energy is accumulated [12].

2.2. Frequency content

In this study, the mean period T_m is chosen as a measure of frequency content of ground motion record to investigate its influence on structural collapse risk. The mean period, originally proposed by Rathje et al. [29], is calculated by the weighted mean periods of the Fourier amplitude spectrum in a specific range of frequency and can be mathematically expressed as [29]:

$$T_m = \frac{\sum_i C_i^2 \times \frac{1}{f_i}}{\sum_i C_i^2} \text{ for } 0.25\,\text{Hz} \le f_i \le 20\,\text{Hz}, \text{with } \Delta f \le 0.05\,\text{Hz} \tag{2}$$