Soil Dynamics and Earthquake Engineering 98 (2017) 222–234

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Fragility curves for RC frames under multiple earthquakes

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A R T I C L E I N F O

Keywords:
Fragility curves
Fiber-based modeling
Multiple earthquakes
RC frames
Degradation

A B S T R A C T

This study aims to overcome previous limitations and derive fragility curves for three RC (reinforced concrete) buildings with different number of stories under multiple earthquakes. As-recorded seismic sequences in different regions around the world are employed and fiber-based modeling approach that captures degradation in concrete and reinforcing steel materials is used. The results indicate that considering damage from previous events, number of stories, and earthquake region significantly affect fragility curves.

1. Introduction

Multiple earthquakes occur frequently all over the world. Structural damage from multiple earthquakes have been reported in many recent seismic sequences including Tohoku (Japan, 2011), Christchurch (New Zealand, 2010–2011), Chile (2010), Chile (2014), Chile (2015), and Nepal (2015). Hence, it is necessary to consider the effect of the damage from an event and its impacts on the nonlinear behavior of structures under subsequent events. Since usually the time spans between successive seismic events (in one earthquake sequence) are short, hence it is usually hard to retrofit a damaged structure due to preceding shaking to withstand succeeding ground motions. Therefore, structures suffer from significant stiffness degradation and strength deterioration as a result of accumulated damage in a seismic sequence.

An important aspect of seismic investigation of the structures is deriving fragility curves to determine the damage probability under different earthquake intensities. Fragility relationships are a required input for commercial loss assessment software. They are useful for identifying the levels of damage reached in a structure under a spectrum of earthquake intensities. This makes fragility curves an important tool for probabilistic assessment of RC structures [1].

In recent years some researchers have investigated the effect of multiple earthquakes on different aspects of nonlinear behavior of structures [1–35]. Amadio et al. [2] investigated nonlinear behavior of SDOF systems under multiple earthquakes. They employed different hysteretic models and showed that multiple earthquakes can cause significant damage accumulation. They also indicated that the most vulnerability is related to the elastic-perfect plastic systems and hence they can be considered as the controlling system. In this study, a moment resisting steel frame was also analyzed under seismic sequences. Findings showed a more reduction in behavior factor for the MDOF structure than the equivalent SDOF system is observed. One of the important parameters employed in their study to compare hysteretic models was q-factor (behavior factor). This factor can be used to approximate nonlinear dynamic analyses results from an elastic analysis. In a study by Amadio et al. [36] the accuracy of N2 method and equivalent linearization procedure for different hysteretic models were evaluated. These methods are used to obtain the inelastic spectra. Results of this study showed a more accurate approximation of inelastic spectra when using N2 method which is obtained by a reduction in elastic spectra using the q-factor. Rinaldin et al. [3] studied the behavior of non and partially re-centering structures under seismic sequences. They employed nonlinear SDOF systems to evaluate the effect of repeated ground motions on the structures with different hysteretic behavior and proposed some design rules for the buildings under multiple earthquakes in seismic regions. Hatzigeorgiou and Liolios [4] studied nonlinear behavior of RC frames under repeated strong ground motions. They employed 45 seismic sequences to investigate the inelastic behavior of eight RC frames including both regular and vertically irregular structures. The results of this study showed that the response and design of RC frames are significantly affected by seismic sequences. They also proposed an empirical expression to estimate the ductility demands under multiple earthquakes using a simple combination of ductility demands under single earthquakes. Efraimiadou et al. [5] investigated the effect of aftershock polarity analytically and studied structural pounding between adjacent buildings under strong earthquakes. They proposed that the inelastic seismic behavior of the structures is strongly affected by aftershock polarity and the sign of the ground motions should be considered in generating artificial sequences. Abdelnaby [6] and Abdelnaby and Elnashai [7,8] studied the effects of multiple earthquakes on degrading RC structures. They used fiber based models to investigate the nonlinear

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http://dx.doi.org/10.1016/j.soildyn.2017.04.013
Received 25 February 2017; Received in revised form 9 April 2017; Accepted 17 April 2017
0267-7261/

Table 1
Multiple earthquakes.

Multiple earthquakes	Mainshock (Date and Magnitude)	Number of employed sequences
Chile 2010	02/27/2010 – M8.8	4
Chile 2014	04/01/2014 – M8.2	42
Chile 2015	09/16/2015 – M8.3	70
Christchurch 2010–2011	09/03/2010 – M7.1	132
Tohoku 2011	03/11/2011 – M9	194
Kumamoto 2016	04/15/2016 – M7	22

behavior of concrete structures under both artificial and as-recorded seismic sequences. Based on the results of this study, degrading models completely changed the response of the structures. Findings also demonstrated that the nonlinear behavior of RC structures is significantly affected by multiple earthquakes. Hatzivassiliou and Hatzigeorgiou [9] studied the effects of seismic sequences on three-dimensional reinforced concrete buildings. They observed that the seismic demands are increased by multiple earthquakes [10]. The effects of different aspects of nonlinear behavior of the RC buildings were considered by Hosseinpour and Abdelnaby [10]. They used two 8 story buildings (regular and vertically irregular buildings) and indicated that considering the vertical component of the earthquake, structure irregularity, and damage from previous events may significantly change the behavior of RC buildings. They also showed that earthquake direction and aftershock polarity affect the responses of the irregular buildings.

Deriving fragility relationships under multiple earthquakes has also been considered in some recent studies [1,11,12]. Li et al. [11] studied collapse fragility of steel structures subjected to earthquake mainshock-aftershock sequences and concluded that structural collapse capacity may significantly reduce when the building is subjected to a high intensity mainshock. They also observed that dispersion of the collapse capacity is low, moderate and large for repeated sequence, randomized sequence, and as-recorded sequence, respectively. Raghunandan et al. [12] also studied aftershock collapse vulnerability of reinforced concrete frame structures. They indicated that if the building is extensively damaged in the mainshock, there is a significant reduction in its collapse capacity in the aftershock and hence the damage level from the mainshock is an important parameter affecting the structural behavior under multiple earthquakes. They also observed high dispersions in results for higher damage levels. Abdelnaby [1] investigated fragility curves for RC frames subjected to Tohoku 2011 mainshock-aftershocks sequences. He considered three different design approaches including gravity, direct and capacity designs and showed that vulnerability relationships of RC frames are significantly affected by multiple earthquakes.

Although some studies have been performed so far to investigate the structural behavior under seismic sequences and to derive fragility curves, there are still some limitations. Most of the studies on fragility curves that are based on numerical simulations are limited to a single earthquake event and the numerical models used do not contain appropriate damage features that account for stiffness and strength degradation due to repeated load excursions. A few studies that consider multiple earthquake effects on fragility curves have been recently conducted, however they are limited by oversimplifying their numerical models. The employed models mostly include either system level based or component level based models. System level based models are the models considering the structure as single degree of freedom. Although these models are simple, they have some deficits. In system level based models, the localized behavior, force redistribution and the effect of higher modes are neglected. It should be noted that SDOF to MDOF transformations can be employed to capture MDOF properties such as the effect of higher modes like the procedure used by Guo and Chris [37] where they used a direct transformation procedure to convert the performance spectra target solution to an equivalent MDOF system. Component level based models or lumped plasticity models have also been extensively used to show the behavior of the MDOF structures under seismic sequences. Although these models are not computationally expensive, they do not account for localized degradation in strength and stiffness. In these models, the length of the plastic hinges is considered as zero. Other than the beam and column ends, the rest of the structure assumes to behave elastically. Most of the present studies have also employed repeated or uncorrelated random earthquakes (artificial sequences) to form sequences used to derive fragility curves. Since the characteristics of the mainshock and aftershock, such as magnitude, intensity, frequency content, and duration are different and characteristics of the ground motions are different in different site conditions as well, using artificial sequences leads to unreliable results [10]. Most of the present studies on fragility curves of RC buildings are also limited to single events; hence, the effect of subsequent events is neglected in these studies. The effects of earthquake intensity type, vertical earthquake component, building height (number of stories), and earthquake region are other important deficits need more attention.

This study aims to employ a wide range of as-recorded seismic sequences from different regions in the world including Japan [38], Chile [39,40], and New Zealand [41] to investigate the vulnerability of RC buildings under different mainshock and aftershock intensities. To

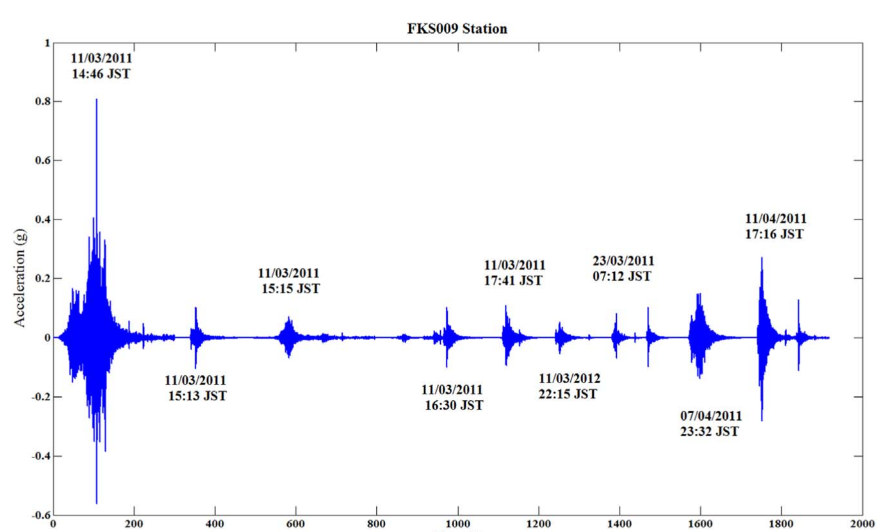

Fig. 1. East-West seismic sequence in FKS009 station (Tohoku 2011).