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Loss estimation of steel buildings to earthquake mainshock–aftershock sequences

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ABSTRACT

Following a large earthquake numerous aftershocks can be triggered due to the complex stress interaction between and within tectonic plates. Although aftershocks are normally smaller in magnitude, their ground motion intensity can be large and have different energy content than the mainshock. Even seemingly undamaged buildings may be damaged as a result of aftershocks. The mainshock-damaged buildings with deteriorated structural properties are more susceptible to damage.

This paper proposes a framework for loss estimation of steel structures subjected to mainshock–aftershock sequences. The analysis is based on a typical 4-story steel frame with a deterioration model. Mainshocks are modeled as a homogeneous Poisson process, while aftershocks are simulated from non-homogeneous Poisson process, magnitudes of which are characterized by the Gutenberg–Richter relationship. The proposed framework is applied to examine the effects of aftershocks on seismic loss. The expected seismic loss of the building subjected to two levels of earthquakes, the Design Earthquake (DE) and the Maximum Considered Earthquake (MCE), followed by aftershocks are examined considering both transition cost and downtime cost. Monte Carlo Simulation (MCS) with Latin Hypercube Sampling (LHS) is applied to examine the uncertainty in the loss estimation. Uncertainty in earthquake ground motions, structural model, damage and loss are all considered. It was found that even if aftershocks have little effect on structural response, they may still have a significant impact on seismic loss due to the uncertainty of the damage state and cost estimation. This methodology can be used to mitigate seismic loss and evaluate the current building design.

1. Introduction

A large mainshock can trigger numerous aftershocks because of the complex stress interaction between and within tectonic plates [1]. Aftershocks have the potential to cause severe damage to mainshock-damaged buildings, threaten life safety, and result in significant economic losses even when only minor damage is present from the mainshock. The 2012 East Azerbaijan earthquake hit northeast of Tabriz on August 11, 2012, and the strongest aftershock measured at M6.3 occurred eleven minutes after the M6.4 mainshock. The mainshock–aftershock sequence caused at least 327 deaths and more than 3000 other injuries [2]. On April 11, 2012, a M8.6 earthquake struck Indonesia, followed by several strong aftershocks with the largest measured at M8.2 just over two hours later, according to the United States Geological Survey [3]. The great Tohoku earthquake on March 11, 2011 in Japan, triggered 60 aftershocks with magnitude 6.0 or greater and three over magnitude 7.0. The total economic loss in Japan was estimated at $309 billion [4]. The February 2011 M6.3 Christchurch earthquake was triggered by the 2010 M7.1 Canterbury earthquake. It incurred approximately $15 billion of rebuilding costs and 181 people were killed [5]. The M8.8 Chile earthquake on February 27, 2010 incurred 304 aftershocks of magnitude 5.0 or greater in the following two months [6] and the earthquake's losses were estimated about $30 billion [7]. Therefore, the effect of mainshock–aftershock (MS–AS) sequences, rather than just the mainshock alone, should be taken into account to evaluate the seismic performance of buildings.

The magnitudes of aftershocks are usually less than the mainshock, but an aftershock record may have a higher peak ground acceleration (PGA), longer duration, larger intensity, and different energy content than the mainshock [8]. Fig. 1 presents an example of an earthquake mainshock–aftershock sequence [9]. The

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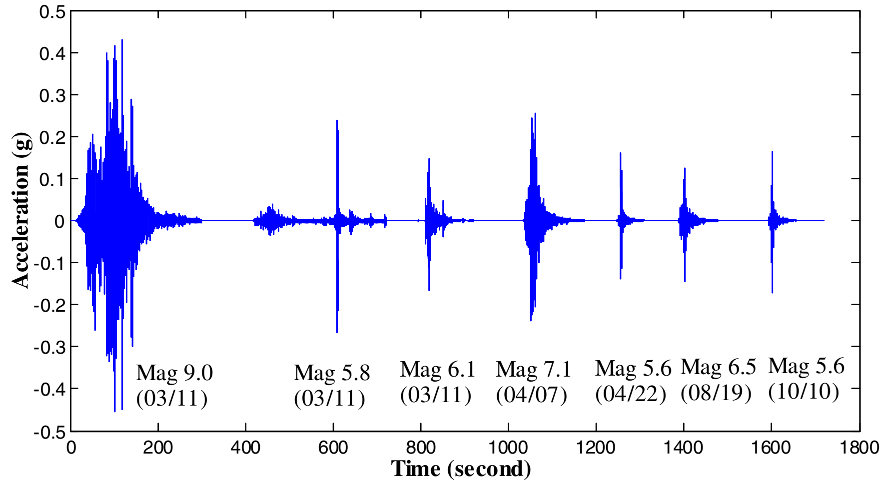

Fig. 1. An example of seismic sequence recorded at Haramachi station from 2011 Tohoku earthquake, Japan.

aftershocks have the potential to result in a larger seismic demand for a specified building, e.g., large spectral acceleration at the fundamental period of the building. Buildings with deteriorated structural properties are even more susceptible to damage from aftershocks. Occurrence of space and time-dependent aftershocks can be characterized by a non-stationary stochastic process. In general, the occurrence rate of aftershocks decreases with time after the mainshock. The delay between the mainshock and largest aftershock can range between several minutes to months. It is not realistic that the building damaged by the mainshock is repaired to an intact state immediately or before the next aftershock. It can take two years or longer to reopen mainshock-damaged buildings depending on the damage level and the aftershock intensities [10], which can result in significant financial loss from business downtime, in addition to human fatalities and repair cost.

The premise of current building codes is based on minimum life-safety design and does not provide provisions to mitigate the risk of seismic loss in earthquake events [11]. However, recent earthquakes have demonstrated that when moderate or severe earthquakes occur, the buildings designed under modern US building codes may suffer significant economic loss although human life has been adequately protected [11,12] which is the intent of the design codes. The magnitude of earthquake economic loss suggests it is necessary to consider other aspects of structural seismic performance besides the minimum life-safety design in modern building codes. Earthquake loss has been considered by researchers in the seismic design community since the early 1970s (e.g., [13]). The Pacific Earthquake Engineering Research (PEER) Center has proposed a conceptual framework for performance-based earthquake engineering (PBEE), which can be used to evaluate several components of total seismic loss, including economic loss, downtime, and casualties [14]. One topic of current research in PBEE is the determination of loss estimation and the uncertainty of the estimation [15]. In order to facilitate a framework in practice, the Applied Technology Council [16] formalized the performance-based seismic design process by examining three types of performance assessment: intensity-based, scenario-based and time-based. Based on the quantitative measures of structural performance, the risk of the probable seismic loss and its influence on structural design decision-making can be evaluated in PBEE. HAZUS-MH [17] has established a methodology for regional seismic loss estimation by calculating structural response, damage, and repair costs using generic building capacity and fragility functions. The Advanced Engineering Building Module (AEBM), which was recently enhanced in HAZUS-MH [18] permits users to capture building-specific damage and loss estimation.

Many researchers have recently looked into seismic loss estimation for different structural types. Porter and Kiremidjian [19] developed an assembly-based vulnerability (ABV) framework for probabilistic financial loss evaluation by calculating the summation of assembly level component losses. Goulet et al. [20] applied the PEER methodology to predict the seismic performance, termed financial loss and collapse safety, of a reinforced concrete moment-frame building, and the relevant sensitivity was investigated. Haselton et al. [21] assessed the performance of a four-story reinforced concrete office building and the performance was quantified in terms of collapse safety, financial losses and fatalities, and different building configurations were taken into account. Mitrani-Reiser [22] implemented the PEER's loss assessment methodology using a MATLAB Damage and Loss Analysis (MDLA) toolbox to estimate the economic losses of a reinforced-concrete moment-frame building. The uncertainty propagation for the PEER seismic loss estimation framework was examined by Baker and Cornell [15] using the first-order second-moment (FOSM) method. Ramirez and Miranda [23] developed a story-based loss estimation approach to simplify PEER's framework by relating structural response directly to loss for each story. Yeo and Cornell [10] proposed stochastic financial loss estimation models over the structural lifetime due to mainshocks and their aftershocks sequences, and a more general Markov and semi-Markov framework for modeling mainshock occurrence with various building damage states was also developed. Pei and van de Lindt [24] proposed a probabilistic framework to assess the long-term seismic financial loss of woodframe structures using a Bayesian model which allowed one to incorporate subjective engineering experience and test data. Bradley and Lee [25] investigated the efficacy of the FOSM method of uncertainty propagation and concluded that great care should be taken, particularly considering the large uncertainties that must be propagated because of large error in the results. Yin and Li [26] proposed an object-oriented framework to estimate seismic losses to light-frame wood buildings to mainshock–aftershock sequences, and showed that the aftershocks and downtime cost are important contributors to total seismic loss. Sanchez-Silva et al. [27] investigated the structural life-cycle performance accounting for loss of sudden events (e.g., seismic loss) and progressive degradation, and found that the progressive deterioration has a significant impact on the structural failure. Ramirez et al. [11] examined the expected repair cost in a set of 30 archetype reinforced concrete