Engineering Structures 168 (2018) 12–22

Contents lists available at ScienceDirect

Engineering Structures

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

Aftershock fragility assessment of steel moment frames with self-centering dampers

Baikuntha Silwal, Osman E. Ozbulut*

Department of Civil and Environmental Engineering, University of Virginia, Charlottesville, VA, USA

ARTICLE INFO

Keywords:
Shape memory alloys
Passive control
Viscoelastic damper
Steel structures
Aftershock fragility

ABSTRACT

This study explores the aftershock collapse performance of steel buildings designed with superelastic viscous dampers (SVDs) under seismic sequences. The SVD strategically combines shape memory alloy (SMA) cables and a viscoelastic compound to provide good self-centering and damping capabilities. A nine-story steel special moment resisting frame (SMRF) is first designed with or without SVDs to satisfy modern seismic design requirements. A mainshock incremental dynamic analysis (IDA) is conducted for the SMRF and SVD frames using a total of ten as-recorded seismic sequences. The specific levels of post-mainshock interstory drift ratios are then induced in both frames and an aftershock IDA analysis is conducted for the mainshock-damaged buildings. The maximum interstory drift and residual drift IDA curves are developed and compared for both frames at different mainshock damage levels. The results are analyzed in terms of aftershock collapse capacity, collapse fragility, and collapse capacity at demolition. The effect of aftershock ground motion polarity on the performance of both frames is also explored. The study reveals that the SMRF has increased vulnerability to aftershocks when higher damages are induced during mainshock, while the aftershock collapse performance of the SVD frame is not affected from the intensity of mainshock event. It is also shown that the SVD frame significantly improves the aftershock capacity associated to a residual story drift that leads to major alignment or demolition.

1. Introduction

In the traditional seismic design of structures, only one earthquake event called as mainshock is generally considered in the design process, while the effect of aftershocks is ignored. Aftershocks typically originate near the rupture zone of the mainshock and include a sequence of events with varying magnitudes and can occur hours, months or even years after the mainshock. For example, in Gorkha, Nepal, a local magnitude (M_L) 7.6 (a moment magnitude M_w of 7.8) earthquake was followed by 120 earthquakes with M_L greater than 4.0 within the first 12 h. There were 42 earthquakes with M_L greater than 5.0 within 30 days as shown in Fig. 1(a). Among these aftershocks, four ground motions with a local magnitude larger than 6.0 were observed within 20 days and the largest aftershock with a $M_L = 6.9$ ($M_w = 7.3$) occurred on May 12, 2015 [1]. Similarly, after February 27, 2010 Chile earthquake that had a M_w of 8.8, there were 306 aftershocks with magnitudes equal to or greater than 5.0 until April 26, 2010, among which 21 had magnitudes greater than 6.0. Fig. 1(b) shows aftershocks with M_w greater than 5.0 within first two days of February 27 Chile earthquake.

Structures that are exposed to the combined effect of a mainshock and a series of aftershocks in a short duration of time have increased vulnerability to structural damage. A number of buildings that were slightly damaged by the mainshock had major damage or even collapsed during an aftershock event in the past earthquakes such as the 1994 Northridge earthquake, 2011 Great East Japan earthquake, 2010 Christchurch earthquake, 1999 Kocaeli earthquake, 2010 Haiti earthquake, 2012 Emili earthquake, and 2015 Gorkha earthquake [2–9]. Aftershocks usually have different frequency, amplitude, energy content, and duration than the mainshock, and therefore they might require a different performance demand. Since aftershocks might occur immediately after the mainshock or several months later than the mainshock, assessing the integrity of a structure after a major earthquake and identifying any damage is critical for ensuring long-term safety of occupants.

In recent years, there have been several attempts to study the performance of buildings under mainshock-aftershock ground motion sequences. Raghunandan et al. [10] studied the collapse vulnerability of ductile reinforced concrete frames under mainshock-aftershock sequences. Their results suggest that the buildings with substantial damage during a mainshock have a 40% decrease in median collapse capacity to resist aftershocks, while there is no significant change in aftershock collapse fragility if the building is not severely damaged

* Corresponding author.
E-mail address: ozbulut@virginia.edu (O.E. Ozbulut).

https://doi.org/10.1016/j.engstruct.2018.04.071
Received 26 June 2017; Received in revised form 15 March 2018; Accepted 20 April 2018
0141-0296/

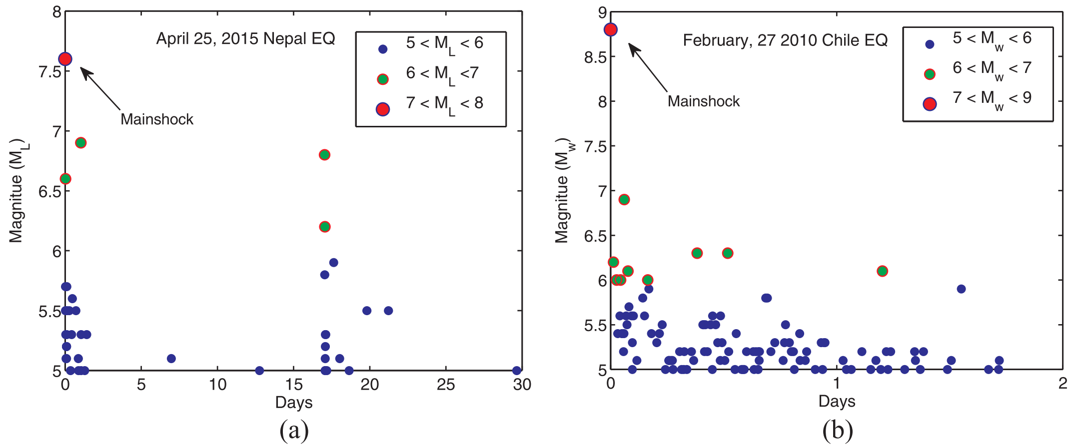

Fig. 1. Major aftershocks (a) within 30 days of April 2015 Nepal earthquake and (b) within 2 days of February 2010 Chile earthquake.

during the mainshock. Jeon et al. [11] proposed a framework that can be used to develop aftershock fragility curves for structures damaged by a mainshock earthquake. They developed fragility curves for three reinforced concrete building frames and found that the vulnerability associated with post-mainshock damage increases mainly for frames that sustain a significant damage during the mainshock. Li et al. [12] conducted a study to integrate mainshock-aftershock seismic hazard into performance-based engineering and explored the collapse probability of mainshock-damaged steel frame buildings in aftershocks. They found that a steel building subjected to a high intensity mainshock is likely to collapse even under a small aftershock. On the other hand, Ruiz-García and Negrete-Manriquez [13] reported that there is no significant increase in peak and residual drift demands in steel moment-resisting frames subjected to recorded historical mainshock-aftershock sequences. Ribeiro et al. [14] developed a reliability-based framework to quantify structural robustness of buildings under mainshock-aftershock seismic sequences. The proposed framework was applied to assess the robustness of three steel frame buildings that were designed by pre-Northridge codes. The results of this study indicated that there is a substantial increase in failure probability when the structure is analyzed under a sequence of seismic events.

Residual deformations sustained by a structural system after a seismic event can have significant role in the post-earthquake structural performance assessment [15–17]. Structural systems that exhibit excessive residual drifts under strong earthquake events may be demolished even if no severe damage or partial collapse exists. For example, Itawa et al. [18] conducted a field investigation over 12 leaned steel frame buildings in Japan after 1995 Kobe earthquake to recommend a reparability limit considering restoration costs and residual drifts. They suggested that a maximum roof residual drift ratio of 0.5% or a maximum residual interstory drift ratio of 1.1% might require demolition of steel frame buildings considering technical and economic perspectives [18]. Similarly, Erochko et al. [19] studied the residual drift response of steel buildings through numerical simulations and found that steel moment resisting frames show significant residual drifts (greater than 0.8%) even under design basis earthquakes, while the residual drift values vary between 2.0 and 4.0% for maximum considered seismic hazard levels. They also reported that a steel building experiencing a 0.5% residual drift from an initial earthquake will not behave as designed under a subsequent design level earthquake. In another study, Ramirez and Miranda [20] revealed that incorporating losses from permanent drifts in loss estimation considerably increases total economic losses. Hence, limiting residual drifts of structures subjected to seismic sequences can minimize repair costs, maintain overall structural integrity, and improve post-event functionality.

In order to enhance the seismic performance and mitigate the residual drifts of steel frame buildings, several researchers have proposed and developed shape memory alloy (SMA)-based passive control devices [21–26]. SMAs are metallic alloys that exhibit excellent re-centering ability and good energy dissipation capacity [27]. The use of SMA elements in a seismic response control device enables inherent self-centering capability to the device. Recently, the authors experimentally studied the behavior of large diameter SMA cables and butyl rubber compounds, and proposed a hybrid passive damper called as a Superelastic Viscous Damper (SVD) [28]. The SVD shown in Fig. 2 strategically combines SMA cables that possess high tensile force capacity and excellent re-centering capability [29] and a viscoelastic damper that consists of two butyl rubber compounds bonded to three steel plates. The butyl rubber has high damping capacity while exhibiting relatively low stiffness. The authors have shown that the steel frame buildings designed with SVDs significantly reduce residual drift demands under different level of seismic hazards [30]. However, the performance of steel buildings with an SMA-based control device under seismic sequences has yet to be investigated.

This study evaluates the performance of steel frame buildings designed with and without SVDs under mainshock-aftershock seismic sequences. First, a nine-story steel building is designed to satisfy the modern seismic design requirements as two different structural systems: a special moment resisting frame (SMRF) and a reduced strength SMRF upgraded with SVDs. Next, a mainshock incremental dynamic analysis (IDA) is conducted under mainshock events only to identify three damage levels for the SMRF and SVD frames. Then, the aftershock IDA for the mainshock-damaged structures is carried out using seismic sequences to assess the collapse capacities of both SMRF and SVD frames at three damage states. To evaluate the effectiveness of the SVDs in improving the performance of steel structures, the results are analyzed in terms of collapse capacity, collapse fragility, and collapse capacity at demolition for both SMRF and SVD frames.

2. Aftershock performance assessment framework

In recent years, several assessment procedures have been proposed

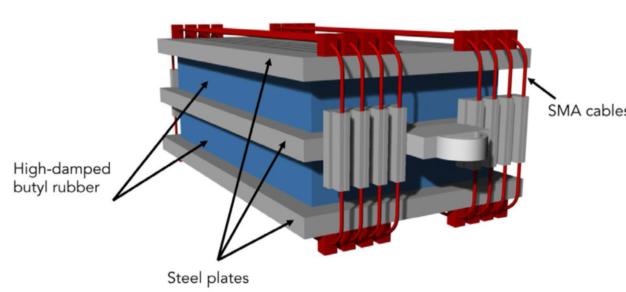

Fig. 2. Superelastic viscous damper.