Soil Dynamics and Earthquake Engineering 115 (2018) 205–216

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Probabilistic mainshock-aftershock collapse risk assessment of buckling restrained braced frames

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ARTICLE INFO

Keywords:
Buckling restrained braces
IDA
Residual drift
Mainshock-aftershocks
Annual collapse risk
After-shock fragility

ABSTRACT

Buckling-Restrained Braced Frames (BRBFs) are among the common seismic resistant systems with many beneficial characteristics such as stable cyclic behavior and high energy dissipation. However, recent studies have shown that BRBFs are susceptible to residual deformations during earthquakes which makes them vulnerable to aftershock events. The aim of the current study is to investigate the aftershock collapse capacity of BRBFs. In the first part of the paper, simplified procedures including IDA and collapse fragility analyses are carried out to gain more insight regarding the residual drift and collapse capacity of the intact frames. Then, aftershock fragility assessment is conducted for several damage states, to highlight the influence of post-mainshock residual drifts on the collapse of the structures. As for the second part, a detailed probabilistic framework is introduced and utilized to include the effects of upcoming aftershocks on the annual collapse probability of the structures. Results show that aftershock can highly intensify the structural response especially when the structure tolerates large residual drifts during the mainshock.

1. Introduction

Buildings in active seismic regions are subjected to severe multiple earthquake sequences and it is not uncommon for a frame to withstand more than one earthquake in a relatively short period of time. Aftershocks could be triggered by a mainshock which alters both static and dynamic stresses in the close zones and release the concentrated stress in the nearby faults [1]. The time span between the seismic motions might be insufficient to retrofit/repair the damaged buildings, leading to accumulation of plastic deformation or even complete structural collapse. For instance, after the M7.9 Wenchuan earthquake which occurred on 12th May 2008, more than 40,000 aftershocks were recorded during the next four months which eight of them were from M6.0 to M6.5 [2], causing more damage to the buildings that sustained the strong mainshock event. On 4th September 2010, a M7.1 earthquake occurred in Christchurch, New Zealand which was followed by an M6.3 aftershock on 22nd February 2011. the latter resulted in 185 deaths which over the half of casualties occurred in the Canterbury Television (CTV) Building [3]. The delay between the largest aftershock (AS) event and the mainshock (MS) is hard to predict and its occurrence rate decreases as the time goes by.

Although in seismic sequence, aftershock contains lower magnitude, it could contain higher peak ground acceleration (PGA) and much different energy content [4] which tends to complicate the analysis for the structure that is already damaged from mainshock earthquake and represent different period and structural features than its undamaged condition [5]. Moreover, it is possible for a mainshock with large wave amplitudes to trigger the aftershocks on its wave path even very far from the mainshock hypocenter [6].

Despite the considerable threats which can be imposed by aftershock events, most current seismic assessment and widespread design codes only take into account the MS effects without the possibility of sequential MS-AS scenarios. Therefore, several researches have been conducted in the last decade, aiming for developing frameworks to integrate the aftershock seismic hazards for different types of structural systems, as well as assessing the performance of various structures during multiple earthquake scenarios. Luco et al. [7] developed a new approach using a "calibrated" static pushover for determining residual capacity. Yeo and Cornell [8] introduced a conceptual framework to address the aftershock hazard in the context of performance-based earthquake engineering. Li and Ellingwood [9] assessed the performance of steel moment frames against MS + AS scenarios and provided probabilistic description for damage states before and following aftershocks.

Hatzigeorgiou et al. [10] examined the effects of multiple near- and far fault seismic ground motion on the ductility demand of single

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https://doi.org/10.1016/j.soildyn.2018.08.029
Received 21 April 2018; Received in revised form 14 August 2018; Accepted 21 August 2018

degree of freedom (SDOF) systems and pinpointed that the multiplicity of earthquakes strongly affects the ductility demands. Zhai et al. [11] utilized Park-Ang damage index to investigate damage spectra for mainshock-aftershock sequence-type ground motions and studied the effect of aftershocks on the damage of inelastic SDOF structure [12]. Efraimiadou et al. [13] studied structural pounding and the effect of collision between adjacent reinforced- concrete building frames under real seismic sequences. Hatzigeorgiou and Liolios [14] examined non-linear behavior of irregular reinforced-concrete (RC) frames subjected to artificial seismic sequences and presented a simple empirical expression, which combines the ductility demands of single ground motions, to estimate cumulative ductility demands due to sequential ground motions. Jeon et al. [15] developed the aftershock fragility curve for non-ductile 3-story RC building. They simulated the mainshock damages by cyclic pushover analyses.

Li et al. [3] utilized a calibrated degradation model of steel moment frame to investigate the effects of damage state from MS on the structure's collapse capacity. Nazari et al. [16] introduced a framework to quantify the required changes in structural design to take into account the aftershock hazard and provided an illustrative example for a woodframe townhouse. They also calculated the AS collapse fragility for the building, using three levels of mainshock intensity (i.e. DBE, MCE and 0.8 g mainshock) [5]. Ruiz-García and Aguilar [17] developed a methodology for assessing the aftershock hazard of the building taking explicitly into account the post-mainshock residual drift as a measure of MS damage state. They provided a 4-story steel moment frame as a case study. Gaetani d'Aragona et al. [18] utilized various return periods of main shocks for developing the AS fragilities of non-ductile RC buildings.

As can be noted, various methodologies are introduced by different researches which aimed for derivation AS fragilities for MDOF systems based on nonlinear time history and IDA analyses for various structural systems such as wood frames [5,16], steel buildings [3,9,17], shear wall systems [19], and RC structures [15,18,20,21]. Although the mentioned researches provide some basic information on performance of buildings with different structural systems, there is still a need for further investigation, taking into account the other lateral-load resisting systems which are being utilized in active seismic zones. One of the common systems are braced frames with Buckling Restrained Braces (BRBs). However, up to the authors' best knowledge only a few studies have investigated the performance of BRBs during MS-AS seismic scenarios [22,23]. Considering the wide applications of such bracing systems in active seismic regions as a well-known prequalified solution for buckling phenomena, more studies should be conducted to gain more insight regarding the performance of BRBs against sequential earthquakes. To bridge such a knowledge gap, this paper investigates the aftershock collapse assessment of BRB frames, taking into account the post-mainshock residual drifts as MS damage states. A set of 4-, 8-, 12- and 15-story BRB frames are modelled using openSEES [24] software package. In the first part of the paper, IDA analyses are being used to provide some basic information regarding the residual drift capacity of the frames. Then, aftershock fragility assessments were conducted to investigate the effect of mainshock residual drift on the collapse probability of structures. As for the second part of the paper, a simple methodology is introduced to determine collapse risk of the BRB frames considering both mainshock and aftershock seismic scenarios. The annual collapse probability is then calculated for MS-only and MS-AS scenarios and results are compared. The calculated results are probabilistic quantification of post-mainshock seismic risk for the BRB frames which can be utilized for design/retrofit modifications of such frames. This study provides a detailed analysis and seismic performance investigation of BRB frames with emphasis on MS-AS scenarios.

2. Buckling restrained braces

Buckling restrained braces were introduced to solve the shortcomings of the conventional braces under compressive loads. The brace is composed of a ductile steel core which is confined by steel sleeve that laterally supports the core and mitigates buckling (Fig. 1). Tests of BRBs have shown a stable, easy to predict and robust behavior during cyclic loads which indicates significant energy dissipation in both inelastic tension and compression loads [25]. However, the low post-yield stiffness of BRBs may cause them to exhibit large maximum and residual drifts which could trigger the formation of soft stories. This is due to the fact that after yielding the BRBs, the strain hardening ratio of the core could provide minimal restoring force and therefore, residual deformation can easily concentrate in the story [26]. Although the issue tends to be more critical in taller buildings with increased sensitivity to P-delta effects, the main concern could be associated to the MS-AS scenarios when the BRBs are at their post-yielding stages (due to the mainshock event) and are in danger of aftershock events. Unfortunately, the number of studies to investigate the performance of BRBs during consecutive seismic events is limited. Among the researches related to the performance of BRBs during MS-AS scenarios are the studies conducted by Guerrero et al. [22] who investigated the performance of steel frames with or without BRBs under artificial sequences and pinpointed the greater effects of aftershock when their peak ground velocity is similar to that of mainshock. Erochko et al. [23] investigated the effect of initial residual drifts on the performance of special moment resisting frames (SMRFs) and BRB frames (BRBFs). By applying the same earthquake twice and comparing the results for the two systems, they highlighted that BRB frames are significantly more sensitive to initial residual drifts than SMRFs. Here, to take into account the influence of initial residual drift on the performance of MS-damaged BRB frames during aftershock events, this parameter is also selected as an indication of post-mainshock damage intensity level for IDA and aftershock fragility assessment. Then, a simple probabilistic framework is presented to calculate the annual collapse probability of BRB frames with inclusion of MS-AS collapse scenarios, based on different levels of post-mainshock residual drifts.

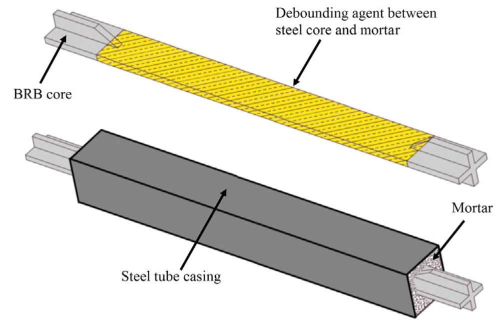

Fig. 1. A typical BRB.

3. Structural characteristics and openSEES modeling

A group of BRB frames including 4-, 8-, 12- and 15-story frames designed by Vafaei and Eskandari [27] were considered for analysis. The plan and elevation view of the frames are depicted in Fig. 2 and 3, respectively. It is worth mentioning that the mega-bracing arrangement which was considered for the frames can enhance the damage distribution capabilities of the frames to some extent and decrease the formation of soft-story mechanism in the lower stories. Frames were considered to be located near to an active seismic fault (Na = 1.2, Nν = 1.6) and designed by behavior factor R = 7 and deflection amplification factor C_d = 5.5. The assumed plan for the frames are symmetrical with bay length and floor height of 6.0 m and 3.2 m, respectively. The beams and braces are pin connected to columns (Fig. 4 [28]), making sure that the entire lateral load would be tolerated by BRB system. More information regarding the element sizes and design of the structures are