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Probabilistic Seismic Assessment of Steel Frames under Consecutive Earthquakes: A Comparison between Moment Frames and Linked-Column Frames

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ABSTRACT: Recent studies show that aftershocks can intensify structural damage and even lead to the collapse of the structures. Among the structural systems, moment frames show desirable ductility, but in such systems damage spreads in many structural elements. Accordingly, it is possible for these systems to experience more severe damage during an earthquake. Recently, Linked-Column Frame (LCF) is introduced to limit structural damage in moment frames, which can prevent the formation of plastic hinges in major structural members. However, only a limited number of investigations are carried out on these systems, and there is a lack of study that investigates post-mainshock performance of this system. The aim of this study is to investigate the influence of mainshock-aftershock (MS-AS) sequence on LCF system and compare the results with conventional moment frames. For this reason, SAC 3-story building, which is designed according to UBC-94, is modeled and analyzed in OpenSEES software package. In the first step, behavior of these structures is investigated using nonlinear dynamic analysis. In the next step, incremental dynamic analysis is employed for different performance levels including IO, LS, and CP states to gain a better insight into the behavior of these structures in MS-AS sequences. Results showed that MS-AS sequences could lead to increase in drift response of the frames with both systems. However, LCF showed a superior performance during seismic sequences.

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1. INTRODUCTION

Recent studies conducted on different structural systems reveal the significant effect of the seismic sequence phenomenon on the nonlinear response of multi-degree-of-freedom systems. Furthermore, since after the mainshock there is no possibility for any structural rehabilitation to mitigate the collapse risk, it is crucial to consider the increased response caused by aftershocks. For instance, after the 2011 Tohoku earthquake in Japan, within four days after the mainshock, 60 aftershocks, having over M6.0, were reported [1]. In Figure 1 an example of Tohoku's aftershocks has been shown. Most of buildings and infrastructures were severely damaged during this seismic sequence event.

To investigate the response of structure, there are several studies conducted about the aforementioned issue. Amadio et al. [2] investigated the effect of consecutive earthquakes on nonlinear single-degree-of-freedom systems.

Also, the elasto-plastic systems are referred to as the most vulnerable systems to the consecutive earthquakes. Hatzigeorgiou et al. [3] noticed that design, based on single-quake, is inadequate to sustain the effect of seismic sequences and thus proposed a reduced behavior factor. Li et al. [4] derived the fragility curves for a steel moment frame and conducted a comparative study on the mainshock and mainshock-aftershock fragility curves. Based on their study, a significant increase in probability of collapse under the effect of seismic sequences is reported.

Most recent researches focus on conventional structural systems, such as moment frames (MF). However, since these systems would spread the damage over all elements, it is important to investigate modern systems, which can concentrate the damage in certain elements. Moreover, it can be helpful for retrofitting purposes. In this paper seismic performance of a new system, named linked-column frame (LCF) [5], is assessed under the effect of consecutive earthquakes. Additionally, to illustrate the results, a comparison between LCF and MF is carried out.

2. CASE-STUDY FRAMES

Linked-column frame is constituted of two main components: Link column and replaceable link beams, bearing the seismic force, and a moment frame, which contributes to sustain gravity load and seismic loads simultaneously. According to Figure 2, in the moment frame, the beam-column connections at one end, are moment free in order to postpone forming the plastic hinges.

Based on the design procedure proposed by Malakoutian [5], elements are proportioned to ensure the formation of the plastic hinges in the moment frame are postponed. Therefore, first, plastic hinges would be generated in link beams then they would spread to adjacent moment frame. Thanks to this

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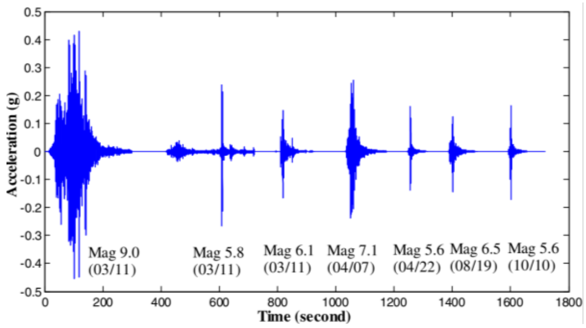

Fig. 1. Seismic sequence recorded at Haramachi station from 2011 Tohoku earthquake, Japan [1]

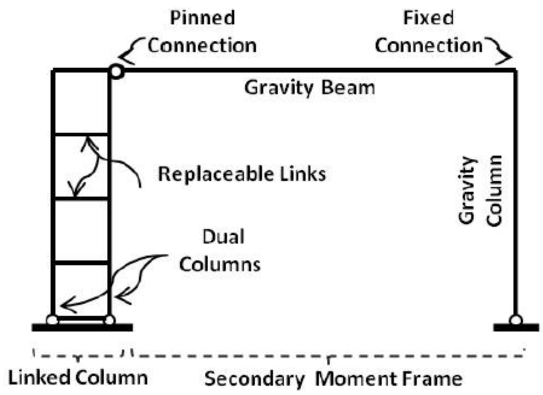

Fig. 2. Linked-column frame [5]

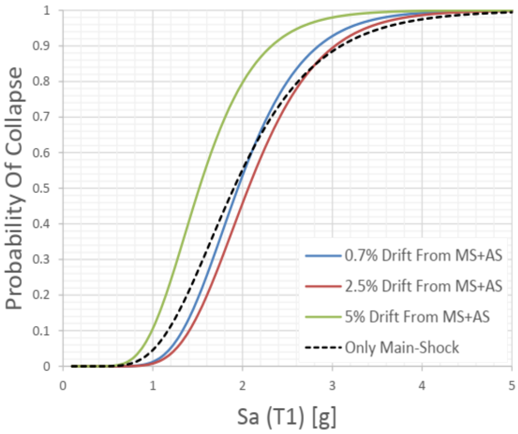

Fig. 3. Aftershock fragility curves for 3-story linked-column frame

configuration, before the onset of plastic hinges formation in the moment frame, a new limit state, called "Rapid Repair", could be defined. Hence, the deformed link-beams can be replaced to re-center the structure.

To compare the results with a moment frame, a 3-story moment frame, adopted from SAC's benchmark buildings, is utilized.

In this paper, OpenSees software package has been employed for finite-element models. Lumped plasticity modeling has been considered by using nonlinear hinges relationships, provided by Lignos et al. [6]. Incremental dynamic analysis (IDA) method has been used to catch the collapse threshold. Since the artificial seismic sequences can lead to overestimate the responses, in this paper, as-recorded seismic scenarios suggested in Ghodrati Amiri et al. [7], have been employed.

3. RESULTS AND DISCUSSION

Based on ASCE 41-13, there are limit states, describing a moment frame damage states: Immediate Occupancy, corresponding to 0.7% inter-story drift ratio (IDR), Life Safety, 2.5% IDR, and Collapse Prevention, 5% IDR. In the current study, the post-mainshock condition of the frames has been divided by the aforementioned limit states. On this basis, slight, moderate, and severe damage states have been defined. After scaling the mainshock to reach the determined limit state, aftershock records have been scaled until the collapse of the structure. According to extracted collapse capacities, aftershock collapse fragility curves have been derived. Figure 3 shows the aftershock collapse fragility for different mainshock intensities. To summarize the results, Table 1 demonstrates the MS-AS collapse capacities for both systems.

According to Table 1, when the main-shock caused a higher damage state, the aftershock collapse capacity would drop significantly. For more energy dissipation in LCF systems, this drop of collapse capacity would be more considerable in moment frames (MF) rather than linked-column frames (LCF).

4. CONCLUSION

This paper examined the nonlinear behavior of SAC moment frames and the linked-column frames, introduced recently, under the effect of consecutive earthquakes. Furthermore, collapse fragility curves caused by MS-AS sequence were derived. A comparison is made between the seismic performance of conventional moment frames and linked column frames. The following conclusions are obtained from this investigation:

• It is demonstrated that the seismic sequence phenomenon can significantly increase the IDR. For instance, IDR in 3–story moment frame, tends to increase up to 100 % due to this effect.

• By investigating fragility curves, it is illustrated that the post-mainshock damage state and collapse capacity are inversely correlated.

• Post-mainshock damage states which correspond to the slight and moderate damage, respectively, represented by IO and LS limit states, are not considerably affected by the aftershocks. But severe damage state, which is represented by CP, shows a significant capacity loss.

•For severe post-mainshock damage state, the comparison between MF and LCF collapse capacities reveals that LCF has lost 38% of its single-event (only mainshock) capacity while MF has lost 53% of its capacity. This attests to the LCF's superior seismic performance in sustaining multiple earthquakes.

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Table 1. Collapse capacities for MF and LCF under the effect of different MS-AS seismic scenarios

Post-mainshock damage state	$Sa(T_1)$ [g]	
	MF	LCF
Slight	2.26	1.95
Moderate	2.12	1.86
Severe	1.01	1.52

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