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RETROFITTING DAMAGED BUILDINGS UNDER SEISMIC MAINSHOCK-AFTERSHOCK SEQUENCE

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Abstract

Mainshock-aftershock sequences are a common occurrence in areas with high seismic activity, and they can significantly increase the damage sustained by a building after the initial seismic event. During severe mainshock earthquake, there is a permanent deformation in the floor levels of the building that increases the risk of further damage and potential collapse in the aftershock earthquake. This research aims to introduce a computational method for retrofitting damaged buildings under seismic mainshock-aftershock sequences using Fluid Viscous Dampers (FVDs) and Buckling-Restrained Braces (BRBs). This retrofitting approach aims to mitigate further damage that may be caused by subsequent aftershocks. The use of computational methods enables engineers to accurately simulate the behavior of damaged structures under various seismic loads, which helps in the design and optimization of retrofitting techniques. Due to ability of FVDs and BRBs, two steel structures having four and six-story floor levels were selected to implement the computational method of retrofitting. The results of analysis confirmed that the mainshock-aftershock sequences can highly affect the performance of damaged buildings, and the proposed method can accurately model the damaged buildings with different pre-defined damage states.

Keywords: Damaged Building, Mainshock-Aftershock Sequence, Computational Methods, Retrofitting Structure, Fluid Viscous Damper.

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1 INTRODUCTION

Fluid viscous dampers (FVDs) are devices that are used in structural engineering to mitigate the effects of seismic activity. They consist of a piston that moves within a cylinder filled with a viscous fluid, which dissipates energy and reduces the force transmitted to the structure during seismic events [1]. Conventional brace and FVDs have been widely used in retrofitting damaged buildings as they can be installed relatively easily and provide effective seismic performance enhancement [2]. Using FVDs either inside of lateral force-resisting system [3] or between the adjacent colliding structures [4, 5] showed that these passive energy dissipation device can widely implement in purpose of retrofitting.

Buckling-Restrained Braces (BRBs) are another type of device commonly used in the retrofitting of steel structures under seismic Mainshock-Aftershock (MA) sequences. BRBs consist of a steel core surrounded by a steel tube, which acts as a restraint to prevent the core from buckling. BRBs dissipate energy by buckling and yielding in a controlled manner, reducing the force transmitted to the structure and enhancing its seismic performance [6]. Asgarkhani et al. [7] used BRBs in reducing the damage caused by earthquakes in steel structures to ensure their safety and reliability after an earthquake. Yakhchalian et al. [8, 9] numerically modeled BRBs to assess the accuracy of the methods in predicting deflection amplification factor, which plays a key role on their actual behavior and capacity. Kazemi and Jankowski introduced a shape memory-based BRBs to improve the safety and reliability of the steel structures while the residual drift was considerably reduced [10].

Seismic Mainshock-Aftershock (MA) sequences occur when a large earthquake is followed by a series of smaller aftershocks. These aftershocks can cause additional damage to already weakened structures and may lead to local or total collapses [11]. As example of significant MA earthquakes in Turkey, Izmir earthquake struck on October 30, 2020, with a magnitude of 6.9 on the Richter scale, and following the mainshock, a number of significant aftershocks occurred, including a magnitude 5.2 that struck just 30 minutes after the mainshock. The recent earthquake struck on February 6, 2023 with mainshock magnitude of 7.8 on the Richter scale and following with aftershock magnitude of 7.7 on the Richter scale and hundreds of aftershocks. Therefore, MA earthquakes has the sequence time between some minutes till some years and the damaged buildings of mainshock needs to be retrofitted [12, 13].

Since the collapse of structures may occur due to external loads such as impact force of adjacent structures [14-16] or internal loss of strengths due to weakness of structural elements such as connections defects or gusset plates [17-19], there is a need to consider the damaged effects on the retrofitting of structures. The use of FVDs and BRBs in retrofitting damaged buildings under seismic MA sequences is especially important as these devices can absorb energy and reduce the force transmitted to the structure during both the mainshock and aftershocks. Steel structures that use FVDs and BRBs have been shown to have significantly improved seismic performance compared to those without these devices [3, 7]. The use of FVDs and BRBs reduces the stress and deformation on the structural members, preventing damage or collapse during seismic activity. These devices can also be retrofitted to existing structures, making them a cost-effective solution for improving seismic performance [3, 7, 10]. The influence of FVDs and BRBs on the retrofitting of damaged buildings is significant. These devices can increase the strength and ductility of steel structures, improving their ability to withstand seismic activity. The retrofitting process involves a detailed analysis of the existing structure to determine the appropriate placement and design of the devices. The devices are then installed, and the structure is tested to ensure that it meets the desired level of seismic performance [20, 21].

In conclusion, FVDs and BRBs are effective devices for retrofitting damaged buildings under seismic MA sequences. They can significantly improve the seismic performance of steel structures by dissipating energy and reducing the force transmitted to the structure during seismic activity, while the implementing time of devices are lower than other proposed procedures. The cost of implementation and workforce is another important matter that should be considered during the retrofitting process. Retrofitting damaged buildings with FVDs and BRBs involves a detailed analysis of the existing structure and the design and placement of the devices. Overall, the use of FVDs and BRBs in retrofitting damaged buildings is a cost-effective solution for improving the seismic performance of steel structures. In this study, to take the advantages of these devices, a numerical modeling procedure for retrofitting steel damaged buildings is introduced, in which, the damaged building is modeled with its real condition after mainshock earthquake. In addition, it is possible to control the distribution of FVDs or BRBs along the floor levels to reduce the cost of retrofitting.

2 MODELS OF STRUCTURES

To properly introduce the proposed modeling approach, two low- to mid-rise steel frames with three-, and five-story floor levels were modeled according to Kazemi et al. [22, 23]. To model the steel frames, it was assumed that the structures had regular plan with five bays in each direction and it was possible to model them as 2D model having the leaning column to consider the p-delta effects (see more detail about modeling process in [24-26]). The frames were located in soil type D with seismic category II having 4 m floor height and 7.5 m bay length. To model frames, OpenSees [27] software was used, in which, the concentrate plastic hinges were assumed for structural members to determine their nonlinear behavior (more details regarding the implementing concentrate plastic hinges can be found in [22-26]). Figure 1 illustrates the structural details of three-, and five-story steel frames.

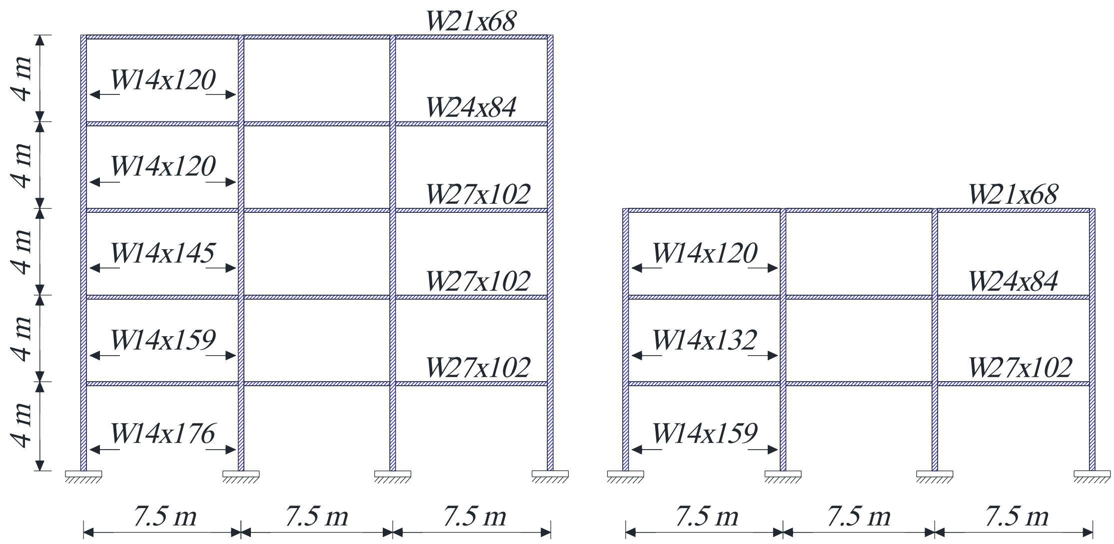

Figure 1: Low- to mid-rise steel frames with three-, and five-story floor levels.

3 RETROFITTING PROCEDURE

In this section, the retrofitting procedure is introduced, in which, the modeling of steel structures can be improved with the real condition of damaged structures. Figure 2 illustrates three main conditions of models in the proposed retrofitting procedure for steel damaged buildings under MA sequences. In the first condition, it is assumed that the model of structure is prepared based on the programming code implemented in OpenSees [27] software, then, mainshock of the assumed MA is applied regarding the selected intensity measure of ground motion. The engineering demand of interstory drift ratio is defined to control the behavior of structure during the analysis. There may be a residual drift after imposing the mainshock. Therefore, the second condition is considered as damaged structural condition, in which, the retrofitting device should be implemented on. Therefore, according to the opinion of the structural designer, the kind of retrofitting device (i.e. FVD or BRB) and the distribution of the devices along floor levels are selected. It is possible to implement device on the all floor levels or specific floor level. In the third condition, the aftershock is applied to the retrofitted damaged structure. It is noteworthy that whole procedure of modeling, applying the MA sequence, and retrofitting are in the one model implemented in OpenSees [27] software; therefore, the real condition of structure after mainshock and its possible structural damages are considered in modeling. In other words, the results of this type of retrofitting procedure is accurate compared to those retrofitted structures that neglects the structural damages in modeling process.

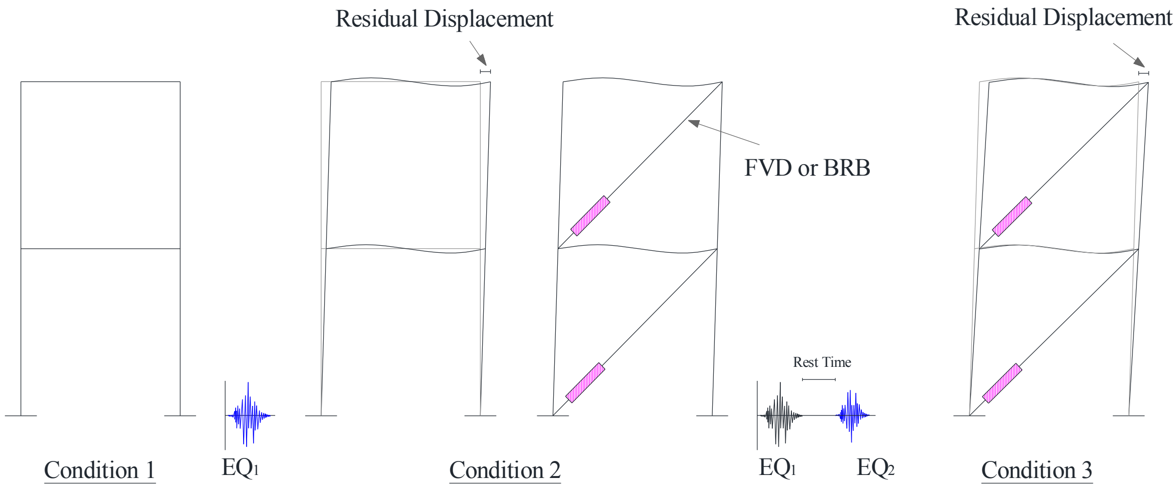

Figure 2: Proposed retrofitting procedure for steel damaged buildings under MA sequences.

4 RESULTS

To better compare the results of the proposed retrofitting process, two type of analysis known as nonlinear time-history analysis and Incremental Dynamic Analysis (IDA) [28, 29] were used. The MA sequence of Friuli earthquake (Tolmezzo station, Italy, 5/7/1976) was selected to perform nonlinear time-history analysis on three-, and five-story structures assuming FVDs and BRBs as retrofitting members, which the retrofitting procedure introduced in Figure 2 was applied in modeling. Figures 3 and 4 illustrate the interstory drift ratio-time history curve of the three-, and five-story structures assuming FVDs and BRBs as retrofitting members under MA sequence.

According to Figure 3, after applying mainshock, the three-story structure had a residual drift of 0.39% that is lower than the life safety allowable residual drift [7, 10]. It means that the structure still is able to resist the lateral loads and can be known as damaged structure. According to the procedure introduced in Figure 2, two retrofitting devices were implemented in modeling and then the aftershock is applied. Whole process is in the one model to consider the damages. The results showed that implementing FVDs and BRBs can considerably decrease the second residual drift of the three-story structure by 57.25% (from 1.31% to 0.56%) and 86.25% (from 1.31% to 0.18%), respectively, compared to the not retrofitted structure.

According to Figure 4, after applying mainshock, the five-story structure had a residual drift of 0.016% that is lower than the immediate occupancy allowable residual drift [7, 10]. Therefore, the small residual drift in the structure confirms the lower damages of structure after mainshock earthquake. After implementing FVDs and BRBs, the aftershock is applied and the second residual drift of the five-story structure has been reduced by 78.35% (from 1.94% to 0.42%) and 91.23% (from 1.94% to -0.17%), respectively, compared to the not retrofitted structure. Therefore, the results of analysis confirmed that the retrofitting approach proposed in this research can be effectively reduce the residual drift of structures, while the structural damages of structure after applying mainshock record was considered.

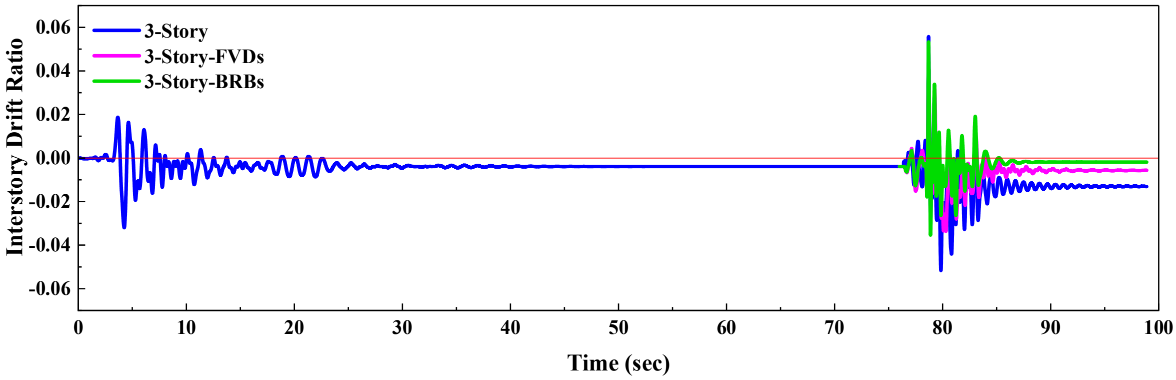

Figure 3: Interstory drift ratio-time history curve of the three-story structure assuming FVDs and BRBs as retrofitting members under MA sequence (Friuli earthquake).

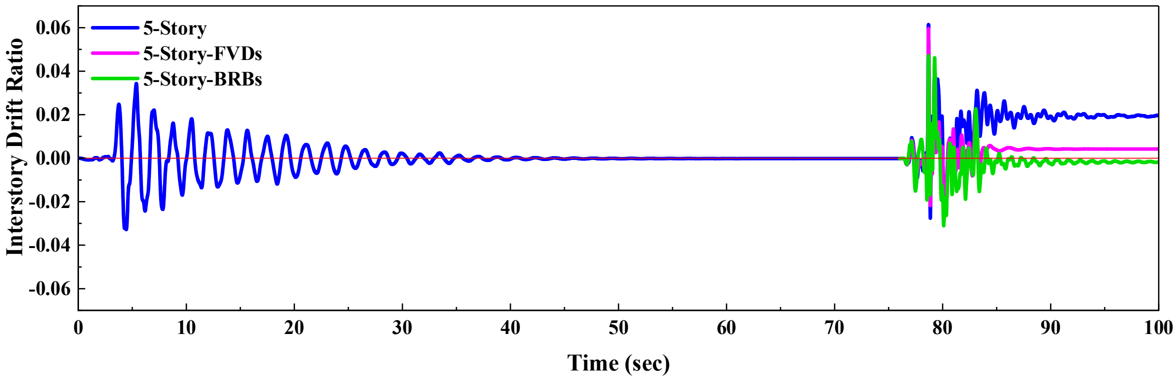

Figure 4: Interstory drift ratio-time history curve of the five-story structure assuming FVDs and BRBs as retrofitting members under MA sequence (Friuli earthquake).

It was assumed that the damaged structures meet the allowable life safety residual drift of 0.5% in the mainshock ground motions. Therefore, the proposed procedure applied for the IDAs of the damaged structures. Figure 5 illustrates the IDA curves of the three-story and five-story structures under ninety mainshock ground motions selected from [11-13]. Figure 6 compares the median of IDAs of the three-story and five-story structures under MA sequences. It can be seen that considered damage state can considerably affect the IDA curves and the median of IDAs, which confirms the importance of the considering the real condition of the structure in the modeling process. The results showed that the median of IDAs were reduced by 9.93% and 14.65% for the three-story and five-story structures under MA sequences considering the damage state of structures.

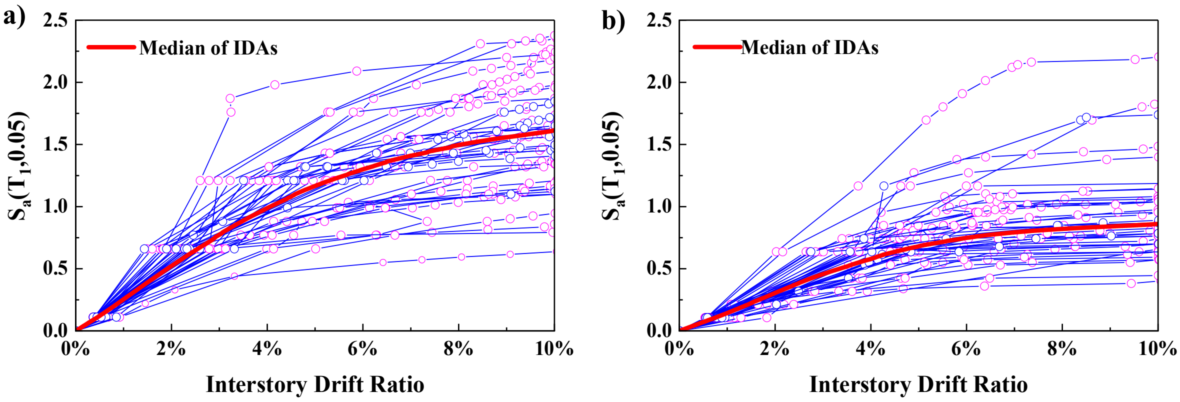

Figure 5: IDA curves of, a) three-story and, b) five-story structures under mainshock.

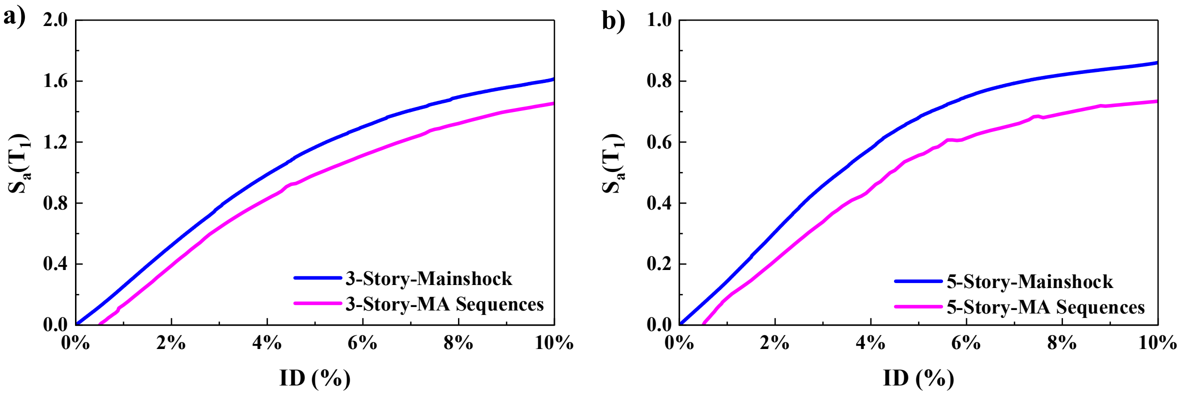

Figure 6: Median of IDAs of, a) three-story and, b) five-story structures under MA sequences.

5 CONCLUSIONS

This research proposed a modeling procedure for retrofitting steel damaged buildings with energy dissipation devices such as FVDs and BRBs. The results confirmed the significant effects of the damages on the results of analysis and the assumed retrofitting process can accurately model the damages of structures as it can be observed in real condition. The results showed that the modeling procedure can be applied for retrofitting structures in one model to reduce the time and efforts, while two type of analysis can be employed. In addition, it is possible to define the mainshock damage state in the modeling.

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