Introducing a computational method to retrofit damaged buildings under seismic mainshock-aftershock sequence

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Abstract. Retrofitting damaged buildings is a challenge for engineers, since commercial software does not have the ability to consider the local damages and deformed shape of a building resulting from the mainshock record of an earthquake before applying the aftershock record. In this research, a computational method for retrofitting of damaged buildings under seismic mainshock-aftershock sequences is proposed, and proposed computational strategy is developed using Tcl programming code in OpenSees and MATLAB. Since the developed programming code has the ability of conducting nonlinear dynamic analysis (e.g. Incremental Dynamic Analysis (IDA)), different types of steel and reinforced concrete structures, assuming different intensity measures and engineering demands, can be on the benefit of this study. To present the ability of method, the 4-Story and 6-Story damaged steel structures were selected. Then, the linear Viscous Dampers (VDs) are used for retrofitting of the damaged structures, and IDAs were performed under aftershock records. The results showed that the proposed method and computational program could improve the seismic performance level of damaged structures subjected to the mainshock-aftershock sequences. In addition, the damaged floor level of the building is recognized by programming code and can be effectively considered for local retrofit schemes.

Keywords: Computational Method, Damaged-Building, Retrofitting of Buildings, Mainshock-Aftershock Sequence.

1 Introduction

Nowadays, seismic activity is known as an external threat to buildings due to its unpredictable external loads that may impose sudden force on the story levels where the weight of the building is concentrated. Investigations have been carried out to propose procedures for assuming the effects of external loads such as pounding phenomenon [1] and impact force [2], which can cause local damages of structures [3, 4]. Then, retrofitting strategies for controlling the lateral loads effects [5], controlling the pounding force [6], and improving the seismic performance level of structures using buckling-restrained brace [7], knee brace [8, 9] and semi-rigid connections having

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shape memory alloys [10, 11] were proposed. Although it is possible to use dissipative devices such as linear Viscous Dampers (VDs), it is not beneficial to construct buildings with these expensive devices. Therefore, most of buildings have not been equipped with VDs and may be exposed to damages of mainshock or seismic sequences [12].

Studies have been conducted to provide the information of using linear and nonlinear VDs having different types of floor level distribution, and their influences on the Residual Drift (RD) and Interstory Drift (ID) of the steel structures [13]. Deringöl and Güneyisi [14] investigated the effectiveness of the using VDs in the seismically isolated steel buildings. Hareen and Mohan [15] introduced an energy-based method for retrofitting of reinforced concrete buildings using VDs, which improved the seismic performance. Pouya et al. [16] investigated the failure mechanism of conventional bracing system under mainshock-aftershock sequences. To overcome economic issues of using VDs, Asgarkhani et al. [17] and Kazemi et al. [18] introduced an optimal VDs placement process to reduce the cost of implementing VDs, while this procedure can be applied to those buildings under seismic mainshock effects.

It should be noted that the VDs may be used as retrofitting strategy for damaged buildings, while the modeling of damaged building and implementing the VDs after observing the local damages in the structures are the case of the present study. This research aims to propose a modeling process to implement VDs after damage of buildings under seismic mainshock, and improve their performances for aftershock earthquakes. This procedure considers the effects of pre-damaging in the building, which may increase the failure probability of the building and impose additional financial loss. The following sections try to present an example of using this procedure.

2 Modeling of structures

The 4-Story and 6-Story frames were designed in accordance with ASCE 7-16 [19] (see also [5, 10, 12] for details of designing process). Fig. 1 illustrates the structural details of the 4-, and 6-Story frames.

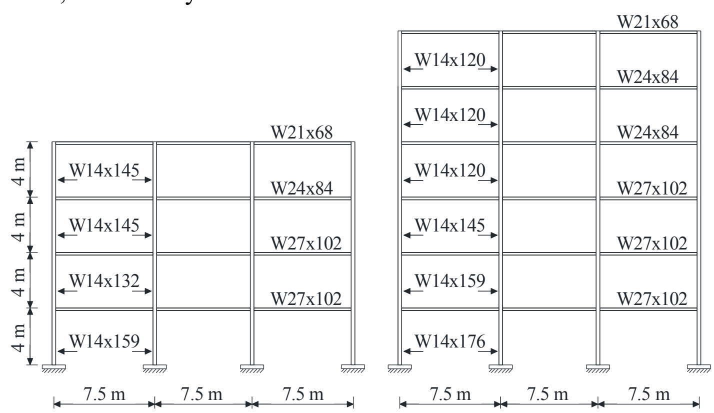

Fig. 1. Structural details of the 4-, and 6-Story frames.

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The structures were modeled in OpenSees [20] software using the procedures that have been employed by Kazemi et al. [21-24]. According to their procedure, to model 3D buildings, due to the symmetric plan of structures, it is possible to use 2D models with the same fundamental period and modal information. They have verified this procedure and used 2D models to facilitate the computational analysis. In addition, the leaning column was employed to represent the gravity columns of building for modeling of the P-delta effects, which plays a crucial role in the lateral behavior of buildings [2-4]. Moreover, the beams of structures were modeled with IMK hinges [10-12] and the columns were assumed to have fiber sections [4, 5].

3 Computational method

Literature review confirmed that VDs can be used to control the RD and ID of the steel structures, in which, this reduction can maintain structure within allowable limitations prescribed by seismic codes. Although implementing VDs for the purpose of retrofitting strategy is a common idea, the correct assessment of ID and RD is a challenging duty in front of structural engineers. Since a pre-damaged building has an initial stage of RD, it should be considered in modeling procedure. It is not easy to model local damages in structural elements, while in each member of building different damage states can be observed due to the strength of elements. Therefore, in this research, a modeling process is proposed to include all damage states of structural members and initial RD due to mainshock earthquake. Fig. 2 illustrates the proposed computational method for retrofitting damaged buildings.

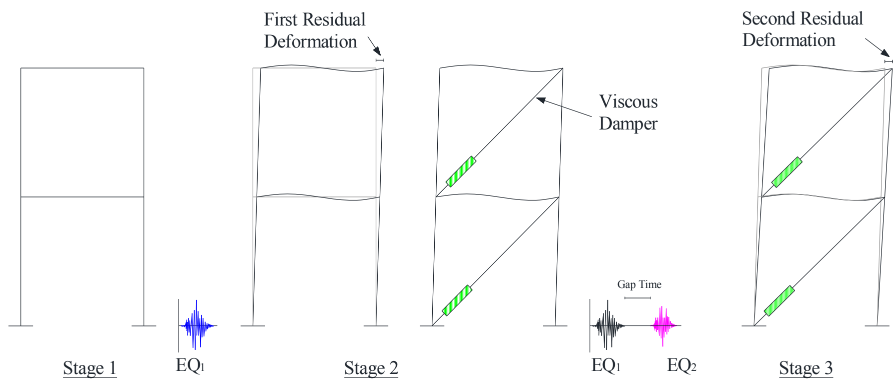

Fig. 2. Proposed computational method for retrofitting damaged buildings.

According to Fig. 2, in first stage, the model of the structure is ready, and in second stage, the first earthquake known as seismic mainshock is applied and first RD is calculated. In second stage, the computational method is applied to the model to implement the VDs as selected retrofitting strategy. In second stage, a Tcl programming code is developed in OpenSees [20] and MATLAB [25] software simultaneously to control the deformed shape model and implement the VDs. It should be noted that the VDs are implemented to a deformed shape model as it looks in Fig. 2. Then, the sec-

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ond earthquake known as aftershock is applied to the structure. To achieve the seismic performance of damaged structure under aftershock records, the Tcl programming code improved with the ability of performing IDAs, in which, three steps of analysis are defined based on the spectral spectrum remarked as $S_a(T_1)$ [26-28]. All of the procedure is automated to reduce the analysis time. The results of the analysis are plotted by MATLAB [25] to have an operator that controls the whole analysis procedure. This software can help the computational method to be repeated for the number of seismic records, and finally, the results of IDA curves are plotted. It is noteworthy that this computational method can be applied to any other methods of retrofitting using dissipative devices, since it is a general method with ability of changing the dissipative device during analysis. The proposed method has the ability of defining different intensity measures (i.e. $S_a(T_1)$) and a wide range of demands (i.e. RD and ID) for any type of structures (i.e. steel and reinforced concrete structures), while increasing the accuracy of the results and reducing computational time.

4 Retrofitting damaged building

To present the capability of proposed method, two selected structures were retrofitted with implementing VDs at all floor levels after mainshock earthquake. Figs. 3 and 4 compare the results of the deformation of the 4-Story and 6-Story frames in the mainshock-aftershock analysis with and without considering VDs, respectively.

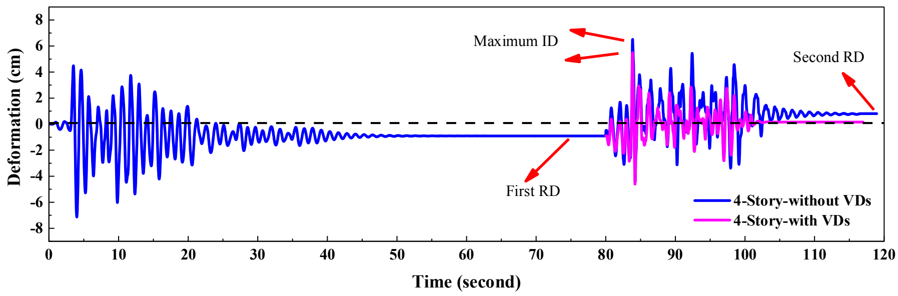

Fig. 3. Comparing the deformation results of the 4-Story frame in the seismic mainshock-aftershock analysis with and without VDs.

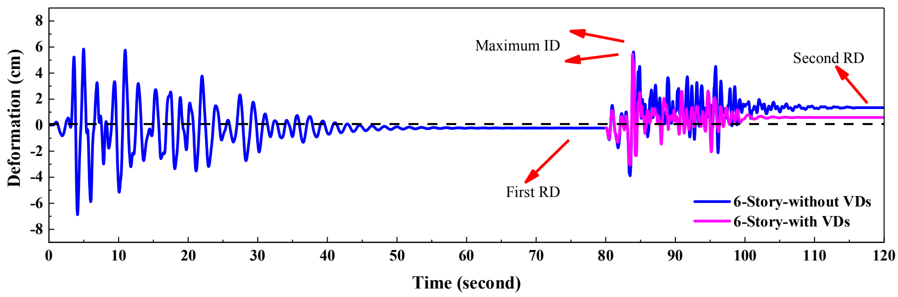

Fig. 4. Comparing the deformation results of the 6-Story frame in the seismic mainshock-aftershock analysis with and without VDs.

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The nonlinear dynamic analysis was conducted based on the Northridge record with RSN 949. In the seismic mainshock, there is a permanent deformation known as the first RD that illustrates the remained deformation in the structural elements and floor levels. In the constant part of the performing analysis (i.e. between 60 s to 80 s), the retrofitting procedure was done without stopping the analysis, while taking the first RD into account (i.e. 0.903 cm and 0.221 cm for the 4-Story and 6-Story frames, respectively). It can be observed that after implementing VDs, there is a significant influence on the values of the second RD. For the 4-Story frame, the second RD significantly decreased by 5.18 times from 0.808 cm to 0.156 cm by implementing VDs. In addition, for the 6-Story frame, the second RD considerably decreased by 2.27 times from 1.347 cm to 0.593 cm by implementing VDs. Therefore, the proposed computational procedure can effectively model the retrofitted structure by taking into account the remained deformation (i.e. RD) as well as the local damages of structure due to mainshock record.

To show the capability of the proposed method, the Tcl programming code was developed to perform Incremental Dynamic Analysis (IDA) that is a well-known method for seismic performance assessment. To perform IDAs, the seismic mainshock is applied to remain at a certain level of RD (i.e. first RD), and then, the aftershock is applied by increasing amplitude of ground motions until the total collapse of structures. All procedure were controlled by MATLAB [25] and results were plotted after analysis. It is noteworthy that the certain level of RD should be defined in order to assess the performance level of aftershock based on the RD of seismic mainshock. For this purpose, the aforementioned structures were selected to perform IDAs based on the first RD equal to 0.005 [5, 8]. To perform IDAs, the as-recorded mainshock-aftershock ground motion considered Ruiz-García and Negrete-Manriquez [29] were used. Fig. 5 presents the IDA curves of the 4-Story and the 6-Story frames under mainshock records. Fig. 6 compares the median of IDA curves (M-IDAs) of the 4-Story and 6-Story frames under mainshock-aftershock records.

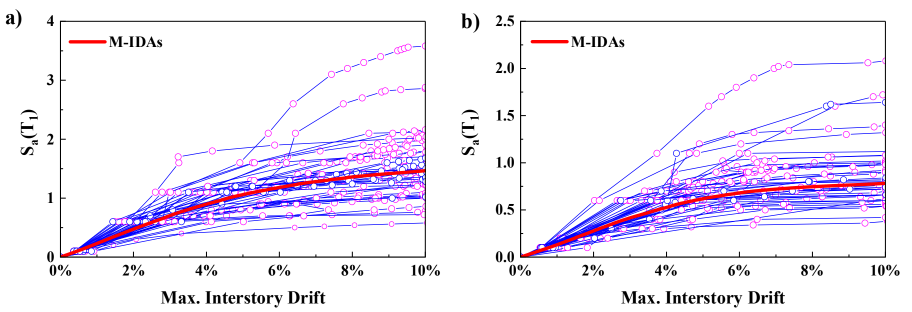

Fig. 5. IDA curves of, a) the 4-Story and, b) the 6-Story frames under mainshock records.

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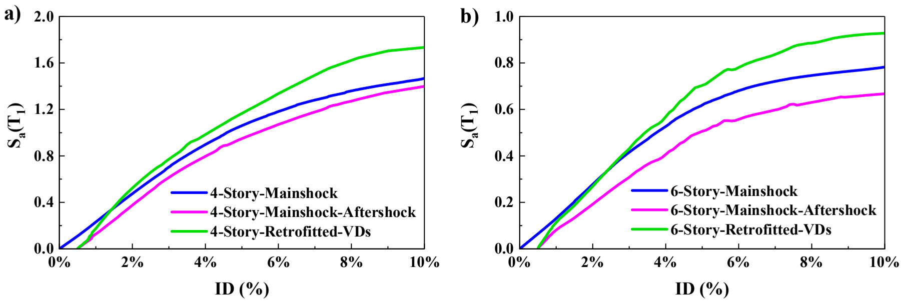

Fig. 6. M-IDAs of, a) the 4-Story and, b) the 6-Story frames under mainshock-aftershock records.

It can be observed that the proposed method can consider the RD of seismic mainshock (i.e. 0.005) for assessing the M-IDAs of structures. Moreover, by implementing VDs after mainshock record, it is possible to consider the RD of mainshock in the result of performance assessment of structures. For instance, in ID of 10%, the aftershock effects reduced the $S_a(T_1)$ values of the 4-Story and 6-Story frames by 5.07% (from 1.468 to 1.398) and 17.24% (from 0.782 to 0.667), respectively. Moreover, implementing VDs improved the seismic performance of the 4-Story and 6-Story damaged frames by 23.965 and 39.13%, respectively.

5 Conclusion

This research proposes an effective computational method for retrofitting damaged buildings under seismic mainshock-aftershock sequences. The proposed method can be applied to retrofit steel and reinforced concrete structures assuming different intensity measures and engineering demands. Moreover, a wide range of retrofitting devices can be applied such as VDs and buckling-restrained braces. To show the capability of the developed Tcl code, two structures having four and six-story levels were selected and the numerical nonlinear dynamic analysis and IDAs were conducted. The results of analysis show that the proposed method can provide the seismic performance level of damaged frames based on the seismic mainshock-aftershock sequences. The developed program increases the ability of performing analysis of damaged buildings assuming lateral deformations and local damages of buildings as a result of mainshock record. In addition, the damaged floor level of building is recognized by programming code and can be used for local retrofit instead of retrofitting of the whole structure.

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