Investigating an optimal computational strategy to retrofit buildings with implementing viscous dampers

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Abstract. Civil engineering structures may seriously suffer from different damage states result of earthquakes. Nowadays, retrofitting the existing buildings is a serious need among designers. Two important factors of required performance level and cost of retrofitting play a crucial role in the retrofitting approach. In this study, a new optimal computational strategy to retrofit structures by implementing linear Viscous Dampers (VDs) is investigated to achieve a higher performance level with lower implementation cost. Regarding this goal, a Tcl programming code was developed with the capability of considering damaged structure due to earthquake-induced structural pounding. The code allows us to improve structural models to take into account the real condition of buildings using both MATLAB and Opensees software simultaneously. To present the capability of this strategy, the 3-, and 6-story colliding Steel Moment-Resisting Frames (SMRFs) were selected. Incremental Dynamic Analysis (IDA) was performed based on the interstory drift ratio of floor levels as engineering demand parameter, and $S_a(T_1)$ as intensity measure. Interstory median IDAs of floor levels of colliding SMRFs were plotted to find out the floor level prone to damage and to retrofit only this floor level instead of all stories. The results show that implementing only two linear VDs with a cost of two units can achieve a higher life safety performance level in the case of 3-, and 6-story SMRFs. Moreover, the proposed computational strategy can be used for any structure (with and without pounding conditions), and in all performance levels prescribed in FEMA 356 code.

Keywords: Optimal Computational Strategy, Opensees Programming, Retrofitting of Buildings, Viscous Damper, Structural Pounding, Earthquakes.

1 Introduction

During severe earthquakes, buildings and bridge structures may suffer from different damage states, from local damage to the total collapse [1, 2]. In the case of buildings, many researchers proposed procedures of retrofitting using structural elements or energy dissipation devices. Using additional structural elements can increase the stiffness of the whole structure and can dissipate lower energy than using energy dissipa-

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tion devices, such as fluid Viscous Dampers (VDs), which would not alter the stiffness of the structure, and consequently, the frequency of vibration. These devices can perform in a wide range of temperatures (between -40 ºC to 70 ºC) and lower maintenance is required during longer life service. Therefore, this type of energy dissipation device was widely investigated and implemented in single structures, or between adjacent structures [3]. Kazemi et al. [4] investigated a seismic retrofitting procedure that uses diagonal VDs in all story levels of buildings. The results confirmed that using this strategy significantly influenced the seismic collapse capacity of the structures. In addition, Kazemi et al. [5] proposed using VDs between adjacent structures, which can prevent pounding during earthquakes. The distribution of VD within a structure is a critical decision due to its effects on the seismic response. While a large number of VD placements have been proposed, a limited comparison was conducted to investigate the effectiveness of these methods [6]. Predicting the seismic limit state or collapse capacity of a structure is a useful tool to determine the performance level of the structure during severe earthquake or due to impact forces induced by the pounding phenomenon [7, 8]. This performance level can help a designer to determine the damage state of a building [9-11]. Regarding this issue, the main purpose of this study is to investigate a new computational strategy to optimize the performance levels of structure and cost of VDs implementation. Regarding this goal, a Tcl programming code was developed with the capability of considering damaged structure due to earthquake-induced structural pounding.

2 Modeling approach

The three and six story level (3-story and 6-story) Steel Moment-Resisting Frames (SMRFs), designed according to ASCE 7-10 [12], were used in this study (see also [4-6]). Fig. 1 presents the documentation and structural elements of them.

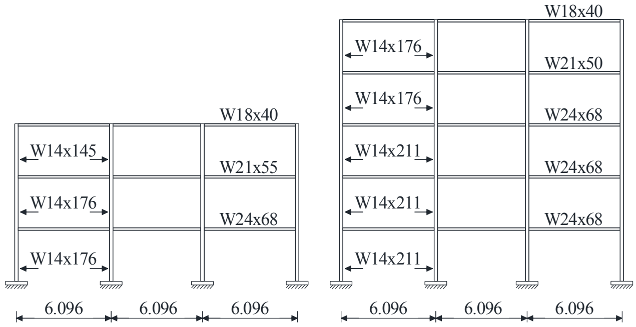

Fig. 1. Documentation and structural elements of the 3-, and 6-story SMRFs.

The plan presented in Fig. 2 was used to design the structures. According to this plan, there are four SMRFs in the three-dimensional building and one of them was modeled in this study. All columns were considered as leaning columns assuming the P-delta effect, except for those which belong to this single SMRF [13-15]. In addition,

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to model beams and columns, nonlinear rotational spring was used according to the Modified Ibarra–Krawinkler bilinear-hysteretic model [16].

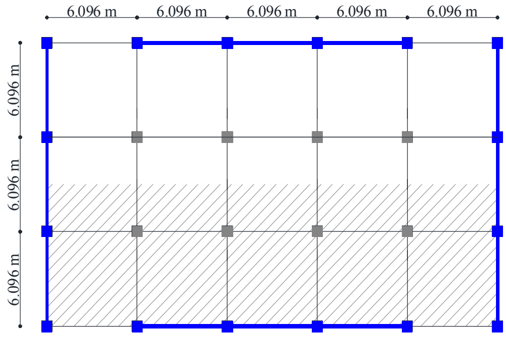

Fig. 2. Structural plan of the 3-, and 6-story SMRFs.

3 Computational retrofitting strategy

Previous researches have confirmed that using linear VDs show higher performance than using nonlinear VDs [4-6]. Therefore, in this paper, the effects of linear VDs are investigated. Kazemi et al. [4-6] used equations and procedures to model the pounding phenomenon, calculating an allowable clear distance between structures and implementing linear VDs. In order to simulate more accurately the real condition of structures exposed to pounding, the 3-story and 6-story SMRFs were modeled in MATLAB [17] and Opensees [18] softwares using a developed Tcl programming code with the capability of considering damages during analysis. Tcl program can analyze a model with high accuracy in nonlinear condition. In these programs, we used some innovative approaches to consider damages by monitoring the structural responses during analysis using MATLAB [17] software. This can help us to create precise models and it results in higher resemble real conditions of buildings prone to earthquake-induced pounding. Then, the retrofitting process started using these models to determine the damaged floor level during a set of ground motion records and automatically implement the linear VDs in that floor level. This developed Tcl programming code has the ability of controlling the engineering demand parameter to find damaged floors and implement the linear VDs automatically to reduce the analysis time. This process can be continued until achieving a higher seismic performance level prescribed by provisions in both adjacent structures.

4 Results of strategy

Incremental Dynamic Analysis (IDA) is a method to determine the total seismic collapse capacity. In this method, the potential levels of a ground motion, known as the intensity measure (e.g. $S_a(T_1)$), and an engineering demand parameter (e.g. Inter-

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story Drift Ratio (IDR)) are used to control the structure condition [4-6, 19, 20]. In this study, to perform IDAs, Near-field Pulse-Like (NPL) ground motion records suggested by FEMA P695 [21] were used, and IDA curves were plotted for all floor levels of the adjacent 3-, and 6-story SMRFs using IDR for all story levels. To compare the IDA curves, the Interstory Median of IDA curves (IM-IDAs) were determined. Fig. 3 presents IM-IDAs of all floor levels of the 3-, and 6-story SMRFs in pounding conditions subjected to NPL record subset assuming a clear distance of 0.298 m. To better illustrate the current state of a structure during severe earthquakes, the performance level was used. According to FEMA 356 [22], for primary structural elements, three performance levels of Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) were assumed regarding damages occurring in the structure. Therefore, the performance levels of IO, LS, and CP for SMRFs have the values of IDR of 0.7%, 2.5%, and 5.0%, respectively. In this study, the optimal retrofitting strategy using linear VDs is investigated to improve the performance level of LS. Therefore, IM-IDAs of all floor levels were compared in LS performance level (2.5%).

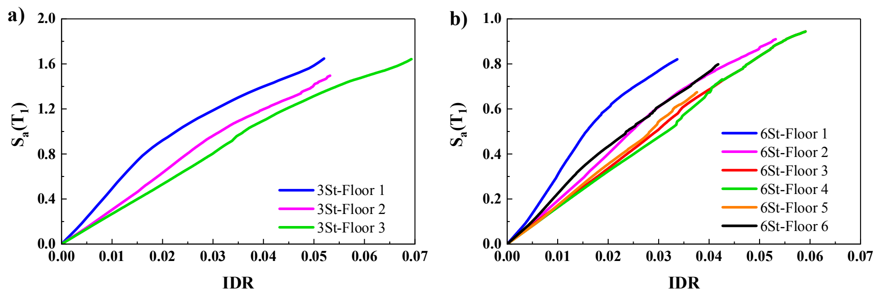

Fig. 3. IM-IDA curves of all floor levels of the 3-, and 6-story colliding SMRFs subjected to NPL record subset given clear distance of 0.298 m.

According to Fig. 3(a), the third floor of 3-story SMRFs has the lowest value of $S_a(T_1)$ in the LS performance level. Moreover, regarding Fig. 3(b), the fourth floor of 6-story SMRFs has the lowest value of $S_a(T_1)$ in the LS performance level. Therefore, these story levels were automatically selected for implementing one linear VD in the first retrofit analysis. Fig. 4(a) presents IM-IDA curves of all floor levels of the 3-story colliding SMRF retrofitted with one linear VD in the third story level. It can be seen that using the linear VD in the third floor level increases IM-IDA curves of the 1st, 2nd, and 3rd floor levels by 3.47%, -0.24%, and 6.45%, respectively. In addition, the third floor level still has the lowest value of $S_a(T_1)$ in the LS performance level. Then this floor level was automatically selected for adding the second linear VD in the second retrofit computational analysis. The results of IM-IDA curves of all floor levels of the 3-story colliding SMRF retrofitted with two linear VDs in the third story level are presented in Fig. 4(b). According to this figure, IM-IDA curves of the 1st, 2nd, and 3rd floor levels have increased by 33.89%, 42.57%, and 97.29%, respectively. Therefore, optimal placement of linear VDs in 3-story colliding SMRF with higher performance level achieved by using only two linear VDs that can be implemented by

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a cost of two units (cost of each linear VD assumed as one unit). Table 1 presents the values of $S_a(T_1)$ in the LS performance level for the 3-story colliding SMRF.

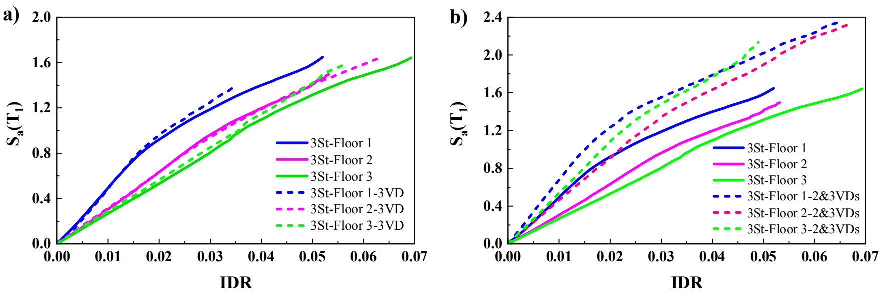

Fig. 4. Comparison between IM-IDA curves of all floor levels of the 3-story colliding SMRF retrofitted with, a) one linear VD in third story level, b) two linear VDs in second and third story levels, subjected to NPL record subset given clear distance of 0.298 m.

Table 1. Limited state capacities of all floor levels of the 3-story colliding SMRF with different implemented linear VDs subjected to NPL record subsets given a clear distance of 0.298 m.

Model Name	Floor 1	Floor 2	Floor 3
3-story SMRF	1.065	0.801	0.666
3-story SMRF-3 VD	1.102	0.799	0.709
3-story SMRF-2 and 3 VDs	1.426	1.142	1.314

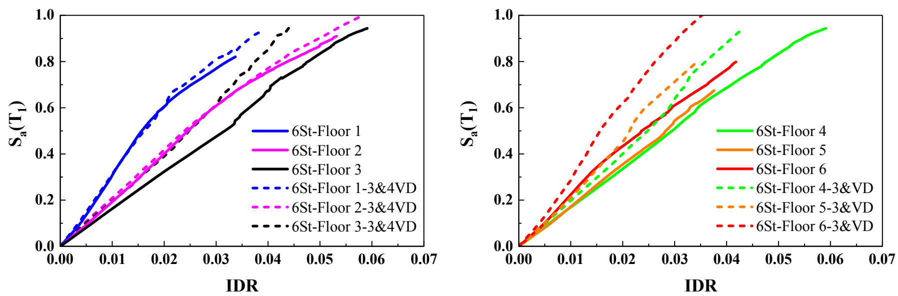

Fig. 6. Comparison between IM-IDA curves of all floor levels of the 6-story colliding SMRF retrofitted with two linear VDs in third and fourth story levels, subjected to NPL record subset given clear distance of 0.298 m.

Table 2. Limited state capacities of all floor levels of the 6-story colliding SMRF with different implemented linear VDs subjected to NPL record subsets given a clear distance of 0.298 m.

Model Name	Floor 1	Floor 2	Floor 3	Floor 4	Floor 5	Floor 6
6-story SMRF	0.696	0.509	0.421	0.398	0.437	0.519
6-story SMRF-4 VD	0.669	0.502	0.449	0.466	0.561	0.677
6-story SMRF-3 and 4 VDs	0.719	0.521	0.506	0.504	0.620	0.767

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In the next, linear VD added on the fourth floor level of the 6-story SMRF and the third floor level has the lowest value of $S_a(T_1)$ and selected for retrofitting. Fig. 6 presents the results of all floor IM-IDA curves of the 6-story colliding SMRF in the second retrofit computational analysis. It is shown that IM-IDA curves of the 1st, 2nd, 3rd, 4th, 5th, and 6th floor levels have increased by 3.3%, 2.35 %, 27.13%, 19.71%, 41.87%, and 47.78%, respectively. Therefore, optimal placement of linear VDs in 6-story colliding SMRF with higher performance level has been achieved by using only two linear VDs that can be implemented by a cost of two units. Table 2 presents the values of $S_a(T_1)$ in the LS performance level for the 6-story colliding SMRF.

5 Conclusion

This study investigated a computational strategy that uses a developed Tcl programming code with the capability of considering damaged structure due to earthquake-induced structural pounding. The developed code allows us to improve structural models to take into account the real condition of buildings using both MATLAB [23] and Opensees [24] softwares simultaneously. Implementing linear VDs on the adjacent structures can be assumed as a retrofitting strategy, while the cost of implementation is an important factor. In the research, IM-IDAs based on IDRs were determined performing IDA analysis subjected to NPL record subset, and these curves were used as the main purpose of retrofitting based on the LS performance level. Regarding this issue, the lower value of $S_a(T_1)$ in each floor level in the LS performance level was selected to implement linear LVDs, and the results were compared to the previous state. This type of retrofitting strategy can help designers to find out the floor level prone to damage, and retrofit this particular floor level instead of all stories. It should be noted that this strategy could be used for any structure with and without pounding conditions and in all performance levels prescribed in FEMA 356 [30].

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