Design of Repairable Regular Steel Buildings with Square Plan Based on Seesaw Motion of Building Structure and Using DADAS Dampers

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Abstract

Almost all of seismic design codes for building systems accept heavy damages to buildings, in case of large earthquakes, although they don't accept the building's collapse. Nevertheless, past earthquakes have shown that level of the accepted damage may be so high that demolishing and reconstruction of the building becomes inevitable. This, in turn, results in some unacceptable consequences in large populated cities, such as thousands of homeless and/or jobless people for a very long time, very time consuming, difficult, and costly demolishing and debris removal processes, and finally very massive, and therefore, costly and time consuming required reconstruction works. Regarding these facts, any idea which can lead to creation of repairable buildings is greatly acknowledgeable. One such idea is 'Directed-Damage Design' (DDD) idea, which means guiding the damage to some pre-decided parts of the structural system, so that other parts do not experience any major plastic deformation, and therefore, making the building easily repairable only by replacing the damaged elements. Design of repairable buildings, have been paid great attention by some researchers in recent decade. Use of rocking mechanism of the building's structure (Azuhata et al. 2004) and employing telescopic columns in buildings with rocking/seesaw motion (Hosseini and Noroozinejad Farsangi 2012, Hosseini and Alavi 2014) are some samples of these researches. In previous researches, yielding base plates, yielding bolts, conventional and adaptive viscous dampers, friction dampers and some other devices have been used for energy dissipation. To use the DDD idea for creation of repairable steel buildings with square plan, in this study, a structural system having the capability of seesaw motion with respect to a central massive support has been considered in which the bottom ends of the all circumferential columns at the lowest story have been equipped with Double-ADAS (DADAS) dampers, which dissipate a great portion of the seismic input energy. The hysteretic behavior of DADAS dampers has been investigated by using finite element analysis. Seesaw motion of the structural system can make it possible to concentrate the damages in DADAS dampers at the base level of the building. At first a set of regular steel multistory buildings with 5, 8, 11 and 14 stories have been designed based on the conventional code provisions. Then, the structures of the designed buildings have been changed into the structure with seesaw motion by using, at the base level of the building, a massive central column, eliminating other middle columns, and equipping circumferential columns with DADAS dampers. To show the efficiency of the proposed structural system and dampers, a series of nonlinear time history analysis (NLTHA) have been performed by using a set of 3-component accelerograms of some selected earthquakes. Numerical results of NLTHA show that the proposed seesaw structures can efficiently decrease the seismic damage in the building, so that plastic deformation happens only in DADAS energy dissipaters, and the main structural elements remain basically elastic, and therefore, the buildings designed and constructed by the proposed technique can be easily repaired even after major earthquakes.

Keywords: Directed-Damage Design, Finite Element Modeling, Nonlinear Time History Analysis

1. Introduction

Most of current seismic design codes accept, either explicitly or implicitly, heavy damages to the building in case of large earthquakes, provided that the building is prevented against collapse. However, this acceptance leads to some unacceptable consequences in populated cities, such as very great number of affected people who lose their residence or work place for very long time, very difficult and time consuming demolishing works of the heavily damaged buildings and related debris removal works, and finally very large volume of the required reconstruction works, which need lots of money, expertise and time. To avoid these adverse consequences one approach is design of „repairable structures‟ for buildings, by using the idea of 'Deliberate Directing of Damage' (DDD), introduced by Hosseini and Alyasin (1996) [1], which means guiding the damage to some pre-decided parts or elements in the system, acting as structural fuses or energy dissipating devices, so that other parts of the system do not experience any plastic deformation, and therefore, the system can be easily repaired after an earthquake.

The DDD idea, which is similar to the 'structural fuse' idea, has been originally introduced for pipelines, however, recently Hosseini and Ebrahimi (2015) modified it as Directed-Damage Design, to lead to a new generation of earthquake resisting buildings [2]. In fact, the idea of using 'structural fuse' is not so new, and some researchers have introduced and worked on this idea for building systems in late 70s to early 80s (Fintel and Ghosh 1981) [3], and some more detailed studied have been also conducted in recent decade (Vargas and Bruneau 2006) [4]. However, it should be noted that in these studies, although the main idea, similar to DDD idea, is concentration of damage in energy dissipaters or fuses, and keeping the main structural members elastic or with minor easily repairable damages, in reality the building created based on the structural fuse idea cannot remain in Immediate Occupancy (IO) Performance Level (PL), and needs to be evacuated, at least partially, for repair works. To overcome this shortcoming, the use of rocking motion of the building has been proposed by some researchers in recent decade (Azuhata et al. 2002) [5]. They used weak base plates, attached to the bottom of each steel column at the first story, to cause rocking vibration under appropriate control, and conducted more recently an experimental study on a structural frame with rocking motion (Azuhata et al. 2008) [6]. Although their proposed rocking structural system is quite effective is seismic response reduction, their studies is limited to 2-dimensional buildings systems, and even in case of experimental studies on 3-D frames the excitation has been only one-directional.

In the current decade Hosseini and Noroozinegad Farsangi (2012) have used the buildings rocking motion (or seesaw motion to be more accurate) in a 3-dimensional state by removing all inner columns of the building at its base level, unless the central one which has been substituted by a specific energy dissipating element, and changing the outer columns at the buildings base level to telescopic columns, equipped with ADAS elements which give them the capability of energy absorption in axial deformation [7]. Similar studies have been also conducted by Hosseini and colleagues (2013) [8] and Hosseini and Alavi (2014) [9] in which a massive central support along with circumferential columns at base level equipped with yielding plate dampers of Double-ADAS (DADAS) type, originally introduced by Hosseini and Bozorgzadeh (2013) [10], or Multi Trapezoidal Yielding Plates Energy Dissipaters (MTYPED) devices with some specific features for higher energy dissipation capacity have been used.

In another study by Hosseini and Kherad (2013) a multi-stud energy dissipating device have been used as the central support of the building at its base level which works as a huge plastic hinge (PH) under the action of vertical load and the moment induced by the lateral seismic load [11]. In another recent study by Hosseini and Ghorbani Amirabad (2015) yielding-curved-bars and hemisphere core energy dissipating device has been suggested as the central support of repairable buildings with seesaw motion [12]. it is obvious that removing the inner columns at the base level of the buildings necessitates the high stiffness and strength of the first floor above the base so that it can carry the loads of all upper floors and transfer them to the central massive support. For this purpose in the last three mentioned studies a set of orthogonal strong girders, mostly of truss type, in the form of grid, has been used in the lowest floor of the building. Recently Hosseini and colleagues (2016) have suggested some other types of central support and the use of friction dampers in all columns of the building at the lowest floor [13].

In the present study two 5-story buildings, one of ordinary fixed base type and the other one with the proposed structural system having the capability of seesaw motion have been considered. The number of bays in the considered building is four in both direction, and two bays at each side of the building have x-bracing to give enough stiffness to the superstructure to minimize its inter-story drifts. A major modification has been made in the yielding-plate energy dissipating devices to be installed at the bottom of all circumferential columns, which makes their manufacturing and installation much more practical, as illustrated in the following sections of the paper.

2. The Proposed Structural System with Seesaw Motion and Equipped with DADAS Energy Dissipaters

In the proposed structural system for regular multistory steel buildings, creation of possibility of seesaw motion has been done by using a set of orthogonal truss girders pivoting on a huge central support at base level with a series of energy dissipating devices of DADAS type installed at the bottom of all circumferential columns at that level. Figure 1 shows a frame of the proposed structural system with one of the truss girders pivoting on the central support, as well as a 3-D view of the considered 5-story building with the capability of seesaw motion considered in this study, which is called 'seesaw building' from now on.

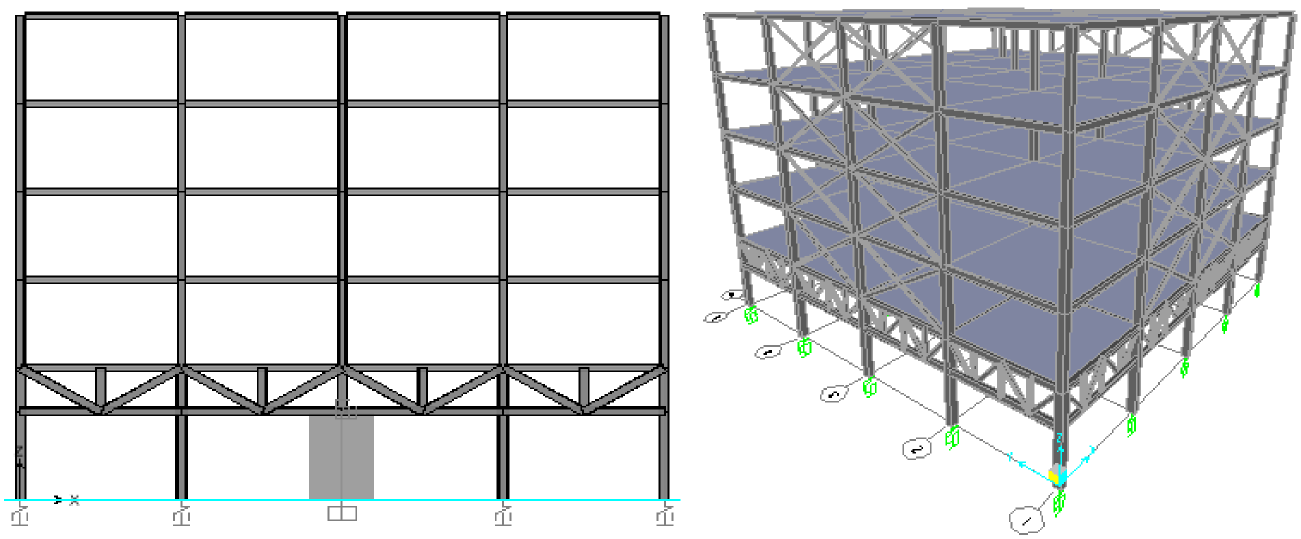


Fig. 1- A frame of the 5-story seesaw buildings in which the bottom truss girder and central support is seen (left) and the 3-D view of the seesaw building with energy dissipating devices at the bottom of all circumferential columns (right)

It is seen in Figure 1 that the building structure above the lowest level, which is called from now on the superstructure, is of concentrically braced frame (CBF) type. In fact, for higher efficiency of the seesaw motion in decreasing the seismic response of the superstructure, it should be relatively stiff to facilitate limiting the inter-story drifts. Therefore, moment resisting frames does not seem to be appropriate for this purpose, and CBFs frames are considered in this study. Energy dissipating devices installed at the bottom of all circumferential columns are of DADAS yielding-plate type, as shown in Figure 2.

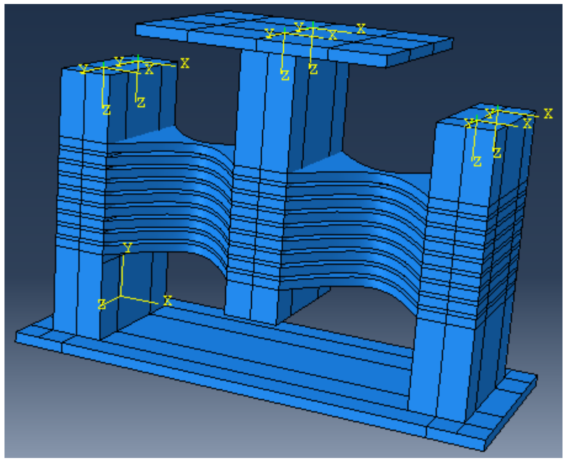


Fig. 2- The DADAS device used at the bottom of the all circumferential columns at the lowest story of the seesaw building

During an earthquake the vertical movement of the DADAS, which is in fact the lower part of the column element, yielding takes place. Special geometry of yielding plates causes the plastic deformation to develop in the majority of their body, leading to remarkable energy dissipation. To assess the realistic hysteretic force-displacement curve of the proposed DADAS devices, a powerful finite element (FE) program was used, and for verification of the numerical modeling process the results of cantilever beam in large plastic deformation were used as explained in the main report of the study (Nejati 2016) [14]. After verification, by performing a set of FE analyses on DADAS devices with different sizes of plates their initial and post-yield (secondary) stiffness values as well as their yielding strength were obtained. The appropriate values of initial and secondary stiffness for the DADAS device may be found by a series of trial and error analysis for each building system. For this purpose, the DADAS devices can be modeled as the multi-linear plastic springs in the numerical model of the whole building structure. Figure 3, which shows a section of the deformed shape of the DADAS device under axial load, and a sample of its hysteretic curves.

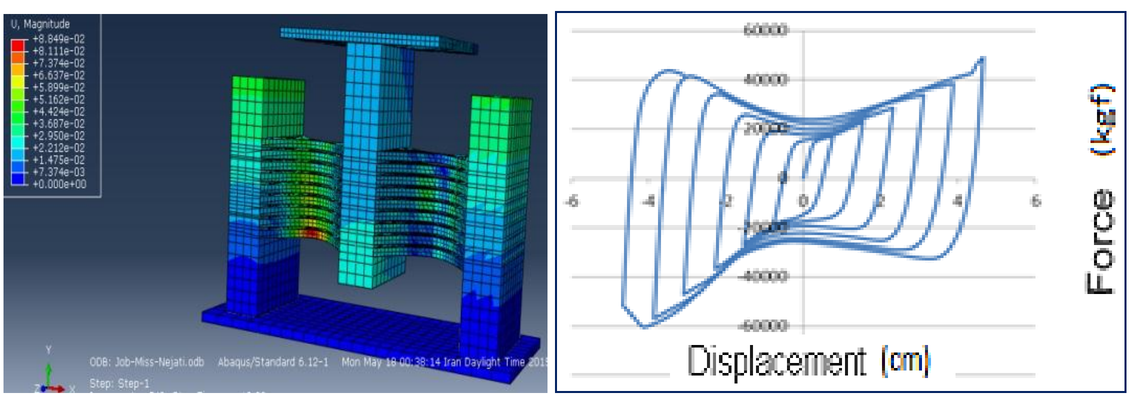
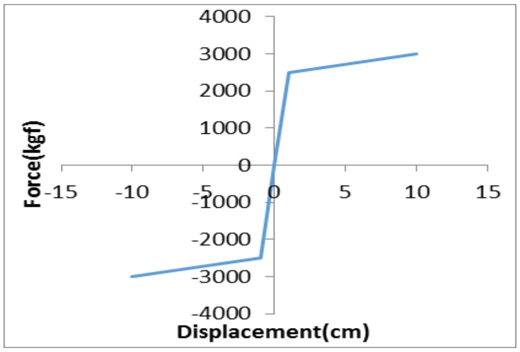


Fig. 3- The DADAS device under axial load (Left) and a sample of its hysteretic curves (Right)

It is seen in Figure 3 that the hysteretic loops of the DADAS device are quite wide, which means that the device has a high capacity of energy dissipation. The main hysteretic features of the device, namely its elastic and post-yielding stiffness values as well as its yield stress can be controlled by selecting appropriate values for the dimensions of the plates, as explained in the next section of the paper.

4. Nonlinear Time History Analyses of Ordinary and the Proposed Seesaw Buildings

The sample building, considered in this study for showing the efficiency of the proposed structural system with seesaw motion in seismic response reduction, is a 5-story regular steel building with 4-bay by 4-bay square plan in which span length of all bays is 5.0 m and height of all stories is 3.0 m. The building was designed once based on the conventional seismic design provisions (UBC), and once by using the suggested seesaw system, using the trial and error scheme explained in the previous section. The yielding and ultimate forces of the DADAS devices used in the seesaw building was finally chosen as 2500 and 3000 kgf, corresponding to displacement values of 1 and 10 cm respectively as given in Figure 4.



Displacement (cm)	-10	-1	0	1	10
Force (kgf)	3000	2500	0	2500	3000

Fig. 4- Displacement and force values for introducing the multi-linear spring to the analysis software

Table 1- Selected earthquakes used for NLTHA and their PGA values in three main directions

No.	Name	PGA (g)	Duration (s)
1	Loma Prieta-x	0.5	39.98
	Loma Prieta-y	0.321	39.98
	Loma Prieta-z	0.36	39.98
2	Cape Mendocino-x	0.597	35.94
	Cape Mendocino-y	0.764	35.94
	Cape Mendocino-z	0.161	35.94
3	Landers-x	0.709	48.11
	Landers-y	0.774	48.11
	Landers-z	0.684	48.11
4	Kocael-x	0.224	29.99
	Kocael-y	0.158	29.99
	Kocael-z	0.147	29.99
5	Chi Chi-x	0.276	89.99
	Chi Chi-y	0.185	89.99
	Chi Chi-z	0.179	89.99
6	Loma Prieta (no pulse)-x	0.467	24.99
	Loma Prieta (no pulse)-y	0.521	24.99
	Loma Prieta (no pulse)-z	0.514	24.99
7	Denali Alaska (no pulse)-x	0.426	92.085
	Denali Alaska (no pulse)-y	0.226	92.085
	Denali Alaska (no pulse)-z	0.24	92.085

For seismic response evaluation of the two designed counterpart buildings a series of nonlinear time history analysis (NLTHA) were performed by using three-component of a set of selected earthquake based on their frequency content to be compatible with the considered site condition and the natural periods of both conventional and seesaw buildings. The specifications of the selected earthquakes are given in Table 1, and a sample of their response spectra is shown in Figure 5.

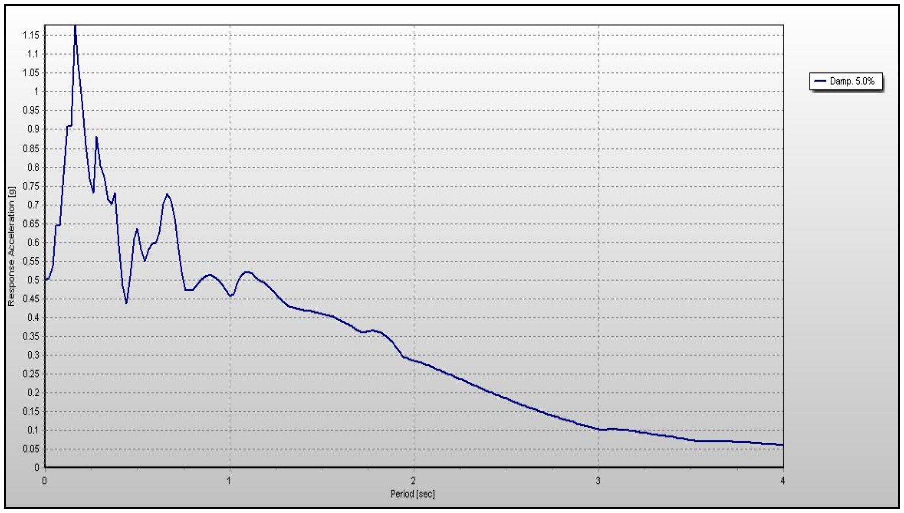


Fig. 5- Acceleration response spectrum of the Loma Prieta earthquake with 5% damping

For conducting the NLTHA it is necessary to scale the selected accelerograms. For this purpose the procedure of Iranian Standard No. 2800, which is similar to that of UBC was used, which resulted in the average spectrum shown in Figure 6.

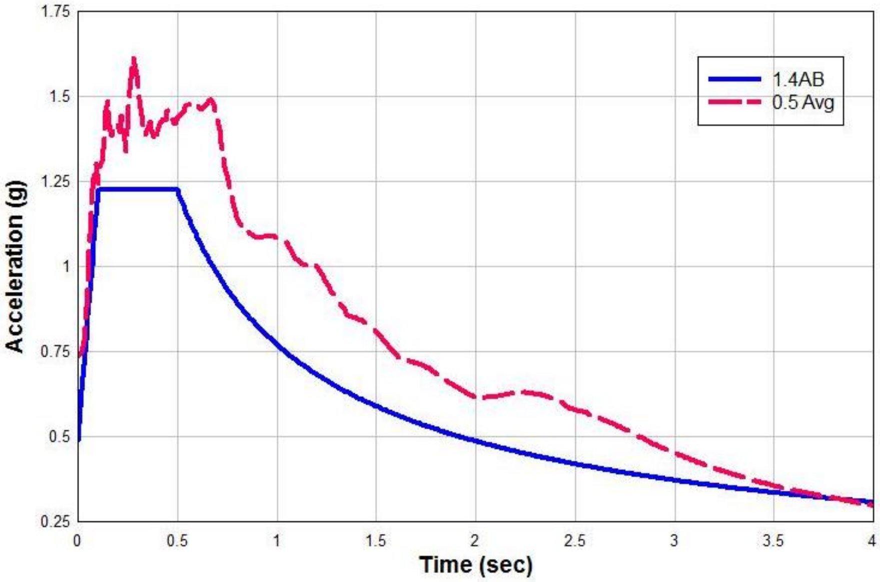


Fig. 6- The average spectrum obtained based on the scaling procedure of accelerograms

The response values considered for comparing the seismic performance of the fixed base building with its seesaw counterpart include displacement and acceleration histories and the plastic hinge (PH) formation. Also the hysteretic force-displacement curves of the yielding dampers, which can show the energy dissipation capacity of the proposed system are included in results. Before presenting the comparative result, two graphs are presented to make sure on the seesaw motion of the proposed building structure and the fact that its body remains almost rigid during the seesaw motion. Figure 7 shows the sample time histories of vertical motion of two points at opposite sides of the seesaw building and also its floors displacements.

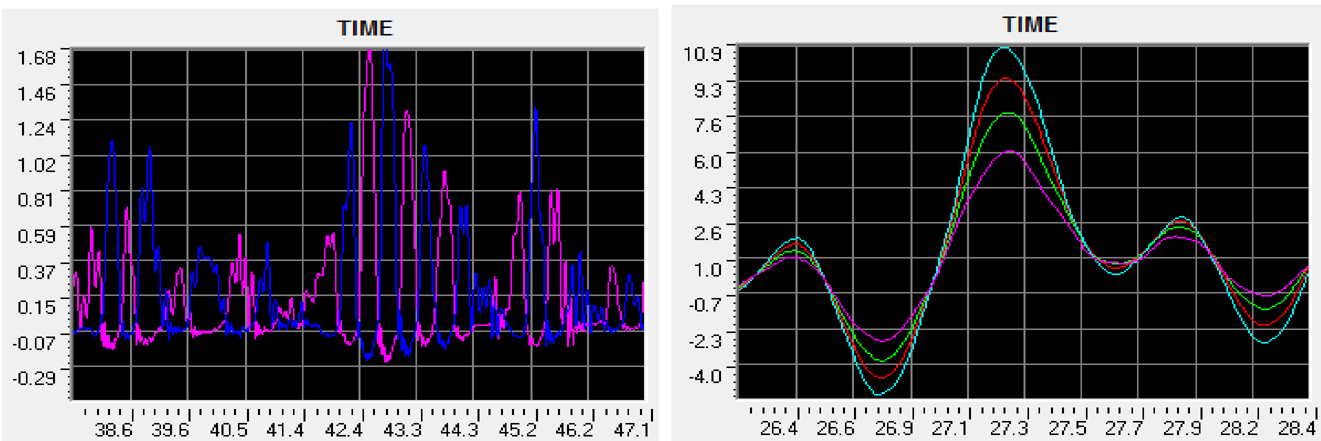


Fig. 7- Sample time histories of vertical motion of two points at opposite sides of the seesaw building (left) and a part of the sample time histories of its floors displacements (in cm)

It can be seen in Figure 7 that the building with the proposed structural system has dome seesaw motion during the earthquake almost as a rigid body. Figures 8 and 9 compare the roof displacement and roof acceleration time histories of the two counterpart buildings.

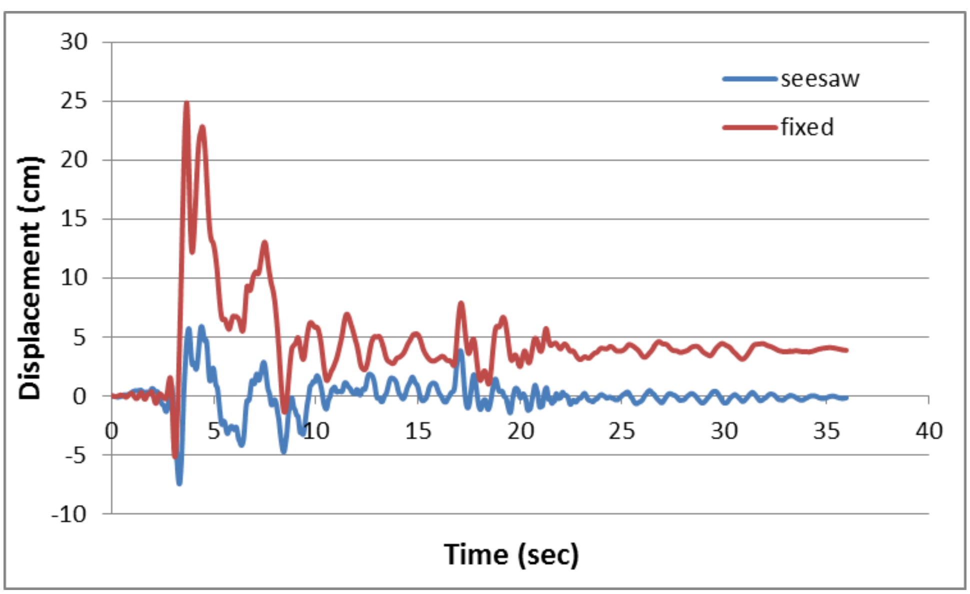


Fig. 8- Sample time histories of horizontal displacements at roof level of the seesaw and fixed base buildings

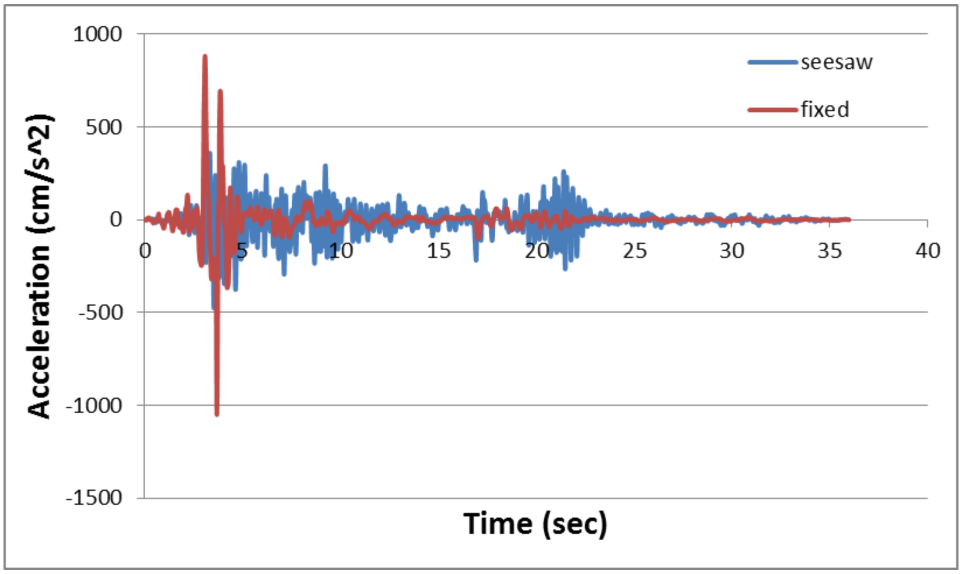


Fig. 9- Sample time histories of horizontal accelerations at roof level of the seesaw and fixed base buildings

It can bee seen in Figures 8 and 9 that both displacemt and acceleration reponses of seesaw bulding in less than its fixed base counterpart. There are two reasons behind this fact. First the longer period of the seesaw building comparing to its fixed base counterpart, which reduces the seismic demand and accordingly the seismic responses, and second the energy dissipation which occurs by the yielding dampers of DADAS type installed at the bottom of all circumferential columns at the lowest level. A sample of the hysteretic loops of one of these dampers is show in Figure 10.

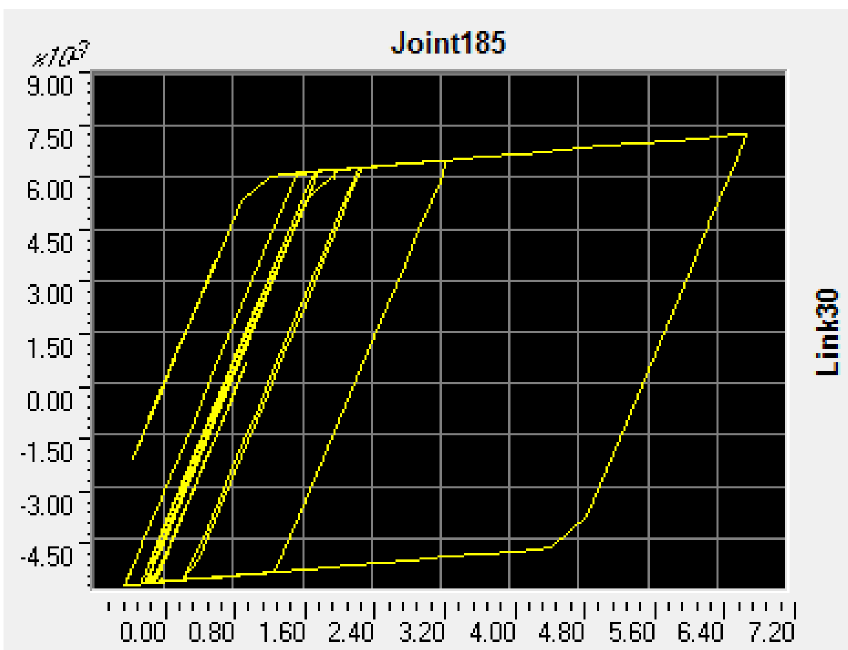


Fig. 10- A sample of the hysteretic loops of one of the DADAS dampers in the seesaw building

As the last set of results for comparing the seismic performance of the two buildings the PHs formed in their elements have been considered. Figure 11 shows samples of the formation of PHs in the two buildings.

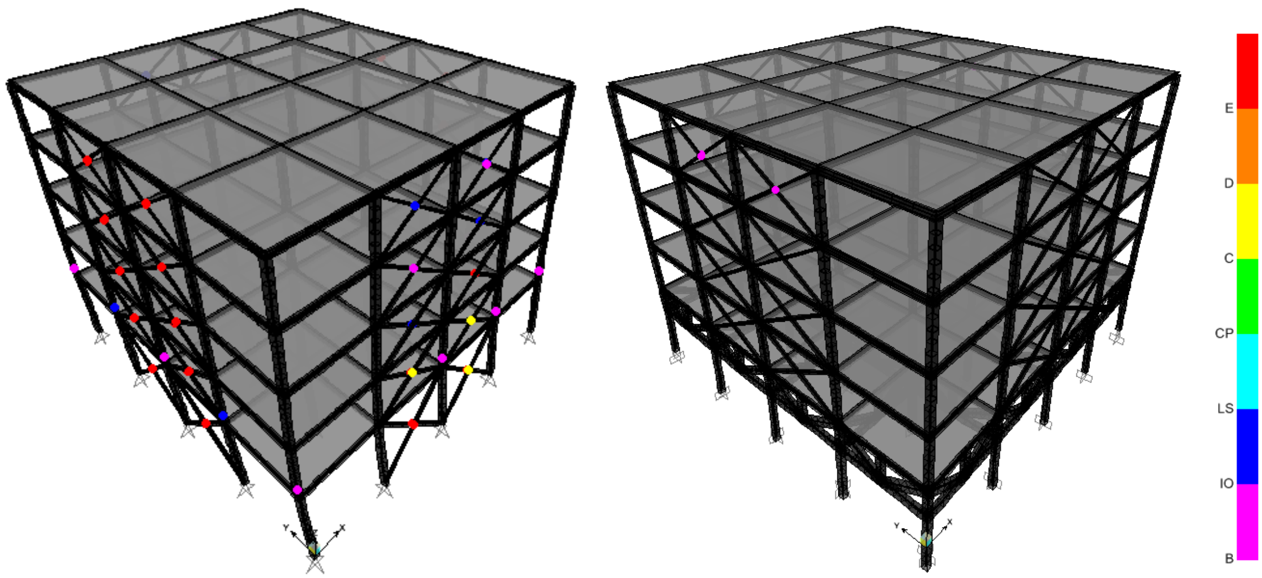


Fig. 11- The PHs formed in the fixed base and seesaw buildings subjected to Alaska earthquake record

It is seen in Figure 11 that PHs formed in the fixed base building are beyond the collapse prevention (CP) level, while in the seesaw building they are at IO level. This shows the superior performance of the seesaw buildings in caparison with the conventional fixed base buildings.

5. Conclusions

Based on the numerical results obtained from NLTHA of conventional and seesaw buildings, subjected to several three-component earthquake records, it can be concluded that:

- The suggested seesaw structural system leads to a more reliable seismic behavior of buildings.
- In seesaw buildings plastic deformations happen mainly in the DADAS devices at ground floor, and therefore, in most cases only a few hinges at the IO or LS performance levels appear in other parts of the building structure. This means that the seesaws building is easily repairable, even after a major earthquake.
- The seesaw motion leads to longer period values and, therefore, lower acceleration values in the building stories which not only results in reduction of the seismic forces imposed to the building system, but also helps higher safety level of nonstructural elements in the whole building.
- Considering the advantages of the proposed structural system with seesaw motion and energy-dissipating capacity in seismic reduction of mid-rise multi-story buildings, and particularly the easiness of manufacturing and installation of the DADAS devices, the use of this system can be strongly recommended for buildings in the vicinity of active faults, particularly in large populated cities.

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