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A kind of repairable steel buildings for seismic regions based on building’s rocking motion and energy dissipation at base level

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Abstract*—Most of current seismic design codes accept 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, like very great number of people who lose their residence or work place for very long time. To overcome these difficulties one approach is design of ‘repairable structures’ for buildings, by using the idea of ‘Deliberate Directing of Damage’ (DDD), which means guiding the damage to some pre-decided parts or elements of the structural system, so that other parts do not experience any plastic deformation. In this study the DDD idea has been employed for design of repairable steel buildings based on creation of building’s rocking motion possibility rather than its shear deformation, by using a central hinge support and circumferential energy dissipating columns at base level. Energy dissipation is done by a Multiple Trapezoidal Yielding Plate Energy Dissipating (MTYPED) device, installed at the bottom of the column, which creates a type of hysteretic behaviour in axial deformation of columns. By performing a set of finite elements analyses on MTYPED devices their initial stiffness as well as their yielding strength were obtained, and then they were modelled in a real size building by using nonlinear springs, and a series of nonlinear time history analysis were performed on both rocking building and the conventional building with the same geometry. Results show that the proposed rocking system equipped with MTYPED devices not only gives the building a longer natural period, leading to lower seismic demand, but also leads to remarkable energy dissipation capacity in the building structure at base level, and therefore, keeping the seismic drifts in elastic range in all stories of the building above the ground floor, so that the building structure does not need any major repair work after a large earthquake. This is while the conventional building suffers from heavy damage and needs to be demolished after an earthquake.

***Keywords*— Seismic Codes, DDD Idea, Nonlinear Time History Analysis, MTYPED Devices**

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I. 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), which means guiding the damage to some pre-decided parts or elements in the system, acting as structural fuses or energy dissipators, so that other parts of the system do not experience any plastic deformation, and therefore, the structure can be easily repaired after an earthquake.

Although the DDD idea has been introduced initialy for pipelines, it can lead to a new generation of earthquake-resisting buildings, if applied to the buildings structures. 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) [2], and some more detailed studied have been also conducted in recent decade (Vargas and Bruneau 2006) [3]. However, it should be noted that in these studies, although the main idea, similar to DDD idea, is concentration of damage in energy dissipators or fuses, and keeping the main structural members elastic or with minor easily repairable damages, in reality the building can not 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 (Midorikawa et al. 2002) [4]. 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) [5]. Although their proposed rocking structural system is quite effective is seismic response reduction, their studies is limited to 2-dimensional buildings systems.

In recent years Hosseini and Noroozinegad Farsangi (2011) have used the building's rocking motion 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 [6]. A similar study has been also conducted by Hosseini and Mousavi Tirabadi (2013) in which a massive central column along with circumferential columns at base level equipped with Double-ADAS devices with some specific features for higher energy dissipation capacity have been used [7]. In a more recent 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 [8]. 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, in the form of grid, has been used. However due to small number of bays in these studies, the size of those strong girders has not been very large.

In the present study the number of bays in the considered building is six in both direction. Therefore, the use of a strong space truss for supporting the set of orthogonal strong girders has been inevitable to keep their size reasonable. Furthermore, a major modification has been made in the yielding-plate energy dissipating elements of the circumferential columns, which makes their manufacturing and installation much practical as illustrated in the following sections of the paper.

II. The Proposed Rocking Structural System

In the proposed rocking structural system for regular multi-story steel buildings, creation of possibility of rocking motion has been done by using a space truss resting on a huge central hinge support at base level with a series of circumferential energy dissipating columns at that level. Energy dissipation in each of these columns is done by using a Multiple Trapezoidal Yielding-Plate Energy Dissipating (MTYPED) device, which is installed at the bottom of the column as shown in Figure 1.

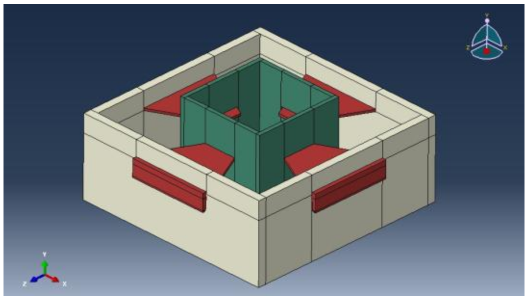


Figure 1. The MTYPED device used at the bottom of the circumferential columns at the rocking building's base level

As shown in Figure 1, each MTYPED device consists of two boxes one inner and one outer, and a set of trapezoidal plates which their larger side is connected to the outer box and their smaller side passes through some sluts in the wall of the inner box. During an earthquake the vertical movement of the inner box, which is in fact the lower part of the column element, cause the trapezoidal plates to yield. Trapezoidal form of the yielding plates causes the plastic deformation to develop in the majority of their body, leading to remarkable energy dissipation and creating a type of hysteretic behaviour in axial deformation of columns, as shown in Figure 2, which shows a section of the deformed shape of the MTYPED device, and a sample of its hysteretic curves.

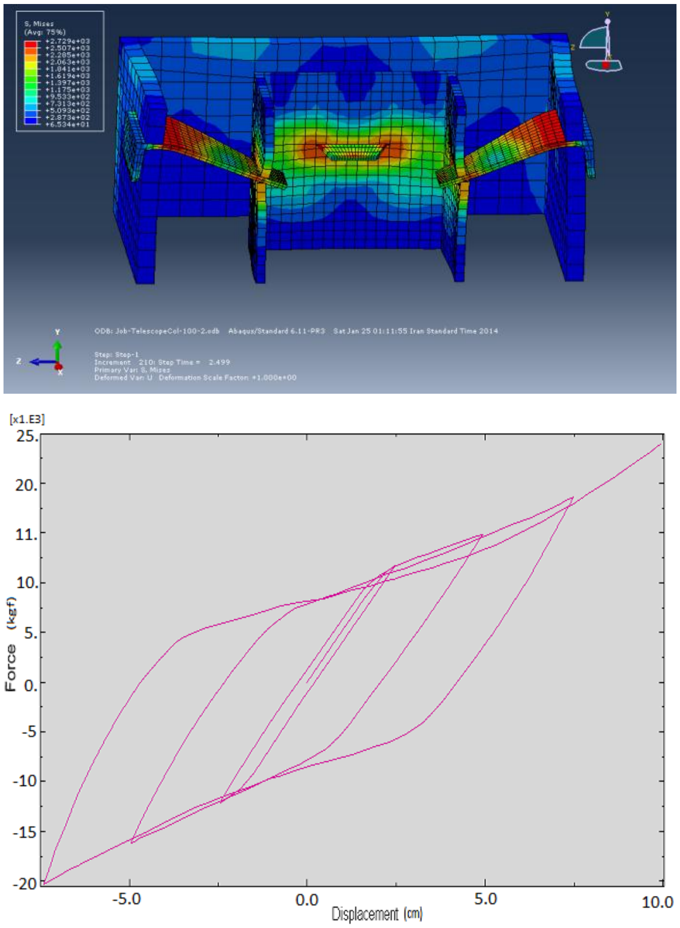


Figure 2. A section of the deformed shape of the MTYPED device (upper) and a sample of its hysteretic curves (lower)

It is seen in Figure 2 that the hysteretic loops of the MTYPED devise are quite wide, which means that the device has a high capacity of energy dissipation. The main hysteretic features of the devise, 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 trapezoidal plates, as explained in the next section of the paper.

The grid of orthogonal strong girders, which form the main skeleton of the first floor of the building structure above its base level, and the corresponding supporting space truss are the other two important parts of the rocking system. This grid makes the first floor to behave almost as a rigid foundation for the columns of upper stories. Figure 3 show a 3-D view of the considered 6-story steel sample building of the study.

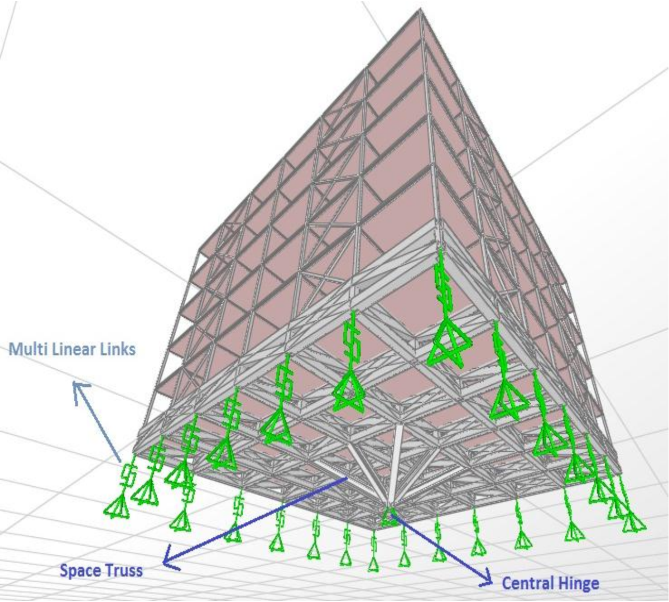


Figure 3. The 3-D view of the rocking building and the grid of strong orthogonal girdger and its supporting space truss

In Figure 3 the circumferential columns of the base level are shown as multi-linear links with hinge connection at their both ends. It is seen in Figure 3 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 rocking 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 or frames with shear walls are used.

III. Numerical Modeling of the MTYPED Device and the Proposed Rocking Building

To assess the realistic hysteretic force-displacement curve of the proposed MTYPED 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 (Alavi 2014) [9].

After verification, by performing a set of FE analyses on MTYPED devices with different sizes of the trapezoidal plates their initial (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 MTYPED device may be found by a series of trial and error analysis for each building system. For this purpose, the MTYPED devices can be modeled as the multi-linear plastic springs in the numerical model of the whole building structure as shown in Figure 3. The initial stiffness of the device affect remarkably the modal periods of the rocking building, and its yield strength and post-yield stiffness control the energy dissipation potential of the system. The MTYPED device stiffness values also affect the values of stress ratio in the superstructure elements, which is on the other side under the effect of the relative stiffness of the grid of the orthogonal strong girders. By assigning different structural properties to both MTYPED device and the grid elements, and observing the stress ratios under the deal and live load of the building decision can be made on the desired values.

IV. Nonlinear Time History Analyses of the Conventional and the Proposed Rocking Buildings

The sample building, considered in this study for showing the efficiency of the proposed rocking structural system in seismic response reduction, is a 6-story regular steel building with 6-bay × 6-bay square plan in which span length of all bays is 4.0 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 rocking system, using the trial and error scheme explained in the previous section. The yielding force of the MTYPED devices used in the rocking building was finally chosen as 5000 kgf, as shown in Figure 4, which gives the specifications of the multi-linear plastic spring used for modeling of MTYPED device.

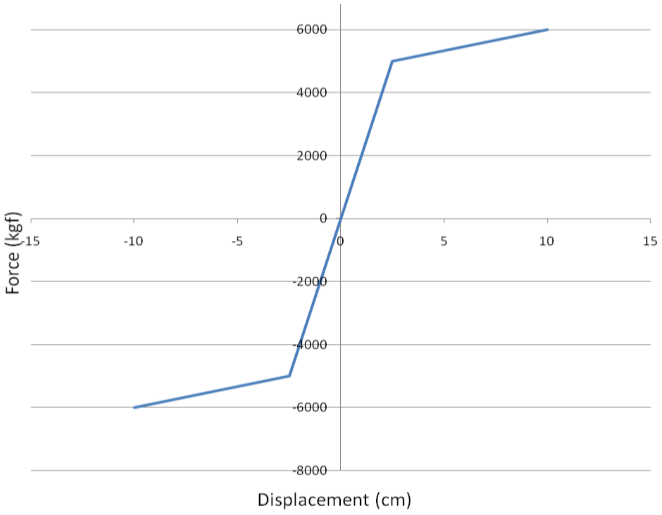
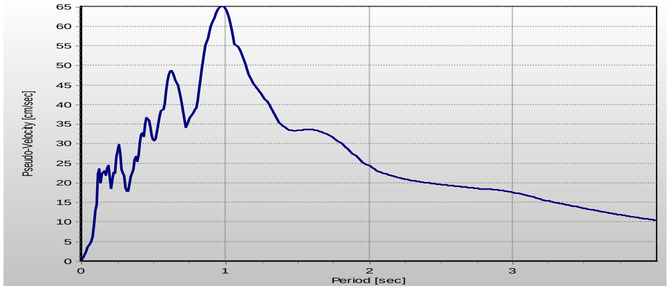


Figure 4. Specifications of the multi-linear plastic spring used for modeling of MTYPED device

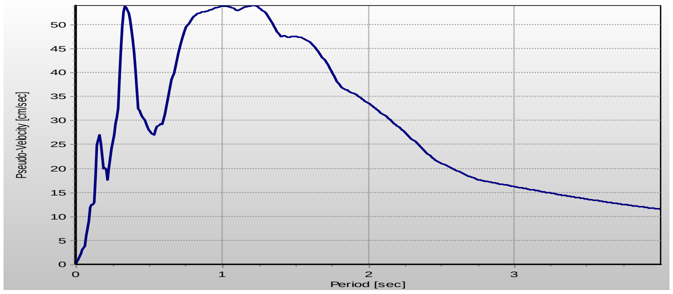
For seismic response evaluation of the two designed counterpart buildings a series of nonlinear time history analysis (NLTHA) were performed by using three-component accelerograms of a set of selected earthquake based on their frequency content to be compatible with the considered site condition and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

TABLE I. SLECTED EARTHQUQKES USED FOR NLTHA AND THEIR PGA VALUES IN THREE MAIN DIRECTIONS

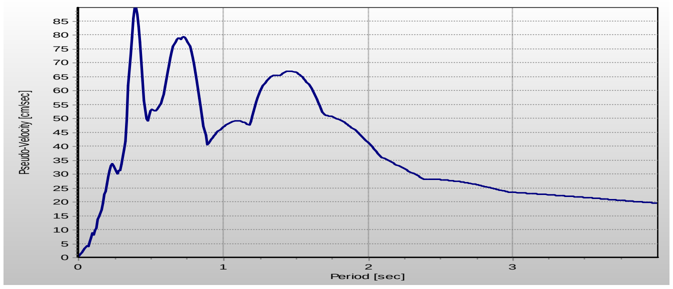
Earthquake	**PGA (g)**		
	In X direction	***In Y direction***	***In Z direction***
Imperial Valley	0.351	0.238	0.145
Coyote Lake	0.339	0.211	0.166
Loma Prieta	0.367	0.322	0.294
North Ridge	0.357	0.267	0.127



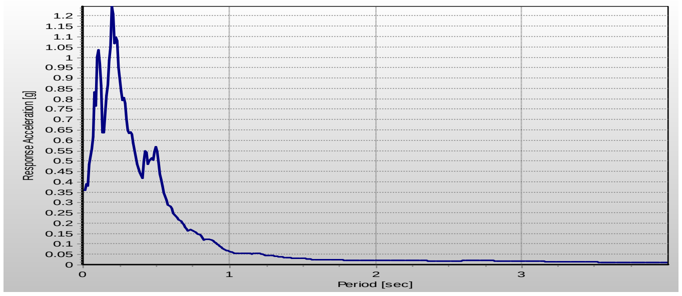
Imperial Valley



Coyote Lake



Loma Prieta



North Ridge

Figure 5. Pseudo velocity response spectra, with 5% damping, of the used earthquakes

The responses considered for comparison include base shear, roof displacement and acceleration, and inter-story drift of the two conventional and rocking buildings as well as the hysteresis of the MTYPED devices in the rocking building. The joint at which the aforementioned responses have been extracted from NLTHA, are shown in Figure 6.

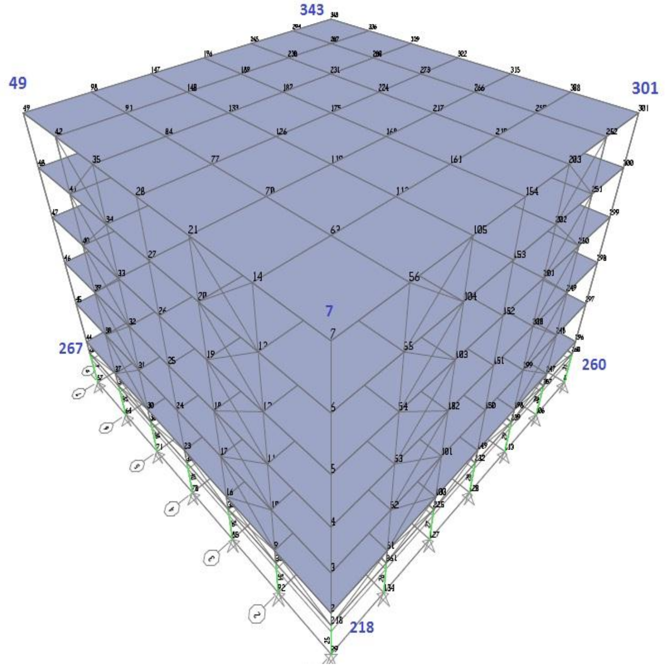


Figure 6. A 3-D view of the rocking building on which the number of corner joints, selected for time history response evaluation, are shown

Figure 7 shows the base shear time histories of the two counterpart buildings.

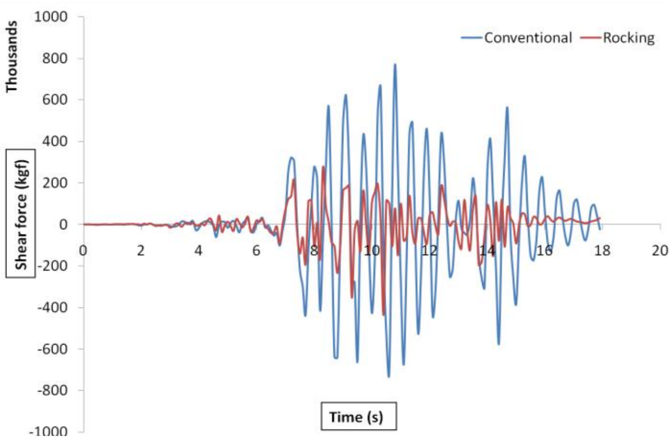


Figure 7. Comparison of the base shear foce historeis of the two counterpart buildigs subjected to Imperial Valley earthquake

It is seen in Figure 7 that the base shear values of the rocking building are generally lower than those of the conventional building. This can be mainly because of longer natural period of the rocking building, which leads to lower seismic demand, and therefore, lower values of roof acceleration as well as lower values of inter-story drift as shown in Figures 8 to 10.

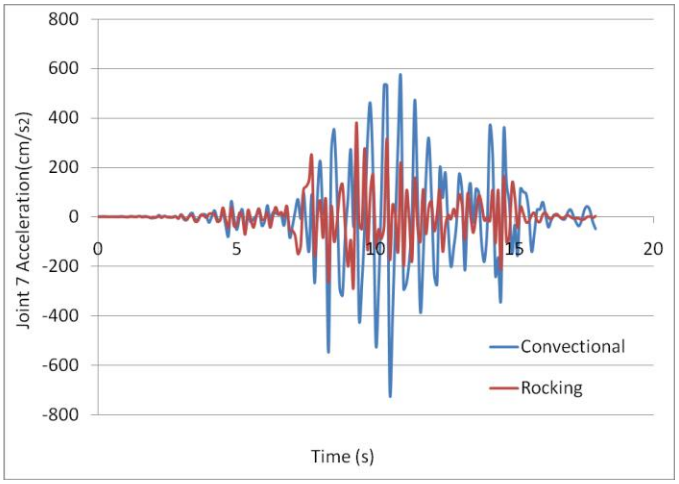


Figure 8. Comparison of roof acceleration time histories of the two counterpart buildings at joint 7 subjected to Imperial Valley earthquake

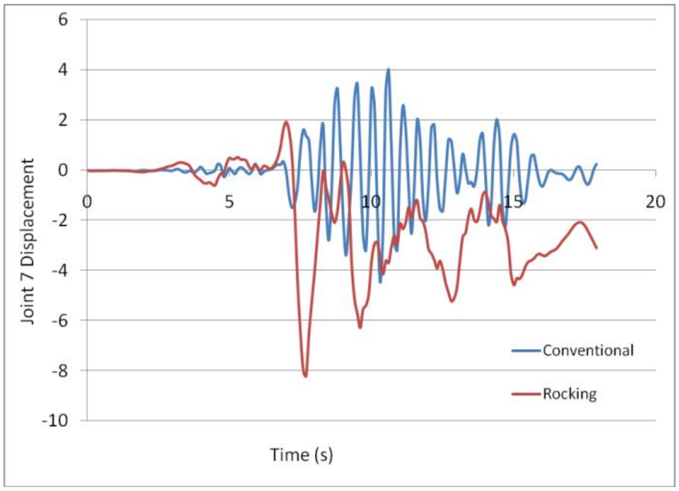


Figure 9. Comparison of roof displacement time histories of the two counterpart buildings at joint 7 subjected to Imperial Valley earthquake

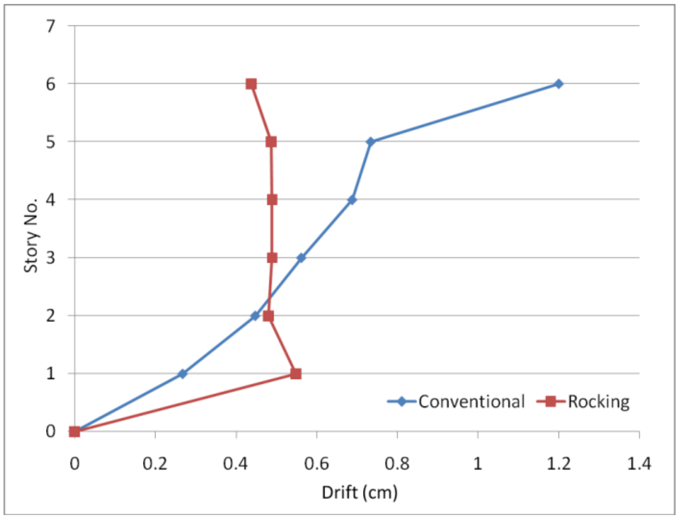
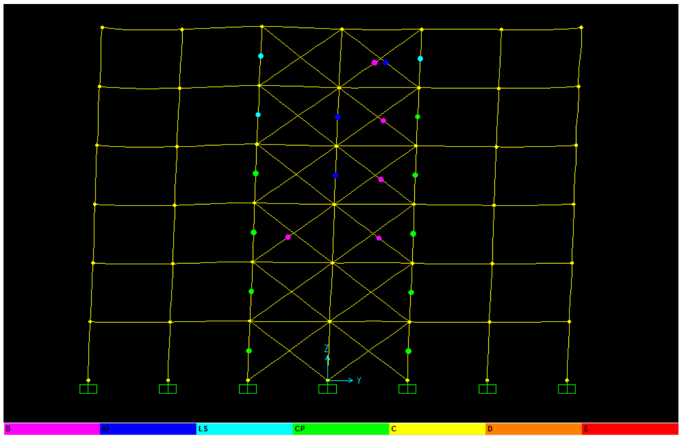


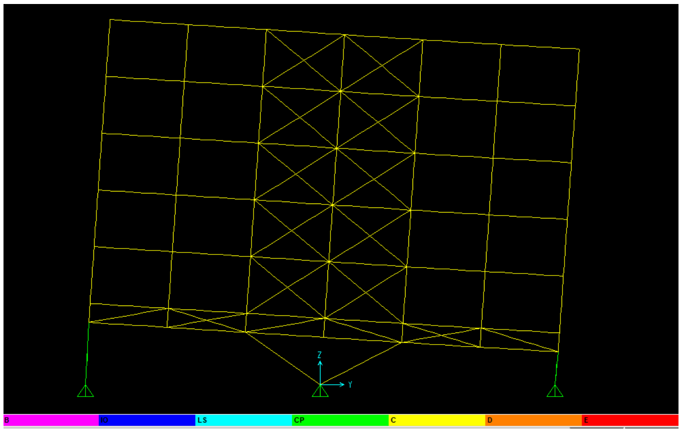
Figure 10. Comparison of inter-story drifts in the two counterpart buildings subjected to Imperial Valley earthquake

It is seen in Figure 9 that rocking motion can lead to larger roof displacement of the building, which is due to the relatively large rotation of the grid of strong orthogonal girders and its supporting space truss on the central hinge of the building at base level, how ever, it can be seen in Figure 10 that the drift values in the rocking building are generally much lower than the conventional building. In fact rocking mechanism can usually keep the drift values in elastic range in all stories of the building above the ground floor, so that the building structure does not need any major repair work after a large earthquake. This is while the conventional building suffers from heavy damage and needs to be demolished after an earthquake, and rebuilt, which imposes the aforementioned unacceptable consequence. More results of the types shown in Figures 8 to 10, obtained for other earthquakes can not be given here because of lack of space, and can be found in the main report of the study (Alavi 2014) [9].

Figures 11 and 12 show the PHs created in the two sample frames of the counterpart buildings subjected to Imperial Valley earthquake.



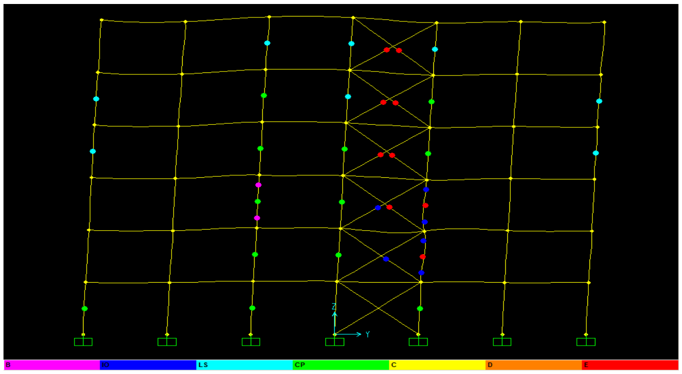
Conventional



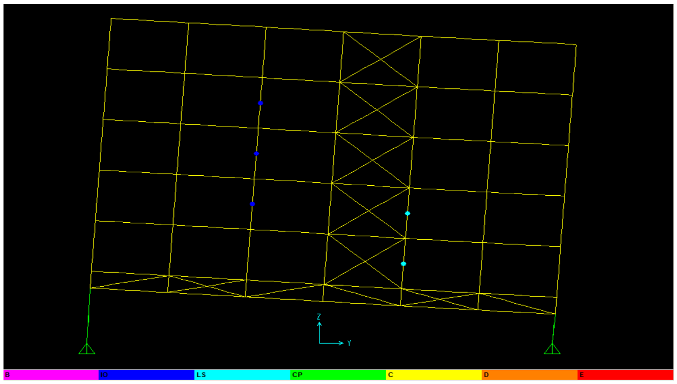
Rocking

Figure 11. Comparison of PHs created in the central frames of the two counterpart buildings subjected to Imperial Valley earthquake

It can be seen in Figure 11 that in the central frame of the conventional building several PHs in the collapse prevention (CP) PL have been formed, while in the counterpart frame of the rocking building no PH has been formed.



Conventional



Rocking

Figure 12. Comparison of PHs created in the frames next to the central frames of the two counterpart buildings subjected to Imperial Valley earthquake

Also it can be seen in Figures 12 that in the other sample frame of the fixed-base building PHs beyond the CP PL have been formed in several bracing element, which means the collapse of the building. This is while in the counterpart frame of the rocking building only some PHs in immediate occupancy IO PL, and few one in life safety (LS) PL has been formed, and this means that the rocking building can be easily repaired after the earthquake.

Figures 13 to 16 show some samples of the hysteretic curves of the MTYPED devices of the rocking building at it four lower corners.

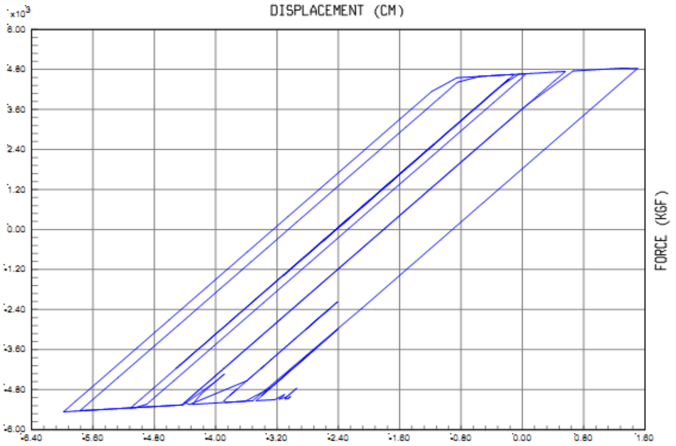


Figure 13. Axial force – displacement hysteretic curves of Joint 260 of the rocking building subjected to Imperial Valley earthquake

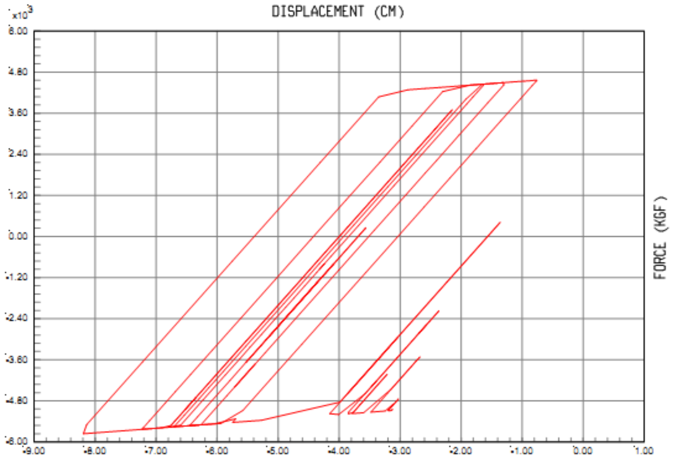


Figure 14. Axial force – displacement hysteretic curves of Joint 267 of the rocking building subjected to Imperial Valley earthquake

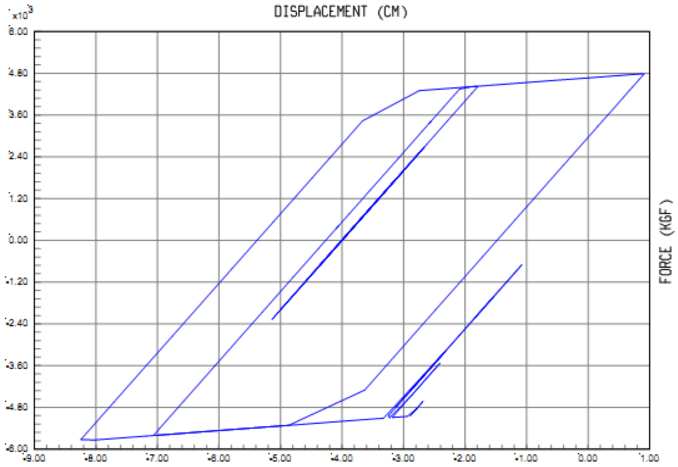


Figure 15. Axial force – displacement hysteretic curves of Joint 218 of the rocking building subjected to Imperial Valley earthquake

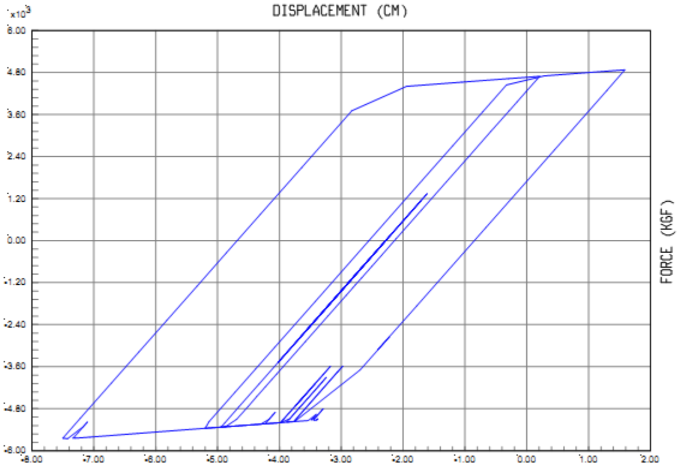


Figure 16. Axial force – displacement hysteretic curves of Joint 295 (opposite corner of joint 218) of the rocking building subjected to Imperial Valley earthquake

It is seen in Figures 13 to 16 that the MTYPED devices have quite stable hysteretic behavior and high capacity of energy dissipation. Therefore, they are quite useful tools for seismic energy absorption for buildings against earthquake.

V. Conclusions

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

- The suggested structural system leads to a more reliable seismic behavior of buildings.
- Plastic deformations happen mainly in the MTYPED 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.
- The rocking 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 rocking and energy-dissipating structural system in seismic reduction of mid-rise multi-story buildings, and particularly the easiness of manufacturing and installation of the MTYPED 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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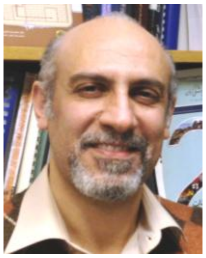

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