APPLYING "DELIBERATE DIRECTING OF DAMAGE" IDEA FOR CREATION OF REPAIRABLE STEEL BUILDINGS BY USING ROCKING TUBULAR FRAME STRUCTURAL SYSTEM AND YIELDING-PLATE DAMPERS ATFOUNDATION LEVEL

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ABSTRACT

Regarding that seismic design codes allow heavy damage to building systems in case of strong earthquake, on the one hand, and the adverse consequences of this allowance, such as very large volume of reconstruction works, on the other, creation of repairable buildings is quite desired. In this study the "deliberate directing of damage" idea has been employed for design of repairable regular 10- to 20-story steel buildings by using tubular frame structural system with rocking motion. The rocking mechanism is created by removing all internal columns in the lowest story, and employing yielding plate dampers under all circumferential columns which give the building structure the required energy dissipation capacity. The dampers should be adjusted so that they work only in tension. In this way the base of each circumferential column can easily move upwards to make possible the building's rocking motion, while behaves almost rigidly downward. The use of tubular system helps the building to reliably carry all its weight in the columns of each of its four sides during rocking motion. To show the efficiency of the proposed structural system in creation of repairable buildings, a series of nonlinear time history analysis were performed by using a set of 3-component accelerograms of some selected earthquakes, containing both mid- and long-period ones, on some buildings with ordinary structural system, designed by using a common seismic code, and their rocking counterparts, and the plastic hinge formation were observed in the two sets. Numerical results show that the proposed rocking structure can efficiently control the seismic damage in the building, so that plastic deformation happens only in the energy dissipaters, and the main structural elements remain elastic, and therefore, the buildings designed and constructed by the proposed technique can be easily repaired even after major earthquakes having up to 0.5g PGA values.

INTRODUCTION

The provisions of seismic design codes for building systems have been intended to lead to structural systems which are prevented against collapse in case of major earthquakes. However, the buildings which are designed based on these provisions are not necessarily prevented against heavy damages, and in fact most of codes allow, either explicitly or implicitly, heavy damages to the building in case of strong earthquakes (provided that the building is prevented against collapse). Unfortunately, recent earthquakes have shown that in many cases level of the allowed damage is so high that necessitates demolishing of the damaged buildings and reconstructing and new ones. This in turn results in some unacceptable consequences in large populated cities located in the vicinity of active faults. These consequences are: a)thousands of people who are rendered homeless and/or jobless for a very long time, b) very time consuming and difficult demolishing process and debris removal activities, and c) very massive, and therefore, time consuming and costly required reconstruction works. What happened in Christchurch earthquake of 11 March 2011 is a good sample of these very unpleasant consequences (Wenget al. 2011). On this basis, it is quite desired to create the buildings in such a way that they remain intact in major earthquakes, or at least can be easily repaired. Base isolation and structural control are two techniques presented for creation of earthquake-proof buildings. However, these techniques are very costly and need high technologies which are not available in most of earthquake prone countries around the world.

Another idea which can lead to creation of easily-repairable buildings is "Deliberate Directing of Damage"(DDD), 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 (Hosseini and Alyasin 1996). Although the DDD idea has been introduced initially for pipelines subjected to permanent ground motions, 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 Ghosh1981), and some more detailed studies have been also conducted in recent decade (Vargas and Bruneau 2006). However, it should be noted that in those 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 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 (Midorikawa et al. 2002). 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 studyon a structural frame with rocking motion (Azuhata et al.2008). A similar experimental study was also done by Gray and Christopoulos (2010). Although their proposed rocking structural system is quite effective is seismic response reduction, their studies islimited to two-dimensional systems.

Considering the buildings in three-dimensional (3-D) state recently Hosseini and Noroozinegad Farsangi(2012)have used the building's rocking motion in a 3-D state by removing all inner columns of the building at its base level, unless the central one which hasbeen substituted by a specific energy dissipating element, and changing the outer columns at the building's base level telescopic columns, equipped with ADAS elements which give them the capability of energy absorption in axial deformation. A similar study has been also conducted by Hosseini and MousaviTirabadi (2013) in which a massive central column along with circumferential columns at baselevel equipped with a kind of Double-ADAS(DADAS) devices with some specific features for higher energy dissipation capacity have been used. In another recent study by Hosseini and Kherad (2013) amulti-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 an the moment induced by the lateral seismic load. 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 those studies, the size of those strong girders has not been very large.

In a more recent study by Hosseini and Alavi (2014) buildings with large size in plan have been considered and in addition to the set of orthogonal strong girders a supporting truss has been also used beneath the set of girders. İn that study energy dissipation has been done by a Multiple Trapezoidal Yielding Plate Energy Dissipating (MTYPED) device, installed at the bottom of the column, which creates a type of hysteretic behavior in axial deformation of columns. İn that study by performing a set of finite elements analyses on MTYPED devices their initial stiffness as well as their yielding strength have been obtained, and then they have been modelled in a real size building by using nonlinear springs, and a series of nonlinear time history analysis have performed on both rocking buildings and the conventional buildings with the same geometry.

In this study the DDD idea has been employed in combination with rocking motion for creating repairable regular 10- to 20-story steel buildings by using tubular frame structural system. The rocking mechanism is created by removing all internal columns in the lowest story, and employing yielding plate dampers under all circumferential columns which give the building structure the required energy dissipation capacity. The yielding plate dampers can be of Double-ADAS type (Hosseini and Bozorgzadeh 2013) or

MTYPED (Hosseini and Alavi 2014). The dampers should be adjusted so that they work only in tension. In this way the base of each circumferential column can easily move upwards to make possible the rocking motion of the building, while behaves almost rigidly downward. The use of tubular system helps the building to reliably carry all its weight in the columns of each of its four sides during rocking motion. To show the efficiency of the proposed structural system in creation of repairable buildings, a series of nonlinear time history analysis (NLTHA) have been performed by using a set of 3-component accelerograms of some selected earthquakes on the considered buildings, once with ordinary structural system, designed by using a common seismic code, and once more on their rocking counterparts by using the proposed structural system. The PH formation has been used as the main comparison measure in the two sets of buildings. The selected records have included both mid-period and long-period ones to be able to excite both ordinary and the rocking systems. Details of the study are presented briefly in the following sections.

THE ROCKING STRUCTURAL SYSTEM

In the previous studies to create rocking motion (or better say, seesaw motion) in the building structure the use of a very strong grid, and in some cases a supporting strong structure, for carrying and transferring the load of columns to the central support or column and the circumferential links has been unavoidable. Furthermore, the amount of load transferred to the central column or support is at least 75% of the whole buildingِ s weight, which necessitates specific design of column, support, and the corresponding foundation. In the systems with seesaw motion the central element is also responsible for carrying the whole base shear force impose to the building structure during an earthquake, and this is obviously not desired from reliability and redundancy point of view.

In this study it has been tried to create a real rocking motion in the building so that during an earthquake the building inclines and rely on one of its four sides, somehow similar to a rocking block. In this way instead of only one central element the weight of the building is carried by the series of columns at either of the four sides of the building as shown in Figure 1.

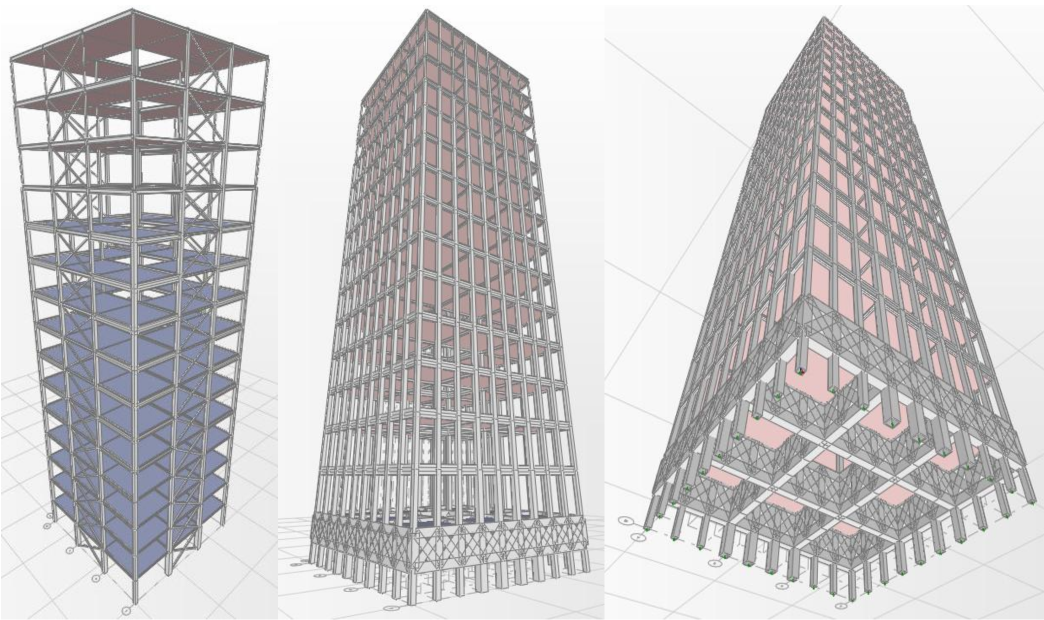

Figure 1. Overall views of 15-story ordinary building (left) and its rocking counterpart with tubular frame system (middle) and the bottom view of the rocking building showing the grid of deep girders (GDG) at its lowest story

It is obvious that the rocking building should be able to carry reliably the whole vertical loads during an earthquake (the gravity loads intensified by the vertical ground acceleration) by only one series of its side columns at either of its four sides. For this purpose it was decided in this study to change the buildingِ s structural system into a tubular frame system with closely-spaced circumferential columns and strong outer beams and set very strong orthogonal beams (a grid of deep girders (GDG)) at the lowest story, as shown in Figure 1. Furthermore, to give the rocking building a good capacity of seismic energy absorption, it was decided to use at the base of each circumferential column an energy dissipater (fuse or damper), which works only in upward motion of the column's base, as the column downward motion is prevented by the stiff foundation. The energy dissipating device used in this study are of the MTYPED, introduced in one of the recent studies of the first author (Hosseini and Alavi 2014), as shown in Figure 2.

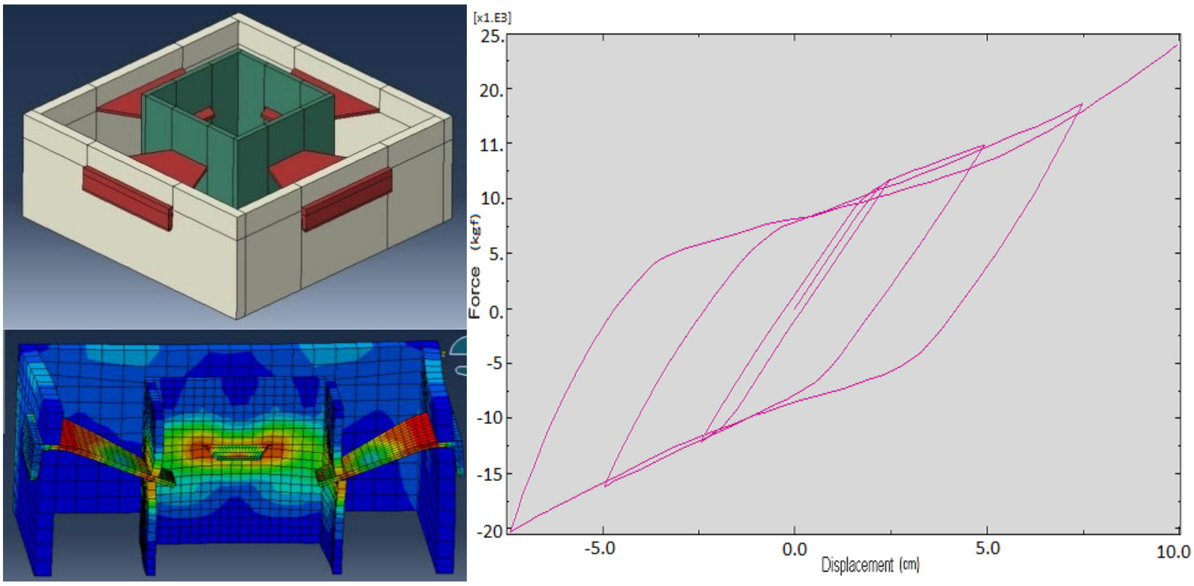

Figure 2.The overall view of the MTYPED device used as damper at the base of circumferential columns of the rocking buildings (upper left), its plastic deformation (lower left) and its hysteretic force-displacement behavior (right) (Hosseini and Alavi 2014)

By using the described system the building can easily and safely rock during an earthquake as shown in Figure 3.

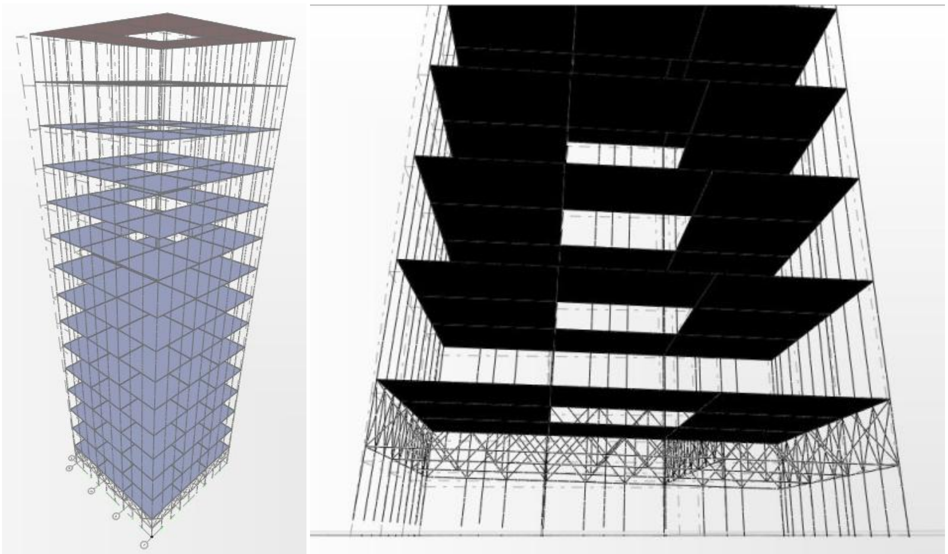

Figure 3.The overall view of the 15-story rocking building during rocking motion (left) and a close-up view showing the building standing on the series of column at its right side, while all other columns have move upward (right)

NONLINEAR TIME HISTORY ANALYSES (NLTHA)

To show the efficiency of the proposed rocking system in creating more reliable seismic behavior in building the considered 10-, 15-, and 20-story ordinary buildings and their rocking counterparts were analyzed nonlinearly subjected to three-component accelerograms of a set of selected earthquakes, whose pseudo acceleration spectra are shown in Figure 4.

Figures 5 to 7 show samples of responses of the analyzed buildings, including displacement histories of bottom ends of columns at opposite side and the hysteretic curves of the energy dissipaters in rocking buildings, as well as the roof displacement histories and the maximum drift values and the plastic hinges in the two sets of ordinary and rocking buildings.

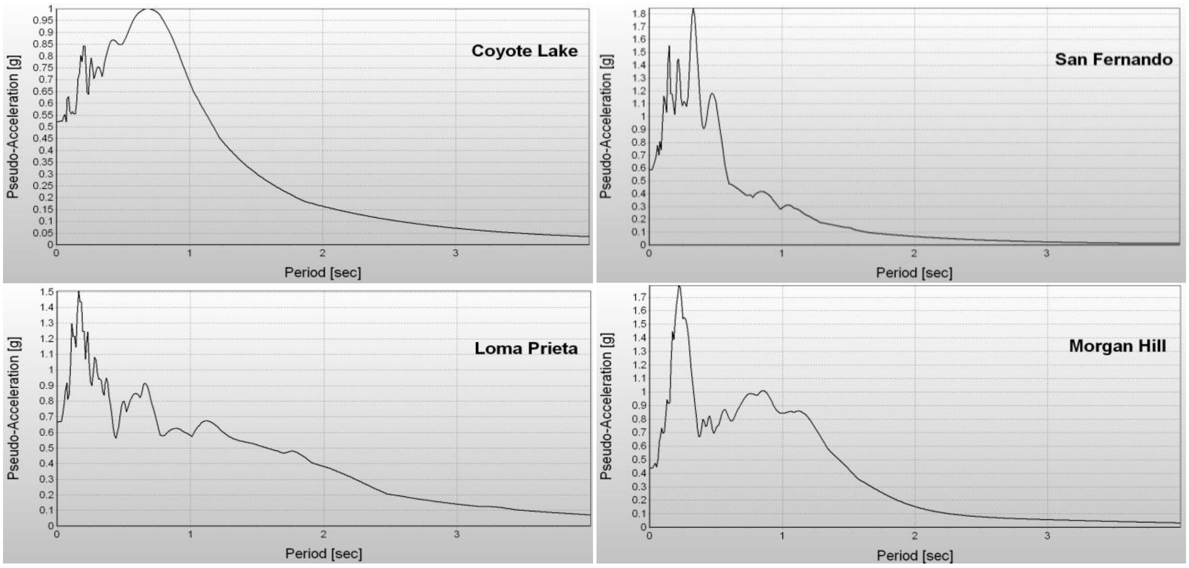

Figure 4.The whose pseudo acceleration spectra of four of selected earthquakes

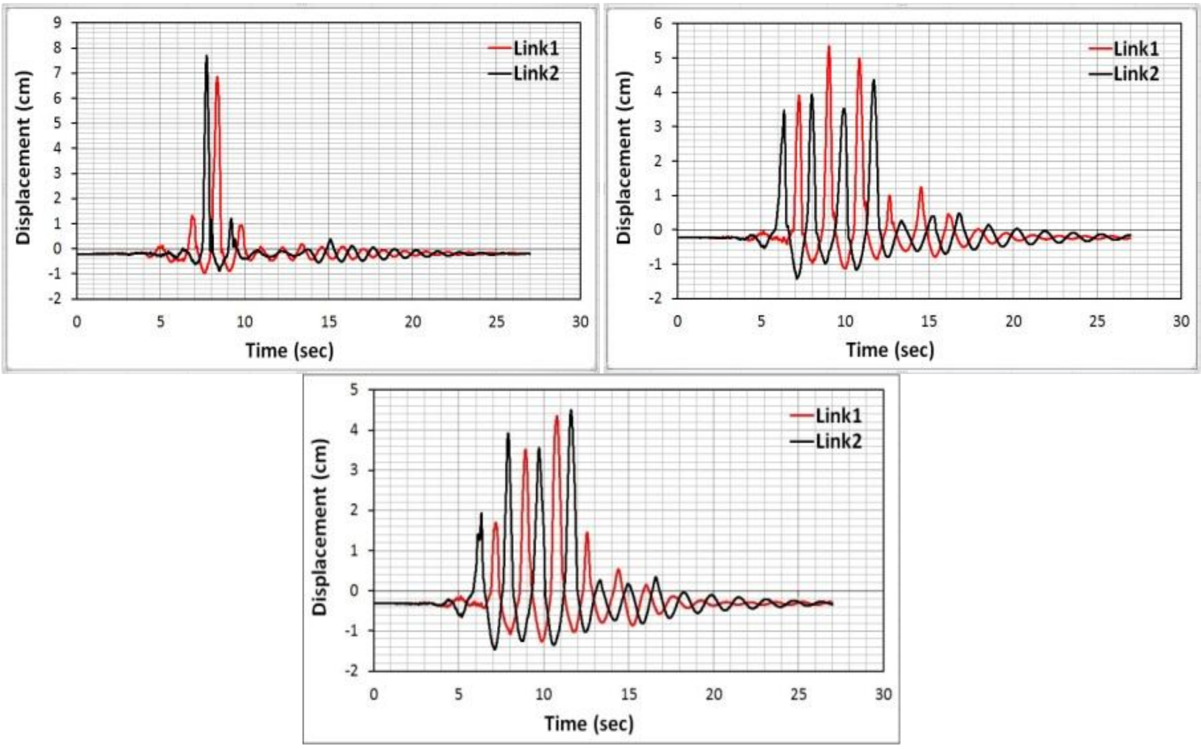

Figure 5. Vertical displacement histories of bottom ends of columns at opposite side of the rocking10- (upper left), 15- (upper right), and 20-story(lower) buildings subjected to LomaPrieta earthquake

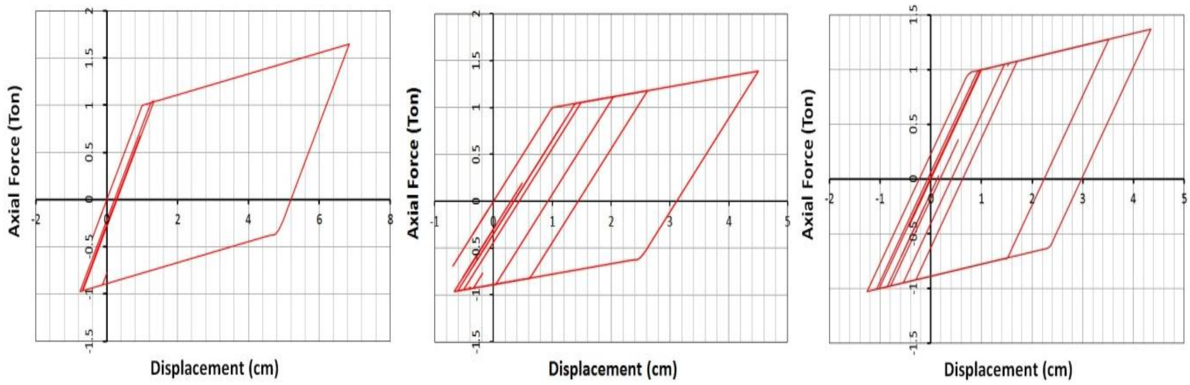

Figure 6. Hysteretic behavior of energy dissipating links in 10-, 15-, and 20-story buildings (left, middle, and right, respectively) subjected to Loma Prieta earthquake

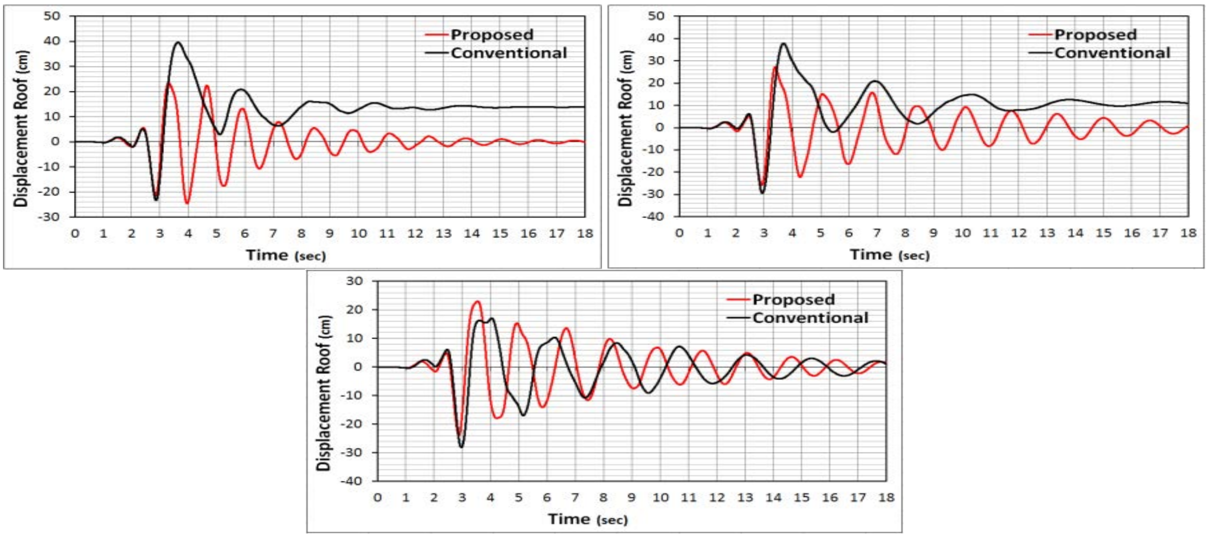

Figure 7.Roof displacement histories of 10-, 15-, and 20-story buildings (upper left, upper right, and lower, respectively) subjected to Loma Prieta earthquake

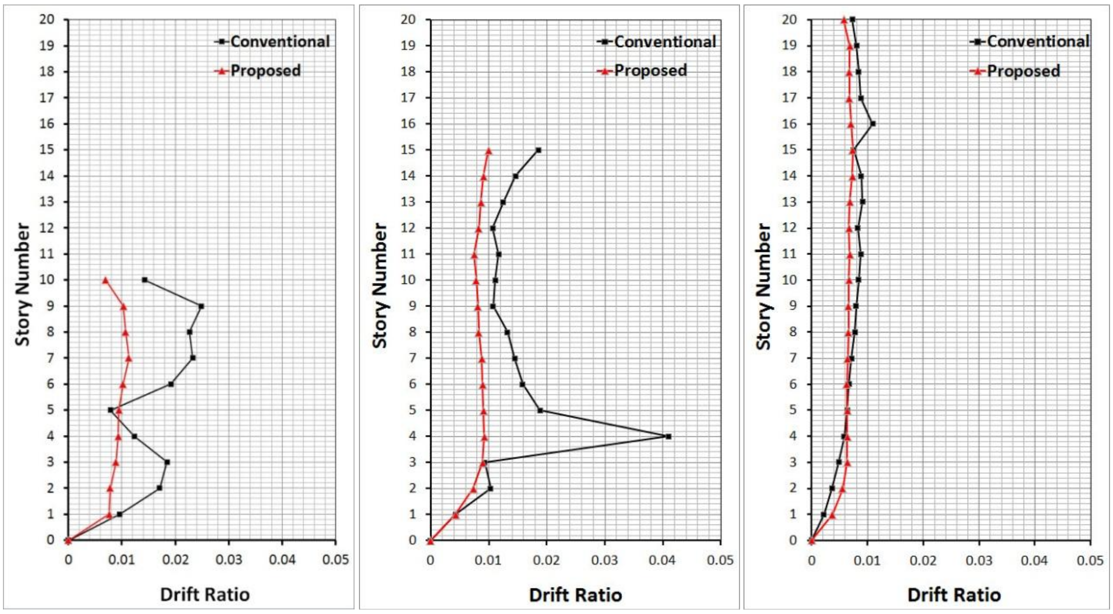

Figure 8. Maximum drifts of ordinary and rocking buildings subjected to LomaPrieta earthquake

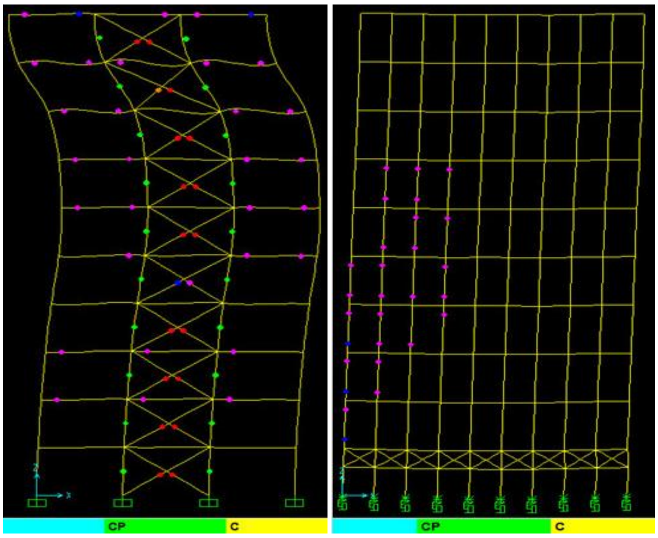

Figure 9. Plastic hinges in 10-story ordinary (left) and rocking (right) buildings subjected to Morgan Hill earthquake

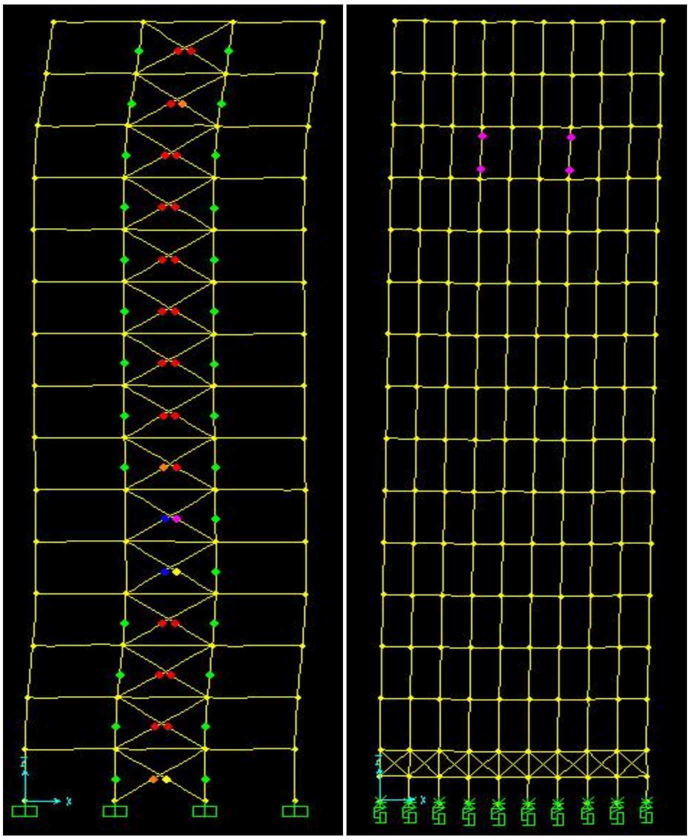

Figure 10. Plastic hinges in 15-story ordinary (left) and rocking (right) buildings subjected to Coyote Lake earthquake

The relatively remarkable upward and limited downward motion of bottom ends of columns of the rocking buildings is seen in Figure 5, which their amounts are in good agreement with those shown in the hysteretic curves of the corresponding links shown in Figure 6. Figure 7 shows that there are some residual displacements at the end of earthquakes in ordinary buildings, while this is not observed in the rocking buildings. It is seen in Figure 8 that the amount of maximum drifts in rocking buildings is much less than the ordinary buildings, however, the difference between drift values decreases as the number of stories increases. The plastic hinges created in 10- and 15-story ordinary and rocking buildings are observed in Figures 9 and 10.Results of this type to 20-story buildings cannot be presented here because of lack of space, and can be found in the main report of the study (Ebrahimi 2015). It is seen in Figures 9 and 10 that ordinary buildings are seriously damaged, while the rocking buildings have performed quite satisfactorily.

CONCLUSIONS

Numerical results of NLTHA show that the proposed rocking structures can efficiently control the seismic damage in the building, so that plastic deformation happens only in the energy dissipaters, and the main structural elements remain elastic, and therefore, the buildings designed and constructed by the proposed technique can be easily repaired even after major earthquakes. The good hysteretic behavior of the energy dissipaters shows that they are quite appropriate as fuses in the proposed rocking structural system. Regarding that the rocking buildings needs tubular frame structure with a grid of deep girders at their lowest story, and this may remarkably affect the total cost of the building structure, a cost-benefit analysis is required as the continuation of this study.

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