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Proposing a Yielding-Plate Energy Dissipating Connection for Circumferential Columns of Steel Rocking Buildings and Investigating its Properties by Nonlinear Finite Element Analyses

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ABSTRACT

Seismic codes usually allow extensive structural damages, in major earthquakes, so that, after the event, demolishing and reconstruction of buildings is inevitable. In megacities this allowance causes undesired consequences, such as very heavy reconstruction works. One idea to prevent these consequences is 'Directed-Damage Design' (DDD), which means creating a condition by which damage is directed to some pre-decided parts of the structural system, to keep other parts intact, and therefore, have the structure easily repairable. In this study DDD idea was employed to create repairable regular multi-story steel buildings based on rocking motion, created by: 1)considering a tubular structural system, 2) disconnecting lowest story internal columns from ground, 3) using a grid-of-stiff-girders at base level, and 4) employing specific Yielding-Plate energy dissipaters, working only in Positive Displacements (YPPD) under circumferential columns at base level, which help the building structure dissipates energy during rocking motion in an earthquake. The YPPDs dissipate energy during upward-downward motion of the columns' bottoms while the building rocks. To investigate the mechanical behavior of YPPDs, as the main focus of this study, their hysteretic characteristics were studied by finite element modeling, and their efficiency was shown by time history analyses of a 15-story rocking buildings.

KEYWORDS: Directed-damage design, Repairable structure, Tubular structural system, Time history analysis

1. INTRODUCTION

The provisions of seismic design codes for building systems usually result in a structural system which is prevented against collapse, however, in case of major earthquakes the provisions allow the building to get heavy structural damages so that after the earthquake demolishing and reconstruction of the building is inevitable. This allowance, in turn, results in unacceptable consequences in large and populated cites, such as thousands of homeless people for a long time, very time consuming and difficult demolishing process and debris removal activities, and very massive, and therefore time consuming and costly reconstruction works. What happened in Christchurch earthquake of 11 March 2011 is a good sample of these very unpleasant consequences (Weng et al., 2011). One idea which can prevent the earthquake prone megacities against these undesired consequences is 'Directed-Damage Design' (DDD), which means guiding or directing the damage to some pre-decided parts of the structural system, acting as fuses, so that other parts, namely the main structural system, do not experience any major plastic deformation, and therefore making the building structure easily repairable, even after major earthquakes.

In fact, DDD idea is somehow similar to the idea of using 'structural fuse' which 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), 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, to keep the main structural members elastic or with minor easily repairable damages, in reality the building equipped with those kind of fuses 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 study on a structural frame with rocking motion (Azuhataet 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 is limited to two-dimensional (2-D) systems or 2-D states of systems' behavior.

Considering the buildings in three-dimensional (3-D) state, in the early years of this decade Hosseini and NoroozinegadFarsangi(2012) 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 was substituted by a specific energy dissipating element, and changing the outer columns at the building's base level totelescopic columns, equipped with ADAS elements which give them the capability of energy absorption in axial deformation. Later, a similar study was also conducted by Hosseini and MousaviTirabadi (2013) in which a massive central column along with circumferential columns at base level equipped with a kind of Double-ADAS(DADAS) devices with some specific features for higher energy dissipation capacity were used. Also another study was performed by Hosseini and Bozorgzadeh (2013) in which an innovative design for repairable regular steel buildings has been proposed by using a 4-cell configuration structure with some inclined columns at base level, equipped with DADAS devices, and security cables at corners. In another recent study by Hosseini and Kherad (2013) a multi-stud energy dissipating device was used as the central support of the building at its base level which was considered to work as a huge plastic hinge (PH) under the action of vertical load and 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, were used. However due to small number of bays in those studies, the size of those strong girders was not 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 modeled 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 a more recent study Hosseini and Ghorbani Amirabad (2015) a specific structural fuse called yielding-curved-bars and hemisphere core energy dissipating device has been introduced as the central support of repairable buildings with seesaw motion, Proceeding of the 7th International Conference on Seismology and Earthquake Engineering (SEE-7), Tehran, Iran, 18-21 May 2015. Finally, Hosseini and Ebrahimi (2015) conducted a study on the application of 'Deliberate Directing of Damage' Idea for creation of repairable buildings by using rocking tubular frame structural system and yielding-plate dampers at foundation level, and showed that by employing the rocking motion remarkable reduction of the seismic response of buildings can be achieved so that the buildings are easily repairable even after major earthquakes.

In this study, which is in fact in continuation of the study, conducted by Hosseini and Ebrahimi (2015) on application of DDD idea for creation of repairable regular multi-story steel buildings based on rocking motion, the focus of the work is on the characteristics of the energy dissipaters or structural fuses, supposed to be used under the circumferential columns of the rocking building at lowest story. Rocking motion in structural system of the building is created by: 1) considering a tubular structural system, 2) disconnecting lowest story internal columns from ground, 3) using a grid-of-stiff-girders at base level, and 4) employing specific Yielding-Plate energy dissipaters, working only in Positive Displacements (YPPD) under all circumferential columns at base level, which help the building structure dissipates energy during rocking motion in an earthquake. Energy dissipation of YPPDs in positive displacement means that the yielding plates of the YPPD experience plastic deformation, and therefore, dissipate energy when columns bottoms move upward and downward above the base plate level (positive displacements) successively during the rocking motion of the building in an earthquake. In fact, columns' bottoms are prevented against downward motion below the base plate level (negative displacements) by the relatively large stiffness of the foundation in vertical downward direction. To investigate the nonlinear hysteretic behavior of the proposed YPDD it has been modeled by using a finite element software, and variation of its upward and downward stiffness values as well as its yielding strength have been obtained by considering different geometric features for the yielding plates used in it, and also the spherical form considered for the bottom end of the corresponding column and its specific concave base plate. After achieving the appropriate mechanical features of the YPEDC a15-story rocking buildings have been equipped with the proposed YPEDC and its seismic behavior subjected to a series of 3-component records has been compared to that of conventional fixed base building of the same geometry. The PH formation has been used as the main comparison measure in the two 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.

2. INTRODUCING THE PROPOSED FUSE

In the proposed rocking structural system for regular multistory repairable steel buildings, creation of possibility of controlled rocking motion is basically based on employing YPPDs as structural fuses installed under all circumferential columns of the building at its base level. YPPDs help the rocking building structure to dissipate energy during rocking motion in an earthquake by plastification of its trapezoidal yielding plates. The trapezoidal form of the yielding plates helps better distributed plastic deformation through its their body, and hence, preventing them from low-cycle fatigue. A perspective view of the rocking building and a close-up of a corner column, equipped with YPPD fuse, as well as a general view of the YPPD and its top view, and also the setting of its trapezoidal yielding plates are shown in Figure 1.

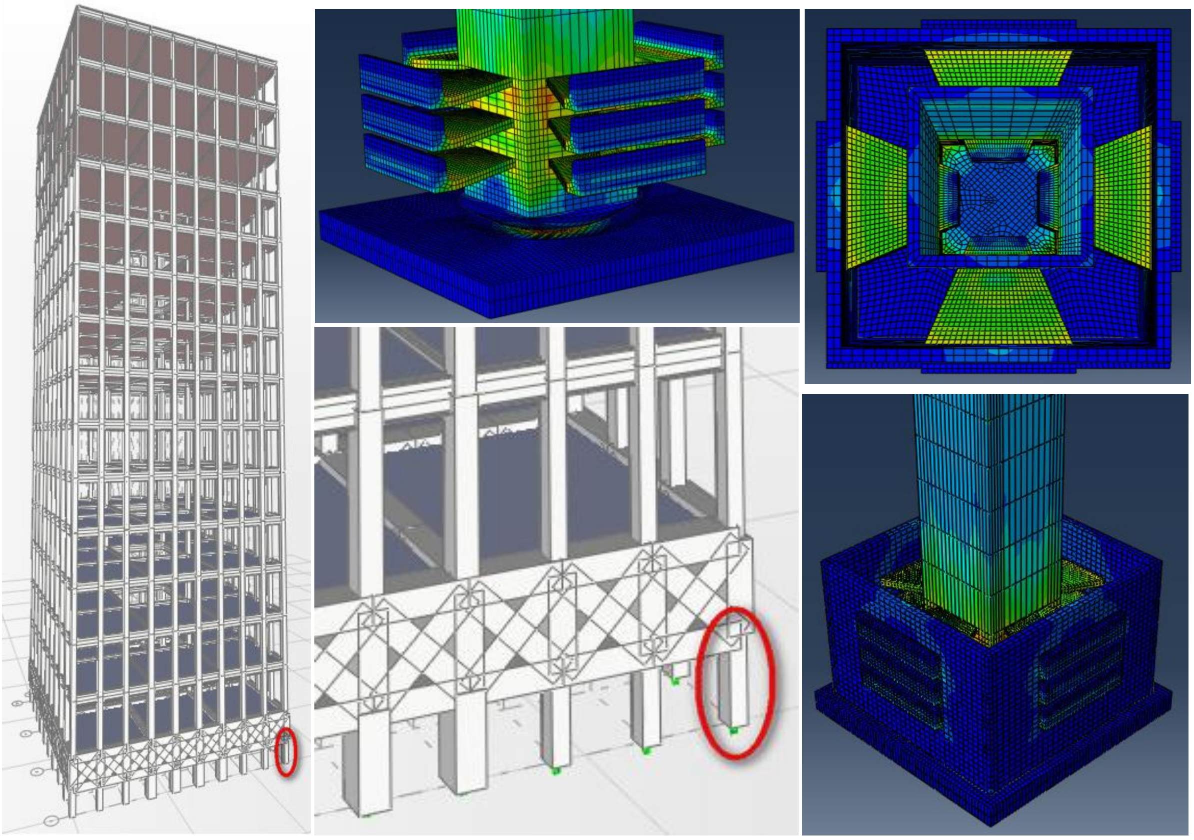


Figure 2.1 A perspective view of the rocking building (left), a close-up of a corner column equipped with YPPD fuse (lower middle), a general view of the YPPD (lower right) and its top view(upper right), and the setting of its trapezoidal yielding plates (upper middle)

3. FINITE ELEMENT MODELING AND ANALYSIS OF THE YPPD FUSE

To study the hysteretic force-displacement behavior of the YPPDs, a powerful finite element (FE) computer program was used. For verification of the numerical modeling process in the employed FE analysis computer program the analysis results of cantilever beam in large plastic deformation under the effect of an increasing moment applied at its free end were used. After verification, by performing a set of FE analyses on the YPPD fuse with some appropriate dimensions for the trapezoidal plates, as shown in Figures 3.1 and 3.2,the initial and post-yield (secondary) stiffness values as well as their yielding strength of the fuse and also the maximum tolerable displacement were obtained.

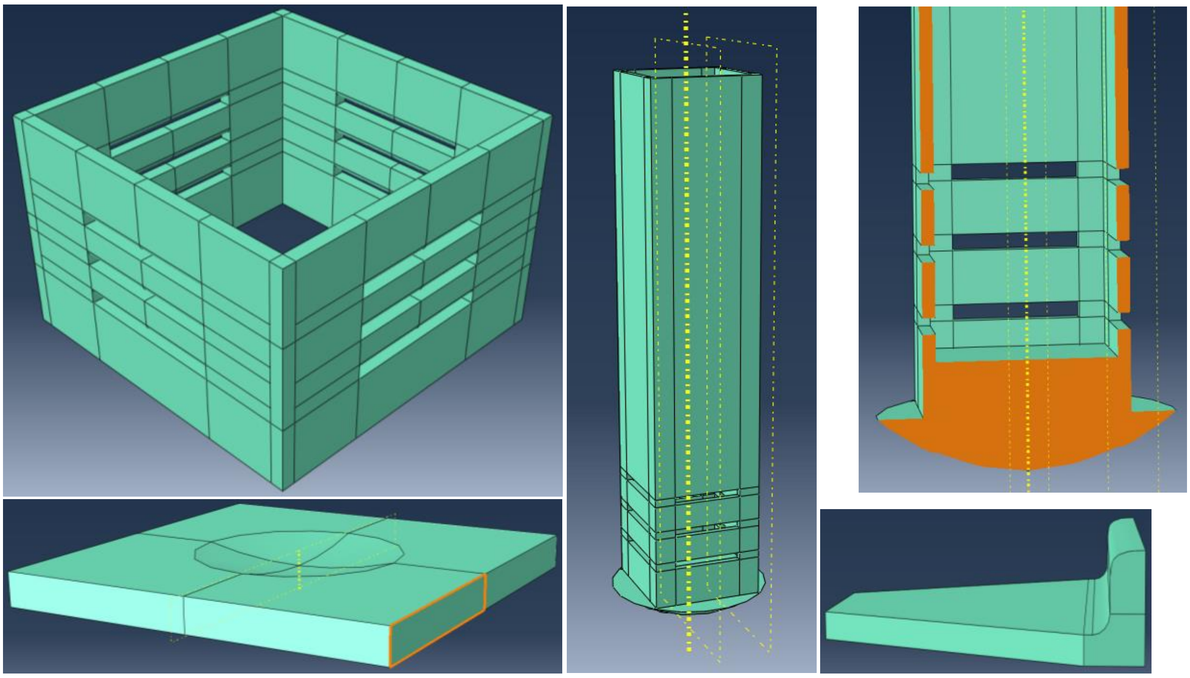


Figure 3.1 Parts of the YPPD fuse for FE modeling: the outer box with slotted walls (upper left), base plate with a concave area at its middle (lower left), the lower part of the column with slotted walls and a spherical pad at its bottom (middle), section of the column and its lower pad (upper right), and one of the yielding plates as the main tools for energy dissipation (lower right)

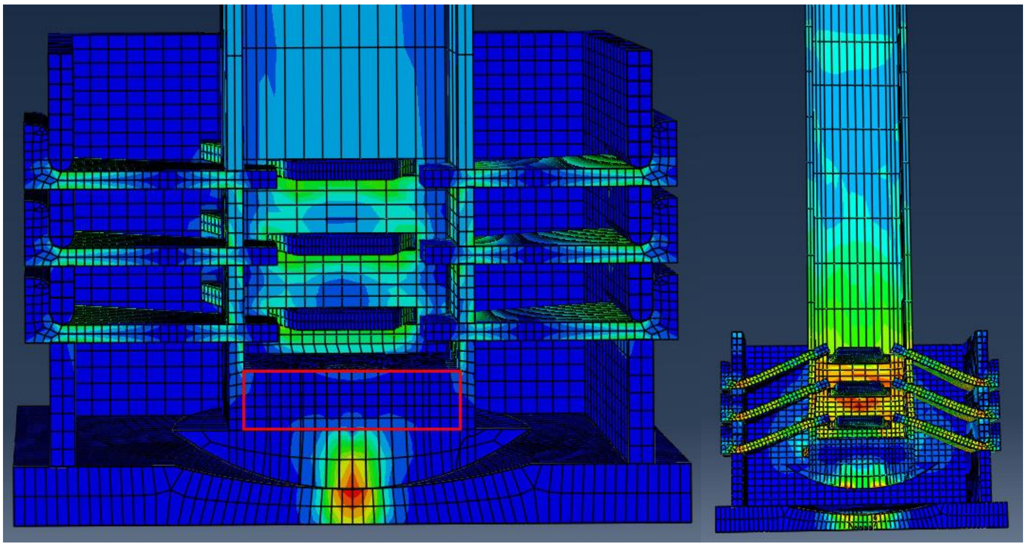
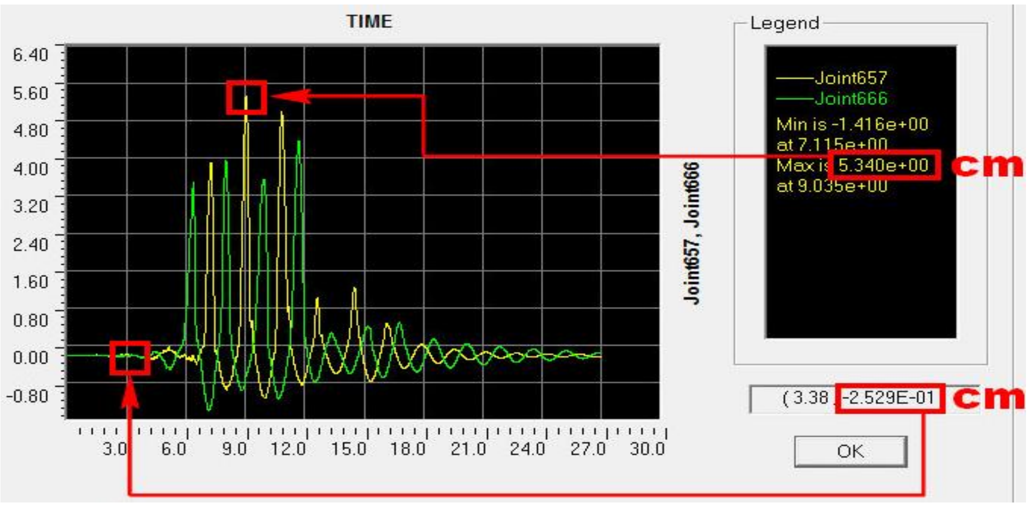


Figure 3.٢The YPPD fuse FE model under downward (left) and upward (right) forces

The area indicated by a red rectangle in Figure 3.2, is a part added to the bottom of the column to prevent local buckling at the wall of the column box section, which may happen when the column's bottom hits the base plate during rocking motion of the building. To investigate the hysteretic characteristics of the YPPD fuse, particularly to obtain its initial and post-yield (secondary) stiffness values as well as its yielding strength, by FE analysis, a displacement-controlled cyclic loading in vertical direction was applied at the top of the column and the total reaction under the base plate was obtained and plotted versus the applied vertical displacement. To find out how much downward and upward displacement should be applied to the FE model of the fuse, an initial nonlinear time history analysis of a sample building was performed by the structural analysis computer program, and then, the obtained displacement values were applied to the FE model of the fuse. Figure 3.3 shows the vertical displacement histories of the lower ends of two circumferential columns locating at two opposite sides of the rocking building subjected to Loma Prieta earthquake accelerograms, which at its ending instants the free vibration of the rocking building structure can be seen as well.



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Min is -1.416e+00
at 7.115e+00
Max is 5.340e+00
at 9.035e+00
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Figure 3.3 Vertical displacement histories of the lower ends of two circumferential columns locating at two opposite sides of the rocking building

It can be seen in Figure 3.3 that in the beginning instants of the earthquake during which the main vertical load on columns is still the gravity load, the maximum downward displacement of the bottom ends of the columns has been almost 2.5 mm, as indicated in the Figure by the lower red box. Also it is seen in the figure that the maximum upward displacement of the bottom end of the column has happened during the strong ground motion, and has been around 5.3 cm as indicated in the Figure by the upper red box. These minimum and maximum values have been used in the FE analysis for obtaining the hysteretic force – displacement loops of the YPPD fuse as shown in Figure 3.4.

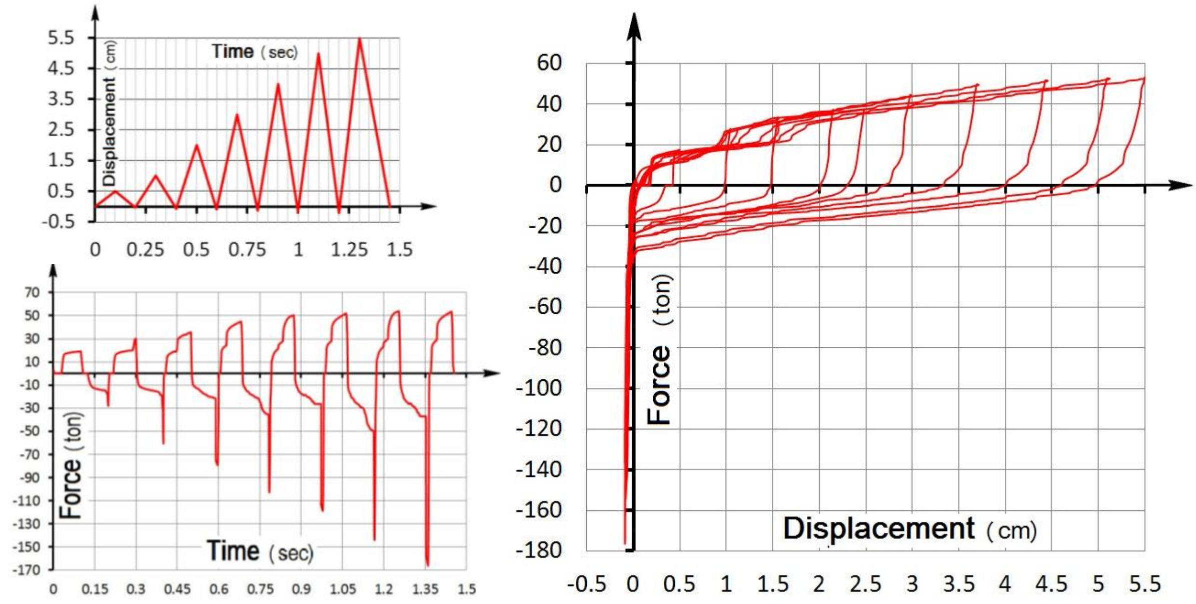

Figure 3.4Sample cyclic displacement loading regime (upper left), the resulted forces in the YPPD fuse (lower left) and the force-displacement hysteretic loops of the fuse obtained by FE analyses (right)

The appropriate stiffness value for the YPPD fuse to be used in any specific building may be found by a series of trial and error analysis of that building system. For this purpose, the fuse is modeled as the multi-linear plastic spring in the numerical model of the whole building structure. The initial stiffness of the fuse affect remarkably the modal periods of the rocking building. Furthermore, the initial and secondary stiffness values and the yield strength and of the fuse, together, control the energy dissipation potential of the fuse. The YPPD fuse stiffness values also affect the values of stress ratio in the superstructure elements, which is from 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 YPPD fuse and the grid elements, and observing the stress ratios under the dead and live loads of the building, decision can be made on the desired values.

4. NUMERICAL MODELING OF THE YPPDFUSEIN A 15-STORY ROCKING BUILDING

The sample building, considered in this study for showing the efficiency of the proposed rocking structural system in seismic response reduction, was a 15-story regular steel building with 3-bay × 3-bay square plan in which span length of all bays is 6.0 m and height of all stories is 4.0 m. The building was designed once based on the conventional seismic design provisions (AISC-ASD89), and once more by using the suggested rocking system, using the trial and error scheme explained in the previous section. It should be noted that the initial stiffness of the YPPD fuse affects remarkably the modal periods of the rocking building. Furthermore, the initial and secondary stiffness and the yield strength of the fuse, together, control the energy dissipation potential of the fuse. The stiffness values also affect the values of stress ratio in the superstructure elements, which is from the other side under the effect of the relative stiffness of the grid of the orthogonal strong girders. By assigning different values to the initial and secondary stiffness and the yield strength of the YPPD fuse, modeled as the multi-linear plastic spring in the numerical model of the whole building structure, and also considering various structural properties for elements of the grid of orthogonal strong girders, and observing the stress ratios under the dead and live loads of the building, and particularly, subjected to selected earthquake records, decision can be made on the desired values. On the other hand the relationships between the values of initial and secondary stiffness, as well as the yielding strength and ultimate tolerable displacement of the YPPD fuse and its geometric features, particularly dimensions of the trapezoidal yielding plates, can be found by a series of FE analysis. On this basis the appropriate values of the parameters were obtained for a 15-story rocking building presented here as a sample. Figure 4.1 show the conventional 15-sotry building with X-bracing and its rocking counterpart.

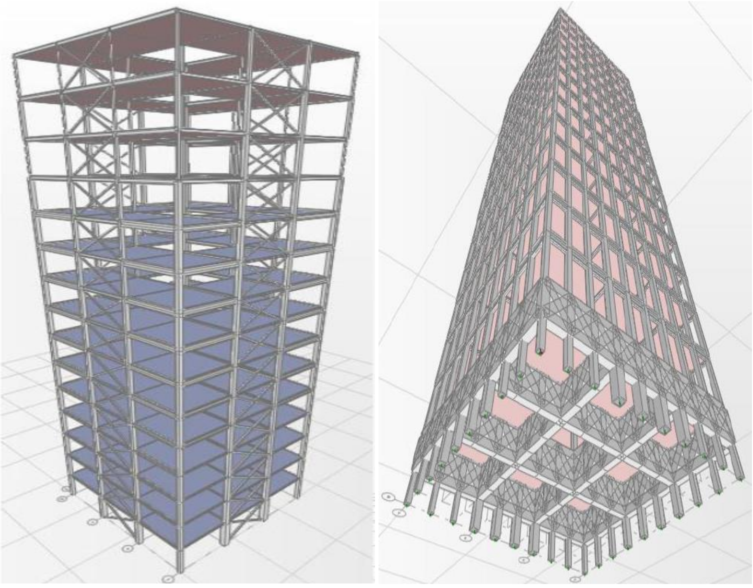

Figure 4.1 Views of the sample 15-story ordinary building with X-bracing (left) and the rocking building with tubular system and the grid of orthogonal strong girders at its 1st story (right)

Table 3.1 presents the specifications of the YPPDs used for this 15-story rocking building obtained by several cases of analysis in a trial and error manner.

Table 3.1 Specifications of the YPPDs used in the sample 15-story rocking building

Initial stiffness (kgf/cm)	1000
Secondary stiffness (kgf/cm)	114
Yielding displacement (cm)	1.0
Ultimate displacement (cm)	5.5

For seismic response evaluation of the two designed counterpart buildings a series of nonlinear time history analysis 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. A sample of response spectra of the selected earthquake along with samples of roof displacement histories of the two buildings are shown in Figure 4.2, and some more response samples in Figures 4.3 and4.4.

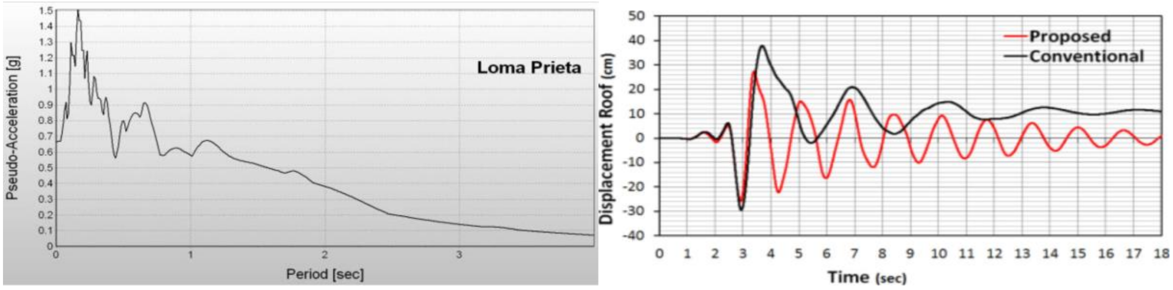

Figure 4.2 A sample of response spectra of the selected earthquakesalong with samples of roof displacement histories of the two buildings

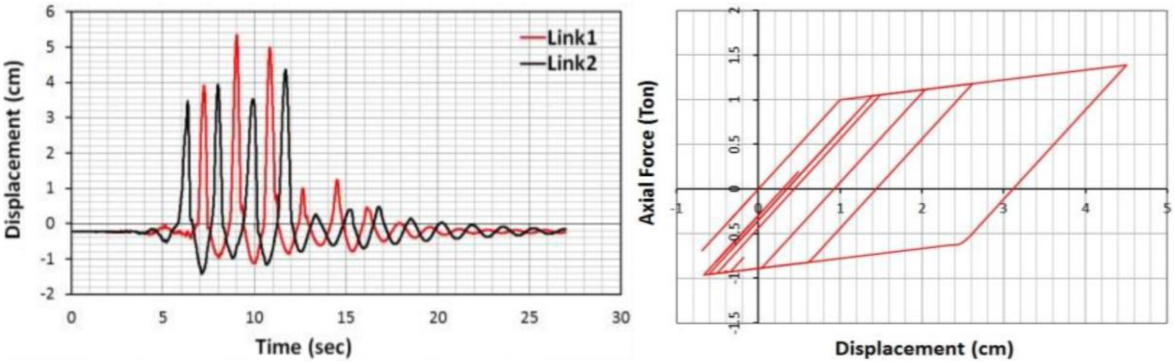

Figure 4.3 Time histories of vertical displacement of two opposite columns' bottom ends (left) and the hysteretic loops of one of the corresponding YPPDs (right)

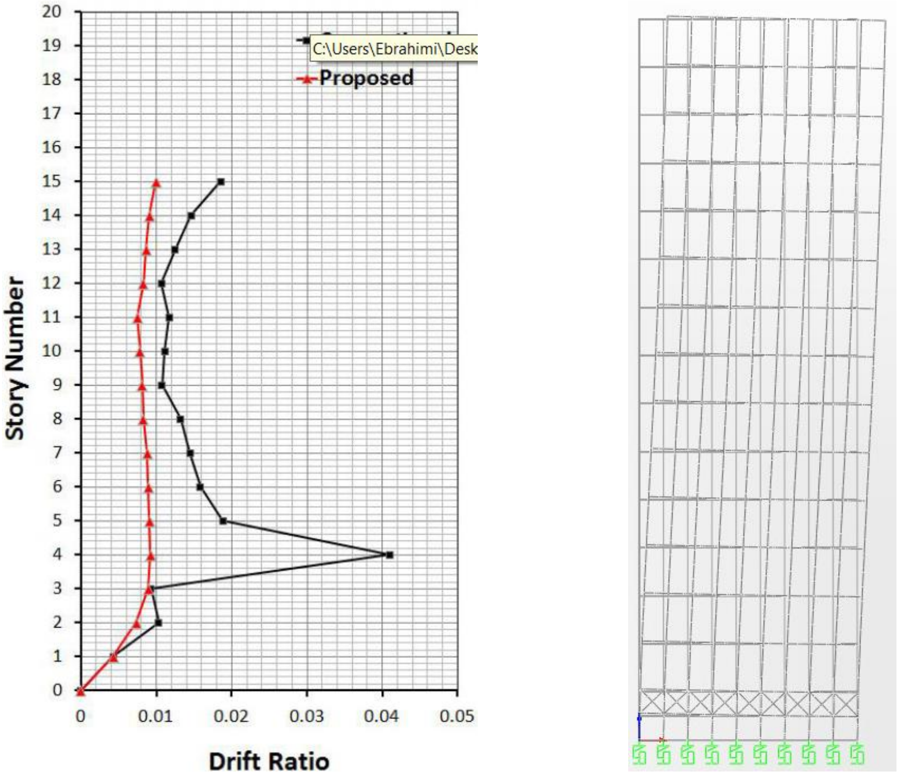

Figure 4.4 Samples of drift ratios (left), and the rocking building in an instant of the earthquake (right)

Satisfactory seismic response of the rocking building in comparison to the conventional one can be easily realized by Figures 4.2 to 4.4. Finally, by comparing the type and distribution of PHs in conventional and rocking building, as shown in Figure 4.5, the superior seismic behavior of the rocking building is observed.

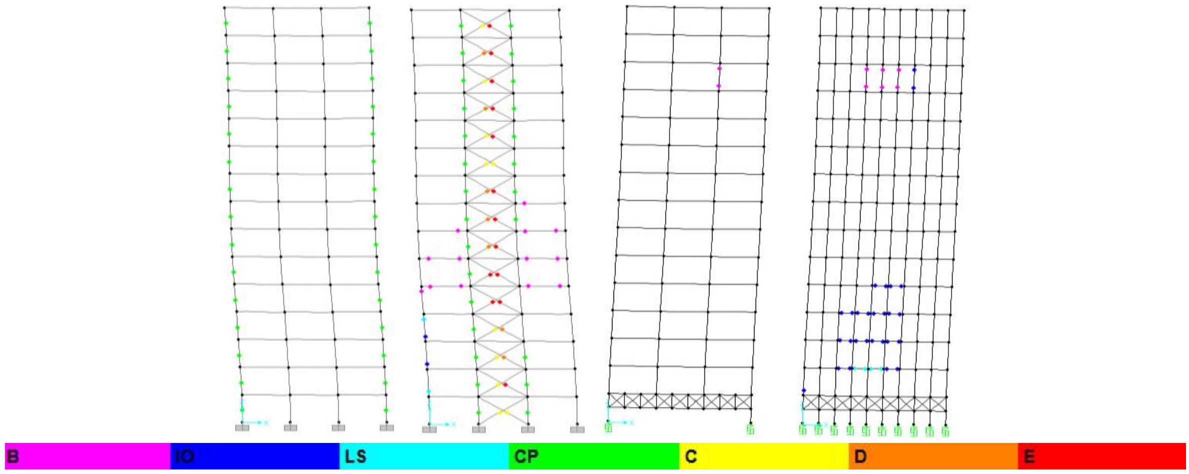

Figure 4.5 Comparing the type and distribution of PHs in a middle and a side frame of the conventional building (left) and rocking building (right)

5. CONCLUSIONS

Numerical results show that the proposed YPPD fuse can be effectively used as a passive control device, acting as both fuse and connection, for rocking buildings, and that by using the proposed rocking structural system it is easily possible to create buildings which are repairable, even after major earthquakes. It is worth mentioning that the amount of roof displacement in the rocking building is usually limited to 1/100 of the building height, and this means that the seismic joint recommended by codes is enough for the distance between adjacent rocking buildings in urban settings. Finally, the ease of making the proposed YPPD fuse is an encouraging factor for using it is all buildings in seismic prone countries.

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