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DIVIDING BUILDING'S STRUCTURE INTO 4 INTERACTIVE ROCKING PARTS TO MAKE IT REPAIRABLE AFTER MAJOR EARTHQUAKES

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Abstract

Most of seismic design codes for building systems allow heavy damages to buildings, in case of major earthquakes, provided that the buildings are prevented against collapse or to keep the buildings' performance in LS or at least CP level. However, amount of the allowed damage can be so high that requires demolishing of the buildings, and 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, 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, based on the DDD idea, have been paid great attention by some researchers in recent decade and rocking as well as seesaw motions have been employed for this purpose. Rocking motion can be easily triggered in buildings with aspect ratio higher than 2 (relatively tall buildings), however, for midrise buildings, which usually have lower aspect ratios, creation of rocking potential is not easy. In this study to create repairable regular midrise steel multistory buildings, the capability of rocking motion has been given to the system by dividing the buildings' skeleton into four similar narrower structures with a 4-cell configuration, each cell having a plan area of almost ¼ of the original structure. Each cell of the 4-cell structure has a tubular frame structural system and is capable to do rocking motion during earthquake, in which the closely-spaced columns at each side can bear the whole weight of the cell. At the base of each of the circumferential closely-spaced columns a yielding plate energy dissipator is used, which works when the column's bottom end moves upward and downward above the foundation level during the rocking motion of the cell. To create more potential of energy dissipation, some dampers can be also used between each pair of the four cells. To show the efficiency of the proposed structural system, a set of 5- and 8-story buildings with similar plans were considered and a series of nonlinear time history analysis (NLTHA) were performed by using a set of 3-component scaled accelerograms of some selected earthquakes, including both far- and near-field events. Numerical results of NLTHA show that the proposed rocking structures can efficiently decrease the seismic damage in the building, so that plastic deformation happens basically in the energy dissipators, 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, and the building can basically keep the IO performance level.

Keywords: Repairable Building, Directed-Damage Design, Nonlinear Time History Analysis, Tubular System

1. Introduction

The philosophy behind most of seismic design codes for building systems is to allow heavy damages to ordinary buildings, in case of major earthquakes, provided that the buildings are prevented against collapse. This means keeping the Life Safety (LS) or at least Collapse Prevention (CP) performance level. However, in many cases, amount of the allowed damage can be so high that requires demolishing of the buildings, and this, in turn, results in some unacceptable consequences in large populated cities, including: 1) thousands of homeless and/or jobless people for a very long time, 2) very time consuming, difficult, and costly demolishing works and debris removal activities, and 3) very massive, and therefore, costly and time consuming required reconstruction works. This is exactly what happened in Christchurch earthquake of February 2011 in New Zealand, in which almost 50% of buildings in the central business district of city of Christchurch, comprising over 1200 multistory buildings, were demolished as a result of heavy damages [1]. Therefore, it seems quite reasonable to design and construct the buildings in such a way that they either do not get any major damage, by using techniques such as seismic isolation and control, or can be easily repaired by replacing only some special parts. Isolation and control, in spite of their rick scientific background and worldwide development, have not been acknowledge in most of the earthquake prone countries because of either high costs or technological limitations. Regarding these facts, any idea which can lead to creation of repairable buildings is greatly acknowledgeable. One such idea is 'Directed-Damage Design' (DDD) [2] or design based on directing the energy dissipation in the system. This idea means guiding the damage to some pre-decided parts of the structural system, as the main source of energy dissipation, so that other parts do not experience any major plastic deformation, and therefore, making the building easily repairable by only replacing the damaged elements.

DDD idea can be considered as a modified version of the concept of 'Capacity Design', introduced by Paulay in 1977 [3], or the strategy of using 'Structural Fuses', presented in early 80s by Fintel and Gosh [4], or the idea of 'Damage Tolerant Structure' discussed by Wada and his colleagues in 1992 [5]. The idea of using structural fuses has been developed more for building systems since early 2000s up to now, in combination with either rocking or seesaw motion in the structural system, by Midorikawa and Azuhata and their colleagues (2002) [6-7], Vargas and Bruneau (2006) [8], Pollino and Bruneau (2007) [9], Wiebe and colleagues (2007) [10], Poirier (2008) [11], Tremblay and colleagues (2008) [12], Eatherton and colleagues (2008) [13], Ma and colleagues (2010) [14], Sause and colleagues (2010) [15], Hosseini and Noroozinejad Farsangi (2012) [16], Sanchez (2013) [17], Hosseini and Mousavi Tirabadi (2013) [18], Hosseini and Bozorgzadeh (2013) [19], Hosseini and Kherad (2013) [20], Hosseini and Ghorbani Amirabad (2015) [21], Hosseini and Alavi (2015) [22], and finally Hosseini and his colleagues (2016) [23].

In fact, to apply the DDD idea to building structures, for making them repairable, even after a large earthquake, one way is creating the potential of rocking or seesaw motion during an earthquake, instead of deforming in shear mode. By rocking and/or seesaw motion, in which the building can move almost as a rigid body, rotating with respect to one of its edges, in case of rocking, or a huge central hinge connection at the lowest level, in case of seesaw motion, the large relative displacements during earthquake happen only in the lowest story, while in shear mode the relative displacements happen between all stories. Rocking and seesaw motions would direct the damage to some fuse or energy dissipating elements, installed in the lowest story of the building. In this way absorption of the seismic input energy would happen only in specific elements at the lowest story, instead of spreading all over the building structure, and causing damage due to inter-story drifts, in most cases randomly, in beams, columns or bracing elements in various stories.

In this study the DDD idea has been employed for design of repairable regular steel multistory buildings, by dividing the buildings' skeleton into four similar narrower structures, having a plan area of almost ¼ of the original structure, creating a 4-cell configuration. The 4-cell configuration has been recently introduced by Hosseini and Bozorgzadeh (2013), however, in that study each cell of the 4-cell structure has a see-saw motion on its central column, while in the present study the tubular frame system has been used for all of the four narrower structures, so that there is no need to the central column at base level and each cell can have a rocking motion during which the closely-spaced columns at each side can bear the whole weight of the cell. Each of the circumferential closely-spaced columns at the base level is connected to the foundation by a yielding plate energy dissipator, which works when the column's bottom end moves upward and downward above the foundation level during the rocking motion of the cell. To create more potential of energy dissipation, some yielding plate dampers can be also used between each pair of the four cells. To show the efficiency of the proposed structural system, a series of nonlinear time history analysis (NLTHA) were performed on a set of 5- and 8-story steel regular buildings by using a set of 3-component scaled accelerograms of some selected earthquakes. Details of the study are presented in the following sections.

2. The Considered Buildings and Their Rocking Counterparts

The main idea followed in this study for creating reparable buildings is to divide its structure into four separate parts each having the capability of rocking motion, and to put between them some energy dissipating elements so that the input energy do not dissipate by plastic deformation of the main structural members. Fig. 1 shows a sample 5-story ordinary building and its 4-cell rocking counterpart, and Fig. 2 shows the plan of the lowest as well as upper stories of the 4-cell rocking building.

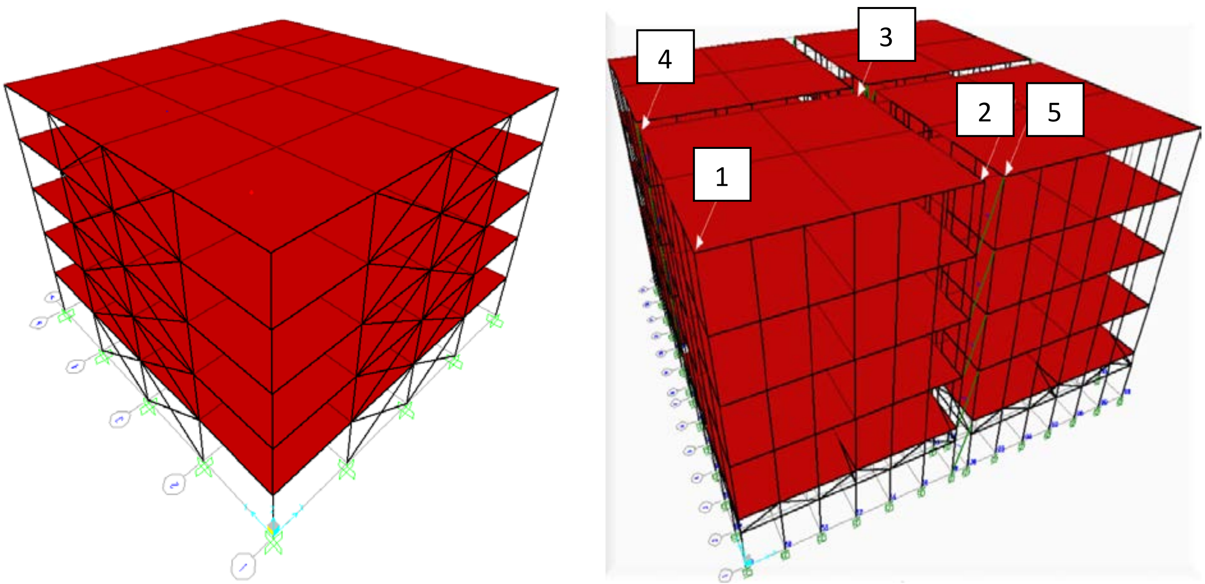


Fig. 1 – A sample 5-story ordinary building (left) and its 4-cell rocking counterpart (right)

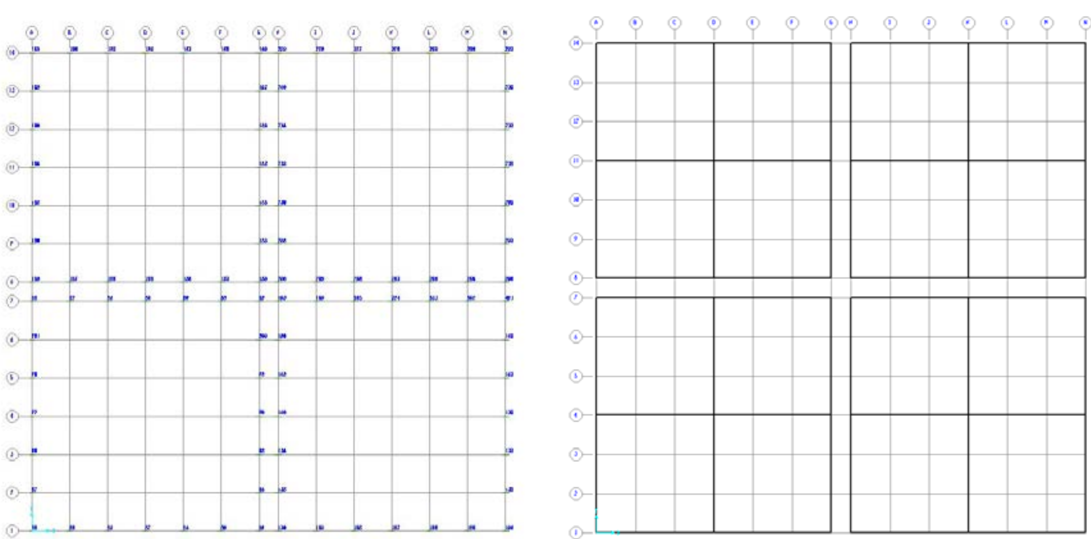


Fig. 2 – The plan of the 1st story (left) and the upper stories (right) of the 4-cell rocking building, showing that there are 24 columns in the lowest story, and only 9 columns in all upper stories

Due to the removal of the central column at the base floor of each cell, a grid of strong girders is required to transfer the load of the upper stories to the circumferential columns at the base level. For this purpose a set of truss beams have been used at the first story of the 4-cell rocking buildings as shown in Fig. 3.

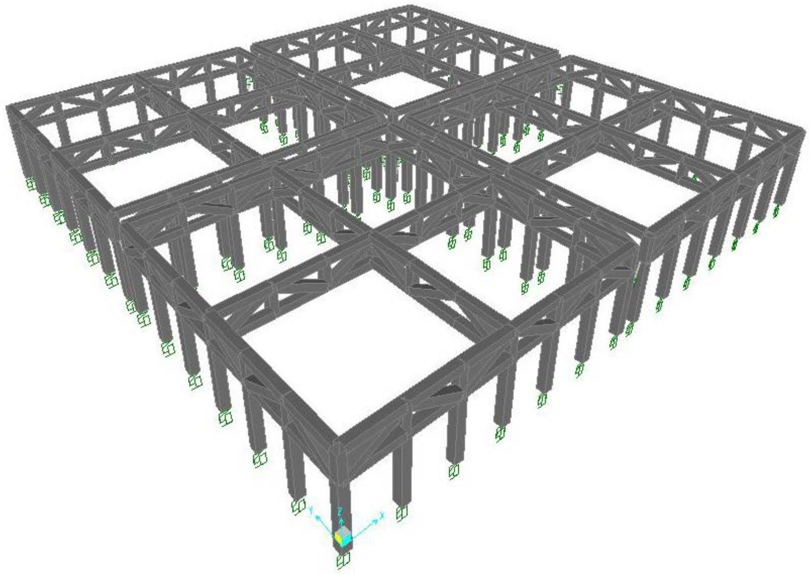


Fig. 3 – The grid of strong girders at the 1st story to transfer the loads of the upper stories to the circumferential columns at the base level

All four cells in the rocking building have a common foundation, and the aim is that they have the same rocking motion. Between these four parts, and also at the bottom of all external columns at the lowest story, some yielding-plate energy dissipators or structural fuses are installed to absorb the input energy during the rocking motion. Fig. 4 shows the considered energy dissipators.

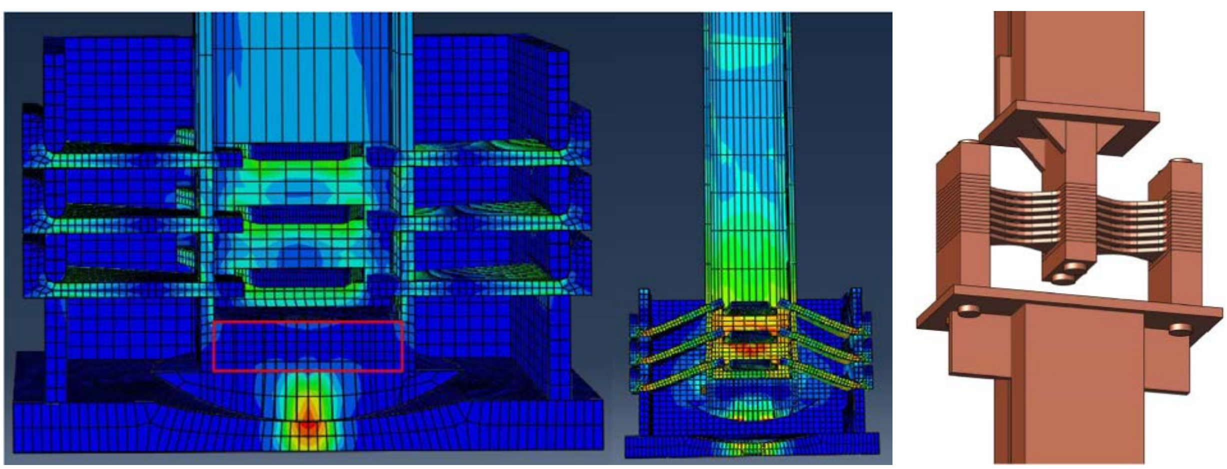


Fig. 4 – The yielding-plate energy dissipators used at the bottom of circumferential columns (left) [2], and between the cells (right) [18]

It is expected that using the proposed rocking system along with the energy dissipators reduces the seismic damages to the structure, so that it can be said in most of extensive earthquakes it is possible to keep the building at IO or at least LS performance level. On this basis, only by replacing the energy dissipators by new ones, the building will be back to operation with much lower costs, comparing to overall repairs and particularly reconstruction.

The buildings considered in this study, for investigating the efficiency of the proposed structural system, include two sets of 5- and 8-story regular steel buildings with square plan, all having 4 bays of 6 meters span in each direction. The first set includes the conventional buildings and the second set includes buildings with the proposed system. The lateral load bearing system of the conventional buildings is x-bracing at two middle bays in each external frame in both directions. The first set of buildings has been designed based on the conventional seismic code, of which the details cannot be presented here because of lack of space, and can be found in the main report of the study [24]. Then the designed buildings have been modified, to create the second set, by dividing the skeleton into four similar parts, removing at the lowest story of each part the internal columns and adding circumferential columns to make a tubular system, and also adding a grid of strong girder at the lowest story to transfer the loads of the removed internal columns to the external ones. To evaluate the seismic behavior of the two sets of buildings and do the required comparisons a series of nonlinear time history analysis (NLTHA) as described in the next section.

3. The Nonlinear Time History Analyses (NLTHA) of the Buildings

To evaluate the seismic behavior of the two sets of the buildings and compare them to show the efficiency of the proposed structural system, 3-component accelerograms of a set of both far-field (FF) and near-field (NF) earthquakes were selected from PEER website. Specifications of the selected FF and NF earthquakes are given respectively in Tables 1 and 2.

Table 1 – Characteristics of the selected FF earthquake records for NLTHA

Earthquake Name	Kobe-Japan	Kocaeli Turkey	Hector Mine	Manjil Iran	San Fernando	Chi-Chi Taiwan	Landers
RSN*	1111	1148	1787	1633	68	1485	900
Year	1995	1999	1999	1990	1971	1999	1992
NEHRP Class	C	C	C	C	D	C	D
Distance**	7.1	13.5	11.7	12.6	22.8	26	23.6
PGA_{max}	0.51	0.22	0.36	0.55	0.21	0.51	0.23
Magnitude	6.9	7.5	7.1	7.4	6.6	7.6	7.3
t_{Arias}***	10.46	9.865	10.64	28.9	13.355	11.25	18.09

*Record Sequence Number (in PEER website) **The closest to plane site-source distance in km ***The average effective duration based on cumulative energy of the two horizontal components

Table 2 – Characteristics of the selected NF earthquake records for NLTHA

Earthquake Name	Landers	Kocaeli Turkey	Cape Mendocino	Loma Prieta	Loma Prieta (No pulse)	Chi-Chi Taiwan	Denali Alaska (No pulse)
RSN*	879	1165	828	802	741	1529	2114
Year	1992	1999	1992	1989	1989	1999	2002
NEHRP Class	C	B	C	C	C	C	C
Distance*	2.2	7.2	8.2	8.5	10.7	1.5	8.9
PGA_{max}	0.79	0.22	0.73	0.5	0.52	0.28	0.43
Magnitude	7.3	7.5	7.0	6.9	6.9	7.6	7.9
t_{Arias}**	13.435	14.18	16.91	8.7	9.41	17.64	25.91

*Record Sequence Number (in PEER website) **The closest to plane site-source distance in km ***The average effective duration based on cumulative energy of the two horizontal components

The response values considered for evaluation of building and comparison of their seismic behavior include roof displacement and acceleration, base shear, and formation of plastic hinges. Before presenting the response histories for comparison, it is useful to see the rocking motion of each cell of the 4-cell structures during earthquakes, as well as the similarity of responses of the four parts. Figs 5 and 6 show respectively, the displacement response histories of points 2 and 5, at two adjacent corners of the two adjacent parts (see Fig. 1), and points 2 and 4 at two corners of the roof level of one part of the 4-cell 5-story building subjected to Kobe earthquake as a sample.

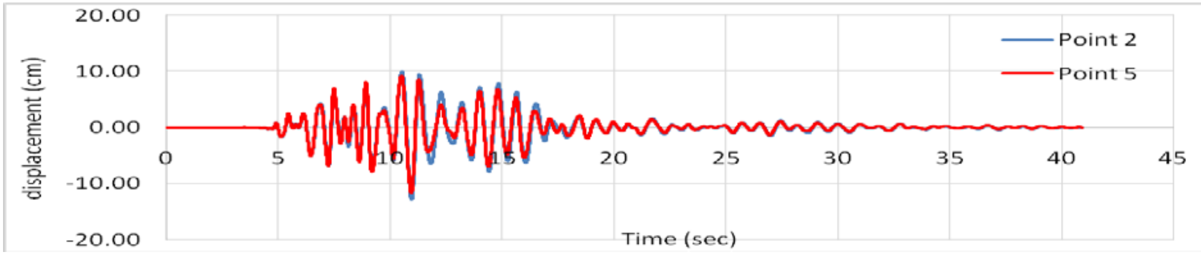


Fig. 5- Horizontal displacement histories of points 2 and 5 at 5-story buildings subjected to Kobe FF earthquake

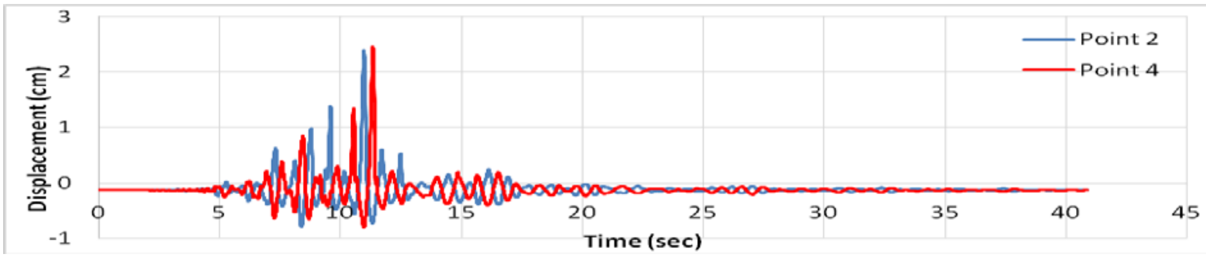


Fig.6- Vertical displacement histories of points 2 and 4 at 5-story buildings subjected to Kobe FF earthquake

Looking at Fig. 5 one can realize that the two cells of the 4-cell structure have moved during the earthquake very similarly. Also Fig. 6 shows that the corresponding cell has done rocking motion. For comparing the responses of the conventional buildings with their 4-cell rocking counterparts their responses are compared in the following figures. Figs 7 to 9 show samples the roof horizontal displacement histories of 5-story buildings subjected to four of the employed earthquakes.

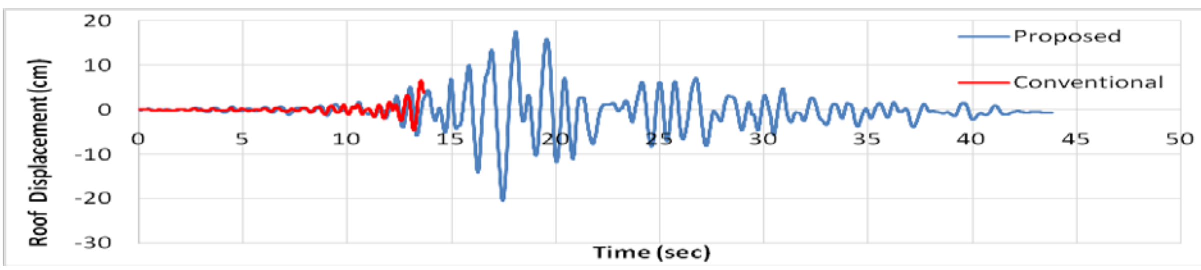


Fig. 7- Roof horizontal displacement histories of 5-story buildings subjected to Landers FF earthquake

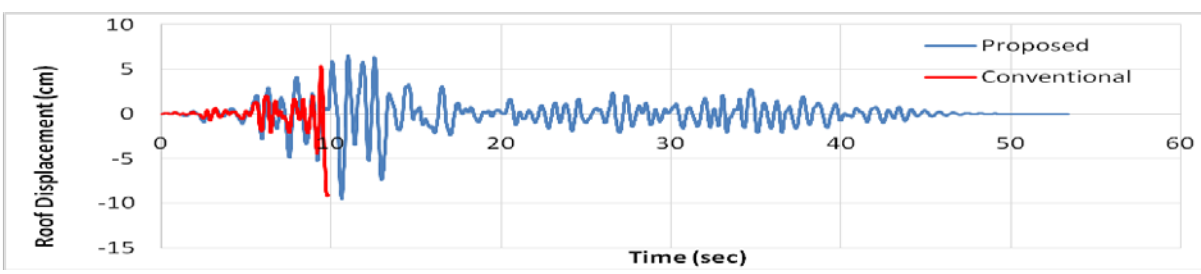


Fig. 8- Roof horizontal displacement histories of 5-story buildings subjected to Manjil FF earthquake

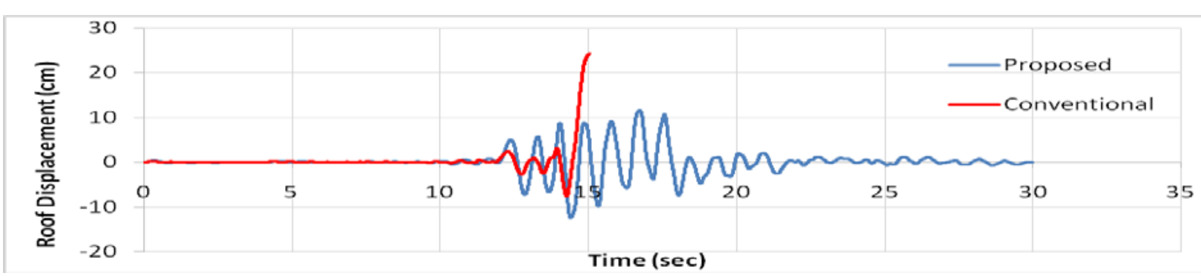


Fig. 9- Roof horizontal displacement histories of 5-story buildings subjected to Kocaeli FF earthquake

It is seen in Figs 7 to 9 that the conventional buildings have not been able to tolerate any of the employed earthquakes till their end instant, while proposed 4-cell rocking buildings have sustained the earthquake excitations in all cases. Figs 10 to 12 show samples of the roof horizontal acceleration histories of the 8-story buildings to two of the employed earthquakes, and Fig. 13 shows a sample of the vertical roof acceleration history of the 8-story buildings to one of the employed earthquakes. Results related to other buildings and other earthquakes cannot be presented here because of the brevity.

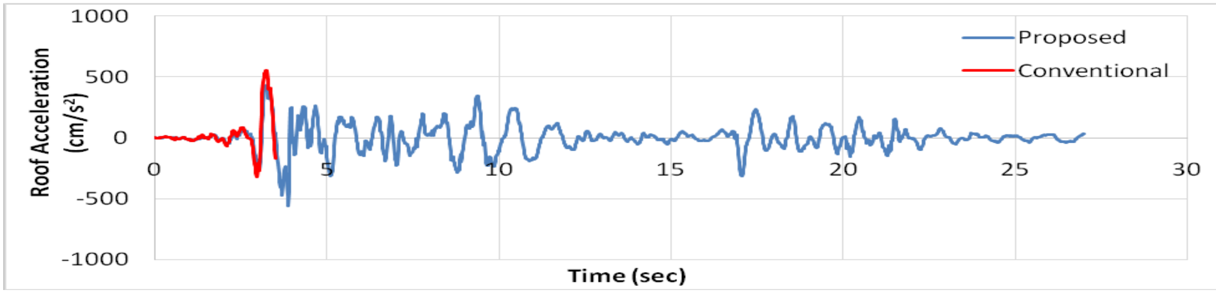


Fig. 10- Roof horizontal acceleration history of 8-story buildings subjected to Cape Mendocino NF earthquake

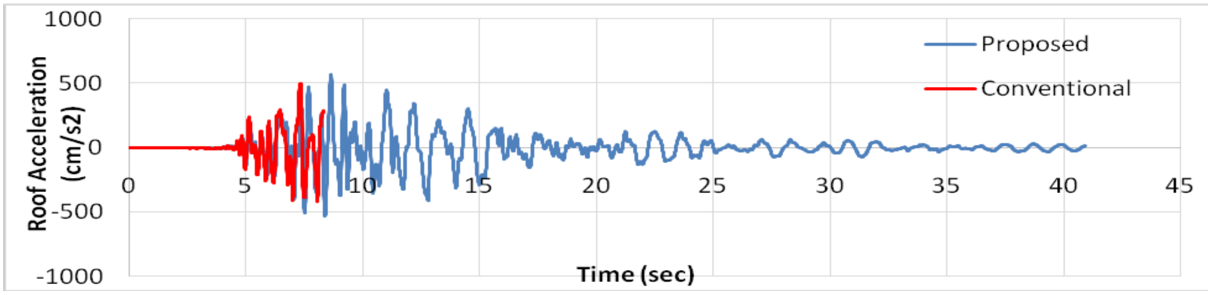


Fig. 11- Roof horizontal acceleration history of 8-story buildings subjected to Kobe FF earthquake

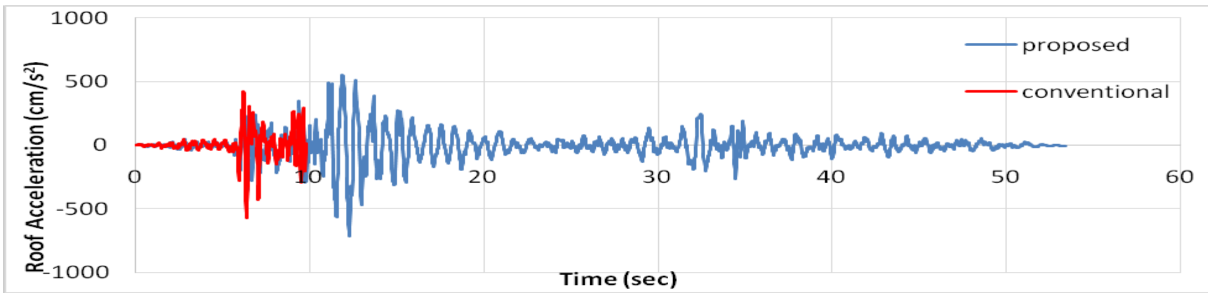


Fig. 12- Roof horizontal acceleration history of 8-story buildings subjected to Kocaeli FF earthquake

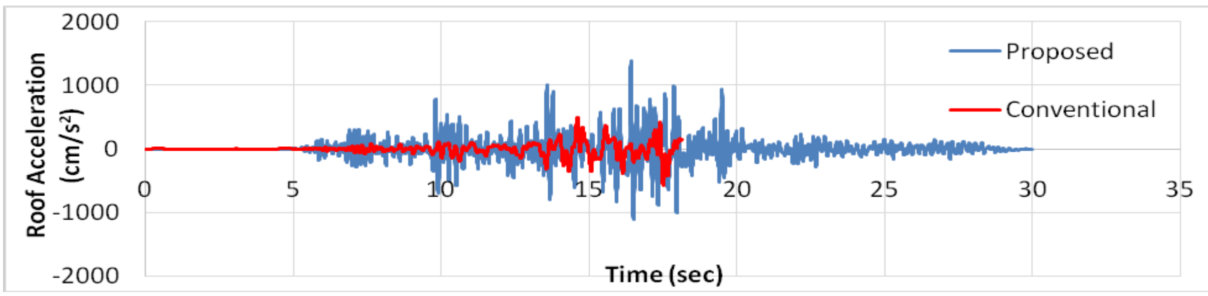


Fig. 13- Roof vertical acceleration history of 8-story buildings subjected to Kocaeli FF earthquake

It is observed in Figs 10 to 12 that the roof horizontal acceleration values are higher in conventional buildings (till the instant they have tolerated the earthquake) than their corresponding values in the proposed rocking buildings. However, as Fig. 13 depicts, this is not the case with regard to the vertical acceleration. In fact, it can be said that in case rocking buildings, due to the collision between the bottoms of the lowest story columns to their foundations the amount of vertical acceleration can be higher than the horizontal acceleration. Figs 14 and 15 show samples of the base shear force time histories of the 5-story buildings subjected to two of the employed earthquakes.

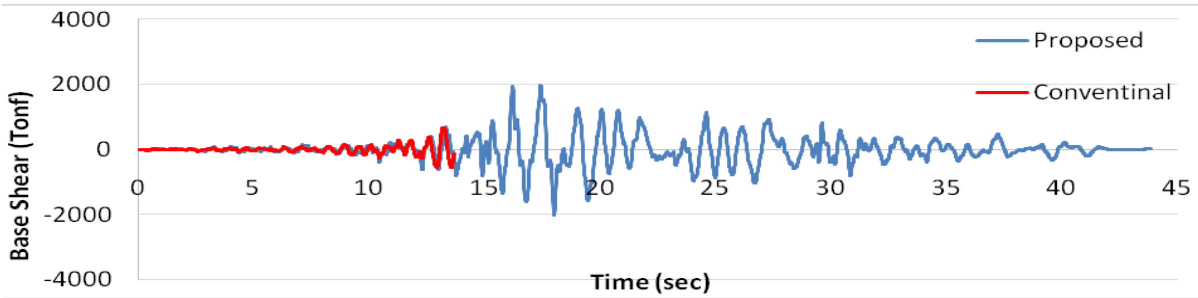


Fig. 14- Base shear force histories of 5-story buildings subjected to Landers earthquake

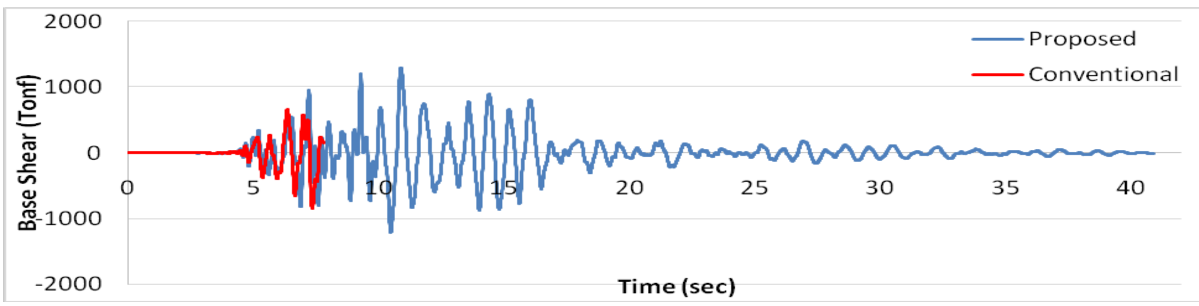
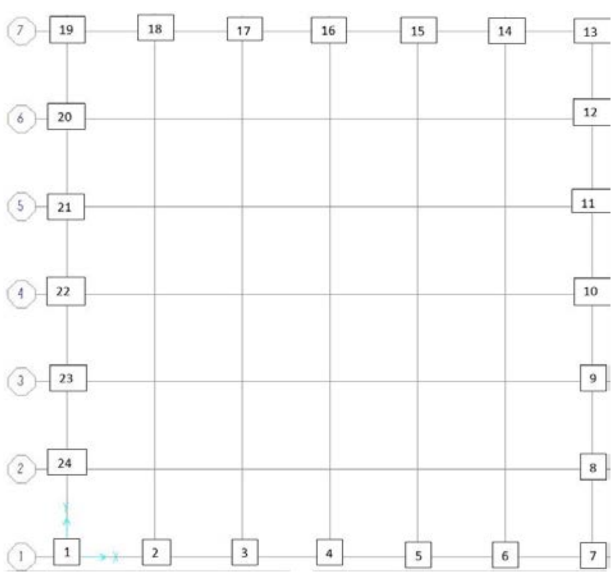


Fig. 15- Base shear force histories of 5-story buildings subjected to Kobe earthquake

It is seen in Figs 14 and 15 that the base shear forces of the conventional buildings are not necessarily more than those of their rocking counterparts, however, they have not been able to tolerate the applied earthquakes, contrary to their rocking counterparts. Energy dissipation distribution in the circumferential fuses is also a good index for satisfactory behavior of rocking buildings. Fig. 16 shows a sample of this distribution.



Link ID	Dissipated Energy (tonf.m)	Link ID	Dissipated Energy (tonf.m)
1	0.889	13	0.592
2	0.700	14	0.420
3	0.644	15	0.316
4	0.641	16	0.272
5	0.644	17	0.283
6	0.733	18	0.447
7	0.954	19	0.663
8	0.793	20	0.589
9	0.668	21	0.579
10	0.579	22	0.585
11	0.530	23	0.633
12	0.556	24	0.758

Fig. 16- Energy dissipation distribution in the circumferential fuses in one cell of the 5-story rocking building subjected to far-filed Landers earthquake

It is seen in Fig. 16 that there is an almost uniform energy dissipation distribution in the circumferential fuses. However, some differences are observed which are due to the three-component excitation of the building. Another important response measure for comparing the seismic performance of the two sets of buildings is the formation of plastic hinges at different performance levels (PLs) of Continuous Operation (CO), Immediate Occupancy (IO), LS, CP and Collapse (C). Figs 17 and 18 shows these plastic hinges in the 5-story buildings in cases of Kobe and Landers FF earthquakes, and Fig. 19 shows the same for Denali NF earthquake for comparison.

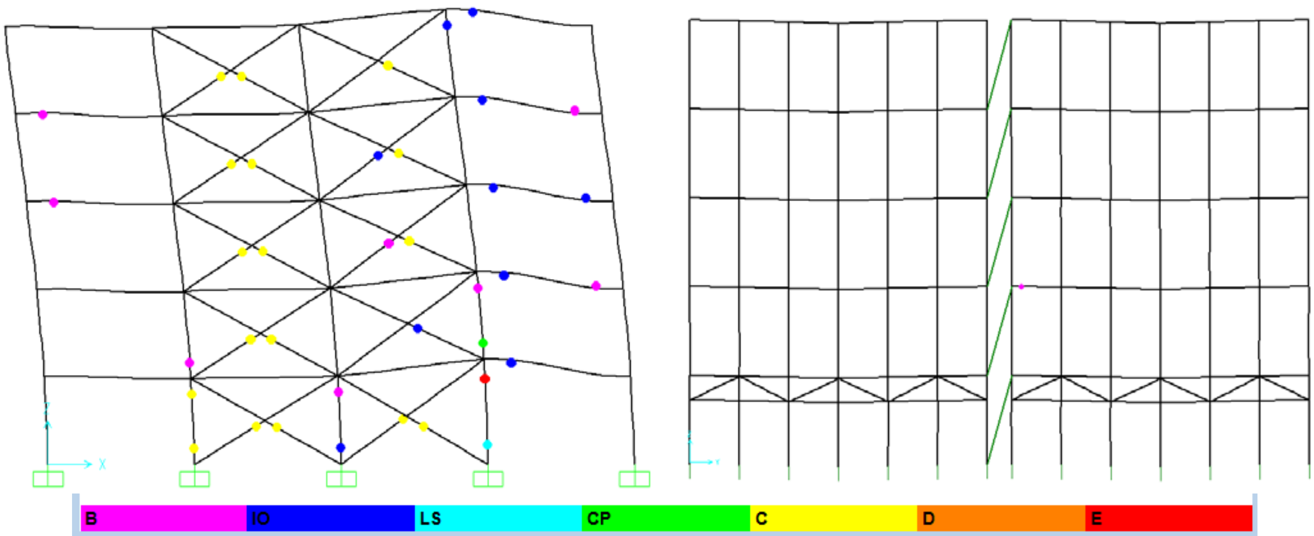


Fig. 17- Plastic hinges at various PLs in the 5-story buildings subjected to Kobe FF earthquake

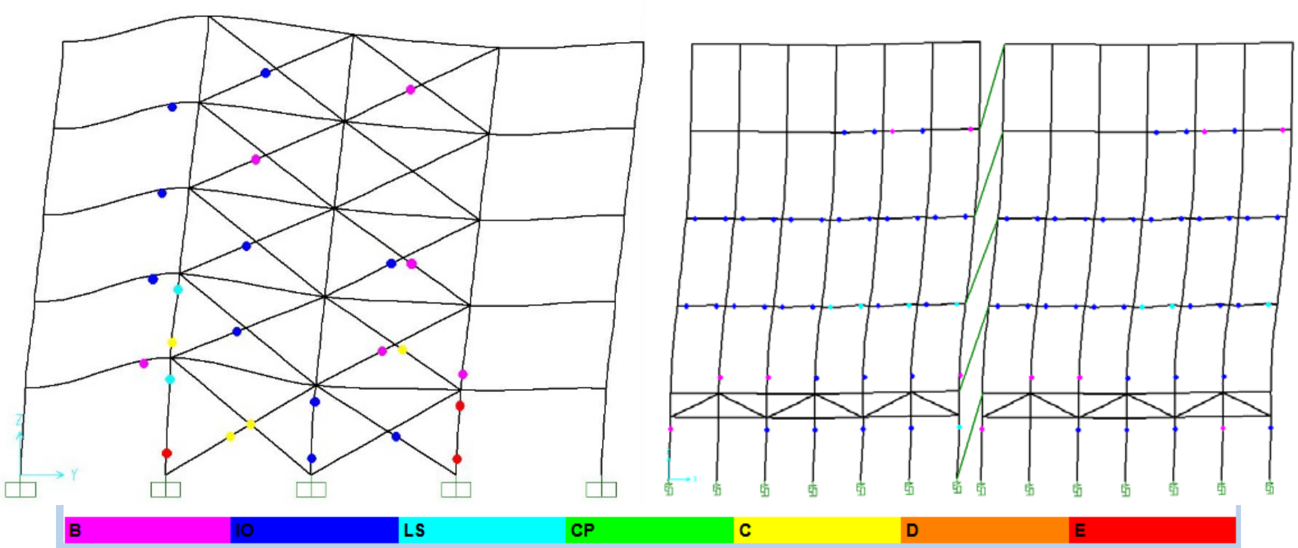


Fig. 18- Plastic hinges at various PLs in the 5-story buildings subjected to Landers FF earthquake

It is seen in Figs 17 and 18 that the plastic hinges at C level and beyond it have been created in the conventional building, while in the rocking building only a few hinges at CO or IO levels have been formed. Comparing Figs 17 and 18 with Fig 19, which is related to one of the NF earthquake, one can realize that NF earthquakes has more destructive effect on both conventional and rocking buildings, so that even some plastic hinges beyond the CP level can be formed in the rocking buildings, as shown in Fig. 19. The main reason behind this fact is the intense vertical ground acceleration in case of NF earthquakes. It is notable that no modification was applied to the cross-sectional properties of structural members of the rocking building to make it fully operational in case of NF earthquakes, while it seems quite possible to do that by just some minor modifications in corner columns at the lowest story.

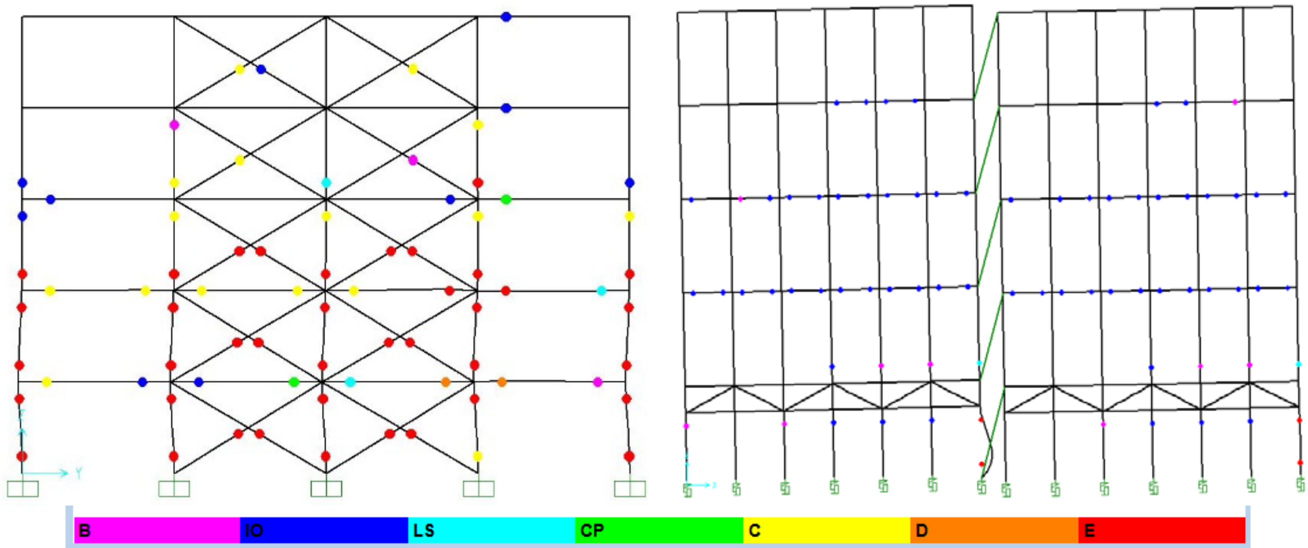


Fig. 19- Plastic hinges at various PLs in the 5-story buildings subjected to Denali Alaska NF No Pulse earthquake

As the last set of the numerical results the force-displacement hysteretic curves of the nonlinear links used at the base of all circumferential columns as well as between each two adjacent cells of the rocking buildings have been considered. Fig. 20 show one sample of each of these curves in case of 5-story rocking building subjected to Kobe earthquake.

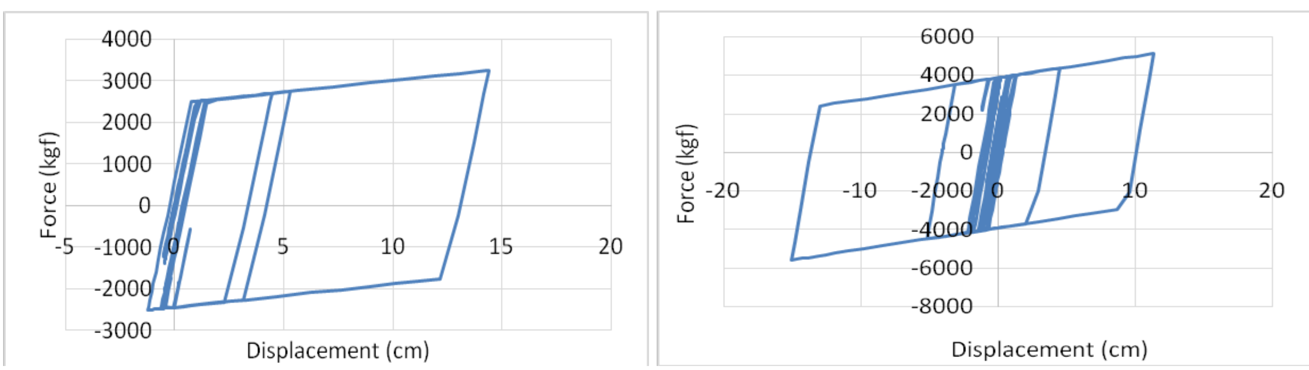


Fig. 20- The hysteretic curves of the nonlinear links used at the base of circumferential columns (left) as well as between adjacent cells of the 5-story rocking buildings subjected to Kobe earthquake

It is seen in Fig. 20 that the link at the bottom of circumferential columns has basically deformed in positive displacements, namely in movement of the columns' bottom upward and returning back to the corresponding foundation, while in the links between the adjacent cells deformations have been occurred in both positive and negative displacements, as expected.

4. Conclusions

Numerical results of NLTHA conducted on conventional and rocking buildings show that the proposed rocking structures can efficiently decrease the seismic responses of the buildings. Both drift values, which are responsible for structural damages, as well as horizontal acceleration values, which are responsible for damage to most of nonstructural components of the buildings are decreased by using the proposed rocking structural system. The amount of damage reduction in the building is usually significant, so that the plastic deformations happen only in the energy dissipators (nonlinear links), 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.

5. Acknowledgement

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