AN INNOVATIVE DESIGN FOR REPAIRABLE REGULAR STEEL BUILDINGS BY USING A 4-CELL CONFIGURATION STRUCTURE WITH SOME INCLINED COLUMNS AT BASE LEVEL, EQUIPPED WITH DOUBLE-ADAS DEVICES, AND SECURITY CABLES AT CORNERS

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ABSTRACT

Most of seismic design codes of buildings, in spite of collapse prevention, allow implicitly some unacceptable consequences, such as massive required reconstruction works, in large populated cities located near active faults. One preventing idea in this regard is 'Deliberate Directing of Damage', 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. This idea has been employed here for design of repairable regular steel multistory buildings, by using a 4-cell configuration structure with inclined columns around the central main vertical column of each cell at its base level. The inclined columns, with their bases shifted toward the central column, which cause the building to move basically in rocking mode, are equipped with Double-ADAS (DADAS) devices, and are connected to some strong girders at the first floor of the building. These girders help the upper floors to remain elastic, while the DADAS devices experience large plastic deformations to dissipate energy. At corners of the building at the base level some cables with initial slackness are used to make the building secure against overturning in case of excessive rocking motion. For performance evaluation of the proposed system, a set of 4-cell multistory buildings were considered, each cell being a space frame with a 2-bay×2-bay square 10m×10m plan, and having the proposed rocking mechanism. DADAS devices were considered in the inclined columns as well as between the cells along their height. The buildings were designed, once by conventional provisions, and once by using the suggested approach, and then were compared by nonlinear time history analysis using several 3-component accelerograms of selected earthquakes. Results show that the suggested design approach leads to a more reliable seismic behavior of buildings.

Keywords: Seismic design codes, Deliberate directing of damage, Nonlinear time history analysis

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1. INTRODUCTION

The philosophy behind most of seismic design codes implicitly accepts heavy damages of the building in case of large earthquakes, provided that the building is prevented against collapse. However, this philosophy, in case of large populated cities located in the vicinity of active faults, leads to unacceptable consequences, such as large number of people who lose their living or working places for a long time, very difficult demolishing work of the heavily damaged buildings, and very large volume of the required reconstruction works.

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 the first author (Hosseini and Alyasin 1996), 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, and therefore, the structure can be easily repaired. Although this technique has been introduced basically for pipelines, researchers have introduced and worked on similar ideas for other types of structures, particularly building systems, among them using the energy dissipating devices or structural fuses can be mentioned, which have been introduced in late 70s to early 80s (Fintel and Ghosh 1981), and have been developed more in recent years (Vargas and Bruneau 2006). It should be noted that in these studies, although the main 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). 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). Although their proposed rocking structural system is quite effective is seismic response reduction, their studies is limited to 2-dimensional systems. Recently, the first author of this paper has used the idea of rocking motion of building in combination with a central fuse, which works as a huge plastic hinge under the vertical load and the moment, induced by the lateral seismic load (Hosseini and Kherad 2013).

In this study the DDD idea has been employed for design of regular steel multistory buildings, which have rocking motion, by using inclined columns around the central main vertical column of the building at its base level. The inclined columns, which their bases have been shifted toward the center of the building plan and cause the building to move basically in rocking motion during an earthquake, are equipped with Double-ADAS (DADAS) devices (Hosseini and Bozorgzadeh 2013), which play the main role of energy dissipating devices or fuses. The inclined columns are connected to the strong beams of the first floor of the building, whose strength and relatively high stiffness help the upper floors of the building to remain elastic, while the DADAS devices experience large plastic deformations and absorb large amounts of seismic input energy. At corners of the building at the base level some cables with initial slackness are used to make the building secure against overturning in case of excessive rocking motion. In this way, the building will have more reliably the IO PL after major earthquakes. The efficiency of the proposed technique has been shown through implementation in some high-rise hybrid steel buildings. Details of the study are given in the following sections.

2. THE BUILDINGS CONSIDERED IN THE STUDY

A set of 4-bay multistory buildings, with square plan, in a 4-cell arrangement, have been considered, with 5, 8, 11 and 14 stories. Each cell, being a space frame with a 2-bay×2-bay square10m×10m plan, have the proposed rocking mechanism. The DADAS devices have been considered in the inclined columns at the lower story as well as between the cells along their height, as shown in Figure 1.

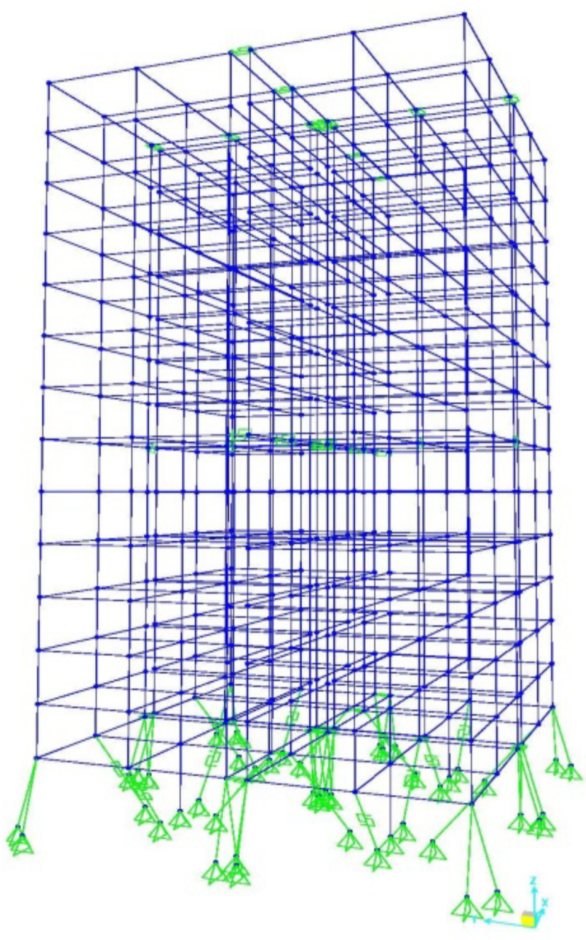

Figure 1: A sample of the multi-story 4-cell buildings used in this study

The buildings have been designed, once based on the conventional provisions, and once based on the suggested approach, by using the inclined columns at their lower story, equipped with DADAS devices. A sample of the used DADAS devices is schematically shown in Figure 2.

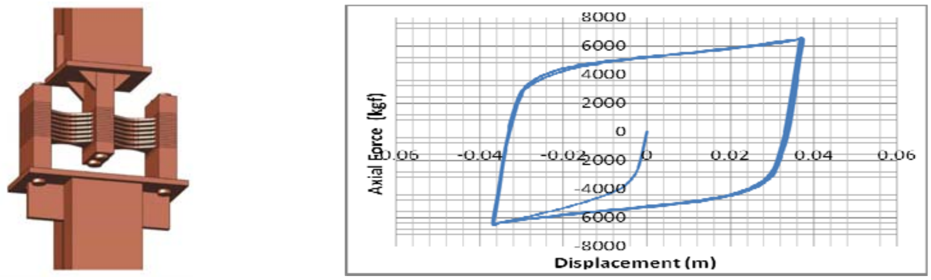

Figure 2: A sample of the DADAS devices used in the inclined columns and between the four cells of each building, and a sample of their hysteretic loop

For using the DADAS devices between the building's cells they have connected to the building cells by hinge connections to prevent them from bending effects. The proposed rocking system cause the building structure to have larger fundamental period comparing to the conventional system, as shown in Table 1, for the case of 8- and 14-story buildings.

Table 1: The fundamental periods (in seconds) of the 8- and 14-story buildings with conventional and the proposed structural systems

8-Story buildings		14-Story buildings	
Conventional	Proposed	Conventional	Proposed
1.22	1.70	1.91	2.6

This increase in the buildings' fundamental periods, in turn, generally leads to lower seismic response values, particularly acceleration response, as discussed in the following section.

3. NONLINEAR TIME HISTORY ANALYSES OF THE BUILDINGS

The considered buildings have been analyzed by nonlinear time history analysis, subjected to several 3-component accelerograms of selected earthquakes, covering a specific range of frequency content and PGA values, compatible with the assumed site conditions. The acceleration spectra of the used accelerograms are shown in Figure 3, and some response samples in Figures 4 to 9.

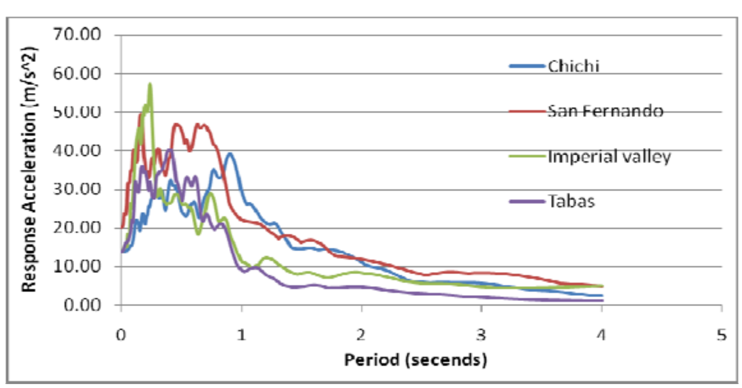

Figure 3: Acceleration response spectra of the selected earthquake records, with 5% damping

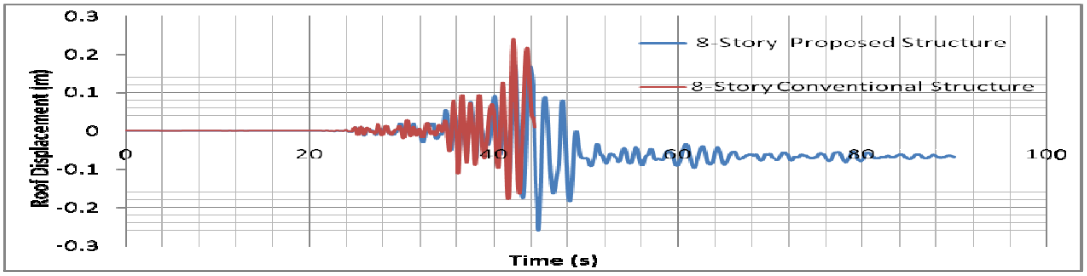

Figure 4: Roof displacement histories of the 8-story buildings subjected to Chichi earthquake

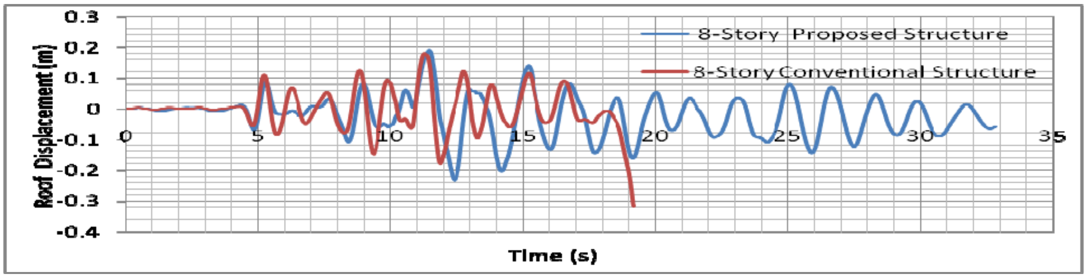

Figure 5: Roof displacement histories of the 8-story buildings subjected to Tabas earthquake

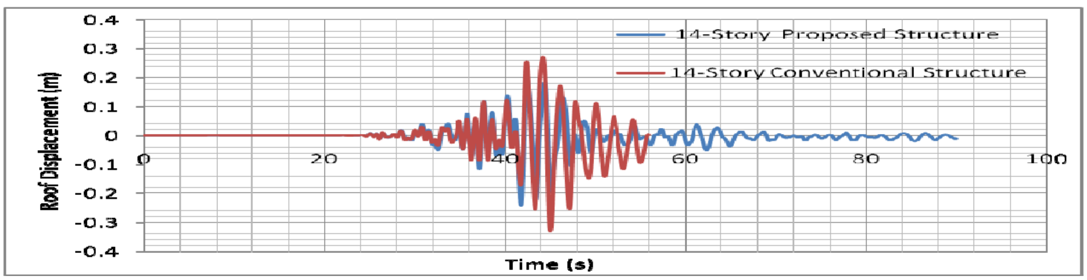

Figure 6: Roof displacement histories of the 14-story buildings subjected to Chichi earthquake

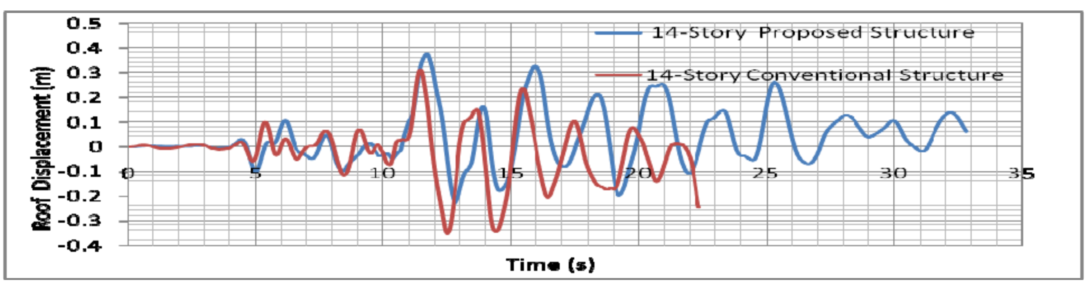

Figure 7: Roof displacement histories of the 14-story buildings subjected to Tabas earthquake

It can be seen in Figures 4 to 7 that in conventional buildings the time history has not continued till the end of earthquake, since the calculations has not been converged due to the system instability (failure), while the proposed systems have withstood till the end of the record. Of special interest is the acceleration response, which is important because of the nonstructural elements. Figure 8 shows the roof acceleration histories of the 8-story buildings subjected to Tabas earthquake (more results of this type can be found in the main report of the study (Bozorgzadeh 2013)).

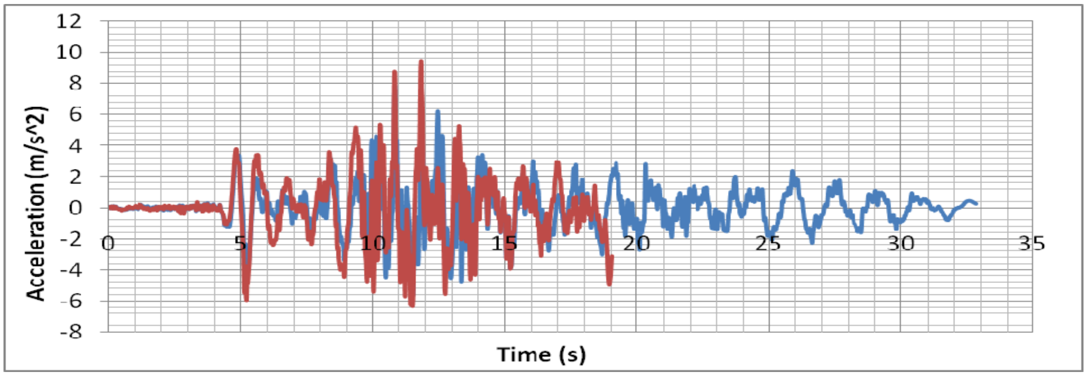

Figure 8: Roof acceleration histories of the 8-story conventional (shorter duration response) and proposed (longer duration response) buildings subjected to Tabas earthquake

It is seen in Figure 8 that not only the maximum response values of the proposed systems are lower, but also again in conventional buildings the time history has not continued till the end of earthquake, due to the system instability (failure), while the proposed systems have withstood till the end of the earthquake. To see this response reduction a little better, the maximum roof acceleration values for the 8- and the 14-story buildings with the conventional design and with the proposed rocking structural system are compared in Tables 2 and 3 for Chichi and Tabas earthquakes.

Table 2: Maximum roof acceleration values (m/s^2) in main directions of the 8- and 14-story buildings with conventional and proposed systems subjected to Chichi earthquake

Direction	8-Story buildings		14-Story buildings	
	Conventional Structure	The Proposed Structure	Conventional Structure	The Proposed Structure
X	7.15	5.07	6.35	5.69
Y	7.14	5.25	6.42	5.70

Table 3: Maximum roof accelerations values (m/s^2) in main directions of the 8- and 14-story buildings with conventional and proposed systems subjected to Tabas earthquake

Direction	8-Story buildings		14-Story buildings	
	Conventional Structure	The Proposed Structure	Conventional Structure	The Proposed Structure
X	9.45	7.76	7.02	6.56
Y	9.45	7.87	8.55	6.61

Another very important index of the performance improvement of the buildings is the number of plastic hinges in various PLs. Figures 9 and 10 show the number of plastic hinges in IO PL and beyond it, created in the buildings, subjected to Chichi and Tabas earthquakes.

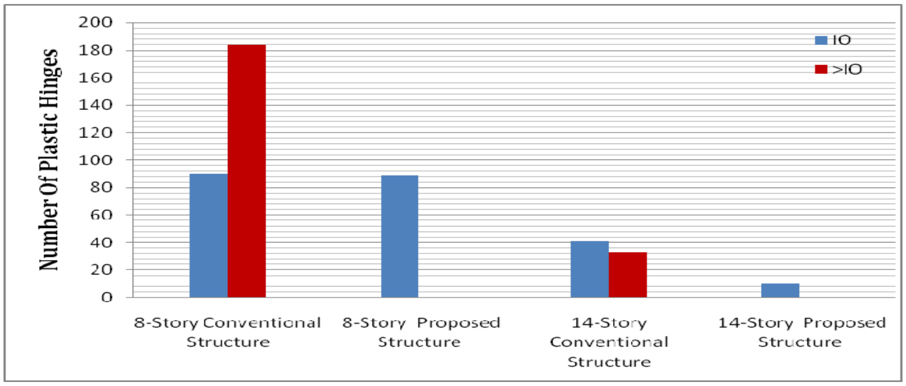

Figure 9: Number of plastic hinges in IO PL and over it in 8- and 14-story buildings subjected to Tabas earthquake

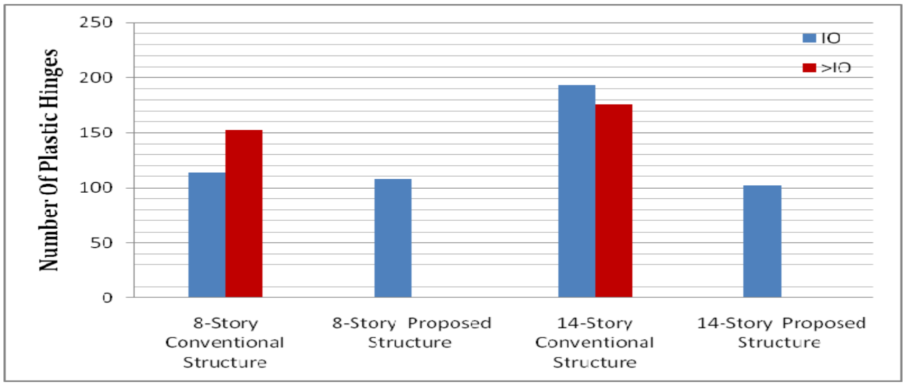

Figure 10: Number of plastic hinges in IO PL and over it in 8- and 14-story buildings subjected to Tabas earthquake

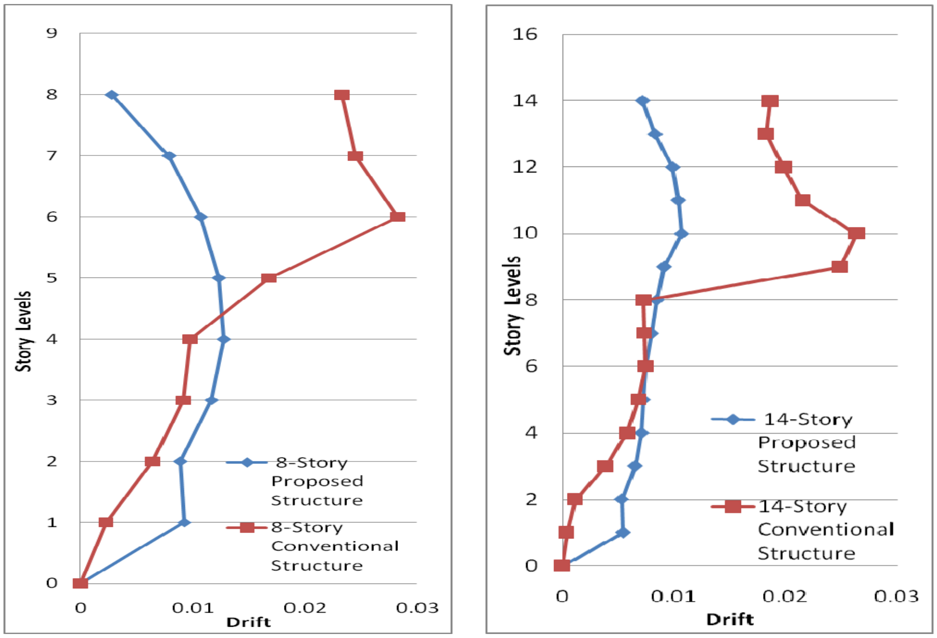

Figure 11: Maximum drift values in 8- and 14-story buildings subjected to Tabas earthquake

As the last set of results, the stories drift values in the buildings with both structural system, subjected to Chichi and Tabas earthquakes are shown in Figure 11. It is seen that in buildings with conventional design the drift values is some specific stories go beyond the expected limits, resulting in the building collapse, while in the proposed rocking systems the drift values are almost the same in the building height, and there is no abrupt changes in their values.

4. CONCLUSIONS

Based on the numerical results the following conclusions can be stated:

- The suggested design approach, resulting in a structural building system in which the rocking motion is facilitated by inclined energy dissipating columns, equipped with DADAS devices, leads to a more reliable seismic behavior of buildings so that plastic deformations happen only in the DADAS devices at ground floor, and just a few hinges at the IO PL appear in other parts of the building structure.
- The achieved rocking motion leads to longer period values and, therefore, lower acceleration values in the building which not only results in reduction of the seismic forces imposed to the building, but also helps higher safety level of nonstructural elements in the whole building.
- As the DADAS devices are easily replaceable after the earthquake, the proposed rocking system equipped with DADAS devices can be highly recommended as an innovative seismic design of future building system in earthquake prone areas.

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