The Performance of High-rise Buildings with Specific Energy Absorbing Stories

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SUMMARY:
Design of tall buildings bases on Life Safety Performance Level (PL) means that the building is permitted to get heavily damaged in case of a large earthquake. However, there are some alternative seismic design approaches which lead to higher performance levels such as Immediate Occupancy (IO). In this paper a design approach by using Specific Energy Absorbing Stories (SEAS) has been applied to a 40-story steel regular building with square plan, and the seismic performance of the designed building has been compared with that of an ordinary building with the same geometry, designed based on the conventional approach. Nonlinear Time History Analyses have been used for seismic evaluation of the buildings. Results show that the proposed approach by SEAS lead to a much more reliable design which fulfill the criteria of IO PL, while the ordinary building behave much lower than this PL.

Key Words: Pall friction damper, Nonlinear dynamic analysis, Performance level, Circumferential frames

1. INTRODUCTION

When a big earthquake occurs in the vicinity of a large and populated city the inhabitants may face such huge human challenges which are hardly manageable. In such conditions giving services to the large groups of users/inhabitants of the heavily damaged tall buildings, for which lots of money and time have been spent to be built, is nearly impossible. On the other hand, demolition and reconstruction of such buildings will be very difficult, time consuming and costly. This means that the design philosophy of the seismic design codes, which permits the building to get heavily damaged in the case of big earthquakes, is not logical. Furthermore, tall buildings are usually occupied by many residents/users and, practically, by preventing them from damages the depth of human calamity of earthquake will be diminished and, as a result, the possibility of giving more services to other earthquake-stricken people will be provided. Therefore, it seems much better in seismic design of tall buildings that the Performance Level (PL) is considered to be Immediate Occupancy (IO) instead of Life Safety (LS).

In order to design the buildings for IO PL, one way is using the energy absorption techniques, so that the main structural elements remain almost intact, or at least, easily repairable. In this regard, several methods have been proposed by different researchers so far. Miyama in 1992 and then Harada and Akiyama in 1998 conducted some research on energy absorbing system in the upper floors and steering the earthquake's energy towards that story. Tsai (1995) has performed a research on TPEA device as seismic damper for high-rise buildings. Also Shiba and his colleagues (1998) have discussed control systems for tall buildings. Ou (2001) has investigated the behavior of composite steel plate yielding energy dissipation and its effectiveness on absorbing seismic vibration of steel tall buildings. McNamara (2003) has studied the energy damping systems in high-rise buildings with a concentration on fluid viscous dampers. Zhou (2004) has worked on the use of high-efficiency energy absorbing device to arrest progressive collapse of tall building.

In the present study the focus is on a 40-story building, considered as a high-rise, and there has been an attempt to design it by considering a few Specific Energy Absorbing Stories (SEASs), which do not have architectural function, but can be used for placing parts of mechanical and electrical facilities of the building in addition to the seismic energy absorber elements. At first a ordinary building structure, which consists of a circumferential tubular framing, equipped by Bucking Restrained Braces (BRBs), as the lateral load bearing system, and simple inner columns for carrying the gravity loads, has been designed in ETABS environment based on the conventional design provision. Then, it has been analyzed by Perform-3D software, subjected to a set of selected earthquakes, taking into account the nonlinear behavior of its structural elements. In the next step, the alternative structural system of the building has been developed, in which the SEASs been considered at every five story, where the friction dampers of the Pall type have been used as the energy absorbing elements. The alternative structure has been modeled and analyzed again by the same procedure to realize if the alternative building structure can meet the criteria of the IO PL. Details of the study are given in the following sections of the paper.

2. INTRODUCING THE BUILDING AND ITS STRUCTURAL DESIGN

The plan of the 40-story building, considered in this study, is a symmetrical one having 5 bays of 5 m span in each direction, as shown in Figure 1, in which the directions of the floor gravity loads distribution are also indicated by arrows.

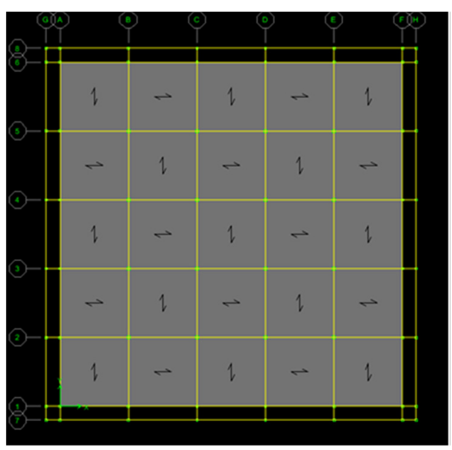

Figure 1. The plan of the considered 40-story building and its floor gravity loads distribution directions

In Figure 1 the circumferential tubular framing, which has been used as the lateral load bearing system of the building structure, is also shown. There has been assumed to be a space of one meter between the circumferential framing and the stories floors, which have been considered to act as rigid diaphragms. The stories floors are connected to the circumferential framing with some links at each floor level as shown in Figure 1. The general as well as the close-up views of the proposed building structure is shown in Figure 2.

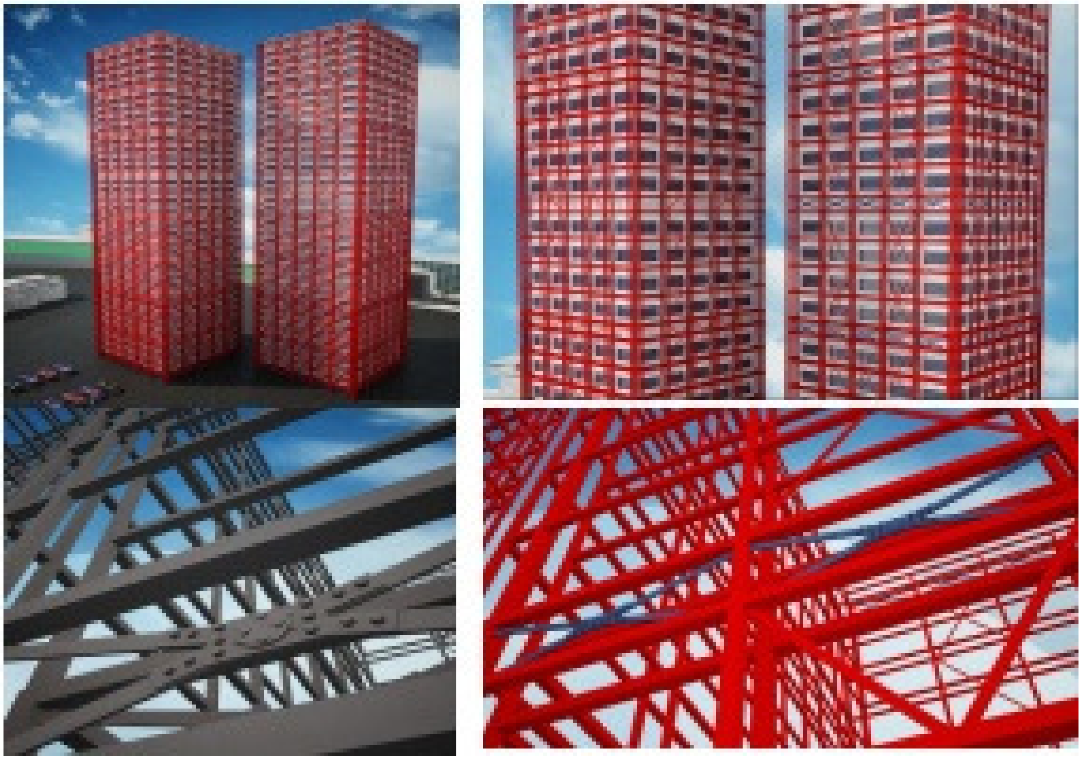

Figure 2. General and close-up views of the proposed structural system of the building

Considering the height of the structure the P-Δ effect has been taken into account in its design. Since the fundamental period of the structure has been more than 0.7 seconds, the design has been controlled by inter-story drift ratio, which has been limited to 0.02.

3. THE FRICTION DAMPERS USED IN THE BUILDING

Taking into consideration all kinds of available dampers in the market, the decision was made to use friction dampers and out of all kinds of friction dampers including Somitomo, Tekton, Belev, Mulla, Smolen, Pall, etc., the Pall friction damper was selected (http://www.palldynamics.com, accessed January 2012) as shown in Figure 3.

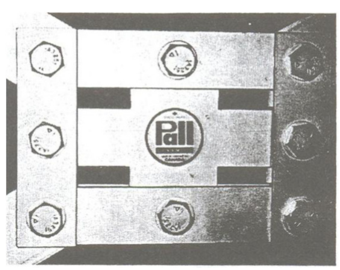

Figure 3. Pall Friction Damper (Friedriechs 1997)

The point to be mentioned with regard to this type of dampers is to get the critical load to start utilizing dampers on each floor and their activation at the appropriate instant during the earthquake. This has been determined by trial and error based on some initial guess for the amount of triggering load for each group of dampers at every floor level. In this process two pints should be kept in mind. First point is related to the amount of dissipated energy by dampers, which should be much more than the amount dissipated by the structural elements. Second point is about the amount of slippage. In this regard Filiatrault and Cherry (1993) have shown that with a change of 20% in the amount of the slippage optimum load of the friction dampers no considerable change occurs in the structure general response. In order to model the brace equipped with friction damper in Perform-3D software, a simple bar element in series with a non-linear bar have been used.

4. NUMERICAL RESULTS AND DISCUSSION

To show the effect of using SEAS on the seismic behavior of the building, a set of Nonlinear Time History Analyses (NLTHA) have been performed on the two designed buildings. For this purpose the accelerograms of three selected components of Chi-Chi, Kobe, and Cape Mendocino earthquakes, have been used whose dominant frequencies are, respectively, lower than 1 Hz, between 2 and 5 Hz, and above 10 Hz, which correspond, respectively to soft, medium, and stiff soils. A sample of the used records is shown in Figure 4, which corresponds to the Kobe earthquake.

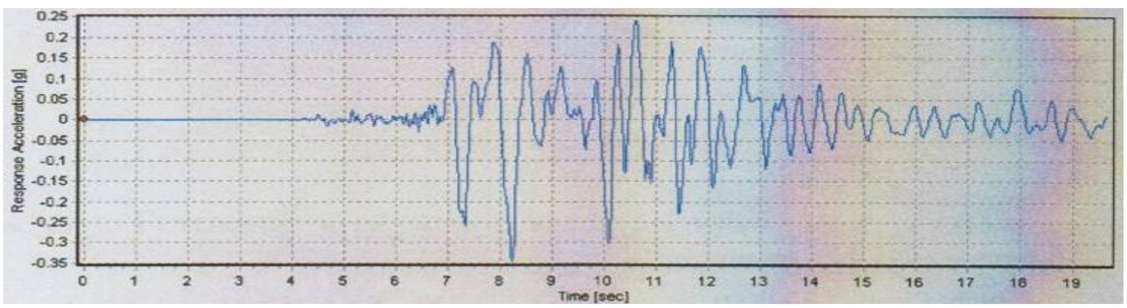

Figure 4. Accelerogram of the selected component of Kobe earthquake for NLTHA

Other used records and their response spectra can be found in the main report of the study (Keihani 2012), and can not be shown here because of lack of space. As the Perform 3D software can show the percentage of the absorbed energy in each set of structural elements, including beams, columns, BRBs, and dampers, it is easily possible to compare the this percentage in the two buildings. Figure 5 show this comparison in case of Kobe earthquake.

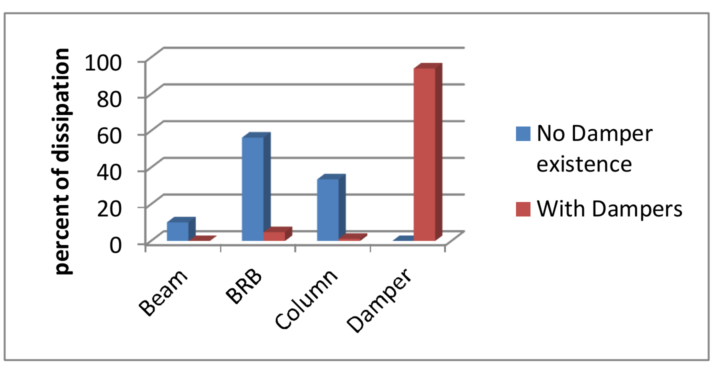

Figure 5. The energy absorption percentage in the two buildings' elements in case of Kobe earthquake

It can be seen in Figure 5 that in the ordinary building the BRBs have absorbed around 56% of the energy, and columns and beams have also taken part in energy absorption by, respectively, around 33% and 11%. Absorption of more that 30% of the energy by columns in the ordinary building means the high level of damage in these elements. This is while in the building with SEAS more than 90% of the energy has been absorbed by the friction dampers, and all other elements together have absorbed only less than 10% of the whole energy. In case of other two used earthquake similar results have obtained (Keihani 2012), which show that the design reliability level in case of building with SEAS is much higher than the ordinary building.

The Perform 3D software is also capable to indicate the PL as well as the Demand over Capacity Ratio (DCR) of each element in the structure based on the NLTHA. Therefore, it is easily possible to realize which elements of the building have not satisfied the criteria of the desired PL in any analysis case. On this basis, Figures 6 to 8 show the performance history of the ordinary building subjected to the three used earthquakes, along with the LS and IO levels of performance for various element groups, including columns, beams, BRB elements in the normal stories, as well as BRB elements in the short-height stories (shown by BRBsh in the figures).

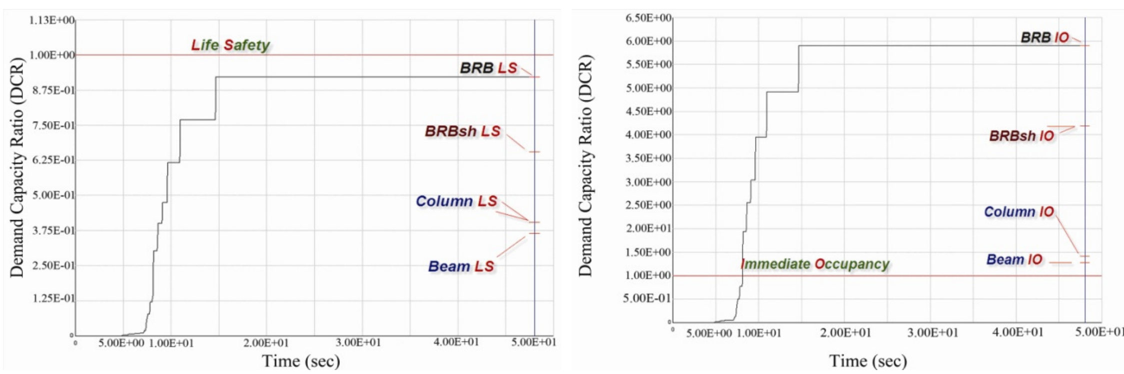

Figure 6. DCR time histories of the ordinary building subjected to Kobe earthquake in LS and IO performance levels

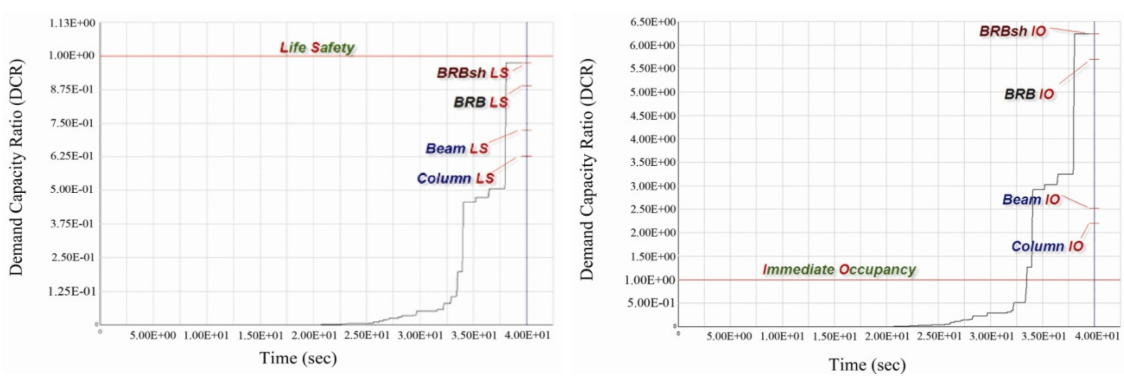

Figure 7. DCR time histories of the ordinary building subjected to Chi-Chi earthquake in LS and IO performance levels

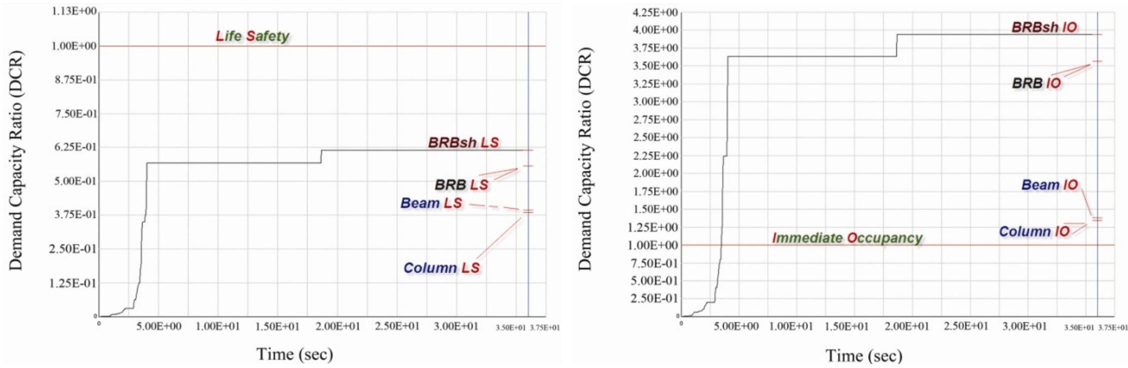

Figure 8. DCR time histories of the ordinary building subjected to Cape Mendocino earthquake in LS and IO performance levels

It is seen in Figures 6 to 8 that the ordinary building has satisfied the criteria of LS PL in case of all three used earthquake, while none of its element groups have been able to satisfy the criteria of IO PL. Figures 9 to 11 show the performance history of the building with SEAS subjected to the three used earthquakes, along with the IO level of performance for various element groups, including columns, beams, BRB elements.

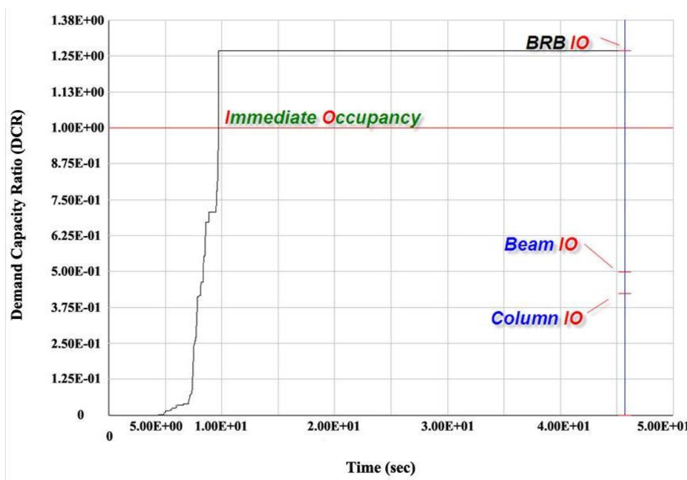

Figure 9. DCR time histories of the building with SEAS subjected to Kobe earthquake in IO PL

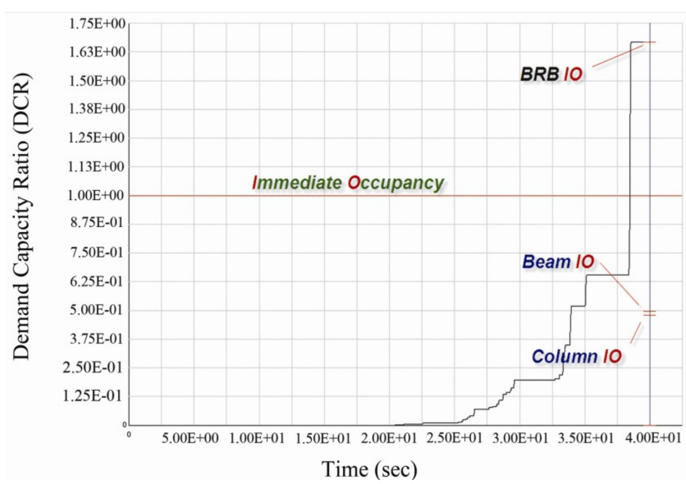

Figure 10. DCR time histories of the building with SEAS subjected to Chi-Chi earthquake in IO PL

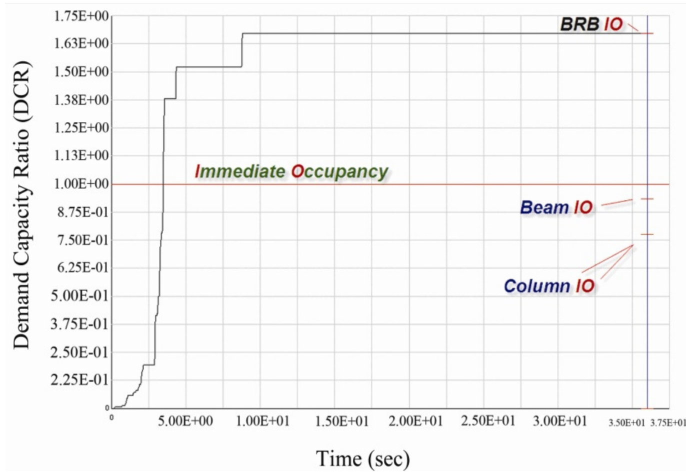

Figure 11. DCR time histories of the building with SEAS subjected to Cape Mendocino earthquake in IO performance level

It can be seen in Figures 9 to 11 that in the building with SEAS only a few of the BRB elements (considering the energy absorption percentage of BRBs in caparison with dampers, shown in Figure 5) have not been able to fulfill the criteria of the IO PL, while the DCR values for the two other groups of elements, particularly columns, are far below one. This means that there is no case of damage to beams and columns in the building with SEAS, subjected to the three used earthquakes. It is worth mentioning that since the BRBs are just in the circumferential tubular framing, the replacement of the few damaged BRBs, after a big earthquake, is not a difficult task. This means that the building with SEAS is easily repairable, even after large earthquakes.

Another good indicator for comparing the performance of the two buildings is the hysteresis of their BRB elements. Figures 12 and 13 show samples of the hysteresis of BRBs in the two buildings subjected to Kobe earthquake.

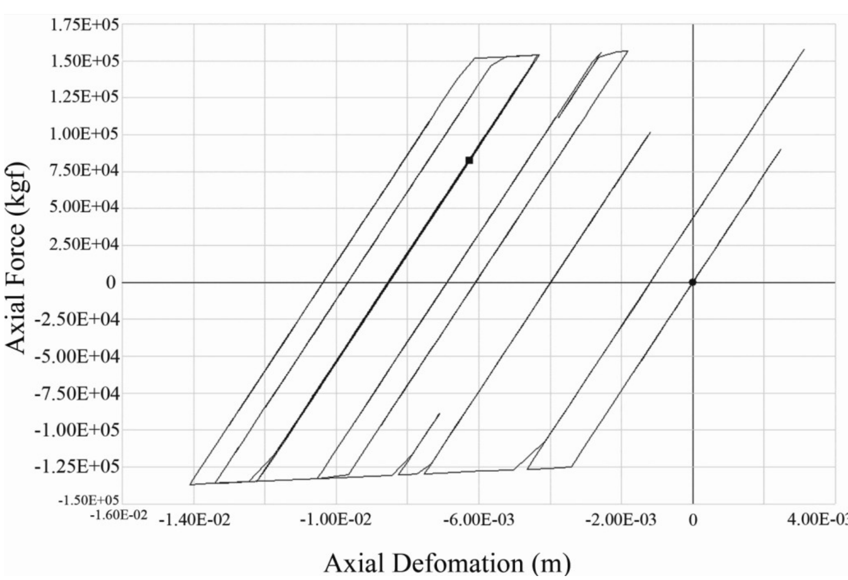

Figure 12. A sample hysteresis diagram of BRBs in the ordinary building subjected to Kobe earthquake

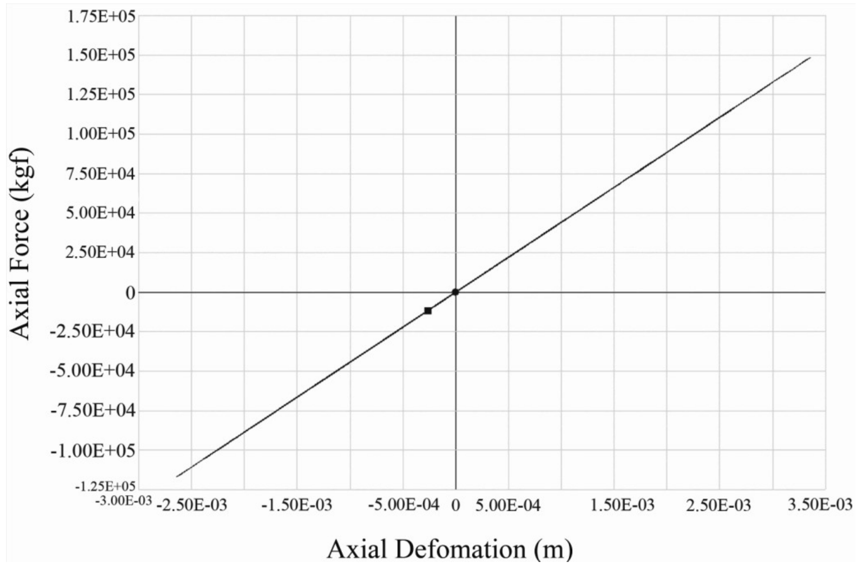

Figure 13. A sample hysteresis diagram of BRBs in the structure with SEAS subjected to Kobe earthquake

It is seen in Figures 12 and 13 that the BRBs in the ordinary building have experienced large plastic deformations, while in the building with SEAS they have remain elastic. Absorption of energy by friction dampers can be seen in Figure 14, which shows a sample hysteresis of the friction dampers in the building with SEAS in case of Kobe earthquake.

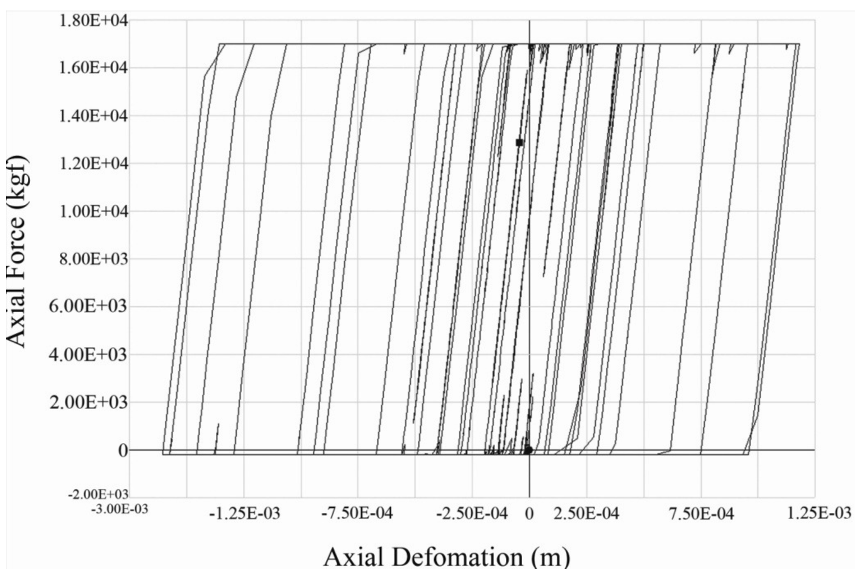

Figure 14. A sample hysteresis diagram of Pall dampers in the building with SEAS subjected to Kobe earthquake

The stable hysteretic behavior of friction dampers can be seen in Figure 14. The superiority of this situation compared to the ordinary building is that the damper does not collapse after consecutive cycles and it is ready to work in the next earthquake, but the BRBs have to be replaced after a big earthquake.

Finally, it is notable that the drift ratio in any story of the building with SEAS, subjected to any one of the used earthquakes, does not exceed the amount of 0.02, which is in accordance with the seismic design regulations. It is also worth mentioning that the friction dampers in the building with SEAS start performing properly with a drift lower than 0.8% (Malhotra et al 2004). This happened in cases of all three used earthquakes in this study.

5. CONCLUSIONS

Based on the numerical results it can be said that the use of Specific Energy Absorption Stories in tall buildings is a reliable approach for achieving the design of buildings in such a way that they can be easily repaired, even after large earthquakes. On this basis it is strongly recommended that this approach is followed in design and construction of high-rise buildings in large and populated cities locating in the vicinity of active faults.

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