# Behavior Evaluation of the Eccentric Buckling-Restrained Braced Frames Under the Near-Fault Ground Motions

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**SUMMARY:**
Near-fault earthquakes have different properties compared to far-fault earthquakes because of forward-directivity, long-period pulses and fling-step motions. Application of systems with high ductility and energy absorption subjected to near-fault earthquakes is inevitable. Buckling-restrained braced frames have high magnitude of energy absorption. Usual configuration of these systems is concentric. Application of ductile beam splices and buckling-restrained braces in eccentric configurations make possibility to use architectural benefits of eccentrically braced frames and also design benefits of buckling-restrained braced frames. In addition to the properties of the eccentric buckling-restrained frames, the system has simple repair after an earthquake because the structural damages concentrate in the braces. Evaluation of performance of these braced frames subject to near-fault ground motions is the aim of this study. Results indicate that eccentric buckling restrained braced frames for high seismicity regions and subject to near-fault ground motions have better dynamic performance compare to eccentrically braced frames.

*Keywords: Eccentric buckling restrained brace; Incremental inelastic dynamic analysis; Near fault earthquake*

## 1. INTRODUCTION

In the past years a number of near fault earthquakes, such as Northridge (1994), Kobe (1995), Izmit and Duzce, Turkey (1999), Chi-Chi, Taiwan (1999), and Bam, Iran (2003) have been occurred. These earthquakes and their effect on the structures led the researchers to evaluate the effect of different near-fault earthquake characteristics on the structural response behaviour. It is interesting to note that the near-fault is not a new subject and initially after Pacoima, San Fernando earthquake (1971) was introduced by Bolt (Bolt, 2004). The extensive damage of structures even designed with the seismic regulations and provided a large ductility in the nonlinear behaviour of structures subjected to the near-fault showed the importance of near-fault ground motions. The effects of the near-fault ground motions and pulse waves are still not properly known. However, some of regulations tried to include their effects in the design spectrum as well as constructional details. The previous studies show that the near-fault ground motions can cause extensive structural damages compare to the far-fault ground motions. Concentration of energy in short interval and in pulses of near-fault ground motions cause impulsive movement.

Different structural system has been used in order to prevent large lateral deformations of steel frames. Use of bracings as additional structural members to increase the stiffness, energy dissipation and control of relative inter story deformation is recommended by different seismic codes.

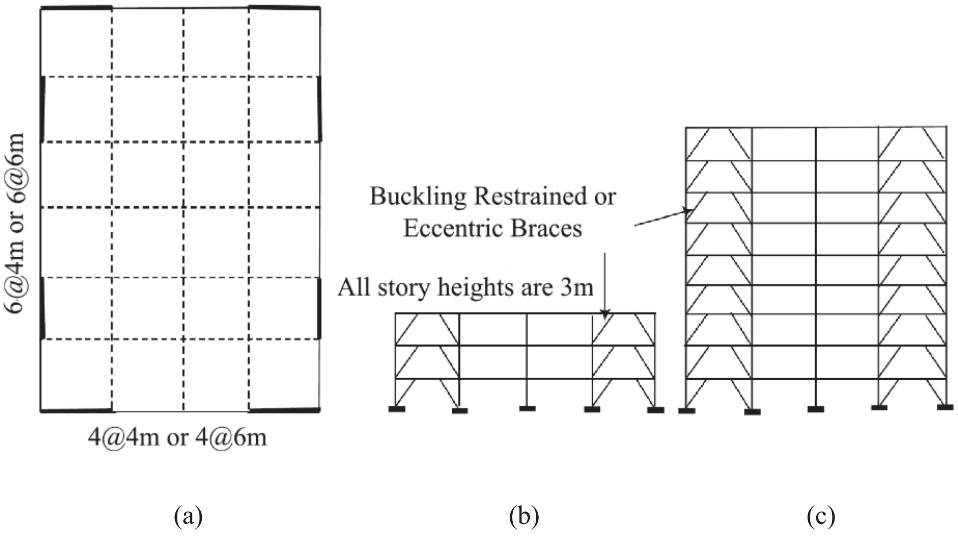
The concentric brace frame can induce some architectural problems but eccentrically braced frame (EBF) is used extensively because of its architectural benefits. If EBF system has been designed accurately, frame and the elements except link beam remain in elastic region and so inelastic deformation is limited to link beam while subject to strong earthquake loading. In general structures which are earthquake resistant using concentrically steel bracing frame, maximum of energy dissipation occurs when the brace element is subjected to tension and yielding of this element led to high energy dissipation. But when the brace element is subjected to compression, it buckles before yielding point and not only energy is not dissipated but also the structure sometimes will be unstable because of brittle buckling. In order to solve this problem, a brace system has been used in Japan thirty years ago. In this bracing system, the deformable steel core is covered by concrete. The function of the concrete is to act as a restraining mechanism for the core to prevent buckling. This system which is called buckling resistant brace (BRB) have symmetric hysteresis curve under both tension and compression loads. The general concentric configuration of BRB does not provide architectural aims; hence using BRB in eccentric configuration is effective.

Prinz (Prinz, 2010) suggested that BRBs can be used in eccentric configuration to get architectural consideration as well. In systems with buckling-restrained braces in eccentric configurations (BRBF-Es), brace element provide lateral stiffness of steel frame and are design to undergo large inelastic axial deformations, and link beam should remain elastic, while, transferring ultimate brace forces into the columns. Prinz have also studied and compared EBF and BRBF-E frame buildings with 3, 6 and 9 stories with two bays of 6.1 and 9.14 metres. Their Results showed that BRBF-Es are an appropriate alternative to the EBF. In addition may result in better design economy than EBFs. Buckling resistant brace has simple repair after an earthquake because the structural damages concentrate in the braces and not in the link beam.

In this study the dynamic performance of BRBF-Es suggested by Prinz are re-examined and compared with EBFs under near-fault and far-fault ground motions. To gain the aim, the incremental inelastic dynamic analyses of 2D frames with different height (3- and 9-story) and length of span (4m and 6m) subject to real near-fault earthquakes are performed. Parameters such as input energy to the systems, and average maximum inter story drift for near-fault and far-fault strong ground motions are compared. The IDA curves for EBF and BRBF-E systems under the selected near-field ground motions are summarized based on statistical methods and the different performance levels are pointed out for both the systems.

## 2. SYSTEM

In this study a building plan as shown in the figure-1is considered. The 3 and 9 stories with 4 bays of 4 and 6 meters steel frames are selected with EBF and BRBF-E systems. In order to compare the seismic behaviour of EBF and BRBF-E performances, firstly the EBF systems with shear link were designed, and then BRBF-Es were designed to have equal story strength as EBF systems. Beam splices in BRBF-Es where modeled as fully pinned connections (Prinz, 2008). St37 steel was used. The geometry of frames is shown in figure 1.



(a) (b) (c)

**Figure 1.** EBF and BRBF-E systems (a) building plan (b) 3 stories frame (c) 9 stories frame

Free vibration analysis of the selected frames was performed and the first mode periods for EBF and BRBF-E frames are showed in table 2.1.

**Table 2.1**. Fundamental period of the systems

| story | System | Bay width | |
|---|---|---|---|
| | | 4m | 6m |
| 3 | EBF | 0.38 | 0.4 |
| | BRBF-E | 0.41 | 0.42 |
| 9 | EBF | 0.95 | 0.96 |
| | BRBF-E | 1 | 1.03 |

## 3. GROUND MOTIONS

Seven near-fault and seven far-fault real earthquake ground motion records on the soil type were selected to carry out the incremental dynamic analysis of system models. Fault-perpendicular component of the ground accelerations were selected. A brief description of the near-field and far-field earthquake ground motions is provided in table 3.1 and table 3.2.

**Table 3.1.** Near-field ground motions (PEER)

| Record | Station | PGA (g) |
|---|---|---|
| Morgan hill | Gilroy array 6 | 0.292 |
| Loma Prieta | LGPC | 0.563 |
| Northridge | LA dam | 0.511 |
| Kobe | KJMA | 0.599 |
| Kocaeli | Arcelike | 0.149 |
| Tabas | Tabas, Iran | 0.795 |
| Abhar | Manjil, Iran | 0.509 |

**Table 3.2.** Far-field ground motions (PEER)

| Record | Station | PGA (g) |
|---|---|---|
| Loma Prieta | Fremont | 0.192 |
| Loma Prieta | APEEL 2E Hayward Muir | 0.171 |
| Loma Prieta | Hayward - BART Sta | 0.159 |
| Northridge | Inglewood - Union Oil | 0.101 |
| Northridge | LA - Baldwin Hills | 0.239 |
| Kocaeli | Mecidiyekoy | 0.68 |
| Kern Country | Taft Lincoln School | 0.178 |

## 4. ANALYTICAL PROCEDURE

In order to carry out the analyses, the incremental dynamic analysis of frames is performed. Peak ground acceleration (PGA) and maximum story drift ($\theta_{max}$) are selected as intensity measure (IM) and damage measure (DM) respectively. A point on the IDA curve which has 20% slope of elastic region or its maximum inter story drift which is 10% (which one is occurred earlier), is selected as Collapse Prevention (CP) limit state and a point which elements (link or BRB) start to behave nonlinear, is selected as Immediate Occupancy (IO) (Trica, 2009). Because of lack of design standards and specified values of limit states for BRBF-E systems, in this section, the limit states have been determined and compare to the EBF systems. IDA curves for each structure are summarized into their 16, 50, and 84% fractile IDA curves and using statistical methods, the limit states are indicated on these curves.

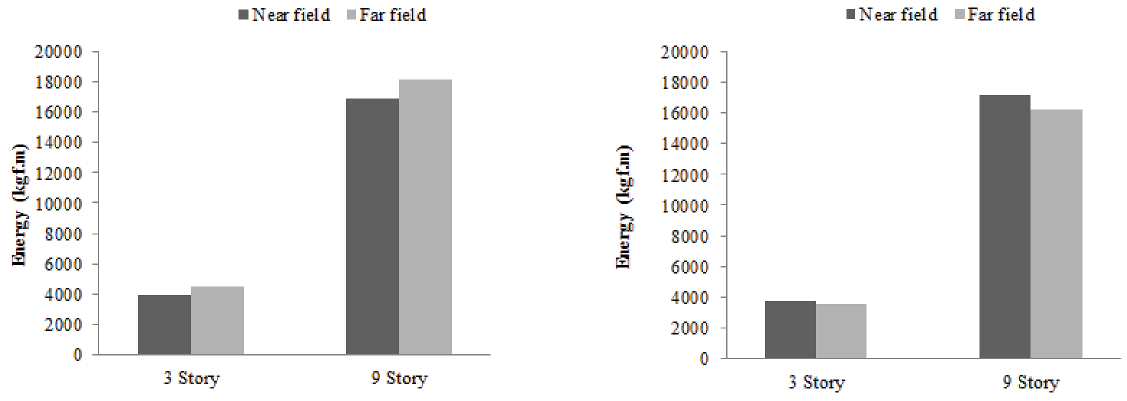
## 5. NUMERICAL ANALYSIS AND DISCUSSION

In order to evaluate the dynamic performance of BRBF-E systems, these systems have compared to EBF systems. Firstly, earthquake input energy to both systems subject to near-field and far-field ground motions have studied for different values of PGA. Secondly, average maximum inter story drift of the systems for different values of PGA and finally, the dynamic limit states for EBF and BRBF-E systems are pointed out. The discussion of the results of the above parameters is given as the following:

### 5.1. Evaluation of the input energy

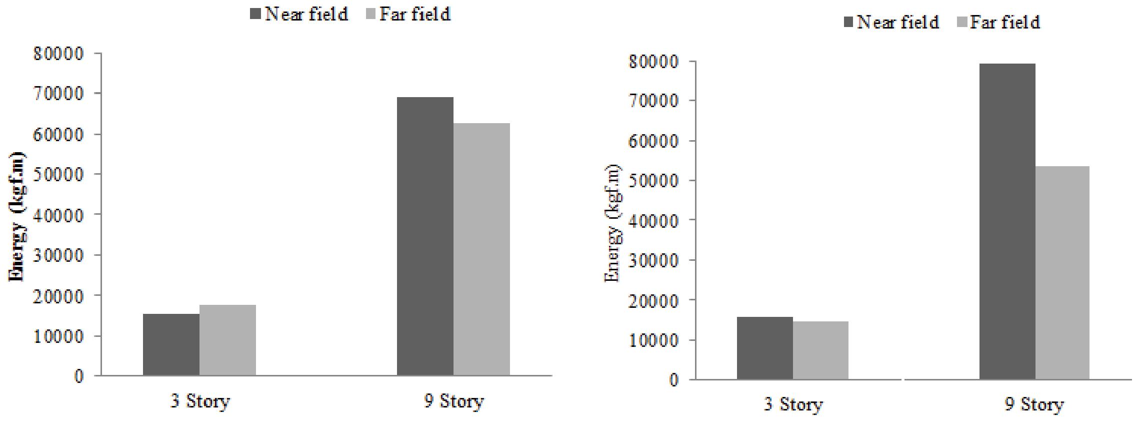
The input energy to structure under earthquake is a function of time, and for comparison performance of different systems subjected to earthquake ground motions, one can compare the input energy at any time step or the cumulative input energy of systems. Structure performance based on input energy at any time step is different because of nonlinear behaviour of systems, variability of frequency content of earthquake at every moment and the period variation of the system during the earthquake; on the other hand cumulative input energy have more concept in the design of the building and earthquake engineering. Hence in this paper the cumulative input energy to the structures is used to evaluate them.

The average of cumulative input energy to the 3- and 9-story EBF and BRBF-E frames with bay width of 4m, for the peak ground acceleration (PGA) values of 0.3g, 0.6g and 1.0g and for near-field and far-field ground motions are showed in figure 2 through figure 4.



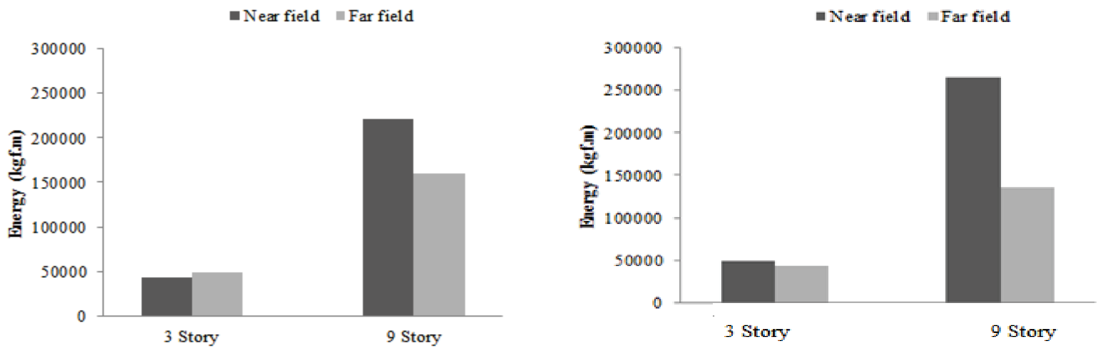
(a) (b)

**Figure 2.** The average of cumulative input energy to the 3 and 9 stories, for the PGA values of 0.3g: (a) BRBF-E system (b) EBF system



(a) (b)

**Figure 3.** The average of cumulative input energy to the 3 and 9 stories, for the PGA values of 0.6g: (a) BRBF-E system (b) EBF system



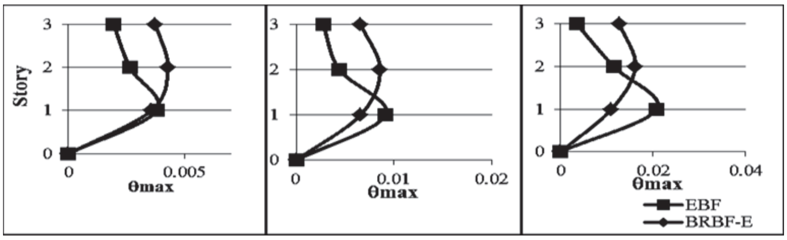
(a) (b)

**Figure 4.** The average of cumulative input energy to the 3 and 9 stories, for the PGA values of 1.0g: (a) BRBF-E system (b) EBF system

According to the Figures the average input energy will increase by increase of period and especially this increase will be more obvious with increase of the PGA. The input energy to the system for near-field ground motions, especially for long periods and higher values of PGA, is more than far-field earthquakes as expected. The input energy to the 9-story EBF frame have much difference as can be seen in the figure 5-b. In the 3-story frames the average input energy to the EBF and BRBF-E systems do not have much difference, but this difference is significant for 9-story building. EBF and BRBF-E systems have little difference in the average input energy for lower magnitude of the PGA, and by increase of the PGA the average input energy to the EBF frames, especially for near- field ground motions is more than BRBF-E frames. The difference of the nonlinear behaviour of the elements of the systems of EBF and BRBF-E bracing is the main reason of the difference of average input energy to the frames

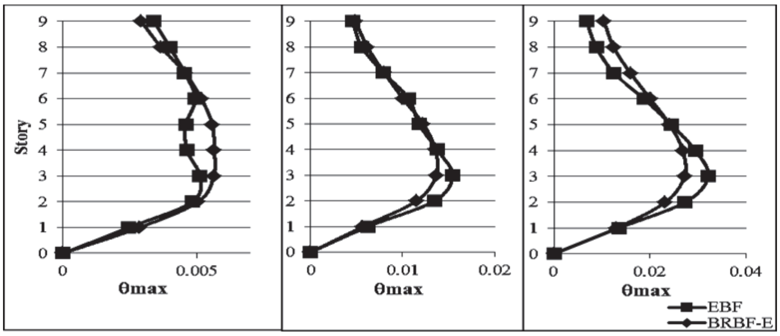
### 5.2. Average maximum inter-story drift for EBF and BRBF-E systems

The average maximum inter-story drift for far-field and near-field ground motions in the PGA values of 0.3g, 0.6g and 1.0g, is compared for the EBF and BRBF-E bracing systems in this section. The results for the EBF and BRBF-E systems under near-field earthquakes are showed in figure 5 through figure 8 and under far-field earthquakes are showed in figure 9 through figure 12. From the comparison of the EBF and BRBF-E systems it is seen that for lower magnitudes of PGA that the structures are elastic, average maximum inter-story drift for BRBF-E systems is more than EBF systems. But by increasing of PGA, when the structure goes into inelastic range, the average maximum inter-story drift for EBF systems is more than BRBF-E systems. Frames with two different bracing systems are designed to have equal story strength, hence the EBF systems had better performance for lower magnitude of PGA but for higher magnitude of PGA the BRBF-E systems had better performance than EBF systems. The difference of average maximum inter-story drift for 3story frames is significant for EBF and BRBF-E systems, but for 9-story frames the difference is not considerable. These variations are constant by increase of the bay width.



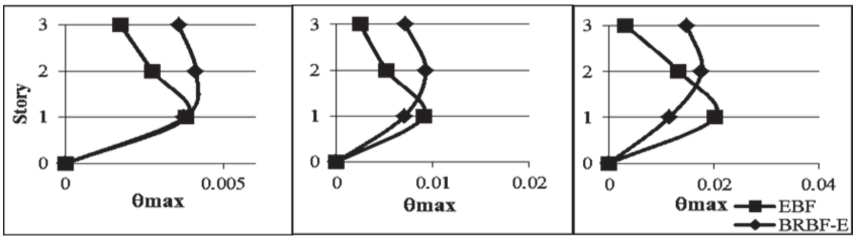
(a) (b) (c)

**Figure 5.** Average maximum inter-story drift for 3-story EBF and BRBF-E systems with 4m bay width under near-field earthquakes for (a) PGA=0.3g (b) PGA=0.6g (c) PGA=1.0g



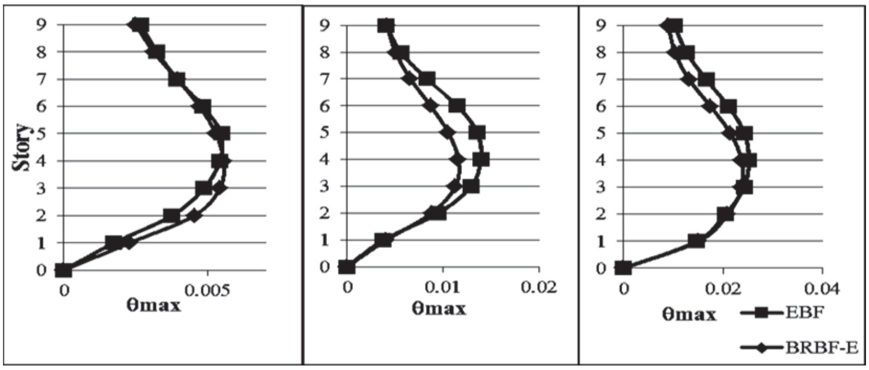
(a) (b) (c)

**Figure 6.** Average maximum inter-story drift for 9-story EBF and BRBF-E systems with 4m bay width under near-field earthquakes for (a) PGA=0.3g (b) PGA=0.6g (c) PGA=1.0g



(a) (b) (c)

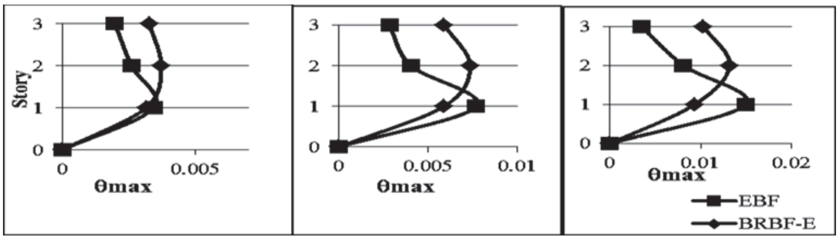
**Figure 7.** Average maximum inter-story drift for 3-story EBF and BRBF-E systems with 6m bay width under near-field earthquakes for (a) PGA=0.3g (b) PGA=0.6g (c) PGA=1.0g



(a) (b) (c)

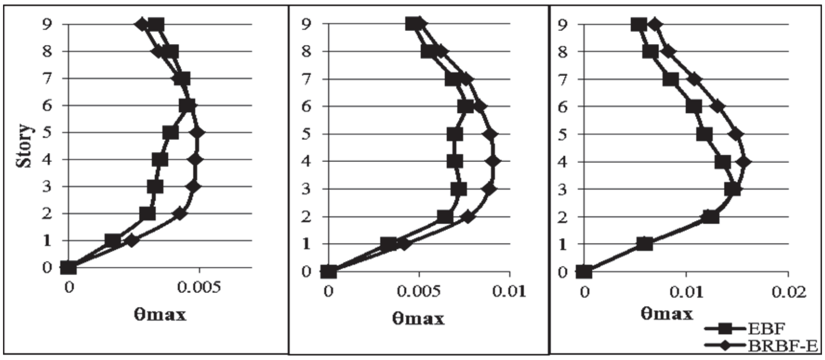
**Figure 8.** Average maximum inter-story drift for 9-story EBF and BRBF-E systems with 6m bay width under near-field earthquakes for (a) PGA=0.3g (b) PGA=0.6g (c) PGA=1.0g

Variations of maximum inter-story drift are different for far-field ground motions for different magnitudes of PGA. Average maximum inter-story drift for EBF is lower that BRBF-E. Difference of Average maximum inter-story drift of EBF and BRBF-E systems are negligible However, EBF performance is partially better than BRBF-E. Variation of bay width does not show the significant effect on the response of the system for far- field ground motions.



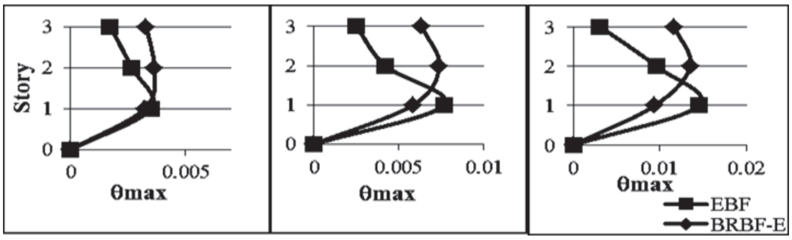
(a) (b) (c)

**Figure 9.** Average maximum inter-story drift for 3-story EBF and BRBF-E systems with 4m bay width under far-field earthquakes for (a) PGA=0.3g (b) PGA=0.6g (c) PGA=1.0g



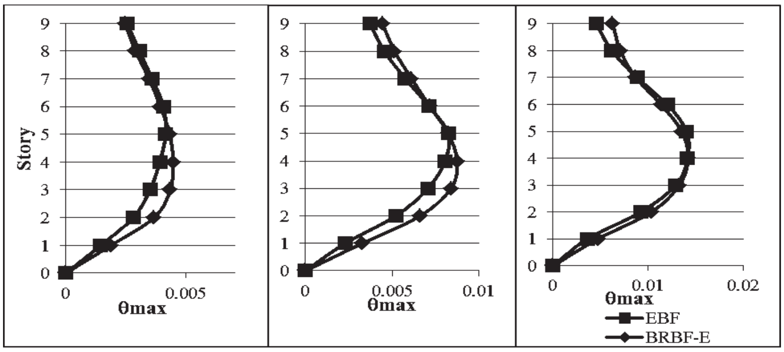
(a) (b) (c)

**Figure 10.** Average maximum inter-story drift for 9-story EBF and BRBF-E systems with 4m bay width under far-field earthquakes for (a) PGA=0.3g (b) PGA=0.6g (c) PGA=1.0g



(a) (b) (c)

**Figure 11.** Average maximum inter-story drift for 3-story EBF and BRBF-E systems with 6m bay width under far-field earthquakes for (a) PGA=0.3g (b) PGA=0.6g (c) PGA=1.0g



(a) (b) (c)

**Figure 12.** Average maximum inter-story drift for 9-story EBF and BRBF-E systems with 6m bay width under far-field earthquakes for (a) PGA=0.3g (b) PGA=0.6g (c) PGA=1.0g

In this part of study, it can be seen that in 3 story frames with BRBF-E systems have lower average maximum inter story drift than EBF systems. But for 9 story frames, there is not considerable difference between BRBF-E and EBF. Thus using BRBF-E systems is preferable especially when the system is subjected to near-field earthquake ground motions.

### 5.3. IDA analysis

The 16%, 50% and 84% fractile IDA curves of frames with 4m bay weight subjected to near-field ground motions are shown in figure 13 through figure 16 and the limit state are determined in table 5.3.1 through table 5.3.4. In all figures, *, ○ and Δ show IO, LS and CP limit states respectively.
By comparison of the limit states for 3 story frames whit EBF and BRBF-E systems which are shown in table 5.3.1 and table 5.3.2, it is obvious that BRBF-E system has better performance and reaches to limit states for higher magnitude of $\theta_{max}$. For example in EBF system, at 50% fractile IDA curve, the CP limit state occurred in PGA of 1.3g and $\theta_{max}$ of 0.028 but in BRBF-E system, at 50% fractile IDA curve, the CP limit state occurred in PGA of 3.08g and $\theta_{max}$ of 0.068.

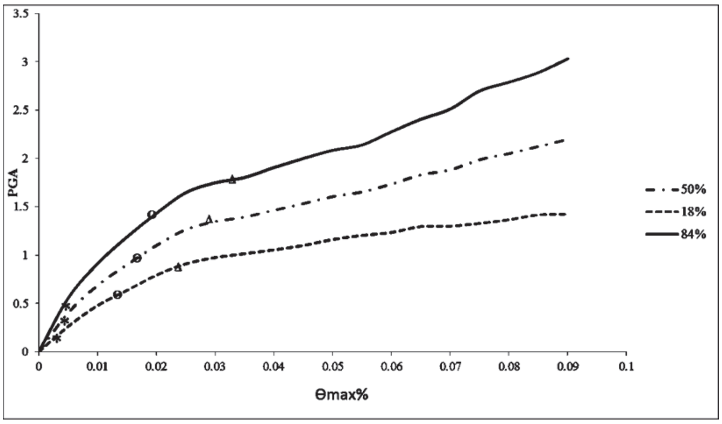


**Figure 13.** Summary of IDA curves for 3 story EBF system subjected to near-field ground motions

**Table 5.3.1.** Summarized capacities for each limit states of 3 story EBF system

| IDA curve | IO | | LS | | CP | |
|---|---|---|---|---|---|---|
| | PGA | qmax% | PGA | qmax% | PGA | qmax% |
| 16% | 0.2 | 0.3 | 0.7 | 1.3 | 0.9 | 2.1 |
| 50% | 0.3 | 0.4 | 1 | 1.6 | 1.3 | 2.8 |
| 84% | 0.5 | 0.4 | 1.3 | 1.9 | 1.7 | 3.4 |

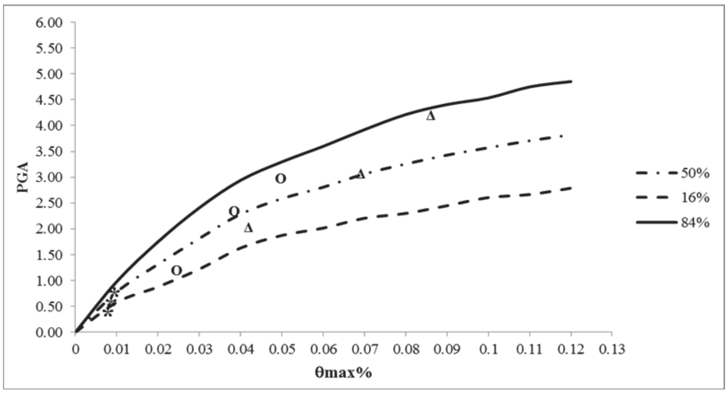


**Figure 14.** Summary of IDA curves for 3 story BRBF-E system subjected to near-field ground motions

**Table 5.3.2.** Summarized capacities for each limit states of 3 story BRBF-E system

| IDA curve | IO | | LS | | CP | |
|---|---|---|---|---|---|---|
| | **PGA** | **θmax%** | **PGA** | **θmax%** | **PGA** | **θmax%** |
| 16% | 0.4 | 0.7 | 1.5 | 2.4 | 2.1 | 4.0 |
| 50% | 0.6 | 0.8 | 2.2 | 3.8 | 3.1 | 6.8 |
| 84% | 0.8 | 0.8 | 2.9 | 5.2 | 4.1 | 9.6 |

As shown in table 5.3.3 and table 5.3.4, BRBF-E has better performance for 9 story frames similar to 3 story frames. But in 9 story buildings, there is no considerable difference in the limit states of EBF and BRBF-E systems, especially for the CP limit state. For example in EBF system, at 50% fractile IDA curve, the CP limit state occurred in PGA of 1.99g and $\theta_{max}$ of 0.0666 but in BRBF-E system, at 50% fractile IDA curve, the CP limit state occurred in PGA of 2.71g and $\theta_{max}$ of 0.0779. Although in this case, BRBF-E system has had better dynamic behaviour, but difference of limit states in 9 story frames is less than 3 story frames.

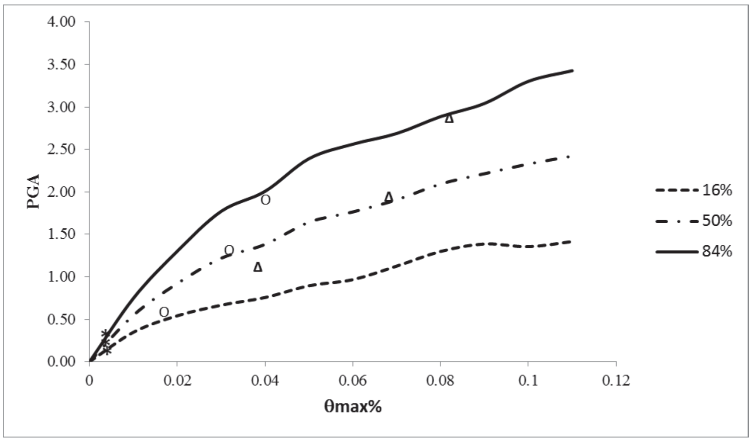


**Figure 15.** Summary of IDA curves for 9 story EBF system subjected to near-field ground motions

**Table 5.3.3.** Summarized capacities for each limit states of 9 story EBF system

| IDA curve | IO | | LS | | CP | |
|---|---|---|---|---|---|---|
| | **PGA** | **θmax%** | **PGA** | **θmax%** | **PGA** | **θmax%** |
| 16% | 0.18 | 0.32 | 0.75 | 2.02 | 1.20 | 3.62 |
| 50% | 0.23 | 0.41 | 1.34 | 3.53 | 1.99 | 6.66 |
| 84% | 0.27 | 0.50 | 1.92 | 5.04 | 2.77 | 9.69 |

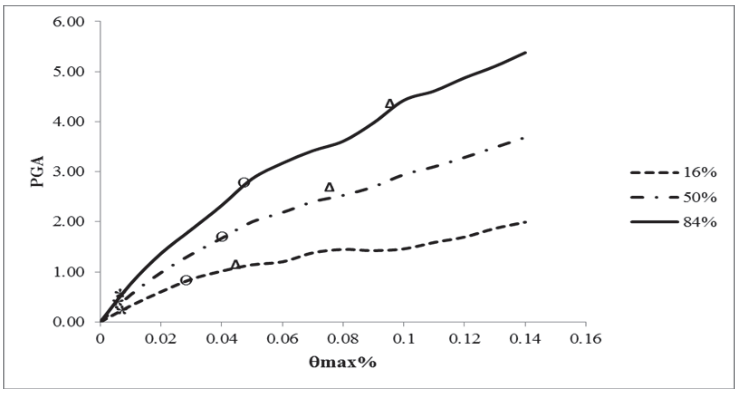


**Figure 16.** Summary of IDA curves for 9 story BRBF-E system subjected to near-field ground motions

**Table 5.3.3.** Summarized capacities for each limit states of 9 story BRBF-E system

| IDA curve | **IO** | | **LS** | | **CP** | |
|---|---|---|---|---|---|---|
| | **PGA** | **θmax%** | **PGA** | **θmax%** | **PGA** | **θmax%** |
| 16% | 0.29 | 0.70 | 0.91 | 2.75 | 1.11 | 4.76 |
| 50% | 0.44 | 0.76 | 1.85 | 4.03 | 2.71 | 7.29 |
| 84% | 0.59 | 0.83 | 2.78 | 5.30 | 4.32 | 9.81 |

## 6. CONCLUSION

The following conclusions can be drawn from this study:

(i)- The average input energy of earthquake to EBF and BRBF-E systems have not significantly difference in lower magnitude of PGA (PGA=0.3). However, by increasing PGA, magnitude of average input energy to EBF systems is more than BRBF-E systems, especially for systems subjected to near-field ground motions and higher system period.
(ii)- The EBF and BRBF-E systems subject to near field ground motions with lower magnitudes of PGA, average maximum inter-story drift for BRBF-E systems is more than EBF systems. Nevertheless, by increasing PGA, when the structure goes into inelastic range, the average maximum inter-story drift for EBF systems is more than BRBF-E systems. Frames with two different bracing systems are designed to have equal story strength, hence the EBF systems have better performance for lower magnitude of PGA but for higher magnitude of PGA, the BRBF-E systems have better performance than EBF systems.
(iii)- When the frames are subjected to far-field ground motions with low magnitudes of PGA, average maximum inter-story drift in EBF systems is lower than BRBF-E systems, and for high magnitudes of PGA, the performance of the systems have not significantly changed.
(iv)- In 3-story frames with BRBF-E system, their limit states have higher magnitude than EBF system. However, in 9-story frames with EBF and BRBF-E systems, their limit states show a little difference. Hence, use of BRBF-E systems in the near-fault is preferred, because it can induce high magnitude of the limit states.

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