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Seismic Performance Evaluation of Knee and EBF Braced Frames Using Nonlinear Static Analysis

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Abstract: Earthquake-resistant structure systems should be designed to stand large deformation to absorb and attenuate imposed energy due to an earthquake while providing sufficient stiffness to transfer the forces to the base without collapse. Knee Braced Frames (KBF), which involves added additional diagonal elements to a frame to increase its ability to withstand lateral loads, is suggested by several researches. In this study, the seismic performance of KBFs are evaluated and compared with Eccentric Braced Frames (EBF). Nonlinear static analyses were utilized for seismic evaluation and comparison between the mentioned frame systems. Three steel structures of 5, 10, and 15-story were numerically modeled, and the seismic parameters such as lateral stiffness, inter-story drift, ductility, and response modification factors were calculated for each structure system. It was observed that using KBF systems resulted in a reduction in intersotry drifts compared to EBFs. KBF systems show more stiff responses in comparison with EBFs and they presented much more stiff response by reducing the knee element length. The KBFs have more ductile behavior in comparison with EBFs, although base shear in KBFs is less than EBFs.

Keywords: EBF Bracing, Knee Bracing, Nonlinear Analysis, Pushover, Seismic Parameters

1. INTRODUCTION

Earthquake-resistant structures should be designed in a way that they are able to stand against large deformation due to the earthquake to absorb and attenuate imposed energy. On the other hand, they should have a sufficient stiffness for transferring the forces to base without collapse. To fulfill these goals, using bracing system which involves added diagonal elements to a frame to increase its ability to withstand lateral loads is an option. There are two major braced frame systems, Concentric Braced Frame (CBF) and Eccentric Braced Frame (EBF). CBFs consist of diagonal braces located in the plane of the frame where both ends of the brace connected to the ends of other framing members while for EBF system one or both ends of the brace do not connected to the ends of other framing members. In the CBF systems, members form a truss-like structure, creating a stiff frame while EBF combines the features of a moment frame and a concentrically braced frame and minimizing the disadvantages of each system resulting to improve in the system performance in the event of earthquakes.

Although EBFs usually have appropriate behavior, after the failure of the link beam (the element between two ends of the brace in the floor), floor beam would be seriously damaged. Since this element is considered as one of the main structural components, structural rehabilitation would be difficult and sometimes impossible. Moreover, bracing elements and shear links dissipate energy when exposed to the strong earthquakes, but in the weak earthquake, link beam would stay in the elastic region. In addition, analysis and design of link beams are complex. Therefore, attempts for finding seismic resistant systems with large ductility and stiffness have been continued. These drawbacks are mitigated to some extent in the works of Aristizabel-Ochoa in 1986 by introducing Disposable Knee Bracing systems as a new alternative structural system for earthquake-resistant steel structures [1]. This system possesses an appropriate stiffness and absorbs earthquake energy through yielding of knee elements. In addition, the diagonal element provides lateral stiffness during moderate earthquakes. However, the knee element is designed to behave in nonlinearity range for dissipation of the energy under strong ground motions.

Many researches have been performed to study the experimental and analytical performance of knee brace systems. Sam et al. 1995 carried out pseudo dynamic testing of 1-story and 2-story specimens using KBF system, which showed the system has enough capacity to reduce the earthquake damage effectively and economically [2]. Maheri et al. 2003 performed pushover testing of KBF and CBF systems mounted on concrete reinforced moment resisting frame structures. The response modification factors of the systems are evaluated and significant improvement in the ductile behavior was observed in the contract of unbraced reinforced concrete building [3].

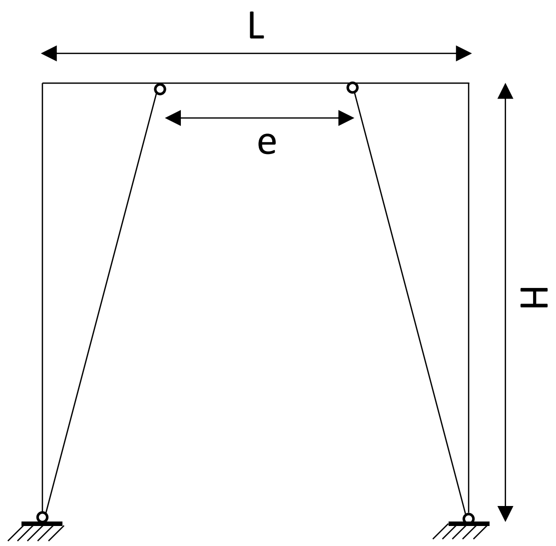
In this study, the seismic performance of KBF systems is evaluated and compared with EBF systems. Nonlinear static analyses were utilized for seismic evaluation and comparison between the mentioned frame systems. Three steel structures of 5-story, 10-story, and 15-story were modeled numerically, and the seismic parameters such as lateral stiffness, ductility, and response modification factors were calculated for each structure system.

2. STRUCTURE DESIGN

Seismic and gravity loads applied to the structures according to ASCE 7-10 [4]. For calculating static equivalent lateral load, it was assumed that the buildings were located in a high seismic region, and soil type C was selected. Response modification factors for EBF and KBF systems are assumed to be 7. Dead and live loads are 700 and 200 kg/m^2, respectively. Design of the structures was performed according to load and resistance factor design method (LRFD) of AISC 2010 [5].

3. STRUCTURE CONFIGURATIONS

In knee braces, the optimum knee element is defined when the frame has the highest stiffness. In another word, according to Fig. 1 *b/B=h/H* i.e. knee element is parallel to the diagonal frame and element extension passes through the intersection between beam and column. The frames have five, four, and three spans, and all span widths equal to 7 *m*. The frames have 5, 10, 15-story and each story height is 3.2 *m*. Lengths of the link beams and knees in the frames are variable. Box sections and plate girders are utilized for designing the columns and beams. In addition double U-sections were used for the braces. Small boxes were also considered for designing the knee elements. The connections between the beams and columns were assumed to be pinned.



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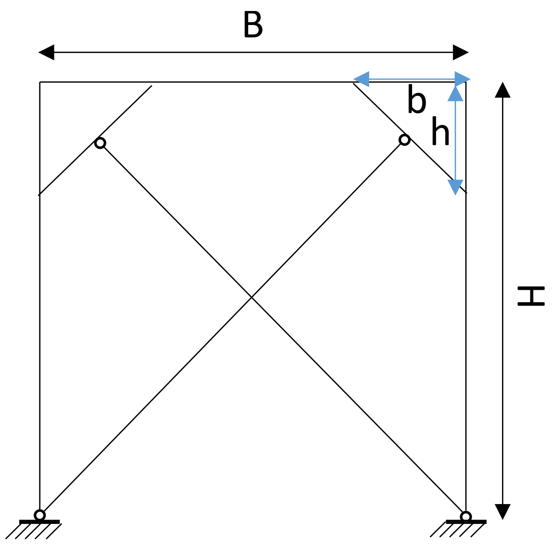

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Fig. 1: Sample frame: (a) EBF, and (b) Knee braced frame.

4. NONLINEAR STATIC ANALYSIS

Nonlinear static analysis (pushover analysis) are now widely used in engineering practice to estimate seismic parameters in building structures. Pushover analysis has been utilized [6-9] for seismic demand and parameter estimation of structures. For instance, Taghinezhad et al used pushover analysis to predict amplification factor, inter-story drift and seismic vulnerability in different structure systems [8]. In this method, the lateral load is statically applied to the structures, and continuously increased until the roof displacement in a specific point (control point) reaches target displacement, which is defined according to the following equation:

$$\delta_t = C_0 C_1 C_2 C_3 S_a \frac{T_e^2}{4\pi} g \qquad (1)$$

Where T_e is an effective fundamental period of building in a specific direction. S_a is spectrum acceleration corresponding to T_e. C_0, C_1, C_2, and C_3 are the modification factors.

In this study two lateral load pattern were applied to the structures:

1. First lateral load pattern was according to the first vibrational mode of the structure.
2. Second lateral load pattern was uniform load according to the story weights based on Eq. (2):

$$F_i = \frac{W}{\sum_{j=1}^{n} W_j} .V \qquad (2)$$

Where F_i is applied force for each story, W_i is weight for *i-th* story, and *V* is base shear force. Plastic hinge properties were defined according to FEMA 356 [10].

5. ELASTIC FRAME STIFFNESS

Stiffness of frames derived from equivalent bilinear form of capacity curves resulted from pushover analysis and presented in Fig. 2 in terms of *h/H* and *e/L* for EBF and KBF systems, for 5-story, 10-story, and 15-story frames. It is observed that using KBF increases the stiffness of braced frames. This difference is higher for lower values of *h/H* and *e/L*.

6. SEISMIC PARAMETERS

By using force-displacement curves of the frames, seismic parameters such as ductility, response modification, and over strength factors can be estimated. In addition, plastic hinge formation of the structures can be evaluated [11]. There are two analytical methods for estimating the capacity curve of a structure (force-displacement curve); using nonlinear static and incremental dynamic analysis. In incremental dynamic analysis, capacity curves of a structure is estimated by applying several earthquakes with incremental scale factors considering the nonlinear phase of structure material. Several researches utilized [12-17] this numerical method to estimate the seismic parameters. Soltangharaei et al, 2015 and 2016, [12, 15] estimated the seismic parameters of steel buckling restrained and steel moment restrained frames using incremental dynamic analysis with considering the near-fault or far-fault earthquake effects. In this study nonlinear static analysis [18-23] was employed to estimate the capacity curves of the structures. In pushover analysis, the nonlinear phase of the structure is considered and lateral load is incrementally increased according to the defined load pattern to capture the real response of the structure under extreme seismic loads [22-24].

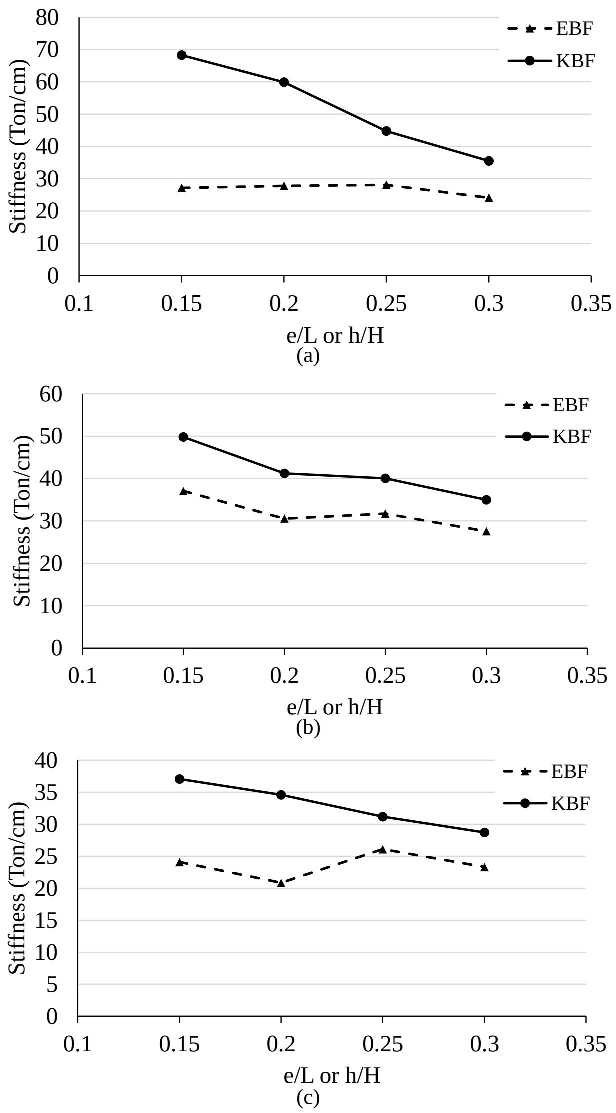


Fig. 2: Frame lateral stiffness: (a) 5-story, (b) 10-story, and (c) 15-story.

This response modification factor is the ratio of yield shear force (V_y) based on bilinear form of capacity curve and corresponding force of first plastic hinge formation (V_s), which is denoted by R_{so} or Ω_0.

$$R_{SO} = \frac{V_y}{V_S} \tag{3}$$

The other equations are:

$$R_s = R_{so} \times F_1 \times F_2 \times ... \tag{4}$$

$$R = R_S \times R\mu \tag{5}$$

Where R_u is response modification factor based on ultimate strength stress, and R_w is response modification factor based on allowable stress design. The ratio of response modification factors between these two design methods is:

$$Y = R_w / R_u \tag{6}$$

Y depends on different design provision ranging from 1.4 to 1.7.

Different equations have been proposed for estimating ductility reduction factor ($R\mu$). One of the comprehensive equation has been proposed by Miranda. His equation includes the effect of fundamental period of structure, soil type, and earthquake ground acceleration [25-28].

$$R_\mu = \frac{\mu - 1}{\phi} + 1 \tag{7}$$

For hard rock type:

$$\phi = 1 + \frac{1}{10T - \mu T} - \frac{1}{2T}\exp\left[-3/2(\ln T - \frac{3}{5})^2\right] \tag{8}$$

Table 1: Seismic parameters of EBF structures.

Structure	T_e (sec)	V_y (*ton*)	V_s (*ton*)	R_{so}	R_s	μ	ϕ	R_μ	R_u	R_w
5-story	0.80	290	249	1.16	1.34	2.51	0.78	2.92	3.92	5.48
10-story	1.23	572	388	1.47	1.70	2.10	0.76	2.45	4.15	5.81
15-story	1.88	972	572	1.70	1.95	2.21	0.91	2.33	4.55	6.64

Table 2: Seismic parameters of KBF structures.

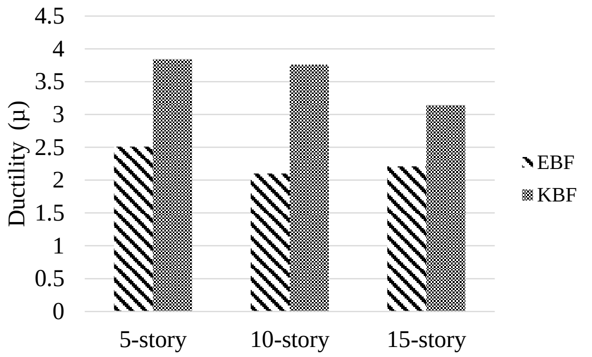
Structure	T_e (sec)	V_y (*ton*)	V_s (*ton*)	R_{so}	R_s	μ	ϕ	R_μ	R_u	R_w
5-story	0.63	178	112	1.59	1.83	3.84	0.93	4.05	7.40	10.36
10-story	1.03	315	265	1.19	1.37	3.76	0.75	4.67	6.39	8.95
15-story	1.72	577	356	1.62	1.86	3.14	0.88	3.43	6.39	8.93

For stiff soil type:

$$\phi = 1 + \frac{1}{12T - \mu T} - \frac{2}{5T}\exp\left[-2(\ln T - \frac{1}{5})^2\right] \quad (9)$$

For soft clay type:

$$\phi = 1 + \frac{T_g}{3T} - \frac{3T_g}{4T}\exp\left[-3(\ln\frac{T}{T_g} - \frac{1}{4})^2\right] \quad (10)$$



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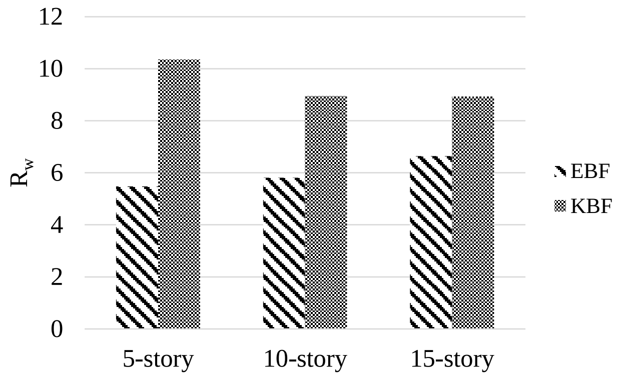

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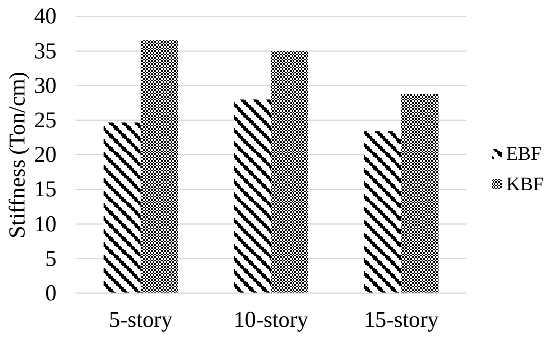
Fig. 3: (a) Ductility and (b) response modification factor for EBF and KBF.

Response modification and ductility factors for EBF and KBF for *h/H=e/L=0.3* are presented in Table 1 and 2, respectively.

According to the Tables 1 and 2, it can be observed that response modification factors for KBF range 8.5 to 10.5; whereas the values for EBFs are much less than them. Furthermore, the ductility values for KBFs are more than EBFs.

It is observed from Fig. 3 that the calculated response modification factors and ductility of KBF system is more than the values of EBFs. Therefore, as expected, KBF systems can provide higher ductility compared to EBFs.

According to Fig. 4, it is shown that base shears in the target displacements for KBFs are more than EBFs, and this difference increases for the frames with larger story numbers. In addition, stiffness for EBFs is larger than for EBF systems.



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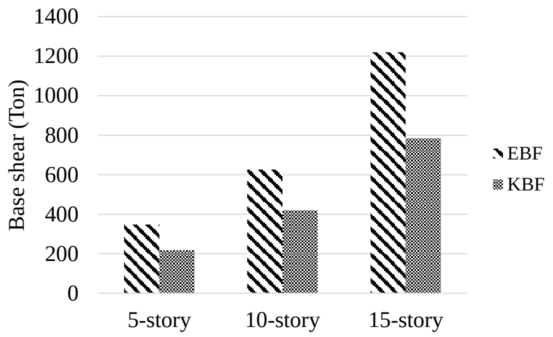

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Fig. 4: (a) Stiffness, and (b) Base shear for EBF and KBF.

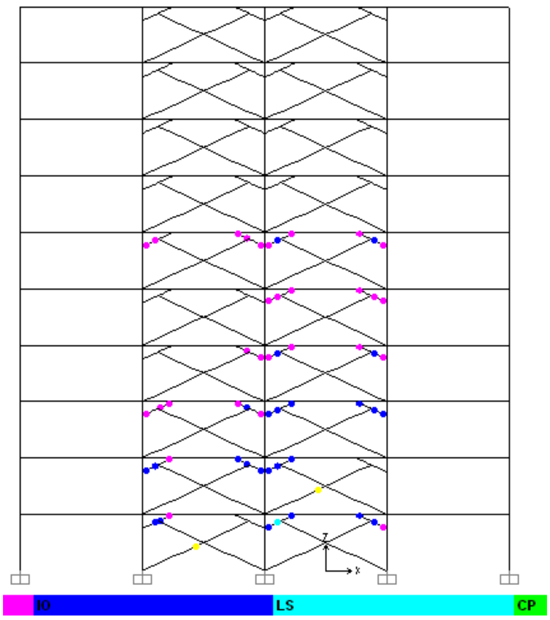
7. NONLINEAR PERFORMANCE OF FRAMES:

Plastic hinge distribution for the KBF and EBF 10-story structure resulted from nonlinear static analyses is shown in Fig. 5.

It is observed that first hinge was formed in the knee elements for KBF system. Knee element is considered as a secondary or fuse element in the lateral resistant system, which can be repaired or replaced easily after a server earthquake. On the other hand, plastic hinges generally started to form in links between two ends of braces, which are the main structural element to dissipate energy, in EBF systems. The produced damages in the links of EBF systems can be very expensive to repair.

8. INTER-STORY DRIFT

According to seismic design codes, one of the significant parameters, which should be considered for seismic designing, is inter-story drift. The inter-story drifts for knee braced frames are less than eccentrically braced frames as shown in Fig. 6.



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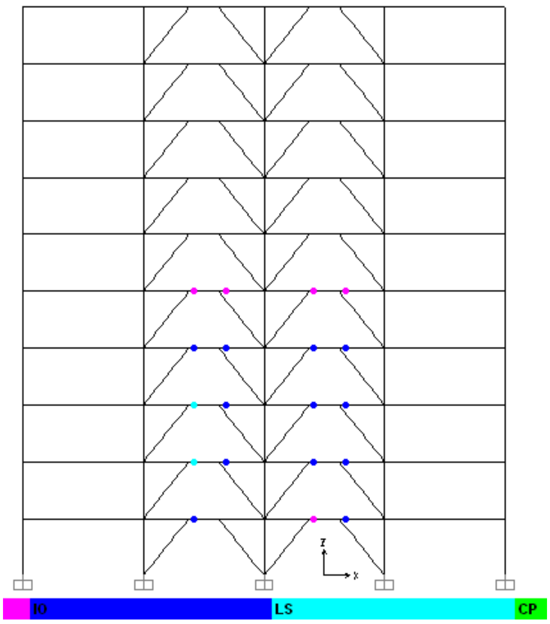

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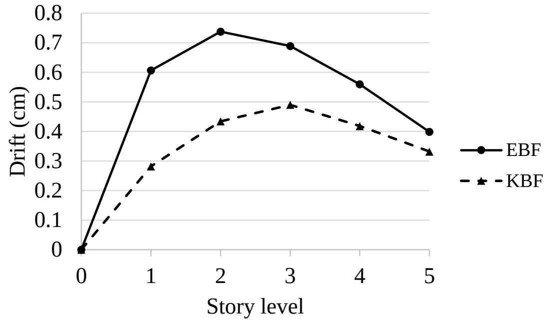
Fig. 5: Plastic hinge distribution for: (a) KBF, and (b) EBF.



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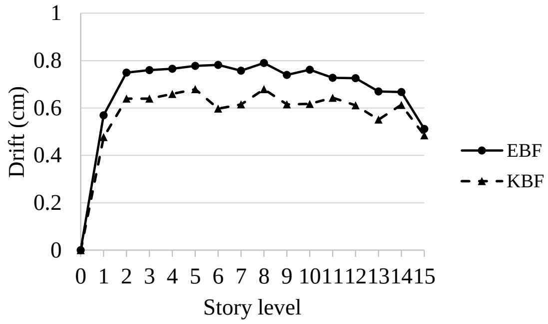

(b)

Fig. 6: Inter-story drift for: (a) 5-story, and (b) 15-story frames.

9. CONCLUSION

In this study, the seismic performance of KBFs and EBFs was evaluated, and the following conclusions were made:

1. Using KBF system causes a reduction in inter-sotry drifts compared to EBFs;
2. Comparing the two similar EBFs and KBFs (identical story number and span length), it is shown that KBFs are stiffer than EBFs. KBFs become much stiffer by reduction of knee element length;
3. Retrofit and maintenance of KBF system is less expensive and more constructible than EBF due to nonlinearity in knee element which is a secondary element in comparison with link beam in EBFs which is a primary structural element;
4. Ductility of KBFs are more than EBFs, although base shear in KBFs is less than EBFs.

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