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Investigations

Investigating the Parameters Influencing the Behavior of Knee Braced Steel Structures

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Abstract: In Knee-Braced Frames (KBF), the brace is connected to the knee element rather than the beam-column joint. For reasons such as having sufficient lateral stiffness despite its adequate ductile behavior, the concentration of damage in the Double Knee-Braced structural elements and also ease of repair and replacement of these elements after an earthquake, this bracing system is preferred over conventional systems. The lateral stiffness of this system is provided by the bracing system and the frame ductility is supplied by the flexural yield or the shear yield of the knee members depending on the knee length. Attempts have been made, in the present study, to investigate the non-linear seismic behavior of Knee-Braced Frame systems for various influencing factors and to formulate the effect(s) of the number of building stories, the length of the knee element and moment of inertia of the bending members on the seismic behavior, the drift of the stories and the failure mode of these systems. Finally, based on the results of the study, some recommendations have been offered for the effective range parameters for the optimal performance of these systems.

Keywords: Knee-Braced Frames, Non-Linear, Seismic Behavior, Drift, Failure Mode

Introduction

The regulations for the seismic design of buildings must satisfy two criteria: first, under low to moderate earthquakes, the structure should have sufficient strength and stiffness to prevent any structural damage and control deflection. Second, under severe earthquakes, the structure must have sufficient ductility and energy absorption capability. The stiffness and ductility of structures are usually opposite. Therefore, it is desirable that there should be a reasonable balance between these two factors in the structural systems in compliance with the economic considerations (Balendra *et al*., 1990a; 1991a).

Currently, moment-resistant frame systems, concentrically-braced frames and eccentrically-braced frames are commonly used in the design of earthquake-resistant steel structures. Moment-resistant frame possesses has good ductility through flexural yielding beam elements, but it has limited stiffness. The concentrically braced frame on the other hand is stiff, however, because of buckling of the diagonal brace, its ductility is limited. To overcome the low stiffness in moment-resistant frame systems and also the low ductility of concentrically-braced frames, Popov proposed the eccentrically-braced frames. By a suitable choice of eccentricity, the system will have sufficient stiffness and the flexibility of the system will be supplied through the shear or bending yield of the connective beam. This system has good ductility and stiffness, but to achieve the required ductility, severe yielding of the link is expected, which may lead to serious floor damage after and could be difficult to repair after an earthquake (Balendra *et al*., 1991b; 1994; Mofid and Lotfollahi, 2010).

In 1986, Achva proposed a new system to be revised later by Balendra *et al*. (1990b; 1995; 1997). In this system, called Knee-Braced Frame (KBF) system, rather than connecting to the beam-column joint, the ends of the diagonal brace are connected to a knee (bending) element which is itself attached to the beam and the column or the column and the support. Furthermore, in these systems the knee elements remain elastic during low earthquakes and yield before the major parts under severe earthquakes, causing the energy to be dissipated without losing peripheral resistance. In these systems, the damages caused by earthquakes are concentrated in the knee members which do not comprise the major parts of the structure and can be changed or repaired after the earthquakes (William and Denis, 2008).

In recent years, several different studies have been carried out on determining the size, shape, properties and other parameters of these systems in an effort to optimize the best combination of stiffness and ductility for the structural system in question.

In this study, the non-linear dynamic analysis has been applied to examine the impact of the building's stories, the length of the knee element and also the moment of inertia of the knee element on the seismic behavior of the knee-braced frames.

Models

To evaluate the behavior of the knee-braced systems, a structure such as the following (Fig. 2), with the described characteristics below was examined.

The building is a steel-framed system with 3 openings along the two original directions. It has 4, 8 and 12 stories and the length of the spans and the height of the stories are 6 and 3/2 meters, respectively. The building has become resistance against the earthquake on the both sides using lateral braces. Each story weighs 274 tons and it is assumed that the buildings are constructed in very high earthquake hazard zones with residential users on soil type 3 in Tehran. In addition, the connection between the beams and the columns has been considered as joints. AISC-ASD standards have been applied as the building codes. The knee brace features are shown in Fig. (2A) and the following:

The knee element is placed on one side of the brace at the top. The connection between the knee element and the intersection of beam and column and the connection between the brace and the knee element have been considered as rigid and joint, respectively. The knee elements is parallel to the other diagonal of the frame so that b/h = B/H and the central axes of the bracing members goes through the beam-column joints (Hjelmstad and Popov, 1983; Jinkoo, 2011).

The parametric study of the seismic behavior of the knee-braced frames for different ratios of length and moments of inertia of the knee member has been carried out as follows:

$$h / H = 0.0, 0.05, 0.10, 0.15, 0.20, 0.25, 0.30$$
$$I_k / I_c = 0.10, 0.15, 0.20, 0.25, 0.30$$

where, in the above equations, 'h' is the vertical length of the knee element; 'H' the height of the story; 'I_c'; the moment of inertia of the column; 'I_k'; the moment of inertia of the knee.

Accelerograms Used

Based on some such factors as the selected soil type, the construction site, which is considered to be on soil type 3 and its similarity with soil type C, 7 accelerograms were selected. The chosen accelerograms were related to soil type C and bore almost similar features. The characteristics of these graphic records, such as the scale used for its adjustment to 2800 design spectra, are herein below presented in Table 1.

Non-Linear Dynamic Analysis

The non-linear dynamic analysis was performed using the OPENSEES software. For the beam, column and bracing members, the fiber-section beam-column element was applied and for the knee member, the section-aggregator non-linear beam-column element was used to make it possible for the shear yield properties to be applied (Fig. 3). The materials used included 02 Steel with the yield stress of 2400 kg/cm^2, modulus of elasticity of 2.1 kg/cm^2 ×2×10^6 and the post-yield stress of 2%. The allowable drift was considered as equal to 0/025 for the 4 and 8-story frames and 0/02 for the 12-story frames on the basis of the UBC (United Building Code) and 2800 designing code. In addition, the failure mode for the system was considered to be that exceeding the maximum allowable drift, column buckling, or brace buckling.

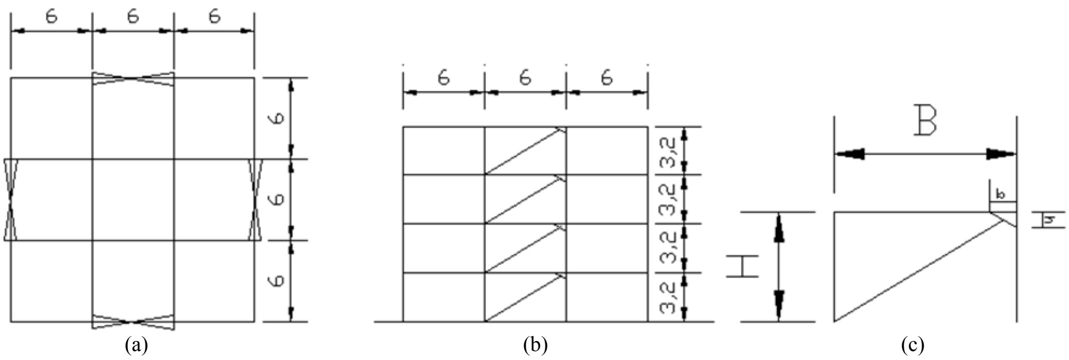

Fig. 2. The geometrical features of the building (a) plane of building (b) view of building (c) knee bracing

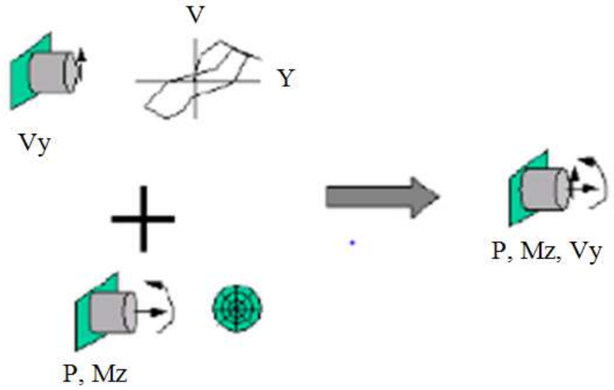

Fig. 3. Section of the knee element

Table 1. Features of the accelerograms

Earthquake	PGA (g)	PGV (cm/s)	PGD (cm)	Magnitude	Displacement (km)	Scale 4story	8story	12story
Imperial Valley	0.313	29.8	13.2	7.0	8.3	1.56	1.37	1.70
Loma Prieta	0.367	32.9	7.15	6.9	12.7	1.00	1.37	1.35
Northridge	0.410	43.0	11.5	6.7	13.0	0.87	0.88	1.35
Cape Mendocino	0.590	48.4	21.4	7.1	9.5	1.00	0.83	0.78
Superstitn Hills	0.172	23.5	13.0	6.7	13.3	2.17	2.60	2.90
Erzican	0.515	83.9	27.5	6.9	2.0	0.85	1.00	0.88
Duzce	0.384	83.9	27.5	7.1	8.2	0.75	1.00	1.00

Analyzing the Behavior of Frames Under the Applied Accelerograms

Figure 4 to 9 show the maximum story drift under the applied accelerograms in some of the knee-braced frames. In these diagrams, the frames have been presented as aHbIc, where ‘a’ is the number of stories; ‘b’ expresses the ratio of h/H; and ‘c’ represents the ratio of I_k/I_c. Considering these figures, it can be seen that:

- In the knee braces, under the application of accelerograms, the absorption of energy on the different stories of the building started with the yield of the knee elements (Fig. 10). In the diagonal braces, however, energy absorption began with the buckling of the braces on one or two particular stories
- At small and medium knee lengths, if the knee elements have a strong moment of inertia, brace buckling occurs
- In 4 and 8-story frames, except for the frames which had brace buckling, a maximum drift of the stories was observed in the frames with high knee length (h/H = 0.25,0.30) for the fixed moments of inertia of the knee element (Fig. 7). This increase in the drift of the stories was observed to a higher degree in the weak moments of inertia of the knee element (Fig. A). In the strong moments of inertia of the knee elements, however, the knee length is less sensitive to changes (Fig. 7B)
- In 4 and 8-story frames, except for the frames which had brace buckling, a maximum drift of the stories was observed in the frames with the least moments of inertia of the knee element ($I_k/I_c = 0.1$) (Fig. 4 and 6). Plus, it was observed that the drift of the stories is more sensitive to decrease of the moment of inertia at greater knee lengths (Fig. 4 and 6)
- In all the 12-story frames with high moments of inertia (I_k/I_c = 0.25,03), brace buckling occurs (Figure 9). In addition, at greater knee lengths (h/H = 0.25,0.30), the drift of the story exceeds the maximum allowable one
- The various modes of failure of the frames under the applied accelerograms are presented in Table 2 to 4

Optimal Range of the Length and the Moment of Inertia of the Knee Member

According to the observations of the study, the selected range of the length and the moment of inertia of the knee element for the short and medium buildings (4 and 8-story structures), on the one hand and for the tall buildings, on the other hand, is presented in Table 5 and 6, respectively.

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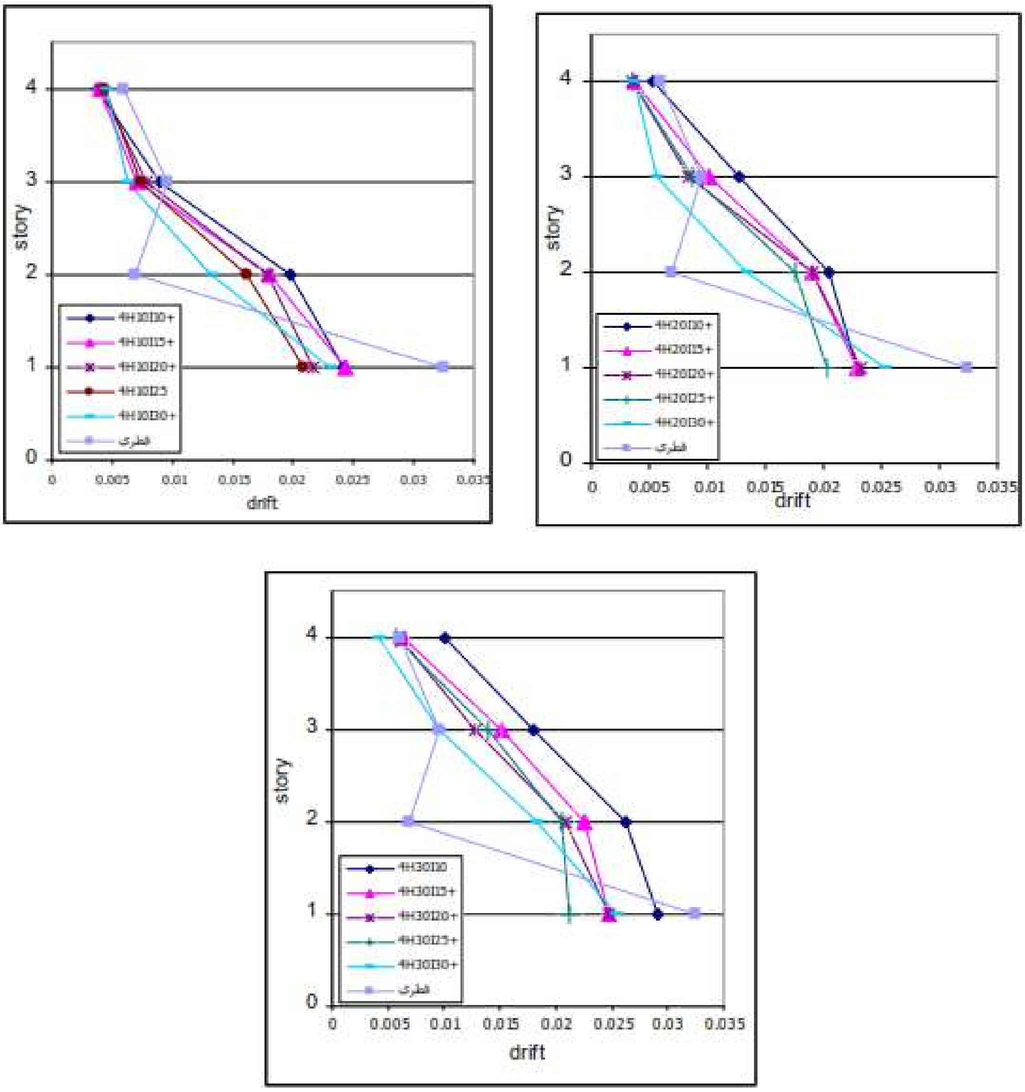
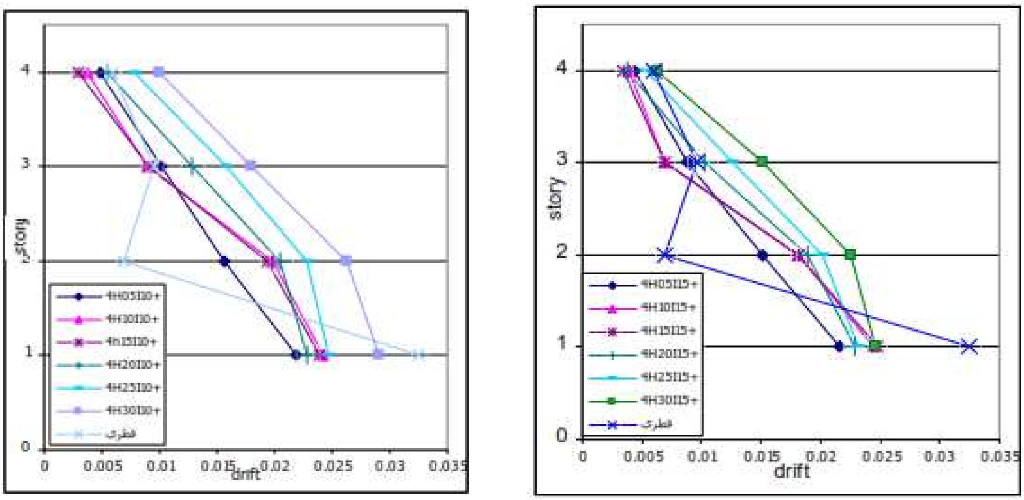


Fig. 4. Drift of the stories in 4-story frames with a fixed length and different moments of inertia of the knee



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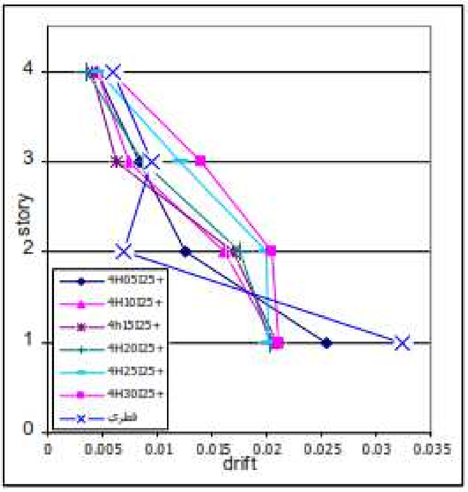


Figure 5. Variations in the drift of the stories in 4-story frames with fixed moment of inertia and different knee lengths

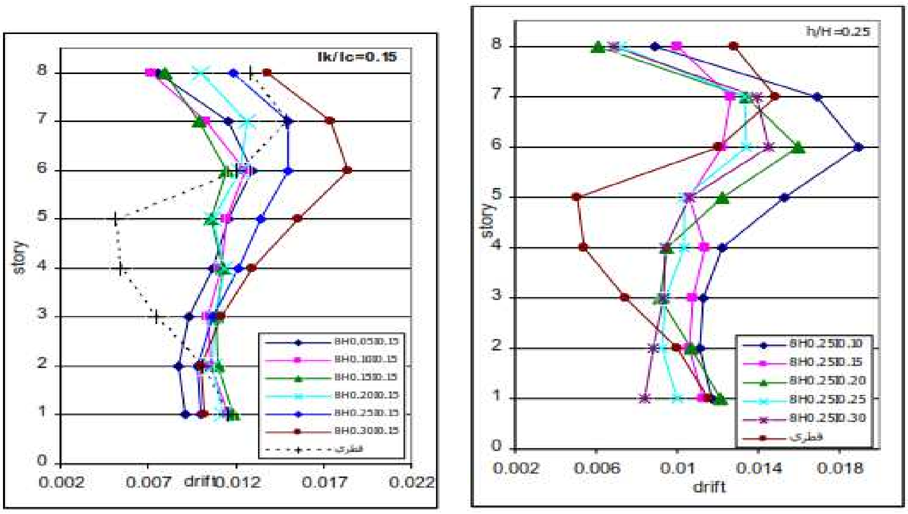


Fig. 6. Drift of the stories in 8-story frames with a fixed length and different moments of inertia of the knee

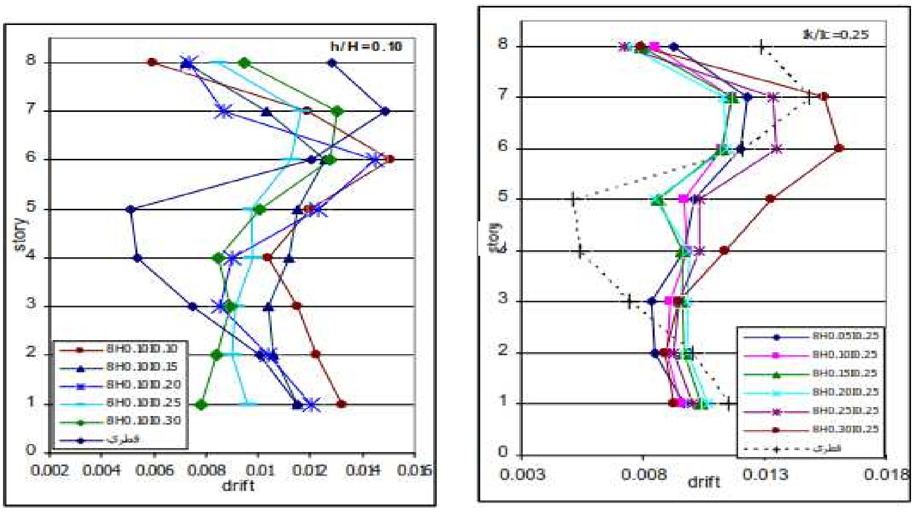


Fig. 7. Variations in the drift of the stories in 8-story frames with fixed moment of inertia and different knee lengths

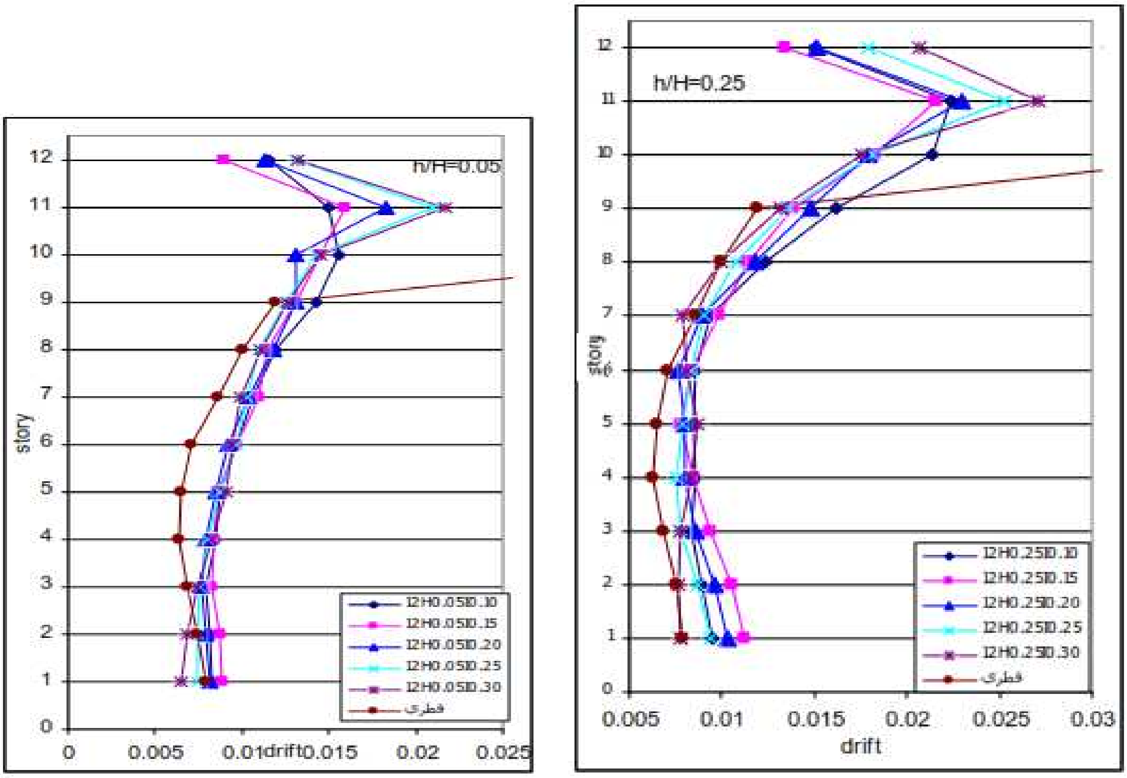


Fig. 8. Drift of the stories in 12-story frames with a fixed length and different moments of inertia of the knee

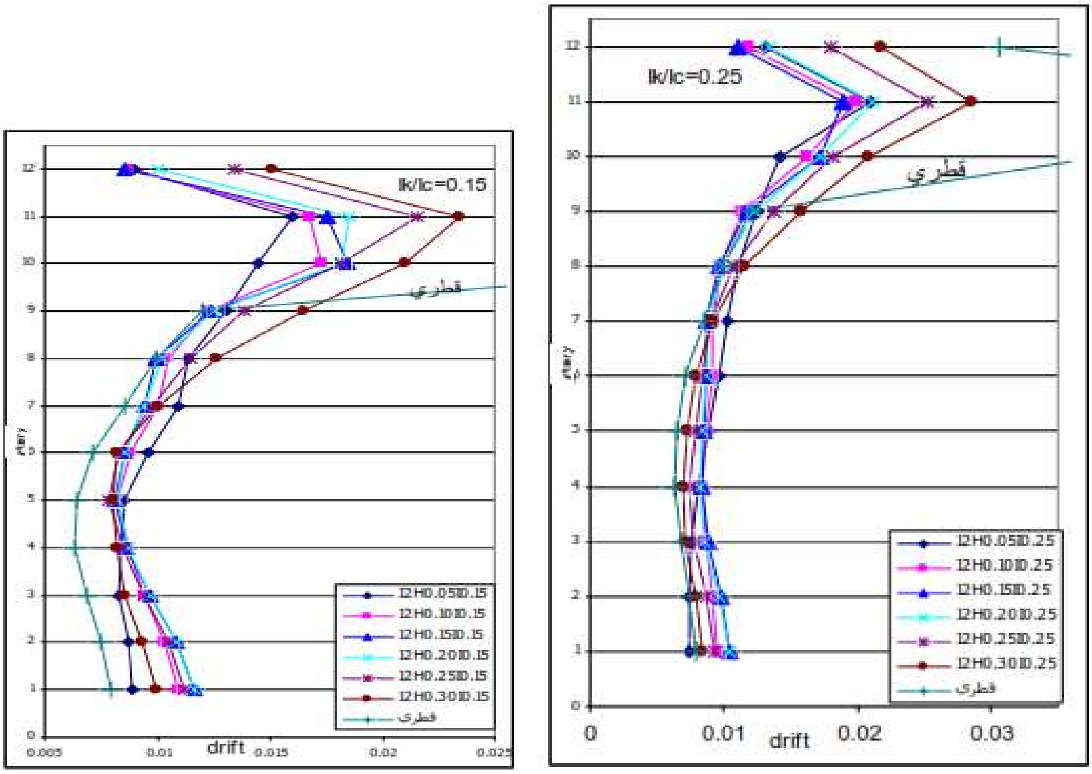
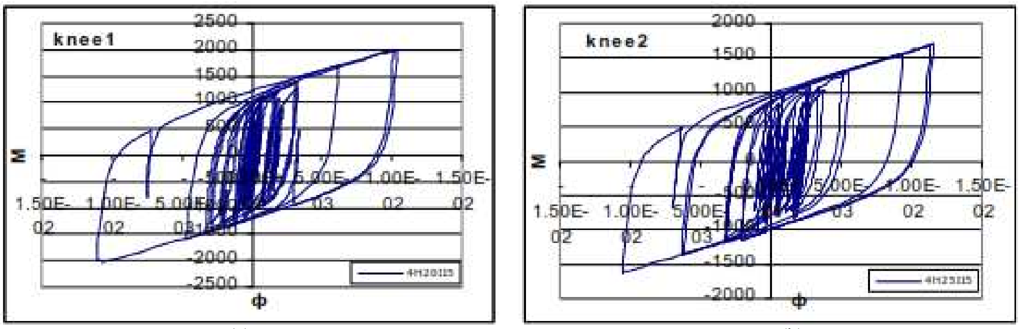


Fig. 9. Variations in the drift of the stories in 12-story frames with fixed moment of inertia and different knee lengths



(a) (b)

Fig. 10. The moment diagram-the curve of the knee elements in the 4-story frames under the El Centro earthquake (a) first floor (b) second floor

Table 2. The failure mode of 4-story frames

L_k/L_c	0.10	0.15	0.20	0.25	0.30
h/H = 0.05	No failure	No failure	No failure	Brace buckling	Brace buckling
h/H = 0.10	No failure	No failure	No failure	No failure	Brace buckling
h/H = 0.15	No failure	No failure	No failure	No failure	Brace buckling
h/H = 0.20	No failure	No failure	No failure	No failure	The drift exceeding the allowable limits
h/H = 0.25	No failure	No failure	No failure	No failure	The drift exceeding the allowable limits

Table 3. The failure mode of 8-story frames

L_k/L_c	0.10	0.15	0.20	0.25	0.30
h/H = 0.05	No failure	No failure	No failure	Brace buckling	Brace buckling
h/H = 0.10	No failure	No failure	No failure	Brace buckling	Brace buckling
h/H = 0.15	No failure	No failure	No failure	No failure	Brace buckling
h/H = 0.20	No failure	No failure	No failure	No failure	No failure
h/H = 0.25	No failure	No failure	No failure	No failure	No failure
h/H = 0.30	No failure	No failure	No failure	No failure	No failure

Table 4. The failure mode of 12-story frames

L_k/L_c	0.10	0.15	0.20	0.25	0.30
h/H = 0.05	No failure	No failure	Brace buckling	Brace buckling	Brace buckling
h/H = 0.10	No failure	No failure	Brace buckling	Brace buckling	Brace buckling
h/H = 0.15	No failure	No failure	No failure	Brace buckling	Brace buckling
h/H = 0.20	No failure	No failure	No failure	Brace buckling	Brace buckling
h/H = 0.25	The drift exceeding the allowable limits	The drift exceeding the allowable limits	The drift exceeding the allowable limits	The drift exceeding the allowable limits	The drift exceeding the allowable limits
h/H = 0.30	The drift exceeding the allowable limits	The drift exceeding the allowable limits	The drift exceeding the allowable limits	The drift exceeding the allowable limits	The drift exceeding the allowable limits

Table 5. The optimal moments of inertia of the knee for various knee lengths in short and medium-sized frames

h/H	I_k/I_c
0.05	0.10,0.15
0.10	0.15,0.20
0.15	0.15,0.20,0.25
0.20	0.15,0.20,0.25
0.25	0.15,0.20,0.25

Table 6. The optimal moments of inertia of the knee for the various knee lengths in tall frames

h/H	I_k/I_c
0.05	0.10,0.15
0.10	0.10,0.15
0.15	0.10,0.15,0.20
0.20	0.10,0.15,0.20

Conclusion

- The diagrams represent the efficient behavior of the knee bracings as compared to the diagonal bracings. In the diagonal-braced frames, the drifts of the building greatly increase in one or two stores due to the severe buckling of the bracings under seismic forces, but in the knee-braced frames, before buckling of the bracing, the knee members will yield, start to absorb the energy and prevent buckling of the bracing
- The drift of the stores under seismic forces is higher in the knee members with great length and weak moment of inertia and, as a result, when the length of the knee is greater, the use of lower moments of inertia for the knee is not recommended

- At small knee lengths, the use of the strong moments of inertia leads to the buckling of the brace; therefore, using the knee element with a small length and a high moment of inertia is not recommended. However, even in the worst conditions, the behavior of this system is more efficient than that of the diagonal system
- Using the values of the length and the moment of inertia proposed in this study will make the drift of the stories under seismic force remain at allowable amounts and will prevent the buckling of the bracing as well. In addition, in this range of the length and the moment of inertia of the knee, the sensitivity to the changes in the levels of the drift of the stores is less than those in the length and the moment of inertia of the knee

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Author's Contributions

Each author of this manuscript made considerable contributions in developing the mathematical modeling, data-analysis and contributed to the writing of this manuscript.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

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