Investigations

Investigating the Parameters Influencing the Behavior of Knee Braced Steel Structures

Edris Farokhi and Mehrdad Gordini

Department of Civil Engineering, College of Engineering, Kermanshah Branch, Islamic Azad University, Kermanshah, Iran

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Corresponding author:
Edris Farokhi
Department of Civil Engineering, College of Engineering, Kermanshah Branch, Islamic Azad University, Kermanshah, Iran
Email: edris.farokhi@gmail.com

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 Lottfollahi, 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:

\[ \frac{h}{H} = 0.0, 0.05, 0.10, 0.15, 0.20, 0.25, 0.30 \]

\[ \frac{I_k}{I_c} = 0.10, 0.15, 0.20, 0.25, 0.30 \]

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 OPENSEEES 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](image-url)
Table 1. Features of the accelerograms

| Earthquake          | PGA (g) | PGV (cm/s) | PGD (cm) | Magnitude | Scale |
|---------------------|---------|------------|----------|-----------|-------|
| Imperial Valley     | 0.313   | 29.8       | 13.2     | 7.0       | 1.56  |
| Loma Prieta         | 0.367   | 32.9       | 7.15     | 6.9       | 1.00  |
| Northridge          | 0.410   | 43.0       | 11.5     | 6.7       | 0.87  |
| Cape Mendocino      | 0.590   | 48.4       | 21.4     | 7.1       | 0.95  |
| Superstition Hills  | 0.172   | 23.5       | 13.0     | 6.7       | 1.33  |
| Erzican             | 0.515   | 83.9       | 27.5     | 6.9       | 2.0   |
| Duzze               | 0.384   | 83.9       | 27.5     | 7.1       | 0.75  |

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 Iκ/Ic. 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 (Iκ/Ic = 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 (Iκ/Ic = 0.25,0.3), 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.
Fig. 4. Drift of the stories in 4-story frames with a fixed length and different moments of inertia of the knee
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
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 | No failure | Brace buckling |
| $h/H = 0.15$ | No failure | No failure | No failure | No failure | No failure |
| $h/H = 0.20$ | No failure | No failure | No failure | No failure | No failure |
| $h/H = 0.25$ | No failure | No failure | No failure | No failure | No failure |

### 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 stories 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 stories 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.

References

Balendra, T., T.S. Tan and S.L. Lee, 1990b. An analytical model for far-field response spectra with soil amplification effects. Eng. Struct., 12: 263-268. DOI: 10.1016/0141-0296(90)90025-N

Balendra, T., M.T. Sam, C.Y. Liaw and S.L. Lee, 1991a. Preliminary studies into the behaviour of knee braced frames subject to seismic loading. Eng. Struct., 13: 67-74. DOI: 10.1016/0141-0296(91)90010-A

Balendra, T., M.T. Sam and C.Y. Liaw, 1991b. Design of earthquake-resistant steel frames with knee bracing. J. Constr. Steel Res., 18: 847-858. DOI: 10.1016/0143-974X(91)90025-V

Balendra, T., M.T. Sam and S.L. Lee, 1994. Ductile knee braced frames with shear yielding knee for seismic resistant structures. Eng. Struct., 19: 847-858. DOI: 10.1016/0141-0296(94)90066-3

Balendra, T., C.M. Wang and H.F. Cheong, 1995. Effectiveness of tuned liquid column dampers for vibration control of towers. Eng. Struct., 17: 668-675. DOI: 10.1016/0141-0296(95)00036-7

Balendra, T., E. Lim and C. Liaw, 1997. Large-scale seismic testing of knee-brace-frame. J. Struct. Eng., 123: 11-19. DOI: 10.1061/(ASCE)0733-9445(1997)123:1(11)

Hjelmstad, K.D. and E.P. Popov, 1983. Seismic Behavior of Active Beam Links in Eccentrically Braced Frames. 1st Edn., Earthquake Engineering Research Center, pp: 169.

Jinkoo, K., 2011. Response modification factors of chevron-braced frames. Eng. Struct., 27: 285-300. DOI: 10.1016/j.engstruct.2004.10.009

Mofid, M. and M. Lotfollahi, 2010. On the characteristics of new ductile knee bracing systems. J. Construct. Steel Res., 62: 271-281. DOI: 10.1016/j.jcsr.2005.07.005

William, M. and C. Denis, 2008. Seismic design and analysis of a knee braced frame building. Earthquake Eng. Struct. Dynamic J., 23: 138-258

Balendra, T., M.T. Sam and C.Y. Liaw, 1990a. Diagonal brace with ductile knee anchor for aseismic steel frame. Earthquake Eng. Struct. Dynamic J., 19: 847-858. DOI: 10.1002/eqe.4290190606