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Elastoplastic analysis of knee bracing frame*

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Abstract: The knee bracing steel frame (KBF) is a new kind of energy dissipating frame, which combines excellent ductility and lateral stiffness. As the structural fuse of the frame, the knee element will yield first during a severe earthquake so that no damage occurs to the major structural members and the rehabilitation is easy and economical. To help fully understand the relations between its seismic performance and the structural parameters, systematic elastoplastic analysis of the KBF structure with finite element method was conducted in this work. Finally, general design recommendations were made according to the results of the analysis.

Key words: Steel frame, Knee bracing frame, Elastoplastic analysis
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INTRODUCTION

Steel framed structures are widely used in industrial and commercial buildings. According to the different lateral load resisting system, the steel frames can be mainly divided into four kinds (Fig.1a): the moment-resisting frame (MRF), concentrically braced frame (CBF), eccentrically braced frame (EBF), and knee bracing frame (KBF).

Fig.1b shows the difference in the lateral performances of the above frames that have similar structural parameters. Although the MRF is an excellent energy dissipating system, its members have to be designed with uneconomically large sections to meet the drift requirement. The CBF is much stiffer than the MRF, but it cannot meet the ductility requirement due to the buckling of the brace. To overcome the deficiencies of the MRF and the CBF, Reoder and Popov (1978) proposed a new structural system, named EBF. It combines sufficient stiffness and excellent ductility by setting the brace eccentrically to the beam to form a shear link. Due to the yielding of the shear link in a severe earthquake, the frame provides reliable protection from buckling. However, as the major part of a frame, the beam should not be severely damaged in view of the difficulties and costs required for rehabilitation of the beam. A new braced frame, called knee bracing frame (KBF), having all the favorable features of the above frames but without having the deficiencies, was presented by Aristizabal-Ochoa (1986) and further investigated by Sam *et al*.(1995), Mofid and Khosravi (2000), Balendra *et al*.(2001) and William *et al*.(2002). The KBF uses a secondary structural member (the knee member) instead of the shear link as the "structural fuse" to ensure enough ductility, but achieves excellent lateral stiff ness through the setting of the diagonal brace. By limiting the plastic hinges formed in the knee only, the major parts of the structure are safe and the rehabilitation may then be easy.

The knee bracing steel frame (KBF) is a new kind of energy dissipating frame which combines excellent ductility with lateral stiffness. As the structural fuse of the frame, the knee element will yield first during a severe earthquake so that no damage occurs to the major structural members and

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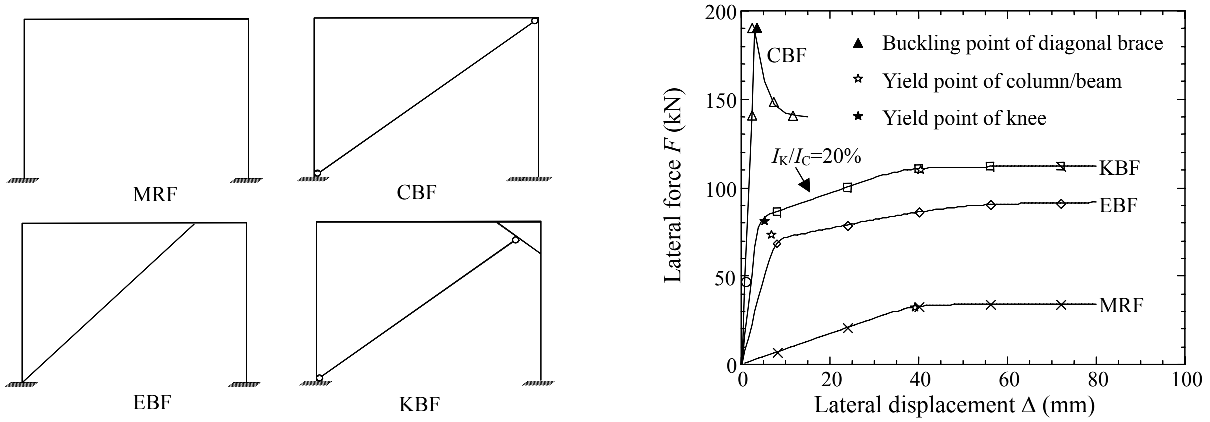
the rehabilitation is easy and economical. To help fully understand the relations between its seismic performance and the structural parameters, systematic elastoplastic analysis of the KBF structure with finite element method was conducted in this work. Finally, general design recommendations were suggested by the analysis results.

BASIC PARAMETERS OF KBF

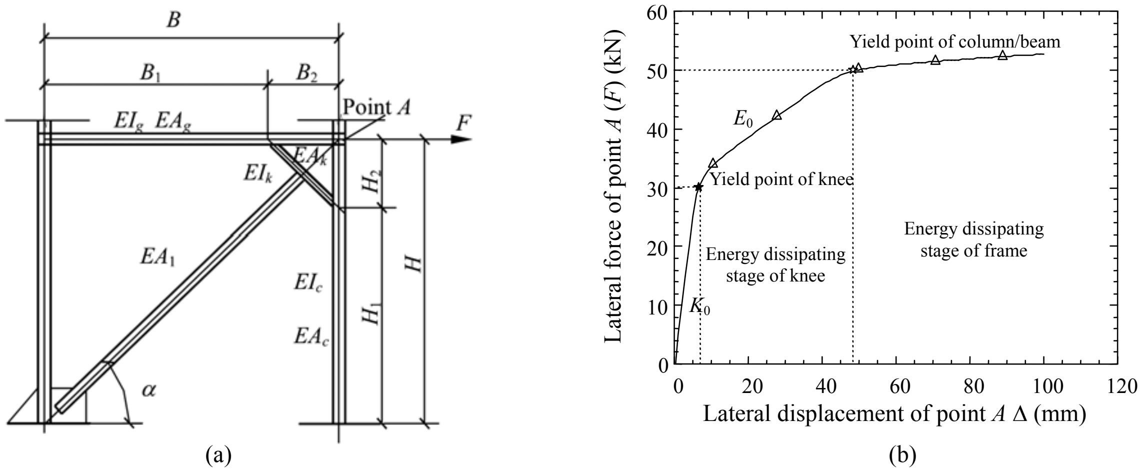
Fig.2a is a typical knee bracing frame with basic research parameters. Fig.2b is the corresponding force-displacement curve. All materials used in the analysis are supposed to have ideal elastic-plastic properties: the elastic module, E=2×10^{11} N/m^2; the shear module, G=7.69×10^{10} N/m^2; and the yielding strength, f_y=2.1×10^8 N/m^2. The profiles of the structural elements are wide flange H. The horizontal load is on point A (Fig.2a).

As shown in Fig.2b, the yielding procedure of KBF could be divided into two stages. First, yielding will occur in the knee member under the action of the lateral force F. At the moment, plastic hinges in the knee-column and the knee-beam connections, and the midpoint of the knee will develop simultaneously. From then on, the structure turns into the energy dissipating stage of the knee, which means that the brace system has reached its ultimate bearing capacity, and the succeeding load should be carried by the main frame until further plastic hinges occur in the columns or the beam, after which a secondary energy dissipat-



(a) (b)

Fig.1 Commonly used steel frame systems and their different lateral performances
(a) Commonly used steel frame systems; (b) Performance comparison of frames



(a) (b)

Fig.2 Typical knee bracing frame
(a) Basic parameters of KBF; (b) Lateral force-displacement curve of KBF

ing stage occurs. Obviously, by making full use of the first stage of energy dissipation, the major structural members can survive a severe earthquake without receiving any permanent damage. Sufficient storage of ductility and safety of the structure can be expected.

BEHAVIOR OF KBF SYSTEM

A KBF frame consists of beam, columns, knee bracing and inclined bracing. The basic dimensional parameters (B, B_1, H, H_1, σ) of KBF are shown in Fig.2a. The research of Mofid and Khosravi (2000) showed that the structure could have maximum earthquake resistance if the knee bracing and inclined brace were parallel to the diagonal of the frame, that means $B_2/B=H_2/H$. At the same time, the dimensional parameters of the frame are reduced to three: B, H, x ($x=B_2/B=H_2/H$), so that the design and research of KFB will be simplified. Fig.3 shows the research parameters used in this paper which are similar to the research parameters of Mofid and Khosravi (2000).

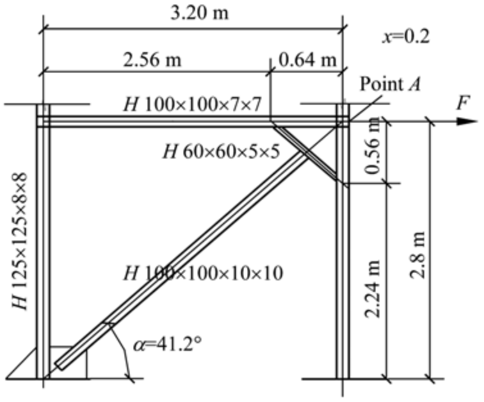


Fig.3 Basic research parameters

Position of knee bracing

The research of Aristizabal-Ochoa (1986) showed that the cross section of knee bracing should meet the requirement that the yield moment of knee bracing is smaller than 50% of the frame column yield moment. But he did not give the details of, and discuss and explain the limitation of the knee cross section. The research of Mofid and Khosravi (2000) yielded only an option parameter x without suggested value. The x value and the lateral performance of frames with different knee elements are compared in Fig.4. Fig.4a shows the force-displacement curves of frames with different x values. Fig.4b shows force-displacement curves of frames with different knee sections.

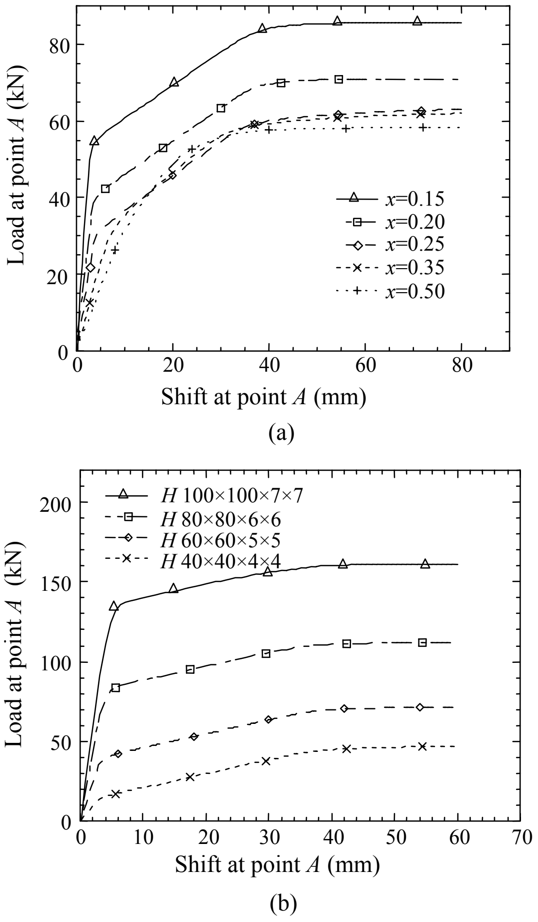


Fig.4 Lateral performance of frames with different knee elements

(a) Force-displacement curves of frames with different x values; (b) Force-displacement curves of frames with different knee sections

In Fig.4a, x ($x=B_2/B=H_2/H$) is 0.15~0.5. This figure shows that the position of the knee has influence on the behavior of the KBF structure. Decrease of x greatly increases the ultimate structural bearing capacity and ductility. Research by William *et al.*(2002) revealed that in order to have good energy dissipating capacity, the knee element should be in bending failure mode rather than shearing failure mode, that is, Eq.(1) should be satisfied.

$$l_k \geq 4M_p/V_p \tag{1}$$

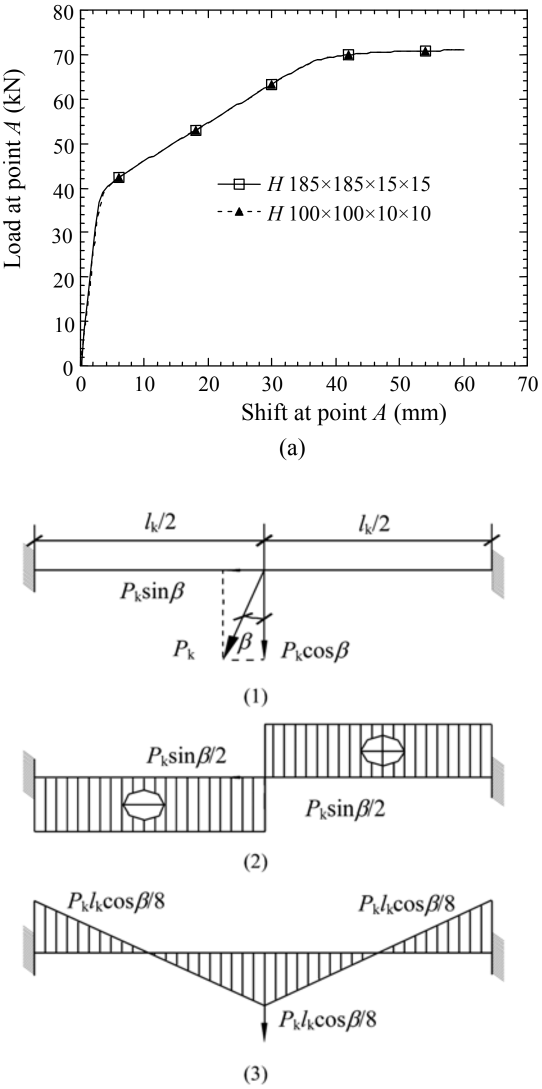
where l_k is the length of knee, M_p is the bending moment, V_p is the shear force.

If x is not less than 0.15, the above equation can be satisfied. The ultimate load reduces as x increases, and tends to a certain value when x is larger than 0.30. At the same time, the ductility tends to decrease. With further increasing of x, the lateral stiffness of the structure in the elastic stage appears somewhat small and the safety of the major structural members is difficult to control. Therefore it is better to choose x (the position of knee) of 0.15~0.30.

Fig.4b shows the force-displacement curves of KBF frames with different knee sections. In Fig.4b the sectional dimensions are H 40×40×4×4~H 100×100×7×7, that is I_K/I_C=1.5%~44%, where I_K is moment of inertia of knee element and I_C is moment of inertia of column. The ultimate bearing capacity is reduced as the area of the knee element is reduced, especially in elastic stage. According to the research results of Aristizabal-Ochoa (1986), the yielding moment of the knee element should be 50% less than that of the column. Same result was obtained in this research. When the sectional area of the knee element is near that of the column, the yielding point of the knee is near the yielding point of the beam or column. Therefore it is difficult to ensure that the knee element yields first in frame. If I_K/I_C<40%, the failure moment of the frame should be more than 1.2 times the yielding moment of the knee element, and so effectively guarantees the safety of the main frame. But if the knee element is too small, the behavior of the total KBF frame should be more like the behavior of an MRF with low stiffness and high ductility. In such case, the knee element easily fails under conditions of normal wind loads, frequent earthquake, or severe earthquake. The analysis indicates that, when I_K/I_C≥20%, the problem mentioned above can be solved perfectly. Generally suitable section ratio of knee element and column element should be I_K/I_C=20%~40%. It is better to choose large I_K/I_C in order to ensure that the knee element will not fail under the normal loads of wind and earthquake.

Lateral performance of frames with different inclined braces

In order to ensure the lateral stiffness of the CBF or EBF frame, brace members with large cross-sections are usually chosen. This not only wastes materials, but also increases the difficulty of construction. Compared to them, the inclined brace member of KBF has many advantages. First, the KBF can be protected with only small cross section knee elements. Second, from Fig.5a, increasing the cross section of the inclined brace members cannot improve the lateral stiffness of the structure. So for economy and convenience of construction, the cross sectional area of inclined brace members of KBF should be small rather than unduly large in order to satisfy the requirement of stability.



(a)

Fig.5 Lateral performance of frames with different inclined braces

(a) Force-displacement curves of frames with different inclined braces; (b) Simplified model and internal forces of knee element

The following formula may be applied to choose suitable inclined brace cross section:

$$P_{\mathrm{cr}}>\gamma P_{\mathrm{k}} \tag{2}$$

where γ is the safety factor, P_{cr} is the yielding load of inclined brace member which yield along the weak axis; P_{k} is the yielding load when the knee member yields. According to the simplified model shown in Fig.5b, the axial force in knee member is $P_{\mathrm{k}}\sin\beta/2$ and the maximum moment in knee member is $P_{\mathrm{k}}l_{\mathrm{k}}\cos\beta/8$. P_{k} can be deduced with the following formula of the total section yielding theory (Shen *et al.*, 2000).

$$\frac{N}{N_{\mathrm{p}}}\leq 0.13,\ \frac{M}{M_{\mathrm{p}}}=1 \tag{3}$$

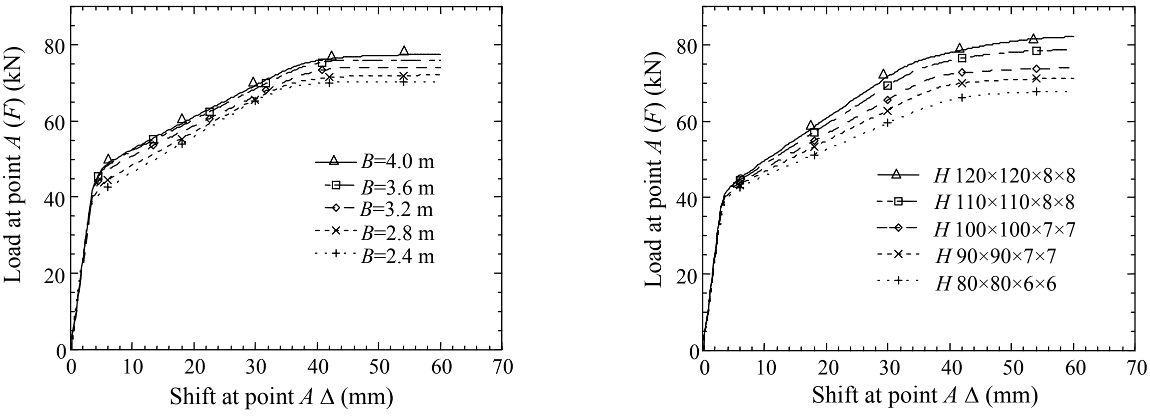
$$\frac{N}{N_{\mathrm{p}}}>0.13,\ \frac{N}{N_{\mathrm{p}}}+\frac{M}{1.15M_{\mathrm{p}}}=1 \tag{4}$$

where M_{p}, N_{p} are the section yielding moment and yielding axial force respectively.

Lateral performance of frames with different columns and beams

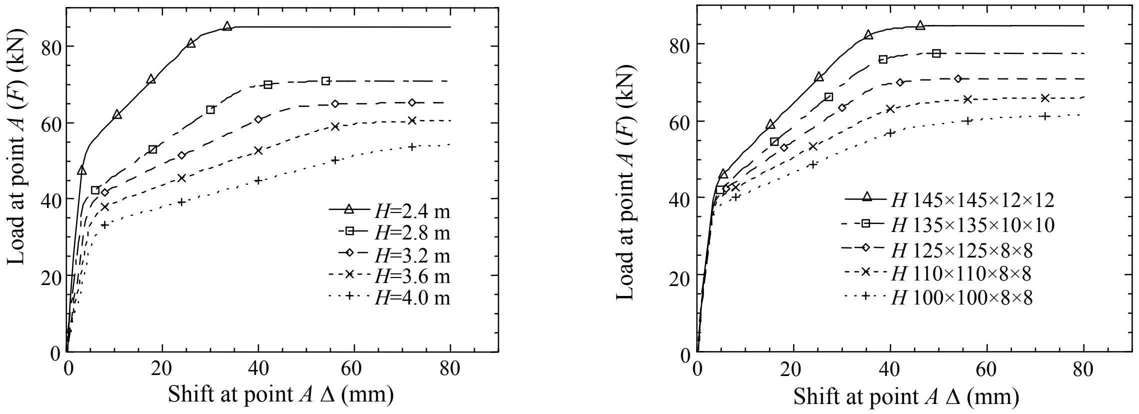
The section stiffness of beams and columns in the frame is determined by their length and cross sections. Their influences on the lateral performance of the frame can be seen in Fig.6 and Fig.7.

Fig.6a shows the force-displacement curves of frames with different beam lengths. Fig.6b shows force-displacement curves of frames with different beam sections. These figures show that the changing



(a) (b)

Fig.6 Lateral performance of frames with different beams. Force-displacement curves of frames with different beam lengths (a) and with different beam sections (b)



(a) (b)

Fig.7 Lateral performance of frames with different column length (a) and different column sections (b)

of beam stiffness has only little influence on the lateral bearing capacity and the ductility of KBF.

Fig.7a shows the force-displacement curves of frames with different column length. Fig.7b shows the force-displacement curves of frames with different column cross section. Evidently, the changing of column length and cross section area has much more influence than that of beam length and cross section area. The most obvious influence can be seen with the changing of column length. Fig.7a shows that with the increasing of column length, the lateral stiffness in elasticity and plasticity stages reduced greatly; the ultimate bearing capacity decreased linearly. But the ductility was much improved while its stiffness was declining. Fig.7b shows that increasing of cross section area had almost no influence on the lateral stiffness at the elasticity stage, but the plastic behavior changed a lot. Therefore, the lateral ability and energy dissipating ability of the steel frame can be feasibly adjusted by changing column stiffness.

In a building, because the length of beams and columns cannot be changed easily, the lateral behavior of the frame can be improved through adjusting the knee elements and the cross sectional dimensions of beam and columns. As the main frame element, changing the cross section area of column is much more effective than changing the beam. As the main lateral force resisting member, the knee element plays an important role. With suitable cross section area and position of knee element, the KBF structure has enough lateral stiffness and good ductility even in severe earthquake.

CONCLUSION

As an energy dissipating system, the knee bracing frame combines excellent ductility and lateral stiffness and is easy for application to rehabilitation if earthquake damaged buildings. With the protection of the knee elements, no damage occurs to the major structural members during a severe earthquake. Systematic FEM elastoplastic analysis of the KBF structure conducted in this work yielded results applicable for general design and suggesting that:

1. The position and stiffness of the knee is the most important factor affecting the lateral resisting ability of KBF and has great influence on its energy dissipating behavior. According to the investigation, the value of I_K/I_C should be 20%~40% and the x value should be 0.15~0.3. In that way the structure has enough lateral stiffness and excellent ductility, and at the same time the failure of knee element under frequent earthquake can be avoided.

2. Inclined bracing member of KBF can be designed with $P_{cr}>\gamma P_k$. Too large cross section area of inclined brace can make construction difficult and waste material, and does not improve the structural lateral resisting ability.

3. As the main members of frame, the beam and columns have influence on the lateral behavior of KBF frame. Changing the column section is much more effective than changing the beam cross section area.

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