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Journal of Constructional Steel Research 62 (2006) 271–281

JOURNAL OF CONSTRUCTIONAL STEEL RESEARCH

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On the characteristics of new ductile knee bracing systems

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Received 6 April 2004; accepted 1 July 2005

Abstract

In this paper, a new structural lateral bracing system called 'Chevron Knee Bracing' (CKB) is investigated. This new form of framing system is constructed through the knee and the diagonal brace elements. The knee part is a fuse-like component that dissipates energy by the formation of plastic flexural and/or shear hinges at its ends and mid-span, when the building is subjected to severe lateral loads. However, the diagonal brace component, on the other hand, provides the required level of lateral stiffness and remains in the elastic range without buckling at any time. In this investigation, first, by studying of the system in the elastic region, three new and practical parameters are established. Then, the best fitting optimal shape and angle of the knee and brace elements are projected, analytically. In the next step, by developing a nonlinear analytical knee element model, the actual behavior of this new CKB system is experienced in the nonlinear static and dynamic analysis, on two example structural systems, where the knee element happens to be in the moment and/or shear yielding mode. Using the results on nonlinear analysis of these test problems, the main properties of the CKB, such as the energy dissipation characteristics of the proposed systems, are properly inspected by establishment of an energy calculation algorithm. Finally, based on the presented optimal shape of the CKB in this paper, two step-by-step algorithms accompanied by appropriate main graphs and charts are suitably demonstrated and nonlinear behavior of the new model for flexural and shear yielding modes is well determined, which is followed in the next paper.

Keywords: Chevron Knee Bracing; Moment link; Shear link; Active parameters; Optimal shape; Energy calculation

1. Introduction

Structures designed to resist moderate and frequently occurring earthquakes must have sufficient stiffness and strength to control deflection and to prevent any possible damage. However, it is inappropriate to design a structure to remain in the elastic region, under severe earthquakes, because of the economic constraints. The inherent damping of yielding structural elements can advantageously be utilized to lower the strength requirement, leading to a more economical design. This yielding usually provides the ductility or toughness of the structure against the sudden brittle type structural failure. Since stiffness and ductility are generally two opposing properties, it is desirable to devise a structural system that combines these properties in the most effective manner without excessive increase in the cost.

In steel structural systems, moment resisting and concentrically braced frames have been widely used to resist earthquake loads. The moment resisting frame possesses 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 deficiencies in moment resisting and concentrically braced frames, Roeder and Popov [1] have proposed the Eccentrically Braced Frame (EBF) system, where the brace is placed eccentric to the beam–column joint. By a suitable choice of eccentricity, a sufficient amount of stiffness from the brace is retained while ductility is achieved through the flexural and/or shear yielding of a segment of the beam, which is called the link, created by the eccentrically placed brace member. To achieve the required ductility, however, severe yielding of the link is expected, which may lead to serious floor damage. Further, as the link is an integral part of a main structural member, retrofitting may be difficult.

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doi:10.1016/j.jcsr.2005.07.005

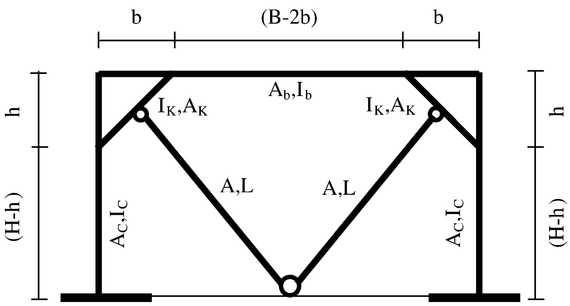

Fig. 1. General form of Chevron Knee Bracing system (CKB).

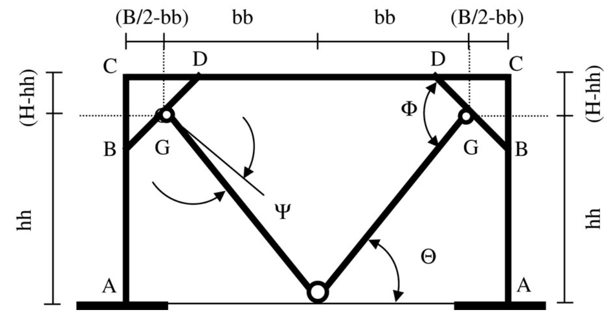

Fig. 2. Form and definition of the parameters.

In recent years, Aristizabel-ochoa [2] has proposed a framing system, which combines the stiffness of a diagonal brace with the ductile behavior of a knee element. This system as originally proposed, however, was not suitable for earthquake-resistant design because the brace was designed to slender. Consequently, the brace buckles and leads to pinching of the hysteresis, which is not efficient for energy dissipation. Further, the inelastic cyclic deformation of the brace which buckles may create a lateral instability problem at the knee–brace joint and causes sudden change to the restoring force of the structure. Subsequently, the system has been re-examined and modified by Balendra et al. [3,6]. The revised system is called the Knee Braced Frame (KBF). In this system, the non-buckling diagonal brace provides most of the lateral stiffness. The flexural or shear yielding of the knee element provides the ductility under a severe earthquake. In this way, the damage is concentrated in a secondary member, which can be easily repaired at minimum cost. Floor distortions are reduced compared to the EBF, to a level similar to that of the conventional moment resisting and concentrically braced frames.

In this paper, the performance of a new knee bracing system called Chevron Knee Bracing (CKB) is discussed, as shown in Fig. 1. The preference of this new system with respect to the similar KBF system, in a nonlinear analytical model is presented. This analytical model is based on the mechanical properties and sectional shape, which are readily defined. The analytical model is verified by comparing with the experimental data from test frames. Also, using this analytical model, the optimal direction of the knee and brace elements is ascertained, via establishment of three new and practical parameters in the elastic as well as inelastic range, employing the static and dynamic analysis. By means of the proposed optimal shape, presented in this paper, the nonlinear response of the new system is carefully demonstrated in the next study, based on the two step-by-step algorithms for flexural and shear yielding mode, through an appropriate and intelligent technique.

2. Elastic analysis

For a single story CKB system, shown in Fig. 1, the expression for the stiffness can be expressed as a function of the variables of the frame as follows:

$$K = f(I_c, A_c, I_b, A_b, I_k, A_k, A, b, h, H, B, E) \tag{1}$$

where b, h, B and H define the frame geometry; E is the Young's modulus of elasticity; A, A_b, A_c and A_k are the cross sectional areas of brace, beam, column and knee, respectively; I_b, I_c and I_k are the sectional second moment of areas of the beam, column and knee, respectively.

Through dimensional analysis, Eq. (1) can be written in a more compact form, after dropping the non-significant parameters as follows:

$$\frac{K}{EI_c/H^3} = f\left\{\frac{I_k}{I_c}, \frac{A/l}{I_c/H^3}, \frac{b}{h}, \frac{h}{H}, \frac{H}{B}\right\} \tag{2}$$

where l is the length of the brace. Based on Eq. (2), for each CKB system, the influence of every parameter in the right side of Eq. (2) on the stiffness of the frame, when the other parameters are constant, can easily be demonstrated. Several studies have been carried out by Balendra et al. [4] to determinate the effect of the right side parameters of Eq. (2), for the KBF system, in the elastic region. However, in this paper three new parameters are established which are described as the following:

$$K_G = \frac{(b/h)}{(B/H)} \tag{3}$$

$$\alpha = \frac{\tan^{-1}(hh/bb) - \tan^{-1}((H-h)/(B/2))}{\tan^{-1}(H/(B/2-b)) - \tan^{-1}((H-h)/(B/2))} \tag{4}$$

$$\beta = \frac{(b/h)}{(hh/bb)} \tag{5}$$

where K_G, α and β are indirectly correlated to the quantity of (b/h), Table 1, the location of point G on the knee element, Fig. 2, and the schematic angle Φ between the brace and the knee element, Fig. 2, respectively.

Referring to Fig. 2 and Table 1, the following remarks can be made:

1. When the brace is a diagonal element which passes through the beam–column intersection and the middle point of the frame and $K_G = 0.5$, this amount remains constant for all related values of (B/H) and (b/h).
2. When point G, the intersection of brace and knee, tends from point D, the intersection of the beam and knee,