The Disposable Knee-bracing Technique in Steel Frames

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A new technique of lateral bracing of steel-framed structures has been suggested by this writer.[1] This technique, denoted as the Disposable Knee Bracing (DKB), combines two elements—the knee element and the diagonal brace element (Fig. 1). The diagonal brace element, whose primary function is to provide the required level of lateral stiffness to the frame, is simply connected to an inclined knee member. The knee-brace member, which is rigidly connected at the ends, is designed to be the first line of dissipation of energy during severe earthquakes without significantly decreasing the lateral stiffness or strength of the frame. This energy dissipation is achieved by the formation of flexural hinges at the ends and midspan of the knees. The knee members should yield by fully developing three plastic hinges prior to any occurrence of yielding elsewhere in the frame during severe earthquakes, so that, during more destructive after shocks the second line of defense, the frame itself, might yield. Further details of this technique are presented elsewhere.[1]

The lateral response of framed structures equipped with DKB's depend mainly on the following parameters: (1) structural geometry and configuration of the structure and bracing system; (2) stiffness and plastic moment capacities of the knee members relative to those of the beams and columns; (3) size (i.e., cross sectional area) of the diagonal members; (4) stiffness and plastic moment capacity of the beams and columns; and (5) type of beam-to-column joint connection and external support restraint conditions.

The main objective of this paper is to investigate, using second-order elasto-plastic analyses, the effects of varying these parameters on the lateral response of steel frames equipped with DKB's. Two test frames, denoted as Test Frames I and II in Fig. 1, were selected in this study. These frames have been investigated previously by the writer.[1] The P-delta effects and the reduction in the plastic moment capacity of each member caused by the axial forces were taken into consideration in the analyses as suggested by Oran.[5] Based on the analytical results obtained, design recommendations are presented.

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PARAMETRIC STUDIES

Parametric studies were carried as follows: (1) the aforementioned parameters were varied one at a time while keeping the rest of them constant; (2) the response of the frames was calculated for every increment of the applied

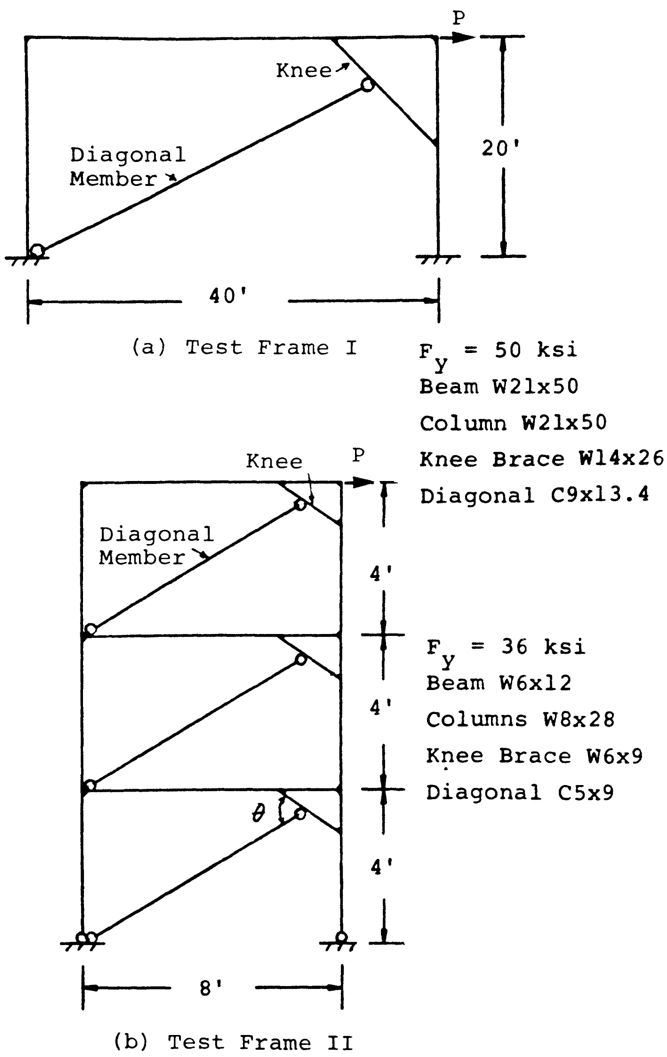

Fig. 1. Test frames

lateral loading; and (3) plots of lateral load vs. lateral deflection of the top floor were first used to indicate the effects of each parameter. The sequence of yielding under the applied loading was also determined and care was taken to verify that the knee members became fully plastic at the ends and midspan prior to any occurrence of yielding elsewhere in the structure. It is also desirable to have the beams yielding before the columns, as this causes less permanent damage to the frames during destructive earthquakes.

The test frames were subjected to a monotonically increasing lateral load which was concentrated at the right-hand top node of the structure. Vertical load effects were not considered in the development of the calculated collapse mechanisms.

Test Frame I

This is a 20 ft (6.1 m) by 40 ft (12.2 m) single-bay, single-story frame. The frame is made up of W21 × 50 A572 Gr. 50 steel members. The base supports and the beam-to-column connections are assumed to be rigid (i.e., Type 1 construction).[4] The first parameter to be varied was the configuration of the knee bracing system.

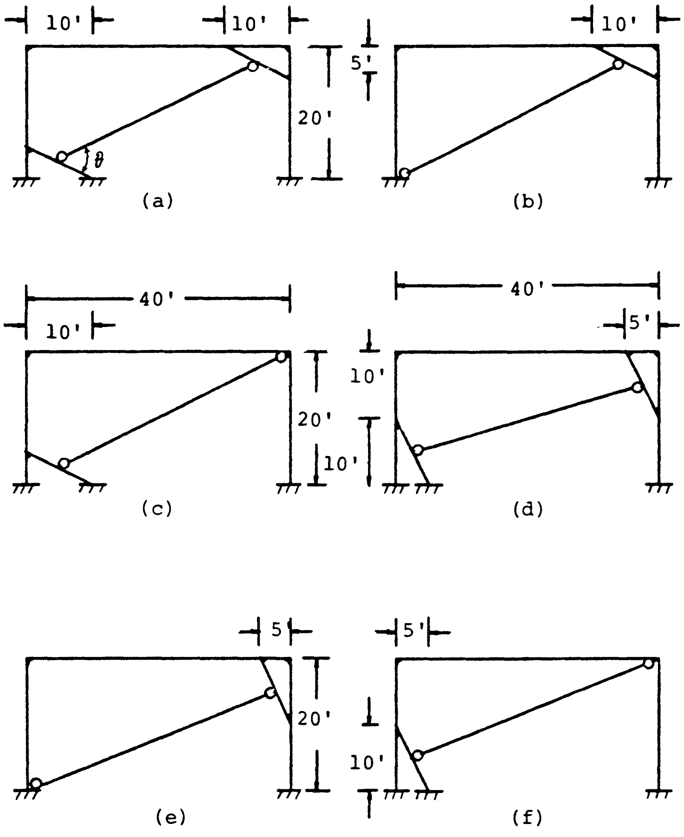

Fig. 2. Different configurations of Test Frame I

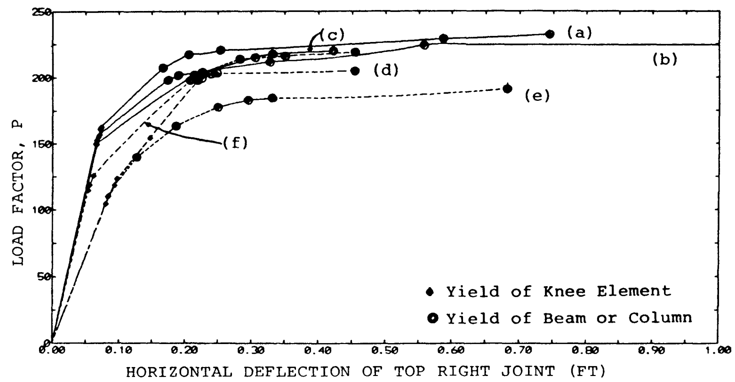

Fig. 3. Lateral responses of different configurations of knee bracing in Test Frame I

Effects of Varying the DKB Configuration—Figure 2 shows the six different DKB configurations of Frame I that were studied. In the first three configurations, $a - c$, the diagonal brace is concentric (i.e., the center line of the diagonal member passes through the center of the beam-column joint). The rest of the configurations, $d - f$, have eccentric DKB's.

Figure 3 indicates that the initial elastic stiffness of Test Frame I depends on the eccentricity of the diagonal bracing. This is largest when the eccentricity of the diagonals is zero, and decreases rapidly as eccentricity increases. With the exception of frame *f*, which has one of the ends of the knee fixed to the foundation, the eccentrically braced frames *d* and *e* show lower initial lateral stiffness and ultimate strength than those of the concentric braced frames $a - c$. The concentric double-knee bracing of frame *a* shows the highest strength, and the top single-knee bracing of frame *b* shows the largest ductility and second best ultimate capacity. The DKB configuration of frame *b* appears to offer the best performance for the least number of connections and members, therefore it will be further investigated in the bracing of Test Frame II.

Effects of Size of Knee Member—Seven different sizes of knee members were considered and their effects on the response of Test Frame I are shown in Fig. 4. The calculated curves indicate initial stiffness, sequence of yielding and lateral ductility of the frame are not affected significantly by the size and plastic moment capacity of the knee member, but it has a considerable effect on the ultimate strength of the frame. Figure 5 indicates the ultimate capacity of the frame varies linearly with the plastic capacity of the knee member. This behavior is expected as long as the plastic moment capacity of the knees is small enough so they become fully plastic before any other member yields, particularly before the columns do.

Effects of Size of Diagonal—The size (area) of the diagonal affects the initial stiffness and ductility of the frame (Fig. 6), as well as the overall stability (buckling) of the columns.[2] Thus the structural designer can use the size of the diagonal to control the initial elastic stiffness of the

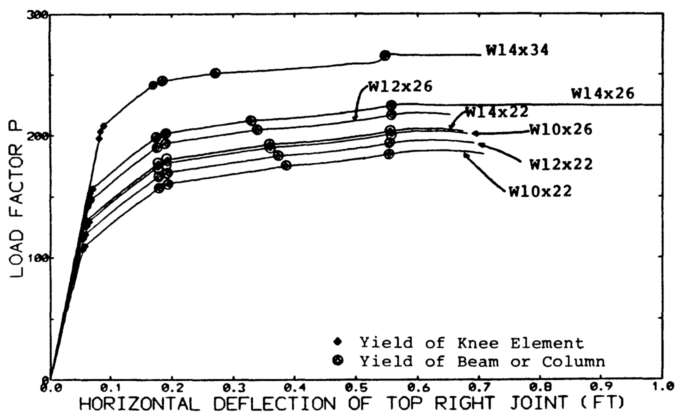

Fig. 4. Effects of size of knee brace on Test Frame I

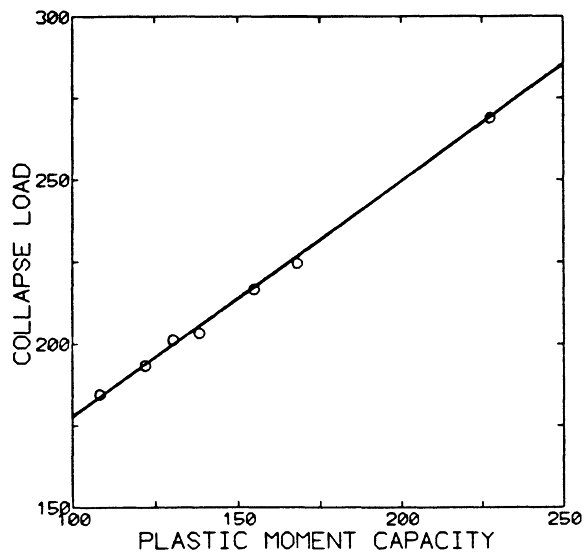

Fig. 5. Effects of plastic moment capacity of knee brace on strength of Test Frame I

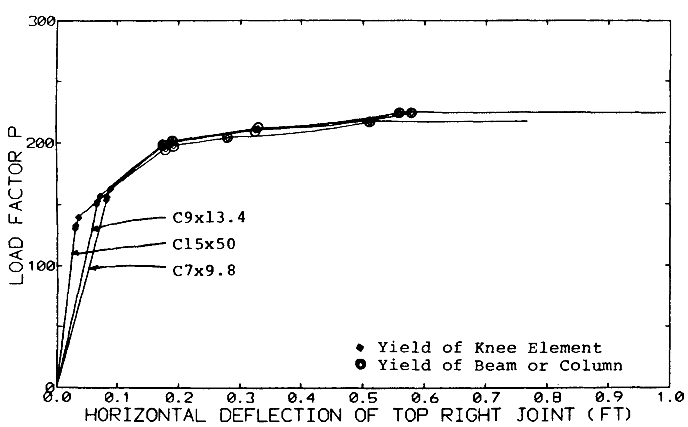

Fig. 6. Effects of diagonal size on Test Frame I

frame. However, the diagonal cannot be excessively strong as they may cause buckling in the most compressed column and also prematurely activate yielding in the knee members at very low drifts and, thus reduce the overall strength and ductility of the frame. The size and capacity of the diagonals shall be chosen as the minimum values that will make them remain elastic at all times.

Effects of Beam Size—The response of Test Frame I with different beam sizes is shown in Fig. 7. The initial lateral stiffness of the frame is slightly increased by the beam size; and after the knee members become fully plastic, the lateral stiffness of the frame is greatly affected by the beam size. As the plastic moment capacity of the beam increases, the beam yields at a larger lateral load and smaller deflection.

However, the major effects of the beam size are on the ultimate strength and mode of failure of the frame. The effects of the plastic moment capacity of the beam on ultimate strength of the frame are shown in Fig. 8. These

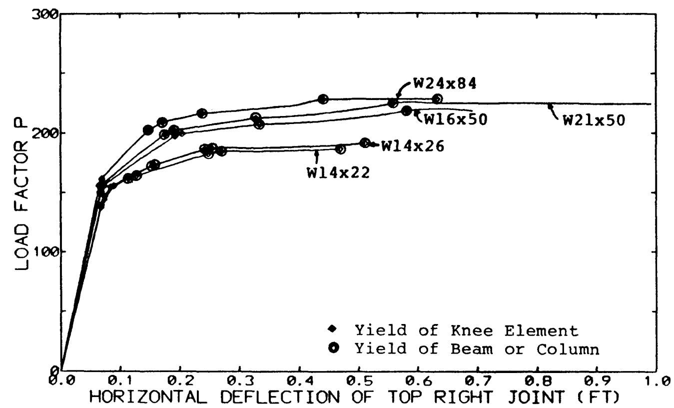

Fig. 7. Effects of size of beam on Test Frame I

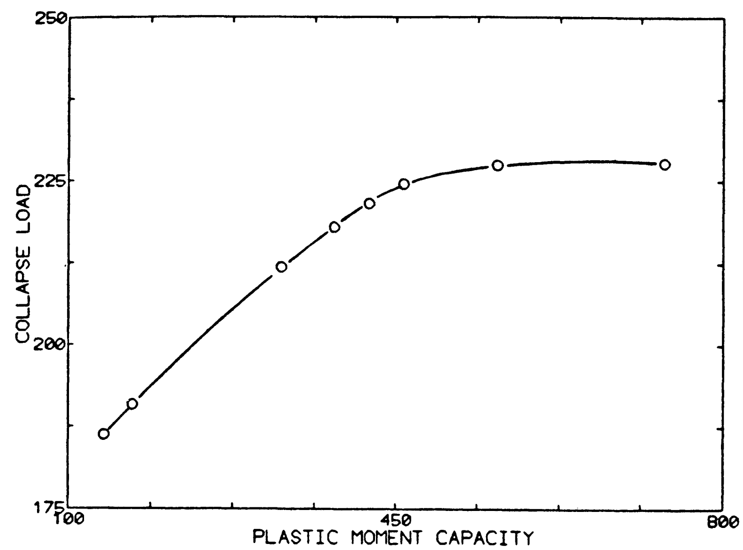

Fig. 8. Effects of plastic moment capacity of beam on strength of Test Frame I

results indicate it is beneficial to have strong beams, but they should not be as strong as the columns. Figures 7 and 8 show that when the beam is made as strong as the columns, the overall lateral strength of the frame ceases to increase and overall lateral ductility tends to decrease. After the knee elements become fully plastic, the beam should be designed to be the next yielding element, so that a catastrophic collapse or damage beyond repair of the frame can be avoided.

Effects of Joint and Support Conditions—The effects of changing the beam-column connections from perfectly rigid (Type 1) to simple (Type 2) are shown in Fig. 9. The initial elastic stiffness is not affected significantly, but overall lateral strength is reduced and ductility is increased by unrestraining the beam-column connections. For an ideally hinged beam-column connected frame, the beam never yields, and after the knee elements become fully plastic, the columns start to yield. However, it is expected that any joint rotational restraint (i.e., some level of beam-column continuity) would be beneficial as long as such restraint has sufficient rotational ductility capacity. If the rotational ductility capacities of the beam-to-column connections cannot be guaranteed, then it is recommended to assume simple or unrestrained connections in the analysis and design of the frame.

The effects of changing the restraint conditions at the base supports from fixed to hinged are shown in Fig. 10. The initial elastic stiffness and lateral strength of the simple supported frame are about 80% and 70% of those of the fixed frame, respectively. The overall ductility is also reduced, because in the frame with hinged supports the collapse mechanism is reached when two plastic hinges are formed at the ends of the beam—while in the frame with fixed supports, two additional plastic hinges at the base level are required in the columns. Because of these behavior and effects, fixed supports are recommended in single-story frames.

Test Frame II

The lateral behavior of the three-story one-bay frame shown in Fig. 1b was analytically investigated. The overall dimensions and structural steel shapes utilized in Test Frame II are those of a ⅓-scaled model frame previously investigated by Manheim and Popov.[3] A direct comparison between the DKB technique and Popov's eccentric bracing technique is presented elsewhere.[1]

Effects of Varying the DKB Configuration—The two configurations investigated are shown in Fig. 11. The configuration with double DKB's, Fig. 2a, offers the highest performance, however, it is not included here. This is partly because the relatively low gain in lateral stiffness, strength and ductility compared to the additional number of knee members and connections needed in the double-knee configuration. Based on the results of Test Frame I, it is expected that the single DKB configuration, Figs. 1b and 2b, offers the most balance between overall structural performance and economy.

Responses of the two DKB configurations of Test Frame II are shown in Fig. 12. The initial elastic stiffnesses are identical, but the ductility and failure mode are remarkably different. In the frame with bottom DKB's, Fig. 11b, the first floor knee failed prematurely by excessive compression near the foundation fixed end, and the complete development of the collapse mechanism of the frame was impaired. The test frame with top DKB's, on the other hand, showed excellent ductility and formation of a complete collapse mechanism.

Effects of Size of Diagonals—The effects of varying the cross area of the diagonals in Test Frame II with top DKB's are in Fig. 13. As expected, the initial elastic stiffness of the frame increases as the area of the diagonals increases. This increase was substantially higher than obtained in Test Frame I. Contrary to what was obtained for Test Frame I, in which the lateral strength was not affected by the size of the diagonals, there is a slight increase in strength as the diagonals are made larger in multi-story frames.

Effects of Beam Size—Similar to the pattern calculated for Test Frame I, the initial elastic lateral stiffness and lateral strength of the frame increased as the size and plastic

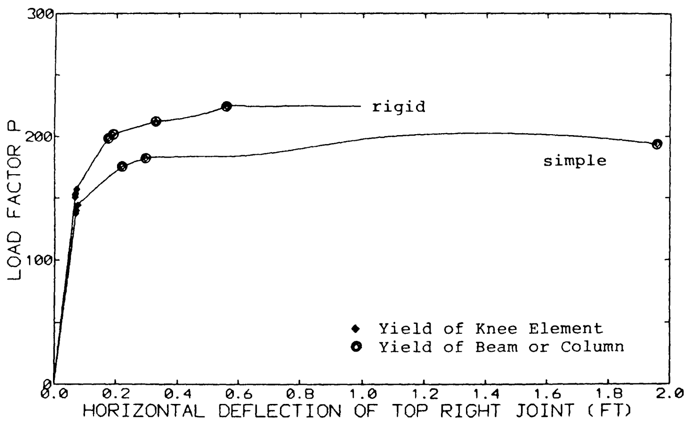

Fig. 9. Effects of beam-column connections on Test Frame I

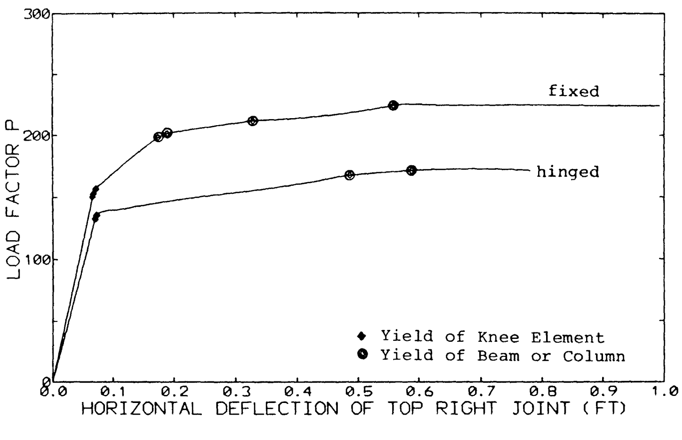

Fig. 10. Effects of support conditions on Test Frame I

capacity of the beams were increased. However, ductility of the frame was reduced.

Effects of Joint and Support Conditions—The effects of changing the type of beam-to-column connections in Test Frame IIb are in Fig. 14. As expected, the stiffness and strength of the frame were reduced and the ductility increased by simply connecting the vertical and horizontal members. It is interesting that the simply connected frame was capable of developing a complete collapse mechanism, but the rigidly connected frame was not because of the premature failure of the bottom brace, as previously discussed.

Figure 15 shows the effects of changing the support conditions from perfectly fixed to perfectly hinged in Test Frame IIb. As expected, restrained supports increase the stiffness, strength and ductility of the structure. Note that by fixing the columns, the expected premature failure of the bottom knee was avoided and a complete collapse mechanism was then obtained.

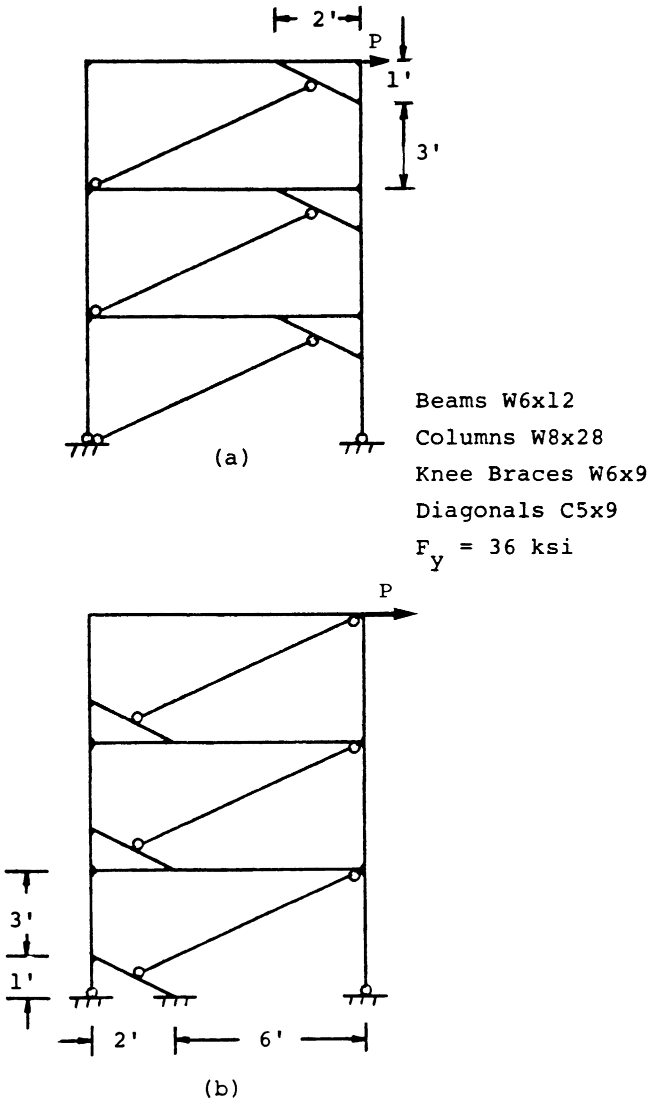

Fig. 11. Different configurations of Test Frame II

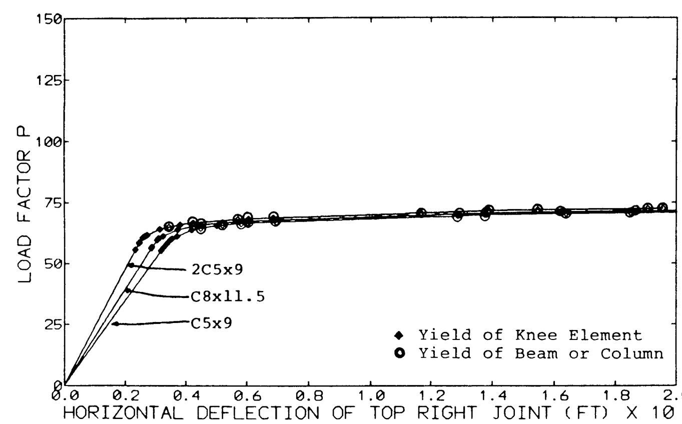

Fig. 13. Effects of diagonal size on Test Frame IIa

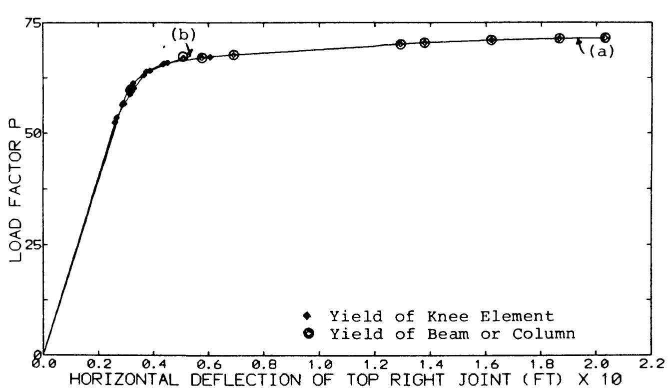

Fig. 12. Lateral responses of different configurations of Test Frame II

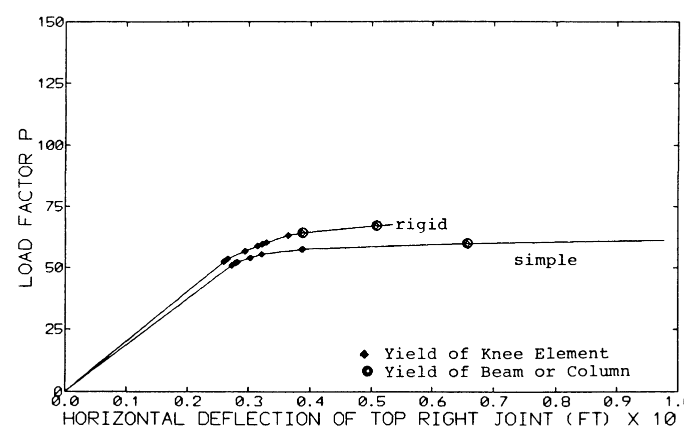

Fig. 14. Effects of beam-column connections on Test Frame IIb

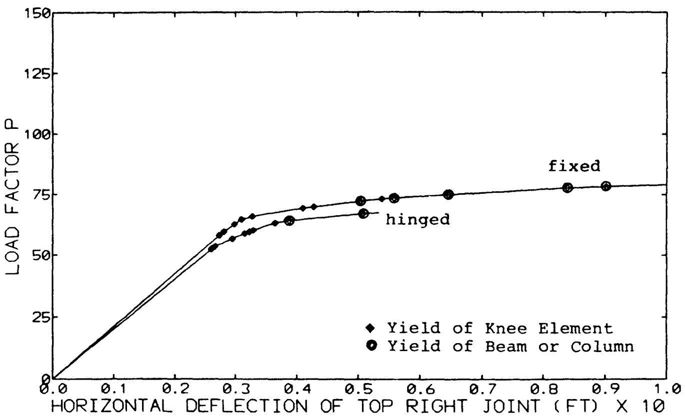

Fig. 15. Effects of support conditions on Test Frame IIb

CONCLUSIONS AND RECOMMENDATIONS

The effects of the DKB technique on the lateral response of single- and multi-story frames were shown using second order elasto-plastic analyses. The reduction in the plastic moment capacity of each member caused by axial deformations were included in the analyses. The effects of shear distortions were not considered.

The structural benefits offered by the DKB technique are quite apparent, particularly the high strength and ductility. The disposable knees have the potential of absorbing the bulk of the energy imposed to framed structures during severe earthquakes without yielding occurring in the main framing system and without a significant loss in lateral stiffness.

Based on the results obtained, a few recommendations are given in the design of DKB's:

1. Diagonal members must be simply connected to the midspan of the knee braces. Concentric diagonals give the best response, thus the ratio of the projections (vertical to horizontal) of the knees must be identical to those of the story bay.
2. The axial stiffness of the diagonals controls the initial elastic stiffness of the frames. Care must be taken to guarantee that diagonals remain in the elastic range at all times. Heavy diagonals must be avoided, since this might lead to premature failure of the frame due to buckling in the most compressed columns.
3. The lateral strength of the frame can be controlled by varying the size of the knee elements. The strength of the frame increases linearly with the plastic capacity of the knees. However, the M_p of the knees must always be less than that of the beams, so the knees can yield first. The lateral strength of the frame also increases with the plastic moment capacity of the beams, but only up to certain value. If the M_p of the beams is made as large as the M_p of the columns or larger, the lateral strength ceases to increase and the ductility of the frame is reduced.
4. To insure lateral stability of the frame after the knees become fully plastic, a weak girder-strong column design is preferred. Therefore, beams must be weaker than columns, but stronger than the knees. In general, it is recommended to use knee elements that are over 50% lighter than the column size with a plastic moment capacity of less than $P\ell$ Sin $\theta/8$ (P = the yield force capacity of the diagonal element, ℓ = the length of the knee element and θ = the angle the diagonal makes with the knee element). This criteria is based on a complete plastic mechanism of a fixed-fixed beam under a concentrated load at mid-span.
5. Knee members located in the first floor level are generally subjected to high bending and compressive axial load, particularly when it is less than 90% and bottom DKB's are used. Therefore, to avoid premature failure of the knees before the complete collapse of the frame is developed, the designer must exercise special caution in proportioning the different elements of the structure at the first floor level, as well as the rotational restraints of the supports.
6. Hinged supports and simple beam-column connections reduce the strength and initial stiffness of the frame. Analytical results suggest the degree of fixity at the beam-column connections and at the supports is not extremely important, as it is with other bracing techniques.[6] However, some degree of stable rotational restraint at the joints and supports is structurally beneficial.
7. Proper detail considerations must be given to the design and construction of the knee connections to the columns and beams to guarantee a high level of rotational ductility.
8. Further analytical and experimental research is needed to corraborate the findings presented and to establish the merits of the DKB technique.

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