BEHAVIOR OF BRACED REINFORCED CONCRETE FRAMES SUBJECTED TO CYCLIC LATERAL LOADS

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SUMMARY

Reinforced concrete frames with K-shaped diagonals, rather than using shear walls for stiffening and strength, were often preferred in buidings to provide open passage. Design guidelines for this type construction were not available. This paper describes the test results of one-third scale frames having K-shape bracing subjected to lateral load reversals, and suggests design recommendations for ductile performance. A theoretical analysis method developed for this study well predicted the behavior of the specimens, and has been successfully applied to the design of a four-storied building.

EXPERIMENTAL STUDY

Specimens: Details of five specimens, KRC-1 to KRC-5, are shown in Table 1 and Fig. 1. KRC-5 had two stories and the other four specimens had single story. The specimens were of approximately one-third scale of the prototype. In specimens KRC-1 & 2, the beams were made stronger such that failure was forced to occur in the compressive brace prior to the beam flexural yielding. The brace dimensions were changed in the two specimens. In specimens KRC-3 & 4, the failure was forced to occur in the beams by reducing beam strength and increasing column strength from the previous two specimens. The two specimens had different beam reinforcements.

Test method: A specimen was placed in a loading frame (Fig. 2). In tests KRC-1 to KRC-3, two oil jacks were prepared, but the compressive side jack was used at a time to apply lateral load. In this case the beam carried only compressive force. In test KRC-4, additinal two jacks were used so that a beam on one side of the brace joint carried compressive force while the other beam carried tensile force of the same magnitude. Consequently, the beam of specimen KRC-4 was provide with more reinforcements to resist tensile axial force than that of specimen KRC-3. Two-storied KRC-5 specimen was loaded at the second beam level by the compressive side jack. The first story was reinforced similar to specimen KRC-4, and the second story similar to KRC-3. Axial forces in the braces were measured by load cells placed at the center of the braces. After two to three cycles of load reversals, the displacement amplitude was increased in all specimens.

Results: The envelop curves of load-displacement relationship are shown in Fig. 3. Loads and deflections (divided by story height) at maximum resistance and at failure are listed in Table 2. In all specimens tensile cracks appeared in the tension braces, followed by flexural cracks in frame members and tensile yielding in the tensile braces. Specimen KRC-1 failed abruptly in crushing of the compressive brace just after yielding occured at the column tops and bottoms. In case of specimen KRC-2, the compressive brace failed in flexural crushing and spalling of crushed concrete well after yielding at

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the column ends, showing ductile performance. The compressive thrust in a brace must be limited to 0.6 times its compressive strength to attain ductile performance of the system. The yielding at the compressive brace ends was observed prior to yielding in beams and columns in specimens KRC-3 & 4. Due to increase in column strength and reduction in beam strength, flexural yielding was observed at the ends of beam segment opposite to loading side, showing higher resistance than specimen KRC-1 & 2. Even after formation of the collapse mechanism as shown in Fig. 4(a) at displacement 1/50 times story height, the displacement increased to 1/30 times story height without reduction in resistance. A sizable reduction in length of the compressive bracing was measured to occur at the location of plastic hinges at the brace ends without reduction in axial load carrying capacity(Fig. 5), which was approximately 60 percents of the pure axial load carrying capacity calculated from material properties(dashed line in Fig. 5). Failure was caused by flexural crushing and spalling of crushed concrete at the top of the compressive brace. The differences between specimen KRC-3 and KRC-4 were in the sequence of the yield hinge formation. The behavior was ductile in both specimens. It is important to determine the beam stregth so that the brace compression force will not exceed the limiting value suggested above at the formation of collapse mechanism. At the same time, the beam must be reinforced against axial tension force developed in the K-shape brace structure. Specimen KRC-5 behaved in a manner similar to specimens KRC-3 & 4 in general. Failure was caused by simultaneous flexural crushing in compressive braces in the two stories and by shear failure in the first story beam.

THEORETICAL ANALYSIS

Method: Frame members and braces were subdivided into layers parallel to longitudinal axis of each member as well as into segments along the member length (Fig. 6), each element representing either concrete or steel. The element stiffness was defined using uniaxial material stress-strain relation. The plane section was assumed to remain plane, and section shear rigidity proportional to the weighted average of element axial stiffness. The slipping of brace reinforcing bars within a connection was represented by springs (Fig. 7).

Discussion: The analytical model simulated successfully the sequence of formation of plastic hinges and collapse mechanism observed in the specimens (Fig. 3). The sudden drop in resistance near the maximum resistance of specimens KRC-1 & 2 is related to a numerical technique used to release an unbalanced force caused by stiffness change during a loading interval. The analysis underestimated the displacement in a region where the resistance was greater than one-half the ultimate strength, probably because the shear deformation and shear cracks were not accurately modelled. The large amount of shortening of the compressive brace was confirmed to be attributable to the interaction of bending and axial resistances at the plastic hinges near the brace ends (Fig. 5). The analytical method using layer elements was concluded to be quite effective to predict the behavior of K-braced frames. Shear deformation and bar slippage should be more accurately modellized.

ACKNOWLEDGMENTS

The authors are grateful to Dr. S. Kokusho for comments and suggestions. The study was supported by the Nippon Telegraph and Telephone Corporation.

Table 1. Details of Test Specimens

member / specimen	column	beam	brace	size: mm depth×width
KRC-1 Fc=265	8-D16	18-D16	4-D13	column
KRC-2 Fc=300	8-D16	18-D16	4-D16	200 × 450
KRC-3 Fc=300	16-D16	8-D16	4-D16	beam
KRC-4 Fc=241	16-D16	14-D16	4-D16	300 × 450
1st. story	16-D16	14-D16	4-D16	brace
KRC-5 Fc=257				†100 × 100
2nd. story	16-D16	8-D16	4-D16	150 × 150

COMMENT: Fc is compressive strength of concrete in kg/cm^2. The 8-D16 means longitudinal reinforcements in total composed of eight deformed bars with 16 mm diameter. Yield strength of steel is 3715 to 4030 kg/cm^2. Braces are reinforced with hoops spacing in four times a main bar diameter. In case of KRC-1, brace size is symboled with †.

Table 2. Test Results

	maximum loading		failure	
specimen	load ($\frac{\text{test}}{\text{cal.}}$) ton	deflect. rad.	load ton	deflect. rad.
KRC-1	47.1 (1.08)	1/138	47.0	1/104
KRC-2	68.2 (1.09)	1/77	67.2	1/45
KRC-3	94.2 (1.20)	1/17	75.0	1/12
KRC-4	84.1 (1.12)	1/31	82.0	1/29
KRC-5	82.6 (1.21)	1/29	-62.0	-1/29

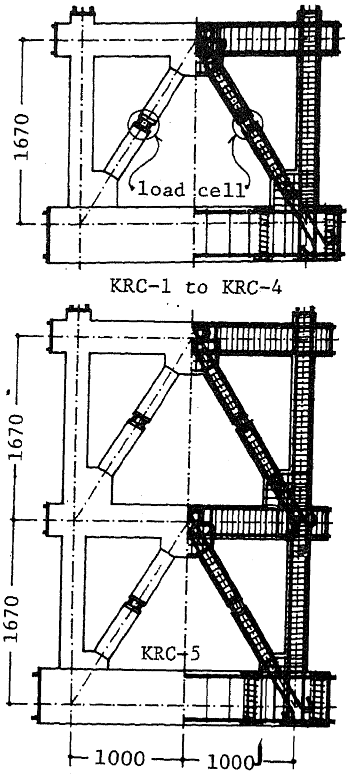


Fig. 1 Test Specimens

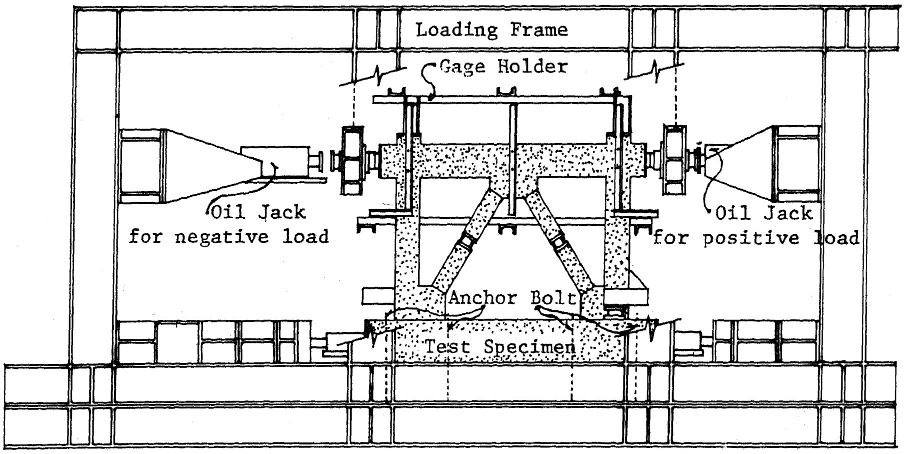


Fig. 2 Testing Frame

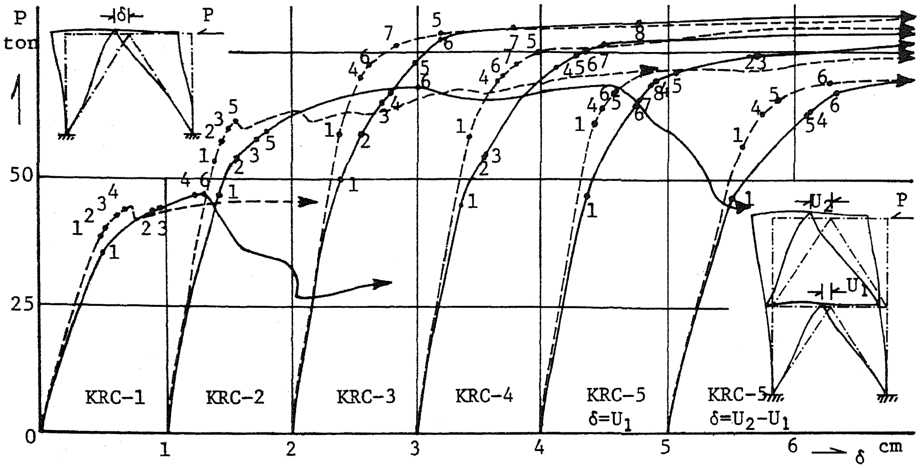
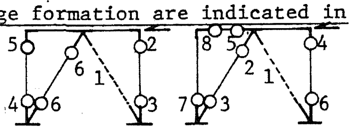


Fig. 3 Envelop Curves (———:tested, -----:analized)
note:the sequential numbers of hinge formation are indicated in Fig. 4.



KRC-1 & 2
(a)

KRC-3 & 4
(b)

Fig. 4 Collapse Mechanism

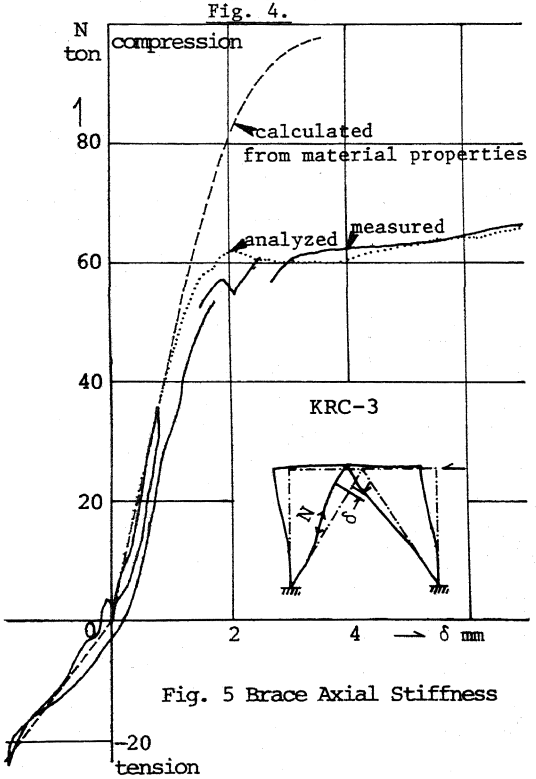


Fig. 5 Brace Axial Stiffness

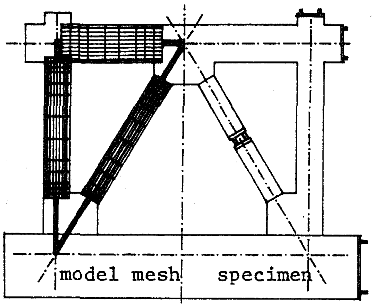
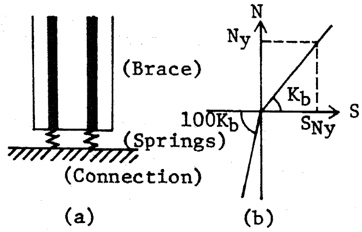


Fig. 6 Model For Analysis



(a)
(b)

Fig. 7 Spring For Bar Slip