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EVALUATION OF SLAB-BEAM-COLUMN JOINT RESPONSE UNDER BIDIRECTIONAL LOADING

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SUMMARY

Reinforced concrete slab-beam-column joints were tested under unidirectional and bidirectional loading conditions simulating earthquake effects. The specimens failed in joint shear after developing beam flexural yielding. Biaxial interaction between applied loads was observed during bidirectional loading cycles. Slab reinforcement appeared to participate in beam negative bending at large drift levels.

INTRODUCTION

A cooperative research program on design of reinforced concrete beam-column joints has been conducted by researchers in the United States, New Zealand, the People's Republic of China and Japan. The objective of the program is to evaluate the behavior of slab-beam-column connections designed following the code requirements or guidelines of these countries.

Three full-scale slab-beam-column connections were tested at the University of Texas as part of the program. The specimens, procedures and results of the tests are described herein.

TEST PROGRAM

Specimens Three reinforced concrete slab-beam-column subassemblies shown in Table 1 were tested under seismic loading conditions. The specimens were full-scale models designed using recommendations of ACI 352 (Ref. 1) and Appendix A of ACI 318 (Ref. 2). Specimen J1 was a plane-frame joint with beams in only one direction and was tested unidirectionally. Specimens J2 and J3 were interior and exterior joints with beams in two orthogonal directions and were subjected to bidirectional loading. The beam or column sections had the same dimensions but were reinforced differently in each specimen to produce forces which were expected to reach the recommended joint shear strength.

Details of Specimen J2 are shown in Figs. 1 and 2. The beam-column joint was laterally reinforced with five layers of #4 bars. Three layers were placed between the top and bottom beam bars. Each layer consisted of one closed hoop and two single-leg crossties (one in each direction). The hoop was closed with 135° hooks and the crosstie had 90° and 135° hooks at its ends. All hooks terminated in a six-bar-diameter extension. Specimens J1 and J3 had the same amount of the joint transverse reinforcement as in J2. The column depth to bar diameter ratio for beam bars passing through the joint was greater than or equal to the recommended value of 20. The top and bottom bars in the normal beam of J3 were anchored with 90° hooks into the exterior joint. The slab of the specimens was 5 in. thick and had double layers of reinforcement in both directions. The top and bottom slab bars were continuous over the beams in J1 and J2 and were anchored with 90° hooks into the spandrel beams in J3.

Normal weight concrete with a design strength of 4000 psi and deformed grade 60 bars were used in the specimens. Concrete was placed in two stages. The lower column, beams and slab were cast in one operation and the upper column was cast several days later.

Loading Program The loading setup for Specimen J2 is shown in Fig. 3. The bottom of the specimen was rested on a pin connection that allowed rotations in all directions. The top of the column was attached to the reaction wall with steel struts that were tensioned to prevent horizontal translation of the column and rotations about the vertical column axis. The specimen was subjected to cyclic loading with hydraulic rams at the beam tips. Two rams were used in one loading operation (one ram up and the other ram down in equal displacement). No axial load was applied to the column.

The cyclic loading was controlled by drift angle as shown in Fig. 4(a). During bidirectional loading cycles at 2% and 4% drift levels, the loading direction was changed alternately at every quarter cycle so that the drift angle orbit traced square paths on the bidirectional drift plane as shown in Fig. 4(b).

TEST RESULTS

Story Shear-Drift Angle Relations The hysteretic response of the specimens showed considerable pinching as plotted in Fig. 5. All specimens reached higher strength than that calculated assuming a beam hinge mechanism (broken lines). First yielding of beam bars (BY or TY) was observed under loading to 2% drift. Column bars yielded at 2% to 4% drift levels (CY).

Specimen J1 failed in joint shear under unidirectional loading to 4% drift and showed a large drop in the story shear. Specimens J2 and J3 were subjected to bidirectional loading which produced the vertical segments in the story shear-drift angle curves. J3 showed a large loss of story shear under downward loading (+ drift) because of anchorage distress in the hooked top beam bars.

Failure Mode The final crack pattern for J2 is shown in Fig. 6. The specimen developed flexural cracks in the slab, beams and columns. Some of the slab flexural cracks propagated into the beams and were inclined to the beam axis. Torsional cracks formed in the beams near the column at 1% to 2% drift levels. Concrete started crushing in and near the joint during bidirectional cycles to 2% drift. Concrete in the joint region spalled considerably during cycles to 4% drift, particularly under bidirectional loading. Spalling exposed reinforcing bars in the joint region. The specimen underwent a rapid increase of joint shear distortion indicating joint shear failure during the final stages of loading.

Bidirectional Interaction The interaction between loading directions is quite apparent in the skewed nature of the story shear orbit for J2 as shown in Fig. 7. Loading or even unloading in one direction lowered the story shear in the other direction and resulted in the vertical segments in the story shear-drift angle curves.

Joint Shear Strength Table 2 shows maximum story shears measured during unidirectional and bidirectional cycles at 4% drift levels. The table also includes story shears calculated from the joint shear strength following the recommendations of ACI 352 (Ref. 1). The measured biaxial shear was defined as the square root of the sum of squares of the story shears in two orthogonal directions. The calculated biaxial shear was based on circular or elliptical interaction curves constructed between calculated uniaxial shear strengths. In all the specimens, the measured maximum shear exceeded the calculated strength under unidirectional or bidirectional loading. Specimen J2 sustained the highest shear probably because the joint was confined by beams in the two directions. The maximum shear for J3 was comparable to that for J1. It should be noted that the measured biaxial strength exceeded the measured uniaxial strength in both J2 and J3.

Effective Slab Width The effective slab width for beam negative moment was calculated from measured slab bar stresses as shown in Fig. 8. The effective slab width was taken as the ratio of tensile force in the slab reinforcement to the force if all slab bars yielded. The effective width thus calculated indicates the increasing participation of slab reinforcement at large drift levels.

Table 3 shows maximum beam moments measured at the column face in comparison with calculated moment capacities. The measured negative moments were 40 to 50% higher than the calculated capacities of rectangular beam sections. However, the negative moment capacities calculated assuming participation of slab reinforcement within 60% of the slab width resulted in good estimation of the measured maximum moments.

CONCLUSIONS

The following conclusions were obtained from the results of the tests:

(1) All specimens failed in joint shear at 4% drift cycles after yielding of beam bars at lower drift levels.

(2) Biaxial interaction was evident in the measured story shears in that loading in one direction lowered the story shear in the other direction at a comparable drift level.

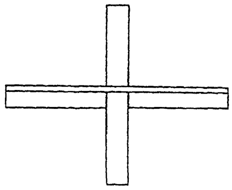
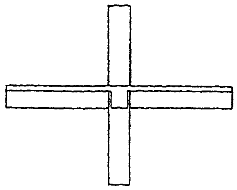
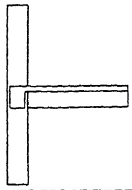
(3) The measured strength of all specimens was higher than that calculated for joint shear failure. The interior joint with beams in two directions reached the highest strength of the three specimens. The measured biaxial strength exceeded the measured uniaxial strength.

(4) The slab width acting with the beam in negative bending increased with the drift level. Beam moment capacities calculated assuming participation of slab reinforcement over 60% of the slab width resulted in good agreement with measured maximum negative moments.

REFERENCES

1. ACI-ASCE Committee 352, "Recommendations for Design of Beam-Column Joints in Monolithic Reinforced Concrete Structures," American Concrete Institute, Detroit, 1985.
2. ACI Committee 318, "Building Code Requirements for Reinforced Concrete (ACI 318-83)," American Concrete Institute, Detroit, 1983.

Table 1 Outline of Specimens

Specimen	J1	J2	J3
Configuration (Side View)			
Joint Type	Plane Joint	Interior Joint	Exterior Joint
Loading	Unidirectional	Bidirectional	Bidirectional
Concrete fc' (psi)	3500 (3520)	4010 (3780)	4700 (3250)

() : concrete strength for upper column

Table 2 Measured Maximum Story Shear in Comparison with Calculated Joint Shear Strength

Maximum Story Shear (kips)	J1	J2		J3	
	(Uniaxial)	Uniaxial	Biaxial	Uniaxial	Biaxial
Measured	50.3	72.0	73.4	45.8	54.8
Calculated	35.6	46.8	46.8	38.2	40.6

Table 3 Measured Maximum Beam Moment in Comparison with Calculated Moment Capacity (Negative Bending)

Beam		M_{test} (k-in)	${}_RM_{calc}$ (k-in)	$\frac{M_{test}}{{}_RM_{calc}}$	${}_TM_{calc}$ (k-in)	$\frac{M_{test}}{{}_TM_{calc}}$
J1	East	4288	3057	1.40	4757	0.90
	West	4516		1.48		0.95
J2	East	6156	4303	1.43	5726	1.08
	West	6478		1.51		1.13
J3	West	6768	4396	1.54	6041	1.12

M_{test} = measured maximum beam moment
${}_RM_{calc}$ = calculated capacity of rectangular beam section
${}_TM_{calc}$ = calculated capacity of T-beam section with 60% of slab width

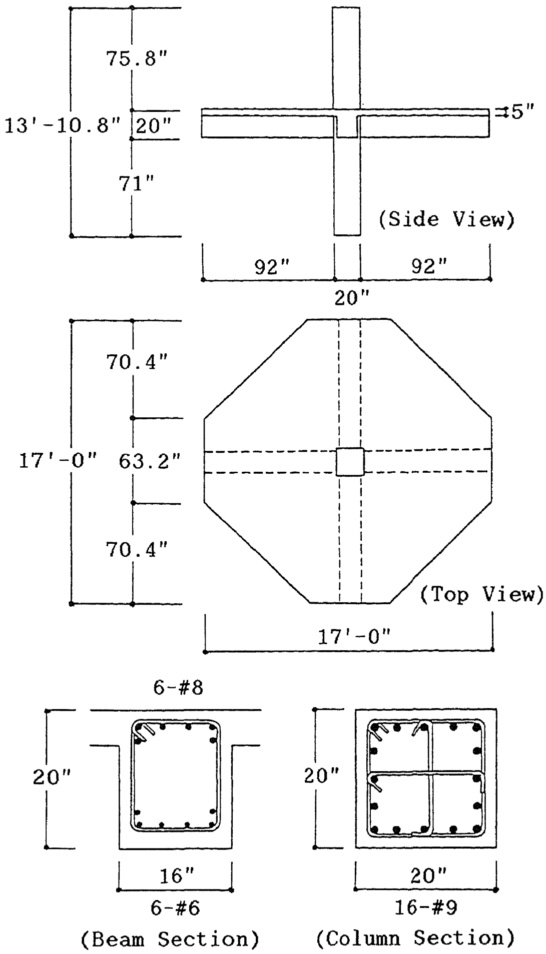


Fig. 1 Details of Specimen J2

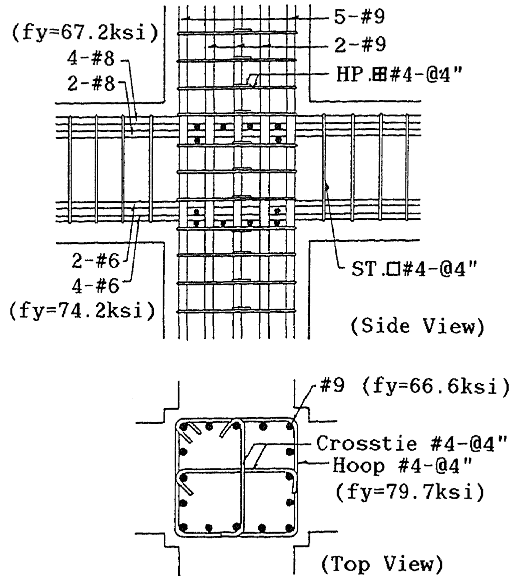


Fig. 2 Beam-Column Joint (J2)

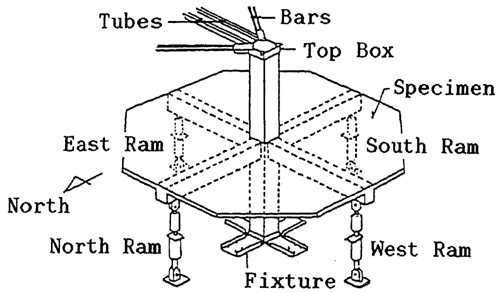
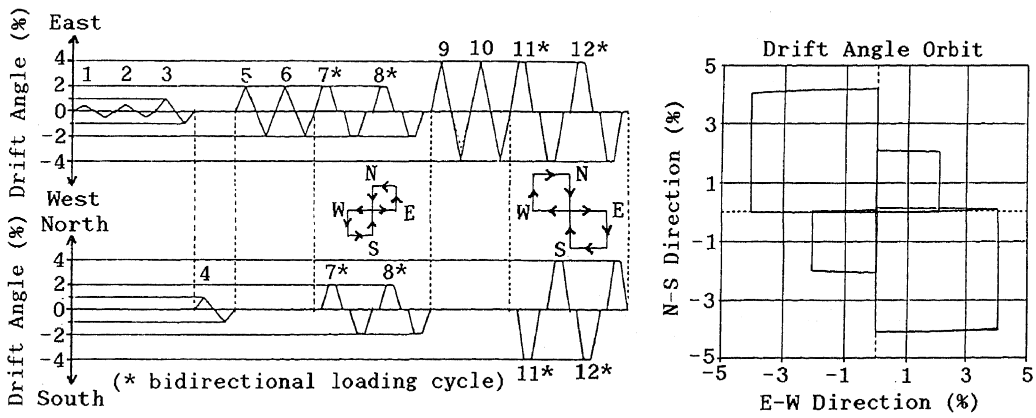


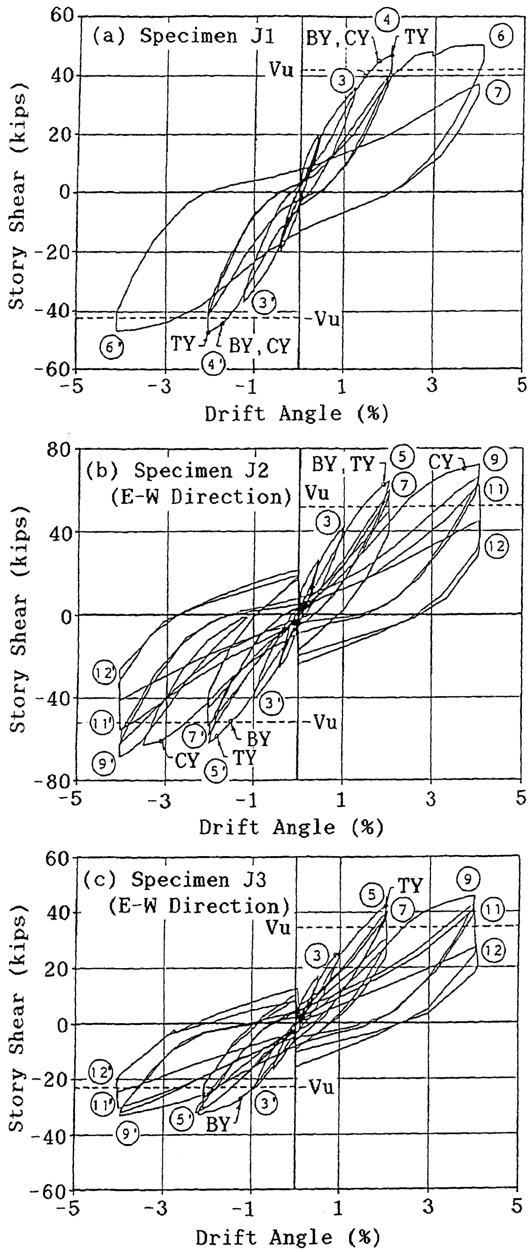
Fig. 3 Loading Setup for J2



(a) Drift Angle History

(b) Bidirectional Drift Path

Fig. 4 Loading History for Specimen J2



where BY : bottom beam bar yielding
CY : column bar yielding
TY : top beam bar yielding
Vu : calculated ultimate load
(beam hinge mechanism)
○ : loading cycle

Fig. 5 Story Shear-Drift Angle Relations

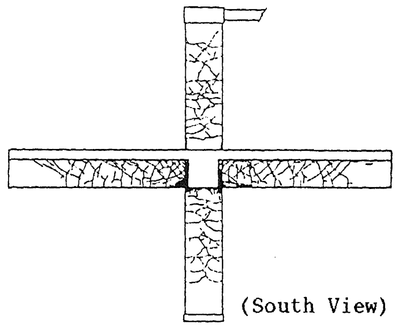


Fig. 6 Final Crack Pattern (J2)

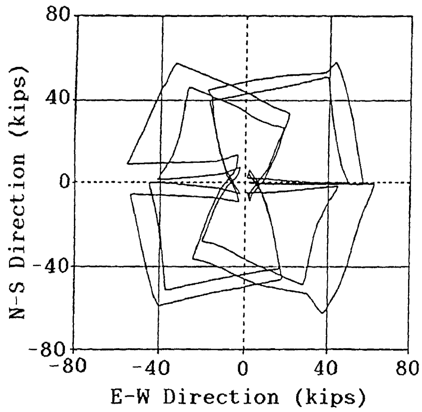


Fig. 7 Story Shear Orbit (J2)

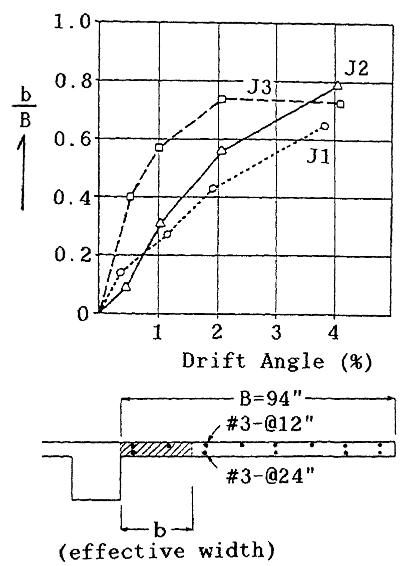


Fig. 8 Effective Slab Width for Beam Negative Moment