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SEISMIC BEHAVIOR OF INDETERMINATE R/C BEAM-TO-COLUMN CONNECTION SUBASSEMBLIES

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SUMMARY

The effect of continuity and load redistribution on the behavior of beam-to-column connections was studied by testing single and multiple-connection subassemblies under earthquake type loading. The behavior of connections in the multiple-connection subassemblies was found to be significantly different from the behavior of connections observed in single-connection tests. This difference is attributed mainly to the development of an axial compressive force in the main beams at large deformations. This axial compression results from elongation of the main beams which is restrained in continuous systems.

INTRODUCTION

Beam-to-column connections in multistory frame buildings have long been recognized as weak links in the response of buildings subjected to strong earthquakes. Consequently, considerable attention has been focused on studying the behavior of connections by testing individual interior or exterior connection subassemblies under pseudo-static loading. Such tests have contributed significantly towards the understanding of the behavior of connections and have formed the basis for the current design procedures. These procedures, however, do not account for the effect of continuity and load redistribution as encountered in a real building.

To achieve satisfactory performance of connections, the present design approach is (1) to have columns stronger than beams, (2) to keep the joint shear stress level low, (3) to provide adequate confining reinforcement in the joint, and (4) to control excessive slippage of beam and column bars through the joint.

This paper briefly presents the results of an investigation on the effects of continuity and load redistribution on the behavior of beam-to-column connections. The behavior of connections observed in single-connection and multiple-connection subassemblies is compared and the reasons for differences in behavior of connections in the two types of tests are explained. The variables investigated during this study were (1) the presence of transverse beams and a slab, (2) the amount of joint transverse reinforcement, and (3) the location of beam flexural hinges relative to the column face.

EXPERIMENTAL PROGRAM

Description of Test Specimens A total of nine specimens were tested during this investigation. Five of these specimens were multiple-connection subassemblies, each representing a story of a two-bay frame isolated at column mid-heights. The remaining four specimens were single-connection subassemblies as used in most of the previous investigations. Details of these test specimens are given in Table 1.

Table 1 Specimen Configuration

Specimen	Specimen Configuration	Slab Width (mm)	Joint Reinf. (%)	Specimen	Specimen Configuration	Slab Width (mm)	Joint Reinf. (%)
C		--	0.96	I		--	0.96
CTB		--	0.96	E		--	0.96
CS1		1422	0.96	IS1		1422	0.96
CS2		1422	0.64	ES1		1422	0.96
CS3*		1422	0.64	*Relocated plastic hinges			

The test specimens were designed according to the ACI 318-83 Building Code (Ref. 1) and satisfied most of the ACI-ASCE Committee 352 recommendations (Ref. 2). The overall dimensions and typical reinforcing detail of a multiple-connection test specimen are shown in Fig. 1.

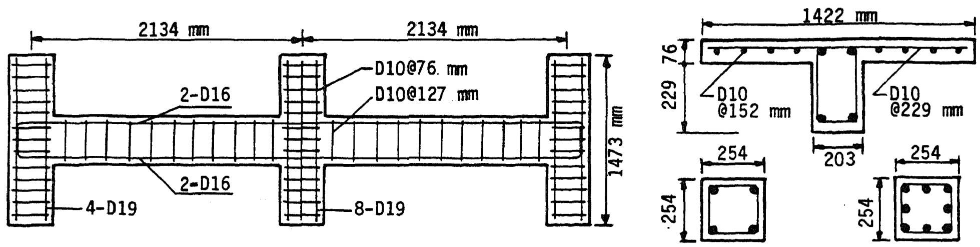

Fig. 1 Reinforcing Detail and Member Cross Sections

Testing Procedure The subassemblies were tested in a steel reaction frame shown in Photo 1. The displacement routine, shown in Fig. 2, was applied through a transfer beam at the top of the columns. It consisted of a total of twelve cycles with displacement amplitude varying from 0.25 percent to 5.0 percent of the total column height. Repeat cycles and small displacement cycles were included in the routine to measure strength and stiffness degradation.

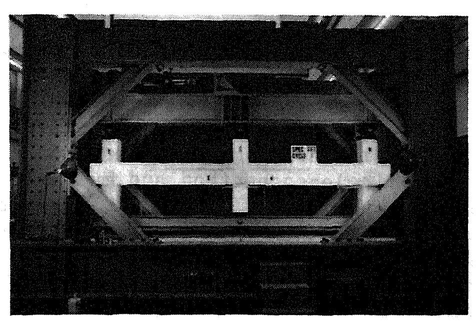

Photo 1 Test Set-up

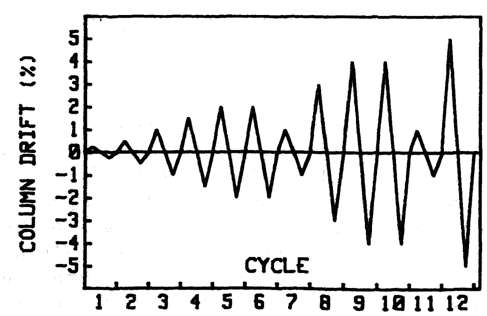

Fig. 2 Displacement Routine

TEST RESULTS

Load Redistribution The distribution of the lateral load among the three columns of the multiple-connection subassemblies was typically as shown for specimen C in Fig. 3. At drift levels of less than 1 percent, the applied lateral load was distributed almost equally among the three columns. As the drift level increased, the load carried by the first exterior column in the direction of loading increased while the load carried by the last column dropped. The load carried by the interior column increased consistently up to a drift level of 2 percent and became nearly constant thereafter. This is attributed to axial compression that develops in the main beams at large deformations. In single-connection subassemblies, the beams are free to elongate and hence no axial force can develop in the beams. In multiple-connection subassemblies, however, the elongation of the main beams, due to inelastic deformations, is restrained by the exterior columns which results in axial compression in the beams. As shown in Fig. 4, the measured elongation of the main beams in multiple-connection subassemblies was less than the total elongation observed in individual connection tests, which suggests the restraining effect in continuous systems. Furthermore, as shown in Fig. 5, extensive flexural cracks were observed on the outer face of the exterior columns of the multiple-connection specimens, despite a high column to beam flexural strength ratio of 2.4. Such cracks did not occur in the case of exterior connections tested individually. These observations suggest a behavior that is peculiar to multiple-connection subassemblies.

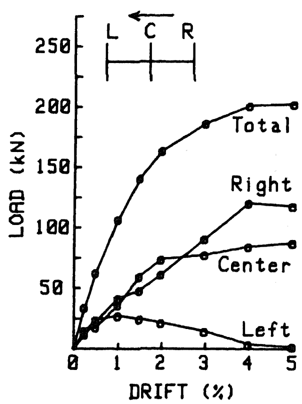

Fig. 3 Typical Distribution of Lateral Load

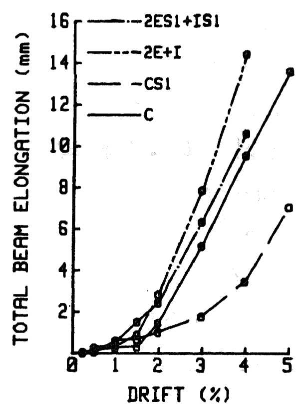

Fig. 4 Elongation of Beam Flexural Hinging Region

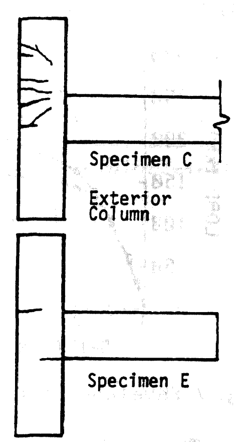

Fig. 5 Flexural Cracks in Exterior Columns

Recognizing the presence of axial force in the main beams and from the equilibrium of the subassembly, as shown in Fig. 6, the lateral load resisted by each column becomes

$$F_L = M/H - N/2 \qquad F_C = 2M/H \qquad F_R = M/H + N/2$$

where F_L, F_C and F_R are the shear forces in the left, center, and right columns, respectively; M is the moment in the main beam, N is the beam axial force, and H is the total column height. At large deformations, as the axial force in the main beam increases, the portion of the total load resisted by the left column decreases and, correspondingly, the lateral load resisted by the right column increases. The load carried by the interior column is not affected as the axial force in the beams on the two sides of the column balance each other.

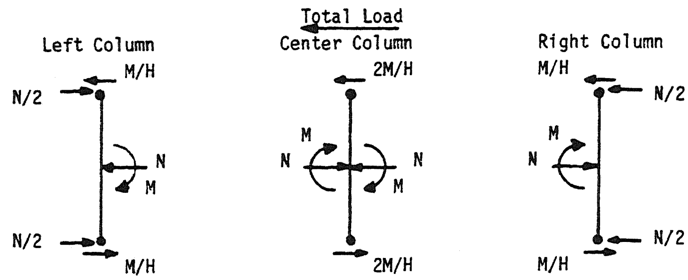

Fig. 6 Mechanism of Load Distribution

Combined vs. Individual Connections The effect of continuity on the strength of connections can be seen by comparing the lateral load resistance of multiple-connection subassemblies with the total load resisted by individual connections. Figure 7 shows such a comparison for connections with and without a floor slab. It is noticed that the strength is not affected by continuity up to a drift level of 1.5 percent. However, beyond the 1.5 percent drift, the multiple-connection subassemblies were able to resist a higher lateral load. At a drift level of 4 percent, the strength of the multiple-connection subassemblies was approximately 25 percent greater than the total strength of individual connections. This increase in strength is partially attributed to the increase in the flexural capacity of the main beams due to the presence of the axial compressive force as explained earlier.

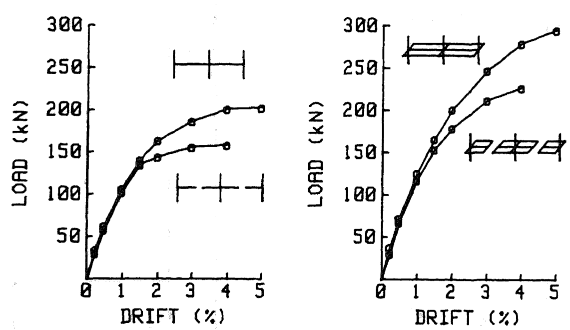

Fig. 7 Envelops of Load vs. Displacement Curves

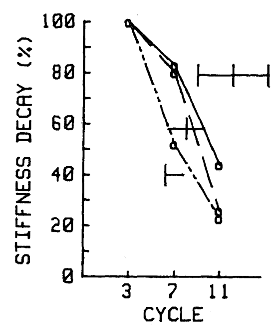

Fig. 8 Stiffness Degradation

The stiffness of individual and multiple-connection subassemblies is compared in Fig. 8. The loss of stiffness in the multiple-connection specimen appears to be less severe than the loss of stiffness observed in interior or exterior connections tested individually. The energy dissipation capacity, however, was not affected by the continuity of the test subassemblies. The energy dissipated by the multiple-connection subassemblies was approximately equal to the total energy dissipated by the individual connections.

The effect of continuity on shear in the joints can be seen by comparing the strain in the joint reinforcement of interior and exterior connections of both the single-connection and multiple-connection subassemblies. Figure 9 shows such a comparison for connections with transverse beams and a floor slab. In both the interior and the exterior connections, which had a joint shear stress level of $21\sqrt{f'_c}$ and $14\sqrt{f'_c}$, respectively, the joint hoop reinforcement did not yield when tested as individual connections. However, when the connections were tested in the form of a continuous subassembly, the strain in the joint reinforcement exceeded the yield strain. This shows increased shear stress in the joints of multiple-connection subassemblies and is attributed to the increased flexural capacity of the main beams. The joint shear stress calculated on the basis of individual connection tests could, therefore, be nonconservative.

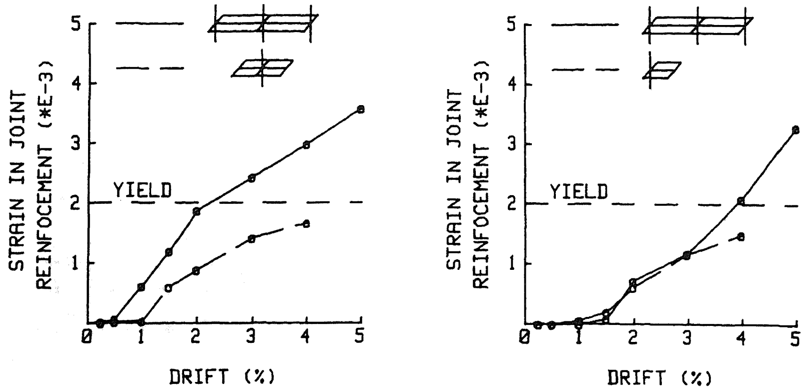

Fig. 9 Strain in Joint Reinforcement of Specimens with a Slab

Joint Confinement A comparison of strain in the joint reinforcement of all the multiple-connection subassemblies is shown in Fig. 10. The specimen C, which is without any transverse beams and a slab, is used as a reference for comparison. As observed in previous tests on single-connection subassemblies (Ref. 3), the transverse beams helped in confining the joint and assisted in resisting the joint shear stress. The transverse beams in specimen CTB were most effective in cofining the joint as shown by the smallest strain in the joint reinforcement. However, when a slab was added in specimen CS1, the shear in the joint increased which caused higher strains in the joint reinforcement of both the interior and the exterior connections.

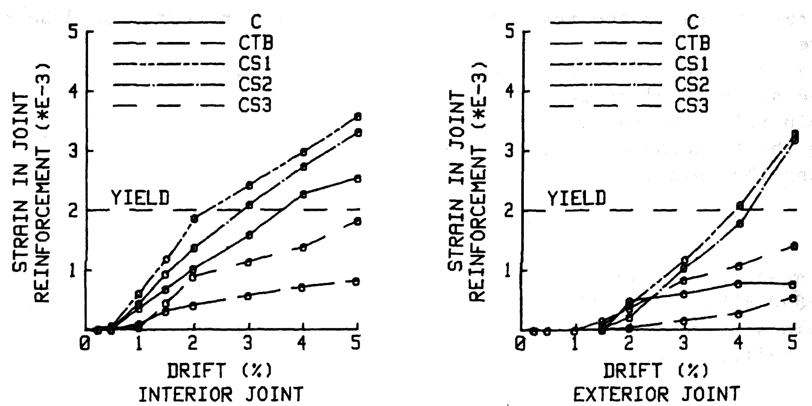

Fig. 10 Strain in Joint Reinforcement of Multiple-Connection Specimens

Despite the smaller amount of joint reinforcement in specimen CS2, the strain in the joint reinforcement was very much similar to that observed in specimen CS1. This shows that the behavior of connections in continuous systems was not very sensitive to changes in the amount of joint reinforcement. This could help reduce the amount of joint reinforcement required by the current design procedure.

Relocation of Beam Flexural Hinge In specimen CS3 the reinforcement detail was modified to move the flexural hinge a distance equal to the beam effective depth away from the face of the column. The amount of joint shear reinforcement was reduced as in specimen CS2. Shifting of the plastic hinge away from the joint protected the connection region and, as shown in Photo 2, no cracks were observed at the beam-column interface. Although specimens CS2 and CS3 had the same amount of joint shear reinforcement, the strain in the joint reinforcement of specimen CS3 was significantly smaller. Obviously, moving the inelastic action away from the face of the joint provided excellent protection against shear in the joint.

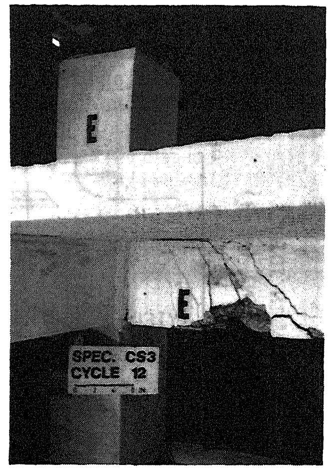

Photo 2 Flexural Hinging in Specimen CS3

CONCLUSIONS

1. The behavior of connections observed from individual connection tests was found to be significantly different than the behavior observed from multiple-connection tests. The continuity and load redistribution appear to play an important role in the performance of connections.
2. At large deformations, significant axial compression developed in the main beams of the continuous subassemblies which increased their flexural capacity. If neglected, this could result in underestimation of the column to beam flexural strength ratio.
3. The joints in multiple-connection subassemblies were observed to experience higher shear than the shear observed in individual connection tests. Calculation of shear stress based on the results of single-connection tests could be non-conservative.
4. The amount of joint transverse reinforcement in continuous systems did not appear to be as critical as perceived by the tests on individual connections. This may help relax the requirement for reinforcement in the joints.
5. Shifting the flexural hinge away from the face of the column proved effective in protecting the joint.

ACKNOWLEDGMENTS

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