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SEISMIC BEHAVIOR OF MULTIPLE-CONNECTION R/C FLAT-SLAB ASSEMBLIES

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SUMMARY

The seismic behavior of reinforced concrete slab-to-column connections was studied by testing two-bay slab-column subassemblies under large deformation reversals. The test subassemblies represented a half-scale model of the second floor of a prototype five-story building. In all tests, both interior and exterior connections attained drift levels of at least three percent before punching shear failure of the slab occured. Slab shear reinforcement in the form of closed hoop stirrups dramatically increased the ductility of both interior and exterior connections. Increased torsional stiffness of the slab edge also increased the ductility of the edge connections.

INTRODUCTION

Flat-slab buildings of low to medium height suffered considerable damage during the September 19, 1985 Mexican earthquake (Ref. 1). This type of construction is very common, not only in Mexico, but throughout North America and, indeed, the world. The attractiveness of this form of construction is based on the low inter-story height and the simplicity of construction. However, because of the flexibility of these structures, their use in areas of high seismic activity has come under question (Ref. 2). Experience from past earthquakes has shown the behavior of slab-to-column connections to be critical in the response of flat-slab buildings to severe ground motion. In the past, the behavior of slab-to-column connections has been studied by testing single interior or exterior connections (Refs. 2,3). However, such tests do not replicate the effect of continuity present in real buildings. In this investigation, the behavior of slab-to-column connections was studied by testing two-bay slab-column subassemblies under large deformation reversals.

TESTING PROGRAM

The experimental program consisted of testing five large-scale flat-slab subassemblies under a simulated earthquake-type loading. Each test subassembly represented a single story of a two-bay frame consisting of two exterior and one interior slab-to-column connection. The test subassemblies represented a half-scale model of the second floor of a prototype five-story building designed for gravity and earthquake loading as shown in Fig. 1. A description of each subassembly is given in Table 1.

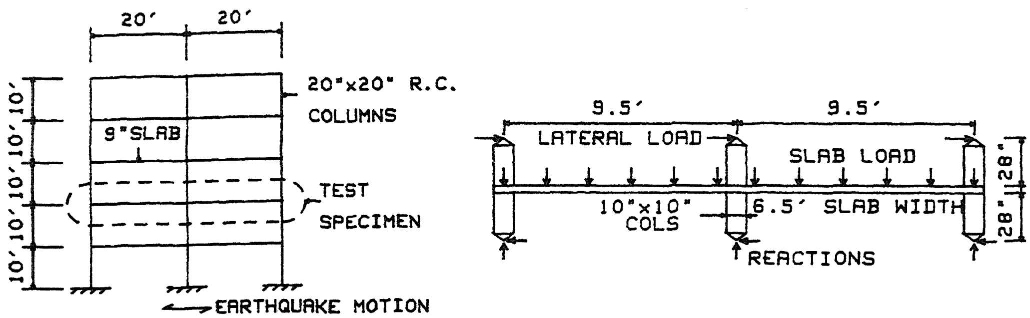

Fig. 1 Prototype Structure and Subassembly Details

Table 1 Test Specimen Details

1	P	FLAT PLATE - CONTROL
2	P2	FLAT PLATE - CONTROL
3	PSE	STIFF EDGE BEAMS AT EXTERIOR CONNECTIONS
4	PS	SLAB SHEAR REINFORCEMENT AS CLOSED HOOP STIRRUPS
5	PO	SLAB OVERHANG BEYOND EXTERIOR CONNECTIONS

The specimens were constructed in the laboratory using ready-mixed concrete with an average compressive strength of 5700 psi at the time of testing of specimens. The specimens were cured for 14 days after casting and then tested at an average age of 6 months.

Testing was performed in a steel reaction frame as shown in Fig. 2. During the test, the slab was subjected to a constant gravity load which simulated the dead load plus 30 percent of the live load on the prototype structure. This gravity load had the effect of introducing a vertical gravity shear at both the interior and exterior connections of $0.8\sqrt{fc'}$. The lateral loading was applied at the top ends of the columns through a stiff distribution beam while the bottom ends of the columns were free to rotate but restrained against vertical and

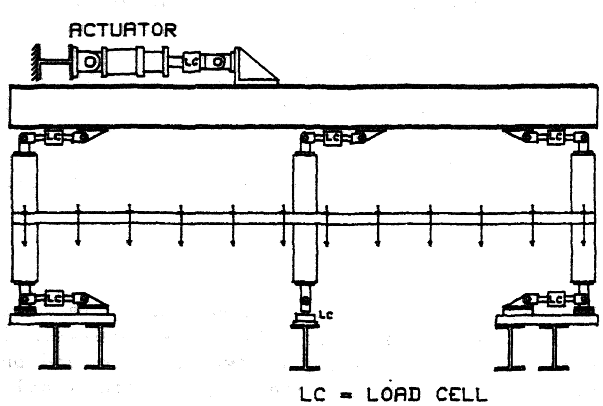

Fig. 2 Test Setup

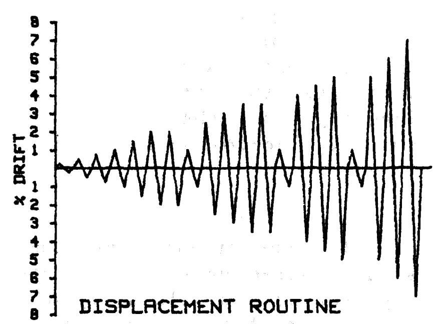

Fig. 3 Displacement Routine

horizontal displacements. The lateral displacement routine used for all test is shown in Fig. 3. Each specimen was extensively instrumented to collect pertinent data during the test.

SPECIMEN DESIGN

The overall size of the specimen, column reinforcement, and the slab flexural reinforcement were kept constant in all specimens. The design and detailing of slab flexural reinforcement was based on ACI 318-83 Building Code (Ref. 4). Besides reinforcement required for resisting flexure in the slab, additional reinforcement was provided in the column strip to transfer portion of the unbalanced moment between the slab and the column. To prevent progressive collapse of the slab, continuous bottom reinforcement was also provided through the columns as suggested in the ACI Committee 352 draft recommendations for the design of flat-slab structures (Ref. 5). Torsional reinforcement was provided in all specimens in the form of closed hoop stirrups along the outer edge of the slab at the exterior connections. Reinforcement details for the control specimens are shown in Fig. 4. The slab thickness was such that under ultimate loading, the punching shear stress around both interior and exterior connections was close to $4\sqrt{fc'}$, the maximum allowed by the Code.

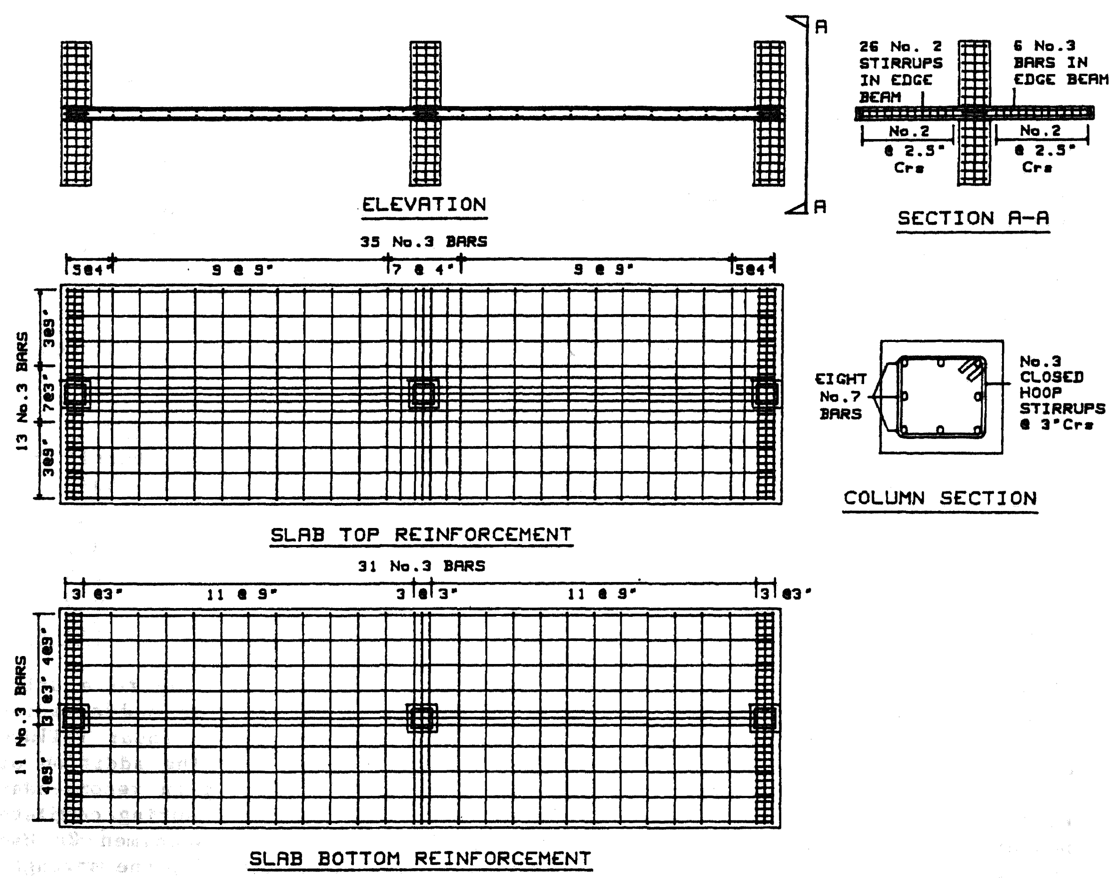

Fig. 4 Control Specimen Reinforcement Details

The first two specimens, 1P and 2P, were control specimens consisting of flat-slabs without edge beams or slab shear reinforcement. These specimens were used as reference for comparing the results of the other specimens. Specimen 3PSE included stiff edge beams at both exterior connections which were designed to remain uncracked in torsion during the test. Specimen 4PS included slab shear reinforcement in the form of closed hoop stirrups. These stirrups were positioned along the column lines at both interior and exterior connections. The stirrups were made from 1/4 inch smooth mild steel bars spaced at 2 inches along the length of the column strips. They enclosed all the slab reinforcement passing through the column. In specimen 5PO, the slab was not curtailed at the outer face of the exterior columns as in the other specimens, but continued ten inches beyond the columns. This feature was included to model an overhang provided to form a closure with the window wall system. The slab reinforcement was continued through the exterior connections to the edge of the slab but the torsional reinforcement along the edge of the slab was placed at the exterior column lines as in the control specimens.

RESULTS

A number of general observations can be made regarding the performance of the specimens. All specimens developed flexural cracks in the slab at drift levels of less than half a percent. Only minor cracking was observed in the columns which can be considered to remain uncracked during the test. Stiffness of the specimens changed gradually without any well defined yield point. The "yield" displacement for the calculation of displacement ductility is defined as shown in Fig. 5 (Ref. 6). Pertinent test results are listed in Table 2.

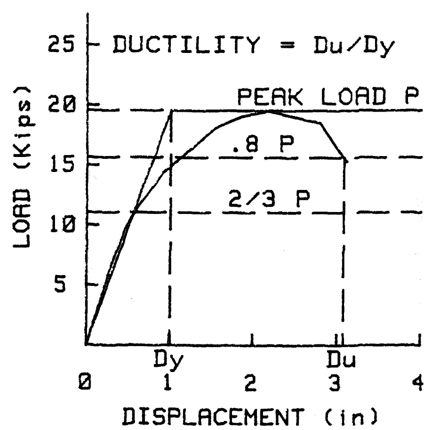

Fig. 5 Definition of Displacement Ductility

The control specimens with reinforcement arrangement as prescribed by the ACI Building code and without slab shear reinforcement or edge beams performed satisfactorily up to a drift level of 4 percent. As the drift level increased, both interior and exterior connections experienced increased damage culminating in punching shear failure of the slab around the connections as seen in Photos 1 and 2. The addition of continuous bottom reinforcement through the columns as suggested in recommendations by the ACI Committee 352 (Ref. 5) proved effective in preventing complete punching of the slab. At 4 percent drift, the stiffness of specimen 2P had reduced to 30 percent of the initial stiffness. At 5 percent drift, the strength of this control specimen had reduced to 80 percent of the peak strength and so failure was considered to have occurred.

Table 2 Test Results

Spec No.	Peak Lateral Load (Kips)	Yield Disp. Dy (in.)	Ultimate Disp. Du (in.)	Ductility Du/Dy
1 P	20.1	1.00	--	--
2 P	20.2	1.01	3.10 (5%)	3.1
3 PSE	25.1	1.10	2.79 (4.5%)	2.5
4 PS	21.7	1.08	4.34 (7.0%)	4.0
5 PO	23.0	1.08	2.17 (3.5%)	2.0

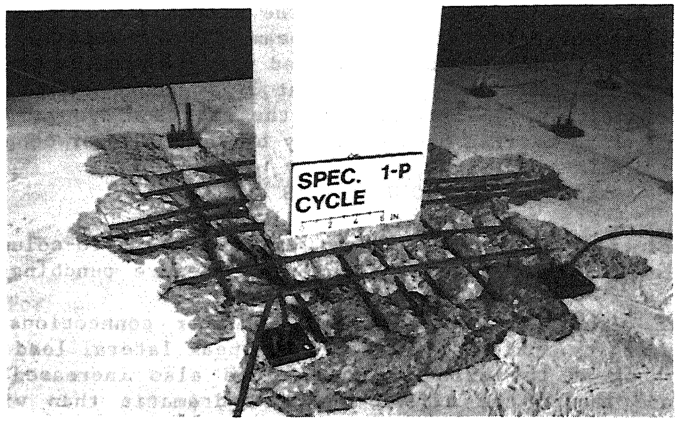

Photo 1   Specimen 1P Interior Connection

Photo 2   Specimen 2P Exterior Connection

Addition of torsionally stiff edge beams in specimens 3PSE dramatically altered the behavior of the edge connections. Flexural yielding of the slab reinforcement occurred across the full slab width at the edge beams as opposed to limited yielding in the column strip observed in the control specimens. Punching shear failure of the exterior connections was not observed even though the specimen was subjected to 5 percent drift. Punching shear failure of the interior connection occurred at 4 percent drift. After punching failure of the interior connection, a 30 percent drop in overall specimen strength was observed. Thereafter, the load was resisted by the relatively intact exterior connections.

Inclusion of slab shear reinforcement in the form of closed hoop stirrups along the column lines increased the specimen strength by only 7.5 percent but resulted in a significant increase in the specimen ductility. The specimen was able to sustain a drift of 8 percent at which considerable damage had occurred in the slab around all three connections. However, none of the connections failed in punching shear. The specimen was also able to maintain its maximum strength up to a drift level of 5 percent which is higher than any other specimen. Although the closed hoop stirrups are somewhat undesirable from a construction point of view, their beneficial effect on the ductility of slab-to-column connections was significant.

A slab overhang beyond the exterior connections had the effect of increasing the ductility of the exterior connections. The effect was, however, not as dramatic as with the torsionally stiff edge beam. Nevertheless, punching shear failure of the exterior connections was delayed until 7 percent drift, long after punching failure of the interior connection at 3.5 percent drift. After failure of the interior connection, the strength of the specimen dropped by 42 percent, the remaining load being carried predominantly by the exterior connections.

CONCLUSIONS

1. In all specimens, both interior and exterior slab-to-column connections attained drift levels of at least three percent before punching shear failure occurred.
2. The presence of a stiff edge beam at exterior connections significantly increased this ductility. It also increased the peak lateral load by 25 percent.
3. A slab overhang at the exterior connections also increased the ductility of the connections though the effect was less dramatic than with stiff edge beams.
4. Slab shear reinforcement in the form of closed hoop stirrups along the column lines dramatically increased the ductility of both interior and exterior connections while increasing the peak lateral load by only 7.5 percent

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