THREE-DIMENSIONAL BEAM-COLUMN SUBASSEMBLAGES UNDER BIDIRECTIONAL EARTHQUAKE LOADINGS

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SUMMARY

Half-scale three-dimensional reinforced concrete interior beam-column subassemblages with slab were tested under unidirectional and bidirectional simulated earthquake loadings to study the effect of slab on the flexural behavior of the beams and the influence of bidirectional lateral loadings on the behavior of the column. The entire width of the slab in tension was found to contribute to the ultimate flexural resistance of the beam. The mechanism of slab contribution was discussed. The bidirectional lateral loading is experimentally confirmed to affect the inelastic action of interior columns.

INTRODUCTION

For realistic nonlinear analyses of a three-dimensional reinforced concrete building, it is necessary to know the effect of slab on hysteretic behavior of beams and the behavior of columns under bidirectional lateral loading.

The slab cast monolithically with beams can contribute to the beam flexural stiffness and resistance. The degree of slab participation in the elastic stiffness has been understood (Ref. 1,2). On the other hand, it is not clear how much width of slab could participate in the ultimate resistance of the beam. Some studies (Ref. 3) suggested that the entire width of slab could be effective at the ultimate stage. However, most design codes (Ref. 4,5) do not permit the use of the entire slab width in evaluating the ultimate strength of a beam.

Many experimental studies (Ref. 6,7) suggested that a rectangular reinforced concrete column is susceptible to the damage under bidirectional lateral loadings. Single column specimens were used in those tests, although the behavior of a column is affected by the presence of beams or slabs. Therefore, it is necessary to test columns with beams or slabs to investigate the influence of bidirectional lateral loading.

This paper discusses (a) the effective width of slab that contributes to the ultimate flexural resistance of the beam, (b) the behavior of the transverse beams, and (c) the influence of bidirectional lateral loading on the interior columns, on the basis of the test of three-dimesional reinforced concrete beam-column connections with slab.

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OUTLINE OF EXPERIMENTAL WORK

The geometry of a test specimen is shown in Fig. 1. The specimen represented the portion of an interior beam-column-slab subassemblage removed from an imaginary three-dimensional reinforced concrete frame by cutting the beams and columns at arbitrarily assumed inflection points. The story height and the span of a specimen were 1.47 m and 2.7 m, respectively. The specimen was designed so that the beam should yield prior to the columns under unidirectional lateral loading. The amplitudes of column axial forces and direction of lateral loads are listed in Table 1.

The properties of materials are listed in Table 2. The concrete was cast in the upright position in two stages; i.e., first to the top of the slab, and then in the upper column.

Fig. 2 shows a specimen placed in the loading apparatus. The base of the subassemblage was supported by a universal joint. The free ends of the beams were supported by vertical rigid members equipped with universal joints at their ends, creating roller support conditions in the horizontal plane. Constant-amplitude vertical and reversing biaxial horizontal loads were applied at the top of the upper column by three servo-controlled actuators. The basic path used in the bidirectional loading test is shown in Figs. 3(a) and (b). The displacement histories in unidirectional loading test are shown in Fig. 3(c).

TEST RESULTS AND DISCUSSION

Observed Behavior

Crack patterns at the final stage of a uniaxial (SU20) and biaxial specimen (SB20) are shown in Fig. 4. In the unidirectional loading test, flexural cracks, crushing and spalling of concrete occurred mainly in the longitudinal beams. Some flexural cracks occurred in columns, but damage was smaller than that in the beams. In bidirectional loading test, not only beams but also columns and beam-column connections were damaged. The shell concrete crushed in the corner at the critical section of the columns. And the shell concrete in the corner of connection spalled.

The Effective Width of Slab

The effective width of a T-beam is studied from the unidirectional loading test results.

The strains in the slab reinforcement parallel to the longitudinal beam, at the face of the transverse beams, are plotted in Fig. 5. They represent strain distribution at the peaks of loading cycles in which the displacement amplitude exceeded the previous maximum value; solid lines for the negative beam moment (slab in tension), dashed lines for the positive beam moment (slab in compression). The load stage numbers in circles correspond to the load stage numbers given in Fig. 3. Note that (a) the strain amplitudes increased toward the longitudinal beam, and they gradually decreased with the distance from the beam, (b) the amplitudes increased with the deflection, and (c) some slab reinforcing bars remained in tension even under the positive beam moment. The region in which slab reinforcement yielded by negative moment spread with the deformation, and finally almost all slab reinforcement exceeded the yield strain at load stage 38 when the story displacement reached 64 mm or about one-twentieth the story height.

In Fig. 6 the beam shear-deflection relations (broken lines) computed using different slab widths are compared with the observed load-deflection relation (solid lines). The plane section was assumed to remain plane after deformation in the analysis. The width of the slab used in the analyses were (a) entire slab width of the specimen, (b) the effective slab width allowed by Standard of Architectural Institute of Japan (AIJ) (Ref. 5)(equal to one-tenth of the span length) and (c) zero slab width. Note that the observed maximum resistance of the beam was nearly equal to the maximum value calculated with the entire slab width. On the other hand, the observed initial stiffness is close to the one calculated with the effective width defined in the AIJ Standard. It is concluded that the effective width of slab spreads with the beam deformation and the entire slab width can contribute to the ultimate flexural resistance of the beam.

Behavior of Transverse Beam

It was believed in the past that the beam perpendicular to the longitudinal beam could not resist a large torsional moment developed by the slab reinforcement within the entire width. If the plane section of the beam and slab is assumed to remain plane, the slab reinforcement yielding in tension develops a torsional moment equal to 85 tonf-cm at the fix end of the transverse beam without considering the contribution of the compressive stresses carried by the opposite slab side (Fig. 7(a)). The torsional cracking moment is computed to be 57 tonf-cm using the formula proposed by Hsu (Ref. 8). Although estimated torsional strength was lower than the value obtained from the flexural assumption, the transverse beams did not fail in this test.

The phenomena can be described as follows. Recall that some slab reinforcement remained in tension even under the positive beam moment where the slab was supposed to carry compressive force. If the stress-strain relationship was assumed to be of bilinear type, these stresses were judged to have remained in tension. The transverse beams were measured to deflect in torsion about its longitudinal axis and in bending in the horizontal plane as shown in Fig. 7(b). The beam is considered to deform in the two modes because the transverse beams were pulled by the slab reinforcement in tension. Under this beam deformation, the stiff slab could not follow the curvature of the beam, and gaps must have developed between the transverse beams and the slabs as shown in Fig. 7(b), creating tensile stresses between the transverse beams and the slabs. The stresses acting on both faces of the transverse beam due to slab reinforcement and concrete can be schematically shown in Fig.7(b). The tensile stresses acting in the opposite directions will be cancelled, reducing the torsional moment and horizontal shear acting on the transverse beam.

The preceding explanation applies only to the inner beam-column assemblages. In the case of exterior beam-column connections, a transverse beam has slab only on one side. Therefore, torsional moment can be significantly large to cause torsional failure.

Behavior of Beam under Bidirectional Lateral Loading

When bidirectional lateral loading is applied to a three-dimensional building, each beam acts as a "longitudinal" and "transverse" beam depending on the directional components of the earthquake loads. Each beam of specimen SB20 under bidirectional loading was deflected in the conditions of biaxial bending; i.e., in dominant bending in the vertical plane and in minor bending in the horizontal plane as shown in Fig. 8. This secondary bending in the horizontal plane may influence the behavior in major bending in the vertical plane due to biaxial interaction.

The flexural characteristics of the longitudinal beam in specimen SU20, subjected to uniaxial bending in the vertical plane, are compared with that of a corresponding beam of specimen SB20, subjected to biaxial bending (Fig. 9) at similar loading conditions. There appeared no significant difference in the response of the two beams. Namely, it appears that the influence of bending in the horizontal plane was negligible on the flexural behavior in the vertical plane probably because the horizontal deflection of the beam was as small as 3.33 mm, by far smaller than the vertical deflection of 25 mm to develop the biaxial bending interaction.

Behavior of Columns under Bidirectional Lateral Loading

The trace of resistances of specimens SB20 under bidirectional load reversals is shown in Fig. 10, which is similar to the shape of displacement trace in Fig. 3(a). A part of resistance trace of specimen SB20 is reproduced in Fig. 11. The story displacements were 32 mm in EW-direction and 0 mm in NS-direction at stage 24, and 32 mm in EW-direction and 32 mm in NS-direction at stage 25. The square chained lines represent calculated ultimate story shears at the developement of beam yielding assuming the elastic behavior of columns, while the circular lines represent those at the developement of column yielding assuming the elastic behavior of beams. The biaxial flexural strength interaction curve of a column is assumed to be expressed as a ellipse with radii equal to yield moments in the two principal directions. The beam yields first under unidirectional loading, while the column yields first under bidirectional loading. Although the story displacement was held constant in EW-direction between load stage 24 and 25, the story shear in EW-direction decreased due to the loading in NS-direction, as observed in the previous test (Ref. 7). After the vector sum of the story shears in EW and NS-directions reached the calculated ultimate story shear represented by a circular line, the story shear response point moved on the circle.

The influence of bidirectional lateral loading on columns was studied by comparing the upper column deflections of specimen SB20 and SU20 at the load stage when the EW-direction story displacements are the same (Fig.12). The integer numbers on abscissa represent load stages (Fig.3). Note that (a) the deflection of SB20 column was larger than that of SU20 column, and (b) although the deflection of SU20 column remained almost constant during the load reversals at the same story displacement amplitude, the deflection of SB20 column increased with load reversals. The damage in specimen SU20 occurred mainly at the critical section of beams, while the columns in SB20 were also damaged. In other words, a column is susceptible to damage under bidirectional lateral loadings.

CONCLUSIONS

The following conclusions may be drawn from the study:

(1) Slab can contribute to the stiffness as well as resistance of a longitudinal beam. The effective width of slab, that contributes to the beam resistance, increases with beam deformation, and can be as wide as the entire slab width at the ultimate stage.

(2) The torsional moment in the transverse beam caused by the forces acting in the slab cannot be large enough to cause torsional failure in an interior beam-column connection.

(3) The torsional moment and shear in the transverse beam could be significant to cause failure if the beam were connected to an exterior beam-column connection.

(4) Under bidirectional lateral loadings, beams are subjected to biaxial bending in the vertical and horizontal planes. However, biaxial interaction is negligible.

(5) When bidirectional lateral load reversals are applied to a column, the deflection of the column becomes greater than that subjected to a uniaxial lateral load of the corresponding amplitudes.

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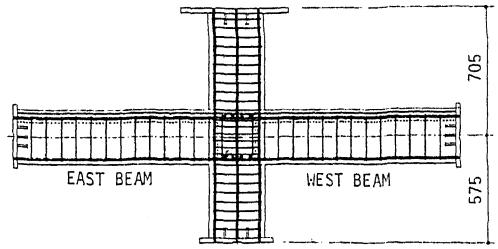
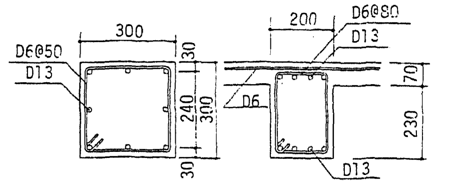
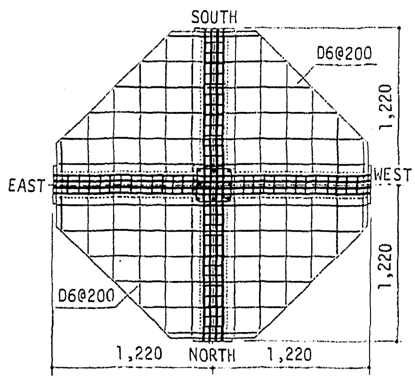


(a) Elevation



(b) Column Section (c) Beam Section



(d) Plan

Fig. 1 Geometry of Test Specimen (unit in mm)

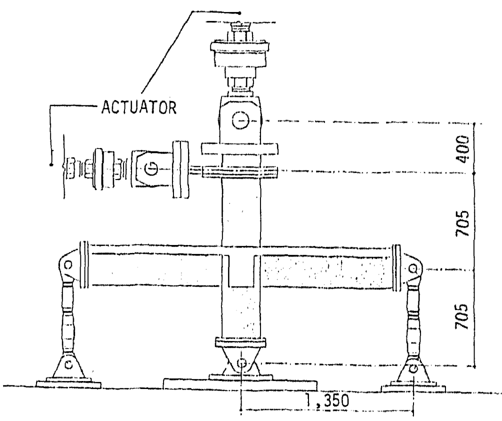
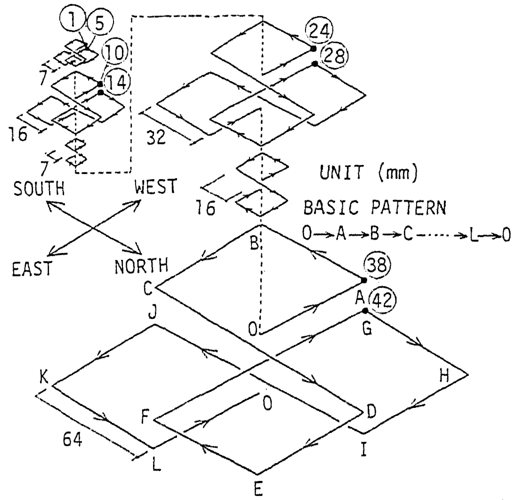
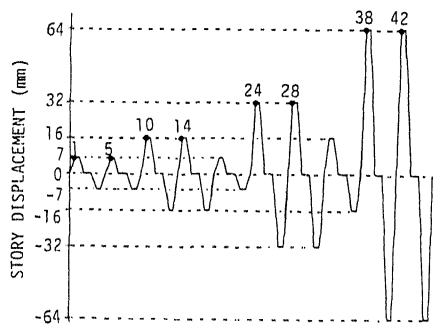


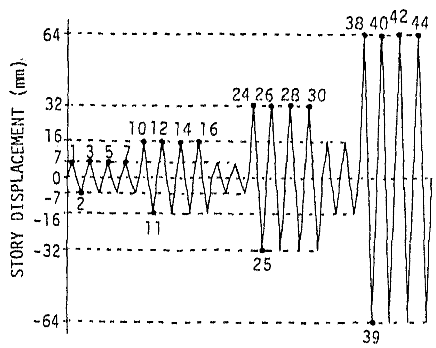
Fig. 2 Specimen in Loading Apparatus



(a) Bidirectional Displacement Path

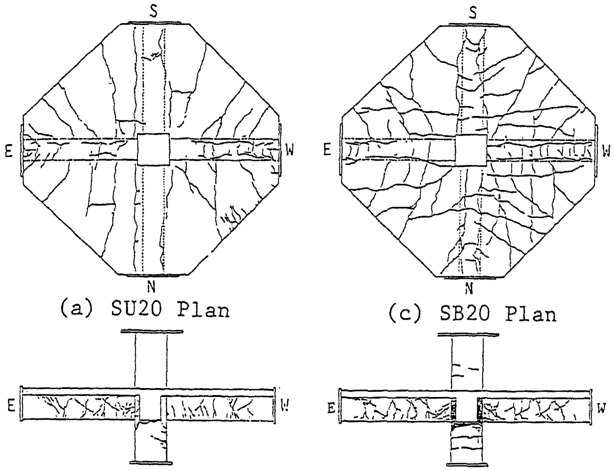


(b) EW Story Displacement History in Bidirectional Test



(c) Story Displacement History in Unidirectional Paths

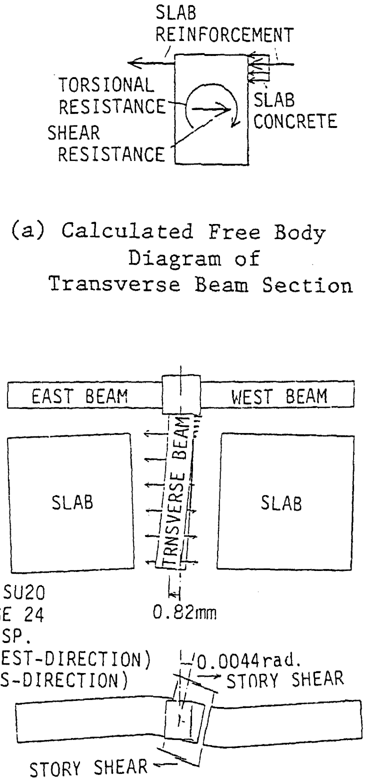
Fig. 3 Controlled Story Displacement Paths



(a) SU20 Plan (c) SB20 Plan

(b) SU20 Elevation (d) SB20 Elevation

Fig. 4 Crack Patterns



(a) Calculated Free Body Diagram of Transverse Beam Section

(b) Deformation and Stresses of Transverse Beam

Fig. 7 Stress Acting on Transverse Beam

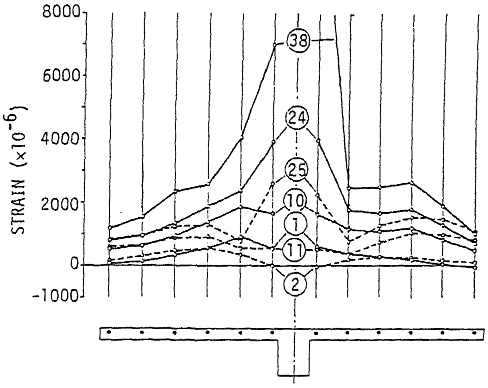


Fig. 5 Strain in Slab Reinforcement (Specimen SU20)

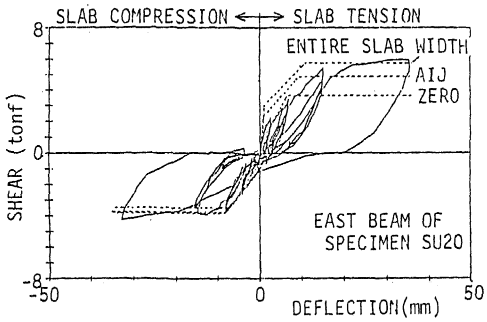


Fig. 6 Shear-Deflection Relationship of SU20 Beam

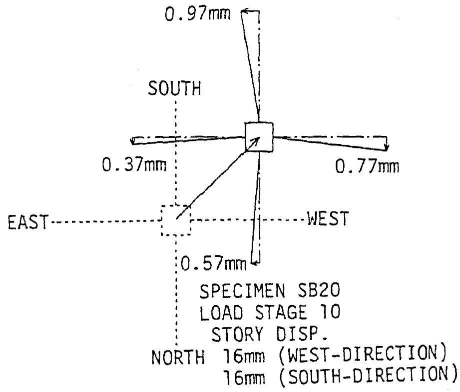


Fig. 8 Horizontal Beam Deflection under Bidirectional Loading

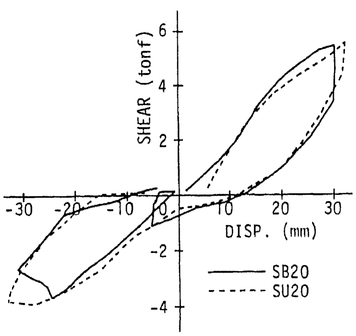


Fig. 9 Histeresis Observed in SU20 and SB20 Beams

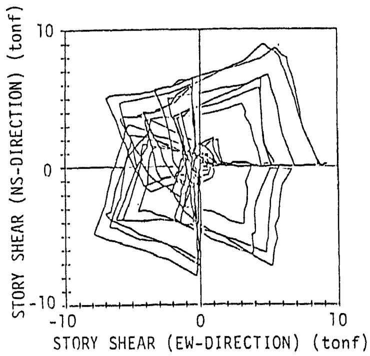


Fig. 10 Trace of Story Shears (Specimen SB20)

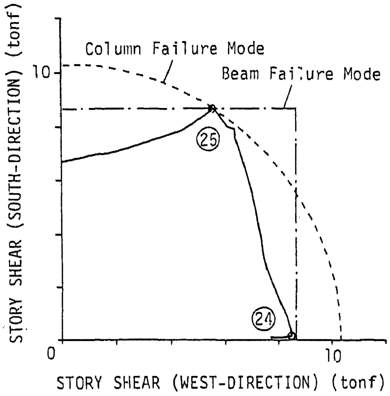


Fig. 11 Detail of Story Shears (Specimen SB20)

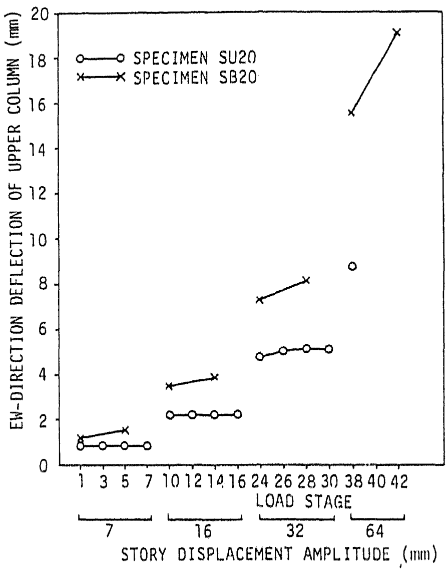


Fig. 12 Column Deflections Observed in SU20 and SB20 Specimens

TAble 1 Specimens

Specimen	Axial Force(kg/cm^2)	Lateral load
SU10	10	Unidirectional
SB10	10	Bidirectional
SU20	20	Unidirectional
SB20	20	Bidirectional
SU60	60	Unidirectional
SB60	60	Bidirectional

Table 2 Material Properties

Concrete Properties	SU20	SB20	SU10&SB10	SU60&SB60
Secant Modulus : Ec($10^5 kg/cm^2$)	1.91(2.46)	1.75(1.97)	2.32(2.15)	2.60(2.57)
Compressive Strength : Fc(kg/cm^2)	191 (234)	158 (188)	220 (227)	239 (286)
Strain at Compressive Strength : ε_b(%)	0.22(0.21)	0.26(0.20)	0.26(0.26)	0.24(0.26)
Splitting Tensile Strength : Ft(kg/cm^2)	14.2(16.2)	15.2(14.3)	26.2(25.0)	24.1(22.0)

Steel Properties	SU20&SB20		SU10,SB10,SU60,SB60		
	D13	D6	D13	D10	D6
Yield Strength : σ_y(kg/cm^2)	3590	3400	3870	3820	4017
Tensile Strength : σ_t(kg/cm^2)	5320	4250	5433	5610	5500