Mechanical behavior of reinforced concrete beam-column assemblage with different floor levels on both sides of column

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ABSTRACT：

The objects of this study are to give consideration to the mechanical behavior of beam-column subassemblage with different floor levels on both sides of column, and also to estimate the shear strength of joint in such a subassemblage. The number of test specimens with beam bar anchorage of the continuous hoop form within a joint is three and the variable of the test series is the distance between one beam axis and the other beam axis on both sides of column only. The failure mode of two specimens with zero distance and with the distance of a half beam depth between one beam axis and the other beam axis was the joint shear failure.

At the maximum strength, the shear force of the joint zone between one beam axis and the other beam axis in the specimen with the distance of a half beam depth is larger than that of the joint zone in the specimen with zero distance. Therefore, the ultimate strength of joint with different floor levels should be estimated by means of the shear force of the joint zone between one axis and the other beam axis. As a result, the ultimate strength of joint relates with the ratio of the distance between one beam axis and the other beam axis to the column depth. Namely, as the value of ratio is smaller, the ultimate strength of joint increases.

KEYWORDS: Beam-column joint, Different floor levels, Shear strength of joint, Strut mechanism

1. INTRODUCTION

Reinforced concrete structures frequently are constituted of a beam-column subassemblage with different floor levels on both sides of column. However, it's impossible to estimate the mechanical behavior of such a beam-column subassemblage.

The equations of joint shear strength for the shape of exterior and interior joint are proposed. But these proposed equations do not reflect the influence of the distance between one beam axis and the other beam axis on both sides of column.

The objects of this study are to give consideration to the mechanical behavior of beam-column subassemblage with different floor levels, and also to estimate the ultimate strength of joint in such a subassemblage.

2. EXPERIMENTAL STUDY ON THE MECHANICAL BEHAVIOR OF REINFORECED CONCRETE BEAM – COLUMN ASSEMBLAGE WITH DIFFERENT FLOOR LEVELS

2.1. Outline of Experimental Work

Test specimens are three interior beam-column joints with different floor levels removed from a plane frame by cutting the beams and columns at arbitrary assumed inflection points, as shown in Fig 1. In these test specimens, beam bars within the joint are arranged in the continuous hoop form. The parameter of the test is the distance between one beam axis and the other beam axis on both sides of column only. The selected distance level is zero for specimen J-0, a half beam depths for specimen J-0.5D, and two and a half beam depths for specimen J-2.5D, respectively. Based on the proposed equation with the same floor level[Architectural Institute of Japan, 1999], specimens J-0 and J-2.5D are designed to be a joint shear failure type.

The specimens were tested in upright position, as shown in Fig 1. The column ends were supported by a horizontal rollers and a mechanical hinge. The constant vertical load was applied at the top of the column by a hydraulic jack, and reversed cyclic load was applied to the beam ends by two hydraulic jacks.

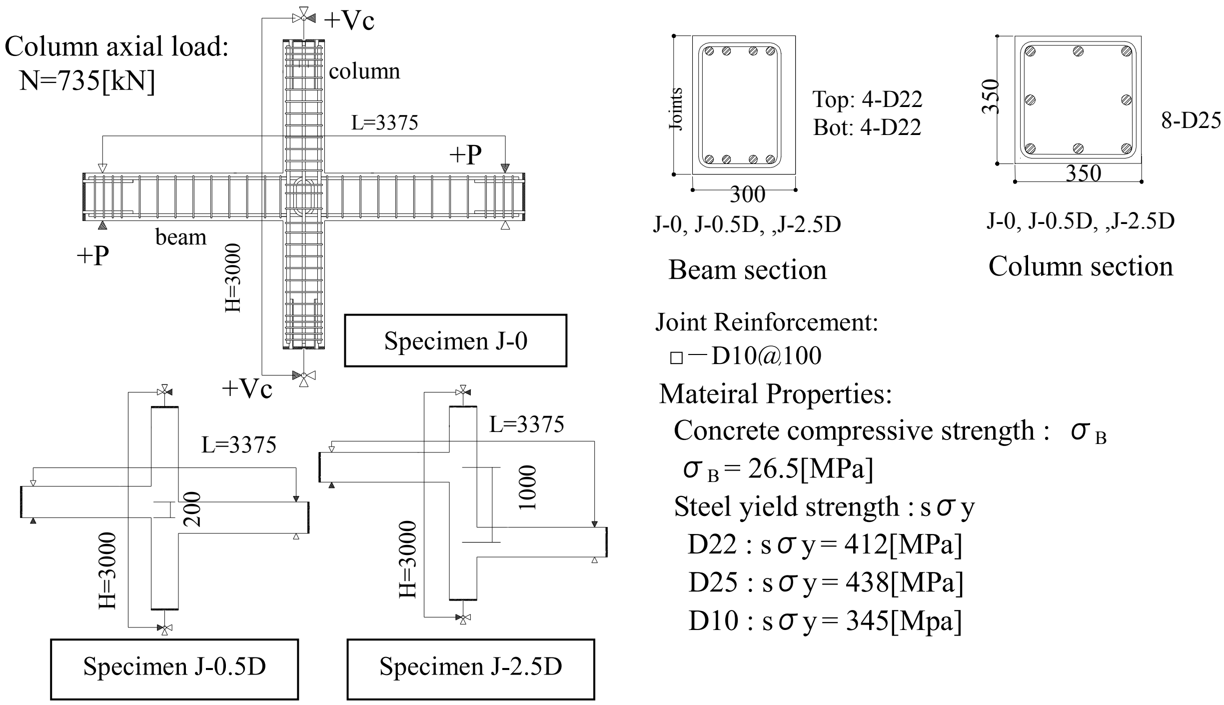


Figure 1 Details of specimen (unit in mm)

2.2. Experimental Results and Discussions

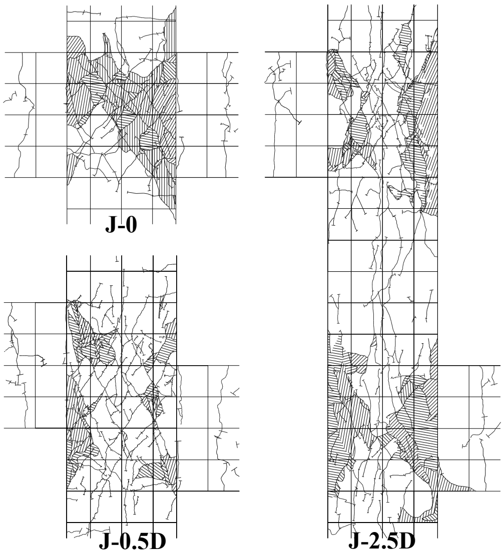
2.2.1 Observed Behavior

Fig 2 shows the crack patterns observed at the final stage of loading for each specimen and the envelope curves of the beam shear(P) – story drift angle(R) relations.

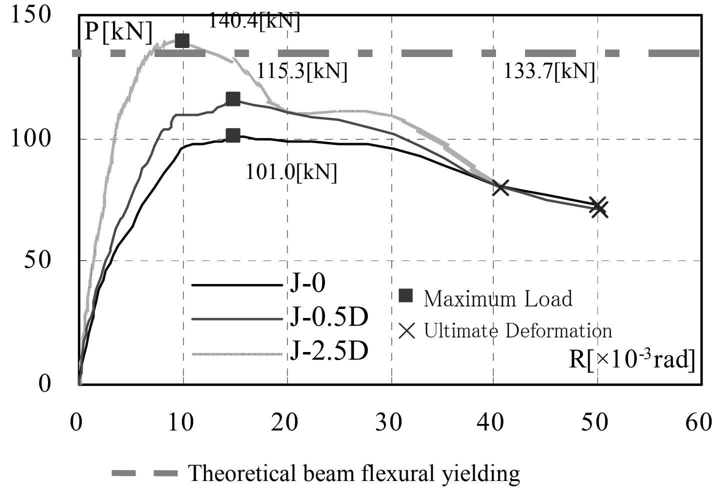
For specimens J-0 and J-0.5D, beam flexural yielding was not observed and the crushing of concrete occurred in the joint panel. And also the joint reinforcement yielded at maximum strength. The deterioration of strength progressed under the subsequent cyclic loading after maximum strength and the spalling of concrete occurred in the joint.

For specimen J-2.5D, the strain in the beam bars at the beam critical section and the joint reinforcement reached the yield strain at the ultimate strength. The strength decay progressed under the subsequent cyclic loading after the maximum load. After the maximum load, the diagonal shear cracks in joint appeared and the width of cracks increased. As a result, the spalling of concrete occurred remarkably in the joint panel.

Accordingly, it was concluded that the failure mode of specimens J-0 and J-0.5D was the joint shear failure, and that of specimen J-2.5D was the joint shear failure after beam flexural yielding.



(a) crack patterns at final stage



(b) Beam shear(P) – story drift angle(R) relation

Figure 2 crack patterns and deformation characteristics

2.2.2 Comparison between observed and calculated strength

Experimental values are compared with theoretical values calculated by flexural theory [Fujii, 1972] and the shear strength of joint calculated by the following proposed equations.

The beam shear force($_tP_{ju}$) at the ultimate shear strength of joint is calculated by the following equations which are defined in Eqn.2.1 and Eqn.2.2 [Architectural Institute of Japan, 1999]:

For specimens J-0 and J-0.5D,

$$Vju = 1.56\sigma_B^{0.712} \cdot bj \cdot Dc \quad \text{(in kgf/cm}^2\text{ units)} \tag{2.1}$$

For specimen J-2.5D,

$$Vju = 1.13\sigma_B^{0.718} \cdot bj \cdot Dc \quad \text{(in kgf/cm}^2\text{ units)} \tag{2.2}$$

where, V_{ju} : joint shear strength, b_j : joint effective width, Dc : column depth

Table 1 Comparison of observed and calculated strength (unit : kN)

Specimens	Beam		Joint		Pmax
	tPby	ePby	tPju	ePju	
J-0	133.7	-	92.4	101.0	101.0
J-0.5D		-	92.4	115.3	115.3
J-2.5D		137.6	120.2	140.4	140.4

$_eP_{by}$ and $_tP_{by}$: beam shear forces at yield strain in beam bar for experimental and calculated values
$_eP_{ju}$ and $_tP_{ju}$: beam shear forces at the joint shear strength for experimental and calculated values

The comparison of observed and calculated strength is shown in Table 1.For specimen J-0 without the distance between one beam axis and the other beam axis on both sides of column, the joint shear strength can be estimated approximately by the proposed equation for the joint shear strength. But the beam shear force at the joint shear strength for specimen J-0.5D with the distance is 115.3kN and is larger than that for specimen J-0.As described above, for specimen J-2.5D, the failure mode was the joint shear failure after beam flexural yielding.

Therefore, the maximum strength of this specimen was obtained approximately from flexural theory.

3. INFLUENCE OF THE DISTANCE BETWEEN ONE BEAM AXIS AND THE OTHER BEAM AXIS ON BOTH SIDES OF COLUMN ON THE ULTIMATE STRENGTH OF JOINT

3.1. Horizontal Shear Force in a Joint

The horizontal shear force in a joint with different floor levels is not a constant value. Forces acting on a joint and horizontal shear forces(V_j) in a joint at maximum strength are as follows.

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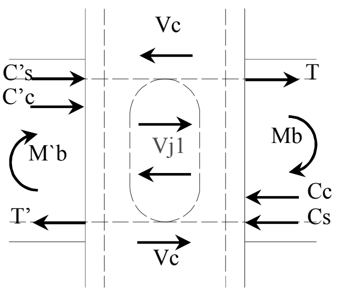
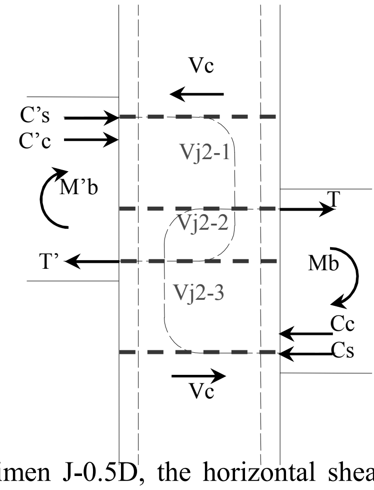
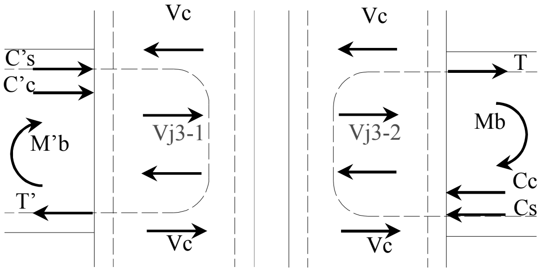


For specimen J-0, the horizontal shear force V_{j1}



For specimen J-0.5D, the horizontal shear forces V_{j2-1}, V_{j2-2} and V_{j2-3}



(the upper panel) (the under panel)

For specimen J-2.5D, the horizontal shear forces V_{j3-1} and V_{j3-2}

T, T' : tensile forces in beam longitudinal reinforcement
C_C, C_C' : concrete compressive forces
C_S, C_S' : compressive forces in beam longitudinal reinforcement
V_C : column shear forces
M_b : beam moment

Figure 4 Shear forces in a joint

3.2. Comparison of Maximum Joint Shear Strength with Ultimate Joint Shear Strength Calculated by The Proposed Equation

The comparison of maximum joint shear forces (V_j) with ultimate joint shear strength calculated by the proposed equations Eqn.2.1 and Eqn.2.2 is shown in Table 2.

For specimens J-0 and J-2.5D, the joint shear strength can be estimated by the proposed equations. However the joint shear strength V_{j2-2} for specimen J-0.5D is larger than that for specimen J-0. This phenomenon indicates that the joint shear strength is influenced by the distance between one beam axis and the other beam axis on both sides of column. Therefore, the ultimate shear strength of joint with different floor levels should be estimated by the joint shear force V_{j2-2}, which is the largest.

3.3. Influence of Shear Span Ratio on Joint Shear Strength

Fig 5 shows joint shear strength index (V_j/V_{ju}) plotted against the shear span ratio ($M/(V_j \cdot j_c)$). The previous

Table 2 Comparison of joint shear strength with ultimate shear strength of joint calculated by the proposed equations

	J-0	J-0.5D			J-2.5D
	V_{j1}	V_{j2-1}	V_{j2-2}	V_{j2-3}	$V_{j3-1,2}$
V_j	863	427	985	427	520
V_{ju}(kN)	937	527	937	527	527
V_j/V_{ju}	0.92	0.81	1.05	0.81	0.99

V_j : joint shear force of V_{j1}, V_{j2-1}, V_{j2-2}, V_{j2-3} and $V_{j3-1,2}$, as shown in Fig 4 at the maximum strength
V_{ju} : joint shear force calculated by Eqn.2.1 and Eqn.2.2
Eqn.2.1 for V_{j1} and V_{j2-2}, Eqn.2.2 for V_{j2-1}, V_{j2-3} and $V_{j3-1,2}$

experimental data of interior - type + - shaped joints and the joints with different floor levels are plotted. The definition of shear span ratio is shown in Fig 6.

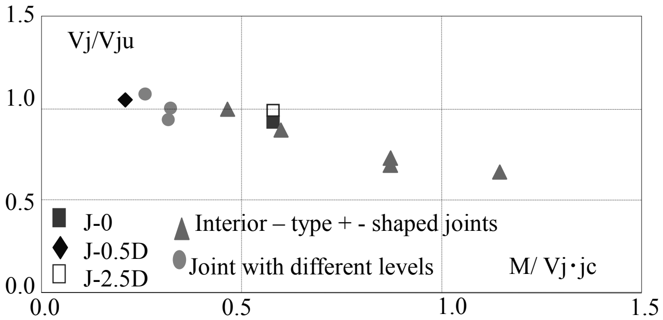
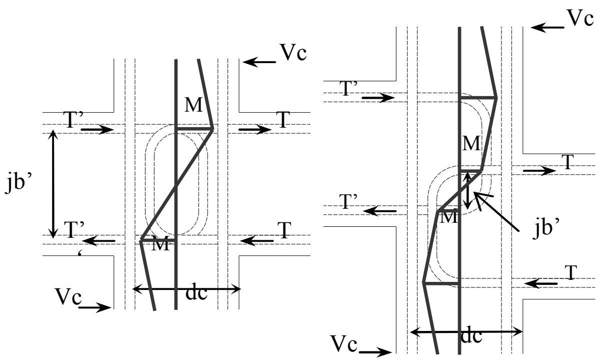


Figure 5 Joint shear strength index (V_j/V_{ju}) – shear span ratio relations



$$M/V_j \cdot j_c = V_j \cdot a / V_j \cdot j_c = a/j_c$$

M : bending moment
a : shear span (= *jb'*/2)
jb' : distance from top beam bar to bottom beam bar
jc : distance from the centroid of compression to centroid of tension of column (=(7/8)· *dc*)

Figure 6 Definition of shear span ratio

Fig 5 indicates that the joint shear strength decrease with the shear span ratio level. Comparing the relations of the joint shear strength obtained by experiment and calculated by proposed equation Eqn.2.1, the joint shear strength has a tendency to overestimate with the shear span ratio level.

Accordingly, proposed equation Eqn.2.1 does not reflected the influence of shear span ratio.

4. SHEAR RESISTANCE MECHANISMS OF BEAM – COLUMN JOINT

4.1. Compressive Strut Resultant Force and Angle of Strut in Strut Mechanism

The shear transfer mechanisms in a joint can be regarded mainly as strut actions at ultimate shear strength, considering the forces acting on the joint. Here, compressive strut resultant force and angle of strut in strut mechanism are discussed. The process for calculating the compressive strut resultant force and angle of strut in strut mechanism consists of the following steps.

Step1 : The depths(a_b,a_c) of the concrete compression zone in the column and beam sections at the end of the joint in Fig.7(a) are given the following equations, respectively.

$$\begin{aligned} j_c &= \left\{{}_cM - \left(D_c - 2{}_cd_c\right)\cdot {}_cC_s + \left(D_c - 2{}_cd_c\right)\cdot N/2\right\} / {}_cC_c \\ a_c &= 2\left\{\left(D_c - {}_cd_c\right) - j_c\right\} \\ j_b &= \left\{{}_bM - \left(D_b - 2{}_bd_c\right)\cdot {}_bC_s\right\} / {}_bC_c \\ a_b &= 2\left\{\left(D_b - {}_bd_c\right) - j_b\right\} \end{aligned} \tag{4.1}$$

where ${}_bC_c$ and ${}_cC_c$ are respectively concrete compressive forces at the beam and column critical section; ${}_bC_s$ and ${}_cC_s$ are respectively steel compressive forces given by the measured strains in beam and column longitudinal reinforcement ; N is column axial force; ${}_cM$ and ${}_bM$ are the bending moments at the end of the joint ; ${}_cd_c$ and ${}_bd_c$ are respectively the distances from the extreme fiber of column and beam section to the centroid of column and beam bar ; D_c and D_b are column and beam depths.

Step2 : In this model, the horizontal and vertical joint shear forces (C_H,C_V) resisted by the compressive strut mechanism are given by

$$\begin{aligned} C_H &= {}_bC_c + \Delta_bT_s - V_c \\ C_V &= {}_cC_c + \Delta_cT_s - p \end{aligned} \tag{4.2}$$

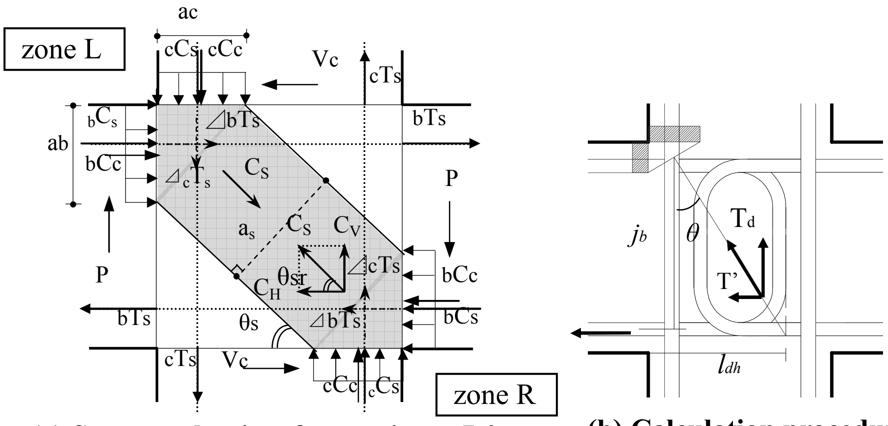
where bond forces (Δ_bT_s, Δ_cT_s) of beam and column longitudinal reinforcement in the main concrete strut, as shown in Fig 7(a). And the compressive strut resultant force(C_s), and the strut stress(σ_s) are given by

$$\begin{aligned} C_s &= \sqrt{C_H^2 + C_V^2} \\ \sigma_s &= C_s / \left(\sqrt{a_b^2 + a_c^2} \cdot t_p\right) \end{aligned} \tag{4.3}$$

where t_p is equal to $(B_b + B_c)/2$; and B_b and B_c are respectively beam and column widths.

Step3 : The angles (θ_{sr}, θ_s) of strut resultant force and strut calculated by the depths of the concrete compression zone in the column and beam sections are given the following equation, respectively.

$$\begin{aligned} \tan\theta_{sr} &= C_V / C_H \\ \tan\theta_s &= \left(D_b - a_b\right)/\left(D_c - a_c\right) \end{aligned} \tag{4.4}$$



$$T = T' \cdot H / (H - j)$$
$$T' = T_d \cdot \sin\theta$$

(a) Strut mechanism for specimen J-0 **(b) Calculation procedure for the bearing force**

Figure 7 Shear Resistance Mechanism of Beam – Column Joint

Table 3 Angle of strut resultant force in strut mechanism and the bearing force in the location of the bent beam bar

Specimen	Location	θ_s[rad]	θ_{sr}[rad]	σ_s[Mpa]	Td[kN]	Cs[kN]	Td/Cs
J-0	ZoneR	0.95	1.22	21.3	568	746	0.76
	ZoneL		1.14	21.0	641	779	0.82
J-0.5D	ZoneR	1.13	1.20	20.4	602	698	0.86
	ZoneL		1.05	19.7	723	751	0.96
J-2.5D	Upper panel	0.94	1.02	19.0	722	655	1.10
	Under panel	0.94	0.87	20.7	907	840	1.08

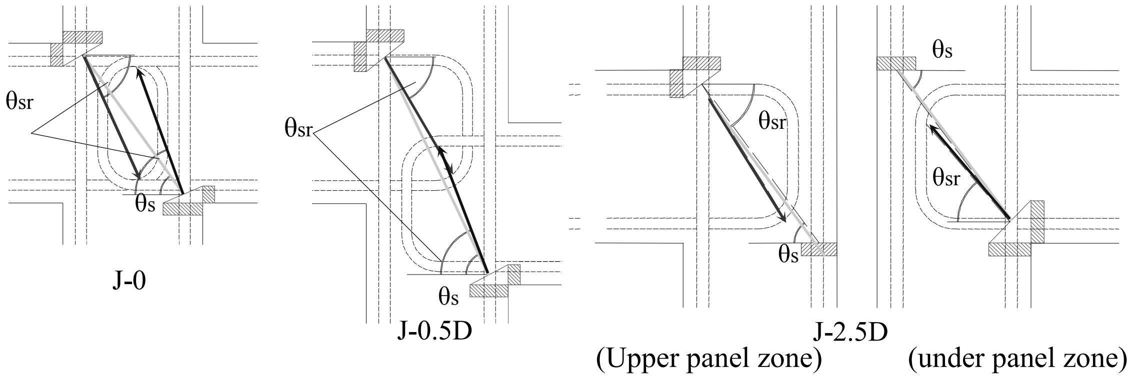


Figure 8 Angles of strut resultant force and strut calculated by the depths of the concrete compression zone

The compressive strut stress(σ_s), and the angles(θ_{sr}, θ_s) of strut resultant force and strut at maximum strength in strut mechanism are shown in Table 3. And also, the angles of strut resultant force and strut calculated by the depths of the concrete compression zone in the column and beam sections are shown in Fig 8.

For specimen J-0, the angle(θ_s) of strut doesn't agree with that(θ_{sr}) of strut resultant force, because strut resultant force is formed between the corner of joint panel zone and the location of bent beam bars within the joint arranged in the continuous hoop form. Namely, the bearing force in the bent beam bar equilibrates the resultant force of concrete compressive forces at the beam and column critical section.

4.2. Comparison of Compressive Strut Resultant Force with The Bearing Force in The Location of The Bent Beam Bar

A calculation procedure for the bearing force (T_d) in the location of the bent beam bar [Architectural Institute of Japan, 1999] is indicated in Fig 7(b). The comparison of compressive strut resultant force (C_s) with the bearing force (T_d) is shown in Table 3. The ratio of compressive strut resultant force (C_s) and the bearing force (T_d) is approximately between 0.8 and 0.9. The contribution to compressive strut resultant force in the compressive concrete strut mechanism is mainly represented by the bearing force.

For all specimens, the strut stress (σ_s) in the strut mechanism at maximum strength is larger than the concrete effective compressive strength ($\nu\,\sigma_B$: 18.2 [MPa]) obtained by the following equation [NAGANUMA,1989] as shown in Table 3.

$$\upsilon\sigma_B = \left(0.8 - \sigma_B / 2400\right)\cdot \sigma_B \quad \text{(in kgf/cm}^2\text{ units)} \tag{4.4}$$

Therefore, it is considered that the crushing of concrete in the joint panel occurred.

5. CONCLUSIONS

The following conclusions may be drawn from the test results and the analysis of the shear force of the joint zone between one beam axis and the other beam axis;

1. The ultimate strength of joint with different floor levels should be estimated by means of the shear force of the joint zone between one beam axis and the other axis.

2. The ultimate strength of joint relates with the ratio of the distance between one beam axis and the other beam axis to column depth. As the value of ratio is smaller, the ultimate strength of joint increase. The ultimate shear strength of joint with same floor levels is to the ratio of beam depth to column depth what that with different floor levels is to the ratio of distance between one beam axis and the other beam axis to column depth.

3. In the specimen with beam bar anchorage of the continuous hoop form within the joint, the contribution to compressive strut resultant force in the compressive concrete strut mechanism is mainly represented by the bearing force.

REFERENCES

Architectural Institute of Japan (1999), Design Guidelines For Earthquake Resistant Reinforced Concrete Buildings Based on Inelastic Displacement Concept, AIJ, Tokyo

Naganuma, K. (1989), “Compressive Characteristics of Cracked Concrete”, Japan Concrete Institute Colloquium Analytical Studies On Shear Design of Reinforced Concrete Structures, pp23-30.

Fujii, S.(1972), “Moment – Curvature Characteristics of Reinforced Concrete Members Based on Material Properties”, Proceeding of AIJ Annual Meeting, pp1261-1262

$$T = T' \cdot h / (h - j)$$
$$T' = T_d \cdot \sin\theta$$

J-0