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AN EXPERIMENTAL STUDY ON SHEAR FAILURE MECHANISM OF RC INTERIOR BEAM-COLUMN JOINTS

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ABSTRACT

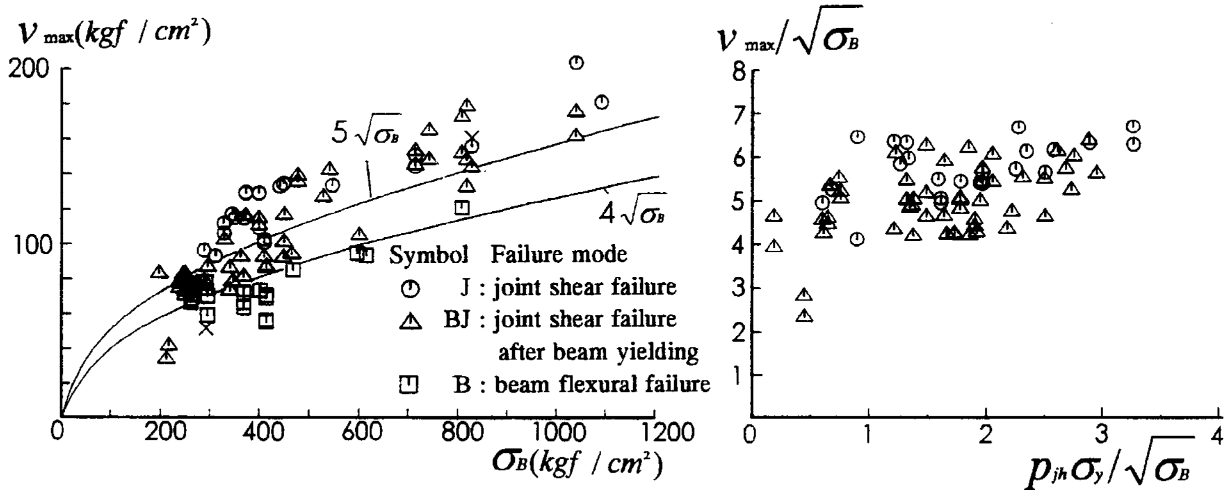
Reinforced Concrete earthquake-resistant frames are generally designed on the basis of "strong-column weak-beam" concept. Besides, shear failure of beam-column joint should be avoided before the adequate ductile behavior of frames is obtained. Joint shear failure occurs when the shear stress level is enough large, but it is different on the condition with or without adjacent beam yielding. The experimental study shows that joint shear failure results from the compressive fracture of joint concrete in which the deterioration occurs due to shear cracking. And joint reinforcement makes a large influence on the joint shear strength if adjacent beams yield, because it becomes the principal confinement for joint.

KEYWORDS

beam-column joint; reinforced concrete; shear failure; joint reinforcement; cyclic loads; cracked concrete; failure mode; beam yielding; joint shear ; strength reduction factor

INTRODUCTION

The aseismatic design concept of reinforced concrete frames is mostly based on "strong-column weak-beam" concept in the many countries. It is desirable that earthquake input energy is dissipated by beam hinging without column failure. And it is necessary to make it sure that beam-column joint should not fail in shear before plastic hinges occur at adjacent beam ends. The failure mode of beam-column assemblages are considered as 1) beam yielding, 2) column yielding, 3) joint shear and 4) beam bar anchorage (Meinheit *et al.*, 1981). If the frames are designed on the prior concept and also considered about the anchorage of reinforcing bar well, the remain to be clarified is the relation between beam yielding and joint shear failure. To avoid joint shear failure before beam hinging, it is said that joint input at beam hinging should be limited lesser than joint strength and arrange adequate joint reinforcement. But even the role of joint reinforcement is different in some code, and the precise equation for the estimation of joint shear strength has not been established yet. In this paper, the experimental study on RC beam-column joint



a) Joint Concrete Compressive Strength b) Joint Horizontal Reinforcement

Fig. 1. Relations of Experimental Parameters on the Specimen Strength

shear failure mechanism is presented.

PRELIMINARY STUDY

The statistical investigation on RC interior joint shear strength had done using experimental data of 96 specimens tested in Japan which had no slab nor transverse beams. At first the failure mode of specimens were defined as 3 modes which were beam flexural failure (B-type), joint shear failure after beam yielding (BJ-type) and joint failure without connecting member yielding (J-type). The number of each type specimen was 19 of B-type, 52 of BJ-type ,23 of J-type and 2 of other failure, respectively.

Effective Parameter on Joint Shear Strength

Maximum strength vs. Concrete compressive strength. Relationship between maximum strength and concrete compressive strength is shown in Fig. 1(a). Maximum strength is indicated in average joint horizontal shear stress which is calculated considering the joint effective area is bounded by the average width of beam and column and column depth. J-type data, that signify joint shear strength, scatter over the line of $5\sqrt{\sigma_B}$ (σ_B :concrete compressive strength, kgf/cm^2), and B-type data, that signify beam flexural strength, scatter under the line of $4\sqrt{\sigma_B}$. BJ-type data mostly scatter between these lines in normal concrete strength. It is said that: 1) if joint shear stress at beam yielding is limited under $4\sqrt{\sigma_B}$ in joint shear stress, joint shear failure would never occur. 2) minimum strength of joint shear is defined as $5\sqrt{\sigma_B}$ in joint shear stress.

Maximum strength vs. Joint reinforcement. Fig.1(b) shows the relationship between the maximum strength (joint shear stress) to horizontal joint reinforcement force index (defined as the product of reinforcement ratio and yield strength). Each value is divided by $\sqrt{\sigma_B}$ for normalization. From the scatter of data, joint reinforcement does not influence on the maximum strength so much, but the larger reinforcement strength is, the maximum strength somewhat increases. In other members like as beam or column, shear reinforcement is effective on the shear strength. What is difference?

EXPERIMENTAL WORK

Scope and Objective

Joint shear failure type is separated into two cases by with or without beam yielding. And the role of joint reinforcement is seemed to be also different in two cases. To investigate the mechanism of joint shear failure and the role of joint reinforcement, the following two series experimental works were carried out.

Outline of the Test

The specimens. All specimens were the same shape and size in both series; cross shaped, half size of actual, column of 300 mm x 300 mm, beam of 200 mm x 350 mm, column height of 1750 mm, beam span of 3000 mm, and without slab nor transverse beams. They had a different beam reinforcement ratio (joint input) in each series, and joint reinforcement ratio (horizontal and vertical) in each specimen. Every specimen was designed as not to occur column hinging before beam yielding.

J-type series. All six specimens had a large amount of beam reinforcement, which would generate joint shear stress of $7\sqrt{\sigma_B}$ at beam yielding, to ensure that joint shear failure would occur before beam yielding. All specimens which have different both horizontal(p_{jh}=0.03 - 1.6%) and vertical(p_{jv}=0 - 1.56%) joint reinforcement volume (see Table 1) to investigate the influence of joint reinforcement on joint shear strength. Reinforcement detail is shown in Fig. 2.

BJ-type series. Two specimens were designed to have different beam bar ratio in each loading direction (forward and backward) which would generate $3.2\sqrt{\sigma_B}$ and $4.5\sqrt{\sigma_B}$ in joint shear stress at beam yielding, respectively. Each specimen was different in horizontal joint reinforcement ratio (p_{jh}=0.37 or 0.93%). Reinforcement detail is shown in Table 1 and Fig. 2.

Loading and Instrumentation. Loading arrangement is schematically shown in Fig. 3. The incremental forced displacement was given to the specimen at top of column cyclically during axial force of $0.3\sigma_B$ (J-type) or $\sigma_B/6$ (BJ-type) had been applied. The forces , displacement and reinforcement strain were measured during test.

Specimen Behavior. Test results are shown in Table 2. In all specimens of J-type series, no beam yielding was observed but joint shear failure during test. Maximum strength of all specimens was about equal to $5\sqrt{\sigma_B}$ in joint shear stress, in spite of the difference in joint reinforcement volume, and any horizontal joint reinforcements were not yield except for 'J-LO' which had a little horizontal joint reinforcement of 0.03%, almost non-reinforcing. In both specimen of BJ-type series, all beam bars completely yielded at the forward loading, and the maximum strength exceeded the calculated beam flexural strength. At the backward loading in which joint input at beam yielding would be larger, only a half beam bars yielded at the beam critical section and joint concrete crashing was observed at the large displacement loading cycle. The maximum strengths of both specimens were less than the calculated flexural strength and that of specimen 'BJ-PH' which had a large amount of horizontal joint reinforcement was larger than that of another. In both test series, joint shear failure was caused by the compressive fracture of cracked joint concrete.

Table 1. Specimen Details and Materials

series	column bar	beam bar	joint reinforcement horizontal	joint reinforcement vertical	joint concrete
J	12-D19 (p_g=3.82%) [5890]	3-D25 (p_t=2.41%) [4340]	H:48-6 φ(1.60%) M:24-6 φ(0.80%) L: 4-3 φ(0.80%) [3890]	H:40-6 φ(1.56%) M:20-6 φ(0.78%) [3890]	[320 - 334]
BJ	8-D19+4-D13 (p_g=3.11%) [6530,4030]	5-D13(forward) (p_t=0.99%) 7-D13(backward) (p_t=1.39%) [4030]	H:24-6 φ(0.93%) L:10- 6 φ(0.37%) [3320]	(4-D13 0.73%) constant	[303 - 311]

Specimen name J-series: LO,MO, HO, OH, MM, HH
first letter: joint horizontal reinforcement last:vertical
BJ-series:PL,PH P:Panel last letter:joint horizontal reinforcement
[ ] : material strength (kgf/cm^2)

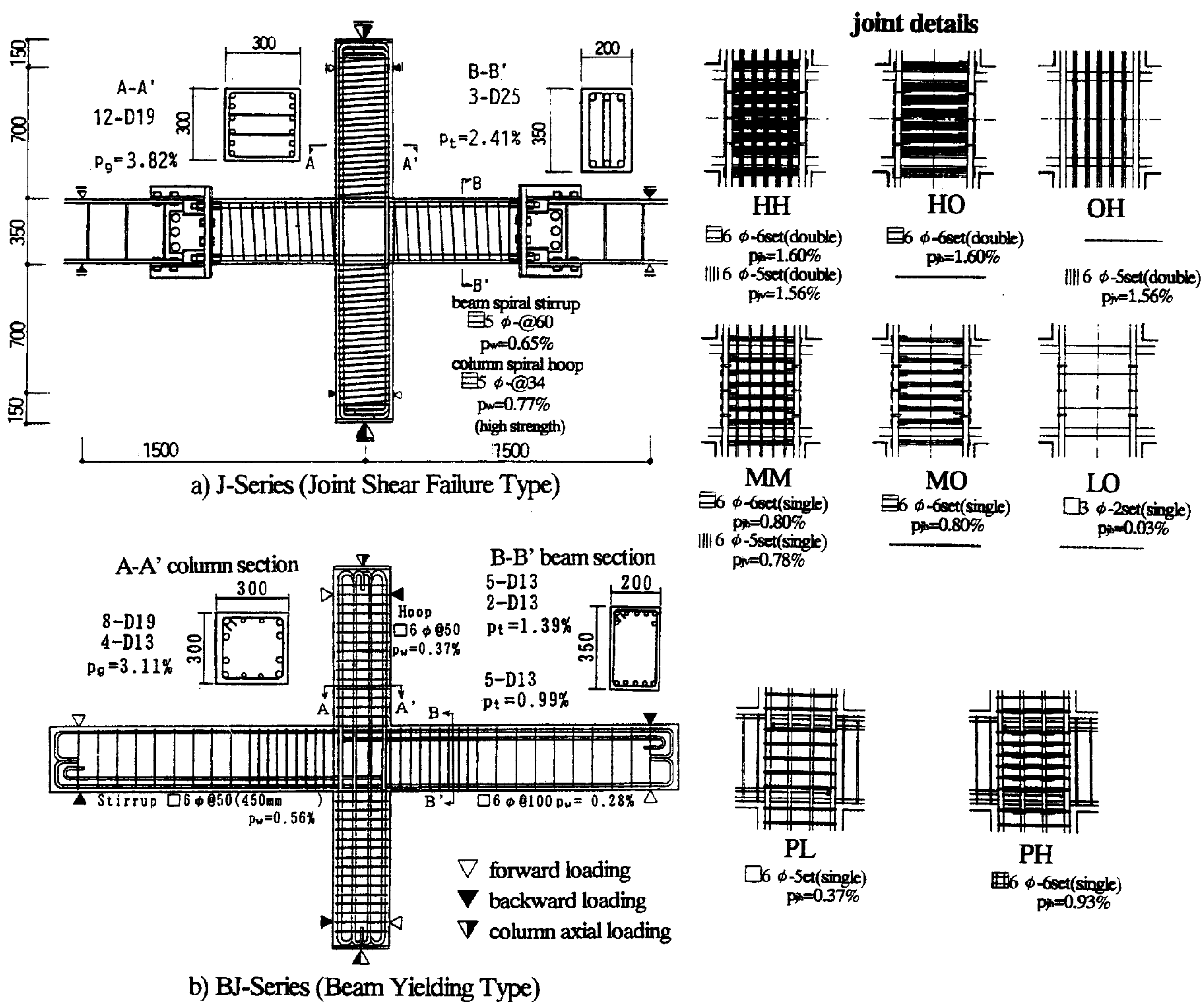


Fig. 2. Specimens

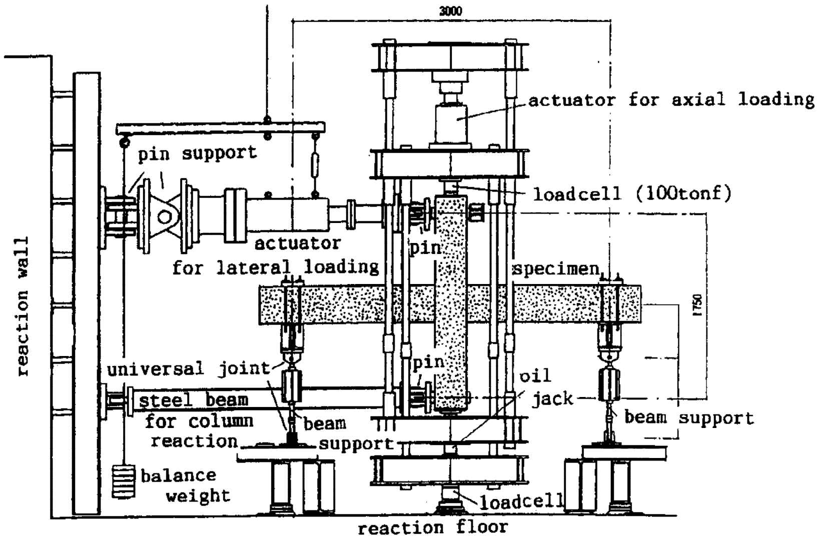


Fig. 3. Loading System

Table 2. Experimental Results

specimen	$_{cr}v_j$	$/\sqrt{\sigma_B}$	$_{max}v_j$	$/\sqrt{\sigma_B}$	σ_B
J-HH	45.1	2.43	98.5	5.39	334
	38.4	2.07	92.8	5.08	
J-HO	46.9	2.62	94.6	5.29	320
	40.6	2.27	88.5	4.95	
J-OH	44.8	2.50	87.3	4.87	321
	46.0	2.57	83.2	4.64	
J-MM	45.0	2.48	100.0	5.50	330
	45.1	2.48	94.6	5.21	
J-MO	45.1	2.47	102.2	5.60	333
	44.9	2.46	97.2	5.33	
J-LO	49.1	2.73	102.1	5.68	323
	51.5	2.87	98.8	5.50	
BJ-PL	39.9	2.29	62.4	3.58	303
	46.3	2.66	66.9	3.84	
BJ-PH	46.6	2.64	68.3	3.87	311
	46.6	2.64	71.2	4.04	

$_{cr}v_j$: joint shear stress at joint shear cracking ($kgf\ /\ cm^2$)

$_{max}v_j$: maximum strength ($kgf\ /\ cm^2$)

σ_B : concrete compressive strength ($kgf\ /\ cm^2$)

upper : forward loading lower : backward loading

DISCUSSION OF RESULTS

Paulay (1989) made a study of the stress transfer mechanism in beam-column joint and the function of joint reinforcement using an equilibrium criteria. In this paper, the investigation on the mechanism of joint shear failure was carried out on the basis of Paulay's study.

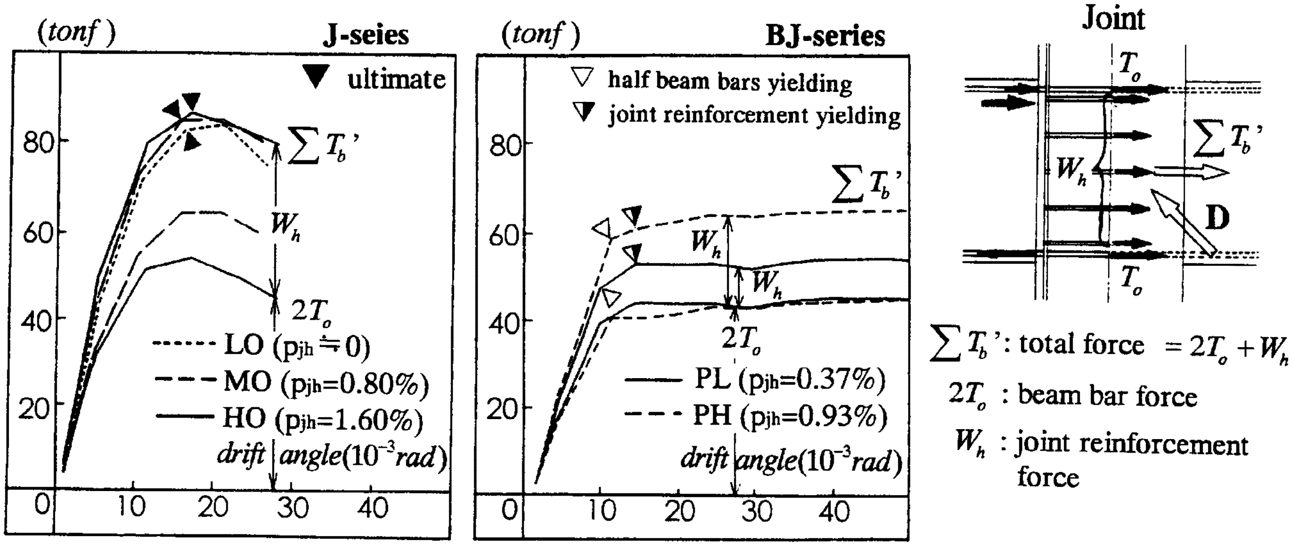


Fig. 4. Internal Horizontal Forces in Joint Center

Internal Horizontal Forces within a Joint

A total amount of beam bar forces and horizontal joint reinforcement forces at joint center was considered as the horizontal component of diagonal concrete strut, and the results of J-type at the forward loading and BJ-type at the backward loading are shown in Fig. 4 as the relationship to the story drift angle. In the figure, both the total force and the total beam bar force are indicated, so the remainder of the total force to the total beam bar force means the total force of horizontal joint reinforcements.

In the J-type specimens, the total force are almost same and the beam bar force changes according to the reinforcement volume as Paulay suggested. It is said that the total force at ultimate strength is limited by the cracked concrete strength and the maximum strengths are the same no matter what the volume of horizontal reinforcement. The result at the backward loading is the same as that at the forward. In the BJ-type specimens, the beam bar forces of both specimens are the same and the difference of the total force between the two is almost equal to that corresponding to the yield force of joint horizontal reinforcement. Strictly speaking the beam bars of the both specimens were not yield completely at the backward, but in such case that joint shear failure occurred when beam bars almost yielded, the strength was influenced by the joint reinforcement ratio.

Consideration of the Joint Shear Failure Mechanism

The investigation of the internal force at joint vertical direction was also carried out. From the total force at the both horizontal and vertical, the principal compressive stress at joint center is calculated in the assumption that joint effective area is the area bounded by the average width and beam depth or column depth. The relationship between the principal stress and the average diagonal tensile strain measured at joint face is shown in Fig. 5. Several studies on the effective compressive strength of cracked concrete have been done in the experimental researches on RC plate. Vecchio and Collins (1986) proposed the following equation to predict the reduction factor of cracked concrete from the experimental work of RC plates subjected to in-plane shear stress and normal stress.

$$\lambda = \frac{1}{0.8 + 0.34(\varepsilon_{1u} / \varepsilon_0)} \leq 1 \qquad (1)$$

Shirai and Noguchi (1989) tested a number of uniaxially reinforced panels under tension-compression states with loading applied in the reinforcement directions. They suggested that the Collins' equation underestimated their results in the reason of $\varepsilon_{1u} / \varepsilon_0 > 2.5$, and they proposed the following equation for the tension-compressive type loading.

$$\lambda = \frac{1}{0.27 + 0.96(\varepsilon_{1u} / \varepsilon_0)^{0.167}} \leq 1 \qquad (2)$$

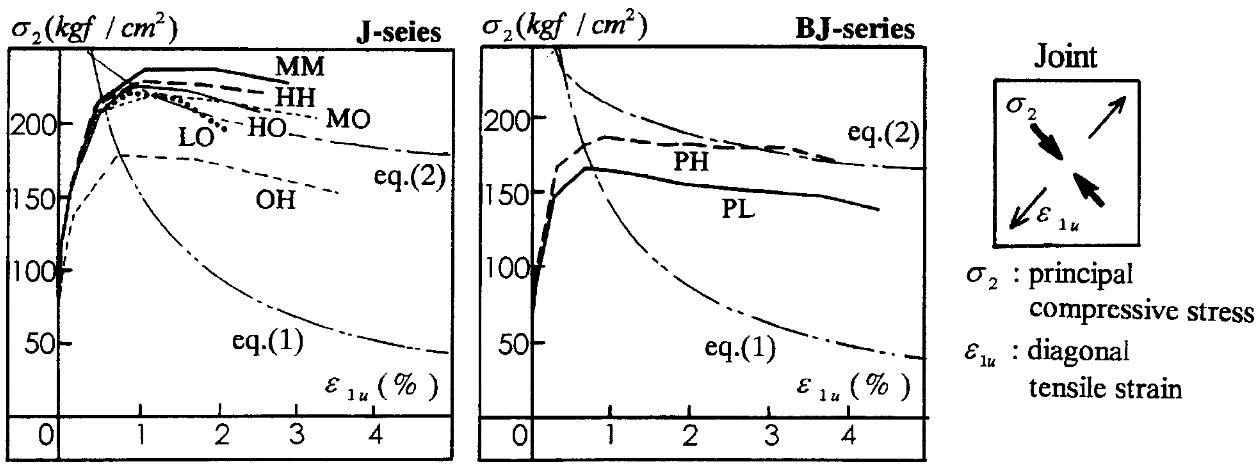


Fig. 5. Principal Compressive Stress in Joint

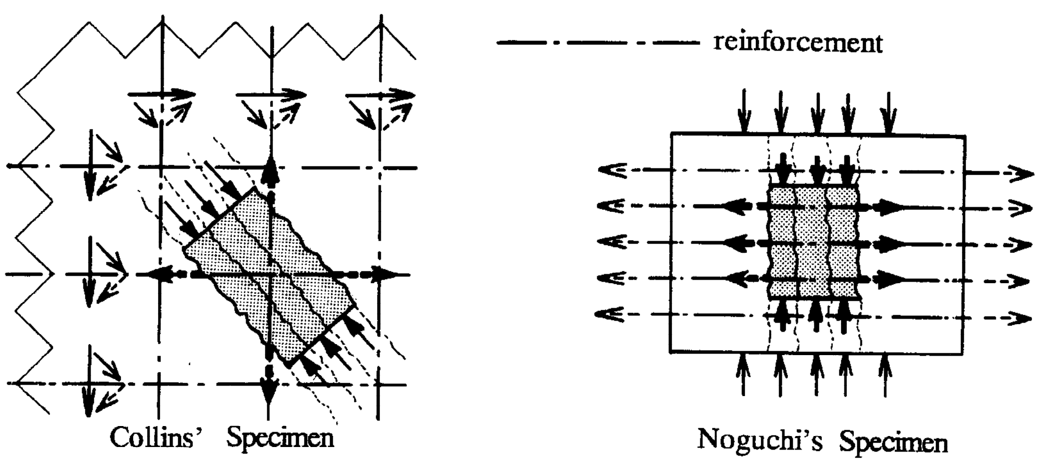


Fig. 6. Stress Conditions of RC Plate Specimens

Both proposed equation are indicated in the figure. The difference of stress condition between Collins' test and Noguchi's is schematically shown in Fig. 6. In Collins' specimen compression had been generated by shear stress, simultaneously tension generated. On the other hand, compression was generated directly while tension applied through bond stress had been kept at a certain degree in Noguchi's specimens.

In case of J-type specimens, apparent changes are observed at shear cracking and at the crossing to Collins' equation line. But the principal stress increases to the value of Noguchi's except for 'J-OH' that was broken in concrete crashing due to the absence of column bar confinement. The aspects of BJ-type specimens are different that the apparent change is observed at some beam bars yielding and the maximum principal stress is limited by the value of Collins' equation after joint reinforcement yielding. The reason why the principal compressive stress of J-type specimen could increase over Collins' value is that large compressive force from beam end maintained in these specimens because beams did not yield, so the stress condition in joint concrete became tension-compression state. Contrary , after beam yielded at the forward loading and a half of beam bars also yielded at the backward in BJ-specimen, the compressive force from beam ends decreased and forces input to joint were almost transferred by the bond stress (i.e. the restrain of beams to joint became weaker), so the input by shear stress maintained as Collins' specimens. And joint reinforcement became effective as joint confinement after beam yielding, but when it yielded the diagonal tensile strain increased rapidly and the strength was limited by cracked concrete strength even though all beam bars did not yield yet (i.e. the larger joint stress could have been generated).

CONCLUSIONS

The statistical investigation on RC interior joint shear strength using experimental data indicated that: 1) minimum joint shear strength is estimated $5\sqrt{\sigma_B}$ in average joint shear stress, and 2) joint shear stress at beam yielding should be limited less than $4\sqrt{\sigma_B}$ in order to make beam yielding infallible.

The experimental results shows that joint shear failure occurs due to the deterioration of shear cracked concrete. In case of joint shear failure without beam yielding, joint shear strength is not influenced by joint horizontal reinforcement, because the component of joint concrete diagonal strut is supported by both beam bars and joint reinforcements proportionally. In case of joint shear failure after beam hinging, joint reinforcement yielding gives a large influence on the cracked concrete strength even on the joint shear strength.

REFERENCES

Meinheit, D.F. and J.O. Jirsa (1981). Shear Strength of R/C Beam-Column Connections. *Proc. ASCE*, **Vol.107**, No. ST11, 2227-2244.

Vecchio, F.J. and M.P. Collins (1986). The Modified Compression-Field Theory for Reinforced Concrete Elements Subjected to Shear. *ACI Structural Journal*, **Vol.83**, No.2, 219-231.

Paulay, T. (1989). Equilibrium Criteria for Reinforced Concrete Beam-Column Joints. *ACI Structural Journal*, **Vol.86**, No.6, 635-643.

Shirai, S. and H. Noguchi (1989). Compressive Deterioration of cracked concrete. *Proc. ASCE Structural Congress 1989: Design, Analysis and Testing*, 1-10.