INFLUENCE OF JOINT REINFORCEMENT ON STRENGTH AND DEFORMATION OF INTERIOR BEAM-COLUMN SUBASSEMBLAGES

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SUMMARY

Experimental work was carried out to study the role of joint reinforcement for reinforced concrete interior beam-column joints which failed in beam flexure and joint shear after beam flexural yielding. Using the shear resistance mechanisms of beam-column joints, the behavior of joint reinforcement is discussed for the test results. As a result, the amount of lateral reinforcement in the joint had little influence on the ductility factor of story drift. And also the role of lateral reinforcement in a joint is considered to confine the joint core concrete after beam flexural yielding.

In order to confirm small dependency of the envelope curves of the story shear-story drift relations on the amount of joint lateral reinforcement in this experimental work, the previous experimental data was analyzed. According to the data base, ductility factor of story drift depends strongly on the joint shear stress level, but is little influenced by the amount of joint reinforcement.

INTRODUCTION

The application of the weak-beam design concept has become popular. The reinforced concrete frames designed so as to develop a weak-beam strong-column frame mechanism under seismic loading have generally the flexural yield regions at the ends of connecting beams. In this design concept, the strength of an interior beam-column joint should be maintained up to a usable limit of deformation after beam flexural yielding. However, the role and requisite amount of joint shear reinforcement in such a beam-column joint are not obvious. Therefore, the investigation is needed for the influence of joint reinforcement on mechanical behavior of beam-column joints which fail in shear at joint after beam flexural yielding and in flexure at beam.

The objects of this study are to give consideration to the role of joint reinforcement, and also to evaluate the influence of the amount of joint reinforcement on the envelope curves of the story shear-story drift relations after beam flexural yielding.

EXPERIMENTAL STUDY ON THE ROLE OF JOINT LATERAL REINFORCEMENT

Outline of Experimental work

Test specimens are five half-scaled interior beam-column joints removed from a plane frame by cutting the beams and columns at arbitrarily assumed inflection points, as shown in Fig.1. The parameters of the test are the amount of joint hoop and the joint shear stress level. Based on author's proposed method [Kamimura,1995], five specimens were designed to be a joint shear failure type after beam flexural yielding. The selected joint shear stress level was ${}_t\tau_{py}/\nu\sigma_B$=0.6 for specimens No.1,No.2 and No.3, and ${}_t\tau_{py}/\nu\sigma_B$=0.4 for specimens No.4 and No.5, where ${}_t\tau_{py}$ is the joint shear stress at the theoretical beam flexural yielding, σ_B is concrete compressive strength and ν is effective factor for concrete compressive strength (ν=0.8-σ_B/235, (in MPa units)) [Naganuma,1989].

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The joint shear stress, τ_p, is defined by the following equation:

$$\tau_p = \{(1-u-v)\cdot L\}/(v\cdot H\cdot t_p\cdot u\cdot L)\cdot V_b \tag{1}$$

where, V_b : beam shear, L : beam span, H : story height, $u{\cdot}L$=7/8$\cdot d_c$, d_c : column effective depth, $v{\cdot}H$ = 7/8$\cdot d_b$, d_b : beam effective depth and t_p : average of beam and column width.

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

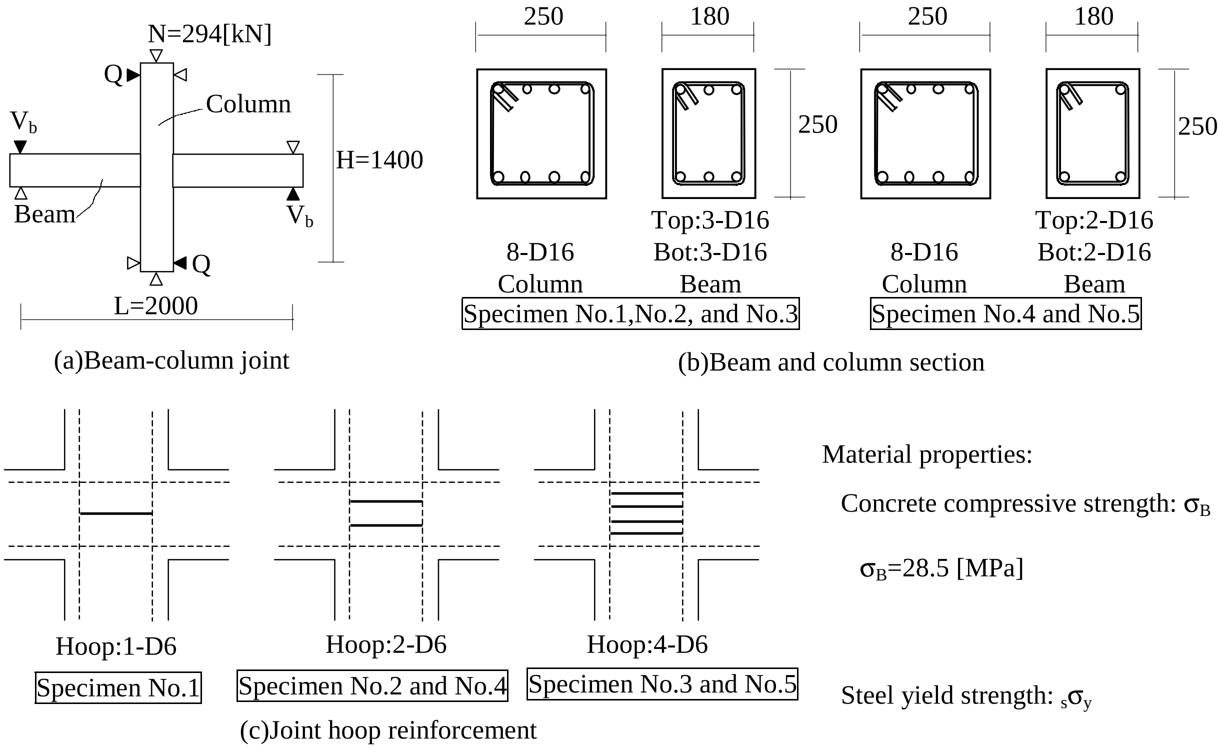


Figure1: Details of specimen (unit in mm)

Experimental Results and Discussions

Observed Behavior

Fig.2 shows the crack patterns observed at the end of loading for the representative specimens. The envelope curves of the beam shear-story drift angle relations and the beam shear-joint shear distortion relations are shown in Fig.3 and Fig.4, respectively. For specimens No.1, No.2 and No.3 with a large amount of beam longitudinal reinforcement, the beam flexural yielding and the crushing of concrete strut in a joint was observed. For specimens No.4 and No.5 with a small amount of beam longitudinal reinforcement, the crushing of concrete strut in a joint was not observed and the beam flexural failure occurred at the end of beam when the load exceeded the strength of theoretical beam flexural yielding.

The shape of the envelope curves in the beam shear-story drift angle relations was the similar one among these specimens with the same joint shear stress level. Comparing the relations of specimens No.1, No.2 and No.3,a large amount of joint shear reinforcement had little effect on the control of the shear strength decay and the shear deformation in the joint after maximum load. For specimens No.4 and No.5, the joint shear distortion was very small and was larger in specimen No.4 with a small amount of joint reinforcement than in specimen No.5 with a large amount of joint reinforcement.

The contribution of measured shear deformation of the panel δ_j to the story drift δ_R is shown in Fig.5. For specimens No.1, No.2 and No.3 with heavier beam longitudinal reinforcement, the deflection of a joint gradually increased and contributed about 60% to the total story drift. For specimens No.4 and No.5 with a small amount of beam longitudinal reinforcement, the deflection of a joint was limited within 15% to the total story drift.

The measured diagonal concrete strains within a panel zone are shown in Fig.6. For specimens No.1, No.2 and No.3, compressive strain after maximum load was larger than the strain at the concrete compressive strength.

Accordingly, it was concluded that the failure mode of specimens No.1, No.2 and No.3 was the joint shear failure after beam flexural yielding, and that of specimens No.4 and No.5 was the beam flexural failure.

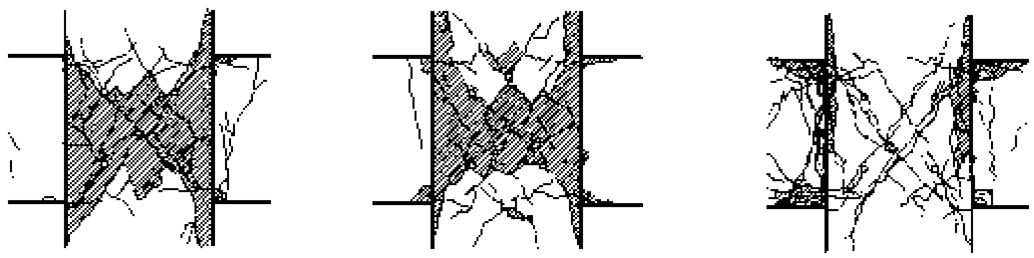


Figure2: Crack patterns after test

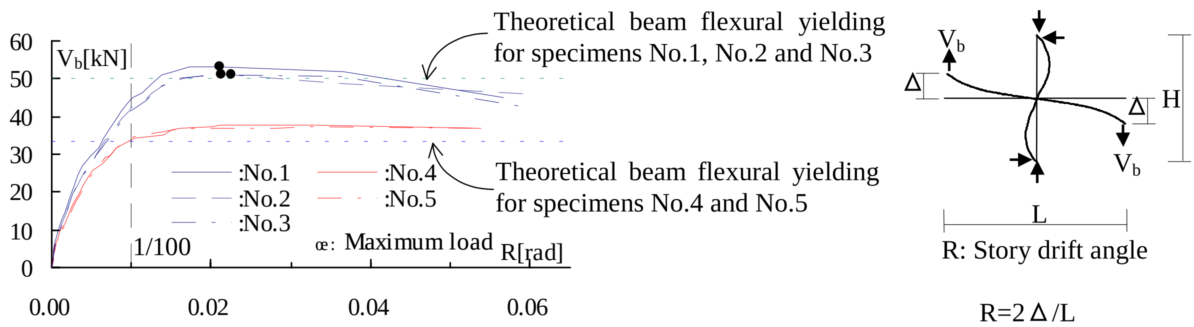


Figure 3: Beam shear-story drift angle relations

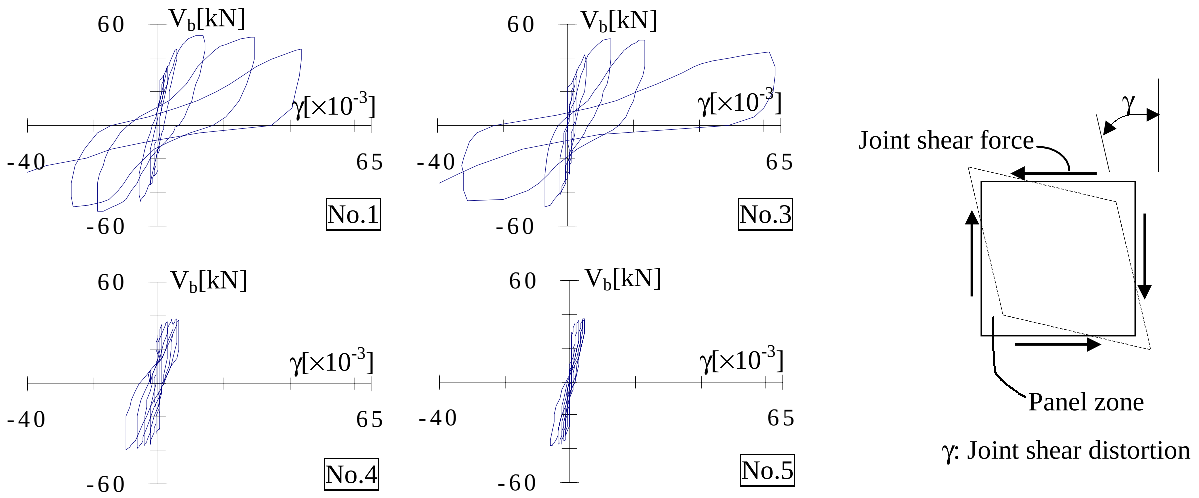


Figure 4: Beam shear-shear distortion relations

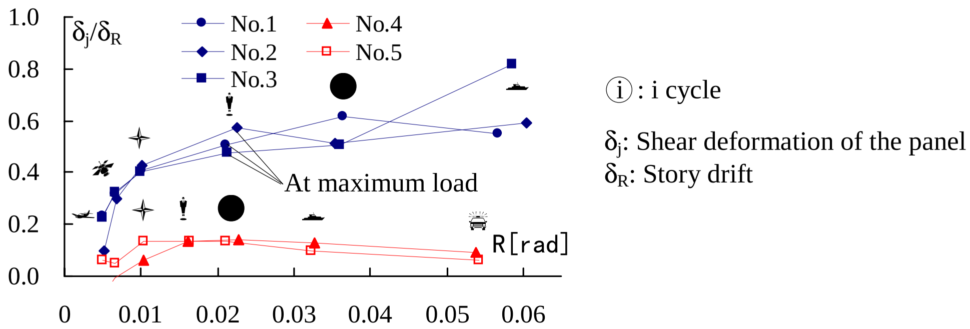


Figure 5: Contribution of joint shear deformation to story drift-story drift angle relations

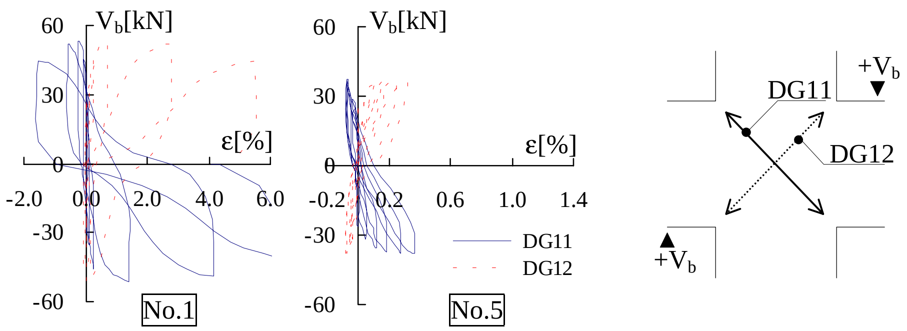


Figure 6: Beam shear-diagonal concrete strain within a panel zone relations

Behavior of joint Shear Reinforcement

Fig.7 shows the relationships between the beam shear and average strain parallel to the loading direction in joint shear reinforcement. For specimens No.1, No.2 and No.3, which the failure mode was the joint shear failure after beam flexural yielding, the joint reinforcement yielded at maximum strength in specimens No.1 and No.2 except specimen No.3, which was provided with a larger amount of joint reinforcement. However, the strains in these specimens increased with progress of the joint failure under the subsequent cyclic loading after maximum strength. For specimens No.4 and No.5, which the failure mode was the beam flexural failure, the strain in specimen No.4 was larger than that in specimen No.5, but the joint reinforcement did not yield in both specimens.

Fig.8 shows the envelope curves of stresses parallel and orthogonal to the loading directions in the joint shear reinforcement-story drift angle relations. The stresses were calculated by the stress-strain hysteretic model of reinforcing steel using Ramberg-Osgood model. The difference in stress between parallel and orthogonal to the loading directions in the joint shear reinforcement decrease for all specimens with the increase in story drift angle. This phenomenon indicates that, when the bond deterioration of beam and column longitudinal reinforcement within a joint progresses due to the shear cracking in a joint and the development of yield regions of the beam longitudinal reinforcement within a joint, the contribution of the truss mechanism may become insignificant. Therefore, the role of joint reinforcement is mainly considered to confine the joint core concrete after the beam flexural yielding.

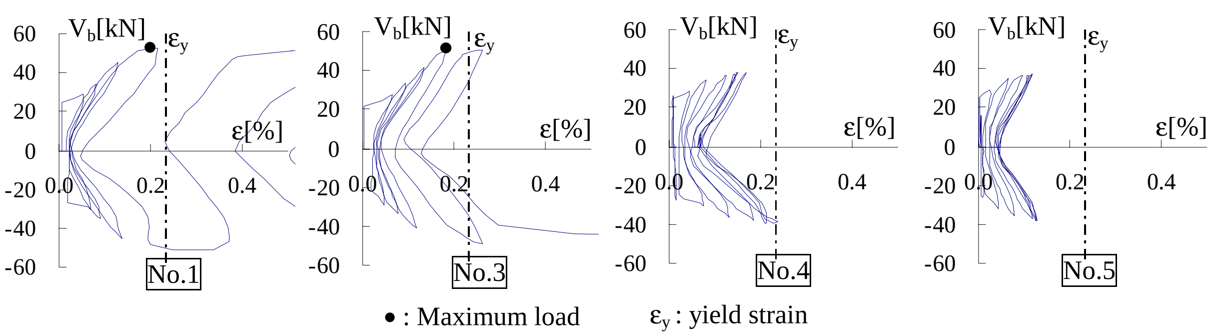


Figure 7: Beam shear-strain in joint shear reinforcement relations

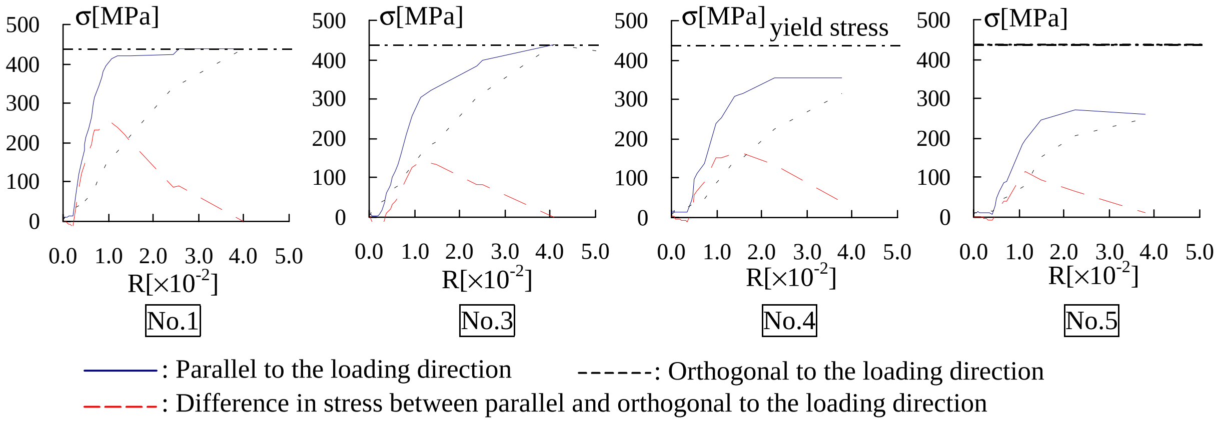
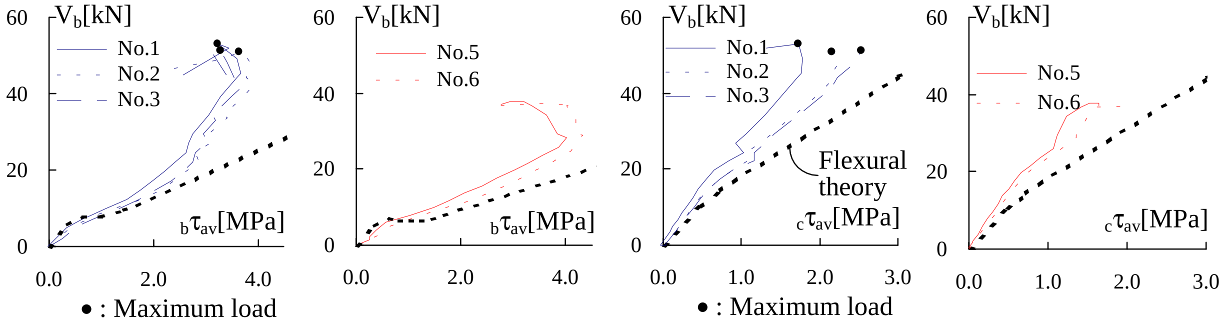


Figure 8: Stresses parallel and orthogonal to the loading directions-story drift angle relations

Bond characteristics of beam and column longitudinal reinforcement

Fig.9 shows the relationships between the beam shear and average bond stress (${}_b\tau_{av}$, ${}_c\tau_{av}$) in beam and column bars passing through a joint for all specimens. Bond stress was calculated using the bar stresses in four gauge points along each longitudinal reinforcing bar. At an early stage of loading, flexural theory [Fujii,1972] gave a good agreement with the test data on the average bond stress in beam and column longitudinal reinforcement for all specimens. From the comparison between these specimens, it was pointed out that the increase in the amount of joint shear reinforcement made slightly the better bond situation along the column and beam longitudinal reinforcement up to the maximum load. The maximum bond stress of beam bars in specimens No.4 and No.5 with a small joint shear stress level was larger than that in specimens No.1, No.2 and No.3 with a large joint shear stress level. Note that this showed the influence of joint shear stress level on the maximum bond stress in beam bar passing through a joint.



(a)Bond stress in beam bar (b)Bond stress in column bar

Figure 9: Beam shear-average bond stress in beam and column bars passing through a joint relations

INFLUENCE OF JOINT REINFORCEMENT ON ENVELOPE CURVE OF STORY SHEAR-STORY DRIFT RELATIONS IN THE PREVIOUS EXPERIMENTAL DATA

Outline of analytical study on the previous test data

As described above, the results of the experimental work showed that the truss mechanism started to diminish with a bond deterioration along the beam reinforcement in a joint after beam flexural yielding and the strut mechanism carried the dominant part of joint shear. Consequently, the principal role of lateral reinforcement is considered to confine the cracked core concrete in a joint. And also, it is expected that joint shear reinforcement prevents the strength decay after maximum strength. However, it was pointed out that the amount of joint shear reinforcement had unexpectedly little influence on the envelope curves of the beam shear-story drift relations in this experimental work. In order to confirm this fact, in addition to this experimental work, a previous experimental data on the influence of joint reinforcement on the envelope curves of the story shear-story drift relations after beam flexural yielding was analyzed.

The effect of lateral reinforcement on the envelope curve is estimated in terms of ductility factor μ which is defined by story drifts at beam yielding R_y and at ultimate situation R_u. These story drifts (R_y, R_u) are extracted from story drift at 90% of maximum strength, as shown in Fig.10. Generally, the factors, concerned in a joint, which affect the story deformation after beam flexural yielding could be the joint shear stress level, the amount of joint reinforcement and the bond situation in a joint. Therefore, the effect of joint reinforcement on the story deformation is discussed in consideration to these factors.

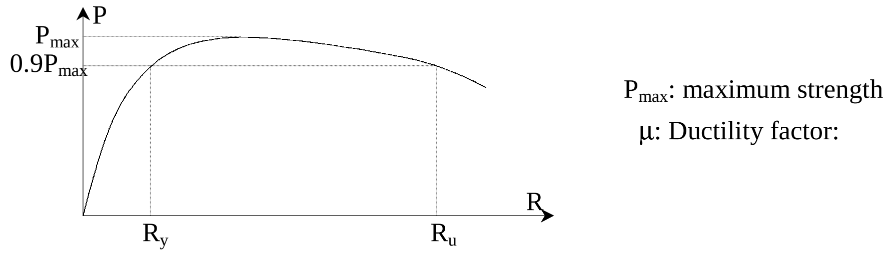


Figure 10: Definition of story drifts at beam yielding R_y and ultimate situation R_u

Review of Experimental Data

The previous experimental data of 87 interior-type +- shaped joints were analyzed. The tests used for the data were carried out in Japan, and these test results were reported in the literature before 1997. Since the classification of the failure modes in experimental study has depended on the subjectivity of the reseachers, the failure modes reported in the literature are judged over again by author's proposed method [Kamimura,1995] of classifying the failure modes of beam-column joints by means of joint shear stress at theoretical beam flexural yielding, as illustrated in Fig.11. Structural factors of specimens are shown in Fig.12.

It should be noted that the strength of specimens indicated by the hollow marks in Fig.11 did not deteriorate up to 90% of maximum strength and the story drift at ultimate situation R_u for these specimens was maximum story drift in the tests.

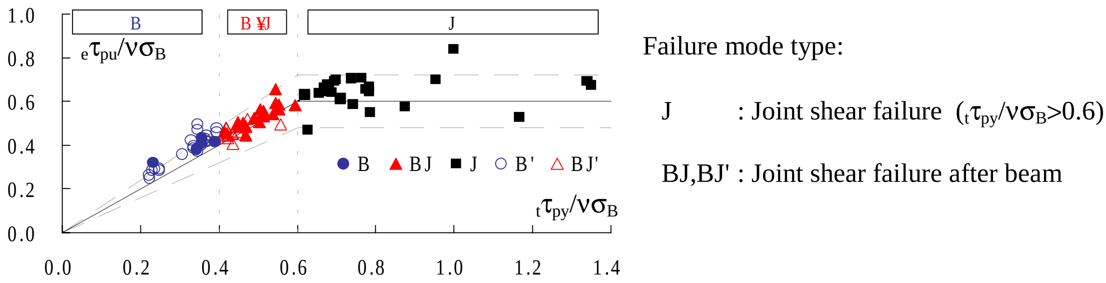


Figure 11: Classification of failure modes by author's method

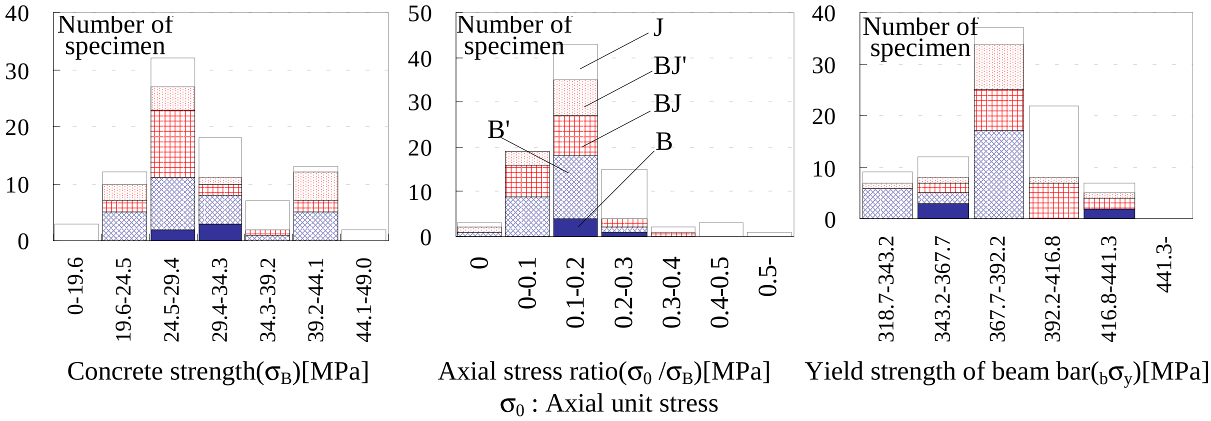


Figure 12: Structural factors of specimens

Analytical Results and Discussions

Relationship between joint shear stress level and story drifts

Fig.13 shows the story drifts at beam yielding and ultimate situation(R_y, R_u) plotted against the joint shear stress level(${}_t\tau_{py}/\sqrt{\sigma_B}$). The story drift at beam yielding R_y has a tendency to increase with joint shear stress level. However, an obvious interaction of the story drift at ultimate situation R_u with joint shear stress level is not seen in Fig.13.

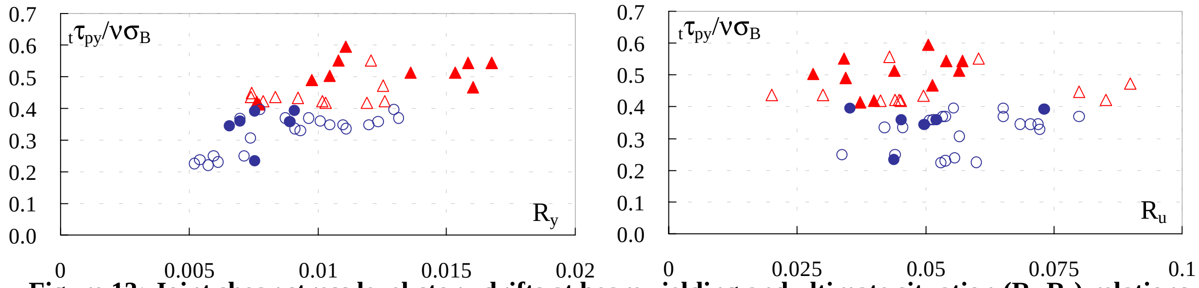


Figure 13: Joint shear stress level-story drifts at beam yielding and ultimate situation (R_y,R_y) relations

Influence of bond situation on maximum strength

Fig.14 shows maximum strength index (${}_e\tau_{pu}/{}_t\tau_{py}$) plotted against the bond index ($\tau_b/\sqrt{\sigma_B}$). Maximum strength index, ${}_e\tau_{pu}/{}_t\tau_{py}$ represents joint shear stress at maximum strength ${}_e\tau_{pu}$ divided by that at theoretical beam flexural yielding ${}_t\tau_{py}$. Bond index, $\tau_b/\sqrt{\sigma_B}$, which is defined in Eq.(2) [AIJ,1990], is used for the quantitative expression of the bond characteristics of beam longitudinal bars passing through a joint:

$$\tau_b/\sqrt{\sigma_B} = 2 \cdot {}_b\sigma_y \cdot A_s/(\Sigma\phi D_c)/\sqrt{\sigma_B} \qquad \text{(in MPa units)} \tag{2}$$

in which ${}_b\sigma_y$ = yielding strength of beam bars, A_s = nominal sectional area of beam bars, ϕ = nominal perimeter of beam bars and D_c = column depth.

It can be deduced from the plot that poor bond situation reduce slightly the maximum strength.

Influence of joint shear reinforcement on ductility factor

The joint shear stress level ${}_t\tau_{py}/\sqrt{\sigma_B}$ and the ductility factor μ plotted against the amount of lateral reinforcement in the joint P_w are shown in Fig.15 and Fig.16, respectively. Area ratio of joint reinforcement P_w was defined by area of joint reinforcement a_w divided by column depth and distance from top beam bar to bottom beam bar.

The solid line in Fig.16 shows the result of linear regression analysis on the test data for specimens with the joint shear stress level $0.4 \le {}_t\tau_{py}/\sqrt{\sigma_B} \le 0.6$ in Fig.15. The ductility factor has a tendency to increase slightly with the amount of joint reinforcement. The relationship between joint shear stress level and ductility factor is shown in Fig.17. This figure indicates that the ductility factor decreases with the joint shear stress level, because the story drift at beam yielding R_y increases with the joint shear stress level and the story drift at ultimate situation R_u has no relation with the joint shear stress level.

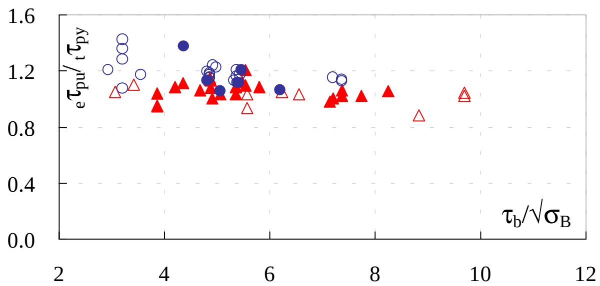


Figure 14: Maximum strength index (${}_e\tau_{pu}/{}_t\tau_{py}$)-bond index ($\tau_b/\sqrt{\sigma_B}$) relations

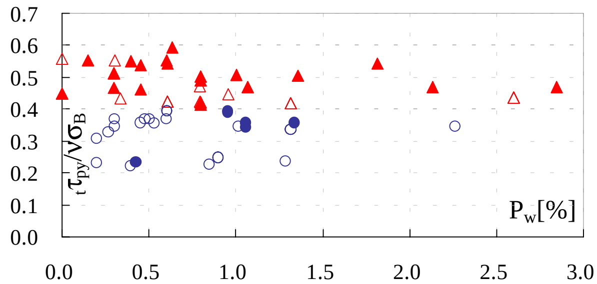


Figure 15: Joint shear stress level-area ratio of joint reinforcement relations

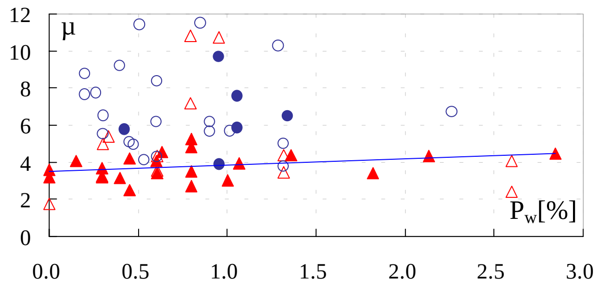


Figure 16: Ductility factor-area ratio of joint reinforcement relations

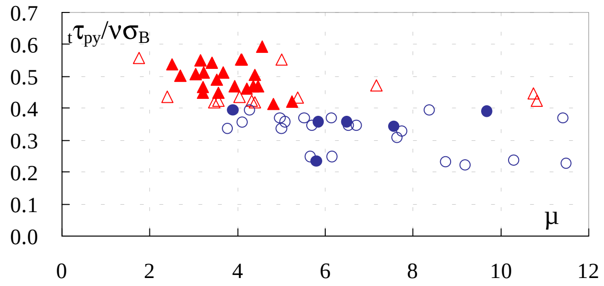


Figure 17: Joint shear stress level-ductility factor relations

CONCLUSIONS

The following conclusions may be drawn from the test results and the analysis of a previous experimental database:

1.For specimens which have the same joint shear stress level, an amount of joint reinforcement had little effect on the strength decay and the shear deformation in the joint after maximum load.

2.The increase in the amount of joint shear reinforcement made slightly the better bond situation along the column and beam longitudinal reinforcement in a joint. The maximum bond stress of beam bars in specimens with a small joint shear stress level was larger than that in specimens with a large shear stress level.

3.The role of joint reinforcement is mainly considered to confine the joint core concrete after the beam flexural yielding.

4.Ductility factor of story drift is little influenced by the amount of joint reinforcement, but depends strongly on the joint shear stress level. Therefore, the amount of joint reinforcement commonly used in a frame structure has no influence on strength and deformation of interior beam-column subassemblages.

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