2003 Pacific Conference on
Earthquake Engineering

Estimation of shear strength of reinforced concrete interior beam-column joints by using database of experimental results

T. Kusakari

Department of Architecture, Kushiro National College of Technology, Kushiro, Japan

O. Joh

Department of Architecture, Hokkaido University, Sapporo, Japan

ABSTRACT: Effective factors on shear resistance of R/C interior beam-column joints were analyzed by using experimental data including 303 specimens tested in Japan and abroad from 1971 to 2000. These specimens could be classified into four types of failure mode: 1) shear failure in joints without beam or column yielding (J-type), 2) shear failure after beam or column yielding (BJ and BJ'-type), 3) flexural failure in beam ends without joints failure (B-type), 4) flexural failure in column ends without joints failure (C-type). The number of specimens in the four failure types is 55, 180, 64, 4, respectively. A reliable equation to evaluate the joint shear strength was proposed using the regression analysis of the shear strength and three factors: concrete strength, column axial stress and bond index which was consisted of joint reinforcement and beam bar bond stress in the joint. The failure modes in joint shear and in beam/column flexure can be easily distinguished by this equation.

1 INTRODUCTION

With the quickly rising cost of reinforced concrete structure (RC) buildings using high strength materials and the progress of toughness design methods for column and beam members, strength and deformability of columns and beams have improved remarkably. As a result, excessive shear stress arises at a beam-column joints that transfer stress between a column and a beam; moreover, compulsive great deformation takes place at joints in order to follow deformation of adjacent columns and beams. Thus, framework weak points are shifting to joints.

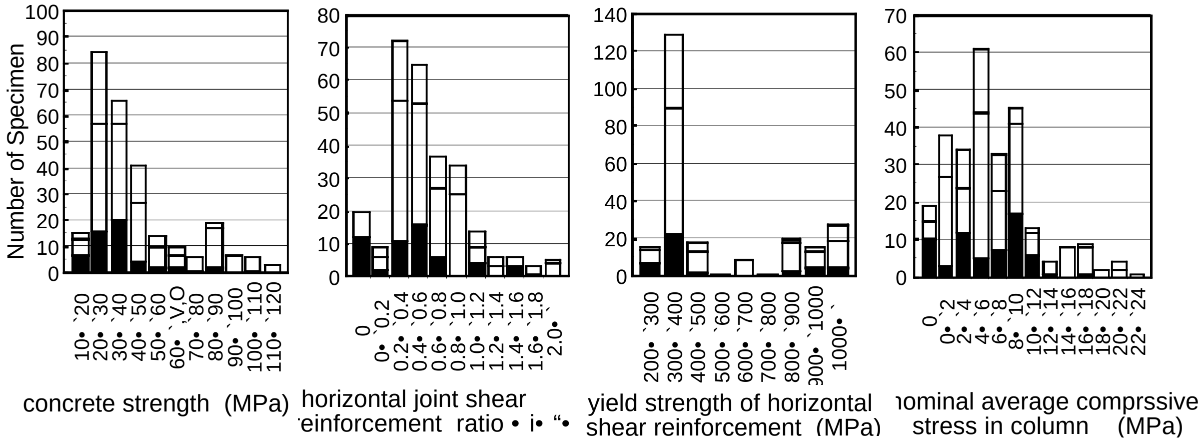
One report of the southern Hyogo earthquake, which occurred in January 1995, concluded that many buildings were damaged at beam-column joints; many of them were designed under present regulations, supporting the trend explained above.

For earthquake-resistance design of beam-column joints, the joints should have sufficient shear strength and deformability simultaneously. Especially for shear strength, a beam (or a column) member connected to the joints should definitely demonstrate bending yield; joints failure occurring before the bending strength is reached must be avoided. Furthermore, for load of repeat force after bending yield, the shear strength of the joints must be maintained so that member end hinges can sufficiently secure energy absorption. Therefore, shear strength of the joints should be presumed appropriately; then, a sufficient margin should be spared from comparison with joints input at the yield of the column and beam.

Conventional joint shear strength estimation methods are based on the strut mechanism depending only on the concrete strength. However, this study considers that the bond property of a beam main reinforcement also influences the joint shear strength; therefore, it is expressed as the combination of the strut mechanism and the truss mechanism due to the bonding force. Based on this view, this study establishes a joint-shear proof-stress estimation method with which many experimental results can be presumed with sufficient accuracy. In addition, the relationship between the failure mode and the safety factor to shear failure is discussed. The effect of various factors on the shear strength of a joint is studied based on experimental data of interior beam-column joints performed in and outside Japan up to the present.

2 INTERIOR BEAM-COLUMN JOINT DATA USED FOR STATISTICAL ANALYSIS

Collected data were published by scientific reports in and outside Japan, company technical reports etc., from 1971 to 2000: 303 data corresponding to the following conditions are extracted from them: (1) normal concrete is used, (2) positive/negative repeat force is loaded, (3) joints are unreinforced or reinforced with ties, (4) no rectangular beam, slab or hunch is attached, and a column and a beam are not eccentricity, (5) neither tensile nor fluctuation axial force is loaded, (6) main column-beam reinforcement is re-barred through a joint and no special processing is performed. The data are classified by mode of failure: 55 pieces of joint failure before the member yields (J-type), 180 pieces of joint failure after the member yields (BJ-type), 9 pieces of joint failure after the first level of two level rebar yields (BJ'-type), and 68 pieces of no joint failure at last (type F), which include 64 pieces of beam bending failure (B-type) and 4 pieces of column bending failure (C-type). Note that this is consistent with the original author's classification concerning the failure mode.



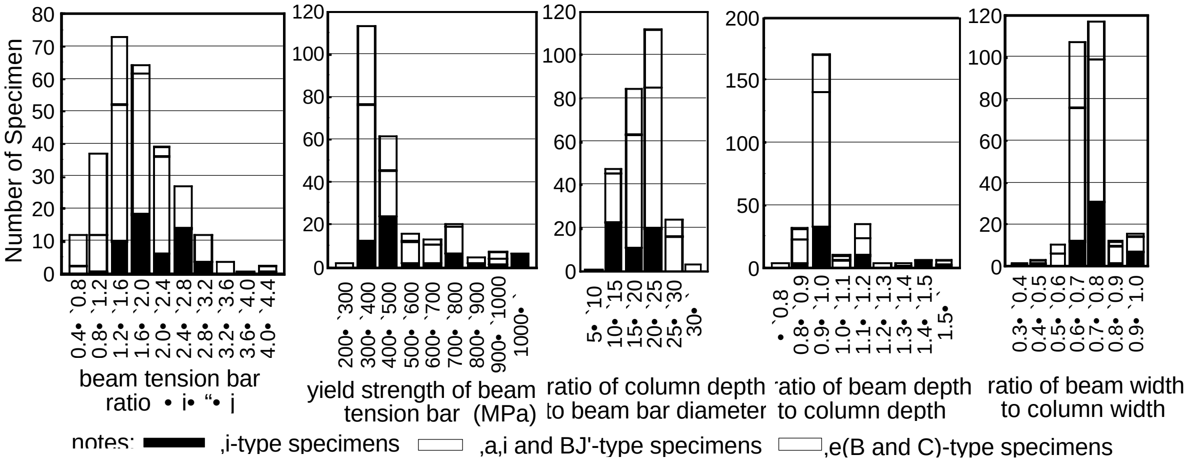


Figure 1 Characteristics of data

Figure 1 shows characteristics of the data employed. The cross-sectional dimension of columns and beams are in the range of 100 mm × 150 mm – 580 mm × 500 mm and 100 mm × 150 mm - 365 mm × 560 mm, respectively.

The joint horizontal reinforcement ratio (${}_{j}p_{w}$) is calculated as

$${}_{j}p_{w}=a_{w}/(B_{c}\cdot x),$$

where, a_w is the cross-sectional area of one set of joint shear reinforcement, B_c is the column width, and x represents the space of joint shear horizontal reinforcement.

3 EFFECT OF VARIOUS FACTORS ON JOINT SHEAR STRENGTH

If the joint shear strength is assumed as the composition of the strength due to the strut mechanism and that of the truss mechanism, it is supposed that the causes affecting the former are the concrete strength in a joint diagonal compressive strut region surrounded by the neutral axis depths of the upper and lower columns and the left and right beams, and the column axial force related to the column neutral axis depth. On the other hand, it is supposed that the cause affecting the latter is the bond property, i.e., the condition of bond forces on horizontal reinforcement and the mid-level column reinforcement rebarred in joints to form the truss mechanism, and on the main reinforcement outside the diagonal strut region. Here, the concrete strength, the column axial stress, the bond property of the horizontal reinforcement of a joint, mid-level column reinforcement, and beam main reinforcement are adopted as effect factors; their effects on joint shear strength are studied.

3.1 Effect of concrete strength

Data at the maximum load experiments obtained in conventional interior beam-column joint experiments are converted into joint average shear stress; it is defined as the joint maximum experimental shear stress (${}_{e}v_{jh}$). It is compared with the concrete strength (fc') and shown in Figure2.

${}_{e}v_{jh}$ is computed with eq. (1),

$${}_{e}V_{jh}=(M_{b1}+M_{b2})/j_{b}-V_{c}$$

$${}_{e}v_{jh}={}_{e}V_{jh}/(b_{j}\cdot D_{c}), \qquad (1)$$

where M_b: is the bending moment at the beam critical section (1 and 2 denote left and right, respectively), V_c represents the column shear force, j_b =(7/8 d_b), b_j is the effective joint width (= (the column width + the beam width) / 2), and D_c is the column depth.

The calculation method of the joint effective cross-sectional area (the joint depth × the effective joint width) may vary among researchers. In this study, a diagonal strut is considered as the main shear resistance mechanism. Therefore, column height, which is the level projection length of a strut, is taken as the joint depth and the average value of the column width and the beam width is taken as the effective joint width.

In contrast with J type, in which joint failure took place before the yield of a member, in BJ type, in which joint failure occurred after the yield of a beam, and in F type with bending failure of a member, the maximum shear strength of a joint is determined by the strength at yielding of members. Accordingly, it is considered appropriate to employ J type data, in which a joint reaches the maximum shear strength for the evaluation of the joint shear strength. Therefore, J type data are used here in regression analysis of joint shear strength and each factor.

Figure 2 shows that joint shear strength tends to increase with concrete strength as an overall tendency in the data. However, the rate of increase decreases with increased concrete strength; 0.3 fc' in Fig. 2 is a joint shear strength expression found in the AIJ Design Guidelines. J-type data are distributed mostly near this line, up to 50 N/mm^2 of the concrete strength. However, exceeding this range, experimental values are much less than estimated; the AIJ equation overestimates shear strength. Regression analysis for all BJ type data yields $_{e}v_{jh} = 0.975(fc')^{'0.656}$ as a regression equation; the correlation coefficient of 0.953 demonstrates a high correlation.

3.2 Effect of column axial stress

Figure 3 shows the comparison between $_{e}v_{jh}$ divided by $(fc')^{0.656}$ in the regression equation mentioned above and normalized (henceforth referred to as normalized shear stress) and the axial stress ratio that is the column axial stress (s_0) normalized by $(fc')^{0.656}$. Overall, among J-type, the proof stress tends to increase linearly with an increased axial stress ratio. Regression analysis for all J-type data provides $_{e}v_{jh}/(fc')^{0.656}=0.113(s_0/fc'^{0.656})+0.908$ as a regression equation; the correlation coefficient between normalized shear stress and computed values from the equation is 0.407.

3.3 Effect of horizontal joint reinforcement

Column ties rebarred into a joint are regarded as horizontal joint reinforcement; their effect is studied.

Horizontal joint reinforcement is an effective reinforcement to form the truss mechanism. When a truss mechanism with the horizontal joint reinforcement is assumed, the maximum of the shear strength is in the state when all horizontal reinforcement yields. However, it is considered practical that a portion of the horizontal reinforcement does not yield or that some fraction of the horizontal reinforcement force contributes to joint shear strength. Accordingly, a joint horizontal reinforcement coefficient is calculated by multiplying the joint horizontal reinforcement ratio by the horizontal reinforcement yield strength ($_{h}f_y$) and normalizing by $(fc')^{0.656}$. The relationship between the joint horizontal reinforcement coefficient and the normalized joint shear stress is shown in Fig. 4 and studied, after removal of 15 data with unknown yield strength. A regression equation of $_{e}v_{jh}/(fc')^{0.656} = 0.182({}_{j}p_{w}\cdot{}_{h}f_y/(fc')^{0.656}) + 0.939$ is obtained by regression analysis of all J-type data. The joint proof stress tends to increase linearly concomitant with increase of the reinforcement coefficient; the correlation coefficient between the normalized shear stress and computed values from the equation is 0.344.

3.4 Effect of mid-level column reinforcement

Multiplying the mid-level column reinforcement yield strength (${}_c f_y$) by the mid-level column reinforcement ratio (${}_c p_m$) and normalizing by $(fc')^{0.656}$ provides a value that is referred to as a mid-level column reinforcement coefficient. The relationship between this coefficient and the normalized shear stress is shown in Fig. 5. Since no general definition of this coefficient is available, it is defined as $\cdot a_s/(d_g B_c)$: the total cross-sectional area of the mid-level column reinforcement except for the column outermost reinforcement which suffers tension or compression according to the load direction (${}_\cdot a_s$) is divided by the product of the cross-sectional area that is the column outermost reinforcement distance (d_g) and the column width (B_c). Regression analysis for all J-type data yields ${}_e v_{jh}/(fc')^{0.656} = 0.042({}_c p_{m\cdot} {}_c f_y/(fc')^{0.656}) + 0.956$ as a regression equation, and the correlation coefficient between the normalized shear stress and computed values with the equation is 0.233.

3.5 Effect of bond property

In order to evaluate the bond property of the main column-beam reinforcement in a joint, the bond index (${}_{\cdot b}$) is employed. This index is obtained by dividing the average bonding stress in the state where the main beam reinforcement (or the main column reinforcement yield at both joint ends, by the power of the concrete strength, as shown in eq. (2). Although 0.5 is generally used as the index, in this study, 0.656 is used from correspondence with the joint shear strength.

$$ {}_{\cdot b} = 2f_yA_s/D_{c\cdot}n, $$

$$ {}_{\cdot b} = {}_{\cdot b}/(fc')^{0.656}, \qquad (2) $$

In the equations above, f_y is the yield strength of a beam (column) main reinforcement, A_s is the total cross-sectional area of the main tensile reinforcement of a beam or column, D_c is the column depth (or D_b: the beam depth), . represents the main reinforcement circumference, and n is the number of main tensile reinforcement bars.

Figure 6 shows the relationship between the bond index of a main beam reinforcement and the normalized shear stress. It has been pointed out that when this kind of bond index becomes large, bond degradation occurs easily, which affects the restoration property of a framework. Figure 6 shows that bond index data are distributed over the large area of 0.2 - 3.5; B-type data are distributed over the range with small input level and bond index. The fracture mode changes from B-type to BJ-type, then to J-type with the increase of the bond index and the input level.

Regression analysis for all J-type data yields ${}_e v_{jh}/(fc')^{0.656} = -0.024({}_{\cdot b}/(fc')^{0.656}) + 1.026$ as a regression equation; the tendency for joint shear strength to decline by increase in the bond index is shown. The correlation coefficient between the input level and computed values with this equation is 0.200.

3.6 Effect of interaction between bond property and reinforcement in joint

It is supposed that the truss mechanism consists of a slanting concrete compression member formed by bonding forces of main beam reinforcement and outermost column reinforcement, horizontal joint reinforcement, and mid-level column reinforcement. The effects of the joint horizontal reinforcement, the column mid-level reinforcement, and the bond property on the joint shear strength were described in 3.3, 3.4, and 3.5, respectively. These factors may be reduced to a single factor.

Since this truss mechanism is formed by the bonding force of main reinforcement, when bond degradation progresses, this mechanism will dissipate gradually; thereupon, its contribution to the joint shear strength will decrease. In this paper, joint shear strength is expressed with the relationship with the inverse of the bond index ($((fc')^{0.656}/_{\cdot b})$.

By multiplying this value by the sum of two reinforcement coefficients, $(fc')^{0.656}$ is cancelled and $({}_jp_{w\cdot h}f_y + {}_cp_{m\cdot c}f_y)/_{\cdot b}$ is obtained. This value is referred to as a bond effect coefficient. Figure 7 shows the relationship between normalized maximum joint shear stress and the bond effect coefficient.

Regression analysis for all J-type data provides ${}_ev_{jh}/(fc')^{0.656} = 0.108({}_jp_{w\cdot h}f_y + {}_cp_{m\cdot c}f_y)/_{\cdot b} + 0.926$ as a regression equation; we found the tendency for normalized shear stress to increase with increased bond effect coefficient. The correlation coefficient between normalized shear stress and computed values with the equation is 0.400. That is, rather than obtaining each correlation by treating horizontal joint reinforcement, mid-level column reinforcement, and bond property individually, a correlation obtained by treating these three factors together gives a higher value.

This result seems to suggest that bond degradation of main beam reinforcement is suppressed by the increase of the bond effect coefficient, so that the contribution to the joint shear strength by the truss mechanism increases.

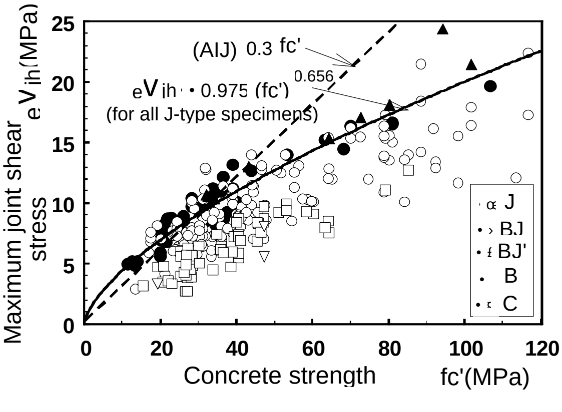


Figure 2. Relationship of joint shear strength to concrete strength

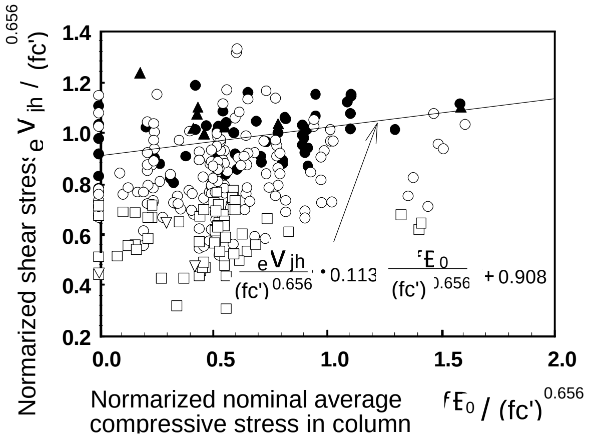


Figure 3 Influence of column axial stress to joint shear strength

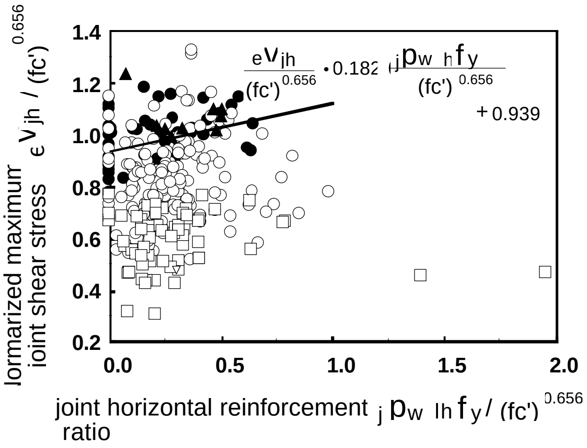


Figure 4. Influence of joint horizontal reinforcement to joint shear strength.

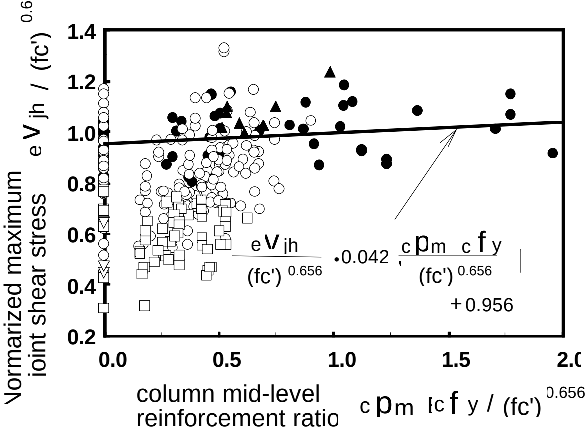


Figure 5 Influence of column mid-level reinforcement to joint shear strength.

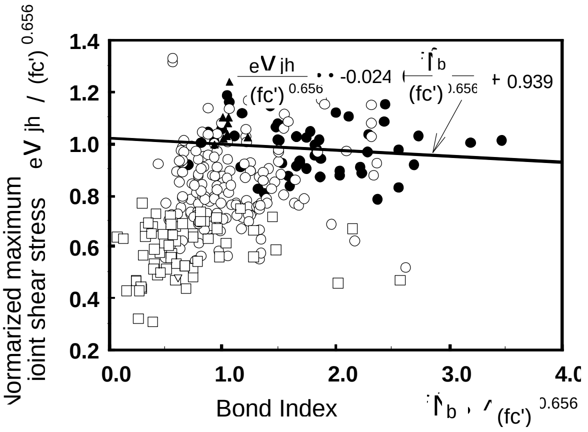


Figure 6. Influence of bond index to joint shear strength.

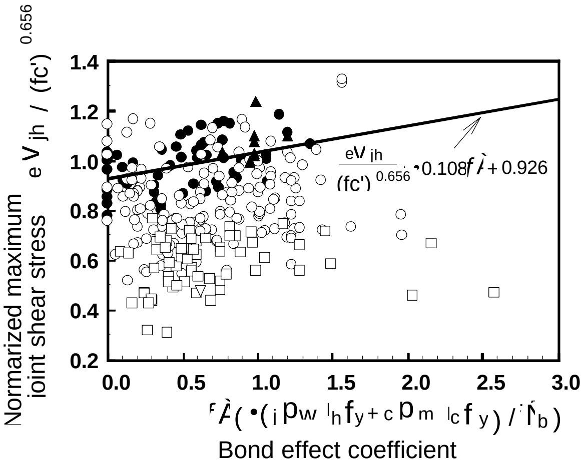


Figure 7. Influence of bond effect coefficient to joint shear strength.

4 JOINT SHEAR STRENGTH BY SYNTHETIC EVALUATION OF VARIOUS FACTORS

In preceding sections, the effect of concrete strength, column axial stress, joint horizontal reinforcement, column mid-level reinforcement, and beam main-reinforcement bonding on the joint shear proof stress is discussed. Consequently, it is revealed that, not only does concrete strength affect the joint shear proof stress most, but column axial stress and interaction by the three factors of joint horizontal reinforcement, column mid-level reinforcement, and the bond index affect it to no small extent. If joint shear proof stress is estimated as the combination of the strut mechanism and the truss mechanism, it is assumed that the concrete strength and column axial stress contribute to the shear proof stress as the strut mechanism; also, the beam main reinforcement bonding force and reinforcement in a joint contribute to it as the truss mechanism. In consideration of these, a multiple regression analysis with experimental values yields eq. (3).

$$ {}_{r}v_{jh} = (f_c')^{0.560}\{1.17 + 0.21({}_{j}p_{w}\cdot{}_{h}f_y + {}_{c}p_{m}\cdot{}_{c}f_y)/\cdot_{b}\} + 0.09s_0. \qquad (3) $$

Comparison of computed values with eq. (3) and experimental values is shown in Figure 8. The correlation coefficient and average value are 0.973 and 1.000, respectively; the experimental and computed values show good correspondence.

By applying eq. (3) to failure mode specimens other than J-type, the ratio of ${}_{r}v_{jh}$ to the joint shear stress at the time of the theoretical bending yield of members is defined as the safety factor to joint shear failure. It is compared with the concrete strength and shown in Fig. 9. As for J type, the safety factor to joint shear failure is 1.0 or less naturally. It is in the range of 1.0 to 1.5 for the great portion of BJ type data; for B type and C type data it is distributed at 1.5 or more. Thus, the failure mode can be classified distinctly. Moreover, in BJ type, for data distributed over 1.0 or less range of the safety factor to joint shear failure, joint shear failure takes place almost simultaneously with or immediately after the yield of a beam. Also, deformation necessary for the joint shear failure after yield becomes larger as the safety factor to joint shear failure increases from 1.0. That is, the mode change is observed within BJ type. Dissipation of the truss mechanism accompanying the shear margin and bond degradation, concentration of the main reinforcement force to the diagonal strut due to this, and degradation of the concrete strength by repeated stress, etc. are inferred to be related. However, this is considered to be a subject for future examination.

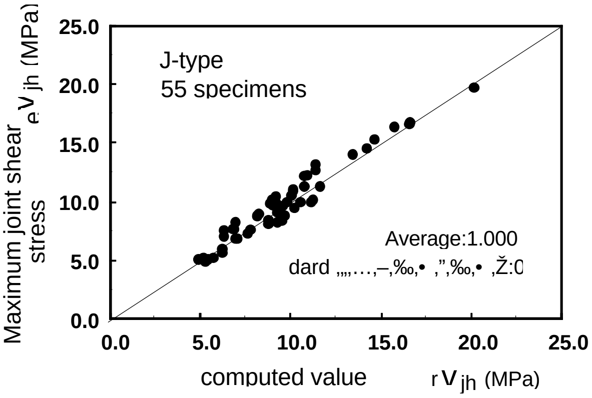


Figure 8. Relationship of experimental value to computed value.

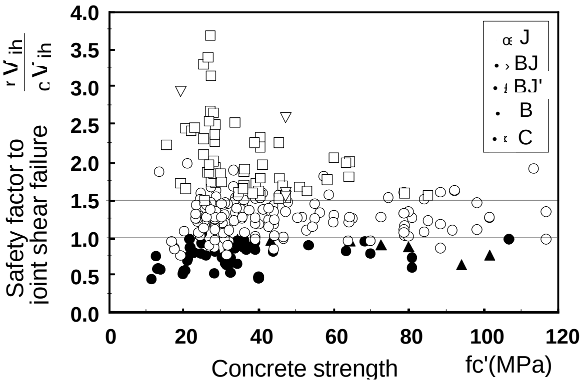


Figure 9. Relationship of safety factor to joint shear failure to concrete strength.

5 CONCLUSION

1. Not only does concrete strength affect joint shear strength most, but column axial stress, joint horizontal reinforcement, column mid-level reinforcement, and the bond index of main reinforcement also affect it to no small extent.
2. Joint shear strength is assumed as the shear resistance mechanisms owing to concrete strength and column axial stress and a shear resistance mechanism in which interaction among the bond index, horizontal joint reinforcement, and mid-level column reinforcement is expressed as the bond effect coefficient (jpw.hfy + cpm.cfy) /b. Thereby, eq. (3) is obtained by regression analysis as a joint shear strength estimation equation; it is confirmed that it gives good correspondence to experimental values.
3. The ratio between joint shear stress of a beam or column member at theoretical bending yield and the estimated joint shear strength (rvjh/ cvjh) is defined as the safety factor to joint shear failure. When this factor is 1 or less, the failure mode is a joint failure type before the yield of a member; as the factor becomes larger, the failure mode shifts to a joint failure type after the yield of a member, then to member fracture without joint failure. Thus, experimental results can be classified distinctly.

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