New Model for Estimation of Shear Strength of Reinforced Concrete Interior Beam-Column Joints

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Abstract

A new model is developed for estimating the shear strength of RC interior beam-column connections. The new model is based on the methods used in current ACI and AIJ design codes with modifications for effective area of joint panel and effective concrete strength. A database of interior beam-column connections is constructed from previous experimental studies and the influence of transverse reinforcements in joint panel and axial force in columns are investigated. Since the investigation showed positive correlations between joint shear strength and both transverse reinforcement and column axial force, the effects of those parameters are included in the new estimation model. The new model is applied to the specimen database and the resulting estimates are compared to those by the current ACI and AIJ codes. Results showed that estimation of shear strength by the new model is much improved by all these modifications.

Keywords: RC Beam–column joints; Shear failure; Transverse reinforcement; Specimen database

1. Introduction

Estimating shear strength of beam-column connections is very important in order to avoid shear failure in connections, which is very brittle and unsafe, in reinforced concrete (RC) moment resisting frame structures. There are many parameters that may affect the strength of an RC beam-column connection and its failure behavior is very complicated. Therefore, there is no established simple and accurate macro model for estimation of strength of beam-column connections. And in the current codes, such as ACI\(^1\) or AIJ\(^2\), the strength estimation is mostly based on empirical rather than theoretical relations.

Shiohara et al.\(^3\)-\(^4\) proposed a new flexible macro model which can include many parameters and phenomena in the connections. This research series caused a stir in the concept of shear failure of joint panels, and this approach may be able to give a simple answer to this issue in the future. The macro model, however, is still under development in order to use it in design practice because of its complexity,
which requires many parameters. Therefore, the classic approach used in ACI or AIJ is taken up for improvement of their estimation ability in this study.

Many experimental studies\textsuperscript{3}-\textsuperscript{9} have been carried out on joint shear strength in which parameters that may affect joint shear failure are investigated. Some say that the axial forces in columns or transverse reinforcement in joint panel have significant effect on the joint strength, while others say otherwise. In this study, the effective area of joint panel is redefined based on the failure mechanism shown in previous experimental studies and the effects of the axial force or the transverse reinforcements in the joint panel are investigated.

2. Database OF Beam-Column Connection Specimens

A database consisting of 30 internal beam-column joint specimens with no out-of-plane beams and which showed joint shear failures is constructed from various experimental studies in order to evaluate joint shear strength estimation methods. The specimen data are shown in Table 1 where $f_c$ is the concrete compressive strength, $b_b$ and $b_c$ are the width of beam and column, $D_b$ and $D_c$ are the depth of beam and column as shown in the Fig. 1, $\rho_w$ is the reinforcement ratio in the panel, $\rho_{col}$ is the axial stress in the column.

| paper name | Specimen name | $f_c$ MPa | $b_b/b_c$ | $D_b/D_c$ | $\rho_w$ (%) | $\rho_{col}/f_c$ | $V_{exp}/V_{cal}$ ACI | $V_{exp}/V_{cal}$ AIJ | $V_{exp}/V_{cal}$ New model |
|------------|---------------|-----------|-----------|-----------|--------------|-----------------|-----------------------|-----------------------|----------------------|
| Hegger\textsuperscript{5} | RA1 | 53.1 | 0.5 | 1.17 | 0.26 | 0.25 | 0.69 | 1.23 | 1.33 |
| | RA2 | 66.1 | 1 | 1.25 | 0 | 0.19 | 1.09 | 1.21 | 1.18 |
| | RA3 | 43.6 | 1 | 1.25 | 0.73 | 0.32 | 1.13 | 1.2 | 1.05 |
| | RA4 | 66.1 | 1 | 1.25 | 1.52 | 0.14 | 1.13 | 1.31 | 0.95 |
| | RA5 | 56.2 | 1 | 1.25 | 0.85 | 0.32 | 1.03 | 1.13 | 0.96 |
| | RA6 | 56.2 | 1 | 1 | 0.85 | 0.32 | 1.03 | 1.13 | 0.96 |
| | RA7 | 79.7 | 1 | 1 | 0.85 | 0.32 | 1.03 | 1.13 | 0.96 |
| | J4-0 | 30.4 | 0.68 | 0.91 | 0.73 | 0.2 | 0.88 | 1.23 | 0.92 |
| | J6-0 | 60.4 | 0.68 | 0.91 | 0.73 | 0.2 | 0.88 | 1.23 | 0.92 |
| Sagano\textsuperscript{6} | J6-1 | 62.3 | 0.68 | 0.91 | 0.73 | 0.2 | 0.88 | 1.23 | 0.92 |
| | J8-0 | 77.6 | 0.68 | 0.91 | 0.73 | 0.2 | 0.88 | 1.23 | 0.92 |
| | J8H-0 | 80.2 | 0.68 | 0.91 | 0.73 | 0.2 | 0.88 | 1.23 | 0.92 |
| | A1 | 40 | 0.73 | 1.14 | 0.53 | 0.08 | 0.81 | 1.1 | 1.07 |
| | A2 | 40 | 0.73 | 1.14 | 0.53 | 0.08 | 0.81 | 1.1 | 1.07 |
| | A3 | 40 | 0.73 | 1.14 | 0.53 | 0.2 | 0.81 | 1.1 | 1.07 |
| | A4 | 40 | 0.73 | 1.14 | 0.53 | 0.2 | 0.81 | 1.1 | 1.07 |
| | E-0.0 | 43.1 | 0.83 | 1 | 0 | 0.00 | 0.73 | 0.91 | 0.97 |
| | H-0.0 | 50.6 | 0.83 | 1 | 0.93 | 0.00 | 0.77 | 0.93 | 0.91 |
| | AD-0.0 | 42.6 | 0.83 | 1 | 0.93 | 0.00 | 0.77 | 0.93 | 0.91 |
| | E-0.3 | 46.1 | 0.83 | 1 | 0 | 0.30 | 0.79 | 0.98 | 1.05 |
| | H-0.3 | 45.1 | 0.83 | 1 | 0.93 | 0.30 | 0.82 | 1.01 | 0.98 |
| | AD-0.3 | 39.4 | 0.83 | 1 | 0.93 | 0.30 | 0.82 | 1.01 | 0.98 |
| Francis\textsuperscript{8} | C1PD | 31.6 | 0.86 | 1.1 | 0.16 | 0.16 | 0.76 | 1.01 | 1 |
| | C4PD | 32.7 | 0.75 | 1.38 | 0 | 0.16 | 0.67 | 0.94 | 0.98 |
3. Estimation of Joint Shear based on Current Design Codes

3.1. Joint Shear Strength

ACI 352 (2005) design guidelines show a method to evaluate joint shear strength based on empirical equations. The nominal joint shear strength $V_n$ of horizontal plane at mid-height of the joint panel in the ACI guidelines is

$$ V_n = \gamma (f'_c)^{0.5} A_j $$

(1)

On the other hand, the nominal joint shear strength $V_n$ in the AIJ guidelines is given by

$$ V_n = k \phi 0.8 (f'_c)^{0.7} A_j $$

(2)

where $A_j = b_j d_j$ is the effective area of the joint, $f'_c$ is specified concrete compressive strength, $b_j$ is effective joint width, $d_j$ is effective depth of joint, $\gamma$ and $k$ are joint shear strength factors for ACI and AIJ, respectively. Factor $\Phi$ is a factor to account for the effect of transverse beam(s) (out-of-plane direction). The effective joint width $b_j$ is calculated from Equations (5) and (6) for ACI and AIJ, respectively, while the effective depth $d_j$ is taken as the total column depth.

![Fig. 1: Geometry and loading of internal joint; Fig. 2: Load transferring mechanism.](image)

3.2 Joint Shear Force

In ACI and AIJ guidelines, the forces in beams and columns are modeled as shown in Fig. 2 and the horizontal shear force $V_j$ is given by

$$ V_j = T_1 + C_{c2} + C_{c3} - V_c, \quad V_j = 2T_1 - V_c $$

(3)

where $T_1$ and $T_2$ are the tensile forces and $C_{c2}$ is the compressive force of the main bars in the beam, $C_{c3}$ is the compressive force of concrete in beam cross-section. $V_c$ is the horizontal force on the column. Only the horizontal force balance in the horizontal section of the joint is considered, based on the assumption that the vertical force is approximately proportional to the horizontal force by the aspect ratio of the panel.
3.3 Calculation of Story Shear

To compare the joint shear forces calculated by the codes with the forces measured in the experimental study specimens in the database, story shear \( V_{\text{cal}} \) is calculated as the lateral force \( V_c \) at the top of the column. To estimate story shear \( V_{\text{cal}} \), joint shear stress in the failure stage \( (V_u) \) is assumed to be equal to the joint shear strength \( (V_n) \). Thus, the estimated story shear strength, \( V_{\text{cal}} \) is calculated from the estimated joint shear strength \( V_n \) as follows,

\[
V_{\text{cal}} = \frac{V_n j d_b L_b}{2L_c I_b - j d_b L_b}
\]  

(4)

where \( d_b = D_b - (c_1 + 0.5c_2) \) and \( d_c = D_c - s_1 \) are effective depths of beam and column respectively.

3.4 Effective Area of Joint Panel

The effective area of joint panel \( A_j \) is calculated by multiplying effective depth by effective width. The effective depth is the column total depth both in ACI and AIJ, while the definitions of the effective width are different. In the ACI code, the effective joint width \( b_j \) is calculated as follows,

\[
b_j = b_b + 2x \leq b_b + D_c
\]  

(5)

where \( b_b \) and \( b_c \) are width of beam and column, respectively, \( x \) is the smaller of the distances measured from either side face of the beam to the corresponding side face of the column, as shown in Fig. 3.

The effective width of the joint \( b_j \) in the AIJ code is given by

\[
b_j = b_b + b_{a1} + b_{a2}
\]  

(6)

where \( b_b \) is the width of beam, \( b_{a1} \) and \( b_{a2} \) are the smaller of one-quarter of column depth \( (D_c/4) \) and one-half of distance between beam and column face \( (x/2) \) on either side of beam, respectively.
4. Estimation of Joint Shear based on the New Model

4.1 Effective Area of Joint Panel

In the ACI and AIJ code models, only horizontal forces are considered in the horizontal section of the joint and the horizontal section is taken as the effective area, based on the assumption that the total vertical force is approximately proportional to the horizontal force by the aspect ratio of the joint panel. In this paper, effective area is taken directly to be the compressive area in the joint panel. A and B are intersection points of beam and column longitudinal bars.

The joint panel is divided into two parts. The uniformly distributed equivalent compressive force $\sigma_c$ (described in Section 4.3) is considered along the diagonal section of the joint for equilibrium of the upper half part of the joint. It means that the distance between the intersection points of the outer layers of the main bars in beam and column, $D_j$ is taken as the effective depth of the joint. Effective width is taken as the same as the definition in AIJ (Equation (6)).

4.2 Joint Shear Stress

By the force balance of the triangular part in the model in Fig. 4, the following equations are derived.

\[
\begin{align*}
\sigma_c A_j D_b / L &= C_b + T_b - V_c \\
\sigma_c A_j D_c / L &= C_c + T_c - V_b \\
V_b L_b &= V_c L_c \\
L &= \sqrt{D_b^2 + D_c^2} \\
C_b &= T_b, \quad C_c = T_c, \quad \text{where } T_b = V_b d_b / j d_b \text{ and } T_c = V_c d_c / j d_c.
\end{align*}
\]  

From the force balance in the beam and the column,

\[
C_b = T_b, \quad C_c = T_c, \quad \text{where } T_b = V_b d_b / j d_b \text{ and } T_c = V_c d_c / j d_c.
\]  

By using Equations (7a) to (7e), the relation between story shear $V_c$ and shear strength of joint $V_n$ is derived as

\[
V_n = \sigma_c A_j = \sigma_c b_j D_j
\]
\[ V_a = \sigma_c d_j = \frac{2(L_b d_b l_c + L_c d_c l_b) - K(L_b + L_c)}{KL_b (D_b + D_c)} \]  

(8)

where \( l_b = L_b - 0.5D_b \) and \( d_b = D_b - s_1 + c_2/2 \) are clear span and effective depth of the beams, \( l_c = L_c - 0.5D_c \) and \( d_c = D_c - s_1 \) are clear span and effective depth of the columns. \( K = j d_b d_c \), where \( j = 0.8 \) based on the flexural theory. Other notations are as shown in the Fig. 1 and Fig. 3.

4.3 Equivalent Concrete Compressive Strength

Actual compressive stress is not distributed uniformly in the joint but distributed so that it takes the maximum value at the center of the joint panel. To simplify this compressive stress distribution, the equivalent concrete strength \( \sigma_c \) is defined as the following expression

\[ \sigma_c = f_c^m \]  

(9)

where \( f_c \) is the concrete compressive strength and \( m \) is an unknown power index. The same concept is employed in the codes where the power index \( m \) equals 0.5 in ACI and 0.7 in AIJ, as in Equations (1) and (2), respectively. Here, the value is determined empirically using the database. The power index is calculated backward from the experimental joint strength and estimated strength using equation (8) and plotted against the concrete strength in Fig. 5. The value of power index \( m \) is determined as 0.67 from the graph.

4.4 Influence of Transverse Reinforcement and Axial load

The influence of the transverse reinforcement is checked using the constructed database. The ratio of experimental to calculated story shear is plotted against the transverse reinforcement ratio in Figs. 6(a) and 6(b) for ACI and AIJ codes, respectively. A positive correlation is shown in these figures, which means that the transverse reinforcement increases the joint strength.

The influence of axial force in column is investigated in the same way. The ratios of experimental to calculated story shear are calculated for ACI and AIJ codes and plotted against the axial force in the column in Figs. 6(d) and 6(e). A slight positive correlation can be seen as well, which means that the axial force in columns also increases the joint strength.

Fig. 5: Power index for equivalent concrete compressive strength
Shear strength of joint panel \( V_n \) is estimated according to the effective area \( A_j \) and the effective concrete strength \( \sigma_c = f_c^{0.67} \). With modifications for the effects of transverse reinforcement and axial force in column, the following equation is given:

\[
V_n = (f_c^{0.67} A_j + 0.7A_t f_t + 0.05P_{col})
\]  

where \( A_j \) is the effective area, \( f_c \) is concrete compressive strength, \( A_t \) and \( f_t \) are the area and yield strength of the transverse reinforcement, \( P_{col} \) is the column axial load.

4.6 Story Shear Calculation

To calculate the story shear, Equation (8) is solved for \( V_c \) and \( V_c \) is called \( V_{cal} \) as follows,

\[
V_{cal} = \frac{V_n KL_0(D_b + D_c)/L}{2(L_b d_b l_c + L_c d_c l_b) - K(L_b + L_c)}
\]

where \( V_n \) estimated from equation (10).
5. Accuracy of the Joint Shear Strength Estimation Methods

The estimated story shears based on the joint shear strength in the ACI and AIJ codes and the new model are plotted against the measured story shear in the experiments in Fig. 7. Histograms of experimental/calculated ratio of story shear are shown in Fig. 8 in addition. These figures show that the variation is smallest for the new model. In other words, the estimation of shear strength of beam-column connections is much improved in the new model. Moreover, the ratios of experimental/calculated story shear are plotted against transverse reinforcement ratio and axial force ratio in Figs. 6(c) and 6(f), respectively, which shows that the influence of transverse reinforcement and axial force in column are successfully included in the new model.

![Fig. 7: Comparison of calculated joint shear strength](image)

![Fig. 8: Ratio of story shears in the joint shear strength, (a) ACI, (b) AIJ and (c) New model.](image)

6. CONCLUSIONS

A new model is developed for estimating the shear strength of RC interior beam column connections. The new model is based on the method used in current ACI and AIJ codes with modifications for effective area and effective concrete strength. Effective area is defined as a diagonal area under
compressive stress and both the horizontal and vertical forces in a joint panel are considered. Effective concrete strength is determined using a constructed database of interior beam-column specimens.

The influence of transverse reinforcement and axial force in columns are investigated using the estimation formula in ACI and AIJ, in which those parameters are not considered. Since positive correlations were found between joint shear strength and the both parameters, the effects of those parameters are included into the new model.

The new model is applied to the database and compared to the current ACI and AIJ design codes. Results showed that the joint shear strength can be well estimated by the new model.

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