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Effects of joint aspect ratio on required transverse reinforcement of exterior joints subjected to cyclic loading

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Abstract. This paper presents an analytical model for determining the transverse reinforcement required for reinforced concrete exterior beam-column joints subjected to reversed cyclic loading. Although the joint aspect ratio can affect joint shear strength, current design codes do not consider its effects in calculating joint shear strength and the necessary amount of transverse reinforcement. This study re-evaluated previous exterior beam-column joint tests collected from 11 references and showed that the joint shear strength decreases as the joint aspect ratio increases. An analytical model was developed, to quantify the transverse reinforcement required to secure safe load flows in exterior beam-column joints. Comparisons with a database of exterior beam-column joint tests from published literature validated the model. The required sectional ratios of horizontal transverse reinforcement calculated by the proposed model were compared with those specified in ACI 352R-02. More transverse reinforcement is required as the joint aspect ratio increases, or as the ratio of vertical reinforcement decreases; however, ACI 352R-02 specifies a constant transverse reinforcement, regardless of the joint aspect ratio. This reevaluation of test data and the results of the analytical model demonstrate a need for new criteria that take the effects of joint aspect ratio into account in exterior joint design.

Keywords: exterior beam-column joints; joint aspect ratio; joint shear strength; transverse reinforcement; strut-and-tie model

1. Introduction

When a span increases from l_{n1} to l_{n2} (Fig. 1), without alteration of the transverse span, the beam depth increases beyond that of the column depth because column depth is proportional to the square root of the span length, to resist the axial load of an allotted area; and the beam depth is proportional to the span length, to control beam deflection. As the span increases, the joint aspect ratio (i.e. the ratio of the beam depth to column depth) increases from β_1 to β_2. The joint aspect ratio can exceed 1.5, and may sometimes reach 2.5 in low-rise buildings with very long spans. However, ACI 318-11 (2011), ACI 352R-02 (2002), and Eurocode 8 (2004), in determining the joint shear strength and required transverse reinforcement, do not consider the joint aspect ratio; and they include no restrictions on joint aspect ratios.

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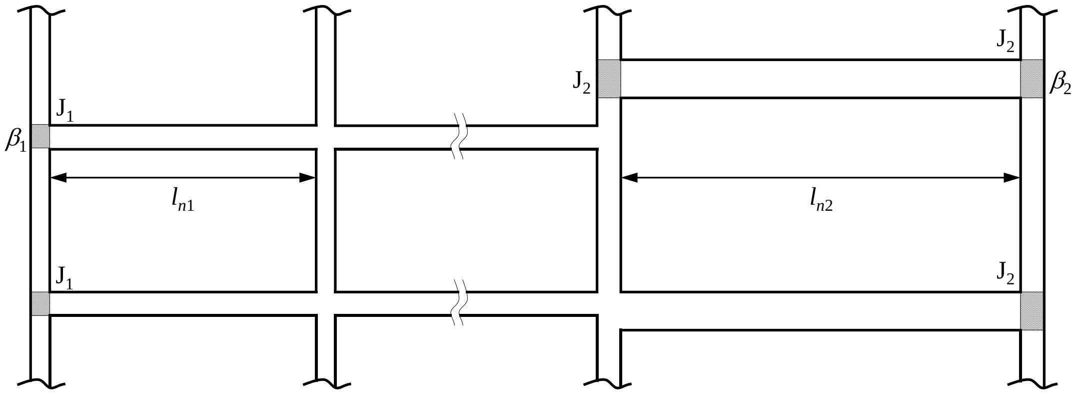


Fig. 1 Joint aspect ratios with different lengths of span

Wong and Kuang (2008) showed from cyclic tests of non-seismically designed joints that the joint aspect ratio had a significant effect on the shear strength and ductility of beam-column joints. Tsonos (2007) conducted cyclic tests of exterior beam-column joints with a joint aspect ratio of 1.5, and proposed a theoretical model for predicting shear strengths. LaFave and Kim (2011) developed joint shear strength and deformation models using an extensive database in conjunction with a Bayesian parameter estimation method. Experimental studies on interior beam-column joints were also conducted with different beam depths or with additional confinement (Xing *et al*. 2013, Lu *et al*. 2012). Chun and Shin (2014) carried out cyclic tests of 14 exterior beam-column joints with joint aspect ratios that varied from 0.67 to 2.5 and showed that for a joint aspect ratio less than or equal to 1.0, all joints showed typical flexural behavior. Even when transverse reinforcement was reduced to two-thirds of that required by ACI 352R-02, the hysteretic behavior and strengths of the joints were similar those of the joints designed in accordance with ACI 352R-02. For a joint aspect ratio equal to or greater than 2.0, nominal joint strengths could not be developed and joint shear failure occurred, even when the joints satisfied the requirements of ACI 352R-02. These results show the need for new criteria that consider the effects of the joint aspect ratio on exterior joint design.

Exterior beam-column joint tests collected from published literature were reevaluated. The roles of transverse reinforcement in exterior beam-column joints were defined and an analytical model was developed to quantify the transverse reinforcement necessary to ensure safe load flows in exterior beam-column joints.

2. Design codes on shear strength and transverse reinforcement in exterior joints

2.1 ACI 352R-02

Joint ACI-ASCE 352 design recommendations for monolithic beam-column joints (ACI 352R-02 (2002)) provides comprehensive design recommendations for a variety of reinforced beam-column joint configurations. The requirements for horizontal transverse reinforcement and joint shear strength of Type 2 connections with rectangular hoops and crossties are specified as:

$$A_{sh,ACI352} = 0.3\frac{s_h b_c'' f_c'}{f_{yh}}\left(\frac{A_g}{A_c} - 1\right) \tag{1}$$

$$\phi V_{n,ACI352} = \phi 0.083\gamma_{ACI352}\sqrt{f_c'}b_j h_c \tag{2}$$

where, $A_{sh,ACI352}$ is the cross-sectional area of transverse reinforcement required by ACI 352 and should not be less than $0.09 s_h b''_c f'_c / f_{yh}$; s_h is the center-to-center spacing of hoops or hoops plus crossties; b_c'' is the core dimension of a tied column, outside to outside edge of transverse reinforcement bars, perpendicular to the transverse reinforcement area being designed; f_c' is the compressive strength of concrete; f_{yh} is the yield strength of horizontal transverse reinforcement; A_c and A_g are the area of column core measured from outside edge to outside edge of hoop reinforcement and the gross area of column section, respectivley; ϕ is 0.85; $V_{n,352}$ is the nominal shear strengths of the joint in accordance with ACI 352; b_j is the effective width of joint transverse to the direction of shear as defined in ACI 352; h_c is the full depth of column; and the factor γ_{ACI352} depends on the joint configuration and is 12 for corner exterior joints with a continuous column.

The required transverse reinforcement in Eq. (1) is the same as Eq. (21-4) of ACI 318-11 (2011), which is the equation for members subjected to bending and axial load, not for joints. The amount of transverse reinforcement is determined with the intent that spalling of shell concrete will not result in the loss of axial load strength of the column. Equation (1) is not directly related to joint shear strength and includes only the plane configuration for confining core concrete. The shear force that should be resisted by the joint is computed on a horizontal plane and the joint shear strength in Eq. (2) depends only on the horizontal configuration, such as the effective area of the joint and the connection classification. Consequently, the joint aspect ratio is not considered in Eqs. (1) and (2).

2.2 Eurocode 8

In Eurocode 8 (2004): Design of structures for earthquake resistance, the joint shear strength and required transverse reinforcement for exterior joints are determined as:

$$V_{n,EC8} = 0.8\eta f_{cd}\sqrt{1-\frac{v_d}{\eta}}b_{j,EC8}h_{jc} \tag{3}$$

$$A_{sh,EC8} = \left\{\frac{\left(\dfrac{V_{jhd}}{b_{j,EC8}h_{jc}}\right)^2}{f_{ctd} + v_d f_{cd}} - f_{ctd}\right\}\frac{b_{j,EC8}h_{jb}}{f_{yh}} \tag{4}$$

where, $V_{n,EC8}$ is the nominal shear strengths of the joint in accordance with Eurocode 8; $\eta = 0.6(1 - f_{ck} / 250)$; h_{jc} and h_{jb} are the distances between extreme layers of longitudinal reinforcement in the column and beam, respectively; $A_{sh,EC8}$ is the cross-sectional area of transverse reinforcements required by Eurocode 8; and f_{cd}, f_{ck}, v_d, $b_{j,EC8}$, V_{jhd}, f_{ctd} are defined in 5.5.3 of Eurocode 8 (2004).

As with Eq. (2), the joint shear strength of Eq. (3) is dependent on the horizontal joint area. Equation (4) for determining the amount of transverse reinforcement includes the depths of the column and beam; however, it uses them only to calculate principal stresses and the joint aspect ratio h_{jb}/h_{jc} does not affect the amount of required transverse reinforcement. Eurocode 8 adopted a simple plane stress model for verification of the shear strength of beam-column joints (Fardis *et al*. 2005). The model assumes homogeneous stresses in the body of the joints, consisting of shear stress, vertical normal stress, and horizontal normal stress.

3. Reevaluation of test data on exterior joints

Eighty-eight tests on exterior beam-column joints from 11 references (Chun and Shin 2014, Ehsani and Alameddine 1991, Ehsani *et al*. 1987, Ehsani and Wight 1985, Fujii and Morita 1991, Hwang *et al*. 2005, Kaku and Asakusa 1991, Lee *et al*. 1977, Tsonos 2007, Uzummeri 1977, Wong and Kuang 2008) were collected. The failure modes of the tests were classified into F1, J1, J2, and J3 groups, which were suggested by Hwang and Lee (1999), according to the seismic performance of the beam-column joints as shown in Fig. 2. Failure mode J3 is an apparent joint shear failure and tests classified as J3 were selected. Tests classified as J2 were also selected because the design requirement of joint strength is considered to be satisfied when the strain hardening increases the tensile stresses in the beam longitudinal reinforcement by ten percent over the actual tensile yield stresses (Hwang and Lee 1999). Some beam-column joints under slight reverse loading, such as tests conducted by Uzummeri (1977), showed better seismic performance, even though they had less transverse reinforcement than that required by ACI 352R-02. Moreover, some beam-column joints that had transverse reinforcement that was less than half of that specified by ACI 352R-02 showed unreliable behavior, because the joints were not properly confined. Finally, 25 tests from 7 references (Chun and Shin 2014, Ehsani and Alameddine 1991, Ehsani *et al* 1987, Ehsani and Wight 1985, Fujii and Morita 1991, Hwang *et al*. 2005, Tsonos 2007) suitable for this study were selected. The selected tests met all of the following criteria: 1) They showed joint shear failure even though beam bars yielded, but the ratio $P_{\max}/P_y$ did not exceed 1.1; 2) they experienced severe reverse loading so that they could be classified as Type 2 according to ACI 352R-02; and 3) they had transverse reinforcement that was more than half of that required by ACI 352R-02.

The measured shear strength factors γ_{exp} ($=V_{peak}\Big/\left(0.083\sqrt{f_c'}b_j h_c\right)$) are plotted in Fig. 3 with the varying ratio of $\rho_{h,prov}/\rho_{h,ACI352}$ where V_{peak} is the maximum shear strength measured in the test; $\rho_{h,prov}$ is the provided sectional ratio of horizontal transverse reinforcement and $\rho_{h,ACI352}$ is the required sectional ratio of horizontal transverse reinforcement according to ACI 352. The joint shear strength increases with an increase in the ratio of $\rho_{h,prov}/\rho_{h,ACI352}$. Some tests had a shear strength factor of less than 12 specified for exterior joints in ACI 352R-02, although they had adequate transverse reinforcement to meet ACI 352R-02. To compensate for the differences in transverse reinforcement, the measured shear strength factors are normalized by $\rho_{h,prov}/\rho_{h,ACI352}$, and are plotted along with the joint aspect ratios in Fig. 4. The normalized shear strength factor decreases as the joint aspect ratio increases, demonstrating the essential role of the joint aspect ratio in the joint shear strength. However, this is generally ignored in the current design codes. Consequently, new criteria are required that consider the effects of the joint aspect ratio on exterior joint design.

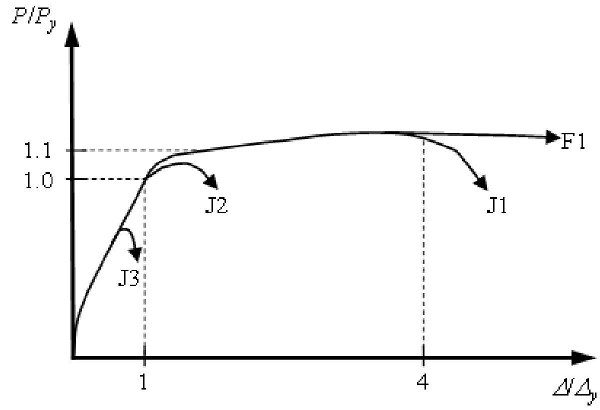


Fig. 2 Classification of failure modes (Hwang and Lee 1999)

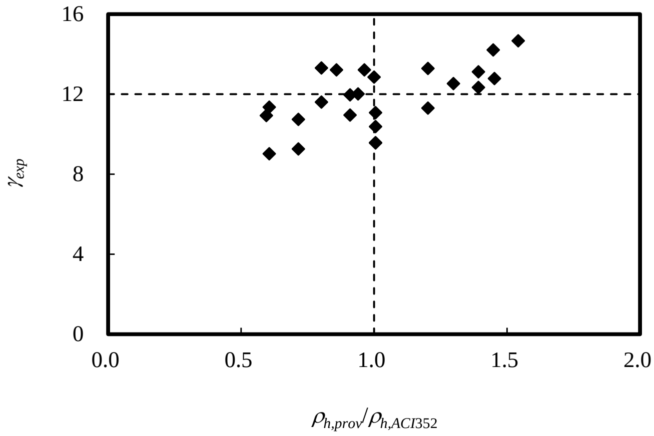


Fig. 3 Measured shear strength factor with varying $\rho_{h,prov}/\rho_{h,ACI352}$

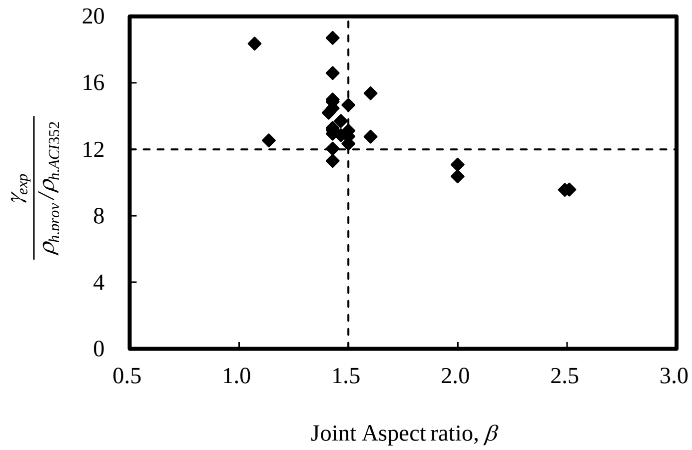


Fig. 4 Shear strength factor normalized by $\rho_{h,prov}/\rho_{h,ACI352}$ with varying joint aspect ratio

4. Development of analytical model

Fig. 5 shows the strut-and-tie modeling (STM) of an exterior beam-column joint. A joint shear force induced by beam bars transfers to the joint via two paths: a direct path, via ST1; and an indirect path, via ST2-T-ST2. This STM for an exterior joint was used effectively (Hong *et al*. 2007) to describe the stress field of an exterior joint. An adequate amount of horizontal transverse reinforcement is required to secure safe load flows in both the direct and indirect paths as shown in Fig. 5, i.e., to transfer a tension tie load T, and to confine compression struts ST1 and ST2. The required transverse reinforcement will be determined in the following sections.

4.1 Transverse reinforcement for ties

The strut-and-tie model shown in Fig. 5 is an indeterminate system. The fraction of the joint shear transferred by the indirect path was suggested by Schäfer (1996) and Jennewein and Schäfer (1992) as follows:

$$T=\frac{2\tan\theta-1}{3}V_n=\frac{2\beta-1}{3}V_n \tag{5}$$

where, T is the tension tie force and V_n is the joint shear strength. This study assumes that the joint aspect ratio β is the same as $\tan\theta$.

CEB-FIP (1999) uses the same equation as Eq. (5) to determine the fraction of tie in D-region with concentration loading. For a given joint aspect ratio, sufficient horizontal transverse reinforcement is required within the tie width, to obtain the required tie force T, for the designed joint shear strength V_n. It is reasonable to assume that two ST2s fan out and engage several hoops and cross-ties and, therefore, the tie width is assumed to be half of h_b. The required sectional ratio of the horizontal transverse reinforcement to develop V_n can be expressed as Eq. (6)

$$\rho_T=\frac{T}{\left(h_b/2\right)b_c f_{yh}}=\frac{2\left(2\beta-1\right)}{3\beta}\frac{v_j}{f_{yh}}\frac{b_j}{b_c} \tag{6}$$

where, v_j is the joint shear stress ($=0.083\gamma\sqrt{f_c'}$).

The upper limit of ρ_T can be determined from the limitation of the strength of nodal zones. In the indirect path, the tensile force of tie T transfers to ST2s at nodes 2 and 3 as shown in Fig. 5. The force equilibrium at node 3 is shown in Fig. 6 and horizontal equilibrium gives the relationship:

$$\frac{h_b}{2}\cos\phi b_j f_{ce}\cos\phi=\rho_T\frac{h_b}{2}b_c f_{yh} \tag{7}$$

where, f_{ce} is the effective compressive strength of the concrete in a nodal zone.

According to A.5 of ACI 318-11, the calculated effective compressive strength, f_{ce}, shall not exceed $0.85\left(0.60\right)f_c'$ on the face of a nodal zone anchoring two or more ties. Therefore, the maximum ratio of the horizontal transverse reinforcement can be expressed as:

$$\rho_{T,\max}=\frac{0.51f_c'h_b}{f_{yh}}\cos^2\phi \tag{8}$$

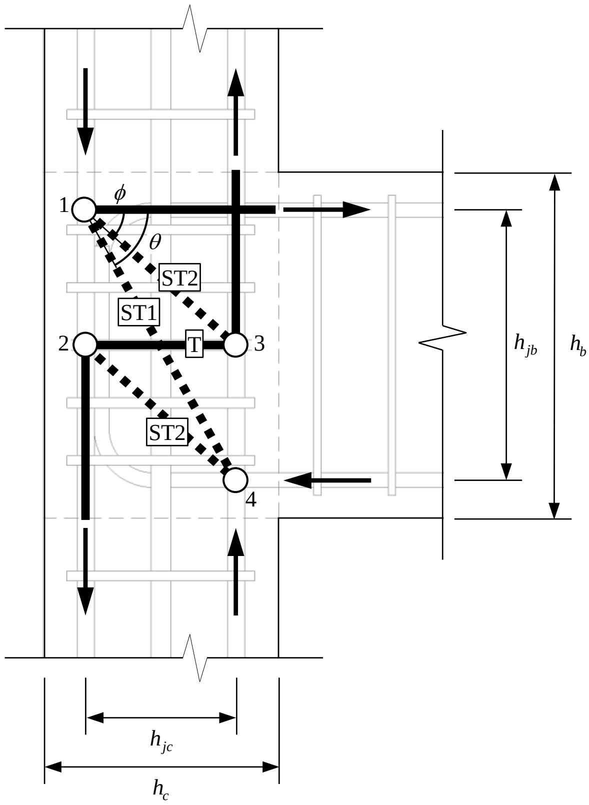


Fig. 5 Strut-and-tie model for exterior beam-column joint

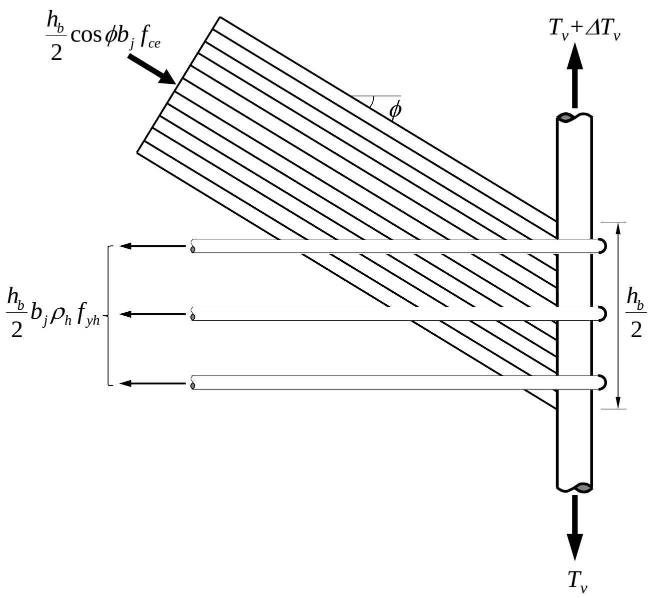


Fig. 6 Force equilibrium at Node 3

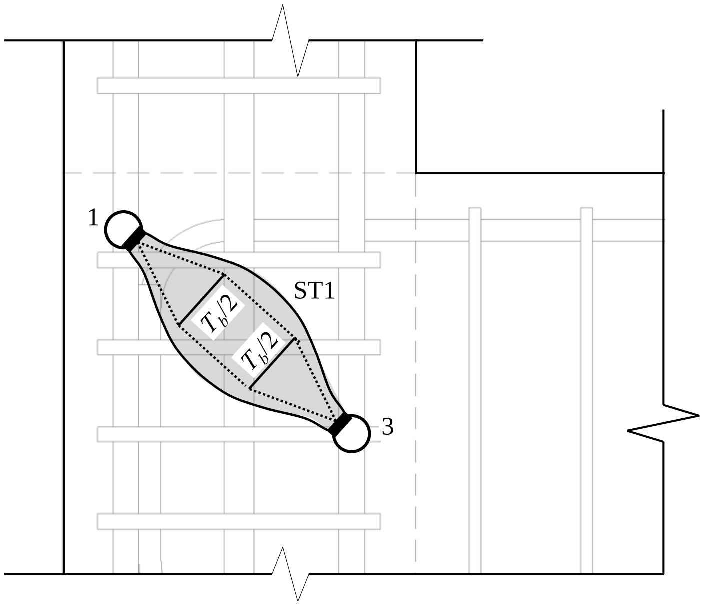


Fig. 7 Strut-and-tie model of bottle-shaped strut ST1

4.2 Transverse reinforcement for struts

ST1 and ST2 in Fig. 5 are classified as bottle-shaped struts as shown in Fig. 7 and stresses inevitably disperse (Brown and Bayrak 2006, Sahoo *et al*. 2011). As the compression disperses, it changes direction, forming an angle to the axis of the strut. To maintain equilibrium, a tensile force is developed to counteract the lateral component of the angled compression forces as shown in Fig. 7. Sahoo *et al*. (2011) assumed that the variation of the transverse tensile stress along the strut axis is represented by a triangular profile and suggested that the total tension resisted by concrete at imminent cracking is given by Eq. (9), using $f_t = 0.56\sqrt{f_c'}$, as recommended by ACI 318-11 for normal weight concrete.

$$F_c = b_c l \frac{f_t}{2} = 0.28 b_c l \sqrt{f_c'} \tag{9}$$

where, F_c is the total tension resisted by the concrete at imminent cracking and l is the strut length from face to face of nodes.

If the transverse reinforcement in a bottle-shaped strut is adequate, force would transfer across the crack following splitting, avoiding a sudden failure. Transverse reinforcement in a bottle-shaped strut is most efficient when it is placed perpendicular to the strut axis. However, vertical and horizontal reinforcement in joints may be placed to provide the necessary transverse reinforcement. Column longitudinal bars placed in the middle of the column can play a role as vertical transverse reinforcement; and hoops and cross-ties do the same for horizontal transverse reinforcement. The forces in the reinforcement bars crossing the crack can be calculated, as shown in Fig. 8 (Brown and Bayrak 2006). The resisting force, perpendicular to the crack, is expressed as (Chun *et al*. 2007):

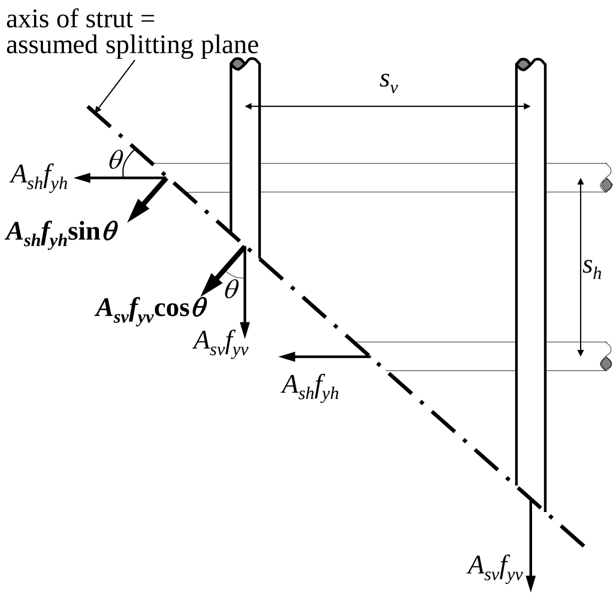


Fig. 8 Forces in transverse reinforcement along axis of strut

$$F_{\perp} = \frac{A_{sv} f_{yv} l \cos^2 \theta}{s_v} + \frac{A_{sh} f_{yh} l \sin^2 \theta}{s_h} \tag{10}$$

where, $F_{\perp}$ is the resisting force perpendicular to the crack; A_{sv} and A_{sh} are the cross-sectional areas of vertical and horizontal transverse reinforcements, respectively; f_{yv} and f_{yh} are the yield strengths of vertical and horizontal transverse reinforcements, respectively; and s_v and s_h are the spacings of vertical and horizontal transverse reinforcements, respectively.

To prevent sudden failure in a strut, $F_{\perp}$ must be equal to or greater than F_c. From Eqs. (9) and (10), the minimum horizontal transverse reinforcement required to prevent a strut from splitting failure is:

$$\rho_{S,\min} = \frac{A_{sh}}{s_h b_c} = \frac{0.28}{\sin^2 \theta} \frac{\sqrt{f_c'}}{f_{yh}} - \rho_v \frac{f_{yv}}{f_{yh}} \cot^2 \theta \tag{11}$$

The minimum ratios of horizontal transverse reinforcement for struts ST1 and ST2 are obtained by substituting the angles (see Fig. 5) between the struts and horizontal transverse reinforcement into Eq. (11).

$$\rho_{ST1,\min} = \frac{0.28\left(1+\beta^2\right)}{\beta^2} \frac{\sqrt{f_c'}}{f_{yh}} - \rho_v \frac{f_{yv}}{f_{yh}} \frac{1}{\beta^2} \tag{12}$$

$$\rho_{ST2,\min} = \frac{0.28\left(4+\beta^2\right)}{\beta^2}\frac{\sqrt{f_c'}}{f_{yh}} - \rho_v \frac{f_{yv}}{f_{yh}}\frac{4}{\beta^2} \quad (13)$$

Hoops and cross-ties in joints always intersect ST1 and ST2 as shown in Fig. 5 and they can simultaneously confine ST1 and ST2. Therefore, the larger ratio of $\rho_{ST1,\min}$ or $\rho_{ST2,\min}$ is sufficient to prevent the splitting failures of ST1 and ST2. In most cases, $\rho_{ST1,\min}$ is greater than $\rho_{ST2,\min}$, except when ρ_v is less than $0.28\sqrt{f_c'}/f_{yv}$.

4.3 Required transverse reinforcement ratio

Transverse reinforcement in exterior beam-column joints transfers the tension in tie T and confines compression struts ST1 and ST2. For given geometric and material properties, the required transverse reinforcement ratio ρ_{req} to obtain the designed v_j is

$$\rho_{req} = \rho_T + \max\left(\rho_{ST1,\min}, \rho_{ST2,\min}\right) \quad (14)$$

The joint shear strength factor γ_{cal} can be calculated using Eq. (6) and (14) with the provided transverse reinforcement ratio ρ_{prov}.

$$\gamma_{cal} = \rho_T \frac{3\beta}{2\left(2\beta-1\right)}\frac{b_c}{b_j}\frac{f_{yh}}{0.083\sqrt{f_c'}} \quad (15)$$

To verify the proposed equations (14) and (15), the test results of the exterior joint specimens used in Fig. 3 are compared to the predictions in Fig. 9 and Fig. 10. The comparison excluded 10 specimens that had transverse reinforcement less than half of that specified by ACI 352R-02, because joints not properly confined do not behave as assumed in Fig. 5. The proposed Eq. (15)

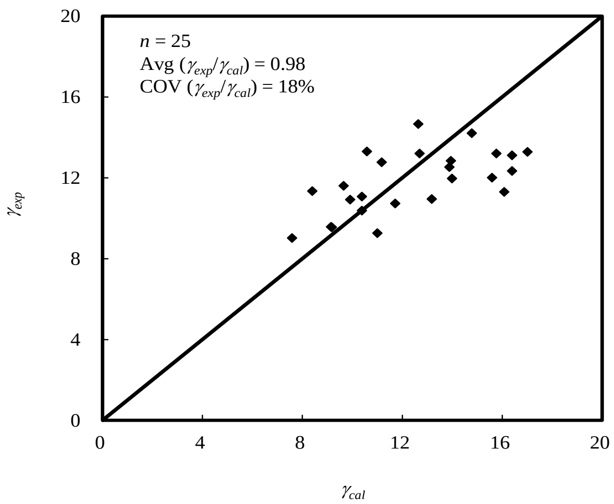


Fig. 9 Correlation of tests and predictions for the shear strength factor

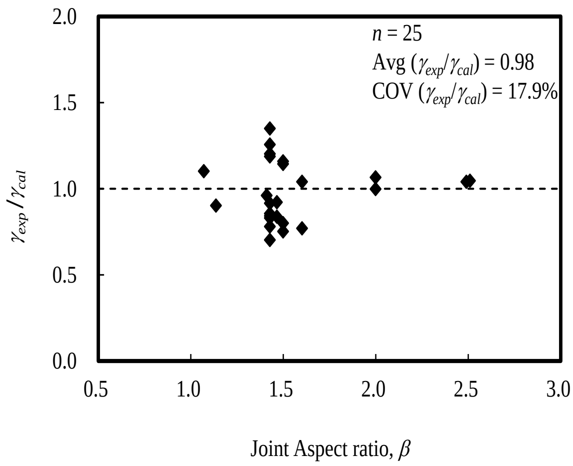
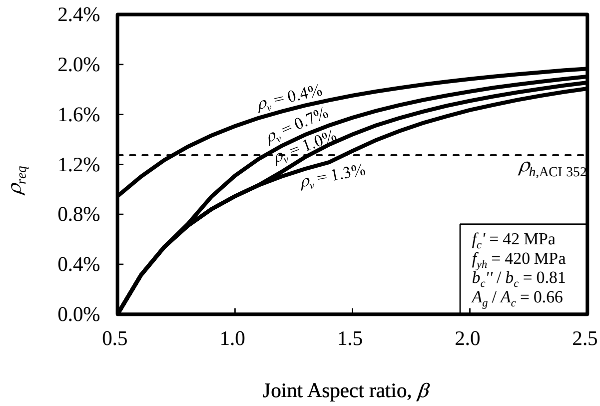
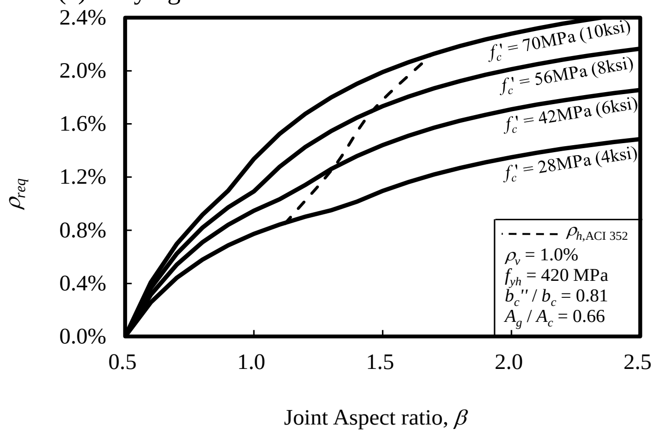


Fig. 10 Comparison of tests and predictions for the shear strength factor with varying joint aspect ratios



(a) Varying vertical transverse reinforcement ratio



(b) Varying compressive strength of concrete

Fig. 11 Comparison of sectional ratios of horizontal transverse reinforcement by the proposed model and ACI 352R-02 predicts the joint shear strengths with a mean value of 0.98 for the ratio between the test results and predictions and with a coefficient of variation (COV) of 18%, as shown in Fig. 9. Equation (15) predicted the joint shear strength without bias for a varying joint aspect ratio, as shown in Fig. 10. The mean value for the ratio between the tests and predictions is 0.98 with the COV of 18%. The minimum and maximum ratios between the tests and predictions are 0.70 and 1.35, respectively.

5. Design considerations

There are two ways to take the joint aspect ratio into account when designing exterior joints. One way is to determine the shear strengths for a given joint aspect ratio and amount of transverse reinforcement; the other is to determine the required transverse reinforcement to obtain the nominal shear strength with a given joint aspect ratio. The latter is more favorable for joint design because joint shear forces are usually fixed early in the design.

Eq. (14) provides the required sectional ratios of horizontal transverse reinforcement and they are shown in Fig. 11. An increasing joint aspect ratio requires more transverse reinforcement. Fig. 11(a) shows that, as the ratio of vertical reinforcement decreases, the required horizontal transverse reinforcement increases although ACI 352R-02 specifies constant transverse reinforcement with the assumed conditions. Fig. 11(b) compares the required transverse reinforcements with varying concrete compressive strength. For high-strength concrete, such as 70 MPa, ACI 352R-02 provisions yield conservative results for joint aspect ratios of less than 1.7. However, for normal-strength concrete, such as 28 MPa, ACI 352R-02 does not produce a safe design for joint aspect ratios higher than 1.1, demonstrating that in determining the requisite amount of transverse reinforcement, the joint aspect ratio should be included.

6. Conclusions

Although the joint aspect ratio affects joint shear strength, current design codes do not consider it in calculating joint shear strength and the required transverse reinforcement. To evaluate the effects of joint aspect ratio on joint shear strength, exterior beam-column join tests collected from 11 references were reevaluated. An analytical model was developed to quantify the amount of transverse reinforcement required to secure safe load flows in exterior beam-column joints. The following conclusions were drawn from the reevaluation and analytical model:

- Reevaluation of exterior beam-column joint tests demonstrated that as more transverse reinforcement was provided, the joint shear strength increased. However, some tests had a shear strength factor less than values specified for exterior joints in ACI 352R-02, although they met the requirements of ACI 352R-02. If the measured shear strength factors are normalized by $\rho_{h,prov}/\rho_{h,ACI352}$, the normalized shear strength factor decreases as the joint aspect ratio increases. Thus, the joint aspect ratio is an essential component of joint shear strength.
- A strut-and-tie model, consisting of one direct strut, two indirect struts, and one horizontal tension tie, was used for an exterior beam-column joint. The roles of horizontal transverse reinforcement were defined to transfer the tie load and to confine the struts; and the required transverse reinforcement for each role was theoretically determined. The proposed model was

validated by comparisons with a database of exterior beam-column joint tests from published literature.

- The required sectional ratios for horizontal transverse reinforcement calculated by the proposed model were compared with those specified in ACI 352R-02. An increase in the joint aspect ratio, or a decrease in the ratio of vertical reinforcement, requires an increase in horizontal transverse reinforcement, although ACI 352R-02 specifies a constant transverse reinforcement.

Acknowledgments

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