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Shear strength of interior slab-column connections

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ABSTRACT: An alternative strength model was developed for evaluating the punching shear strength of interior slab-column connections without shear reinforcement. The punching shear was assumed to be resisted mainly by the compression zone at the critical section, addressing the damage due to flexural cracking at slab-column connections by flexural cracking In defining the punching shear strength, the material failure criteria of concrete was used. In the evaluation of the punching shear strength, the interaction between the shear stress and the compressive normal stress developed by the flexural moment of the slab was considered. The proposed strength model was verified by existing test specimens.

1 INTRODUCTION

A flat plate is susceptible to punching shear failure at its slab-column connection. The failure causes significant degradation of the overall resistance of the structure, and thus the structure may collapse. Due to that, a lot of research efforts have been made to investigate the punching shear strength of slab-column connections.

Based on the results of research, so far, several design methods for slab-column connections have been developed, including ACI 318-05 (2005), CEB-FIP MC 90 (1993), BS 8110 (1997), and Eurocode 2 (2002). However, the current design codes differ in the definition of the shear strength and the location of the critical section of the slab-column connection. Figure 1 shows the punching shear strengths of test specimens obtained from FIP bulletin 12 (2001). As shown in the figure, ACI 318-08 shows the greatest deviations in the strength-predictions. ACI 318-05 and CEB-FIP MC 90 greatly overestimated the punching shear strength for several specimens.

Recently, Choi et al. (2007a) developed the strain-based shear strength model to predict the one way shear strength of reinforced concrete slender beams. In the model, the shear strength was defined based on the material failure criteria of concrete. By addressing the interaction between the shear capacity and normal stress caused by the flexural deformation, the effect of the flexural damage was considered in the evaluation of the shear strength of beams.

In the present study, the strain-based shear strength model was applied to the punching shear of slab-column connections. The applicability of the proposed model was verified by comparisons with existing test results.

2 FAILURE CRITERIA OF CONCRETE

Because a flat plate has a large span-to-thickness ratio, the punching shear behavior is heavily dependent on flexural deformation. Usually, at its slab-column connection, flexural cracking occurs prior to punching shear failure (Farhey et al. 1997, Elstner & Hognestad 1953, Kotsovos & Pavlovic 1998). The

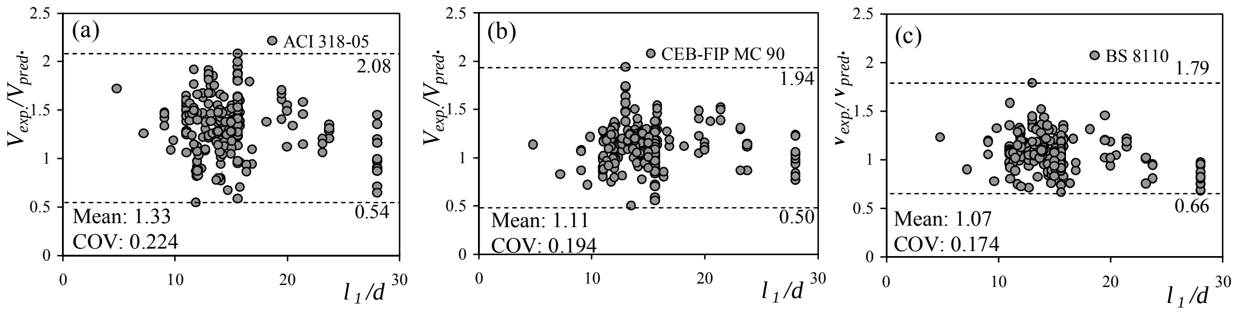

Figure 1. Punching shear strength-predictions for test specimen.

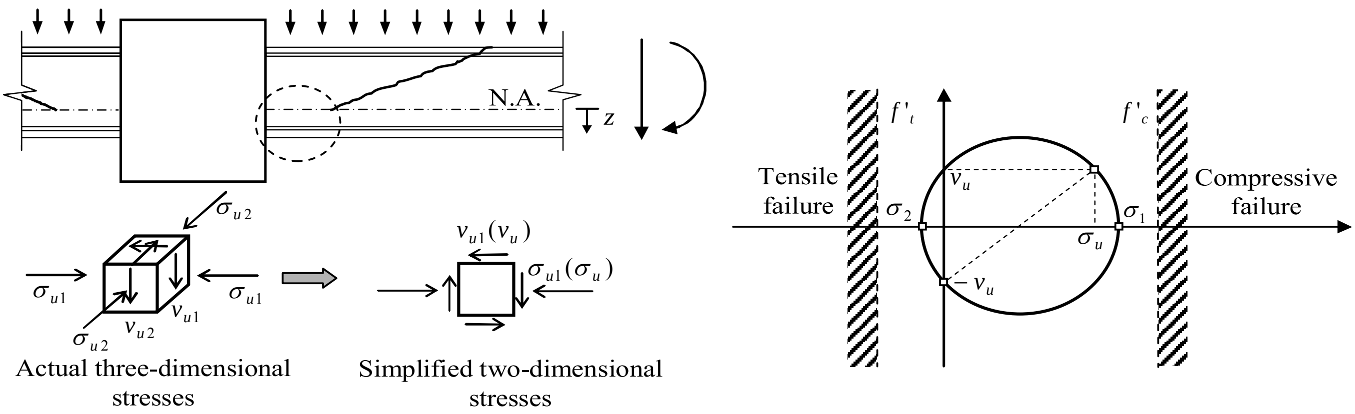

Figure 2. Principal stress failure criteria of concrete subjected to shear-compression.

proposed shear strength model was developed based on the shear-contribution of the compression zone.

Figure 2 shows the three-dimensional stresses that develop in the compression zone of the critical section of a slab-column connection: two orthogonal compressive normal stresses (σ_{u1} and σ_{u2}) and two shear stresses (v_{u1} and v_{u2}). The compression zone of the critical section is subjected to a combination of these compressive normal stresses and shear stresses. Therefore, the interaction between the stress components must be considered to accurately evaluate the punching shear strength of the slab-column connection (Zaghlool & Rawdon 1973).

In the present study, to develop a simplified design equation, two-dimensional compressive and shear stresses (σ_{u1} and v_{u1}) acting on the cross-section of the compression zone were considered.

Addressing the failure mechanism of concrete (Chen 1982) subjected to the combined compressive and shear stresses, the maximum shear stress capacity can be defined as a function of the compressive normal stress.

for a failure controlled by compression.

$$v_{nc}(z) = \sqrt{f'_c[f'_c - \sigma_u(z)]} \tag{1a}$$

for a failure controlled by tension.

$$v_{nt}(z) = \sqrt{f'_t[f'_t + \sigma_u(z)]} \tag{1b}$$

Since the compressive stress in the compression zone, σ_u, varies with the distance from the neutral axis, the shear stress capacity at each location in the compression zone is defined as a function of the distance from the neutral axis z. Throughout this paper, compression and tension are defined with positive and negative signs, respectively.

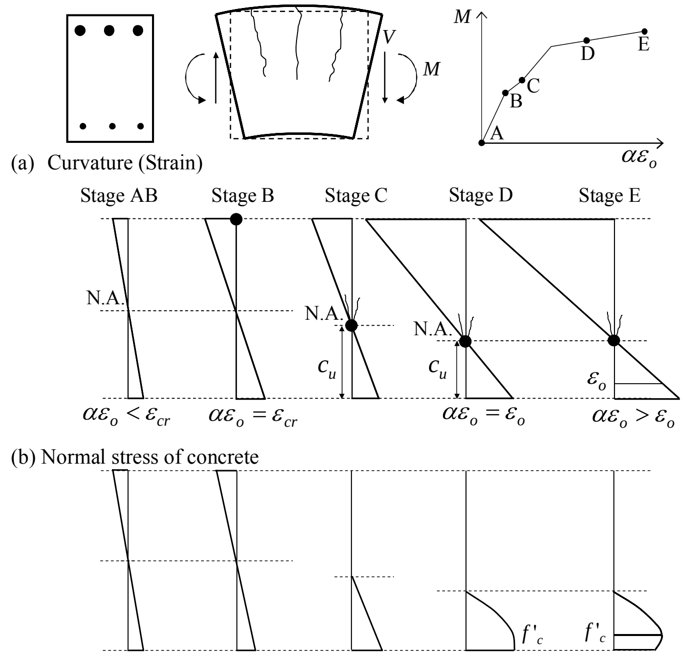

Figure 3. Variations of normal stress according to curvature at a cross section.

At a cross-section of a flexure-dominated member, the distribution of compressive normal stress is affected by the curvature of the cross-section. Figures 3(a) ~ (b) show the variations of the curvature of the cross-section and the compressive normal stress. As the curvature of the cross-section, representing the degree of flexural damage, increases, the depth of the compression zone decreases, and the distributions of the compressive stress and shear stress capacities vary.

The governing shear stress capacity v_n at a location in the compression zone is defined as the minimum of v_{nc} and v_{nt} in Equation (1). At most locations in the compression zone, except for the extreme compression fiber experiencing compression softening, v_n is determined as the shear stress capacity v_{nt} controlled by tension.

3 PUNCHING SHEAR CAPACITY AT CROSS SECTION

The compressive stress is assumed to be parabolically distributed along the depth of the compression zone. The punching shear capacity V_n at a potential critical section can be calculated by integrating the governing shear stress capacity v_n:

$$V_n = b_o \int v_n(z) dz \tag{2}$$

where b_o = perimeter of the critical section at a slab-column connection.

In Figure 3, before tensile cracking (Stage AB), the entire cross-section provides shear resistance. After tensile cracking is initiated (Stage BC), the effective depth of the cross-section resisting the shear force decreases as the tensile crack propagates to the neutral axis. Because of this, the shear capacity decreases. After the tensile crack reaches the neutral axis (Stage CD), shear resistance is provided mainly by the compression zone. In Stage DE ($\alpha\varepsilon_o > \varepsilon_o$), the part of the compression zone experiencing compression softening no longer develops shear resistance.

4 PUNCHING SHEAR STRENGTH

In the proposed strength model, the punching shear capacity of a critical section is mainly affected by the degree of flexural cracking and the perimeter of the critical section b_o. Flexural cracking is most severe and the perimeter of the critical section reaches its minimum at the slab-column connection, and thus, the punching shear capacity is expected to reach its minimum. On the other hand, the punching shear demand reaches its maximum at the slab-column connection. Therefore, for a slab with uniform thickness, the critical section can be determined as the cross-section having the minimum perimeter, which is close to the slab-column connection.

The critical section for the proposed shear strength model was defined approximately as the rectangular cross-section with the average perimeter b_o of the truncated pyramid-shaped failure surface. Therefore, the cross-sectional area of the critical section for punching shear design is defined as $b_o c_u$, where b_o is the perimeter of the critical section, and c_u is the depth of the compression zone. b_o can be calculated by using the angle of the inclined punching shear crack:

$$b_o = 2c_1 + 2c_2 + 4\cot\bar{\phi} \cdot c_u . \tag{3}$$

For $\bar{\phi} = 34$ degrees, $b_o = 2c_1 + 2c_2 + 5.93 \cdot c_u$. c_1 and c_2 are the edge lengths of a rectangular column-section. For circular cross-sections, an equivalent rectangular cross-section with $c_1 = c_2 = (\sqrt{\pi}/2) \cdot D$ is used (ACI 318-05), where D is the diameter of the circular cross-section.

In the present study, a simple design equation for the determination of the punching shear strength was developed to enable the proposed method to be used in design practice. If a design value for the maximum compressive strain $\alpha\varepsilon_0$, corresponding to the punching shear failure, is used, the punching shear strength of a slab-column connection can easily be calculated, without evaluating the shear demand curve. In the present study, based on the results of Kinnunen and Nylander's study (1960), $\alpha\varepsilon_0 = 0.00196$ ($\alpha \approx 1$) was used.

The shear capacity of the compression zone was approximately evaluated by using the average compressive stress $\bar{\sigma}$ over the compression zone. $\bar{\sigma}$ can be simplified as $\bar{\sigma} = (2/3) f'_c$ by using $\alpha = 1$. Further, by using $\sigma_1 \approx \bar{\sigma} [= (2/3) f'_c]$ and $\sigma_2 = -f'_t$, the average tensile strength of the concrete over the compression zone is calculated as $f'_t = (2/3) f_t$ (Choi et al. 2007b). Therefore, from Equation (1a) and (2), the punching shear strength of a slab-column connection can be simplified as

$$V_n = (2/3)\sqrt{f_t [f_t + f'_c]}\, b_o c_u . \tag{4}$$

According to Bažant and Cao (1987), and BS 8110 (1997), the punching shear strength of a slab-column connection is affected by the slab size. To address this size effect, the size effect factor λ_s [$= \sqrt[4]{400/d}$ mm] specified in BS 8110 was used.

According to ACI 318-05 (2005) and Vanderbilt (1972), the punching shear strength of slab-column connections is also affected by the ratio of the perimeter of the critical section to the effective slab depth, b_o/d (or the ratio of column size to the effective slab depth, c_1/d). In this study, to address the effect of b_o/d (or c_1/d) on the punching shear strength, a modification factor λ_{bo} was introduced. To calibrate the proposed strength model, 52 sets of test data selected from FIP bulletin 12 (2001) were used: Bernaert and Puech; Manterola; Yitzhaki; Moe. For the best fit, λ_{bo} was defined as $3.0/\sqrt{b_o/d}$.

Using λ_s and λ_{bo}, the punching shear strength of a slab-column connection can be redefined as

$$V_n = (2/3)\lambda_{bo}\lambda_s\sqrt{f_t [f_t + f'_c]}\, b_o c_u , \tag{5}$$

where $\lambda_{bo} = 3.0/\sqrt{b_o/d}$ and (6)

$$\lambda_s = \sqrt[4]{400/d} \quad (d \text{ in mm}) \tag{7}$$

5 VERIFICATION AND DISCUSSION

The proposed strength model [Eq. (5)] was applied to specimens tested in previous studies. 197 specimens from FIP bulletin 12 (2001).

Figure 4 shows the predictions for the test specimens excluding the specimens, which were used to calibrate the proposed model. The results showed that the proposed design method predicted the punching shear strengths of the test specimens with reasonable precision. In Figure 4, the ratios of the test results to the strengths predicted by the proposed method range from 0.80 to 1.59. The mean value of the strength ratios was 1.20, with a standard deviation of 0.163. The proposed strength model showed better predictions than ACI 318-05, CEB-FIP MC 90, and BS 8110 (See Fig. 1).

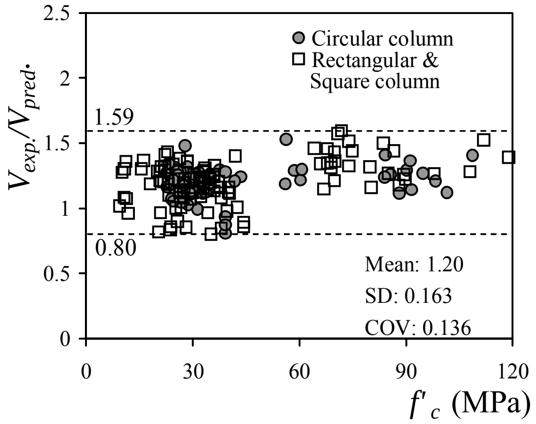

Figure 4. Strength-predictions for test specimen by proposed method.

6 CONCLUSIONS

At the slab-column connection of a flat plate, the applied shear force is resisted mainly by the compression zone of the intact concrete at the critical section, which is not damaged by flexural cracking. The compression zone of the critical section is subjected to the compressive stress developed by the flexural moment, as well as by the shear stress. Therefore, the punching shear strength of the slab-column connection was defined by considering the interaction between the compressive stress and shear stress. The proposed strength model was applied to existing test specimens. The results showed that the proposed method predicted the test results with reasonable precision.

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