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ESTIMATING THE PUNCHING SHEAR CAPACITY OF REINFORCED CONCRETE PILE CAPS

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Abstract

Reinforced concrete pile caps are commonly used in the foundations of buildings and bridge structures. The design of pile caps should be carried out judiciously, considering both the bearing capacity of the soil and the strength of the pile caps. Pile caps experience significantly high punching shear forces transferring the load from the structure to the soil. Accurate estimation of shear strength is required to carry out a safe and economical design of pile caps. Currently, the strength of pile caps estimated through ACI code considers only the pile cap dimensions and concrete strength while ignoring other key parameters such as the contribution of tension steel and the positioning of columns, which is likely to produce estimations with large errors.

In this paper, load resisting paths in the D-region near the column connecting with the pile slab are discussed and the shear strength of reinforced concrete pile caps is evaluated using the softened strut-and-tie model. The proposed model satisfies force equilibrium, strain compatibility and constitutive relationships of the cracked concrete. It can also accurately estimate cracking and strength points and provide a force-displacement load path for reinforced concrete pile caps. The predicted shear strength values are compared with the test results for six pile cap specimens reported previously with varying geometry and reinforcement configurations. The comparison showed an excellent correlation between the predicted shear capacity and force-displacement load path with the test results. The proposed model also provided much better estimates for shear capacity than the ACI code for all the specimens.

Keywords: strut-and-tie; shear strength; pile cap; analytical model; punching shear

1. Introduction

Pile caps are common structural elements in bridges and buildings, transmitting the load from the column to a group of piles that are a part of the foundation system. The span-to-depth ratios in pile caps vary from 0.5 to 2.0, which results in shear-dominant behavior. The pile caps are subjected to concentrated loads from columns and piles with severe punching stresses, often resulting in brittle failure. Due to the difficulty in accessibility for repairs, pile caps should be designed more carefully with reliable strength estimations to ensure no failure. Hence, it is important to conduct a proper evaluation and accurate strength estimation of pile caps by analytical means to facilitate a safe and economical design.

Currently, the American design code ACI 318-19 [1] recommends either one-way or two-way footing shear check for pile caps while ensuring a minimum overall depth of pile cap. Alternatively, a more reliable strut-and-tie model is used for the design of pile caps. The strut-and-tie model, which considers the flow of forces rather than the forces at one particular section, is somewhat more appropriate for the strength estimation of pile caps. However, this procedure only considers parameters such as the size of the pile cap and the compressive strength of concrete. This procedure does not take into account the effect of tensile reinforcement, pile spacing, column geometry, and span-to-depth ratio in estimating the strength of pile caps [2].

Moreover, this procedure does not distinguish between the flexure design and shear design. As a result, both the shear design provisions and strut-and-tie estimations tend to be un-conservative for shear-dominant pile caps. In other words, the strength of struts and nodes by the strut-and-tie method was found to be un-conservative for the specimens that did not fail by reinforcement yielding [3].

2. Previous work

Adebar et al. [4] tested six large pile caps designed to fail in two-way shear to study the suitability of strut-and-tie models for pile caps. The test results showed that the strain distributions were highly nonlinear throughout the loading. The authors also remarked that the strut-and-tie models do not separate flexural and shear design; however, it may be used to design the tension reinforcement to ensure that the tension reinforcement yields before concrete shear failure. The authors proposed that maximum bearing stress at failure is a good indicator of strut splitting failure and suggested to limit the bearing stress to about 1.1 f_c'. In further studies, this maximum allowable bearing stress was modified further to include the amount of confinement as well as the aspect ratio (height-to-width) of compression struts [2]. However, even the modified bearing stress limitations were somewhat conservative, with a mean value of 1.55 for the test-to-predicted strength ratios.

Otsuki and Suzuki [5] observed that the ultimate strength of pile caps with uniform grid arrangement was lower than that of pile caps with an equivalent amount of reinforcement grouped between the pile bearings. Other parameters such as the influence of edge distance, bar arrangement, taper and concrete strength were also studied. Miguel-Tortola et al. [6] tested nine three-pile cap specimens to study the influence of secondary reinforcement and shear span-depth ratio on pile cap strength. In their study, it was observed that the secondary reinforcement in horizontal and vertical directions is efficient in enhancing the pile cap by taking part in complementary resistance mechanisms. The authors also observed that the failure load increases with the shear span-depth ratio, which is usually neglected by the conventional strut-and-tie procedure.

In this paper, the strength of pile caps is estimated through the softened strut-and-tie model, which was successfully adopted for predicting the strength of several types of discontinuity regions such as deep beams, corbels, squat walls and all types of beam-column joints [7]. The softened strut-and-tie model is very effective in accurately predicting the strength of several shear dominant regions due to the sound theoretical background on which it was developed. The softened strut-and-tie model was further simplified to facilitate easy, fast and efficient design procedures for the engineering fraternity [8]. In this paper, the simplified softened strut-and-tie model is used to estimate the shear strength of pile caps. Besides, a simple force-displacement relationship is also proposed for pile caps using the concepts of initial crack point and strength point.

3. Simplified softened strut-and-tie model

The pile caps are subjected to concentrated vertical loads through columns and piles, producing a vertical shearing effect, as well as, horizontal shearing effect through the flexural action of the pile cap. The geometric discontinuity in the force transfer path from column to pile cap to piles creates a disturbed region with severe stress concentrations. As a result, pile caps are considered as D-regions. The failure of such a member is typically due to the crushing of the concrete in the diagonal strut formed to transfer the forces between the bottom of the column and the top of each pile. The formation of diagonal struts in resisting the column load is shown in Fig.1. The proportion of forces distributed among the four struts depends on their respective geometry and inclination angles, with the broader and steeper concrete struts generally carrying greater fractions of the load.

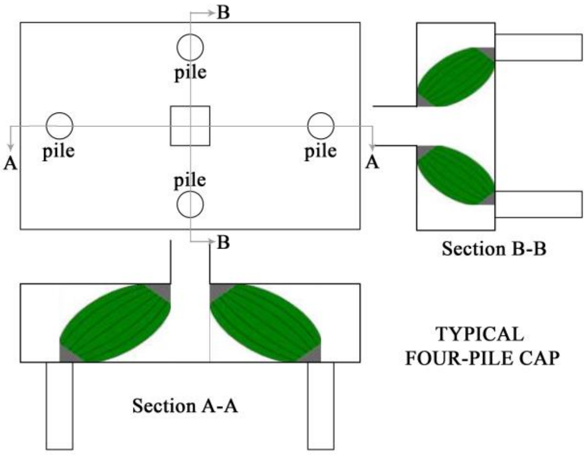

Fig. 1 - Typical four pile cap specimen with diagonal struts

Zhang and Jirsa [9] suggested that the strength of the D-region of the member, which encounters a shear failure is caused by the crushing of the diagonal concrete strut at one end. Based on this suggestion, the nominal strength of the diagonal compression strut C_d, as given by Eq. (1) was adopted for the simplified strut-and-tie model [8].

$$C_d = K\zeta f_c' A_{str} \tag{1}$$

where K represents the strut-and-tie index which represents the additional strut strength provided to the strut through transverse reinforcement, which is taken as 1 for pile caps; ζ is the softening coefficient of cracked reinforced concrete approximated from Eq. (2); f_c' is the standard concrete cylinder compressive strength; A_{str} denotes the effective area on the nodal zone of the diagonal concrete strut.

$$\zeta = \frac{3.35}{\sqrt{f_c'(\text{MPa})}} \leq 0.52 \tag{2}$$

The area of compression strut A_{str} is calculated as

$$A_{str} = b_s \times a_s \tag{3}$$

where b_s is the effective strut width and a_s is the depth of the compression strut equal to kd calculated through Eq. (7).

Fig.2 shows the idealized shear element in the RC pile cap between the column and pile members. The angle of the diagonal compression strut θ is given by Eq. (4).

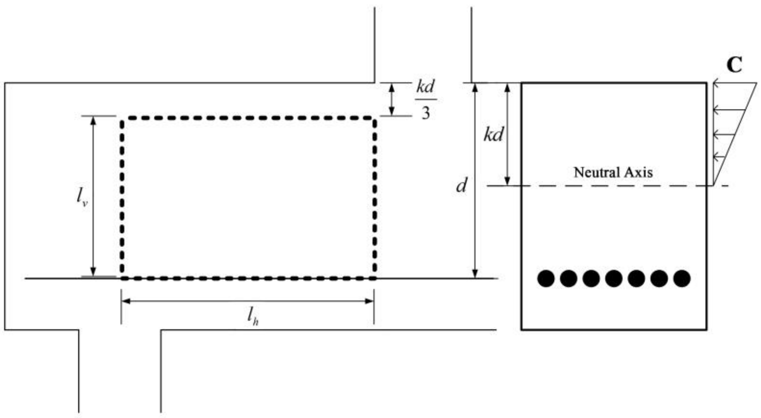

Fig. 2 - Shear element in RC pile cap

Fig.2 shows the idealized shear element in the RC pile cap between the column and pile members. The angle of the diagonal compression strut θ is given by Eq. (4), where l_h is the distance between the edge of the column to the center of the pile, l_v is the perpendicular distance between the centroid of the compression zone to the tensile reinforcement given by Eq. (5).

$$\theta = \tan^{-1}(\frac{l_v}{l_h}) \tag{4}$$

$$l_v = d - \frac{kd}{3} \tag{5}$$

where d is the effective depth and kd is the depth of the neutral axis from the top surface of the pile cap.

Furthermore, the vertical load capacity from the column is determined through Eq. (6).

$$V_n = C_d \sin\theta \tag{6}$$

The geometry and inclination of the compression path depend on the depth of the pile cap, size of the column, size of the pile and the perpendicular distance from the pile to the column. Furthermore, it is not realistic to assume the entire width of the pile cap as the width of the compression strut. In this study, instead of the full width, the effective width is calculated through an iterative procedure shown in Fig.3. This procedure starts with the initial assumption of b_e equal to the sum of the column width b_c and the effective depth d of the pile cap. Under the assumption of flexural behavior of pile cap, the depth of the neutral axis kd is calculated by assuming it as a singly reinforced beam section with width b_e as follows:

$$kd = \left(\sqrt{(n\rho)^2 + 2n\rho} - n\rho\right) \times d \tag{7}$$

where n is the ratio of modulus of elasticity of steel to the modulus of elasticity of concrete and ρ is the longitudinal reinforcement area ratio.

The compression zone above the neutral axis is assumed to be an inverted triangle in shape with the effective compression force acting at a distance $kd/3$. The compression bearing pressure from the column is assumed to be transmitted downwards into the pile cap with a slope of 1:2. The width of the compression region corresponding to the depth of $kd/3$ is calculated as b_s. If this flexural width b_s is equal to the assumed effective width b_e, the iteration ends and the effective width b_e is selected. Otherwise, b_e is modified and the iteration is carried out again. In the case where the total width of the pile cap is smaller than the calculated width, and the iteration does not converge, the total geometric width of the pile cap can be adopted as the width of the compression strut.

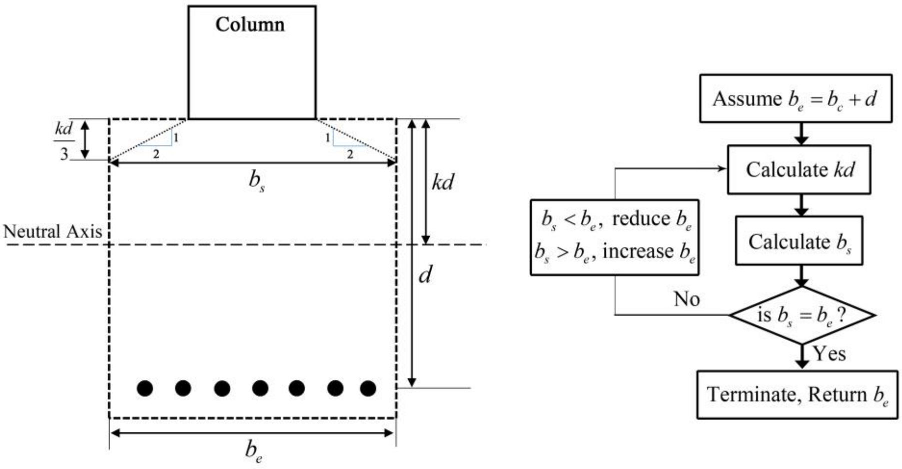

Fig. 3 - Calculation of the effective width b_e

The total number of compression paths in a pile cap is equal to the number of piles connected to the pile cap. The total strength of the pile cap is obtained by summing the vertical components of the intermediate strength offered by each compression strut originating from underneath the column, at the time when the strongest strut reaches its capacity. The intermediate strength provided by weaker compression struts is calculated by plotting the force-displacement relationships using the concepts of crack point and strength point for each strut. In order to reflect the realistic behavior of pile caps in a simplified fashion, pile caps are assumed to have two stiffnesses: one for the range of loads from unloaded state to cracked state and other stiffness (lower of the two) from the cracked state to ultimate state. This procedure is adopted from the work of Weng et al. [10] predicting the force-displacement relationships in shear dominant squat walls. The cracking strength proposed for squat shear walls is modified for the pile caps as shown in Eq. (8) with an upper limit of $0.6V_u$.

$$V_{cr} = 0.27\sqrt{f_c'}b_e d \leq 0.6V_u \tag{8}$$

The displacement at the cracking point has three components: shear deformation $\delta_{s,cr}$, flexural deformation $\delta_{f,cr}$ and slip deformation $\delta_{slip,cr}$ determined through Eqs. (9-11).

$$\delta_{s,cr} = \frac{V_{cr} l_h}{0.4(E_c bd)} \tag{9}$$

$$\delta_{f,cr} = \frac{V_{cr} l_h^{\ 3}}{12(0.7 E_c I_g)} \tag{10}$$

$$\delta_{slip,cr} = \frac{V_{cr}}{V_y} \times \delta_{slip,y} \text{ where } V_y = \frac{M_y}{l_h} \text{ and } \delta_{slip,y} = \frac{d_b f_y^2}{8uE_s(d - a_c)} \times H \tag{11}$$

where l_h is the distance between the column center and pile center; V_y is shear corresponding to the yielding of tension reinforcement. As the pile cap deforms in single curvature bending, V_y is obtained as $V_y = M_y / l_h$; d_b is the diameter of the outermost tensile bar; f_y is the yield stress of the longitudinal steel; u is the average bonding stress of steel which is taken as $1.0\sqrt{f_c'}$ and a_c is the depth of the compression bearing zone.

The displacement corresponding to the strength point has three components: shear deformation $\delta_{s,sn}$, flexural deformation $\delta_{f,sn}$, and slip deformation $\delta_{slip,sn}$ calculated as shown in Eqs. (12-14).

$$\delta_{s,sn} = 0.006 \sin 2\theta \times l_h \tag{12}$$

$$\delta_{f,sn} = \frac{V_{sn} l_h^3}{12(0.5 E_c I_g)} \tag{13}$$

$$\delta_{slip,sn} = \frac{V_{sn}}{V_y} \times \delta_y \tag{14}$$

where V_{sn} is the shear strength of the compression strut; V_y and δ_y is obtained from Eq. (11). The force and displacement corresponding to the initial crack point and the strength point for all struts are calculated. Under the progressive vertical loading on the pile caps, the stronger strut is expected to reach the strength point first. At this displacement, the corresponding strength in the remaining struts is the resistance offered by those struts at the failure of the pile cap. Thus, the total capacity of the pile cap is determined through the summation of the strengths of individual struts in the pile cap.

$$V_{SST} = \sum V_n \tag{15}$$

In the above procedure, for the calculation of the neutral axis, it is assumed that the tensile reinforcement in the pile cap is aligned in the direction of the diagonal strut formation. If the reinforcement is not consistent with the formation of diagonal strut i.e., if there is a non-zero angle θ_s between the alignment of tension bars and diagonal struts, the area of reinforcement in the calculation of the neutral axis shall be modified as $A_{s,p}$ shown in Eq. (16).

$$A_{s,p} = A_s \cos \theta_s \tag{16}$$

4. Verification of the proposed model

The analytical model proposed in the previous sections is used to predict the strength and force-displacement relationships of six specimens tested by Adebar et al. [4]. The geometry, reinforcement layout and the pile locations are varied in these six specimens. These specimens are chosen for verification to understand the effectiveness of the proposed model despite varied configurations in the pile caps. The authors direct the readers to the paper presenting the experimental details [4] for more details about the test specimens.

Fig. 4 shows the predicted force-displacement relationships for stronger and weaker diagonal struts in the six pile cap specimens.

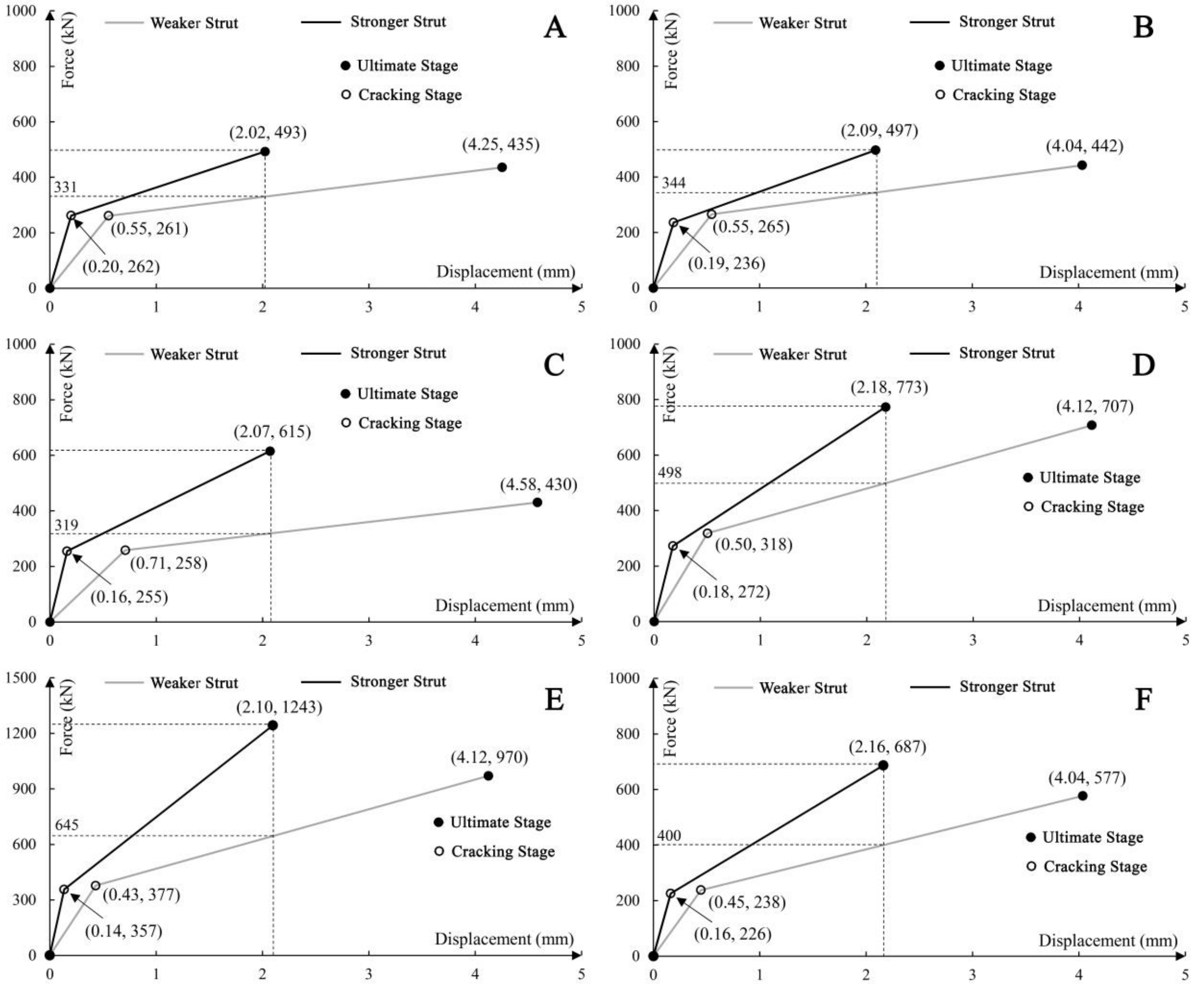

Fig. 4 - Predicted pile cap force-displacement relationships

The overall predicted strength V_{SST} for the six specimens is calculated and compared with the experimental capacities to verify the accuracy of the proposed model. Table 1 presents the experimental vs predicted strength values in the six test specimens. Despite the variety of property variations among the considered pile cap specimens, a mean test-to-model strength ratio of 1.35 and a coefficient of variation of 0.08 suggests that the proposed model is suitable for predicting the strength of the pile caps with reasonable accuracy.

Table 1 – Verification of the proposed analytical model

Author	Specimen Label	f'_c (MPa)	V_{test} (kN)	V_{cr} (MPa) (weak,strong)*	V_n (MPa) (weak,strong)*	V_{SST} (MPa)	$\frac{V_{test}}{V_{SST}}$
Adebar et al. [4]	A	24.8	1781	(261, 262)	(435, 493)	1647	1.08
	B	24.8	2189	(265, 236)	(442, 497)	1682	1.30
	C	27.1	2892	(258, 255)	(430, 615)	1868	1.55
	D	30.3	3222	(318, 272)	(707, 773)	2544	1.27
	E	41.1	4709	(377, 357)	(970, 1243)	3775	1.25
	F	30.3	3026	(238, 226)	(577, 687)	2172	1.39
* The vertical component of the cracking and ultimate strength of the long and short compression struts.						**Mean**	**1.35**
						CoV	**0.08**

5. Conclusion

A strength prediction analytical model for reinforced concrete pile caps based on the softened strut-and-tie model, along with the force-displacement relationships is proposed in this paper. The accuracy of the predicted model is verified with six pile cap specimens with varied geometry and reinforcement layout variations. A comparison of the results suggests that the analytical model is suitable for the prediction of the strength and force-displacement relationships of reinforced concrete pile caps.

6. References

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