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Punching of flat slabs supported on rectangular columns

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ABSTRACT

This paper investigates the structural behaviour of RC flat slabs supported on rectangular interior columns and the influence of the loading conditions (one or two-way bending) on their punching shear strength. The punching shear strength of slabs at rectangular columns can be lower than at equivalent square columns with a similar length of the control perimeter. This is due to a potential concentration of shear forces along the control perimeter. Some, but not all design formulas for punching design, consider this reduction on strength using empirical factors, which are written in terms of the column geometry only. However, in reality, the concentration of shear forces depends also on the deflected shape of the slab. It is shown in this paper that this can be consistently considered by means of the shear-resisting control perimeter. A sound approach is presented to estimate the shear-resisting control perimeter based on the shear fields of the slab accounting for the loading and boundary conditions. An alternative approach is presented based on the contact pressure in the support region which gives comparable predictions of the shear-resisting control perimeter. Both approaches give a physical explanation of the phenomenon. It is also shown that the model previously developed by the authors for non-axis-symmetrical punching of square columns based on the critical shear crack theory can also be applied to rectangular columns. Four punching shear tests are presented of slabs with one-way & two-way bending to validate the theoretical models presented. Accurate strength and deformation capacity predictions were obtained for the tests investigated.

1. Introduction

Reinforced concrete flat slabs supported on rectangular columns, with an elongated cross-section in one direction, are commonly used in practice, for example in underground parking garages and multi-storey buildings. Rectangular columns are typically used to reduce the effective span length (i.e. distance between inner faces of adjacent columns) and to provide lateral stiffness to the structure. Punching shear around such columns is generally the governing design criterion in flat slabs for the ultimate limit states. With respect to circular or square columns, there are two main concerns regarding punching shear around rectangular columns

(a) Actual (non-uniform) distribution of shear forces along the control perimeter around the column.
(b) Influence of the loading conditions and bending moments on the opening of the critical shear crack widths leading to punching failure.

These two concerns are also relevant in cases of punching shear in connections with moment transfer although in this paper only concentric loading will be investigated.

The distribution of normal stresses in large or elongated columns is non-uniform near the intersection with the slab. This was observed experimentally by several researchers such as Moe [1], Hawkins et al. [2], Vanderbilt [3] and Urban [4], amongst others. These tests showed that the strains measured in the concrete at the columns concentrated at the corners whereas the distribution of strains was uniform along circular columns with similar perimeters. Fig. 1a and b show the influence of the loading conditions and that this can result in a concentration of stresses at the column by considering two eccentric contact surfaces between the column and the slab.

The concentration of normal stresses at the column is influenced mainly by the column geometry and slab deformations in bending as shown schematically in Fig. 1a and b. However, most

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Notation

b_0	shear-resisting control perimeter
b_1	basic control perimeter
$b_{1,red}$	reduced basic control perimeter
$b_{0,el}$	shear-resisting control perimeter predicted from shear fields
$b_{0,3d}$	shear-resisting control perimeter from simplified approach
$b_{0,pr}$	shear-resisting control perimeter from contact pressures
b_x, b_y	lengths of segments of control perimeter corresponding to x and y directions
c	side length of a column
$c_{\max}$, $c_{\min}$	longer and shorter side lengths of a column
d	average effective depth of the slab
$d_{avg.}$	average distance measured in the tests from the bottom of the slab to the contact between reinforcement in the x–y directions
d_g	maximum size of the aggregate
e	load eccentricity
E_s	modulus of elasticity of reinforcement
f_c	concrete cylinder strength
f_{cu}	concrete cube strength
f_y	yield strength of flexural reinforcement
k_e	coefficient of eccentricity
L_x, L_y	spans in the x–y directions between centres of columns
m_E	average moment per unit width in the support strip for the calculation of the flexural reinforcement (for the considered direction)
m_R	design average flexural strength per unit width in the support strip (for the considered direction)
r_s	distance from the centre of support to the surrounding line of radial contraflexure
V	shear force
V_{flex}	shear force associated with flexural capacity of the slab
V_R	punching shear strength
$V_{R,c}$	predicted punching shear strength
V_{Rx}, V_{Ry}	punching shear strength corresponding to b_x and b_y
V_{test}	observed punching shear strength
v	shear force per unit length (nominal shear force)
v_R	punching shear strength per unit length (nominal strength)
θ	polar coordinate at the corner of the column
ρ_l	average flexural reinforcement ratio in the test specimen obtained from ρ_x, ρ_y according to design codes
ρ_x, ρ_y	average flexural reinforcement ratio in the x, y directions
ψ	rotation of the slab outside the column region
ψ_x, ψ_y	rotation of the slab in the x, y directions

design approaches for punching only consider the column geometry in the calculations. The concentration of stresses is also influenced by the type of slab–column connection used (e.g. slab simply supported on the column or monolithically connected). It is noteworthy that concentration of shear forces can occur around interior rectangular columns even if loaded concentrically (i.e. balanced moments, $e = 0$). The punching shear strength of slabs at rectangular columns can be overestimated if the concentration of shear forces along the control perimeter is neglected in the calculations.

Another aspect regarding punching shear around rectangular columns is that the development of one-way bending action is enhanced especially in columns with one side considerably longer than the other and $c_{\max}$ in the direction parallel to the predominant bending moment. This effect is also influenced by the clear span length between adjacent columns in both orthogonal directions.

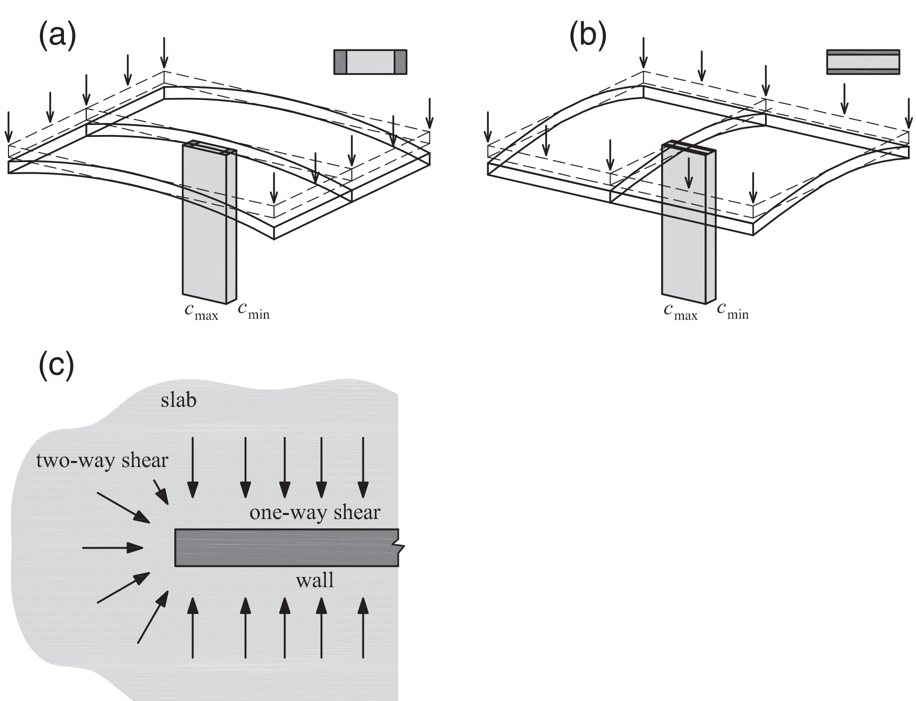

Fig. 1. Concentration of reaction forces towards the edges in internal columns with rectangular cross-section: (a) one-way action in the direction of the elongated side of the column ($c_{\max}$); (b) one-way action in the direction perpendicular to $c_{\max}$ and (c) one-way shear and two-way shear in a slab supported by a wall.