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Effect of mid-thickness rebar mesh on the behavior and punching shear strength of interior slab–column connection

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Abstract Punching shear failure is a major problem encountered in the design of reinforced concrete flat plates. The utilization of shear reinforcement via shear studs or other means has become a choice for improving the punching shear capacity. In this study, a new alternative of reinforcement, the introduction of rebar mesh at the middle of flat plate thickness covering the punching zone and anchored outside this zone, is proposed. Nevertheless, in this investigation, the proposed reinforcement system is examined for interior columns only.

An experimental work consisting of eight specimens, of normal and high strength concrete, and an expanded analytical work using the finite element method had been carried out in order to investigate the effect of this additional reinforcement for both normal strength and high strength concrete. The computer program ANSYS-V12.0 has been utilized in the finite element analysis.

The obtained results indicate that, the proposed shear reinforcement system has a positive effect in the enhancement of both the punching shear capacity and the strain energy of interior slab–column connection of both normal and high strength concrete. The general finite element software ANSYS can be used successfully to simulate the punching shear behavior of reinforced concrete flat plates.

Introduction

Punching shear is a critical design factor of reinforced concrete flat plates since it is associated with brittle failure. Many alternative reinforcement systems had been introduced in literature; e.g., shear studs, bent bars, in order to enhance the punching shear and the strain energy of slab–column connection.

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The punching shear strength and deformation capacity are strongly influenced by the type and characteristics of the shear reinforcing system. Ruiz and Muttoni [1] carried out a series of a six full scale slab tests (3.0 × 3.0 × 0.25 m) with the same flexural and shear reinforcing ratio but with different punching shear reinforcing systems; e.g., separated stirrups, continuous stirrups, bonded reinforcement with anchorage plates, vertical studs and inclined studs. The improvement in punching shear strength and ductility as a result of these systems increased with the same order as they have been mentioned, with the vertical and inclined studs giving the best results; 77% and 119% improvement, respectively. Bent-up bars also improve the punching shear strength and deformation capacity as reported by Tassinari [2]. Lips [3] and Lips and Muttoni [4], with full-scale tests, demonstrated the positive effect of both shear studs and continuous stirrups on the punching shear strength and deformation capacity of slab–column connection. The same conclusion was achieved by Pilakoutas [5] for inclined shear band reinforcement. The shear strength is proportional to the flexural reinforcement ratio; in contrast, the rotation capacity is inversely proportional to the flexural reinforcement (Kinnunen and Nylander [6]).

This study explores the possibility of enhancing the punching shear strength by introducing horizontal mesh reinforcement at the middle of the depth of slab–column connection zone. This reinforcement arrangement is easy to apply and economic in comparison with the other reinforcement types.

Codes provisions

The provisions for calculating the ultimate punching shear capacity recommended by different building codes are reviewed in the following. For concentric loading, the punching shear capacity, P_u, is

$$P_u = v_c b_o d \tag{1}$$

where v_c is the concrete shear strength at the critical shear plane, b_o is the critical shear perimeter and d is the average effective slab depth.

In the Egyptian Code of Practice, ECP-203 [7], the critical shear perimeter is located at a distance 0.5d from the column face, and v_c is the smallest of the following:

$$v_c = 0.8[(\alpha d/b_o) + 0.2]\sqrt{\frac{f_{cu}}{\gamma_c}}\ \mathrm{N/mm^2} \tag{2a}$$

$$v_c = 0.316[0.5 + (a/b)]\sqrt{\frac{f_{cu}}{\gamma_c}}\ \mathrm{N/mm^2} \tag{2b}$$

$$v_c = 0.316\sqrt{\frac{f_{cu}}{\gamma_c}}\ \mathrm{N/mm^2} \tag{2c}$$

where $\alpha = 4$ for interior column, a and b are the smaller and larger column dimensions, respectively, γ_c is the material strength reduction factor and f_{cu} is the strength of the standard cube 150 mm. The ECP-203 [7] does not account for the flexural reinforcement effect and the concrete strength is limited to 40 MPa. Besides, it does not take into consideration the contribution of punching shear reinforcement.

According to the ACI 318-11 [8], the critical perimeter is assumed at 0.5d from the perimeter of the loaded area, and the nominal punching shear strength v_c for slabs without shear reinforcement is the smallest of the following:

$$v_c = \frac{1}{12}[(\alpha_s d/b_o) + 2.0]\sqrt{f'_c}\ \mathrm{N/mm^2} \tag{3a}$$

$$v_c = \frac{1}{6}[0.5 + (2.0/\beta_c)]\sqrt{f'_c}\ \mathrm{N/mm^2} \tag{3b}$$

$$v_c = \frac{1}{3}\sqrt{f'_c}\ \mathrm{N/mm^2} \tag{3c}$$

where $\alpha_s = 40$ for interior columns, β_c = long side/short side of column and should be taken at least equal to 2, $\beta_c \geqslant 2$ and f'_c is the concrete cylinder strength.

For slabs with stirrups as shown in Fig. 1a, according to the ACI 318-11 [8], the punching shear strength is defined as

$$P_u = \frac{1}{6} b_{o,ACI} d\sqrt{f'_c} + A_s f_{ys}(d/s)\quad \mathrm{N} \tag{4}$$

and in slabs with shear studs, Fig. 1b, it is defined as:

$$P_u = \frac{1}{4} b_{o,ACI} d\sqrt{f'_c} + A_s f_{ys}(d/s)\quad \mathrm{N} \tag{5}$$

where A_s is the cross-sectional area of one perimeter of shear reinforcement around the column, s is the distance between perimeters of shear reinforcement, and f_{ys} is the yield strength of the shear reinforcement. In the ACI 318-11 [8], f'_c is limited to 68 MPa, and no effect of flexural reinforcement is considered.

The critical section adopted by the British Standard, BS-8110 [9], lies at 1.5d from the column face, and the ultimate punching shear is calculated as follows:

$$P_u = \left(0.79(100\rho)^{1/3}(400/d)^{1/4}(f_{cu}/25)^{1/3} b_{o,BS} d\right)/\gamma_m\ \mathrm{N} \tag{6}$$

$f_{cu} \leqslant 40$ MPa, $400/d \geqslant 1$, ρ is the flexural reinforcement ratio which is limited to the maximum of 3% and γ_m is the material partial safety factor and is equal to 1.25.

If shear reinforcement is considered, Fig. 2, then it should be provided on at least two perimeters within the punching zone. The first perimeter of reinforcement should be located at approximately 0.5d from the face of the loaded area and should contain not less than 40% of the calculated area of reinforcement. The spacing of perimeters of reinforcement should not exceed 0.75d and the spacing of the shear reinforcement around any perimeter should not exceed 1.5d. The shear reinforcement should be anchored round at least one layer of tension reinforcement. The shear stress should then be checked on successive perimeters at 0.75d intervals until a perimeter is reached which does not require shear reinforcement.

The critical section adopted by the Eurocode 2, EC2 [10], lies at 2d from the column face, and the ultimate punching shear is calculated as follow:

$$P_u = 0.18(100\rho f'_c)1/3 K b_{o,EC} d\quad \mathrm{N} \tag{7a}$$

where ρ is the flexural reinforcement ratio which is limited to the maximum of 2%, and K is a factor accounting for the size effect that is defined as:

$$K = 1 + \sqrt{(200/d)} \leqslant 2.0 \tag{7b}$$

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