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Finite element simulation of concrete slabs with various placement and amount of shear bolts

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Abstract

Three-dimensional (3-D) finite element analysis (FEA) in ABAQUS software examines the punching shear behaviour of reinforced concrete slabs. Four interior reinforced concrete slab-column connections (one slab is without shear reinforcement, while the other slabs are with shear bolts) previously tested under static loading are analysed. The shear reinforced slabs differ in the amount of the shear bolts. The coupled plasticity damaged model previously calibrated is considered for modelling the concrete. In this paper, parametric studies are presented to examine the effect of the amount and placement of the shear bolts. The amount of shear bolts is increased by adding more rows of shear bolts and also decreased by considering less shear bolts in each row. Also, two different arrangements are studied: rectangular and radial. The adopted FEA model is used to analyse and investigate the failure modes, loads and the crack patterns of the slab-column connections. The numerical results are compared to two current design codes for punching shear (ACI 318-14 and EC2-2004).

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Keywords: punching shear; shear bolts; finite element analysis; concrete damaged plasticity model; design codes

1. Introduction

Punching shear failure of reinforced concrete slabs is brittle and it can lead to a progressive collapse of the structure. In order to avoid punching shear, shear reinforcement is installed around the slab-column connections to increase the punching shear capacity and ductility of the slabs.

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In a new slab-column connection, shear reinforcement consists of stirrups or bent bars [1-6], shear heads [7-9] and shear studs [10,11,12]. In existing slabs with inadequate punching shear, strengthening techniques can be considered [13,14]. For retrofit purposes, Adetifa and Polak (2005) [15] and Polak and Bu (2015) [16] tested slabs with shear bolts. The shear bolt system consists of smooth steel bars with a forged circular head on the one end while the other end is threaded with a washer and a nut for anchorage. Shear bolts were found as an appropriate retrofit technique since they increased both the load capacity and ductility of the slabs.

The punching shear failure of reinforced concrete slabs can be examined using nonlinear finite element analysis (FEA). FEA can provide important information about the predicted failure modes within a rapid and non-expensive manner. Many researchers used FEA methods to simulate the behavior of reinforced concrete slabs. Research has been conducted with the layer approach [17,18] and three-dimensional (3D) FEA models [19, 20].

In this paper, the concrete damaged plasticity model in ABAQUS [21], previously calibrated, is considered for parametric investigation to study the effect of placement and amount of shear reinforcement. Finally, the numerical results are compared with two current code provisions for punching shear, where ACI 318-14 [22] uses different equations for slabs with stirrups and shear studs, while EC2-2004 [23] considers the same equation for all different types of shear reinforcement. Regarding the arrangement of the shear reinforcement, ACI 318-14 proposes the rectangular placement, while EC2-2004 considers both the rectangular and the radial placements.

2. Test specimens and results

Four interior reinforced concrete slab-column connections tested by Adetifa and Polak (2005) [15] and analyzed by Genikomsou and Polak (2016) [20,24] are viewed in this study as the control specimens to examine the effect of the amount and placement of the shear bolts. All slabs were tested under static loading through the column stub. The square columns (150 x150 mm) are extended 150 mm from the top and bottom slabs' surfaces, while the thickness of the slabs is 120 mm and the effective depth is equal to 90 mm. The dimensions of the slabs and the applied loads are presented in Fig. 1. The flexural reinforcement consists of 10M bars placed at distance 100 mm and 90 mm in tension side and 200 mm in compression side. Slab SB1 has no shear reinforcement, while SB2, SB3 and SB4 have two, three and four rows of shear bolts, respectively. Prior to testing, holes of 16 mm diameter were drilled around the slab-column connections to install the shear bolts. The placement of the shear bolts was concentric and parallel to the perimeter of the column and each row of shear bolts had two parallel bolts to each face of the column (eight bolts in each row in total). The first row of the shear bolts was placed at a distance of 45 mm from the face of the column, while all following rows were spaced at 80 mm. The material properties of concrete and reinforcement for the slabs are shown in Table 1, while Table 2 presents the test results. Fig. 2 shows the test results for the slabs in terms of load-deflection response. Slab SB1 failed in punching shear and the flexural yield lines did not fully form; no cracks at the compression surface observed. Slab SB2 failed in a mixed punching/flexure mode, where first the flexural capacity was achieved and then the punching shear cone was formed outside the shear reinforced area. Slabs SB3 and SB4 first showed yielding of the tensile flexural reinforcement followed by a general yielding of the flexural reinforcement. Finally, both slabs failed in punching shear (secondary failure) outside the shear-reinforced zone. Fig. 3 presents the crack patterns of the slabs SB1 and SB4 on the tension surface at failure.

Table 1. Material properties of the slabs

	Concrete				Steel			
Slab	**f'_c (MPa)**	**f'_t (MPa)**	**G_f (N/mm)**	**E_c (MPa)**	**f_y (MPa)**	**f_t (MPa)**	**E_s (MPa)**	**$f_{y,bolts}$ (MPa)**
SB1	44	2.2	0.082	36483	455	620	200000	-
SB2 SB3 SB4	41	2.1	0.077	35217	455	620	200000	381