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Finite element implementation of punching shear behaviors in shear-reinforced flat slabs

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Abstract Punching shear reinforcement systems such as studs and stirrups are used to improve the punching shear strength of flat slabs. A three dimensional finite element model (FEM) is developed through Ansys 10 computer software, to carry out the nonlinear analysis of 16 flat-slab models with and without punching shear reinforcement. Several important parameters are incorporated in the analysis, namely the column size, the slab thickness and the punching shear reinforcement system in order to study their effects on the flat slab behavior. A parametric study was carried out to look at the variables that can mainly affect the mechanical behaviors of the model such as the change of loading types and positions and slab with openings. Good correlation is observed between the results of the proposed model and other experimental one, resulting in its capability of capturing the fracture of flat slab under punching shear behavior to an acceptable accuracy.

1. Introduction

Punching shear reinforcement is an efficient way to increase not only the strength but also the deformation capacity of slab–column connections. However, the analysis of such a connection is rather complex and includes several challenges. One challenge is the difference in performance of different types of punching shear reinforcement. Each type leads to a rather different performance, largely depending on the anchorage condition of the shear reinforcement system and the distribution of the shear reinforcement.

Moreover, the amount and the arrangement of the shear reinforcement do not only influence the performance but also define the failure mode. Consequently, the punching strength depends on various parameters that have to be investigated individually.

The following brief summary presents the main developments of research on the punching of flat slabs with punching shear reinforcement. Kinnunen and Nylander [1] developed an approach that concentrates on the mechanical properties of slabs without punching shear reinforcement at failure criteria. Moreover, it served as the basis for other researchers who implemented punching shear reinforcement. Andersson [2] introduced another approach that considers shear reinforcement. In the tests that he performed for the model validation, he used bent-up bars and continuous stirrups as punching shear

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Nomenclature

b_o	perimeter of critical section set at $d/2$
c	side length of column
d	effective depth (distance from extreme compression fiber to centroid of longitudinal tensile reinforcement)
d_g	maximum diameter of aggregate
d_{go}	reference aggregate size (16 mm)
d_t	diameter of shear reinforcement
h	slab thickness
f_c	average compressive strength of concrete (measured on cylinders)
f_y	yield strength of flexural reinforcement
f_{yt}	yield strength of shear reinforcement
h	slab thickness
h_t	stud length, length of vertical branch of stirrup
n_r	number of radii of shear reinforcement
n_s	number of shear reinforcements per radius
q	punching shear distributed load
S_o	distance measured with respect to slab plane between border of support region and first shear stud
S_1	distance measured with respect to slab plane between two adjacent studs of same radius
S_t	distance measured with respect to slab plane between two adjacent vertical branches of stirrups
V	punching shear concentrated load
w	vertical displacement
Δh	change in slab thickness
Δw	vertical displacement due to shear deformations at column face
ε_t	strain in shear reinforcement
ρ	flexural reinforcement ratio
ρ_t	shear reinforcement ratio
ψ	maximum slab rotation

reinforcement. Hawkins [3] published a paper presenting an overview of tests performed with different punching shear reinforcement systems such as steel heads, bent-up bars, and stirrups. He concluded that shear reinforcement increases the punching strength even for small slabs and that the detailing is crucial to increase the strength and to avoid undesired failure modes. Dilger and Ghali [4] focus on improving existing shear reinforcement systems, which were at this time generally bent-up bars or different types of stirrups. They found that the anchorage conditions of the shear reinforcement are crucial. This research was accompanied by the development of the shear friction model that was first developed for shear in beams as illustrated by Loov [5], Tozser [6], and later applied for slab–column connections as indicated by Dechka [7] and Birkle [8]. Shehata [9], Shehata and Regan [10], and Shehata [11] developed a model for slabs without shear reinforcement that was based on the approach of Kinnunen and Nylander. Gomes and Regan [12,13] extended Shehata's model by implementing the contribution of the shear reinforcement. Further research has been conducted by Regan and Samadian [14] and Oliveira et al. [15] who continued their work leading to several recent publications introduced by Trautwein et al. [16] and Carvalho et al. [17] about punching tests with shear reinforcement. Chana and Desai [18] and Chana [19] performed an extensive experimental campaign of punching shear tests with shear reinforcement. Thereby, they tested slabs with conventional shear links and slabs with a special shear reinforcement system consisting of links welded together to a cage (known as "shearhoop" system). Broms [20,21] presented a further development of the model of Kinnunen and Nylander and introduced a combination of stirrups and bent-up bars as punching shear reinforcement. In 2005, he summarized a main part of his earlier work in his dissertation treating design methods for punching of flat slabs and footings with and without shear reinforcement; Broms [22]. The research group of Hegger, Hegger et al. [23], Hegger et al. [24], Hegger et al. [25], Hegger et al. [26], Siburg and Hegger [27] performed extensive experimental research on punching of flat slabs and foundations and thoroughly investigated the structural behavior of slabs with and without punching shear reinforcement. With respect to punching of slabs with punching shear reinforcement, the dissertations written by Beutel [28] and Hausler [29] contributed largely to the understanding of the flat slab behavior. Other recent experimental research has been performed by Vollum et al. [30] in which the arrangement of the punching shear reinforcement was investigated. Ruiz and Muttoni [31] introduced a physical model based on critical shear crack theory (CSCT) that allows one to estimate, on a rational basis, the contributions of concrete and of shear reinforcement to the punching shear strength. This approach allows to account for the layout of shear reinforcement as well as the diameter, bond conditions, reinforcement ratio, and other mechanical and geometrical parameters. Ruiz et al. [32] performed extensive research on the results of an experimental campaign on 16 flat-slab specimens with and without punching shear reinforcement. The tests aimed to investigate the influence of a set of mechanical and geometrical parameters on the punching shear strength and deformation capacity of flat slabs supported by interior columns. The test results were compared with reference to design codes (ACI 318-08 and EC2) and the mechanical model of the critical shear crack theory (CSCT). Micallef et al. [33] introduced an analytical model based on the critical shear crack theory which can be applied to flat slabs subjected to impact loading. This model is particularly useful for cases such as progressive collapse analysis and flat slab–column connections subjected to an impulsive axial load in the column.

The objective of the current paper was to demonstrate a proposed analytical finite element model of flat slab structures to estimate the initiation of punching shear failure of tested specimens produced by Ruiz et al. [32], through Ansys 10. The analytical model and the results of system level study can be of interest in assessing progressive collapse resistance of existing structures that contain flat slabs with interior columns and in design of new structures.