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ORIGINAL ARTICLE

Punching strengthening of two-way slabs using external steel plates

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Abstract An experimental and analytical study on the punching strengthening of reinforced concrete two-way slabs using external steel plates is presented. Five reinforced concrete square slabs of 100 mm thickness were tested over simply supported four sides of 1000 mm span under central square patch load of 100 mm size up to failure. One control slab was tested without strengthening; however, four tested slabs were strengthened using four configurations of square steel plates provided with steel anchor shear studs. Such configurations considered two different plate thickness, two plate side dimensions and different arrangement and diameter of shear studs. The strengthened four slabs showed improved stiffness and punching shear capacity. The magnitude of improvement depended on the plate dimensions and the studs diameter and arrangement. An analytical approach was proposed for predicting the punching shear strength increase due to using the strengthening steel plate. The proposed approach was applied to the tested specimens with the use of the punching shear strength equations adopted by several codes of practice and proved to be in good agreement with the test results. Generally, this research presented a practical strengthening concept that can be used to increase the punching shear capacity of two-way slabs.
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1. Introduction

Reinforced concrete flat slabs are widely used as a flooring system for multistory structures such as office buildings, warehouses and parking garages. Flat slabs are typically directly supported on columns either with or without the use of drop panels and/or column capitals providing aesthetically and functionally pleasing clear space without the obstruction of drop beams. The slab–column connection is the most critical part of this structural system due to its vulnerability to the brittle and sudden punching shear failure. This type of failure is also possible where the columns are supported on the slab or high concentrated loads exist due to special installations. In normal design situations, this type of failure is avoided by proper selection of slab thickness, column capital and optional special shear reinforcement. Several research studies have been reported on the punching shear strength of reinforced concrete slabs with or without special shear reinforcement [1–5]. However, insufficient punching shear capacity due to several reasons, such as changing the use of a building, adding new installations or design/construction mistakes, provides the need to strengthen existing structures. In recent decades, a significant amount of

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research work has been conducted to study several punching shear strengthening techniques. Generally, the common strengthening methods include the use of steel plates or fiber reinforced polymer (FRP) composites externally bonded to the slab tension face, or the use of vertical steel bolts or FRP rods.

Ebead and Marzouk [6] conducted an experimental research on strengthening two way reinforced concrete slabs subjected to punching loading using steel plates and steel bolts. Different plate arrangements and different number of bolts were considered in the study. The combined action of the steel plates and bolts transferred the mode of failure of the slab from a ductile punching shear mode of failure to a flexural mode of failure. Gains in the ultimate load of the specimens ranging from 36% to 65% were obtained depending on the plates arrangement and the used number of bolts. Another experimental study by Sim and Oh [7] showed that using externally bonded steel plates to strengthen reinforced concrete bridge deck panels subjected to punching loads substantially increased the load carrying capacity and the flexural stiffness.

An experimental study was conducted by Chen and Li [8] on strengthening reinforced concrete slabs for punching shear using glass FRP (GFRP) laminates externally bonded to the concrete surface. They concluded that the GFRP laminates significantly increased the punching shear capacity of slab–column connections because the laminates substantially functioned as external reinforcement. They also concluded that the use of GFRP laminates may change the flexural punching failure into brittle punching shear failure for lightly reinforced slabs. Similar findings were reported by Taouche-Kheloui et al. [9] who used carbon FRP (CFRP) patches to strengthen reinforced concrete slabs. Soudki et al. [10] studied the effect of strengthening the interior reinforced concrete slab–column connection subjected to punching shear using CFRP strips. The considered variables were the configuration and the amount of CFRP strips externally bonded to the tension face of the slab. The study revealed that the increase in the punching shear capacity of the tested slabs due to the use of CFRP strips was up to 29% depending on the configuration and orientation of the CFRP strips. The amount of the CFRP strips did not significantly increase the punching capacity of the slabs. They also reported up to 80% increase in the stiffness of the strengthened slabs compared with the unstrengthened one.

Sissakis and Sheikh [11] developed a then innovative technique for strengthening reinforced concrete slabs subjected to punching shear using FRP laminates. Their technique involved reinforcing the slab in the vicinity of the column with FRP laminates through an elaborated pattern of vertical holes. Conceptually, the slab was stitched with FRP fabric and the holes were filled with epoxy. They presented an extensive experimental program studying the effect of the holes pattern and the amount of the CFRP used to strengthen a reinforced concrete slab. They concluded that the slab specimens retrofitted with CFRP laminate shear reinforcement demonstrated a substantial increase in shear strength, ductility and energy dissipation capacity. Shear strength increase of over 80% and enhancement of ductility of over 700% were observed. Meisami et al. [12] conducted experimental tests on reinforced concrete slabs strengthened for punching shear using steel bolts and CFRP rods. They reported 17% and 20% increase in the shear capacity for slabs strengthened with 8 CFRP rods and 8 steel bolts respectively. For slabs strengthened with 24 CFRP rods, up to 67% increase in shear capacity was obtained. The use of either prestressed or non-prestressed steel shear studs to repair damaged flat plates as a result of punching shear was experimentally studied by Asker [13,14]. He concludes that the adopted technique was efficient in improving the punching shear strength of the damaged slabs and that the strength of the repaired slabs could exceed the original strength depending on the number of studs.

Several analytical equations are proposed for calculating the punching shear capacity of reinforced concrete slabs. Some of these equations consider only the concrete dimensions and strength, ignoring the flexural reinforcement ratio, as adopted by the American code ACI 318-14 [15] and the Egyptian code ECP 203-2007 [16]. Other equations account for the effect of the flexural reinforcement as well as the concrete dimensions and strength such as the equations adopted by the British standards BS8110-1985 [17], the Eurocode 2-2004 [18] and the Japanese code JSCE-1986 [19], and the equation presented by Moe [20].

Several attempts have been made to analytically estimate the punching shear capacity of strengthened reinforced concrete slabs. Some researchers adopted the finite element method [21]. Others opted for simplified methods based on dividing the punching shear capacity into two components. The first component is the contribution of the original reinforced concrete slab which is typically calculated using the equations proposed by design codes [6,8,10,22,23]. The second component is the contribution of the strengthening steel or FRP plates which is calculated using two main approaches. The first approach was based on the effect of the strengthening plate on increasing the effective flexural reinforcement ratio, which could equally be applied to slabs strengthened using FRP laminates, and consequently indirectly increasing the punching shear capacity [8,10]. The second approach, additionally, considered the contribution of the strengthening plate to the punching shear capacity by directly resisting the punching failure mechanism [6,22]. Two methods were reported by researchers for calculating this direct contribution. The first method was based on assuming that the concrete slab and the steel plate function together as a composite section and, therefore, an equivalent depth for the composite section is used for calculating the height of the punching failure surface [6]. The second method, proposed by Oh and Sim [22], was generally based on assuming that the contribution of the strengthening plate to the shear strength resulted from the pull-out strength of the shear studs used to anchor the plate to the concrete slab.

In this research, strengthening two way slabs for punching shear using externally bonded steel plates with anchor shear studs at the tension face of slab was studied. One control specimen without strengthening and four strengthened specimens using different plate sizes, shear stud numbers and stud diameters were experimentally tested. Analytical predictions for the punching shear capacity using simplified approaches were calculated and compared with experimental results.

2. Experimental program

2.1. Test specimens

Five simply supported square reinforced concrete slabs subjected to punching loading were fabricated and tested in the current experimental program. The main objective of the

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