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Punching-shear behavior of slabs with bar truss shear reinforcement on rectangular columns

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ABSTRACT

In this study, punching-shear tests were performed to investigate the behavior of slabs supported by rectangular columns with capital. The slabs were subjected to an uneven shear transfer in two orthogonal directions by using the rectangular columns and different span lengths. Column capitals were used at the slab-column joints and preassembled bar trusses were placed at the periphery of the column capital to enhance the punching-shear capacity. Furthermore, the corners of the rectangular column and column capital were rounded to alleviate the shear stress concentration at the corners of the critical perimeter for shear. The test results show that the punching-shear strength of the slabs were significantly enhanced by the bar trusses. The shear resistance of the bar trusses was mostly contributed by the diagonal bars undergoing significant strains. On the basis of the results, the effects of the uneven shear transfer and bar truss arrangement on the slab shear behavior were investigated. In addition, the punching-shear strengths predicted by ACI 318-14, Eurocode 2, and KCI 2012 were compared with the test strengths.

1. Introduction

Fig. 1 shows a flat-plate system for underground parking garage in which cast-in-place reinforced concrete (RC) slabs are supported by precast concrete (PC) columns with capital. In the flat-plate system, the PC columns are erected on the lower floor slab by bolting, and the bolt joints are then covered with cast-in-place concrete for protection. At the top of the PC columns, column capitals are placed to increase shear resistance against punching. Finally, cast-in-place RC slab for the upper floor is constructed on top of the PC column capitals. Fig. 1a shows a prototype floor plan for the proposed flat-plate system. The PC columns and capitals have rectangular sections because the flat plate slab has different spans in two orthogonal directions. Such rectangular columns and column capitals are beneficial in reducing the effective span length along the long-span direction, thereby decreasing negative design moments near the columns. Furthermore, the rectangular columns and column capitals are rounded at the corners to relax shear stress concentration.

Generally, the flat plate system is vulnerable to punching-shear failure. Particularly, previous studies have shown the following limitations with respect to the punching-shear strength of the slabs supported by rectangular columns or column capitals [1–4].

(1) Generally, the distribution of concrete shear stresses around the perimeter of a column or column capital is not uniform. This indicates that higher shear stresses are transferred through the corners of the column or column capital rather than the sides. Such uneven shear stress transfer becomes more significant in a slab supported by rectangular columns or column capitals, because the shear stress along the longer sides of the column or column capital is less than that at the corners. Thus, the punching-shear strength of the slab might be affected by the rectangularity of the supporting columns and column capitals.
(2) In Fig. 1a, bending moments and shear forces at the shorter sides of the column and column capital are greater than those at the longer sides because the slab span along the vertical direction is longer. Thus, flexural/shear cracking of the slab occurs earlier near the shorter sides. This indicates that if shear transfer along the both orthogonal directions is unsymmetrical, the punching-shear resistance of shear reinforcements can be affected by their locations and arrangements.

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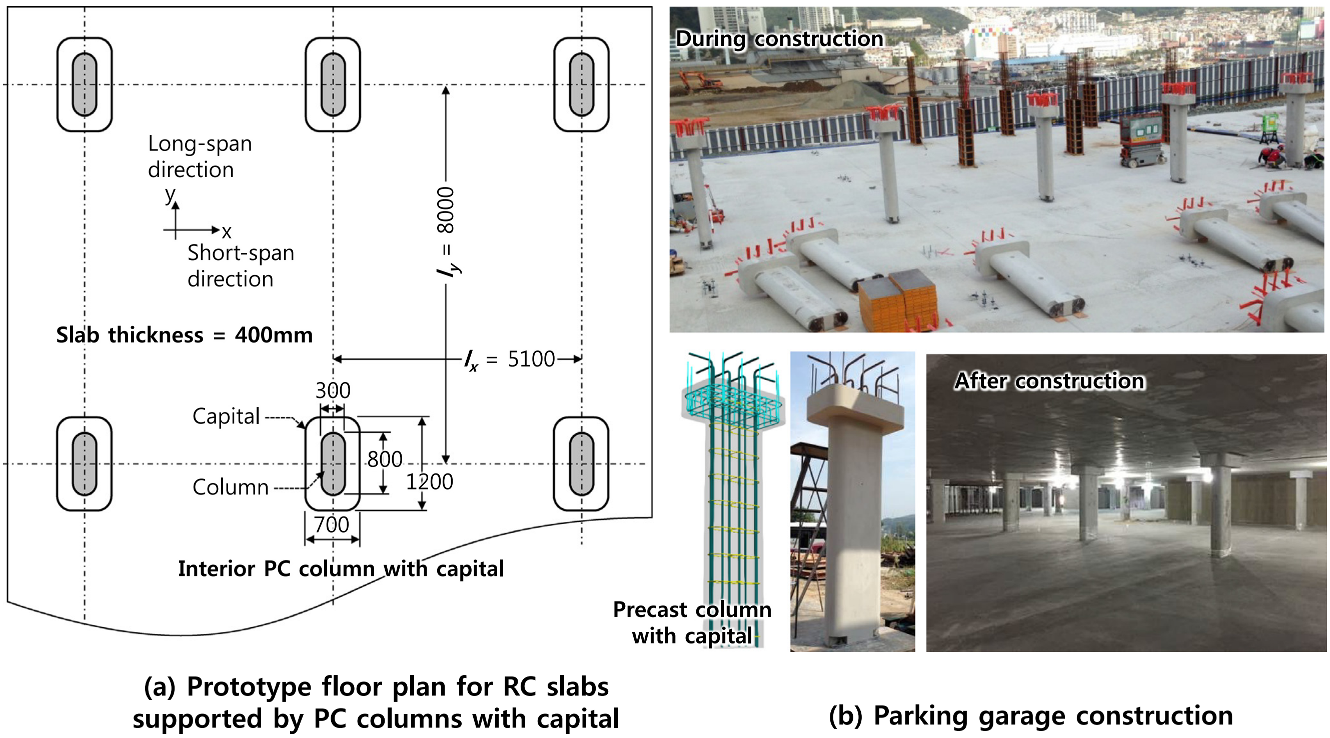

Fig. 1. Cast-in-place RC slab – PC column construction for flat-plate system.

The effects of the column rectangularity on the slab punching-shear strength have been considered in ACI 318 [5] and Eurocode 2 [6]. For example, in ACI 318-14, the punching-shear strength carried by concrete (V_c) is defined as the minimum of $0.33\sqrt{f_c'}b_od$, $0.33(0.5 + 1/\beta)\sqrt{f_c'}b_od$, and $0.33(0.5 + 0.25\alpha_sd/b_o)\sqrt{f_c'}b_od$, where f_c = compressive strength of the concrete, b_o = length of the critical shear perimeter, d = effective depth of the slab, β = ratio of the long side-to-short side dimensions of the column, and α_s = a coefficient considering the concentration of shear stresses at the corners of the critical shear perimeter in large columns with $b_o/d > 20$ ($\alpha_s = 40$ for interior columns). In these equations, if the column rectangularity and the shear-stress concentration at the corners are significant (i.e., $\beta > 2.0$ and $d/b_o > 20$) the maximum value of V_c is limited by β and α_sd/b_o. On the other hand, in Eurocode 2 [6], the control perimeter b_o is determined at a distance $2d$ from the column face or column capital face where the shear stress concentration is significantly reduced. This indicates that coefficients such as β and α_sd/b_o are not necessary for Eurocode 2. The column rectangularity is not considered in KCI 2012 [7], either.

Thus, the primary objective of the present study is to investigate the effects of the uneven shear transfer around rectangular columns on the slab punching-shear strength.

Another objective of the present study is to verify the effects of preassembled bar trusses on the punching-shear strength and failure mode of the slab. Stirrup-type shear reinforcements such as single-leg, multi-leg, and closed stirrups have been successfully used [8]. However, it is difficult to place the stirrups within thin slabs due to bar intervention because anchorage hooks are required to engage the top and bottom flexural reinforcing bars. Hence, preassembled bar trusses can be used as an alternative slab shear reinforcement for easier bar placement [9–11]. The bar trusses consist of the top/bottom chord bars and crossing diagonal bars, as shown in Fig. 2. The shear resistance of the bar trusses is contributed by the diagonal and vertical bars crossing shear cracks. By welding with the top/bottom chord bars, the anchorage capacity of the shear-resisting diagonal and vertical bars can be enhanced. These preassembled bar trusses are placed on top of the bottom slab flexural bars without engaging the slab bars. Thus, bar placement is very convenient.

In the present study, punching-shear tests were performed to investigate the shear behavior of the slabs supported by rectangular columns. By using different span lengths in both orthogonal directions, the slabs were subjected to an uneven shear transfer. To enhance the punching-shear strength, the column capitals were used at the slab-column joints and the preassembled bar trusses were placed around the column capitals. From the test results, the effects of the column rectangularity and bar trusses on the punching-shear behavior were investigated. In addition, the punching-shear strengths predicted by ACI 318-14, Eurocode 2, and KCI 2012 were compared with the test strengths.

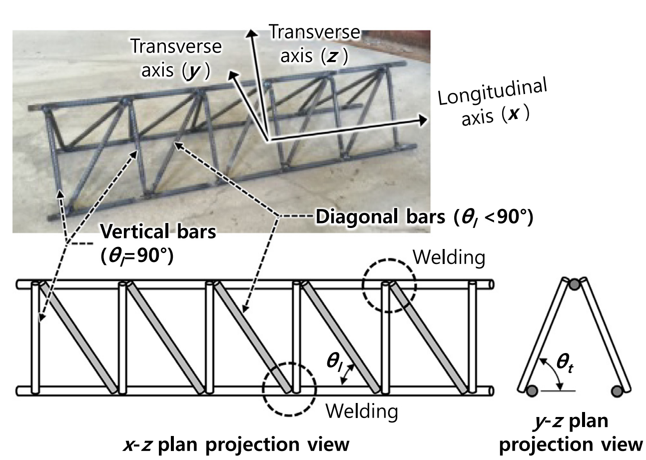

Fig. 2. Bar truss for shear reinforcement of slabs.