Experimental investigation of reinforced concrete slabs with punching shear reinforcement

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Abstract
Over the past century, the use of flat slabs in buildings and especially in parking garages has been growing as it is an economic and efficient solution. Flat slabs are easy to build and have, through their smaller depth, an economical and architectural advantage compared to slabs on girders. Because of their limited depth, flat slabs are especially sensitive to deflections and to punching shear, which are their main design criteria. Furthermore, flat slabs without punching shear reinforcement have a rather brittle failure mode with little deformation capacity. This behavior potentially limits the redistribution of the internal forces in flat slabs in the case of punching of an isolated column and can thus lead to progressive collapse of the entire structure. To increase both the strength and the deformation capacity of flat slabs, punching shear reinforcement can be provided in the vicinity of the columns. Although the influence of punching shear reinforcement on the strength of flat slabs has been intensively investigated, there are still fundamental uncertainties such as the contribution of the shear reinforcement and the strength of the concrete struts close to the column.

The paper presents the results of an extensive experimental campaign performed at the Ecole Polytechnique Fédérale de Lausanne (EPFL). Sixteen full-scale slab specimens (3.0 x 3.0 m in plane) with varying parameters such as the column size, the slab thickness, the shear reinforcement ratio, and the shear reinforcing system have been investigated. The performance of these specimens is analyzed and compared to modern design codes and to the critical shear crack theory.

1. Introduction

Punching shear reinforcement improves the strength and the rotation capacity of flat slab-column connections significantly. It is an efficient method to enhance the rotation capacity of the flat slab-column connection, which is rather brittle without transverse reinforcement. Additionally, compared to slabs without transverse reinforcement, the strength of the connection increases due to the provided shear reinforcement within the critical section. However, in presence of shear reinforcement, other failure modes can occur. Figure 1 shows possible failure modes of flat slabs with punching shear reinforcement such as failure of concrete struts close to the column, failure within the region of the shear reinforcement, failure outside the shear reinforced region, or failure between the transverse reinforcement [1]. Each of these failure modes needs to be investigated independently.

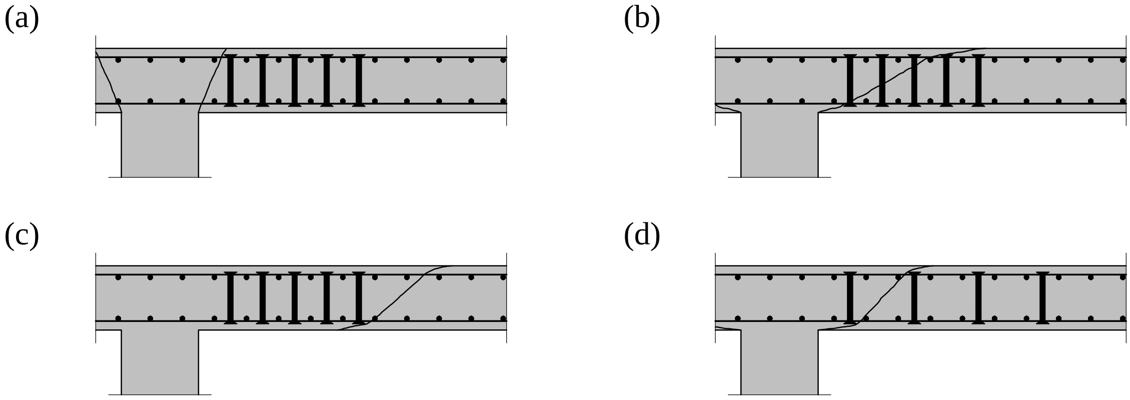

Figure 1: Possible failure modes of flat slabs with punching shear reinforcement: (a) failure of concrete struts close to the column; (b) failure within the region of the shear reinforcement; (c) failure outside the shear reinforced region; and (d) failure between the transverse reinforcement

This research focuses on the failure of the concrete strut close to the column (Figure 1a) and within the region of the shear reinforcement (Figure 1b). Current codes are mostly based on empirical approaches with respect to such failure modes. To improve this, a new promising approach based on the critical shear crack theory CSCT has been developed by Fernandez and Muttoni [1]. The model has shown a good agreement with existing test results [1]. In this paper a series of sixteen tests is presented to complement available test data and to compare the results provided by the CSCT and several codes of practice.

2. Test specimens and procedure

Sixteen full-scale slab specimens with varying parameters such as the column size, the slab thickness, the shear reinforcement ratio, and the shear reinforcing system have been investigated. All specimens were square slabs with a dimension of 3.0 x 3.0 m in plane, were supported by a square column, and had a flexural reinforcement ratio ρ_L of 1.5%. To analyze the influence of various parameters on the punching strength and the rotation capacity, the experimental campaign was divided into three series. The first series studied the influence of the column size by varying the ratio of the column size to the effective depth (c/d) from 0.62 to 2.48. The second series investigated the influence of the slab thickness, which varied from 250 mm to 400 mm whereas the ratio c/d was kept constant 1.24. The third series investigated the influence of the shear reinforcement ratio ρ_w at the critical section defined according to SIA 262 (2003) [2] (Figure 2). Additionally, series one and two have been performed with two different shear reinforcement systems: vertical shear studs and cages of continuous stirrups. Table 1 presents an overview of the main parameters of the test specimens, whereby Specimen PG1 is a reference specimen tested at the EPFL by Guandalini [3] and included in the results for completeness.

Table 1: Specimen parameters

Specimen	h [mm]	c [mm]	d [mm]	ρ_L [%]	ρ_w [%]	System
PL1	250	130 x 130	210	1.50	-	-
PL6	250	130 x 130	210	1.50	0.99	Studs
PF1	250	130 x 130	210	1.50	0.79	Cage
PG1	250	260 x 260	210	1.50	-	-
PL7	250	260 x 260	210	1.50	0.91	Studs
PF2	250	260 x 260	210	1.50	0.79	Cage
PL3	250	520 x 520	210	1.50	-	-
PL8	250	520 x 520	210	1.50	0.85	Studs
PF3	250	520 x 520	210	1.50	0.79	Cage
PL4	320	340 x 340	274	1.53	-	-
PL9	320	340 x 340	274	1.53	0.87	Studs
PF4	320	340 x 340	274	1.53	0.79	Cage
PL5	400	440 x 440	354	1.50	-	-
PL10	400	440 x 440	354	1.50	0.79	Studs
PF5	400	440 x 440	354	1.50	0.79	Cage
PL11	250	260 x 260	210	1.50	0.23	Studs
PL12	250	260 x 260	210	1.50	0.47	Studs

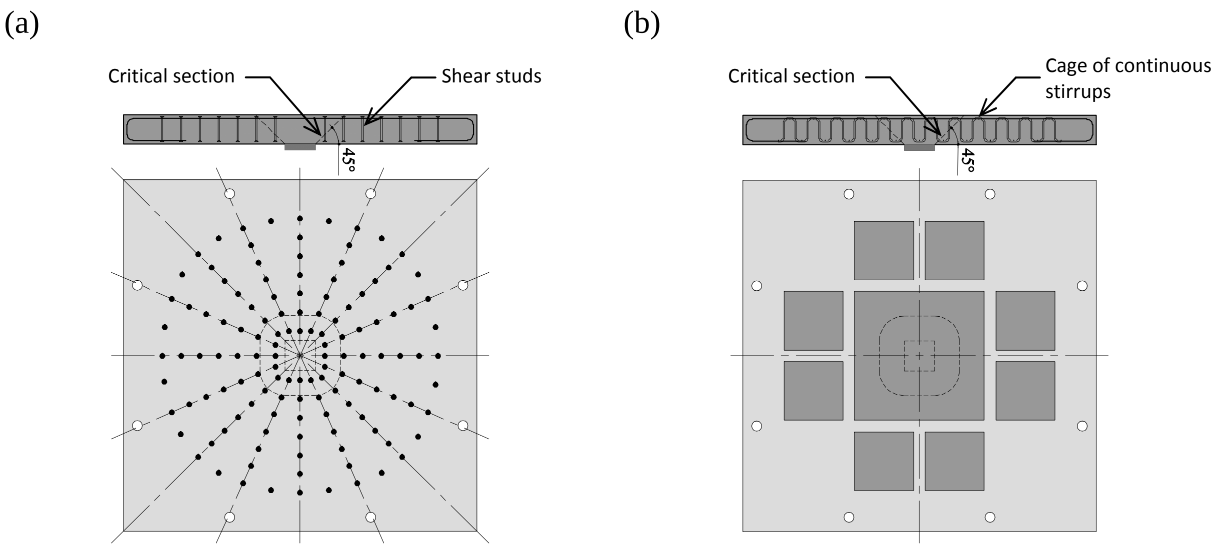

Figure 2: Definition of the critical section and shear reinforcement layouts: (a) shear studs and (b) cage of continuous stirrups

The applied force was introduced by four hydraulic jacks underneath the strong floor. Four tension bars running through the floor were connected to four steel spreader beams, which distributed the load to eight tension bars. These bars applied the downward force on the top surface of the slab. The slab was supported by a square steel plate corresponding to the column size.

3. Test Results

During the experiments, continuous measurements have been recorded such as the slab's rotation, displacements and surface deformations, and the strains in the shear reinforcement. Figure 3 shows the load-rotation curves of selected specimens.

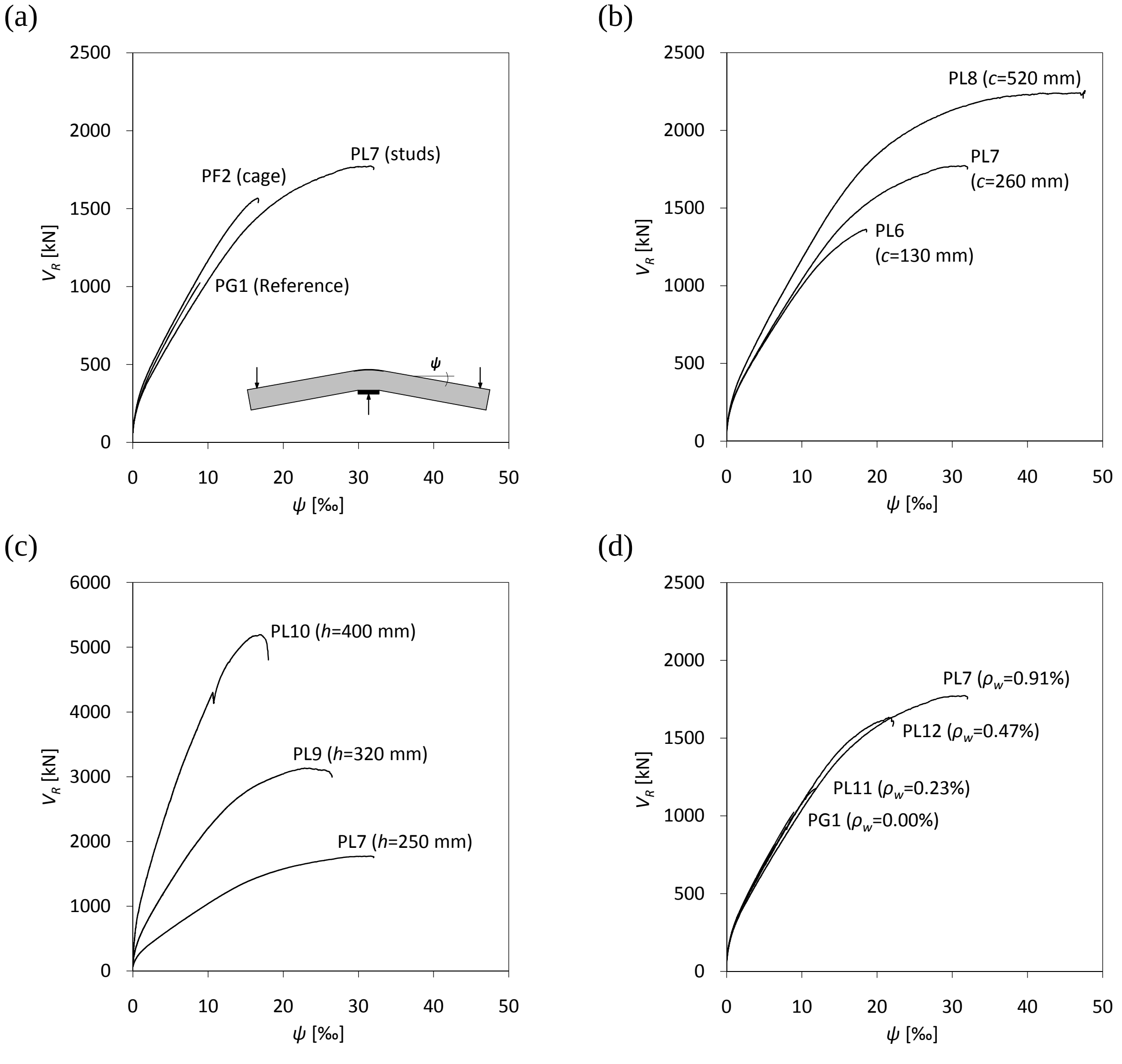

Figure 3: Load-rotation curves of selected specimens: (a) varying the shear reinforcement system; (b) varying the column size *c*; (c) varying the slab thickness *h*; and (d) varying the shear reinforcement ratio ρ_w

Figure 3a shows the performance of slabs with and without punching shear reinforcement. Punching shear reinforcement evidently increases the strength and the rotation capacity of the slab depending on the shear reinforcement system. The slab with shear studs behaves in a more ductile manner and reaches a slightly higher strength than the one with cages of continuous stirrups. Figure 3b shows the performance of the slab for different column sizes. As expected, as larger the column is as larger the strength and the rotation capacity of the slab. Slab PL8 even reached its flexural strength and no punching failure occurred despite large rotations. Figure 3c shows the performance of the slab for different slab thicknesses. While the strength of the slab increases, the rotation capacity decreases due to the stiffer load-rotation behavior of the slab. Figure 3d shows the performance of the slab for various amounts of shear reinforcement. Even a small amount of shear reinforcement increases the strength and the rotation capacity of the slab.

4. Discussion of the test results

Except for slab PL8, which reached its flexural strength, slab PL11, and slab PL12, which both had a failure within the shear reinforced region; all specimens had a failure of the concrete strut close to the column. Therefore, the ultimate load is compared to the corresponding failure formulation of the codes SIA 262 (2003) [2], ACI 318 (2008) [4], EN EC2 (2004) [5], and the critical shear crack theory [1]. Figure 4 shows the ratio of the punching shear strength of the test to the theoretical value in function of the shear reinforcement ratio ρ_w at the critical section defined according to SIA 262 (2003) [2], whereby slab PL8 is not shown as it did not fail in punching.

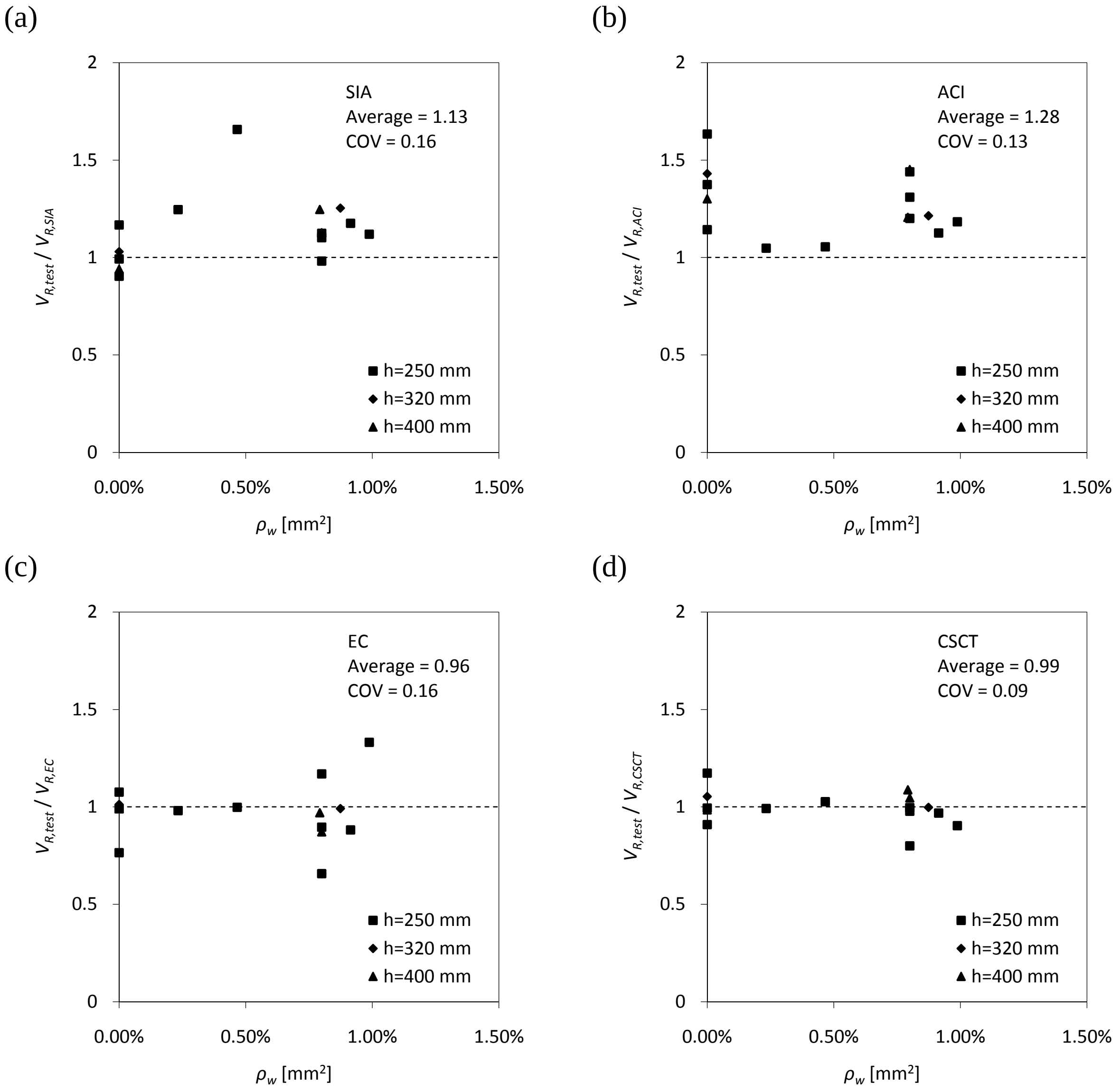

Figure 4: Ratio of V_{test} to V_{theory} for different models in function of the shear reinforcement ratio ρ_w at the critical section defined according to SIA 262 (2003) [2]: (a) SIA; (b) ACI; (c) EC; and (d) CSCT; COV=Coefficient of variation

In case of crushing of the concrete strut, SIA 262 (2003) [2] achieves good agreement with the test results. However, in case of failure within the shear reinforced region SIA 262

(2003) [2] clearly underestimates the strength because it neglects the shear strength of the concrete. ACI 318 (2008) [4] underestimates the strength for the specimens with and without shear reinforcement and for both failure modes. Additionally, it leads to scattered results. EN EC2 (2004) [5] leads to similar scattered results as ACI 318 (2008) [4]. However, it overestimates the strength for several specimens. The CSCT leads to the best agreement with the test results. For the CSCT calculations, the following assumptions were made: The crushing strength parameter λ was chosen to be 3 for the studs and 2.5 for the cages of continuous stirrups [1]. For calculations using the CSCT, a quadrilinear moment-curvature relationship, proposed by Muttoni [6], was used for the load-rotation behavior of the slab.

5. Conclusions

The tests presented indicate that shear reinforcement increases both strength and rotation capacity of flat slab-column connections. By using vertical shear studs, the strength is up to twice and the rotation capacity more than three times as large as that of slabs without shear reinforcement. The increase in strength and rotation capacity depends on various factors, mainly on the amount of provided shear reinforcement and the punching shear reinforcement system. Vertical shear studs perform better than cages of continuous stirrups. The comparison with current design models shows that generally codes of practice lead to either conservative (SIA 262 (2003) [2], ACI 318 (2008) [4]) or to scattered (ACI 318 (2008) [4]) and even unsafe results (EN EC2 (2004) [5]). The critical shear crack theory shows a good agreement with the test results.

6. References

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