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PUNCHING SHEAR STRENGTH OF PC SLABS

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Abstract

This paper presents the results of an experimental research on the influence of prestressing on the punching shear strength of flat slabs. The tests refer to 13 geometrically identical specimens 250 mm thick that were loaded in order to investigate the influence of bending moments (due to prestressing eccentricity), normal forces and bonded tendons on the strength and behaviour of flat slabs. The tests show that the three effects have a significant influence and should be incorporated in design provisions, although some codes neglect the influence of some of these phenomena.

Keywords: Flat Slabs, Model Code 2010, Prestressing, Punching Shear, Slab Bridges

1 Introduction

A large number of bridges in Europe with span lengths up to 35-40 meters correspond to prestressed slabs supported by columns. This kind of structure is economical, allows easy fitting to variable width or slope of the bridge and leads to relatively slender decks (with enhanced clearance under the bridges). Design of these bridges is governed by the allowable deflections under service loads as well as by their bending and punching shear strength at ultimate.

Prestressing has shown to be an effective manner of ensuring suitable behaviour both for serviceability and ultimate limit states. Design for bending (strength and deflections) accounting for prestressing effects can be performed on a consistent basis by introducing for instance prestressing deviation forces or by considering imposed strains in the tendons. On the contrary, no general agreement is available on the influence of prestressing on the punching shear strength (which normally depends on the physical model or empirical equation grounding the punching shear design expressions) and on its governing parameters (average compressive stress, bending moments due to the prestressing tendons, rotations at the failure region…)

In this paper, the results of an experimental programme performed at Ecole Polytechnique Fédérale de Lausanne (Switzerland) on 13 RC slabs 250 mm thick and failing in punching shear are presented. The tests were designed to reproduce the different effects originated by prestressing on slab bridges: uniform compressive stresses (6 specimens), bending moments (4 specimens) as well as a combination of these effects by means of bonded post-tensioned tendons (3 specimens). The results are used to identify the influence of these phenomena on the punching shear strength.

2 Testing program

Three test series with a total of 13 specimens were performed with the aim to investigate separately the various effects of prestressing. To do so, the geometrical parameters of the slabs were kept constant (3000 x 3000 x 250mm). In addition, only two longitudinal (bending) reinforcement ratios (ρ) were used: 0.75% and 1.50%. The varying parameters are those from prestressing. In the first test series (PC1-4), in order to simulate prestressing eccentricities, slabs were subjected to a moment without normal force (by means of a couple of vertical forces introduced in the specimens, m_p = 75kN.m/m and 150kN.m/m for ρ =0.75% and 1.50%) as shown in Figure 1a for nominal values.

In the second test series (PC5-10), slabs were subjected to a normal in-plane compression force without any moment. The longitudinal reinforcement ratio was 0.75% or1.50% and the amount of normal in-plane compression stress were 1.25, 2.50 and 5.00 MPa as represented in Figure 1b for nominal values (the compressive stress was applied by means of prestressing bars arranged outside the specimens).

The last test series (PC11-13) consisted on three specimens having eccentric prestressing tendons (combined moment and axial compression force) with a longitudinal reinforcement ratio kept at 0.75%. The nominal parameters are also shown on Figure 1c.

In addition, two references specimens with same geometry and mechanical properties will be used in the following for comparisons, test PG19 (nominal ρ =0.75%) and PG20 (nominal ρ =1.5%).

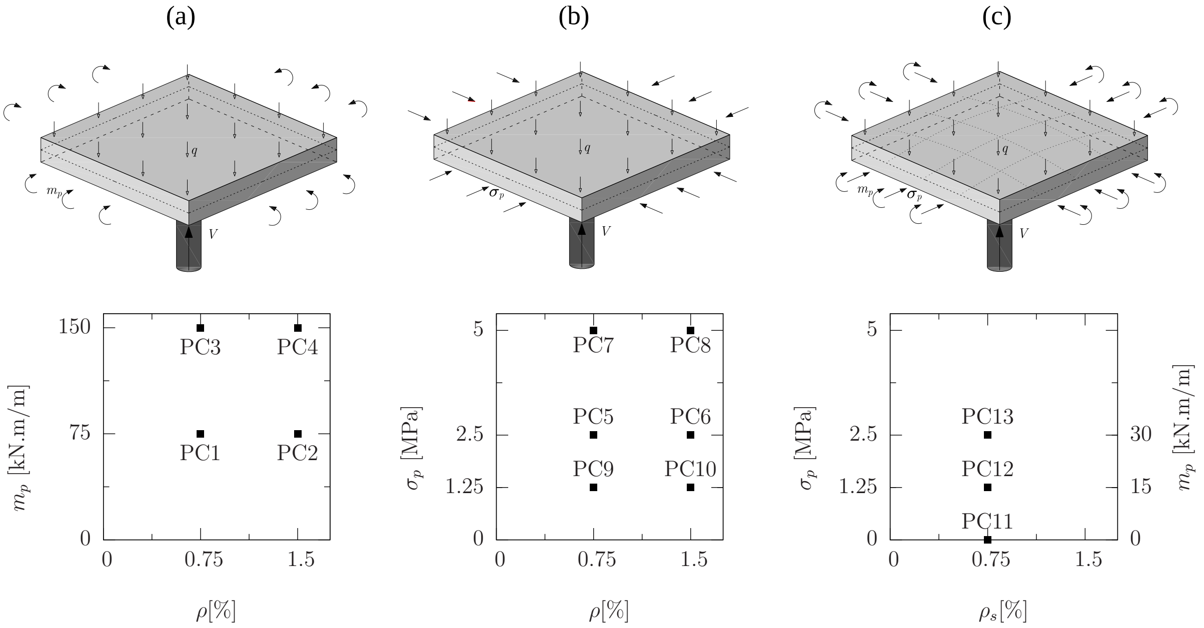

Fig. 1 Test parameters for series: (a) PC1 to PC4, (b) PC5 to PC10; and (c) PC11 to PC13

All specimens were cast with normal strength concrete with a maximum aggregate diameter size of 16 mm and a water-cement ratio varying between 0.54 and 0.56. The concrete compressive strength was measured on cylinders the day of testing (values are summarized in Table 1). The top flexural reinforcement was made of hot-rolled steel for whose yield strengths are also given in Table 1. The prestressing tendons consisted in monostrand with characteristic tensile strength $f_{p,k}$ = 1860 MPa. For more details, refer to Table 1.

For the three test series, the test setup varied. In the first test series (PC1 to PC4), a moment and a shear force had to be introduced. In the second test series (PC5 to PC10), a normal in-plane compression and a shear force had to be introduced. In the last test series (PC11 to PC13), the slabs used prestressing tendons and where subjected to shear force as well as for the two other test series, refer to Figure 1. More details can be found in Clément and Muttoni (2010).

3 Testing results

Figure 2 shows the load-rotation curves for slabs PC1 to PC4 (influence of bending moments) compared with reference slabs PG19 (ρ = 0.75%) and PG20 (ρ = 1.50%), where the rotation (ψ) is given at the edge of the slab. The moment does not significantly influence the tangent stiffness of the specimen after cracking, the load-rotation curves for slabs with the same longitudinal reinforcement having approximately the same slope. The applied moment tends to increase the punching shear strength (Fig. 2a) and to reduce significantly the rotation (deformation capacity) at failure for both flexural reinforcement ratios.

An increasing normal in-plane compressive stress tends to increase punching shear strength (Fig.

3a), but the failure rotations do not seem to be affected (Fig. 3b). For both longitudinal reinforcement ratios, failure rotations are comparable to reference slabs rotations.

Slabs PC11 to PC13 use prestressing tendons, in addition to longitudinal reinforcement. In slab PC11, tendons were not prestressed. In the other two specimens, tendons were prestressed at two different levels (Table 1). It can be observed first that the stiffness in the cracked phase is somewhat higher than for the reference slab. This is due to the fact that slabs PC11 to PC13 have the same longitudinal reinforcement as PG19, but also bonded prestressing tendons.

Table 1

Main characteristics of tested specimens (V_R and ψ_R at maximum applied load)

Slab	σ_p [MPa]	m_p [kN.m/m]	d_{eff} [mm]	f_c [MPa]	ρ_s [%]	f_y [MPa]	$f_{p,0.1}$ [MPa]	V_R [kN]	ψ_R [%]
PG19	0	0	206	46.2	0.84	607	-	860	1.21
PG20	0	0	201	51.7	1.64	659	-	1014	0.92
PC1	0	75	192	44.0	0.83	583	-	1201	0.61
PC2	0	75	192	45.3	1.63	549	-	1397	0.70
PC3	0	150	194	43.8	0.82	591	-	1338	0.21
PC4	0	150	190	44.4	1.65	602	-	1433	0.28
PC5	2.50	0	201	33.8	0.80	560	-	1141	1.20
PC6	2.50	0	203	34.7	1.54	586	-	1205	0.86
PC7	5.00	0	204	40.5	0.78	580	-	1370	1.07
PC8	5.00	0	198	41.9	1.59	528	-	1494	0.93
PC9	1.25	0	210	37.2	0.77	601	-	1105	1.21
PC10	1.25	0	208	37.5	1.51	548	-	1259	0.96
PC11	0	0	212	35.7	0.76	584	1689	919	1.04
PC12	1.25	15	210	35.8	0.77	584	1689	1129	0.95
PC13	2.50	30	207	35.2	0.78	584	1689	1058	0.74

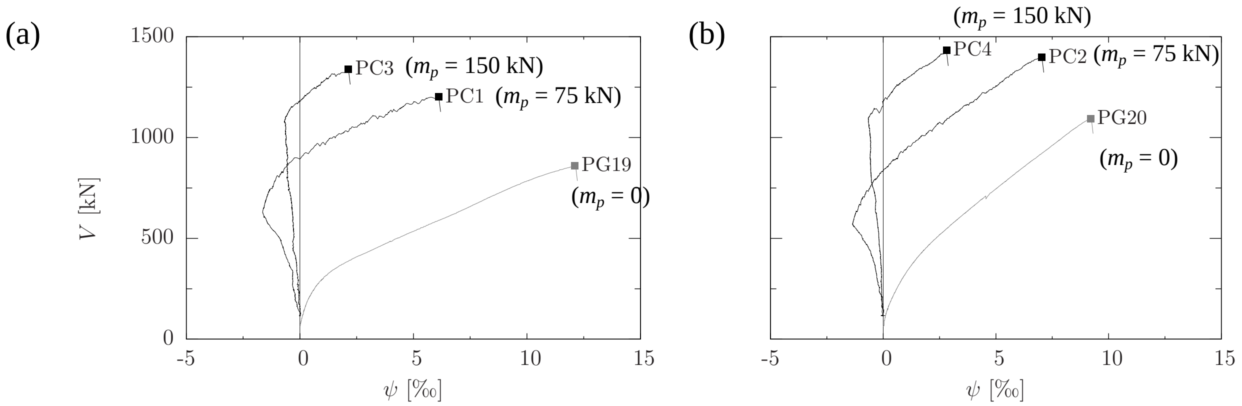

Fig. 2 Load-rotation curves for slabs PC1 to PC4 compared to reference slabs PG19 and PG20 for: (a) ρ = 0.75%; and (b) ρ = 1.50%

4 Conclusions, design implications

The tests show that the three effects due to prestressing (normal forces, tendon eccentricity, and bonded behaviour) have an influence on the behaviour (deformation capacity) and punching shear strength of a slab. On that basis, it can be stated that consistent design has to account for all of them.

Empirically-based provisions such as Eurocode 2 (2004) or ACI 318-11 (2011) do not always account for all of these effects (particularly for the tendon eccentricity) and do not necessarily lead to safe estimates of the strength. As shown in Clément (2012), other design provisions as Model Code 2010 (based on the mechanical model of the Critical Shear Crack Theory) suitably accounts for the influence of the three effects. A comparison of the performance of empirical and mechanical models (Clément 2012) shows significantly better results for the mechanical models, with lower scatter and trend-free predictions.

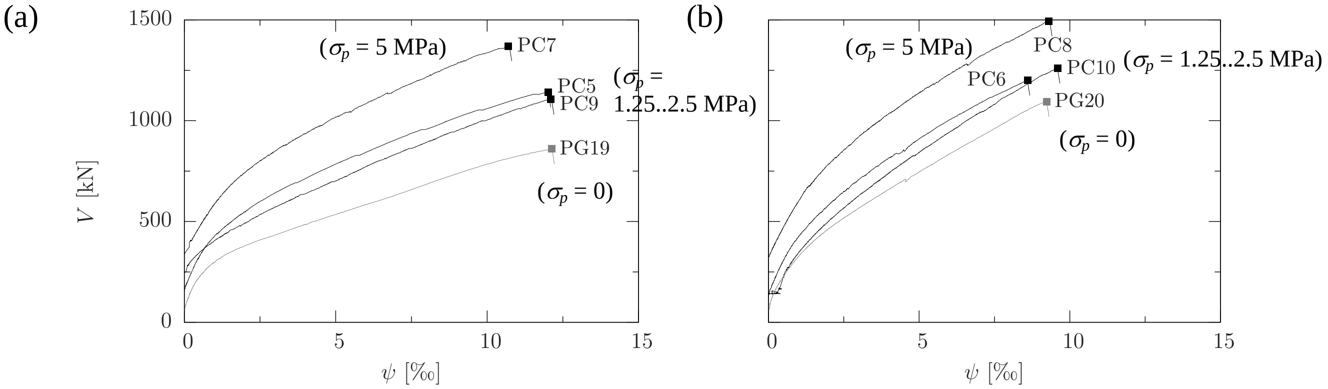

Fig. 3 Load-rotation curves for slabs PC5 to PC10 compared to reference slabs PG19 and PG20 for: (a) ρ = 0.75%; and (b) ρ = 1.50%

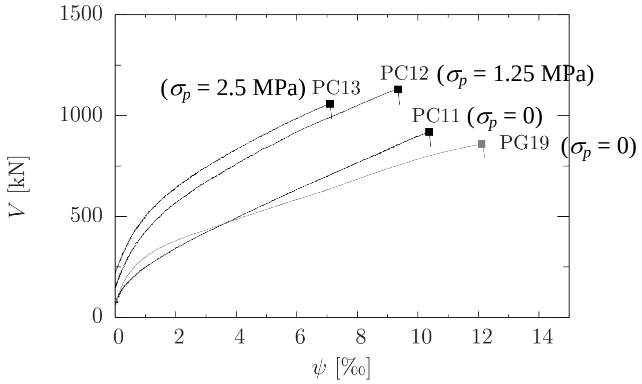

Fig. 4 Load-rotation curves for slabs PC11 to PC13 compared to reference slabs PG19

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