Engineering Structures 72 (2014) 56–69

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Influence of prestressing on the punching strength of post-tensioned slabs

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ARTICLE INFO

Article history:
Received 30 September 2013
Revised 2 April 2014
Accepted 16 April 2014
Available online 9 May 2014

Keywords:
Punching
Post-tensioned slabs
Critical Shear Crack Theory
In-plane forces
Prestressing tendons

ABSTRACT

Previous researches on punching of post-tensioned slabs have shown a number of phenomena significantly influencing their strength and behaviour. However, no general agreement is yet found on a physical theory (either in codes of practice or in design models) suitably describing the influence of prestressing and how should it be accounted on the punching shear behaviour. In this paper, the authors present the results of tests on 15 slabs (3000 × 3000 × 250 mm) tested to failure under different loading conditions. The aim of the tests was to investigate in a separate manner the different actions induced by prestressing on the punching shear strength (in-plane forces, bending moments and bonded tendons). These results are finally investigated on the basis of the physical model of the Critical Shear Crack Theory. The fundamentals of this theory are presented and adapted to post-tensioned slabs, providing a rational explanation of the observed phenomena and measured strengths.

1. Introduction

The use of prestressing is a common solution for slab bridges and for flat slabs with large spans. It is also an efficient solution for slabs subjected to significant concentrated loads, as in raft foundations. Prestressing is in this cases a suitable technique as it helps to control the deflections at the serviceability limit state and to increase the punching shear strength at ultimate. Failures by punching in these members are particularly significant as, in the absence of particular measures (such as integrity or shear reinforcement or fairly low ratios of flexural reinforcement), they are brittle and can propagate to adjacent columns (overloaded after first punching of a column) thus triggering the progressive collapse of the entire structure [1].

Previous research on punching of flat slabs [2–12] has shown that prestressing has a number of potential beneficial influences (refer to Fig. 1):

- In-plane compressive stresses developed in concrete due to prestressing lead to an increase on its capacity to carry shear forces.
- Eccentricity of the tendons which usually produces bending moments opposing those of the external actions. This leads to smaller crack openings in the failure region and thus increases the capacity of concrete to transfer shear forces.
- The vertical components of the prestressing forces of inclined tendons intercepted by the punching failure surface are in equilibrium with the deviation forces which can be directly transferred to the supported area. This component can thus be subtracted from the shear load transferred by concrete.

However, not all design codes (as ACI 318 [13], Eurocode 2 [14]) acknowledge the influence of these effects. This is due to the fact that the empirical design formulas where they are grounded only account for the influence of in-plane stresses and deviation forces, but not for the bending moments due to prestressing eccentricity. In addition, the section at which such phenomena are accounted for may significantly differ (typically ranging from a half to twice the effective depth of the slab). This location is particularly relevant for calculation of the number and inclination of the tendons contributing to carrying directly shear forces (vertical component of the prestressing force acting on the control perimeter) [2].

Although a number of experimental researches have been performed in the past on the topic of prestressed slabs, only a limited number of series analyses independently the influence of each phenomenon (deviation forces, in-plane forces and bending moments) due to prestressing. From these series, some previous works have concentrated on the influence of in-plane stresses on the punching shear strength (Moreillon [6], Regan [10] and Ramos [15]) whereas others have studied the influences of tendon arrangement and inclination (Hassanzadeh [3], Ramos [9], Silva [12]). In order to complement the available experimental data, this paper presents

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http://dx.doi.org/10.1016/j.engstruct.2014.04.034
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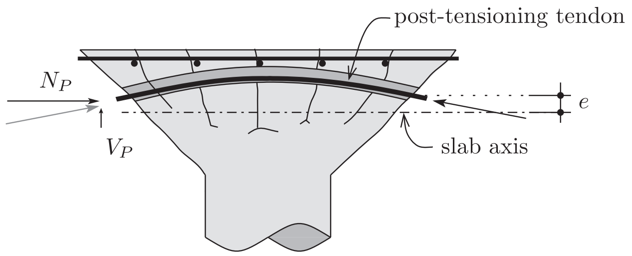

Fig. 1. Effects of post-tensioning on slab-column connections: in plane force (N_P), tendon eccentricity (e) and vertical component of tendons (V_P).

the results of three experimental series aimed at investigating the influences of moments, in-plane forces and the location of the control perimeter for assessment of prestressing effects. All tests were performed at the Ecole Polytechnique Fédérale de Lausanne (Switzerland) and comprise a total of 15 tests on 250 mm-thick slabs respectively.

On the basis of these results, and by using the principles of the Critical Shear Crack Theory (CSCT), the influences of the various parameters described above are analysed. The CSCT is shown to provide a consistent frame to account for prestressing effects and to lead to consistent predictions when compared to the test results.

2. Testing programme

2.1. Specimens

Three specific test series with a total of 15 specimens were performed with the aim to investigate separately the influence of bending moments, in-plane forces and bonded tendons on the punching shear strength. Thirteen tests (PC1 to PC13, refer to Table 1) were performed under different loading conditions and tendon arrangements. In addition, two reference specimens (PG19 and PG20, see Table 1) were also tested. The geometrical parameters of all slabs were kept constant (3000 × 3000 × 250 mm), refer to Fig. 2. The bending reinforcement was arranged following the same layout as for similar (non-prestressed) specimens presented in [16]. Only two nominal longitudinal reinforcement ratios (ρ) were used for the top reinforcement layers: 0.75% (2 × 24 reinforcing bars with diameter of 16 mm constantly spaced at 125 mm) and 1.50% (2 × 30 reinforcing bars with diameter of 20 mm constantly spaced at 100 mm), as shown in Fig. 3. The actual reinforcement ratios of the top reinforcement calculated on the basis of the effective depths measured after testing are given in Table 1 (average depth of the reinforcement in both directions). The bottom reinforcement was kept constant for all specimens (reinforcing bars with diameter of 10 mm constantly spaced at 100 mm) but was locally reinforced for some specimens near the edges (load introduction region), refer to Fig. 3a. In addition, transverse reinforcement (shear studs) and horizontal pins were arranged at the load introduction regions near the edges (not disturbing in the central region where punching developed), refer to Fig. 3a–c.

The first test series was named “M” (specimens PC1 to PC4) and was aimed at investigating the effect of an external moment (as those due to eccentric prestressing) on the punching behaviour. The slabs of this series were subjected to a bending moment without in-plane forces (nominal values m_p = 75 kN m/m and 150 kN m/m for ρ = 0.75% and 1.50% respectively). The second test series, named “N” (specimens PC5 to PC10), investigated the influence of in-plane forces. The slabs were subjected to an in-plane compression force (identical in two directions) without any external bending moment. The amount of in-plane compression stress was 1.25, 2.50 and 5.00 MPa (nominal values). The third test series, named “P” (specimens PC11 to PC13), aimed at investigating the influence of bonded post-tensioning tendons. It consisted of specimens with a nominal reinforcement ratio ρ = 0.75%. Both in-plane compression forces and moments were introduced by means of eccentric (straight) bonded tendons, refer to Fig. 3c. A summary of the actual investigated parameters (accounting for actual forces introduced and effective depths measured after saw cutting of the specimens) for the three series is shown in Table 1. The reference specimens had the same dimensions and nominal flexural reinforcement ratio (Table 1) and were subjected only to vertical (shear) loading at the same location as the other specimens.

2.2. Materials

All specimens were cast with normal strength concrete with maximum aggregate size of 16 mm and a water–cement ratio varying between 0.54 and 0.56. The concrete compressive strength was measured on 300 × 150 mm concrete cylinders the day of testing and the values are summarised in Table 1. The top flexural reinforcement was made of hot-rolled steel (well-defined yield plateau) for which yield stresses are also provided in Table 1. The prestressing tendons were monostrands (150 mm^2 cross section) for which the average stress at steel rupture (f_{pm}) was 1897 MPa and the stress at 0.1% residual strain was 1689 MPa.

Table 1
Main characteristics of tested specimens (V_R and ψ_R measured at maximum applied load; (*) effective depth of post-tensioning tendons).

Slab	σ_p (MPa)	m_p (kN m/m)	d_{eff} (mm)	f_c (MPa)	ρ (%)	f_y (MPa)	f_t (MPa)	V_R (kN)	ψ_R (%)
PG19	0	0	206	46.2	0.78	510	607	860	1.214
PG20	0	0	201	51.7	1.56	551	659	1094	0.923
PC1	0	78	192	44.0	0.84	583	692	1202	0.828
PC2	0	77	192	45.3	1.64	549	664	1397	0.821
PC3	0	152	194	43.8	0.83	591	691	1338	0.431
PC4	0	152	190	44.4	1.65	602	701	1431	0.581
PC5	−2.53	0	201	33.8	0.80	560	683	1141	1.202
PC6	−2.53	0	203	34.7	1.55	586	690	1205	0.860
PC7	−5.04	0	204	40.5	0.79	580	685	1370	1.073
PC8	−5.00	0	198	41.9	1.59	528	646	1494	0.952
PC9	−1.24	0	210	37.2	0.77	601	710	1105	1.213
PC10	−1.32	0	208	37.5	1.51	548	661	1260	0.924
PC11	−0.06	0.7	212 (182*)	35.7	0.76	584	698	920	1.038
PC12	−1.23	15	210 (184*)	35.8	0.77	584	698	1130	0.956
PC13	−2.46	30	207 (173*)	35.2	0.78	584	698	1059	0.744