Influence of a Prestressing Eccentricity on the Punching Shear Strength of Post-Tensionned Slab Bridges

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Abstract

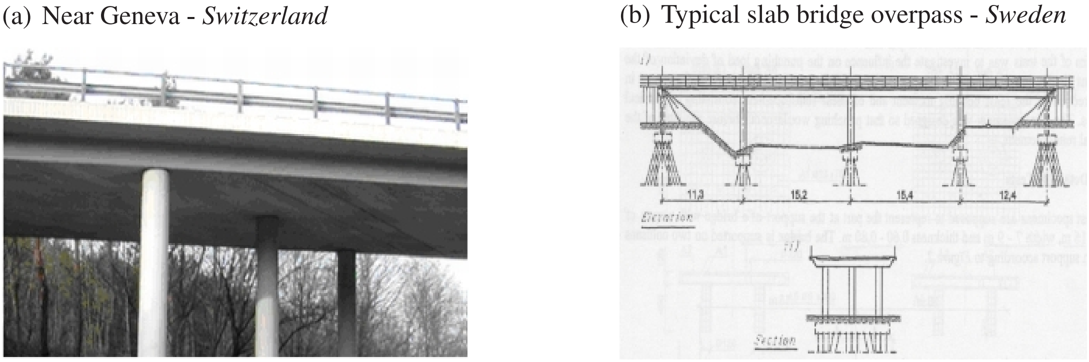
A large number of medium and small span bridges in Switzerland and in other countries are slab bridges, often prestressed, multi-span and supported by columns. Punching in such structures is typically governing at failure. So far, the knowledge of the influence of prestressing on the punching shear strength is limited. Most results published in the litterature have been obtained on slabs prestressed with tendons. As a result the influence of prestressing is investigated globally, because all its effects (axial force, bending moment and deviation forces) have been investigated simultaneously. This paper presents a test campaign currently under way at the Ecole Polytechnique Fédérale de Lausanne. The aim of the tests is to investigate separately and then quantify the various effects of prestressing on the punching shear strength. The paper presents the first part of the test campaign (consideration of a moment), on reinforced concrete slabs. The first results will be presented and discussed on the basis of the critical shear crack theory.

1. Introduction

The solution of slab bridges is commonly used in Switzerland for crossing of motorways. This structural solution is also often used in several others countries such as Sweden, Germany and Canada (figure 1). These bridges are often multi-span and supported by cylindrical or rectangular columns so that risk of punching is in almost cases decisive for the design. Even if the spans are small for bridges (about 20m), the use of prestressing is quite systematic. Due to the use of prestressing, the behaviour of the structural elements near the column is modified. First, the prestressing introduces an axial and normal compression N_p in the critical zone above the column. In addition, due to the parabolic layout of tendons leading to an eccentricity of the prestressing, the mentionned critical zone is subjected to a moment M_p balacing a fraction of those introduced by the self weight and others loads. Finally, the layout of cables allows those to carry a fraction of the shear force in the critical zone V_p (figure 2). As a result, the critical zone is subjected to an interaction between the shear force and the various prestressing effects.

To date, some rational theories have been proposed for punching, particularly for reinforced slabs. Few researches have been conducted on the contrary on prestressing [3], [4], [5], [7], [8]. All of them have been carried using tendons in the slab. As a result, effects of prestressing are considered globally. According to [10] : *"A generally acceptable physical theory for the punching of post-tensionned slab has still to be developed, and there are considerable divergencies* *between current design recommendations"*. Today, all the existing codes consider the effects of prestressing as a shear resistance, but none of them treats the three aspects of the prestressing. To clarify the influence of each effects and to propose a complete consideration of the prestressing on punching shear, it has been decided to perform an innovative test campaign at the Ecole Polytechnique Fédérale de Lausanne. This campaign investigates separately the various effects of the prestressing on punching shear strength. Consequently, a first series of test focuses on the influence of a bending moment, a second will investigate the influence of an axial compression force and a third will include tendons in the slab so that the interaction between the various effects can be taken into account.

This article will first present the part of the test compaign investigating the influence of a moment, on reinforced concrete slabs with dimensions of $3000 \times 3000 \times 250$ mm. Then, the results will be presented and discussed on the basis of the critical shear crack theory. This will lead to discuss the existing codes like Eurocode (Europe), BBK (Sweden) and SIA (Switzerland) and the way the influence of prestressing on punching shear resitance is considered.


(a) Near Geneva - *Switzerland*

(b) Typical slab bridge overpass - *Sweden*

Figure 1: Example of typical slab bridges

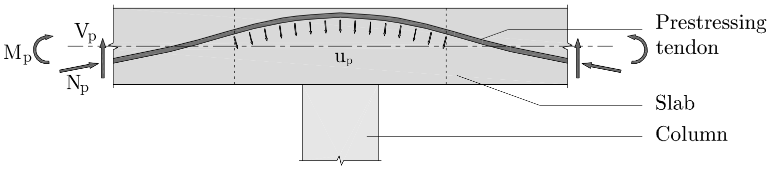


Figure 2: Effects of prestress on a column region

2. Test programme

2.1. Description of the test setup

Many researches have been conducted on reinforced ordinary slabs (figure 3 (a)). To that aim axisymetric slabs loaded symetrically allowed to reach the today's state of art for existing and new buildings. For slab bridges, in which prestressing is used, such test setup cannot represent actual and geometrical loading conditions. All effects have to be investigated (figure 3 (b)). A first series of four slabs investigates the influence of a prestressing moment solliciting the slab. The specimens $3000 \times 3000 \times 250$ mm are supported by a central square column of 260×260 mm. The nominal static depth (d) of each slab is 210 mm. The parameters varied in the specimens are the top flexural ratio ρ (0.75% and 1.5%) and the external moment m_p (75 kNm/m and 150 kNm/m).

The slabs are loaded by a shear force and a moment. The shear force is introduced in eight points, $V/8$ on each point, distributed along the edge of the slab (figure 4 (b)). The moment

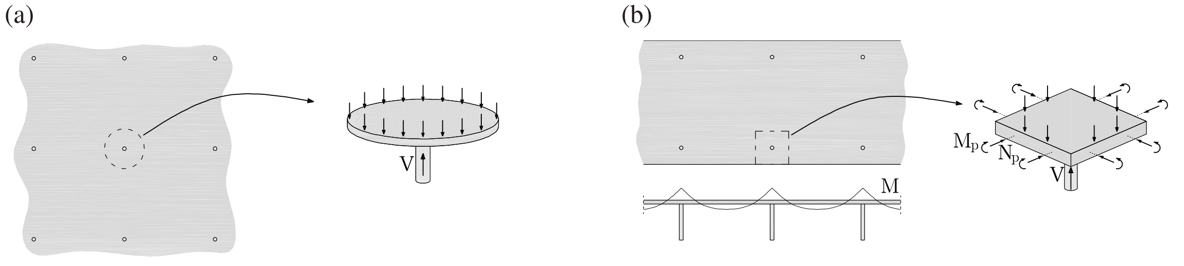


Figure 3: Test slabs : Axisymetric cases (RC Slabs) (a) - Introduction of a moment, a normal force and a shear force (PC Slabs) (b)

is introduced along the diagonal of the slab with the newly developed loading rig shown in figure 4. Two elements placed in the opposite corner along the diagonal of the slab, made of a horizontal, a vertical metallic box girder and a RRK $120 \times 120 \times 10$ mm are linked at their top by bars and at their bottom by the central frame. On top, a hydraulic jack introduces a force F_h equilibrated by $-F_h$ thank to the central frame (figure 4 (a)). This frame allows to avoid introducing any axial force in the slab, in accordance with the first goal to distinguish effects of prestressing and not to couple moment and axial force. The couple of forces $[F_h; -F_h]$ is in equilibrium with the couple $[F_v; -F_v]$, which introduces the moment m_p, constant in center of the slab. Thank to the crossing device, the slab is subjected to an equal moment in each direction (N-S) and (E-W).

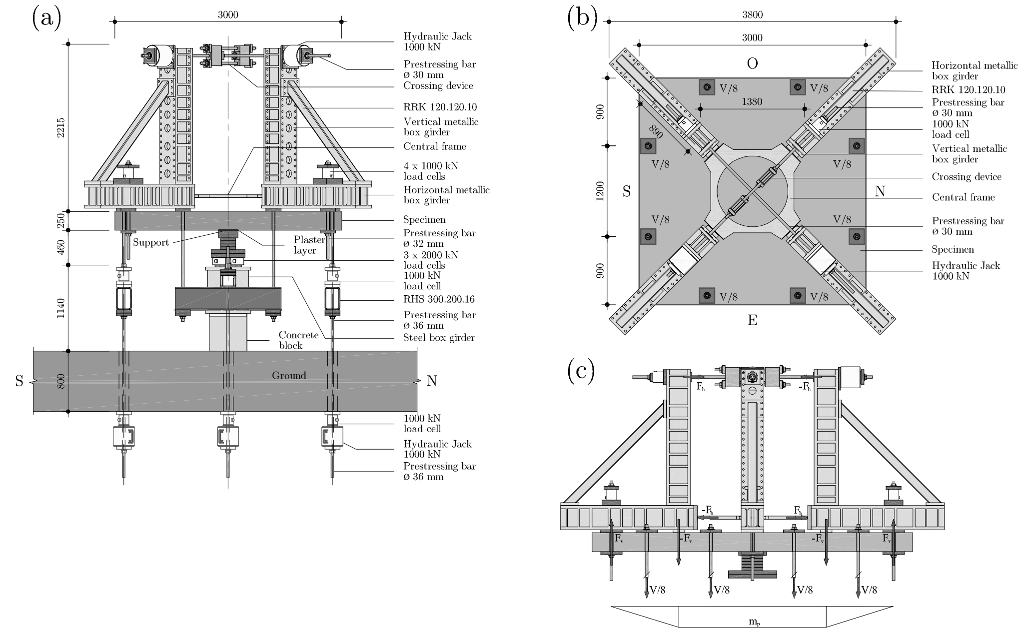


Figure 4: Description of the test setup (dimensions in [mm]) : General view (a), Top side (b), Introduction of the moment (c)

Two values of moment m_p, representing the moment due to prestress in typical slab bridges were chosen for the tests, 75 kNm/m and 150 kNm/m. The moment was progressively introduced in the slab to avoid cracking at the bottom face. The introduction was performed in order to compensate rotations around the column region, due to the introduction of the shear force (eight time $V/8$).

2.2. Materials properties

The slabs were fabricated with normal strength concrete, with a maximum aggregate size d_g of 16mm. The compressive strength of concrete f_c measured on cylinders varied between 43.8 and 45.3 MPa. For the top flexural reinforcement hot-rolled steel was used for which the yield point f_y varied between 577 and 591 MPa. These materials properties are summerized in the table 1. This table gives also the resistance of the slab V_R and the maximal rotation ψ_R when failure occured.

Slab	ρ_{nom} [%]	m_p [kNm/m]	f_c [MPa]	f_y [MPa]	V_R [kN]	ψ_R [‰]
PG19	0.766	0	46.2	607	860	12.14
PG20	1.496	0	51.7	659	1014	9.23
PC1	0.766	75	44.0	591	1201	6.12
PC2	1.496	75	45.3	577	1397	7.04
PC2	0.766	150	43.8	591	1338	2.14
PC4	1.496	150	44.4	577	1433	2.81

Table 1: Principal parameters of the test slabs

2.3. Measurements

The shear force was measured through four 1000 kN load cells placed under the strong floor. Four redundant 1000 kN load cells were installed on the four RHS $300 \times 200 \times 16$ mm. The difference between these two measurements did not exceed 1%. The load under the column was measured through three 2000 kN load cells. The introduced moment is measured first through two 1000 kN load cells at the top of the vertical metallic box girder measuring F_h. For redundancy and for the control of accurancy of the moment introduction device, four additionnal 1000 kN load cells were placed on the horizontal metallic box girder measuring F_v. The rotation of the slab was measured through inclinometers, placed at 1380 mm from the center of the slab in each cardinal direction (N-S being the weaker axis). The rotations given in this paper (table 1) corresponds to the maximal deformation of the slab when punching occurs.

3. Results and comparisons to codes

3.1. Test results

The two slabs PG19 and PG20 are reference slabs (neither moment nor external forces applied) with reinforcement ratios of respectively 0.75% and 1.5%. The normalized load-rotation curves are presented in figure 5 (a), where u is the critical perimeter and d_{g0} a constant value. For each slabs (PC1 to PC4) rotation during the test in the two directions (N-S and W-E) are given in figure 6. The curves also show the theoretical loading curve and the critical shear crack theory criterion [6].

From figure 5, it can be obsverved :

- The punching shear strength increases with increasing values of the external moment.
- Without external moment, the deformation capacity is higher when the reinforcement ratio is low. This tendance seems to inverse when a moment is introduced.
- The cracked stiffness with and without external moment is similar.

3.2. Comparisons to codes

In this section three codes of practice (European Code Eurocode 2 [2], Swedish Code BBK 04 [1] and Swiss Code SIA 262 [9]) will be compared to test results. The european code accounts

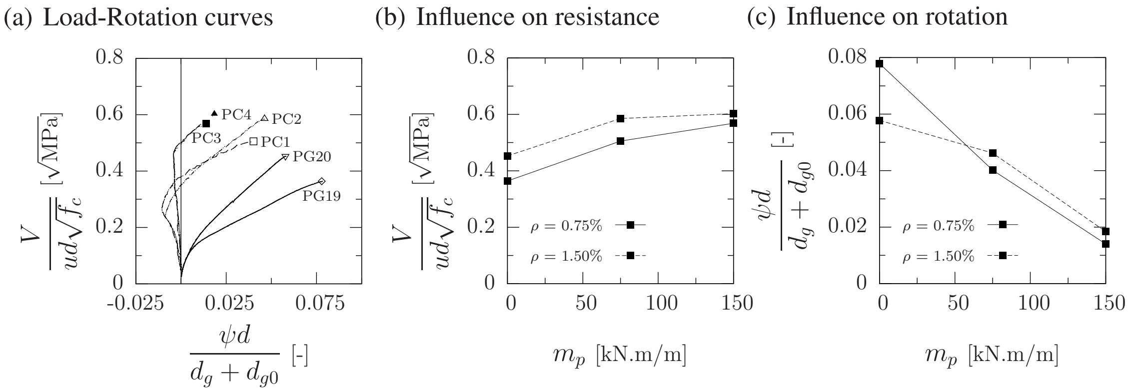


Figure 5: Load-Rotation curves for slabs PC1 to PC4 and for references slabs PG19 and PG20 (a) Influence of moment and flexural reinforcement ratio on resistance (b) and rotation (c)

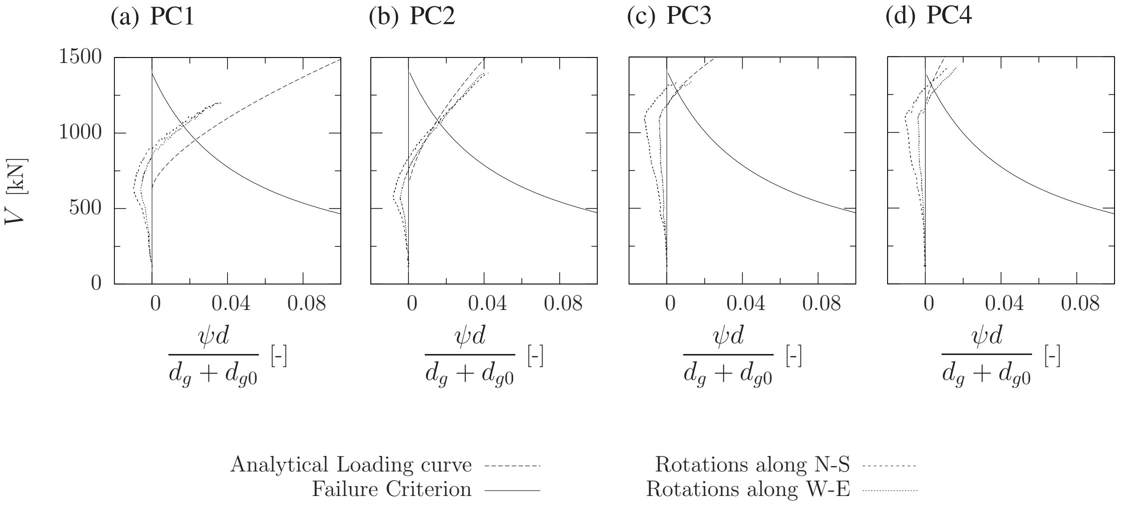


Figure 6: Loading curves for slabs PC1 to PC4 - Analytical loading curve according to [6]

only for the axial force and deviation forces. The Swedish code considers only the vertical component, while SIA does not consider the axial force of compression. A comparison between test results and code provisions is shown in table 2. The best results are obtained using SIA 262, what is logical since this code is the only one to account for the influence of an external moment near the column region. This analysis validates the theoretical approach of SIA 262.

Slab	$V_{R,Test}/V_{R,SIA}$ [-]	$V_{R,Test}/V_{R,EC}$ [-]	$V_{R,Test}/V_{R,BBK}$ [-]
PC1	1.14	1.51	1.58
PC2	1.31	1.41	1.43
PC3	1.01	1.66	1.74
PC4	1.08	1.47	1.48
PG19	1.14	0.95	1.05
PG20	1.22	0.98	1.04
Mean	1.15	1.33	1.39
COV	0.09	0.22	0.20

Table 2: Strength according to various codes compared to test strength

4. Conclusion

This paper presents the first tests carried at the Ecole Polytechnique Fédérale de Lausanne investigating the influence of prestress on punching shear resistance focusing on the influence of an external moment. The main conclusions are :

1. Punching shear strength increases when an external moment, balancing the one due to applied loads, is applied.
2. The deformation capacity decreases in this case.
3. Codes that do not account for external moment du to prestressing do not provide accurate results.
4. Good agreement between predictions and test results presented within this paper are obtained by using the approach used in the swiss code SIA 262.

Further work

The test campaign will continue by investigating the influence of a normal axial force. Since in actual bridges prestressing exists by using tendons, others tests with tendons will be carried out to propose a general rule to consider the complete influence of prestressing on punching shear resistance.

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