PERFORMANCE OF SLABS REINFORCED BY PEIKKO PSB STUDS

DEMONSTRATED BY FULL SCALE TESTS AND VALIDATED BY ETA APPROVAL STARTING APRIL 2013

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Figure 1 Peikko PSB Studs

INTRODUCTION

Double headed studs (e.g. Peikko PSB Studs - Figure 1) are one of the most efficient systems for the reinforcement of concrete flat slabs against failure by punching. The studs are the most typically used to reinforce floor slabs, foundation slabs or column footings. This reinforcement technique has become almost a standard in Central Europe over the past 20 years; it is nowadays becoming increasingly popular in other parts of Europe as well.

One of the main arguments for the application of studs as punching reinforcement is that they enable the slab to reach resistance levels that are significantly higher than resistances of slabs reinforced by traditional techniques (opened or closed stirrups) and they enhance the deformation capacity of the member. A series of full scale tests of slabs reinforced by Peikko PSB Studs has been performed during year 2012 at the Swiss Federal Institute of Technology (EPFL) in Lausanne in order to support this argument. The results of these tests have been used as the basis for the development of the European Technical Approval (ETA) for Peikko PSB Studs. These design concepts of the ETA approval calibrated on the basis of the results of tests will now enable to take account of the benefits of the studs in the design of the slab (the maximum resistance of the slab may be up to 30% higher than the resistance of slabs designed according to Eurocode 2). The details about the tests and background of the design concepts of the ETA approval are presented in this paper.

The legal status of Peikko PSB Studs within the framework of Eurocodes as well as tools for the design of Peikko PSB Studs will be defined by the ETA starting from April 2013. The main motivation of this paper is to provide further added value to the potential users of PSB Studs (designers, contractors, investors) by presenting transparent and unambiguous information about the background of the ETA approval and tests performed on slabs with Peikko PSB Studs.

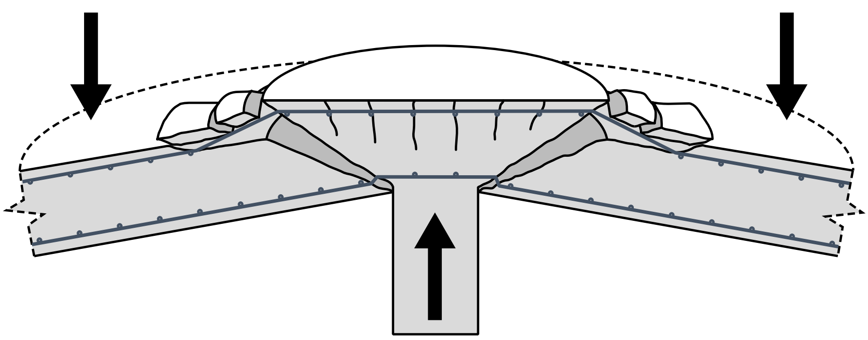

Figure 2 Failure of a slab by punching

REINFORCEMENT AGAINST PUNCHING

Punching is often one of the decisive failure modes that limit the load bearing capacity of reinforced concrete flat slabs (floor slabs, column foundations, footings). It is a particularly dangerous failure mode since it is a brittle phenomenon that happens suddenly without visible signs of warning (extensive deformations, cracks...). Moreover, the failure of one column may impact on adjacent columns and lead to an in-chain failure of the whole reinforced concrete floor. Failure usually occurs so that a concrete cone is separated from the slab, bending reinforcement is pulled away from concrete and the slab collapse due to gravity forces (Figure 2).

The resistance of the slab against this type of failure may be increased by using shear reinforcement designed and detailed in order to prevent the development of such concrete cone. One of the most efficient punching reinforcement systems for flat slabs currently available on the market are double-headed studs (refer to Figure 1).

Some of the most advanced models for the assessment of the behavior of reinforced concrete flat slabs under punching loads have been developed at the Concrete Structures Laboratory (IBeton) of the EPFL during the last 15 years. The research on this topic is of particular interest also for Peikko Group. It is thus somehow natural that Peikko and IBeton found common interest and agreed to cooperate within a research program focused on demonstrating performances of concrete slabs reinforced by Peikko PSB Studs by full-scale testing. Besides being used for the purpose of ETA approval of PSB Studs, the database of test results will also be used to validate other advanced conceptual models for the assessment of the behavior of slabs reinforced by double headed studs in future.

One of the most comprehensive physical models for the assessment of punching in concrete slabs is based on the Critical Shear Crack Theory (CSCT) developed by Muttoni [7], [8], [9], which has been adopted as the theoretical basis for the punching provisions of Model Code 2010 [4]. The model is based on the assumption that the punching resistance of a slab is limited by the capacity of a critical shear crack to transfer loads between the potential concrete cone and the slab. This capacity is principally governed by the roughness of concrete inside of the crack and by the width of the crack. While roughness depends on the material properties of concrete (aggregate size), the width of the crack is assumed to be proportional to the rotation of the slab times the effective depth of the member.

The principle of reinforcing the slab with vertical punching reinforcement consists in strengthening the load transfer mechanism in the crack with additional links. It is assumed that the shear reinforcement is activated after the shear crack is formed. The elongation of reinforcement links, and thus the force carried by the punching reinforcement, is proportional to the width of the crack of the slab. While directly carrying a certain part of punching load, the reinforcement also prevents excessive opening of the shear crack and thus enables concrete to carry a fraction of the acting shear. The strength and deformation capacity are thus increased with respect to members without transverse reinforcement.

The potential failure modes of a slabs reinforced by punching reinforcement that have to be assessed in the design of the slab are shown in Figure 3.

Failure modes a, b, d, e, f may be prevented by correct design and detailing of the punching and bending reinforcement. The failure mode c represents the crushing of the concrete strut between the support and the first row of punching reinforcement. The compressive resistance of this concrete strut thus determines the maximum value of resistance that can be achieved by reinforcing the slab with punching reinforcement. Within the CSCT it is assumed that the compressive strength of concrete in the strut among other influences depends also on the cracking state of concrete in the shear-critical region. It is also assumed that such cracking state is proportional to the opening of the shear crack. Control of cracking in the shear-critical region depends much on the bond, development and anchorage properties of each shear reinforcing system. Due to this reason, experimental validation of the maximum punching shear capacity (crushing of concrete struts) is required to suitably assess the performance of a specific system.

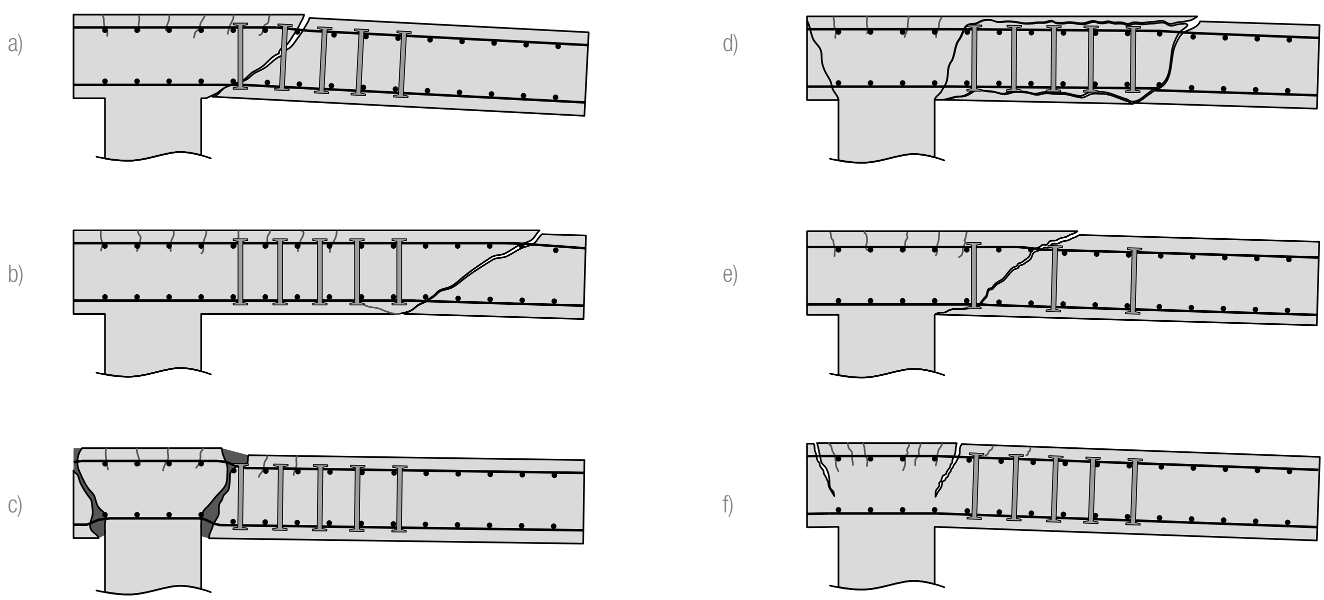

Figure 3 Failure modes of slabs reinforced with punching reinforcement [6]

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		B	h	d	r_s	c	A_s	dA	f_c	$V_{R,test}$	ρ [%]
		[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[MPa]	[kN]	
Peikko	PP1	1700	180	136	765	180	Φ16/90	10	26,4	864	1,64
	PP2	1700	180	139	765	180	Φ16/90	12	54,8	1095	1,61
	PP3	3000	400	330	1505	440	Φ26/100	25	26,9	4754	1,61
	PP4	1700	250	211	765	260	Φ20/100	16	30,9	2076	1,49
	PP5	2300	250	205	1120	260	Φ20/100	16	31,5	1812	1,53
	PP6*	3900	250	203	1926	260	Φ20/100	16	32,7	1569	1,55
Ibeton	PL6*	3000	250	198	1505	130	Φ20/100	14	36,6	1363	1,59
	PL7*	3000	250	197	1505	260	Φ20/100	14	35,9	1773	1,59
	PL9	3000	320	266	1505	340	Φ26/100	18	32,1	3132	1,59
	PL10	3000	400	343	1505	440	Φ26/100	22	33,0	5193	1,55

*Slabs outside of the scope of CUAP

Table 1 Properties of slabs reinforced with double headed studs

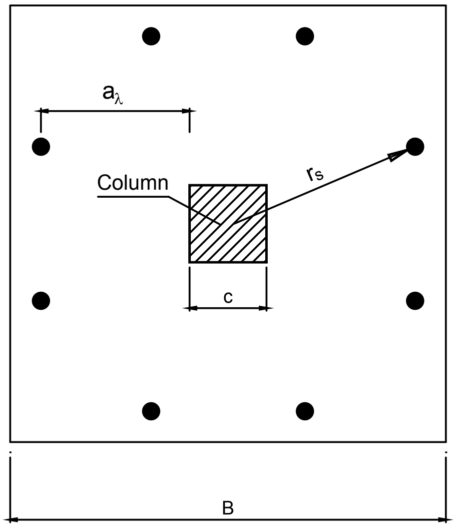


Figure 4 Schematic top view of the tested slab

DESIGN OF PUNCHING REINFORCEMENT

The influence of the anchorage properties of the reinforcement on the maximum resistance of the slabs is not represented in most of current codes of practice. For instance, EN 1992-1-1 [1] (Eurocode 2) assumes the maximum resistance of the slab to be proportional to geometrical and material properties of the concrete slab only:

$$V_{Rd,max}=0{,}4\cdot 0{,}6\cdot \left[1-\frac{f_{ck}}{250}\right]\cdot f_{cd}\cdot u_0\cdot d \quad (1)$$

It should be noted that in 2010 the corrigendum of Eurocode 2 [3] proposed to replace in Eq. (1) the value 0,5 by 0,4. A different approach, where the maximum resistance of the slab is defined as a multiple of the resistance of the slab without punching reinforcement, is used within the German national annex of Eurocode 2 [2] (DIN EN 1992-1-1):

$$V_{Rd,max}=1{,}4\cdot V_{Rd,c} \quad (2)$$

It has to be mentioned that EN 1992-1-1 approach is based on the beam analogy. Although this model has some safe assumptions (as neglecting the out-of-plane confinement of concrete), it does not account for the fact that strain localization occurs (refer to Figure 3c, contrary to beams with transverse reinforcement) and this may lead potentially to unsafe predictions of the strength. With respect to Eq. (2), it is based on the empirical formula of Eurocode 2 for calculating the punching shear strength of members without transverse reinforcement and thus inherits all its potential deficiencies and ranges of application.

The common understanding of assessment procedure [5] (CUAP) for double-headed studs has been published by the European organization for technical approvals (EOTA) in February 2012. The CUAP defines the framework for the elaboration of ETA approvals of double headed studs used as punching reinforcement, including Peikko PSB Studs. Among other requirements, the CUAP defines the necessity to demonstrate the maximum resistances of slabs reinforced by double headed studs by full scale testing. It also includes rather explicit definition of test specimen, test procedure and evaluation methods that have to be used for the development of the ETA approvals. The design model for the maximum resistance of slab reinforced by double headed studs is defined analogous to the empirical model of DIN EN 1992-1-1 [2] under the following form:

$$V_{Rd,max}=k_{max}\cdot V_{Rd,c} \quad (3)$$

where the factor k_{max} is to be defined by testing.

EXPERIMENTAL INVESTIGATION

As mentioned earlier, the principal objective of the experimental camping performed in cooperation between Peikko Group and IBeton was the development of a database of test results for the validation of a design model for the maximum resistance of slabs for the ETA approval of Peikko PSB Studs. Slabs reinforced with double headed studs analogous to Peikko PSB Studs have already been tested at IBeton previously [6]. Some basic parameters of slabs reinforced with double headed studs tested previously at IBeton are given in Table 1.

The geometric and material properties of slabs to be tested for the development of ETA approvals of double headed studs are explicitly defined by CUAP. Amongst others, CUAP deems sufficient to take account of slabs with slenderness $3{,}0\leq a_\lambda/d\leq 5{,}0$.

To develop a database of test results that would satisfy the recommendations of CUAP, it was needed to perform 5 more tests on slabs reinforced by Peikko PSB Studs in addition to tests previously performed at IBeton. The parameters of these slabs were strictly conditioned by the requirements of CUAP. In addition to these 5 tests, one further test with geometric properties outside of the scope of CUAP was tested (test PP6). The motivation of this test was to enlarge the database of test results relevant for the validation of advanced physical models based on the CSCT. The basic parameters of slabs reinforced with Peikko PSB Studs tested at IBeton are also given in Table 1.

The tested slabs were cast with normal strength concrete with a maximum aggregate size of 16 mm. The compressive strength was determined on cylinders with a height of 320 mm and a diameter of 160 mm at 14 days, 28 days, and the day of testing. The characteristic yield strength of Peikko PSB Studs and flexural reinforcement was determined by tensile testing. The summary of material properties may be found in Table 1.

The applied force was introduced by four hydraulic jacks underneath the strong floor Figure 5. Four tension bars running

Figure 5 Test arrangement for a) small and b) large slabs

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. The test arrangement for smaller slabs is shown on Figure 5a, the test arrangement used for larger slabs is shown on Figure 5 b.

During the tests, various continuous measurements were recorded. Load cells measured the applied load at the hydraulic jacks and the reaction forces at the support. Rotations of slabs were measured by inclinometers. Vertical displacements of the slabs were measured using linear variable displacement transducers (LVDTs). Surface deformations on the bottom side of the slab were followed with omega-shaped deformation transducers. After the test, the slab specimens were cut in half to demonstrate the deformed shape of the slab after failure. The deformed shape of the section cut slabs after failure can be seen on Figure 6. In all of the tested slabs, failure of concrete occurred within the punching zone by crushing of concrete.

The testing procedure used for the slabs reinforced by Peikko PSB Studs is analogous to the testing procedure used for the slabs previously tested at IBeton. Comprehensive information about the testing series previously performed at IBeton may be found in reference [6].

EVALUATION OF THE TEST RESULTS

The maximum characteristic loads VR,test reached in the tests (both tests done with PSB Studs and tests performed previously at IBeton) are summarized in Table 2.

The evaluation of tests of slabs with properties within the scope of CUAP shows that a magnification factor k_{max}=1,96 provides sufficient level of safety (5% fractile equal to 1.0). This magnification factor is implemented in the ETA approval of Peikko PSB Studs.

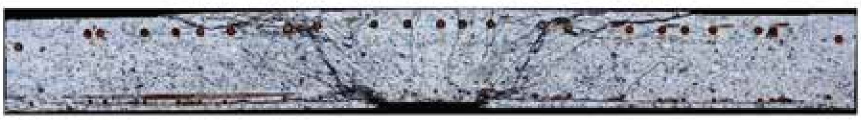
Double headed studs are currently being produced by several manufacturers in Europe and thus are available on the market under different commercial names. At the same time, the material and geometric properties of the studs available under different commercial names are very similar, if not identical. Since the same assessment procedure based on CUAP has or will be used for the development of ETA approvals of all types of studs, the same magnification factor k_{max}=1,96 is or will be used in all ETA approvals of double headed studs no matter of their commercial name.

a) Slab PP1

b) Slab PP2

c) Slab PP3

d) Slab PP4



e) Slab PP5

f) Slab PP6

Figure 6 Saw cut sections of slabs with Peikko PSB Studs after failure

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Table 2 Evaluation of test results and development of design model

							k_{max} = 1,96			k_{max} acc. to Eq. (4)	
	$V_{R,test}$	$V_{R,EC}$	$V_{R,test}/V_{R,Ec}$	a_λ/d	r_s/d		$V_{R,test}/V_{R,ETA}$	$V_{R,test}/V_{R,ETA}$		$k_{max,i}$	$V_{R,test}/V_{R,eq(4)}$
PP1	864	395,3	2,19	5,0	5,6	CUAP/ETA (1)	1,12	1,12	Complete test database	1,88	1,16
PP2	1095	535,8	2,04	4,9	5,5		1,04	1,04		1,90	1,08
PP3	4754	2076,9	2,29	3,9	4,6		1,17	1,17		2,02	1,13
PP4	2076	946,9	2,19	3,0	3,6		1,12	1,12		2,18	1,00
PP5	1812	922,5	1,96	4,8	5,5		1,00	1,00		1,90	1,03
PL9	3132	1491,8	2,10	5,0	5,7		1,07	1,07		1,88	1,12
PL10	5193	2350,1	2,21	3,7	4,4		1,13	1,13		2,05	1,08
PP6	1569	926,4	1,69	8,8	9,5			0,86		1,58	1,07
PL6	1363	689,6	1,98	7,3	7,6			1,01		1,70	1,16
PL7	1773	922,9	1,92	7,0	7,6			0,98		1,70	1,13
						AVG	1,09	1,05			1,10
						SDEV	0,05	0,09			0,05
						5%	1,00	0,90			1,01

(1) Slabs within the scope of CUAP

If all tests are considered with a constant value k_{max}=1,96 (including results of tests PP6, PL6, PL7 with geometric properties outside of the scope of CUAP), the evaluation leads to a 5% fractile of 0,90 meaning that the design model does not have a satisfactory safety level within the framework of Eurocodes (EN 1990). This conclusion is principally valid for slender slabs with span to depth ratio L/d>30. This deficiency of the ETA approvals results from a gap in the rules of CUAP, where it is deemed sufficient to take account only of tests performed on slabs with limited slenderness but the results can be extrapolated to any value of the actual slenderness. The conclusion is thus applicable to ETA approvals of all studs available on European market, no matter of their commercial denomination.

An improvement of the safety level for slabs reinforced by double headed studs may be achieved by introducing the effect of the slenderness of the slab in the design model. The improved design model is formulated as follows:

$$k_{max,i}=1{,}96\cdot\left(\frac{5\cdot d}{r_s}\right)^{1/3} \qquad (4)$$

where r_s is the location where the radial bending moment is zero with respect to the support axis. For regular flat slabs it may be approximated as r_s=0,22.L. The comparison of the results of complete test database with model using constant factor k_{max}=1,96 and improved model is on Figure 7.

CONCLUSIONS

The paper presents an overview on test series focused on demonstrating the maximum resistances of slabs reinforced with Peikko PSB Studs. The results of these test series, together with results of tests previously performed at IBeton institute of the Ecole Polytechnique Fédérale de Lausanne (Switzerland), have been used as the basis for the development of the ETA approval for Peikko PSB Studs. The design model formulated strictly on the basis of recommendations given by CUAP (model with constant factor k_{max}=1,96) and that is used in the ETA approvals of double headed studs (Peikko PSB or other studs available on the market under different commercial names) has a sufficient safety level only for slabs with a slenderness L/d<30. For slabs with higher slenderness, this model is potentially unsafe. A model with improved safety level is also proposed in this paper. Both design models will be available in the PSB module of Peikko's own design software Peikko Designer®.

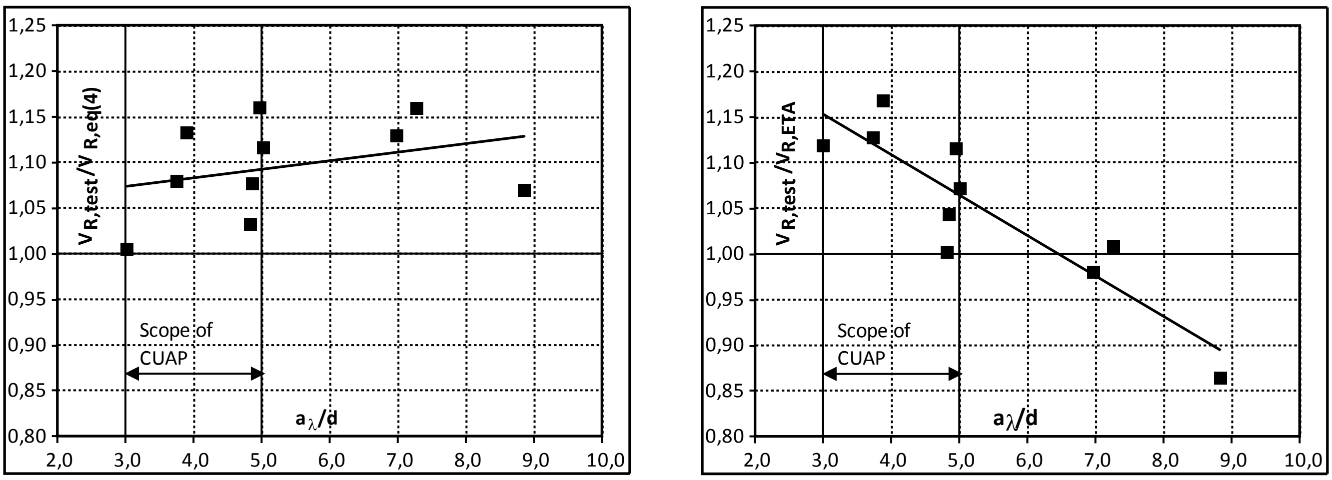
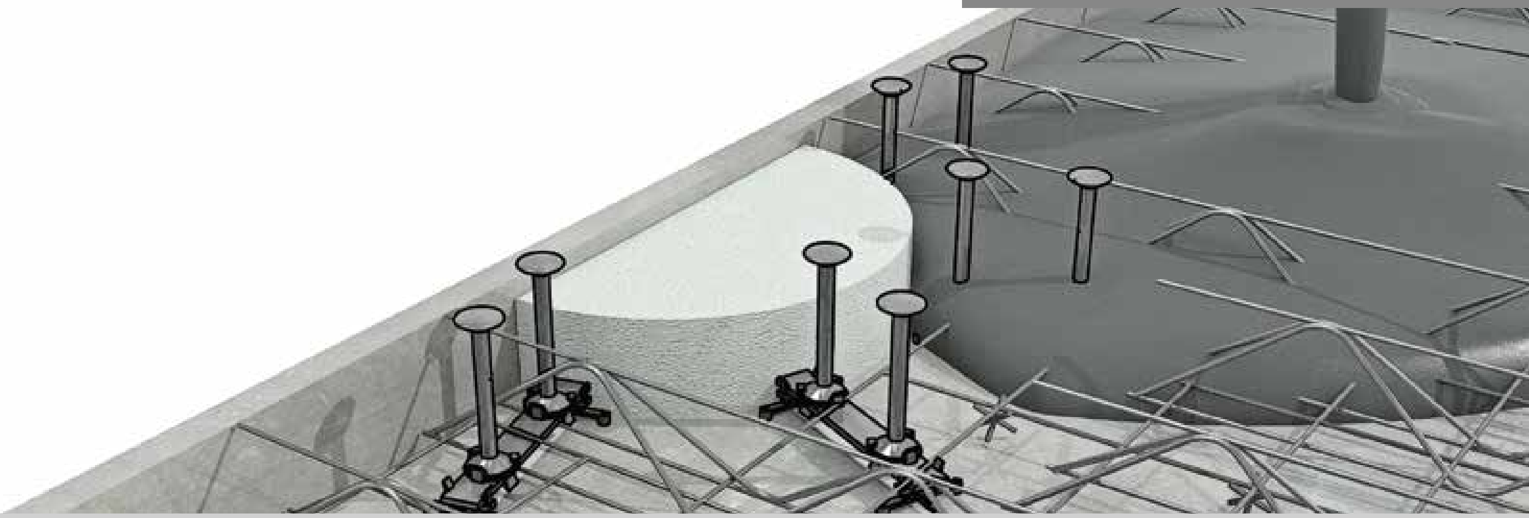


Figure 7 Safety level of a) Improved design model b) ETA design model

REFERENCES

[1] EN 1992-1-1, Eurocode 2: Design of Concrete Structures—Part 1-1: General Rules and Rules for Buildings, CEN, Brussels, Belgium, 2004, 225 pp.
[2] DIN EN 1992-1-1/NA:2011 Nationaler Anhang - Eurocode 2: Bemessung und Konstruktion von Stahlbetonund Spannbetontragwerken, Berlin, Germany, 2011,101 pp.
[3] EN 1992-1-1/AC: Corrigendum AC - Eurocode 2: Design of Concrete Structures—Part 1-1: General Rules and Rules for Buildings, CEN, Brussels, Belgium, 2010, 23 pp.
[4] fib Bulletin No. 66: Model Code 2010 - Final draft, V. 2, Lausanne, Switzerland, 2012, 370 pp.
[5] EOTA, Common Understanding of Assessment Procedure 03.01/05, Double headed studs for the increase of punching resistance in flat slabs on column, for European Technical Approval, Brussels, Belgium, February 2012, 29 p.
[6] Lips, S., Fernández Ruiz, M., Muttoni, A., Experimental investigation on the punching strength and the deformation capacity of shear-reinforced slabs, ACI Structural Journal, V. 109, No. 6, 2012, pp. 889-900
[7] Muttoni A., Punching shear strength of reinforced concrete slabs without transverse reinforcement, ACI Structural Journal, V. 105, No. 4, 2008, pp. 440-450
[8] Muttoni, A., Fernández Ruiz, M., The Levels-of-Approximation approach in MC 2010: applications to punching shear provisions, Structural Concrete, Ernst & Sohn, V.13, No. 1, 2012, pp. 32—41
[9] Fernández Ruiz, M., Muttoni, A., Applications of the critical shear crack theory to punching of R/C slabs with transverse reinforcement, ACI Structural Journal, V. 106, No. 4, 2009, pp. 485—494

a_λ	Distance from the edge of the support to the loading perimeter
c	Side length of a support
d	Effective depth of slab
f_c	Cylinder compressive strength of concrete
h	Depth of the slab
r_s	Radial distance from the center of the slab to the load application points
u_0	Length of column periphery
B	Side length of a slab
L	Maximum span of slab
dA	Diameter of the studs
ρ	Nominal flexural reinforcement ratio
$V_{R,test}$	Maximum punching load measured during the test
$V_{Rd,c}$	Design value of resistance of slab without punching reinforcement
$V_{Rd,max}$	Design value of maximum resistance of slab with punching reinforcement
$V_{R,ETA}$	Nominal value of maximum resistance in accordance with ETA
$V_{R,PSB}$	Nominal value of maximum resistance in accordance with advanced model



PEIKKO PSB TESTING IN LAUSANNE, SWITZERLAND

Text: Gatis Pocs

In December 2012 Peikko Group organized a customer visit to the Swiss Federal Institute of Technology (EPFL) in Lausanne, where Peikko's latest full-scale PSB tests for the ETA Approval were performed. It was a unique opportunity to have closer insight to one of the leading research centres in Europe with expertise around the punching phenomena of concrete, and to see how punching reinforcement is being tested.

The visitors were structural designers from several European countries. The day consisted of presentation of the testing process and full-scale testing setting, results of Peikko's latest tests, and open discussion with questions and answers. The visit was a good opportunity to discuss with experienced reserchers in order to receive answers to some tricky so far unanswered questions. The participants thus had the possibility to improve their knowledge of the punching phenomena in concrete slabs with and without shear reinforcement.

An update on Peikko's PSB testing and the ETA Approval procedure will follow in the next issue of Concrete Connections to be published in the autumn 2013.