Title:	Influence of punching shear reinforcement on the flexural response of flat slabs
Authors:	Lips S., Muttoni A.
Published in:	fib Symposium Tel-Aviv 2013
Pages:	4 p.
City, country:	Tel-Aviv, Israel
Year of publication:	2013
Type of publication:	Peer reviewed conference paper

Please quote as:	Lips S., Muttoni A., *Influence of punching shear reinforcement on the flexural response of flat slabs*, fib Symposium Tel-Aviv 2013, Tel-Aviv, Israel, 2013, 4 p..

INFLUENCE OF PUNCHING SHEAR REINFORCEMENT ON THE FLEXURAL RESPONSE OF FLAT SLABS

Stefan Lips and Aurelio Muttoni

Ecole Polytechnique Fédérale de Lausanne, ENAC-IBETON, Lausanne, Switzerland

Abstract

Physical punching shear models such as the Critical Shear Crack Theory (CSCT), which is the basis of Model Code 2010 (MC 2010), describe generally the punching strength as a function of the slab deformation. Thus, the prediction of an accurate load-deformation curve is essential for the prediction of the punching strength as well as the deformation capacity of flat slabs. In the vicinity of columns, the flexural response of flat slabs depends not only on the flexural moments but also on the concentrated shear forces. In the case of slender slabs, slabs with low amounts of flexural reinforcement, or slabs without shear reinforcement, the shear forces are limited and thus their influence in the flexural response is low. However, in the case of thick slabs with shear reinforcement, large shear forces are carried influencing the flexural response of the flat slab. Despite the importance of an accurate prediction of the load-rotation response, little research has yet been performed on this subject.

This paper presents an investigation on the flexural response of 6 full-scale flat slab specimens. The specimens presented herein belong to an extensive experimental campaign of 16 full-scale flat slab specimens performed at the Ecole Polytechnique Fédérale de Lausanne (Switzerland) with the aim to investigate the punching strength and the rotation capacity of flat slabs with and without shear reinforcement. The investigated parameters were the column size, the slab thickness, the amount of shear reinforcement, and the type of shear reinforcement system. The investigation of the flexural response consists of the comparison of the experimentally obtained load-rotation responses to the predictions by the CSCT, MC 2010, and a modified approach based on the CSCT.

Keywords: Critical Shear Crack Theory, Flat slabs, Flexural Response, Model Code 2010, Punching Shear

1 Introduction

In 1960, Kinnunen and Nylander (1960) defined in their model the punching strength as a function of the slab deformation. This approach was later adopted by other researchers and further developed. Similar to the model of Kinnunen and Nylander, Muttoni developed the Critical Shear Crack Theory (CSCT), which served as a basis for the *fib* Model Code 2010 and describes the punching strength as a function of the slab rotation whereby the slab response can be calculated with a Quadrilinear moment-curvature relationship approach (Muttoni, 2008). However, it has to be noted that most models using such an approach are based on the theory of an axisymmetric slab. Nevertheless, most punching tests were performed with specimens that were not axisymmetric and thus the validation of the model cannot directly be performed. In these cases several adjustments have to be made such as the consideration of an orthogonal flexural reinforcement layout, the shape of the column and the shape of the slab specimen.

The influence of the orthogonal reinforcement can be considered in the CSCT by an efficiency factor of the bending reinforcement (Muttoni, 2008). This efficiency factor depends mainly on the slab geometry and the loading conditions. Lips (2012) proposed a value of 0.75 for square slabs with 8 loading points (Fig. 1a) and a value of 0.65 for circular slabs with distributed loading at the slab perimeter. The influence of square column shapes can be considered by using a circular support with an equal perimeter leading to equal shear stresses at the column face (Guandalini, 2005). The shape of the slab and the application of the load are considered by defining a circular slab with a diameter which leads to the same shear force associated with the flexural strength of the slab. Thus, both slabs reach the flexural strength at the same load level. In the case of a square slab with 8 load application points the flexural strength can be calculated according to the mechanism shown in Fig. 1b.

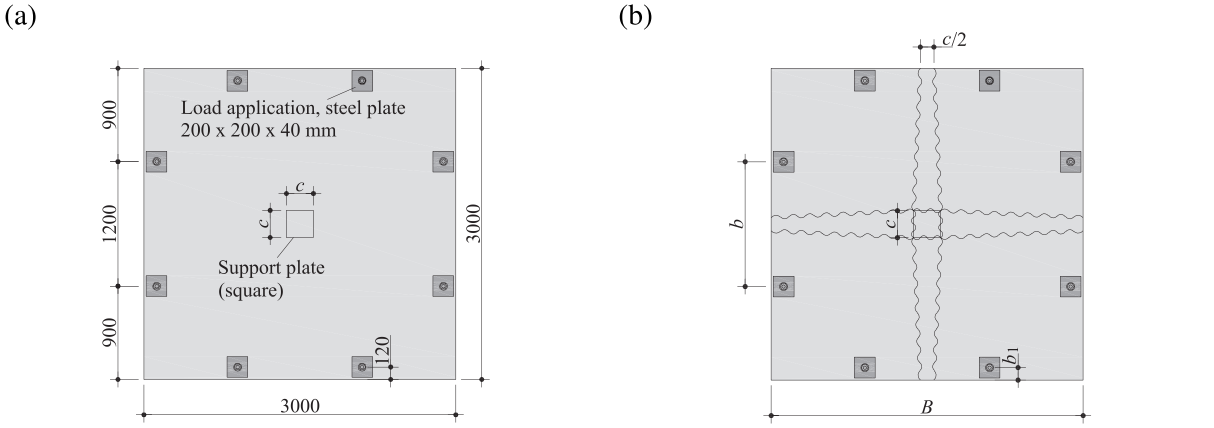

Fig. 1 (a) Slab geometry and load application for a square slab; (b) Yield line mechanism for a square slab with 8 load application points used for the calculation of the flexural strength (V_{flex})

In previous research (Guandalini et al., 2009), it has been shown that these adjustments lead to good results compared to tests with moderate shear strength such as slender slabs without shear reinforcement. However, for more rigid slabs and slabs with shear reinforcement, larger shear forces can occur. In these cases the influence of the concentrated shear forces in the vicinity may have an influence on the flexural strength as well as on the load-rotation response of the slab. This influence was investigated on a test campaign on full-scale slabs with and without shear reinforcement performed at the Ecole Polytechnique Fédérale de Lausanne.

2 Overview of the test campaign

The whole test campaign consisted of 16 full-scale flat slab specimens. The investigated parameters were the column size to effective depth ratio *c*/*d*, the thickness of the slab *h*, the amount of shear reinforcement, and the shear reinforcement system. Constant parameters were the side length of the slab, which was 3.0 x 3.0 m and the flexural reinforcement ratio, which was approximately 1.5%. Fig 1a shows the general slab geometry and Table 1 shows the main parameters of the six test specimens used within this paper. More details of all the specimens of the experimental campaign can be found in Lips et al. (2012).

Table 1
Main parameters of the test specimens

Specimen[1]	h [mm]	c [mm]	d_{eff} [mm]	c/d_{eff} [-]	$f_{c,test}$ [MPa]	ρ_{eff} [%]	f_y [MPa]	$\rho_{w,eff}$ [%]	f_{yw} [MPa]	V_R [kN]
PV1	250	260 x 260	210	1.24	34.0	1.50	709	-	-	974
PL7	250	260 x 260	197	1.32	35.9	1.59	583	0.93	519	1773
PL3	250	520 x 520	197	2.64	36.5	1.59	583	-	-	1324
PL8	250	520 x 520	200	2.60	36.0	1.57	583	0.85	519	2256
PL5	400	440 x 440	353	1.25	31.9	1.50	580	-	-	2491
PL10	400	440 x 440	343	1.28	33.0	1.55	580	0.82	563	5193

[1] PL and PF: Lips et al. 2012; PV: Fernández-Ruiz et al. 2010

3 Main results

Fig. 2 shows the measured and the calculated load-rotation response of selected specimens. The calculations were made according to the *fib* Model Code 2010, the CSCT (Muttoni 2008; Fernández Ruiz and Muttoni 2009), and the refinement of the CSCT proposed by Lips (2012). Fig. 2a shows the load-rotation response for a moderate thick slab (h=250 mm) with a column size of 260 mm and no shear reinforcement. It can be seen that all the three models show the same good agreement with the test measurements. Fig 2b shows the load-rotation curve for a moderate thick slab (h=250 mm) with a large column size (c= 520 mm) and no shear reinforcement. Due to the larger column size, the specimen reached larger shear forces. Although the CSCT and its refinement proposed by Lips (2012) diverge at larger shear forces, the difference in rotation between the two models and the measured response is rather small at the obtained punching strength. The Model Code 2010, which generally assumes a less stiff response than the CSCT shows the best agreement with the measured response for this specimen. Fig. 2c shows the load-rotation response for a thick slab (h=400 mm) with a column size of 440 mm and no shear reinforcement. Although the punching strength is rather large, all models predict the load-rotation response accurately compared to the experimentally obtained response.

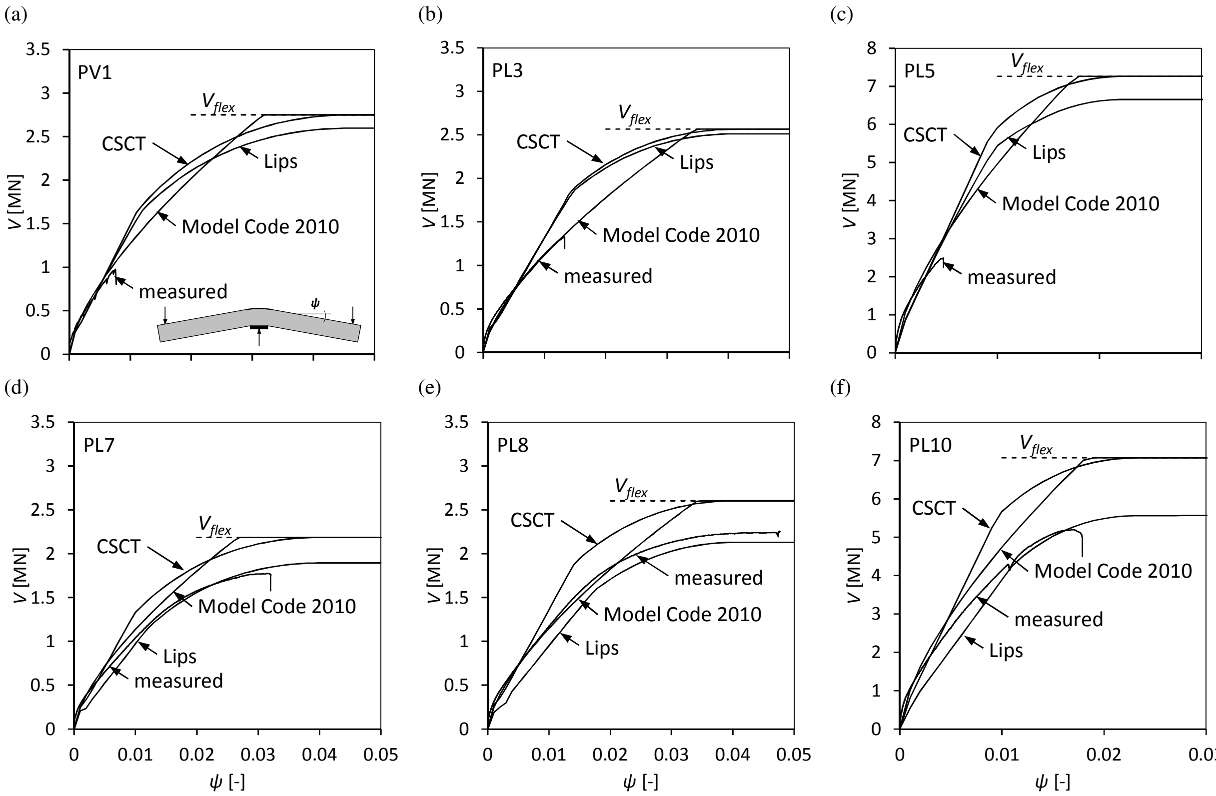

Fig. 2 Measured and calculated load-rotation response for (a-c) slabs without shear reinforcement, (d-f) slabs with shear reinforcement. (V_{flex}: calculated flexural strength)

Fig. 2 d-f show the load-rotation response of specimens with the same geometry of the specimens as shown in Fig. 2 a-c but that had stud shear reinforcement. The figures show that all the specimens being close to or even seem to reach the flexural strength at failure. However, it can be noted that this plateau is much lower than the calculated flexural strength based on the mechanism presented in Fig 1b. The difference between the calculated (V_{flex}) and experimentally obtained flexural strength can best be seen in the case of specimen PL8 that had a column size of c= 520 mm. This specimen underwent large deformations without experiencing a punching failure. It reached its flexural strength at 2256 kN, which is around 14% less than the calculated flexural strength. Similar behavior is obtained for the standard specimen PL7 (h=250 mm; c= 260 mm) and the specimen with increased thickness PL10 (h=400 mm; c= 440 mm).

The comparison of the experimentally obtained flexural response and the response predicted shows that the CSCT and the model code predict a slightly stiffer behavior as the experimentally measured response. This can be attributed to the fact, that both models consider the calculated flexural strength V_{flex} as limit, which overestimates the flexural strength. Nevertheless, it can be noted that despite the slight overestimation of the stiffness, the CSCT and the Model Code shows good prediction of the punching strength (Lips 2012; Lips et al. 2012). The refinement of the CSCT proposed by Lips (2012), which was developed for slabs with large amounts of shear reinforcement, accounts for the influence of the shear forces on the flexural response and the flexural strength and shows thus a better agreement with the test results.

4 Conclusions

Based on the comparison of the experimentally to the theoretically obtained results, the following conclusions are drawn:

1. The flexural response and the flexural strength of slabs without shear reinforcement, which have a small to moderate punching shear strength, can be well predicted without considering the influence of the concentrated shear forces in the column vicinity.
2. The flexural response and the flexural strength of slabs with large punching shear strength such as thick slabs or slabs with shear reinforcement can only be accurately predicted by considering the concentrated shear forces in the column vicinity.
3. The Model Code 2010 and the CSCT predict accurately the flexural response for slabs with small to moderate punching shear strength. However, for slabs that reach large shear forces, both model tend to slightly overestimate the stiffness and the flexural strength. Nevertheless, the punching strength can be accurately predicted with both models.
4. The refinement of the CSCT proposed by Lips (2012), which considers the load transfer path in the vicinity of the column, enables a good prediction of the load-rotation response for slabs without as well as for slabs with shear reinforcement.

Acknowledgments

The authors wish to express their gratitude and sincere appreciation to the Swiss National Science Foundation (Project No. 121566) for financing this research.

References

Fernández Ruiz, M. and Muttoni, A., Applications of the critical shear crack theory to punching of R/C slabs with transverse reinforcement, ACI Structural Journal, Vol. 106 No. 4, pp. 485-494, USA, 2009.

Fernández Ruiz, M., Muttoni, A., and Kunz, J., Strengthening of flat slabs against punching shear using post-installed shear reinforcement, ACI Structural Journal, Vol. 107, No. 4, pp. 434-442, USA, 2010.

fib, Model Code 2010 (Final Draft Version 23.09.2011), Fédération internationale du béton *fib*, Lausanne, Switzerland, 2011.

Guandalini, S., Poinçonnement symétrique des dalles en béton armé, Thèse de doctorat No. 3380, 289 pp., Lausanne, Switzerland, 2005.

Guandalini S., Burdet O., Muttoni A., Punching tests of slabs with low reinforcement ratios, ACI Structural Journal, V. 106, No. 1, USA , pp. 87-95, 2009.

Kinnunen, S. and Nylander, H., Punching of Concrete Slabs Without Shear Reinforcement, Transactions of the Royal Institute of Technology, No. 158, 112 pp., Stockholm, Sweden, 1960.

Lips, S., Punching of Flat Slabs with large Amounts of Shear Reinforcement, Ecole Polytechnique Fédérale de Lausanne, PhD Thesis 5409, 217 pp., Lausanne, Switzerland, 2012

Lips, S., Muttoni, A., and Fernández-Ruiz, M., Experimental Investigation on the Punching Strength and the Deformation Capacity of Shear-Reinforced Slabs, ACI Structural Journal, Vol. 109, No. 6, pp. 889-900, USA, 2012.

Muttoni, A., Punching shear strength of reinforced concrete slabs without transverse reinforcement, ACI Structural Journal, Vol. 105, No. 4, pp. 440-450, USA, 2008.