NEW PROVISIONS FOR PUNCHING SHEAR IN MODEL CODE 2010 BASED ON THE CRITICAL SHEAR CRACK THEORY

Juan Sagaseta **Luca Tassinari** **Aurelio Muttoni** **Miguel Fernández Ruiz**

Abstract

The provisions for punching shear around concentrated loads in the new Model Code 2010 (MC2010) have been updated, covering a large number of design cases such as slabs with and without transverse reinforcement, different column/slab geometries and prestressed slabs amongst others. The theoretical framework used was based on the mechanical model of the Critical Shear Crack Theory (CSCT). This approach, in contrast to empirical formulas, provides the designer with a physical understanding of the phenomenon and allows an enhanced flexibility to implement new parameters, which may arise in practice when introducing innovative structural solutions to increase the punching strength.

This paper summarizes the basis for the derivation of the design formulas introduced in the new Model Code 2010 and shows a comparison with test data from the literature including tests carried out at École Polytechnique Fédérale de Lausanne. Several levels of approximation are presented depending on the complexity of the method used to estimate the slab rotations. Lastly, it is shown that approximated formulas and shear fields can be used for particular and general cases consistently with the CSCT to estimate the shear-resisting control perimeter as suggested in the new Model Code 2010.

Keywords: Punching Shear, Critical Shear Crack Theory, New Model Code 2010, Design

1   Introduction to new provisions for punching shear in MC2010

The first draft of the new Model code 2010 was published in *fib* Bulletins 55 and 56 in April and May 2010. This document gathers a comprehensive state-of-the art regarding design and construction of structural concrete. Several chapters on the verification of structural safety (ULS) were revised, in particular the provisions for shear, torsion and punching shear were updated by *fib* Task group 4.2. The authors of this paper contributed to the new provisions of punching shear, which generally governs the design at ULS of flat slab construction. The new provisions for punching shear were derived based on the Critical Shear Crack Theory (CSCT), which was first established in the 80's as part of the first draft of the Swiss Code for structural concrete SIA162 (Muttoni 1985). The CSCT is based on a mechanical model as opposed to empirical approaches used in MC90, EC2 or ACI-318. The main advantage of physical models is that several levels of

approximation can be derived by refining the hypothesis assumed in the model. The levels of approximation proposed for punching shear include from simple formulas used for design new structures to more advanced formulas for assessment of existing structures or design of more complex structures. The CSCT was originally developed for slabs without transverse reinforcement and axis-symmetrical conditions. Extensive experimental and theoretical work has been carried out at École Polytechnique Fédérale de Lausanne (EPFL) over the last 10 years on different punching shear design cases. More recent developments on the CSCT extended its used to shear-reinforced slabs (Fernández Ruiz et al. 2009) or bridge deck slabs (Vaz Rodrigues et al. 2008) amongst others. Moreover, work by Sagaseta et al. 2010 and Tassinari 2011 investigated and extended the theory to columns with non-symmetrical conditions and concentric or eccentric loading.

The new provisions for punching shear in MC2010 allow estimating both the strength and deformation capacity in terms of the maximum slab rotation ψ (**Fig. 1**). The failure criterion used in MC2010 provides a characteristic strength with a target fractile of 5%. **Fig. 1b** shows that the activation of the transverse reinforcement can be considered introducing the component V_s which varies with ψ (Fernández Ruiz et al. 2009).
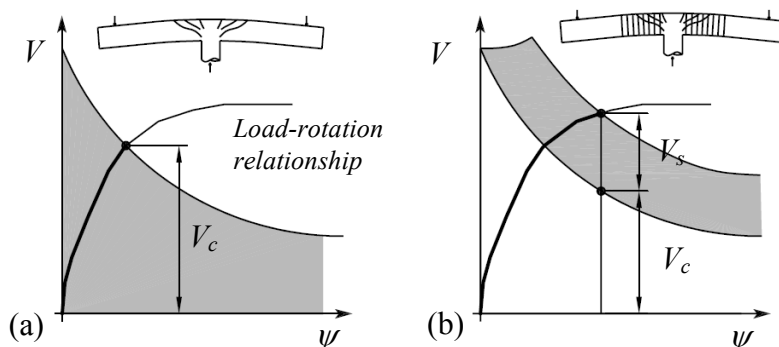

Fig. 1   Contribution of V_c and V_s with slab rotation: slabs (a) without & (b) with shear reinforcement

2   Estimation of load-rotation relationship and shear-resisting perimeter

In order to calculate the punching shear strength the load-rotation relationship (V-ψ) needs to be estimated by means of simplified formulas (analytically or semi-empirically) or even through a more refined finite element analysis. Four levels of approximation are shown.   The   most accurate predictions of the slab rotations are generally obtained on the basis of a nonlinear analysis using analytical and numerical techniques (Sagaseta et al. 2010, Tassinari 2011). However, this level of approximation, denoted as Level IV, it is only suggested for assessment of existing or complex structures. In more general cases of geometry or loading, Level III is sufficient; refer to eqn. (1). This approach only requires solving a simple elastic model to obtain both the distance r_s from the column axis to the point with zero radial moments and m_{sd} (average bending moment in the support strip).

$$\psi = 1.2 \cdot \frac{r_s}{d} \frac{f_{yd}}{E_s} \left(\frac{m_{sd}}{m_{Rd}} \right)^{1.5} \tag{1}$$

Level III is a relatively simple approach and it allows solving general cases of geometry including irregular slabs. **Fig. 2** shows that the load-rotation was estimated accurately using Level III for symmetrical and non-symmetrical tests carried out at EPFL. These tests had been used in the past to validate Level IV approach (Sagaseta et al. 2010). In regular slabs (i.e. the ratio of span lengths L_x/L_y=0.5-2) parameters r_s and m_{sd} can be estimated using simplified rules (Level II); r_s=0.22L or m_{sd}=V/8 for internal columns. In Level II, the factor 1.2 in eqn. (1) should be replaced by 1.5. In

practice, a safe and simple estimation of the punching strength (Level I) can be obtained adopting $m_{sd}/m_{Rd} =1$ in eqn. (1). Level I gives most reasonable predictions in regular slabs without significant redistribution of stresses and ensures a certain deformation capacity prior to punching.
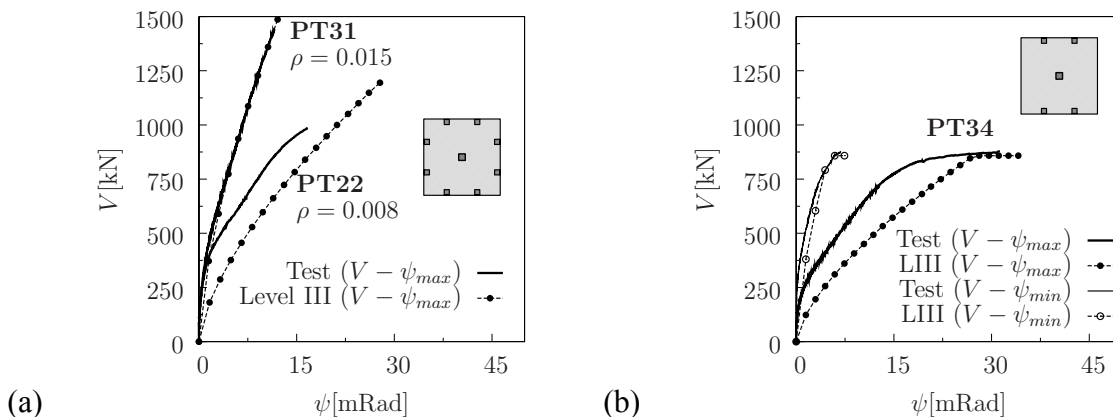

Fig. 2   Load-rotation predictions (Level III) for (a) symmetrical and (b) non-symmetrical cases

As an example of application of this methodology, **Fig 3** compares V_{test}/V_{calc} obtained for tests with moment transfer from the literature; the load-rotation was estimated using Level II & III. The results shown in **Fig. 3a** and **b** are comparable in this case, with an average V_{test}/V_{calc} ratio of 1.28 and 1.21; the 5% fractile was 1.08 and 1 which is acceptable.
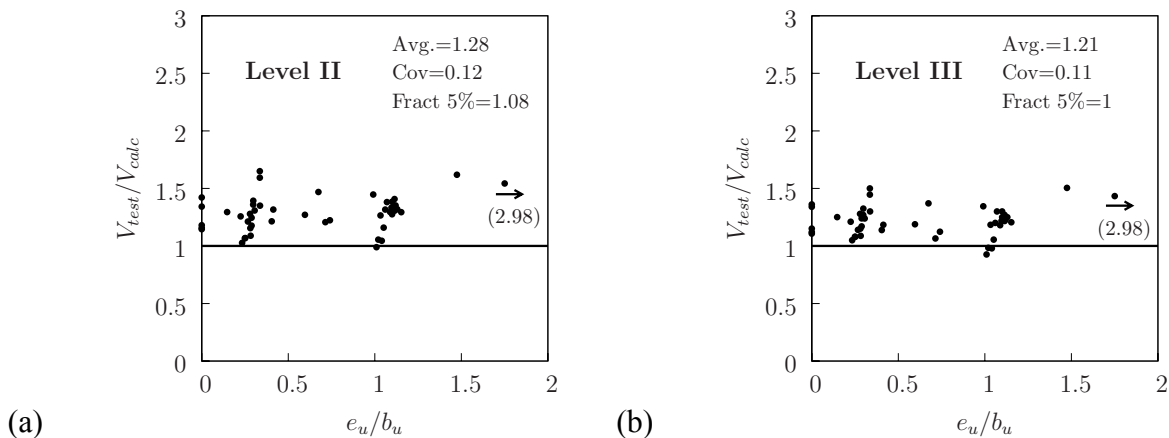

Fig. 3 V_{test}/V_{calc} ratio for punching tests with moment transfer: (a) Level II and (b) Level III

The basic control perimeter adopted (b_1) is located at a distance of λ=0.5d from the column face which is significantly closer to the failure region than the one adopted in MC90 or EC2 (λ=2d). The shear-resisting control perimeter (b_0) needs to be estimated by means of approximate rules or more refined analysis such as shear fields (Vaz Rodrigues et al. 2008). The reduction of b_1 is needed in common cases such as large columns or columns with load eccentricity (e_u). **Fig. 3** shows that the coefficient of eccentricity k_e proposed in MC2010 to obtain b_0, provides reasonable predictions of internal columns with moment transfer; similar results were obtained for corner & border columns (Tassinari 2011).

3   Conclusions

The new provisions for punching shear in MC2010 proposed by the authors and their implications on practice are discussed in this paper. The main conclusions are:

1. The proposed formulas are based on a physical model which allows firstly, the derivation of several levels of approximation suitable for both design and analysis of simple and complex structures and secondly, these formulas offer more flexibility to introduce new parameters than empirical approaches.
2. The formulas can be used to predict strength and deformation capacity which is relevant since punching shear failures can be sudden and lead to the progressive collapse of the structure.
3. Developments of the CSCT had shown that the approach can be extended to a large number of practical cases such as slabs with and without shear reinforcement, prestressed slabs or non-symmetrical cases with eccentric and concentric loading.
4. Significant changes are introduced with respect to previous empirical formulas in MC90, including considerations on the control perimeter. More detailed information about the proposed formulas, relevant literature on the fundamentals of the CSCT and practical examples can be found in http://ibeton.epfl.ch/MC2010Punching/

References

[1]   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, pp. 485-494, Detroit, USA, 2009.
[2]   MUTTONI A.: *Punching shear – Draft code proposal*, SIA 162, Zürich, 1985.
[3]   MUTTONI, A.: *Punching shear strength of reinforced concrete slabs without transverse reinforcement*. ACI Structural Journal, V. 105, No. 4, pp. 440-450, Detroit, USA, 2008.
[4]   SAGASETA, J., MUTTONI, A., FERNÁNDEZ RUIZ, M., TASSINARI, L.: *Non axis-symmetrical punching shear around internal columns of RC slabs without transverse reinforcement*. Magazine of Concrete Research (in press).
[5]   TASSINARI, L.: *Poinçonnement non symétrique des dalles en béton armé*. PhD Thesis (to be submitted in 2011), École Polytechnique Fédérale de Lausanne.
[6]   VAZ RODRIGUES, R., FERNÁNDEZ RUIZ, M., MUTTONI, A.: *Punching shear strength of R/C bridge cantilever slabs*, Eng. Structures, Vol. 30, No. 11, 2008.

Juan Sagaseta

Corresponding author
⊠   University of Surrey
      Division of Civil, Chemical and
      Environmental Engineering (C5)
      Faculty of Eng. & Physical Sciences
      Guildford,GU27XH, United Kingdom
☎   +44(0) 1483 686649
🖷   +44(0) 1483 682135
☺   j.sagaseta@surrey.ac.uk
URL   http://www.surrey.ac.uk/cce

Luca Tassinari, Aurelio Muttoni,
Miguel Fernández Ruiz
Co-authors
⊠   École Polytechnique Fédérale de
      Lausanne; EPFL IBETON; Station 18
      CH-1015, Lausanne, Switzerland
☎   +41(0) 21 693 2886
🖷   +41(0) 21 693 5884
☺   luca.tassiniari@epfl.ch;
      aurelio.muttoni@epfl.ch;
      miguel.fernandezruiz@epfl.ch
URL   http://ibeton.epfl.ch/