PERFORMANCE AND DESIGN OF PUNCHING SHEAR REINFORCING SYSTEMS

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ABSTRACT

Punching shear reinforcement is increasingly used in flat slabs as an effective solution to increase their strength and deformation capacity. Several punching shear reinforcing systems have been developed in the past, such as studs, stirrups or bent-up bars. The efficiency of such systems is strongly influenced by their development conditions (anchorage, bond) and detailing rules. Codes of practice, however, do not typically acknowledge such differences, proposing the same set of design formulas for all systems. This approach is detrimental for some systems (with better detailing rules and anchorage characteristics) and does not provide enough guidance for design of others (not respecting codes' detailing rules).

In this paper, the fundamentals of the critical shear crack theory are explained with respect to the design of punching shear reinforcing systems. It is shown that this theory provides a consistent basis for design of shear reinforcing systems accounting for their particularities and modes of failure. The results of 6 tests on full scale slabs (3.0× 3.0× 0.25 m) with same flexural and shear reinforcing ratio but with different punching shear reinforcing systems are presented and discussed. The experimental results confirm that the strength and deformation capacity are strongly influenced by the characteristics of the shear reinforcing system. The results for the various systems are finally investigated within the frame of the critical shear crack theory, leading to a series of recommendations for design.

Keywords: Punching, Flat slabs, Shear Reinforcement, Critical shear crack theory

INTRODUCTION

Punching shear reinforcement is increasingly used in flat slabs because of the significant improvements introduced both in terms of strength and ductility. The enhancement on the behaviour of the slab is shown in Figure 1 with reference to two tests with same geometric and mechanical characteristics[1], one containing shear reinforcement and the other not. The strength is almost doubled for the test with shear reinforcement. Also, the deformation capacity is significantly increased, being more than three times that of the member without shear reinforcement.

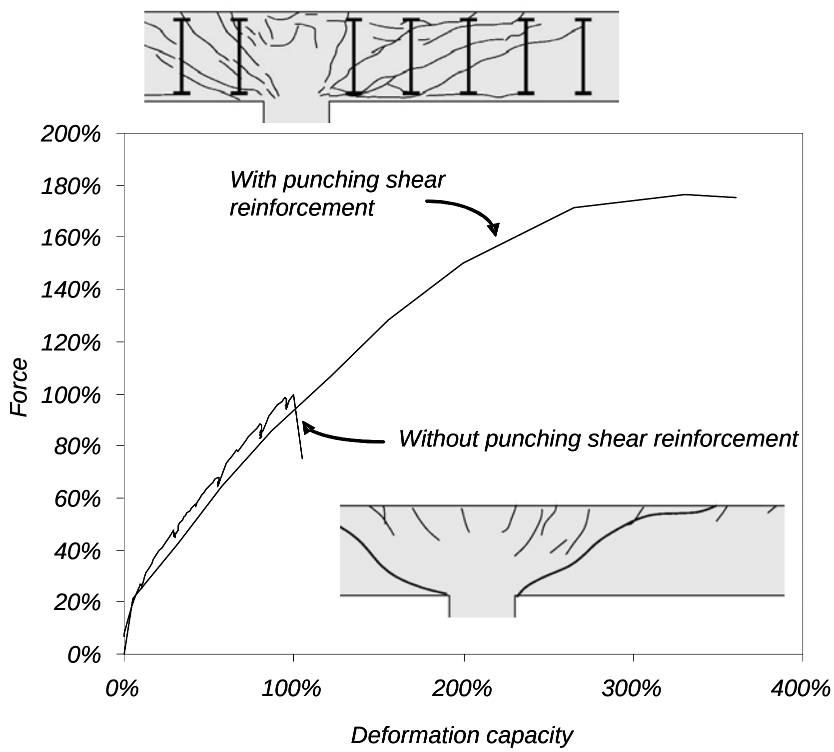

Fig. 1: Comparison of the behaviour and strength of two slabs with and without shear reinforcement (adapted from Muttoni et al.[1]).

The main consequences of the increase on strength and ductility of members with transverse reinforcement are:

- If punching shear is the governing design criterion for flat slabs, the live load can be increased for a given thickness of the slab if shear reinforcement is provided. Conversely the thickness of the slab (and/or the size of the column) can be diminished
- The remarkable increase in ductility enhances safety of flat slabs with transverse reinforcement at ultimate. This is true as redistribution of internal forces is made possible and because the vulnerability of the structure with respect to accidental actions (earthquake, explosion, fire, impact,...) is reduced. Also, significant deflections develop prior to failure, giving advice of potential problems in the slab

Design of slabs with punching shear reinforcement typically considers several potential failure modes[2], see Figure 2:

a Crushing of compression struts (Fig. 2a). This failure mode becomes governing for high amounts of bending and transverse reinforcement, where large compressive stresses develop in the concrete near the column region. Crushing of concrete struts limits thus the maximum strength that can be provided by a shear reinforcing system. This is instrumental for design as it determines the applicability of such systems with respect to the effective depth of the slab and size of support region.

b Punching within the shear-reinforced zone (Fig. 2b). Such failure develops for moderate or low amounts of shear reinforcement, when a shear crack localizes the strains within the shear-reinforced zone. Shear strength is thus governed by the contribution of concrete and of the transverse reinforcement. For design, this failure mode is used to determine the amount of shear reinforcement to be arranged.

c Punching outside the shear-reinforced zone (Fig. 2c). This failure mode may be governing when the shear-reinforced zone extends over a small region. Check of this failure mode is typically performed in design to determine the extent of the slab to be shear reinforced.

d Delamination of concrete core (Fig. 2d). When the shear reinforcement is not enclosing the flexural reinforcement, delamination of the concrete core may occur. This leads to a rather ductile failure mode but with limited strength and with loss of development on the flexural reinforcement. Typical detailing provided in codes of practice avoids the use of shear reinforcement systems leading to such failure mode.

e Flexural yielding (Fig. 2e). Slabs with low flexural reinforcement ratios and with sufficient transverse reinforcement can fail by development of a flexural plastic mechanism. Bending strength and not punching shear strength is thus governing for the strength of the slab.

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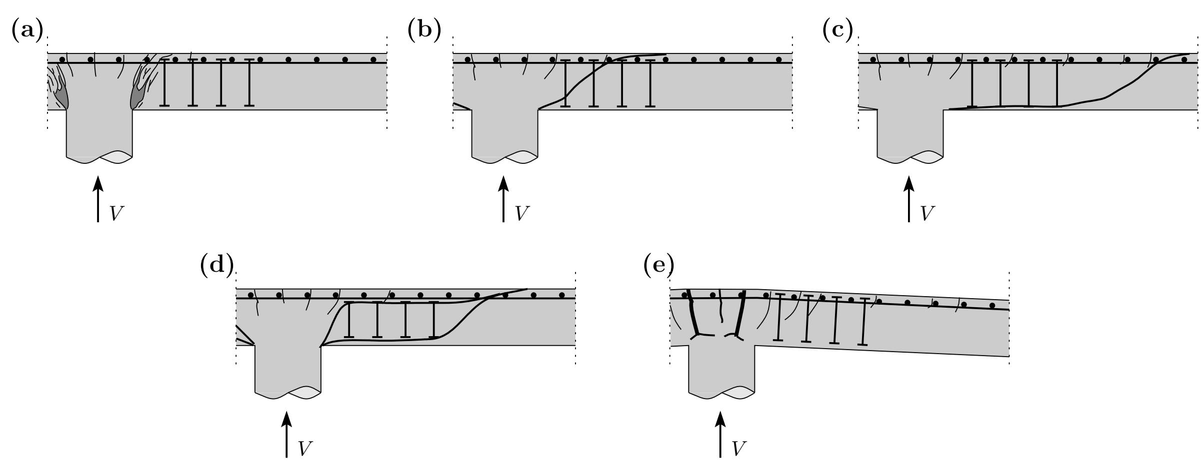

Fig. 2: Failure modes in flat slabs: (a) crushing of concrete struts; (b) punching within the shear-reinforced zone; (c) punching outside the shear-reinforced zone; (d) delamination; and (e) flexural yielding

Apart from flexural yielding, the strength of the other potential failure modes is in fact highly dependent on the characteristics of the shear reinforcing system[2,3,21]. In most current codes of practice[4,5] such dependence is however not always addressed. Instead, a series of detailing rules are typically provided, describing anchorage, bar spacing and other parameters to be respected. This approach is detrimental for some systems (with better detailing rules and anchorage characteristics) and does not provide enough guidance for design of others (not respecting detailing rules). In some countries, like in Switzerland[3] or Germany[6], national codes are applicable for some general systems, leading manufacturers the possibility to develop their own design methods for specific products not complying with codes' detailing rules.

Recently[2], an application of the critical shear crack theory[7,8] (CSCT) has been proposed allowing to account consistently for the geometric and development properties of shear reinforcing systems on their design. Applications[2,9,10] to shear studs (deformed, smooth, prestressed), steel offcuts, stirrups, headed stirrups and post-installed bonded bars have shown excellent results for prediction of strength and ductility, significantly better than those provided by codes of practice.

In this paper, the influence of the properties of the shear reinforcing systems on the strength of the various failure modes is discussed on the basis of the CSCT and several test results. The specimens had same geometric and mechanical properties but they were reinforced with different systems. The experimental results confirm the significant influence on the shear strength of the type of shear reinforcement used and lead to some recommendations for design.

BACKGROUND OF THE CRITICAL SHEAR CRACK THEORY

The critical shear crack theory was first developed for flat slabs without transverse reinforcement failing in punching shear[11,7] and it was later extended to beams without stirrups[12,8] and slabs with shear reinforcement[13,2]. The theory proposes that the shear load that can be carried by members without shear reinforcement is a function of the opening and of the roughness of a critical shear[8]:

$$\frac{V_R}{b_0 \cdot d} = \sqrt{f_c} \cdot f(w, d_g) \tag{1}$$

where V_R is the shear strength, b_0 is a control perimeter (set at $d/2$ of the border of the support region for punching shear), d is the effective depth of the member, f_c is the compressive strength of the concrete, w is the width of the shear critical crack and d_g is the maximum size of the aggregate (accounting for the roughness of the lips of the cracks).
For two-way slabs, the opening of the critical shear can be correlated in an effective way[7] to the rotation of the slab (ψ) times the effective depth of the member (d), see Figure 3:

$$w \propto \psi \cdot d \tag{2}$$

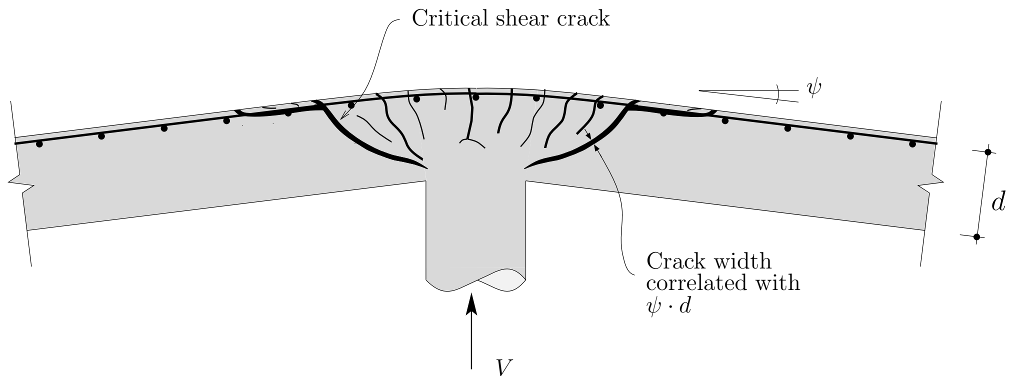

Fig. 3: Critical shear crack and punching shear cone

The following failure criterion was proposed for punching shear failures in slabs without transverse reinforcement[7]:

$$\frac{V_R}{b_0 \cdot d \cdot \sqrt{f_c}} = \frac{3/4}{1 + 15\dfrac{\psi \cdot d}{d_{g0} + d_g}} \qquad \left[\text{SI - units : MPa, mm}\right] \tag{3}$$

where d_{g0} is a reference aggregate size (equal to 16 mm). This failure criterion reduces the maximum shear force that can be carried as deformations (rotations) increase. This is logical since wider cracks reduce the ability of concrete to transfer shear. Figure 4 compares the failure criterion of Eq. (3) to 99 test results available in the scientific literature[7] showing good agreement.

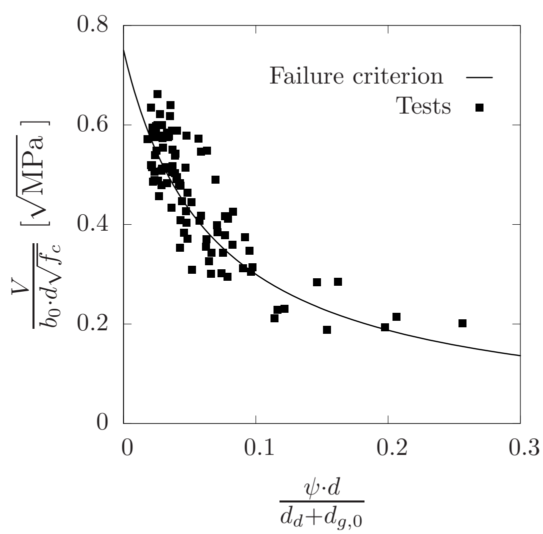

Fig. 4: Comparison of failure criterion for slabs without shear reinforcement (Eq. (3)) to 99 test results[7]

Such punching shear criterion can be used to calculate the strength and ductility of slabs failing in punching shear by considering a suitable load-rotation relationship for the slab, see Figure 5. A design expression for this relationship has been proposed by Muttoni[7] considering a number of simplifications from a more general theoretically-derived expression:

$$\psi = 1.5 \cdot \frac{r_s}{d} \cdot \frac{f_y}{E_s} \cdot \left(\frac{V}{V_{flex}} \right)^{3/2} \qquad (4)$$

where r_s is the distance of the edge of the support region to the line of contraflexure of bending moments (that can be taken equal to 0.22 times the span length for regularly-supported flat slabs), f_y is the yield strength of the flexural reinforcing steel, E_s is the modulus of elasticity of the rebars and V_{flex} is the load necessary to develop the plastic mechanism of the slab.

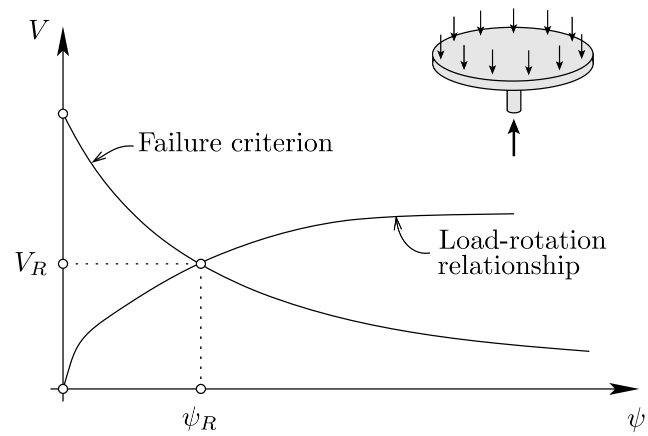

Fig. 5: Calculation of strength and deformation capacity at failure according to the CSCT

APPLICATIONS OF THE CRITICAL SHEAR CRACK THEORY TO PUNCHING OF SHEAR-REINFORCED SLABS

The CSCT can be used to calculate the punching shear strength of the various failure modes previously described[2] (see Figure 2). In this section, the way it allows accounting for the particularities of each punching shear reinforcing system will be discussed.

PUNCHING OUTSIDE THE SHEAR-REINFORCED ZONE

As shown in Figure 2c, punching outside the shear-reinforced zone occurs by development of a single crack localizing strains. This behaviour can be reproduced by using the CSCT formulation but considering[2] an effective perimeter ($b_{0,out}$) and depth of the slab (d_v):

$$\frac{V_R}{b_{0,out} \cdot d_v \cdot \sqrt{f_c}} = \frac{3/4}{1 + 15 \dfrac{\psi \cdot d}{d_{g0} + d_g}} \qquad [\text{SI - units : MPa, mm}] \tag{5}$$

The effective control perimeter ($b_{0,out}$) is defined at $d/2$ beyond the outer layer of shear reinforcement and considering $4d$ as the maximum effective distance between two shear reinforcements. This approach is similar to that followed by most current codes of practice[3,5,6] in order to account for largely spaced shear reinforcement.

With respect to the effective depth of the slab (d_v), it accounts for the fact that the punching shear crack develops around the shear reinforcement (Fig. 2c). This value is thus dependent on the type and geometry of the shear reinforcement, as shown in Figure 6 for various cases. This approach provides very good agreement to test results[2] and is currently adopted by the Swiss code for structural concrete[3].

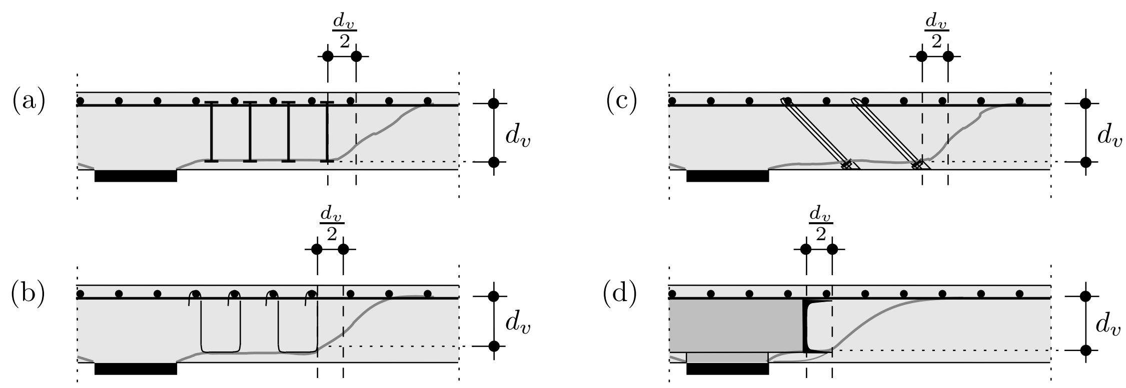

Figure 6: Effective depth and control perimeter outside the shear-reinforced zone as a function of the punching shear reinforcing system[2,3]: (a) studs; (b) stirrups; (c) bonded reinforcement with anchorage plates; and (d) shearheads

PUNCHING WITHIN THE SHEAR-REINFORCED ZONE

Taking advantage of the fact that the deformation (rotation) of the slab is the key parameter governing the amount of shear carried by concrete, the theory has also been extended to flat slabs with shear reinforcement[2,9]. This can be done by considering that as the rotations of the slab increase, the shear cracks open (according to Eq. (2)), progressively activating the shear reinforcements, see Figure 7a.

The shear reinforcement develops thus tensile stresses depending on the opening of the critical shear crack and on the shear reinforcement bond conditions, see Figure 7b. This allows adapting the model to the particularities of each shear reinforcing system (applications for smooth and deformed bars can be found in Fernández Ruiz and Muttoni[2]).

For low or moderate rotations, shear reinforcement remains elastic and follows thus an activation phase where its tensile stress increases with rotations (see profile A of Figure 7b, point A in Figure 7d). This phase ends when the steel reinforcement yields (point B of Figure 7b), leading to the maximum contribution of such reinforcement. The sum of all vertical components of shear reinforcements (V_{si}, see Figure 7c) allows determining the shear carried by the transverse reinforcement (Figure 7d). It can be noted that when all shear reinforcements reach their yield strength (or anchorage strength in some cases[9]) the contribution of shear reinforcement remains constant even if rotations increase (point C in Figure 7d).

The total shear strength can finally be calculated by intersecting the failure criterion (accounting for concrete and shear reinforcement contributions) with the load-rotation relationship of the slab, see point D in Figure 7d. It is interesting to note that, with respect to the shear strength of members without transverse reinforcement (value V_{c0} in Figure 6d), the total shear strength is increased by adding a shear reinforcement, although concrete contribution at failure diminishes as the developed rotations are larger ($V_c < V_{c0}$). This theoretical result is in agreement to the empirical approach followed in most codes of practice[4,5].

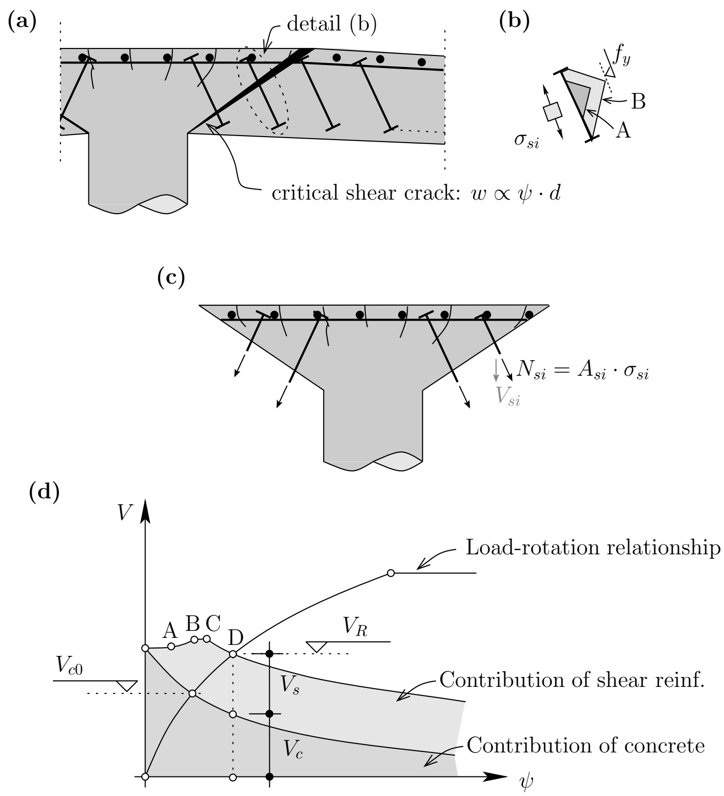

Fig. 7: Contribution of shear reinforcement: (a) opening of critical shear crack intersecting shear reinforcements; (b) profiles of longitudinal stresses in shear reinforcement for increasing opening of critical shear crack (stresses increasing from profile A to profile B, see figure (d)); (c) forces developed by shear reinforcements; and (d) total shear strength (V_R) and shear carried by concrete (V_c) and shear reinforcement (V_s)

CRUSHING SHEAR FAILURE

Crushing shear strength depends on the effective compressive strength of concrete near the column region. This strength is mainly[2] influenced by the concrete compressive strength and by the state of transverse strains of concrete.

As Figure 8 shows, compression struts may be disturbed by the presence of transverse cracking. Such cracks may be originated by bending of the slab (Fig. 8b, whose width is controlled by the flexural reinforcement), by shear (Fig. 8c, whose width is controlled by the transverse reinforcement as previously discussed) or by delamination of the core (Fig. 8d). Such cracks reduce the effective compressive strength of concrete in the crushing critical region[14]. The actual crushing strength depends thus not only on the geometry of the slab and on its mechanical and material properties, but it is also significantly influenced by the type shear reinforcement used. This is justified because the position, development and opening of the cracks affecting the compression struts is strongly influenced by the shear reinforcing system. As a consequence, detailing rules (arrangement and angle of reinforcement, sizes of anchorages,...) have a significant influence on the crushing shear strength of a shear reinforcing system.

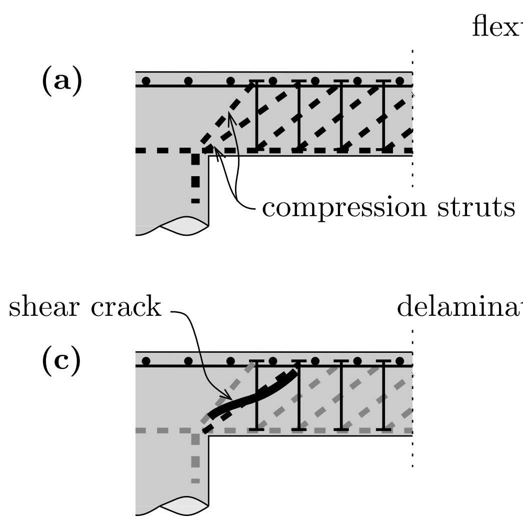

Fig. 8: Influence of cracking on crushing shear strength: (a) detail of compression struts near the support region; (b) development of flexural crack; (c) development of a shear crack; and (d) development of delamination crack

The previous considerations were taken into account in the CSCT[2], leading to the following equation to assess the crushing shear strength of flat slabs:

$$\frac{V_R}{b_0 \cdot d \cdot \sqrt{f_c}} = \lambda \cdot \frac{3/4}{1+15\dfrac{\psi \cdot d}{d_{g0}+d_g}} \qquad [\text{SI - units : MPa, mm}] \qquad (6)$$

In this equation, the same expression for the failure criterion in members without shear reinforcement is used, but multiplying it by a factor λ. The formula proposes thus to consider that the shear strength depends on the square-root of the concrete compressive strength. In addition, the shear strength is reduced for increasing rotations of the slab. This is justified because for larger rotations, crack widths and transverse strains increase and thus the effective compressive strength of concrete reduces.

With respect to factor λ, it depends on the type of shear reinforcement used since it affects the location, development and width of the cracks developing in the crushing critical region. For conventional (vertical headed) studs, where an enhanced control of shear cracking is provided, λ can be set[2] equal to 3.0. Otherwise, for systems where bars are developed by bond[2], a value of 2.0 provides conservative and realistic results. Recent researches on bonded post-installed reinforcement with anchorage plates[9] on the compression face of the member have shown an intermediate performance with a reported value[15] λ = 2.60. Also, systems based on stirrups but with stringent detailing rules[16] allow considering values of λ = 2.50.

EXPERIMENTAL RESEARCH – PERFORMANCE OF PUNCHING SHEAR REINFORCEMENT SYSTEMS

Six slabs were tested by the authors at École Polytechnique Fédérale de Lausanne. Specimens had same geometric and mechanical properties (see Figure 9 and Table 1):

- Flexural reinforcement ratio (ρ) equal to 1.50 %
- Nominal effective depth (d) equal to 210 mm
- Slabs supported on a square steel plate (260×260 mm)
- The concrete compressive strength was kept rather constant, varying between 28.4 and 36.8 MPa.

All tests had a similar shear reinforcement ratio ($\rho_w \approx 1.0\%$) except test PF2 where shear reinforcement ration was $\rho_w = 0.8\%$ and test PV1 (reference test, no shear reinforcement). The shear reinforcement ratio (ρ_w) is defined for the different specimens as:

$$\rho_w = \frac{A_{sw}}{s_l \cdot s_t} \tag{7}$$

where A_{sw} is the cross sectional area of a shear reinforcement, s_l is the distance between two shear reinforcements in longitudinal direction (radial direction for axis-symmetric arrangement) and s_t is the distance between two shear reinforcements in the transverse direction (equal to the average distance between shear reinforcements at a perimeter located at d/2 from the support region for axis-symmetric arrangement).

All tests were monotonically loaded until failure following the procedure explained by Guandalini et al.[17]. Figure 10 plots the experimental results normalized in the format of Eq.

(3). Reference test (PV1) developed a classical punching cone near the support region. Tests PV15 and PR1 failed by destruction (crushing) of the concrete nearby the support plate after experiencing large deformations. Test PB1developed the largest strength, with significant strains in the compression zone. However, it eventually punched outside the shear-reinforced zone. No information[17] is currently available on the actual failure mode of test PA6 and PF2.

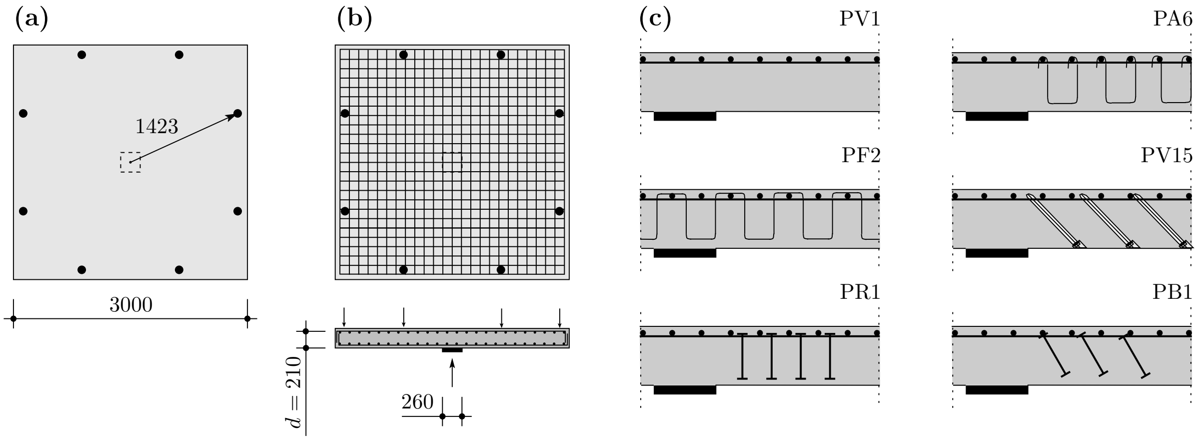

Fig. 9: Tested specimens: (a) geometry; (b) reinforcement layout (all slabs with flexural reinforcement ratio ρ = 1.50%); and (c) sketch of shear reinforcement systems investigated

Slab[Ref]	ρ_w [%]	f_c [MPa]	f_y [MPa]	f_{yw} [MPa]	V_R [kN]	ψ_R [%]	$\frac{V_R}{b_0 \cdot d_v \cdot \sqrt{f_c}}$ [-]
PV1[9]	–	34.0	709	–	974	0.76	0.470
PA6[16]	1.01	33.8	N/A	N/A	1345	N/A	0.648
PV15[15]	0.95	36.8	527	547	1609	3.11	0.741
PF2[20]	0.80	32.0	583	500*	1567	1.83	0.776
PR1[18]	1.04	31.0	515	580	1654	1.98	0.832
PB1[19]	1.04	28.4	576	388	1960	2.35	1.03

N/A: Not available
* Nominal characteristic strength of steel. Values for tested specimen not available

Table 1: Main properties of tested specimens (ρ_w: shear reinforcement ratio, f_c: concrete compressive strength; f_y: yield strength of bending reinforcement; f_{yw}: yield strength of shear reinforcement; V_R maximum load during testing; ψ_R slab rotation at maximum load) and calculated values of coefficient λ.

Significant differences both on strength and deformation capacity at failure can be observed depending on the type of shear reinforcement considered, see Figs 10 and 11. Stirrups with development lengths on the tension side (test PA6) show the less performing behaviour, with an increase on the failure load of 38% with respect to the reference test. Post-installed shear reinforcement (specimen PV15, fig. 10a) shows better performance (57% increase on normalized failure load) with a large deformation capacity at ultimate. Such good behaviour is due to the good performance of the epoxy mortar and to the development capacity provided by the lower anchorage plates. Continuous cages of stirrups (specimen PF2) allow a slightly better performance in terms of strength (70% increase) but with a fairly brittle failure mode (Fig. 10b). With respect to studs, they exhibit the largest capacities, with increases on the failure load of 77% and 119% for vertical and inclined arrangements respectively (Figs. 10c,d). Deformation capacity is also significantly increased for slabs with studs as shear reinforcement.

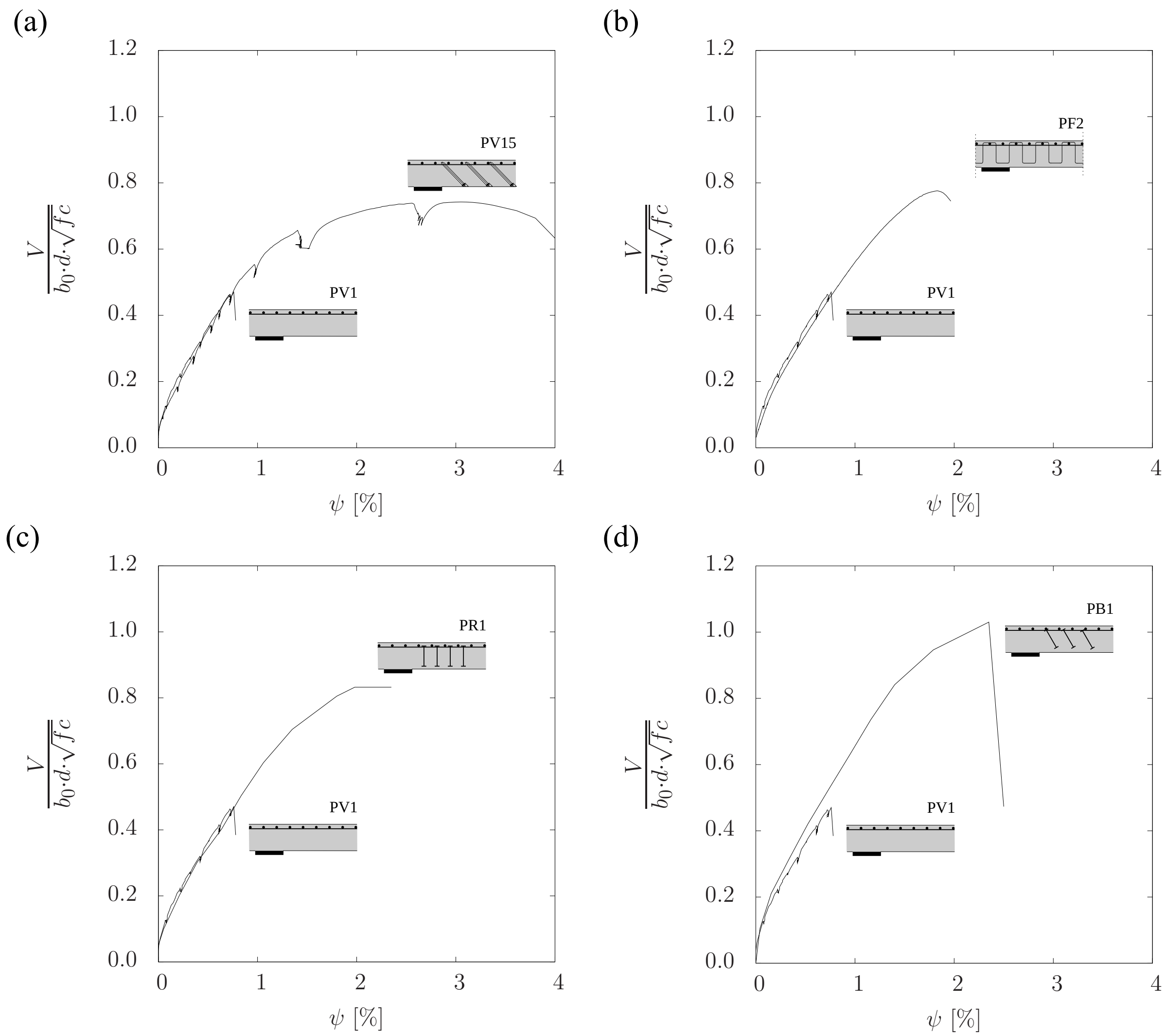

Fig. 10: Measured load-rotation curves of specimens: (a) PV1 and PV15; (b) PV1 and PF2; (c) PV1 and PR1; and (d) PV1 and PB1

It should be noted that each system presented within this paper is only investigated on the basis of one test result (consistent conclusions for each system should account for more test results as discussed elsewhere[2,15,16]). Nevertheless, the experimental results confirm the following aspects:

- Crushing shear failure strength is highly influenced by detailing rules, anchorage and development conditions (which should be taken into account with coefficient λ).
- Systems with more performing anchorage (headed bars usually) exhibit larger strengths and deformation capacities. Best performance is shown by studs followed by cages of continuous stirrups. Stirrups with development lengths on the tension side of the slab show the lowest strength increases
- Inclined reinforcement is an effective way to increase crushing shear strength of slabs as a significant fraction of the applied load can be transmitted by direct strutting to the support region
- Bonded (post-installed) shear reinforcement provides large deformation capacities with a notable increase on the punching shear strength.
- Experimental research is needed to assess a safe and realistic value of coefficient λ and to eventually propose a design method for a shear reinforcing system

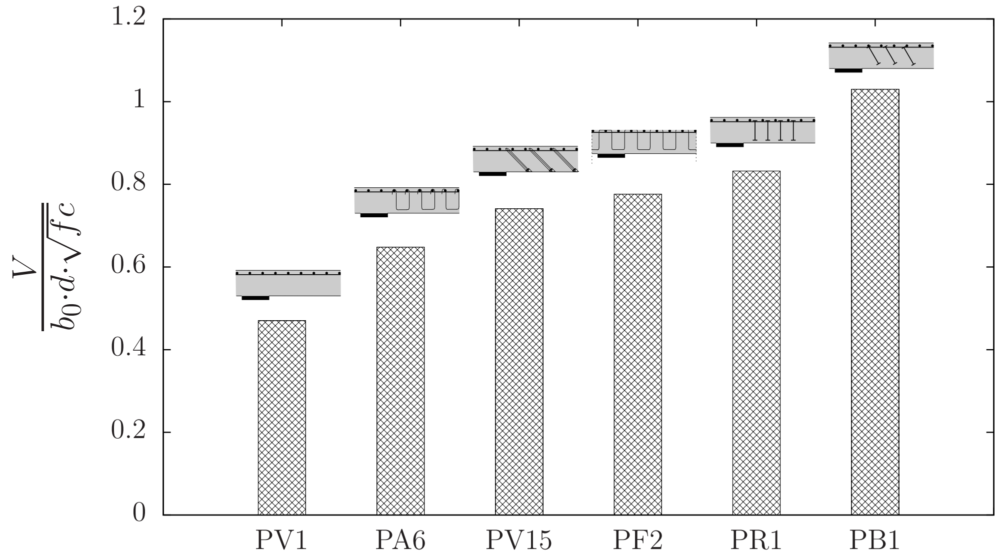

Fig. 11: Comparison of normalized failure loads for all specimens

CONCLUSIONS

This paper investigates the performance of punching shear reinforcing systems on the basis of the critical shear crack theory. The main conclusions of the paper are:

1. The behaviour of punching shear reinforcing systems is largely influenced by the detailing rules of the transverse reinforcement and by its anchorage or development conditions
2. Most current codes do not account for such influences, limiting the applicability of their approaches to a number of systems complying with their detailing rules

3. The critical shear crack theory, based on a physical model, allows considering the influence of bond and anchorage conditions on the various potential failure modes of punching shear reinforcing systems
4. With reference to crushing shear strength, the experimental results presented within this paper confirm the influence of the type of punching shear reinforcing system on the strength and deformation capacity of slabs. Systems with more performing anchorages and with inclined bars exhibit the largest capacities.

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