

PUNCHING SHEAR RESISTANCE OF UHPFRC SLABS: EXPERIMENTAL WORKS AND DESIGN MODEL

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Abstract

For members and flat slabs without shear reinforcement, the shear and punching shear strength are often the determining design criteria. These failure modes are characterized by a brittle behaviour with possible partial or total collapse of the structure. The ability of Steel Fibre Reinforced Concrete (SFRC) to reduce shear reinforcement of reinforced concrete members and slabs or even to eliminate it, is supported by several experimental studies. However its practical application remains marginal mainly due to the lack of standards, procedures and rules adapted to its performance. In comparison with conventional SFRC, the high tensile strength and toughness of UHPFRC allow the structural elements to achieve a significantly higher resistance and deformation capacity. This paper presents several results of an original experimental campaign carried out at the HES-SO, Fribourg, on UHPFRC slabs with and without conventional steel reinforcement. On the basis of the test results, the authors propose harmonized models for the punching shear strength of UHPFRC structures.

Résumé

Le cisaillement est un mode de rupture souvent déterminant pour assurer la résistance des structures en béton armé. Pour des éléments ne comportant pas d'armatures transversales, ce mode de rupture est généralement fragile entraînant l'effondrement de la structure sans signes avant-coureurs. Dès les premiers développements des bétons de fibres, la réduction voire la suppression totale des armatures dites secondaires dans les éléments de structure s'est avéré être une solution technique intéressante. L'augmentation de la ténacité en traction des BFUP par rapport aux bétons de fibres ordinaires permet aux éléments de structure d'atteindre une résistance et une capacité de déformation au cisaillement élevée. Cet article présente dans une première partie des expérimentations, menées à l'Ecole d'Ingénieurs et d'Architectes de Fribourg, visant à quantifier le comportement au poinçonnement de dalles en BFUP. Dans une seconde partie, une méthode de vérification des BFUP pour ces sollicitations, mise au point à partir du corpus expérimental est proposée.

1. INTRODUCTION

Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) present significantly higher mechanical properties and very low permeability compared to plain concrete. UHPFRC has undeniable potential to allow innovative design and to improve durability of structures [1, 2]. Thanks to this high tensile strength and toughness, elements subjected to moderate stress or having complex shape can be realized without ordinary reinforcement especially the shear reinforcement.

For members and flat slabs without shear reinforcement, the shear and punching shear strength are often the determining design criteria. These failure modes are characterized by a brittle behaviour with possible partial or total collapse of the structure. The ability of Steel Fibre Reinforced Concrete (SFRC) to reduce shear reinforcement of reinforced concrete members and slabs, or even to eliminate it, is supported by several experimental studies. However its practical application remains marginal mainly due to the lack of standards, procedures and rules adapted to its performance. In comparison with conventional SFRC, the high tensile strength and toughness of UHPFRC allow the structural elements to achieve a significantly higher resistance and deformation capacity.

Therefore, adapted rules based on the latest developments on shear and punching shear strength of reinforced concrete members need to be developed. This paper presents several results of an experimental campaign carried out at the University of Applied Sciences (HES-SO), Fribourg, on UHPFRC thin slabs with and without conventional steel reinforcement. The principal aim of this research was to analyse the interaction between the thickness, the reinforcement ratio and the fibre volume ratio on punching shear strength. The tests have highlighted the beneficial contribution of UHPFRC combined with steel reinforcement on flexural and shear capacity.

2. MATERIAL PROPERTIES

The test specimens were made in Béton Composite Vicat BCV[®]. The BCV is developed by Vicat and belongs to the family of UHPFRC as defined in the interim recommendations of the French Civil Engineering Association (AFGC) [3]. The two following compositions with their respective names were analysed:

- BCV-1 %A short steel fibre 13/0.18 mm, $V_f = 1\%$ (79 kg/m³)
- BCV-2 % mix steel fibre 13/0.18 and 20/0.30 mm, $V_f = 2\%$ (158 kg/m³)

The BCV had an average compressive strength f_{cm28} of 130 MPa and a f_{cm90} of 150 MPa on cylinder. The Young's modulus at 28 days was around 45 GPa. According to the French interim recommendations for UHPFRC [3], the post-cracking response of a thin element is defined by a bending test on a prism with the same thickness. In order to evaluate the thickness influence on the post-cracking response, an experimental campaign was performed. The experimental study was composed of 32 prisms with 200 mm wide and 700 mm length. The varying parameters were the thickness h and the fibre volume ratio V_f . The prisms were tested in three-points bending on a specially designed setup (Figure 1). The prisms were simply supported on steel roller supports with a clear span of 500 mm. A single load was applied at the centre by a hydraulic jack via a steel roller.

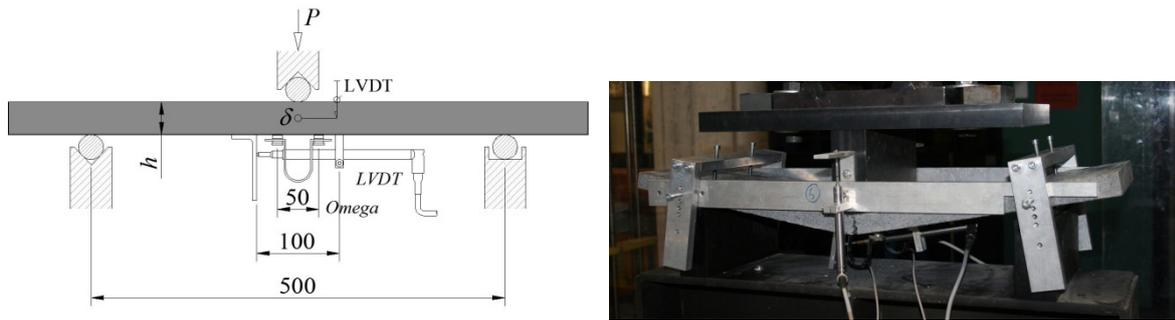


Figure 1: Three-point bending test setup of the UHPFRC prisms

The two mixes showed a hardening behaviour in bending, with an equivalent bending stress going from 14 to 16 MPa for the BCV 1%A and from 23 to 28 MPa for the BCV 2 % (Figure 2). The bending stress was positively influenced by small thickness, especially for the BCV-2 %. This fact is due to a preferential orientation of the 20 mm length fibre in thin specimens. For the BCV-1 %, which was only composed of straight short fibre, this trend is not clear. The deflection capacity is inversely proportional to the thickness. The deflection capacity of thin prism in BCV-1 % ($h = 30$ and 40 mm) is higher compared to the prisms in BCV-2 % probably due to the formation of several macro-cracks. For thick prisms the deflection capacity is similar between the mixes BCV-1 % and 2 %. The tensile were identified according to AFGC inverse analysis for thin element [3].

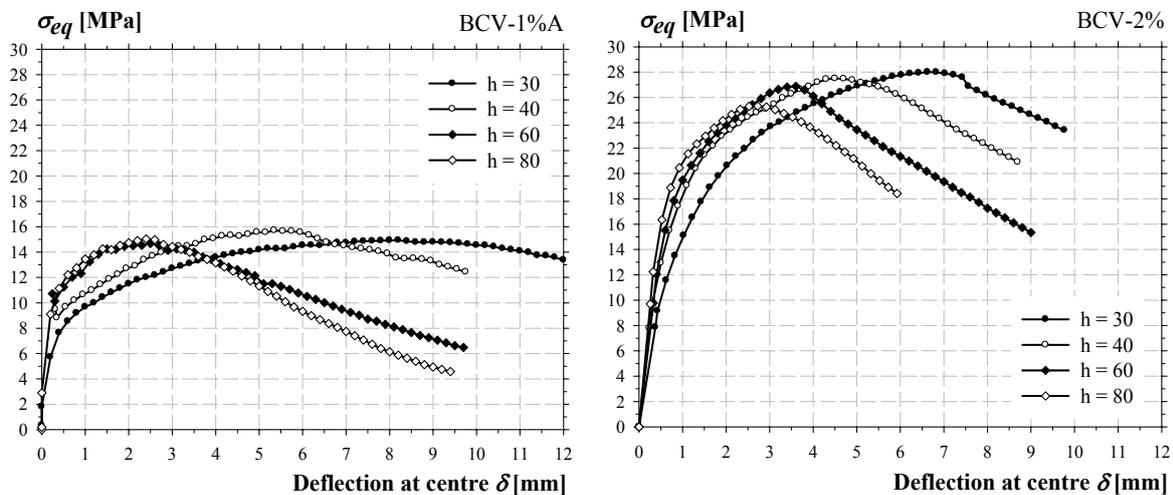


Figure 2: Average curves equivalent bending stress vs. deflection at centre of the UHPFRC prisms

3. DESCRIPTION OF EXPERIMENTAL STUDY ON PUNCHING SHEAR

The experimental study was conducted on nineteen square slabs with a 960 mm side in order to evaluate the flexural and punching shear behaviour of UHPFRC thin slabs [4]. The varying parameters among the specimens were: the thickness h , the fibre volume ratio V_f , the reinforcement ratio ρ and the reinforcement arrangement (Table 1).

Table 1: Specifications of the test slabs

Series	Thickness h [mm]	Reinforcement ρ [%] / [mm]	Fiber volume ratio V_f [%]	Effective depth d [mm]
BCV- V_f _30_ ρ	30	without	1 / 2	15
		1.36 / $\phi 5$ #100 A*	2	
		2.67 / $\phi 7$ #100 A	1	
BCV- V_f _40_ ρ	40	without	2	20
		1.02 / $\phi 5$ #100 A	1 / 2	
BCV- V_f _60_ ρ	60	without	2	40
		1.00 / $\phi 7$ #100 A	2	
		1.49 / $\phi 9$ #100 B	1 / 2	
		1.66 / $\phi 9$ #100 A	2	
BCV- V_f _80_ ρ	80	without	2	60
		1.10 / $\phi 9$ #100 A	1 / 2	
		1.77 / $\phi 12$ #100 B	1 / 2	
		1.96 / $\phi 12$ #100 A	1	

* reinforcement arrangement according to Figure 3

Two reinforcement arrangements were adopted (Figure 3). The first arrangement, type A, consisted of a regular square mesh, positioned in a way to have the centre of a cell positioned at the centre of the slab. The second arrangement, type B, consisted also of a regular square mesh, placed in a way to have the rebars positioned at the centre of the slab. This second arrangement was only applied on 4 slabs having high reinforcement ratios with 60 and 80 mm thicknesses. According to the reinforcement ratio, the steel mesh was composed of $\phi 5/7/9/10/12$ diameter with a 100 mm pitch. The effective depths were 15, 20, 40 and 60 mm for the respective thicknesses of 30, 40, 60 and 80 mm.

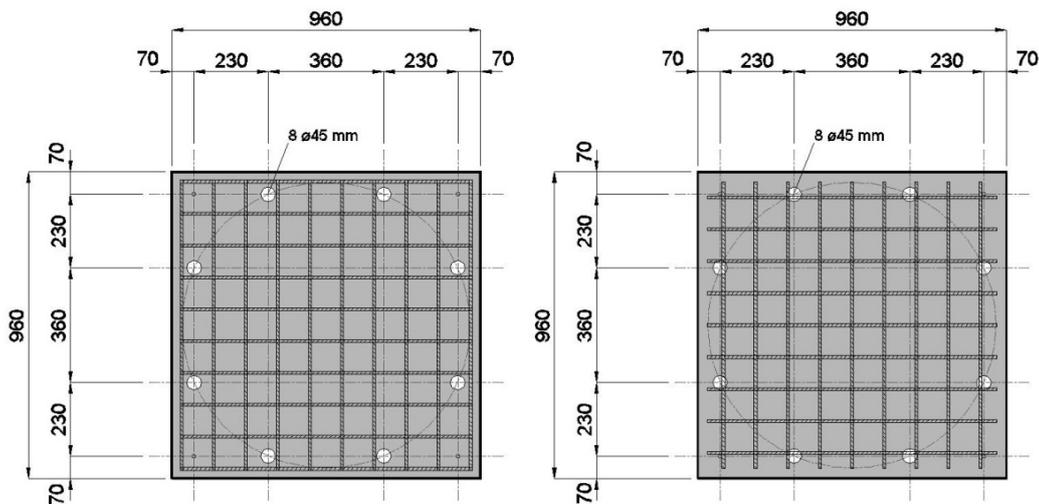


Figure 3: Reinforcement arrangement type A on left and B on right

One part of the test slabs were made in a precast plant of the firm Creabeton Matériaux and the other part at the laboratory of UAS Fribourg. All slabs were casted in a similar manner without any vibration. The UHPFRC was poured in the middle of the formwork (Figure 4). The flow was regular for the slabs without reinforcement and disturbed for the reinforced ones. They were then removed of the framework after 1 day and stored inside the plant surrounded by plastic sheet, approximately for two weeks.



Figure 4: Casting process with and without reinforcement

The load tests have been carried out, on a punching test setup specially designed for this study (Figure 5). The load was applied with an actuator located at the centre point of the slab through a 80 mm diameter punch in steel. The slab was supported by eight steel rods, anchored to a steel frame. The support system described a circle with a diameter of 878 mm and spherical plain thrust bearings allowed free rotations. The tests were controlled in displacement by a servo-electronic system. The load was applied by increments until the failure load and the load increments depended on the thickness. At each step, the cracking pattern was plotted.

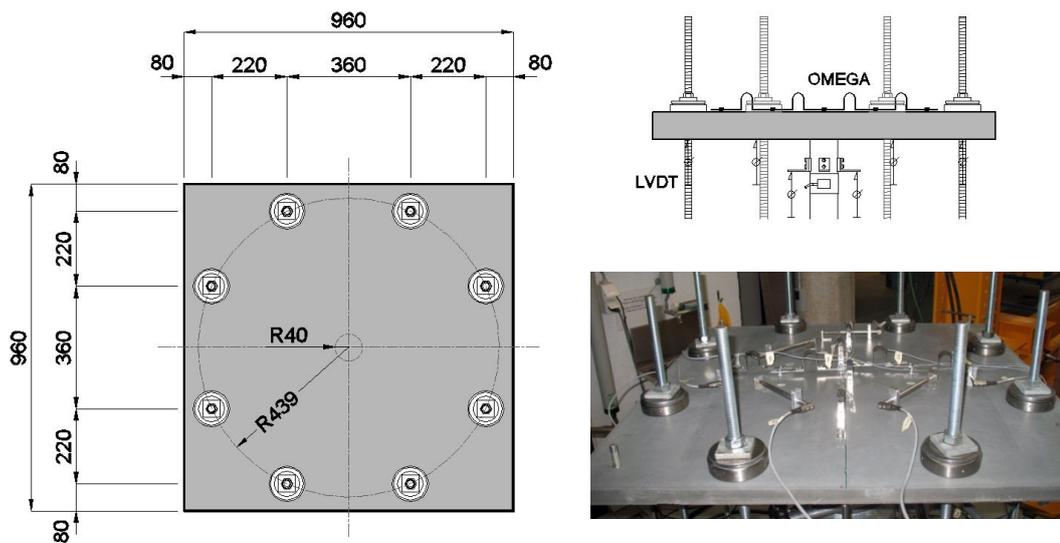


Figure 5: Punching shear test setup of the UHPFRC slabs

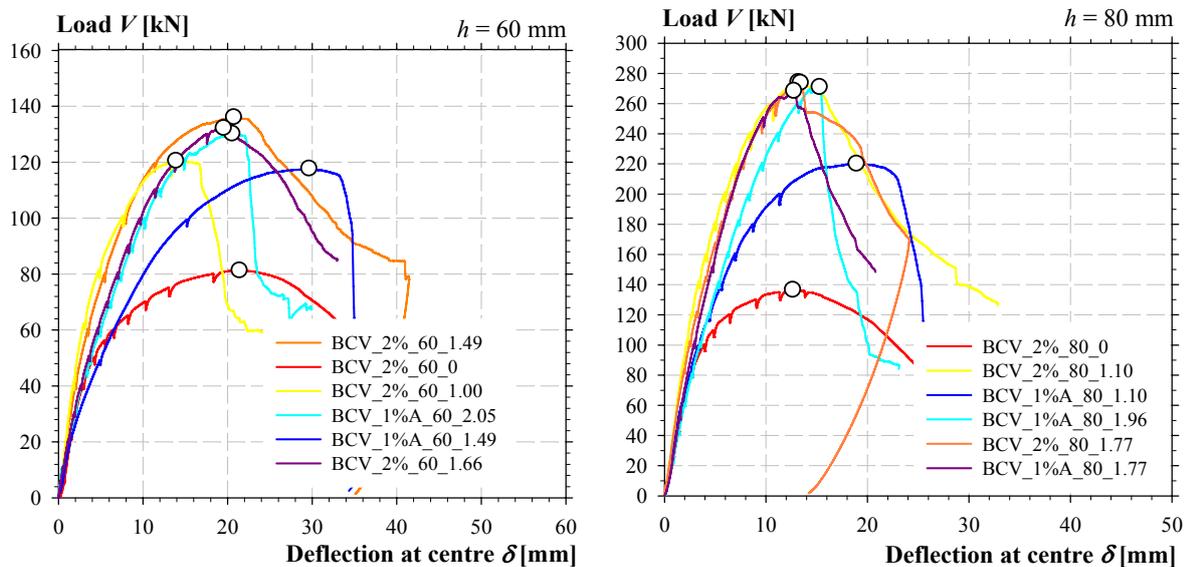


Figure 6: Curves load vs deflection at centre of the UHPFRC slabs of 60 and 80 mm thick

Tests results for UHPFRC slabs of 60 and 80 mm thick are shown on Figure 6. The reinforced slabs in BCV-2 % showed a higher stiffness in the elastic-cracked state compared to the slabs BCV-1 %A. For slabs, BCV_x_80_1.10 and BCV_x_60_1.49 having the same reinforcement ratio and thickness, as the fibre content increases, the flexural and punching shear strength increases as well, but the deformation capacity decreases. The slabs BCV_x_80_1.77 with the reinforcement arrangement type B exhibited the same pre-peak behaviour. These two slabs failed in punching shear, but the slab in BCV-2% showed a more ductile post-peak behaviour. For the specimens with the reinforcement arrangement B, BCV_x_60_1.49 and BCV_x_80_1.77, the dowel action of the rebars at the centre was important in the post-peak response.

As the thickness increases, the difference between the slabs with reinforcement is higher. The effective depth of the reinforcement is more efficient for thick specimens compared to the thin slabs with a reinforcement located at the neutral axis. For the reinforcement arrangement type A, we distinguished two types of punching shear failure mechanisms; In the first type, the critical shear crack intercepts the rebars, resulting in the development of a large punching cone and thus the load carrying capacity was high (Figure 8). In the second type, the critical shear crack didn't intercept the rebars, the punching cone was restrained in a mesh's cell and the load carrying capacity was lower (Figure 7). The second type concerned particularly the slabs with a thickness of 30 and 40 mm. The rebars included in the punching cone allowed a better control of the shear cracks development compared to the cone formed in the slabs reinforced with the fibre alone.



Figure 7: Internal shear crack of thin slab

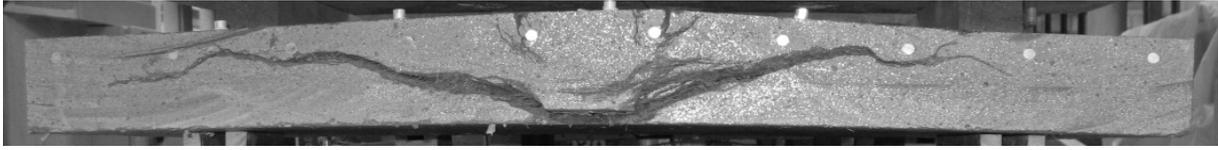


Figure 8: Internal shear crack of thick slab

4. ANALYTICAL STUDY

On the basis of the Critical Shear Crack Theory (CSCT) and a proposal for fibre reinforced concrete developed by Muttoni and Fernandez [5]-[7], we adapted the punching shear strength model to the UHPFRC. The developed punching shear model involves the contributions of the matrix $V_{R,c}$ and the fibres $V_{R,f}$. For the matrix contribution, it is assumed that the punching shear strength is carried by the shear friction and is a function of the critical crack opening. The critical crack opening is assumed to be proportional to the product of the effective depth d with the slab rotation ψ . Based on these assumptions, the concrete contribution is defined as the following:

$$V_{R,c} = \frac{3/4}{1 + 15 \cdot \frac{\psi \cdot d}{16 + d_g}} \cdot b_0 \cdot d \cdot \sqrt{f_c} \quad (1)$$

where b_0 is the control perimeter, located at $d/2$ of the edges of the loading support, d_g is the diameter of the biggest aggregate, for UHPFRC $d_g = 0$. The fibres contribution corresponds to the vertical component of the integration of the tensile stresses across the punching shear plan A_p (Figure 9). The distribution of the crack opening is assumed to be linear. With the tensile stress – opening law $\sigma(w)$, the distribution of the tensile stresses is defined along the failure plan. The contribution of the fibres to the punching shear strength is given by:

$$V_{R,f} = \frac{1}{K} \cdot \int_{A_p} \sigma_f(w) \cdot dA_p \quad (2)$$

where K is a factor to account for the fibres orientation.

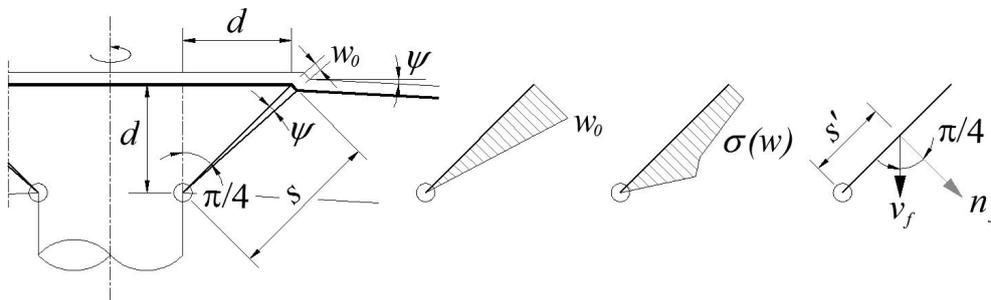


Figure 9: Mechanical model and parameters

In the following equation, we propose a simplified design model integrating the safety factors, V_R become V_{Rd} . The integration of complicated tensile law (2) is not appropriate for a simplified design approach. A constant stress distribution allows a rapid and a simple

computation. The fibre contribution $V_{Rd,f}$ depends on the slab's rotation ψ , the ultimate crack opening w_u is assumed to be equal to 5 mm. The simplified contribution of the fibres to the punching shear strength is given by:

$$V_{Rd,f} = \frac{f_{Utk}/\gamma_U \cdot b_0 \cdot d}{1 + \frac{\psi \cdot d}{w_u}} \quad (3)$$

where f_{Utk} is the post-cracking tensile strength determined on uniaxial tests, ψ_U is the partial safety factor and w_u is the ultimate crack opening.

For determining the punching strength, the load – rotation curve must be previously calculated. The relationship $V(\psi)$ can be modelled by finite difference or finite element methods [7]. The intersection between this curve and the failure criteria corresponds to the punching shear strength. If the curve does not cut the criteria, the flexural strength is determining. In the graphics of Figure 10 the dotted curves represent the fibres contribution along the thickness h and the plain curves represent the sum of the matrix and fibres contribution on the effective depth d . The different criteria show a good correlation with the tests results and the observed mechanisms. However, the punching shear is a local phenomenon and thus the variability due to fibres orientation can affect the strength in a non-negligible manner.

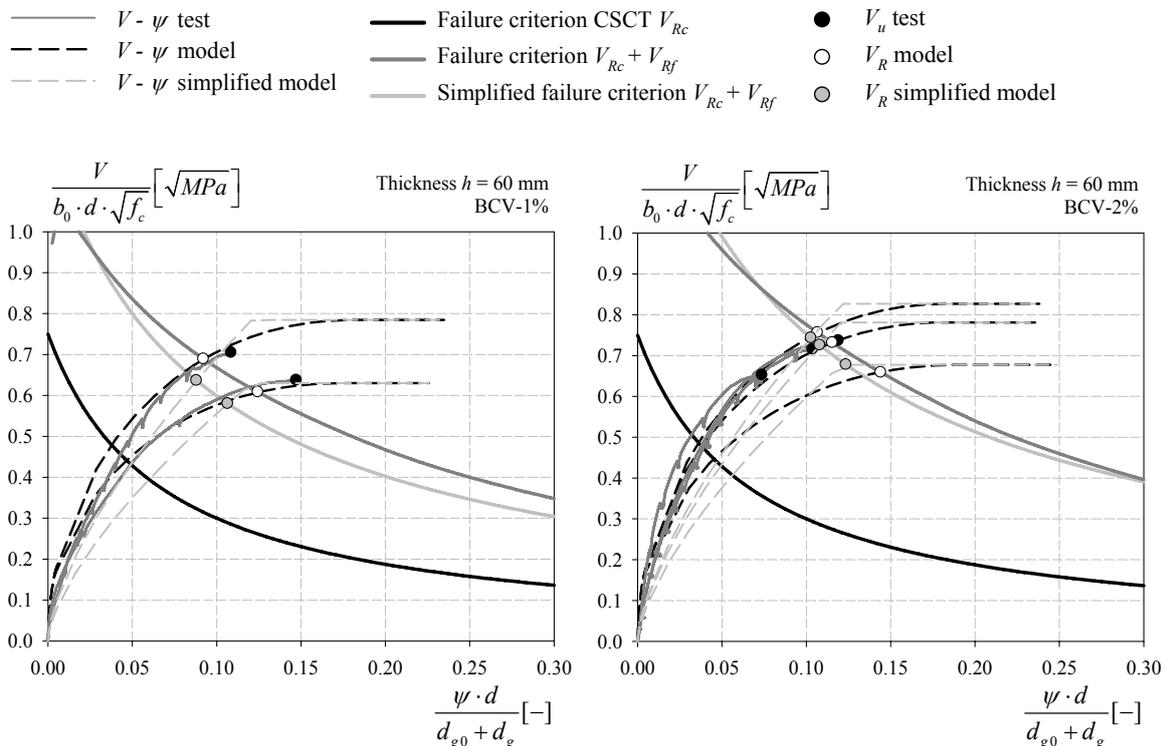


Figure 10: Comparison between the test results and the model for the reinforced slabs of 60 mm thickness in UHPFRC with a fibre volume ratio of 1 % and 2 %

Table 2: Summary of tests and computed values for UHPFRC slabs

Specimen	V_f [%]	h [mm]	ρ_s [%]	V_u [kN]	V_R [kN]	V_u/V_R [-]	$V_{R,simpl.}$ [kN]	$V_u/V_{R,simpl.}$ [-]
BCV-1%A_30_2.67	1	30	2.67	49.6	34.3	1.45	33.3	1.49
BCV-1%A_40_1.02	1	40	1.02	49.0	44.1	1.11	43.5	1.13
BCV-1%A_60_1.49	1	60	1.49	118	112	1.05	107	1.10
BCV-1%A_60_2.05	1	60	2.05	130	127	1.02	117	1.11
BCV-1%A_80_1.10	1	80	1.10	220	202	1.09	192	1.15
BCV-1%A_80_1.77	1	80	1.77	268	236	1.14	214	1.25
BCV-1%A_80_1.96	1	80	1.96	49.6	243	1.11	221	1.23
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BCV-2%_30_1.36	2	30	1.36	41.9	39.1	1.07	39.9	1.05
BCV-2%_40_1.02	2	40	1.02	47.9	45.5	1.05	49.5	0.97
BCV-2%_60_1.00	2	60	1.00	120	122	0.99	126	0.96
BCV-2%_60_1.49	2	60	1.49	136	140	0.97	137	0.99
BCV-2%_60_1.66	2	60	1.66	132	135	0.98	134	0.99
BCV-2%_80_1.10	2	80	1.10	274	241	1.14	239	1.15
BCV-2%_80_1.77	2	80	1.77	274	271	1.01	261	1.05
						Mean	1.08	1.11
						CoV	0.11	0.13

The complete and simplified models present a good agreement compared to the 14 UHPFRC slabs with reinforcement. The average ratio between measured-to-predicted punching shear strength is 1.08 and 1.11 the coefficient of variation is 0.11 and 0.13, for complete model and simplified model respectively. The proposed models are based on the post-cracking response determined on specimens. A good and representative identification of the tensile post-cracking response is the key factor of this model. For design computation, partial safety factor may be considered for the characteristic values of the material properties according to the European practice.

5. CONCLUSIONS

Since 2007, the University of Applied Sciences Fribourg has conducted a large research program on UHPFRC structures. The principal aim of this project was to analyse the behaviour of UHPFRC and reinforced-UHPFRC elements and to propose design models, particularly for shear and punching shear resistance. Several experimental studies on structural elements, beams and slabs, were undertaken for this purpose. The different results will contribute to the development of a recommendation of the Swiss Society of Engineers and Architects (SIA) for the design and the construction of UHPFRC structures [9]. This contribution shows the principal results of the theoretical and experimental studies on the punching shear resistance. The experimental program was composed of 19 UHPFRC slabs

according to 3 principal parameters, the thickness, the steel reinforcement ratio and the fibre content.

The studies have highlighted the following points:

- The high tensile strength and toughness of UHPFRC allows an effective control of the punching critical shear crack so that the slabs showed a high punching shear resistance.
- The flexural strength of UHPFRC slabs without reinforcement was moderate, therefore the punching shear resistance was not determining in the studied case.
- For reinforced-UHPFRC slabs, distinct failure mechanisms were observed: (i) flexural failure, characterized by large deformations with a post-peak softening behaviour; (ii) punching shear failure described by a sudden drop in the load without a significant plastic deformation and (iii) a combined flexural and shear failure where the flexural strength was reached, but the punching shear limit restricted the plastic deformation capacity. These failure mechanisms depend on the different parameters.
- On the basis of the Critical Shear Crack Theory the authors propose harmonized model for the punching shear strength of reinforced-UHPFRC slabs. On the same basis a code like approach is also proposed. In comparison with the test results the models give accurate prediction.

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