

Punching shear resistance of UHPFRC

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1 Abstract

Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) is a high performance cementitious material with enhanced strength in tension and compression and significantly high energy absorption in the post crack region. Its mix composition is not much dissimilar from that of normal strength concrete. The main difference is that only fine aggregates are used in order to enhance the homogeneity of the mix, while microsilica is used to improve the density of the mix thereby reducing voids and defects. A high percentage of steel fibres is used to increase the tensile strength and at the same time to provide ductility.

UHPFRC has been recently introduced in applications such as bridge decks, thin slabs and for the strengthening of existing elements. Even if there are various published studies on the compressive, tensile and flexural characteristics of UHPFRC, the punching shear performance of UHPFRC without additional steel bars has not been sufficiently studied. In this paper an extensive experimental work has been conducted on UHPFRC tiles with various thicknesses and various percentages of steel fibres and tests have been conducted under a concentrated load. Using the experimental results, the punching shear characteristics of the various UHPFRC mixes have been evaluated and shear resistance values have been proposed.

Keywords: UHPFRC; slabs; punching shear.

2 Introduction

Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) is a relatively new construction material which has been extensively used in the last few years in various applications including, bridge decks, thin structural elements and strengthening applications. Its special mix design provides superior mechanical characteristics and enhanced ductility, and this makes UHPFRC one of the most popular high strength cementitious material for structural applications. There is quite extensive research on the effectiveness of UHPFRC for the

structural upgrade and more specifically on the flexural and shear strengthening of existing Reinforced Concrete (RC) elements and it has been found that the addition of UHPFRC can significantly improve the structural performance of the existing elements [1-3]. The effectiveness of the addition of UHPFRC layers for the improvement of the punching shear resistance of RC slabs has also been examined and it has been found that significant improvement of the punching shear resistance of existing slabs can be achieved by the addition of UHPFRC [4] layers, while an analytical model for the prediction of the punching shear of

the composite/strengthened elements has also been proposed [5]. Most of these published papers are focused on the performance of strengthened elements with UHPFRC. To date there are very limited studies on the punching shear performance of Steel Fibre Reinforced Concrete (SFRC) [6, 7] and UHPFRC slabs [8, 9] and so far, there are not any published studies on the punching shear resistance of thin UHPFRC slabs without additional steel bar reinforcement.

This paper is focused on the evaluation of the punching shear performance of thin unreinforced UHPFRC slabs. Various thicknesses have been examined and the results have been used to calculate the punching shear resistance of UHPFRC.

3 Experimental Investigation

In this paper, UHPFRC slabs with different thicknesses were examined. Central loading was applied, and the experimental results were used for the evaluation of the flexural and punching shear performance of thin UHPFRC specimens.

3.1 UHPFRC preparation and mix-design

UHPFRC is a material with enhanced strength in tension and compression and significantly high energy absorption in the post-cracking region. One of the main characteristics of UHPFRC is the enhanced homogeneity which is achieved by using fine aggregates only. In the mix design of the present study, silica sand with maximum particle size of 500 μ m was used together with silica fume and Ground Granulated Blast Furnace Slag (GGBS). Silica fume, with particle size almost 100 times smaller than cement, improve not only the density of the matrix but also the rheological properties, while GGBS is used as a partial replacement of cement. High steel fibre content (3%) of straight fibres with 13 mm length and 0.16 mm diameter were used. The mix design is presented in Table 1.

For the preparation of UHPFRC the dry ingredients were mixed first for 3 minutes in a high shear mixer Zyklos (Pan Mixer ZZ 75 HE), then the water and the superplasticizer were added to the mix and, at the end, the steel fibres were added gradually. The specimens were cured at ambient temperature and humidity conditions for almost two months until the day of the testing.

Table 1. UHPFRC Mix design

Material	Mix proportions (Kg/m ³)
Cement (32.5)	657
GGBS	418
Silica fume	119
Silica Sand	1051
Superplasticizers	59
Water	185
3% Steel Fibres (13 mm length and 0.16 mm diameter)	236

3.2 Description of the examined slabs

The examined slabs had dimensions 600mmx600mm and four different thicknesses were examined, 12 mm, 22 mm, 32 mm and 42 mm. In addition to the UHPFRC specimens with 3% steel fibres, specimens with plain Ultra High Performance Concrete (UHPC) without steel fibres were examined (S-30-P).

Three specimens were examined for each thickness and the examined specimens are presented in Table 2.

Table 2. Description of the examined slabs

Specimen ID	Target thickness	Average actual thickness (mm)
S-10-1	10mm	12mm
S-10-2		
S-10-3		
S-20-1	20 mm	22mm
S-20-2		
S-20-3		
S-30-1	30 mm	32mm
S-30-2		
S-30-3		
S-40-1	40 mm	42mm
S-40-2		
S-40-3		
S-30P-1	30 mm	31mm
S-30P-2		
S-30P-3		

In addition to the slabs, cubes with 100 mm side and dog bone shaped specimens with 20 mm x 14 mm cross section were examined to evaluate the compressive and tensile strength respectively.

3.3 Testing of the examined specimens

3.3.1 Description of the testing setup

For the testing of the slabs, Instron Universal Testing machine was used. The load was applied to the middle of the slab using a circular loading area of 46 mm diameter and two Linear Variable Differential Transformers (LVDTs) were used to record the deflection of the plates during the loading as illustrated in Figure 1. The slabs were simply supported and the spacing between the supports in both sides was equal to 540 mm.

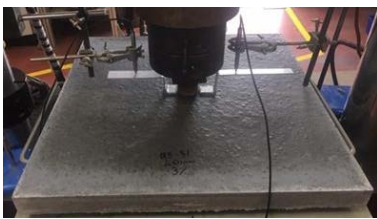


Figure 1. Loading setup used for slabs' testing

Deflection control was used for the testing of the slabs with a loading rate equal to 0.5 mm/min.

For all the different UHPFRC mixes, standard cubes with 100 mm side and dog-bone specimens were also tested to evaluate the compressive and the tensile strength characteristics of the material.

3.3.2 Experimental results

The average load deflections results for all the examined types are presented in Figure 2. The main observation from the results of Figure 2, is that the maximum load capacity is increased as the thickness of the slabs is increased as expected.

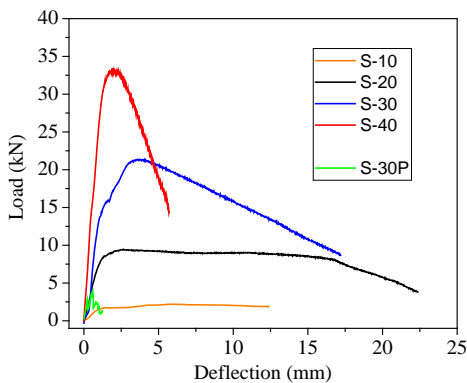


Figure 2. Average curves for all the examined types

The specimens without steel fibres (S-30-P) performed in a very brittle way and failed at a significantly lower load value compared to the respective specimens with 3% steel fibres (S-30).

The typical failure mode for each type of specimens is presented in Figure 3.

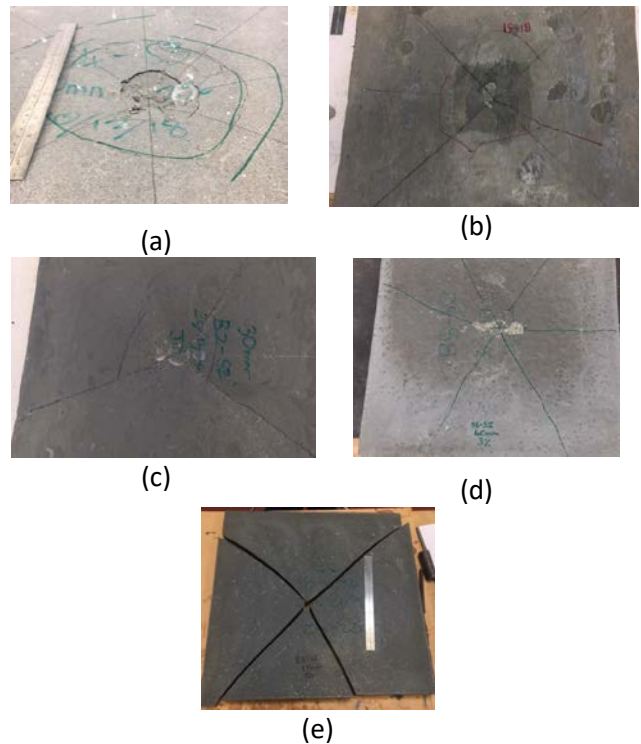


Figure 3. Typical failure mode for a) S-10, b) S-20, c) S-30, d) S-40 and e) S-30-P slabs

All the specimens with 12mm thickness had a clear punching shear failure as demonstrated in Figure 3a. In case of 22 mm slabs, the failure occurred with punching shear cracks while flexural cracks also occurred (Figure 3b). For 32 mm slabs, flexural failure was mainly occurred while some punching shear cracks also appeared (Figure 3c). As the thickness of the slabs was further increased and for all the examined specimens with 42 mm thickness clear flexural failure was observed (Figure 3d). Regarding the specimens without steel fibres (S-30-P), flexural failure occurred in a brittle way (Figure 3e) as expected, and the load capacity of these specimens was considerably lower compared to the respective specimens with the same target thickness and steel fibres (S-30).

From the specimens where punching shear failure was observed (S-10 and S-20) the failure perimeter was obtained. The perimeter of the punching shear

failure crack was measured in all the three S-10 specimens and the failure perimeters were found equal to 301.59 mm, 270.18 mm, and 282.74 mm leading to an average critical shear perimeter of 284.84 mm. For S-20 slabs, the perimeter of the shear crack was measured in two of the examined specimens which exhibited a clear punching shear failure and the critical perimeters were found equal to 534.07 mm and 502.65 mm leading to an average punching shear perimeter of 518.36 mm.

The compressive and tensile stress characteristics of all the examined specimens were also evaluated from standard 100 mm cube testing and from the direct tensile testing of dog bone specimens which was conducted at the same day with the testing of the slabs and the compressive test results are presented in Table 3. For S-10 specimens, only one cube was available since the other two cubes were damaged during the demoulding.

Table 3. Compressive test results

Corresponding slab type	Age at testing (days)	Compressive Strength, f_c (MPa)	Average, f_c (MPa)
S-10	58	119.6	119.6
		157	
S-20	69	147.4	151.4
		149.8	
		123.1	
S-30	64	120.2	122.9
		125.4	
		102.8	
S-40	69	119	119.4
		136.4	
		121.4	
S-30-P	63	112.9	116.1
		114	

The tensile strength characteristics were evaluated from the dog bone specimens. Some of the examined specimens failed near the grips at a very early loading stage due to stress concentrations and local weak points at these areas. The results of the successful tests were collected, and the tensile strength was calculated to have an average value of 3.5 MPa. The compressive and tensile strength characteristics were lower than what is normally expected for UHPFRC and this is attributed to the

low strength cement of the mix (32.5) and the ambient curing conditions.

3.3.3 Analytical calculation of the punching shear and flexural strength of UHPFRC slabs

In this section, the analytical calculation of the maximum load capacity of the UHPFRC slabs will be presented.

For the analytical calculation of the punching shear resistance (V_u), models proposed for SFRC by Harajli *et al.* [6] (1) and Shaaban and Gesund [7] (2) were examined.

$$V_u(N) = (0.54 + 0.09 \cdot v_f) \cdot b_o \cdot d \cdot \sqrt{f_c} \quad (1)$$

$$V_u(N) = \frac{(0.3 \cdot w_f + 6.8)}{12} \cdot b_o \cdot d \cdot \sqrt{f_c} \quad (2)$$

where:

- v_f is the volumetric percentage of fibres in %;
- w_f is the percentage of fibres per weight of concrete;
- b_o is the perimeter of punching in mm;
- d is the effective depth of the slab in mm;
- f_c is concrete compressive strength in MPa.

In all the examined specimens, $v_f=3\%$ was used while the equivalent w_f is equal to 9%. For specimens S-10 the measured punching perimeter (b_o) was 284.84 mm and for specimens S-20 the punching perimeter (b_o) was 518.36 mm as mentioned in section 3.3.2.

By applying Equations (1) and (2), the maximum punching shear load for S-10 was calculated as 20.29 kN and 21.27 kN respectively which are considerably higher (almost ten times higher) than the obtained experimental load which was found equal to 2.2 kN.

The same equations (1 and 2) were used for specimens S-20 and the calculated values were equal to 76.12 kN and 79.8 kN respectively which are considerably higher than the experimental load of 9.49 kN.

This deviation from the experimental results is attributed to the fact that these models were derived using conventional steel fibre reinforced concretes with considerably lower steel fibre percentages and lower compressive strength values and therefore they cannot be applied for UHPFRC slabs.

To calculate the punching shear resistance (V_{uf}) of UHPFRC, a simplified method was examined based on the procedure proposed by Moreillon [8] (3).

$$V_{uf} = f_{ut} \cdot b_o \cdot d \quad (3)$$

where f_{ut} is the residual tensile strength at specific crack opening value.

However, this study was focused on slabs with higher thickness values (30-80mm) and with additional steel bar reinforcement.

In the current investigation, the punching shear resistance (V_u) which was obtained experimentally for S-10 and S-20 specimens were used to calculate the shear strength UHPFRC using Equation 4:

$$V_u = v_u \cdot b_o \cdot d \quad (4)$$

where v_u is the shear resistance of the UHPFRC slabs and d is taken as the thickness of the slabs.

For the calculation of the basic control perimeter, Eurocode 2 [10] provision was initially examined based on which basic control perimeter (5) should be calculated at distance $x=2d$.

$$b_o = 2 \cdot \pi \cdot \left(x \cdot d + \frac{diam_{load}}{2} \right) \quad (5)$$

where $diam_{load}$ is the diameter of the loading area which in this study is equal to 46 mm.

Following this procedure, b_o values were calculated equal to 295.31 mm and 420.97 mm for S-10 and S-20 while the respective experimental values were found equal to 284.84 mm and 518.36 mm. The results show good agreement for S-10 specimens but for S-20 specimens the experimental value (518.34 mm) is quite higher compared to the analytical one (420.97 mm).

Al-Quraishi [9] proposed a model according to which the formation of the basic control perimeter at UHPFRC should be taken at distance $2.5 \cdot d$ from the face of the support. By applying this model, the failure perimeters for S-10 and S-20 were calculated equal to 333.01 mm and 490.09 mm. The calculated value for S-20 is quite close to the respective experimental and therefore this model was adopted in this study.

From Equation (4) and (5) with x equal to 2.5, and using the maximum punching shear load values (V_u), the shear resistance v_u was calculated for S-10 and S-20. The obtained values were equal to

0.64 MPa and 0.87 MPa for S-10 and S-20 which shows that the thickness of the specimens affects the shear strength v_u of the slabs.

More data are required to investigate the correlation of the shear resistance v_u with the thickness. Considering linear relationship for the increment of shear resistance of S-10 and S-20 and by extrapolating the values for higher thickness values the results of Figure 4 were derived.

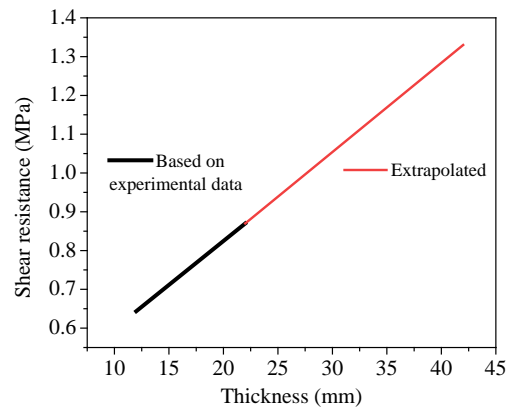


Figure 4. Shear resistance for various thickness

The results of Figure 4 could be used to calculate the shear resistance of UHPFRC specimens with various thicknesses. However, further work is required for the calculation of the shear resistance for higher thickness values and to check the assumption of the linear distribution of the extrapolated values of Figure 4.

For specimens S-30 and S-40 which exhibited flexural failure, yield line analysis was used to calculate the maximum load capacity. Equation 6 was derived for the correlation of the maximum flexural load (P_f) with the moment resistance of the cross section (M_f).

$$P_f = 8 \cdot M_f \quad (6)$$

For the calculation of M_f , cross sectional analysis was conducted considering linear distribution of the compressive stresses until the maximum compressive strength and uniform distribution of the tensile stresses. For the compressive strength, the values of Table 3 were used while the tensile strength was taken equal to 3.5 MPa; value obtained experimentally from the dog bone tests.

Following this procedure, the maximum flexural load resistance for all the examined thicknesses

was calculated. Also, the punching shear resistance was calculated using the results of Figure 4 and Equation 4 and the comparisons with the experimental results and with the flexural load resistance are presented in Figure 5.

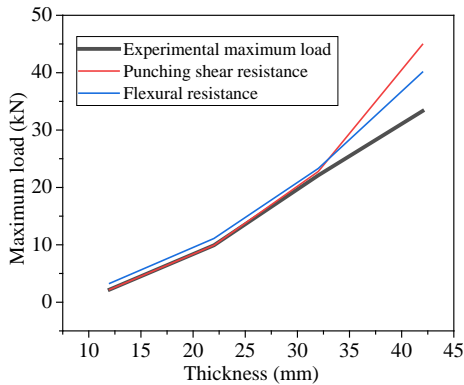


Figure 5. Experimental results and calculated values for punching shear and flexural resistance

The results of Figure 5 show that the punching shear resistance was lower than the flexural resistance for 12 mm and 22 mm which confirms the punching shear failure mode for these thicknesses. For 22 mm and 32 mm thicknesses, the flexural was very close to the punching shear resistance and both flexural and punching shear cracks were observed in these specimens. As the thickness was further increased and for 42 mm slabs, the flexural resistance became significantly lower than the punching shear resistance and this is confirmed by the experimental failure modes.

4 Conclusions

In this study UHPFRC slabs with various thickness and without additional steel bar reinforcement were tested under central loading and the main findings are summarized below:

- The addition of steel fibres significantly enhanced the load capacity of the slabs which was increased with the thickness of the slabs as expected.
- The slabs with small thickness (12 mm and 22 mm) failed in punching shear, while for higher thicknesses flexural failure occurred.
- The punching shear resistance models proposed for conventional steel fibre reinforced concrete cannot be used for UHPFRC.

- The shear strength was found to be affected by the thickness of the slabs. Further investigation is required to evaluate the effect of the elements' thickness on the UHPFRC shear strength.

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