PUNCHING SHEAR CAPACITY OF UHPC – PLATE TESTS

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Abstract

Ultra-high-performance concrete, a very high performance concrete with usually a compressive strength of 130 N/mm2 or more, is obtained with a number of mix design modifications compared to HPC. These modifications include, among others, the use of high quantities of cement and superplasticizers and the addition of fillers and micro-fillers (often silica fume) combined with rather specific granular distributions and sometimes a post-treatment. Altogether, this gives the wanted low porosity and high performance of the concrete, with an influence on all concrete properties compared to High Performance Concrete or ordinary concrete for which the Eurocode 2 describes material properties and design rules. Research illustrates that UHPC sometimes shows a different material behaviour, consequently resulting in the requirement for a case-by-case specification and material check.

This paper focuses on the study of the shear punching capacity of UHPC plates. A set of 18 UHPC plates have been used, different by mix design, plate thickness or punching configuration.

The experimental program indicated that the formulas proposed by EC2, and the additions described in FIB Modelcode 2010 for fibrous mixtures, can be used for the design of UHPC slabs.

1 INTRODUCTION [1,2, 3]

Developments in admixture technology have given last years a tremendous boost for developing advanced concrete types. With the latest generation of superplasticizers for instance, water-cement ratio can be decreased dramatically, allowing among others self-compactibility of concrete. Addition of (ultra)fine materials increases furthermore packing densities. The combination of these techniques results in concrete types with extra-ordinary mechanical properties and durability, usually referred to as Ultra High Performance Concrete (UHPC). A Belgian Building Research Institute (BBRI) and Vrije Universiteit Brussel (VUB) research evaluated, to name a few, the mix design of this type of concrete, its mechanical properties, shrinkage at early age and its applications.

The Belgian Building Research Institute (BBRI) wants to investigate the usefulness of this type of concrete for the building industry, and to introduce this new material on the market. Its high compressive strength, ranging from 130 to 250 MPa, could eventually open new perspectives for (slender) concrete design. However, before this concrete can be used beyond lab scale, it is necessary to evaluate the applicability of the design rules of Eurocode 2 (EC 2) for UHPC structures which today only cover the High Performance Concrete (HPC) and ordinary concrete (OC) range.

One of the properties that have to be examined is the punching shear resistance of concrete slabs in UHPC. This type of concrete has a higher tensile strength, a higher compressive strength, a lower inclination angle of the failure surface and usually contains steel fibers. It is unsure if the formulas of EC 2 still apply for types of concrete. Furthermore, EC 2 today does not allow the use of fibrous reinforcements, which is generally spoken the case for the types of mixtures.

The paper represents an experimental study to validate the use EC 2 for calculating UHPC concrete slabs subjected to punching. All slabs were designed following EC 2/Model Code 2010 and after mechanical testing their resistance is compared to the theoretical punching resistance from three different calculation models: the *FIB Model Code 2010; Swamy – Theodorakopoulos and Menétrey).* In total 18 slabs, representing 7 different configurations, were used in the experiments.

2. THEORETICAL MODELS FOR SHEAR PUNCHING DESIGN [4,5, 6]

Hereafter a brief summary is given of three design models for punching shear in slabs, which will be compared with the tested specimens.

- <u>Model Code 2010:</u>

This code is comparable to Eurocode 2, with an addition factor for fibre reinforcement. It was used for the design of the slabs in this study.

$$V_{Rd,F} = \left[\frac{0.18}{\gamma_c} \cdot k \cdot \left(100 \cdot \rho_l \cdot \left(1 + 7.5 \cdot \frac{f_{Ftum}}{f_{ctm}} \right) \cdot f_{cm} \right)^{1/3} + k_1 \cdot \sigma_{cp} \right] \cdot b_w \cdot d \tag{1}$$

With $V_{Rd,F}$: design value for the shear punching resistance in the absence of shear reinforcement;
γc: safety factor for concrete without fibres;
k: a correction factor that takes the “size-effect” into acount;
ρ_l: geometrical reinforcement ratio;
f_{Ftuk}: characteristic tensile strength of fibre reinforced concrete;
f_{ctk}: characteristic tensile strength of concrete;
f_{ck}: characteristic compressive strength of concrete;
σ_{cp}: average stress in section;
b_w: minimum width of the section loaded in tension;
d: effective height of the slab.

- *Model of Menétrey:*

The basic idea of the model, which is based on the strut-and-tie analogy, is to assume that punching failure corresponds to the failure of the concrete tie, which means that the tie strength is equivalent to the punching strength. The contribution of the concrete (F_{ct}), dowel resistance of the longitudinal reinforcement (F_{dow}), vertical component of the shear reinforcement (F_{sw}) and of the prestressing force (F_p) are individually calculated. The resulting punching load (F_{pun}) is expressed as:

$$F_{pun} = F_{ct} + F_{dow} + F_{sw} + F_p \tag{2}$$

The disadvantage of this model is the neglection of the contribution of the fibre reinforcement.

- *Model of Swamy en Theodorakopoulos:*

This analytical model is based on the physical behaviour of plate-column connections, and is applicable to both lightweight and normal weight concrete. It also incorporates several variables that affect the punching shear strength of flat slabs including the concrete strength, tension steel ratio, compression reinforcement, and loaded area. The model can be used for both non fibre reinforced concrete and fibre reinforced concrete.

3. EXPERIMENTAL PROGRAM

3.1 Materials and test specimens.

All circular slabs, 1100 mm in diameter, are reinforced with a perpendicular reinforcement grid of conventional S500 steel ribbed re-bars (figure 1). All were designed following EC 2, except the slab with an additional 0,5% in volume of steel fibres. For this additionally fibre reinforced slab, the punching shear resistance was calculated with FIB Model Code 2010. For the calculation of the flexural resistance the presence of fibres was neglected, thus underestimated. In total 7 different samples were tested, each representing 2-3 identical specimens (further specifications see table 1). The parameters of the 7 samples are the following:

- *Height of the slab;*
- *Type of the concrete mixture;*
- *Diameter of the contact area of the hydraulic punching jack;*
- *Fibre Volume Fraction*

Table 1: sample specifications

SAMPLE	height [mm]	contact diameter [mm]	mixture	6mm microfibres [%]	steel reinforcement [mm^2]	punching resistance [kN]	flexural resistance [kN]	predicted failure mode
1	68	50	M2	/	2413	134	155	PUNCH
2	68	100	M2	/	2413	161	191	PUNCH
3	58	100	M2	/	2262	125	148	PUNCH
4	68	100	M2	0.5	2413	209	191	BENDING
5	68	100	M1	/	2413	152	187	PUNCH
6	68	100	M3	/	2413	159	190	PUNCH
7	68	100	C30/37	/	2413	92	84	BENDING

Three different types of UHPC and one OC were used in this study. Their composition is given in table 2. In sample 4, 0.5% of 6 mm long microfibers were used.

Table 2: composition of UHPC M1,M2 and M3

Component	**M1 [kg/m^3]**	**M2 [kg/m^3]**	**M3 [kg/m^3]**
Cement CEM I 42.5 R HSR LA	500	830	777
Quartz powder 7µm	50	83	211
Quartz sand 0/0.5mm	786	335	1007
Porphyry 1/4	0	723	0
Basalt 1/3	510	0	0
Basalt 5/8	327	0	0
Silica fume Dry	100	166	155,5
Water	150	178	161,5
Superplasticizer (polycarboxylate based)	15	24	28

Table 3 summarizes the material parameters used for the design. The compressive strength has been measured at 28 days using 100x100x100 mm^3 cubes preserved in moist conditions (RH > 95%) at 20°C. The results for Young Modulus and tensile strength however, were obtained from previous tests on identical mixtures.

Table 3: Material parameters

SAMPLE	σ_{comp} [Mpa]	$\sigma_{tensile}$ [Mpa]	E [Gpa]
1	152	5,8	46
2	147	5,8	46
3	148	5,8	46
4	147	5,8	46
5	138	5,6	57
6	128	5,2	45
7	47	3,0	32

Figure 1: reinforcement grid

3.2 Test Setup

All slabs were preserved in moist conditions (RH > 95%) at 20°C and were tested after 28 days of curing. The slabs were all simply supported on a metal ring. The support width was 100 mm, resulting in a 900 mm span. In order to avoid high contact stresses due to the roughness of the concrete slab, gypsum was applied in the contact area. A hydraulic actuator with a capacity of 250 kN equipped with a load cell was used to induce and measure the punching force (figure 2). The mid-span displacement was measured by linear variable differential transformer. The punching test was performed with a constant displacement of 3 mm/min.

Figure 2: Test Setup

3.3 Test Results and discussion

All plates failed due to punching. The EC2 predictions differ from the test results within a small range for all possible variations of the properties of the slabs, except for the contact diameter of 50 mm (table 4; figure 3). Also the prediction of the FIB Model Code 2010, which was used for the design of the fibre reinforced specimen, correlates well with the tested specimen: the differences between the test results and the design values of these slabs were comparable with the variation found with the other slabs without steel fibres in the mixture. The difference found between the calculated and the actual failure loads for a small punching surface with a diameter of 50mm was however quite large (sample 3). All design strengths slightly underestimated the real punching resistance, except for the slabs charged with a small contact diameter.

Table 4: TEST vs. EC2

	Punching Resistance [kN]		theory
Specimen	ECII;MC 2010	TEST	test
1	132	117	1,13
2	157	163	0,96
3	122	159	0,78
4	204	218	0,94
5	153	163	0,94
6	147	168	0,88
7	107	112	0,96

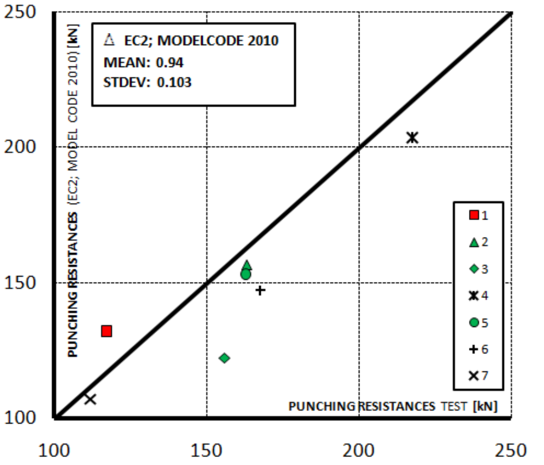
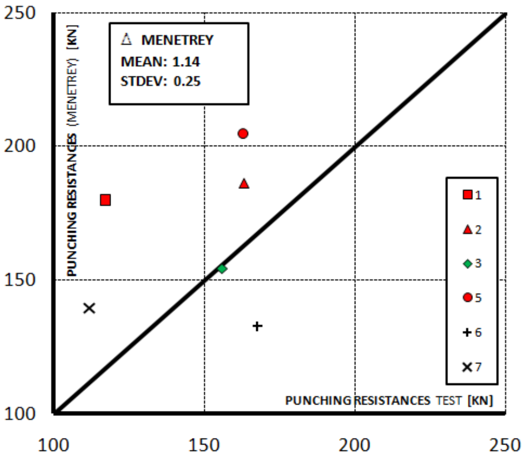


Figure 3: TEST vs. EC2

The actual punching resistances differ from those of the calculation model of Menétrey with an apparently random variation (figure 4; table 5). The model generally overestimates the real punching resistance. The difference between the test and actual values from the plates tested with a small punching area with a perimeter of 50mm (1) is very large and unacceptable to make a correct comparison. The only (serious) underestimation is given for the concrete M3 (6), probably caused by the concrete composition. The calculation model of Menétrey takes the aggregate size into account, which leads to abnormal values for types of concrete with small aggregates. In fact, concrete (of "UHPC") M3 is a reactive powder concrete without large aggregates, which can explain the large difference between test and model.

The model of Swamy-Theodorakopoulos gives a quite accurate prediction of the punching loads found in the tests (figure 5; table 6). The used formulas give a very good result for the punching tests with a small pressure zone, this unlike the other two used models. Also for the plates with a height of 58mm the calculation model gives an acceptable result.



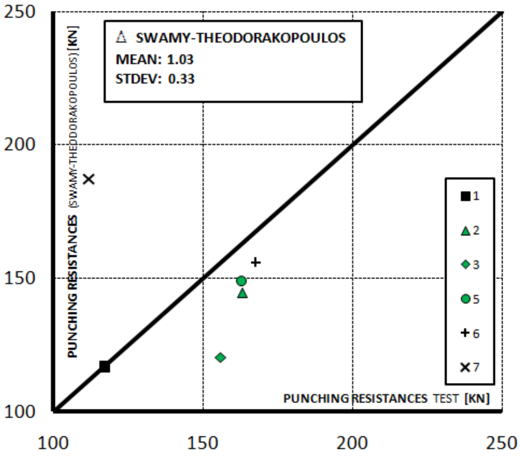


Figure 4: TEST vs. Menétrey

Figure 5: TEST vs. Swamy-Theodorakopoulos

Table 5: TEST vs. Menetrey

	Punching Resistance [kN]		theory
Specimen	**Menetrey**	**TEST**	test
1	180	117	1,54
2	186	163	1,14
3	154	156	0,99
5	205	163	1,26
6	133	168	0,79
7	139	112	1,25

Table 6: TEST vs. Swamy-Theodorakopoulos

	Punching Resistance [kN]		theory
Specimen	**Swamy-Theodorakopoulos**	**TEST**	test
1	117	117	1,00
2	145	163	0,88
3	120	156	0,77
5	149	169	0,92
6	156	168	0,93
7	187	112	1,68

4. CONCLUSIONS

Three models, proposed for analytical calculation of the punching resistance of ordinary concrete and high strength concrete, were evaluated experimentally on their compatibility with recently developed ultra high performance concrete mixtures.

The experimental program indicated that the formulas proposed by EC2, and the additions described in FIB Modelcode 2010 for fibrous mixtures, can be used for the design of UHPC slabs.

The improved mechanical behaviour of UHPC, with a further increased compressive strength compared to HPC, had a significant influence on the punching resistance. For the specific example discussed in this study an increase of almost 50% opposed to the C30/37 was noticed. When a limited amount of fibres were used (0.5% in volume), which is generally spoken the case in UHPC mixtures, the resistance was about doubled.

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