THIN UHPFRC SLABS WITHOUT CONVENTIONAL REINFORCEMENT AS LIGHT-WEIGHT STRUCTURAL ELEMENTS

A. Spasojevic*, D. Redaelli & A. Muttoni*****

* PhD, Guscetti & Tournier SA, Genève.
Formerly PhD Candidate at Ecole Polytechnique Fédérale de Lausanne

** PhD, Ecole Polytechnique Fédérale de Lausanne (EPFL)

*** Professor and Head of the Structural Concrete Laboratory at EPFL

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Abstract:
Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC) is a material characterised by significantly improved mechanical and durability properties compared to other concretes. In recent years, an important research effort has been made to identify appropriate structural forms and to provide practical design rules allowing efficient UHPFRC structures to be conceived.
This paper presents the results of an experimental and theoretical study on the structural behaviour of thin UHPFRC slabs without conventional reinforcement. It is shown that these elements can provide high bending resistance, and, applied in an appropriate structural arrangement, lead to strong and light-weight structures that cannot be built with ordinary reinforced concrete. The favourable behaviour of thin UHPFRC members results from material mechanical properties: high compressive strength and significant ductility in tension of thin UHPFRC members lead to a ductile bending response, even when conventional reinforcement is not provided. It is demonstrated that the theory of plasticity can be safely used to assess the bending failure load for thin UHPFRC slabs. A practical expression is proposed to define the resistant plastic moment, allowing an easy estimation of the bending load-bearing capacity of thin statically indeterminate UHPFRC elements. The results are compared with experimental data on slabs of various thicknesses, showing good agreement.

1. INTRODUCTION

Ultra high performance fibre reinforced concrete (UHPFRC) is an advanced cementitious material, characterised by highly improved material properties (mechanical strengths, durability, workability)[1]. In spite of its qualities and after more than ten years since its first appearance on the market, UHPFRC is still not widely used in structural engineering. This may be related to the high cost of the material and to the difficulties of predicting its structural response, governed by non-linear material behaviour (Section 2). An important effort has been made to provide first recommendations for the design of UHPFRC members[2,3]. However, simple though robust design approaches are still missing.
A research project has been carried out in the last years at the Structural concrete laboratory of the Ecole Polytechnique Fédérale de Lausanne (EPFL) with the two main purposes of identifying appropriate structural forms or structural members to exploit UHPFRC properties and determining rational and practical design approaches.

a) b)

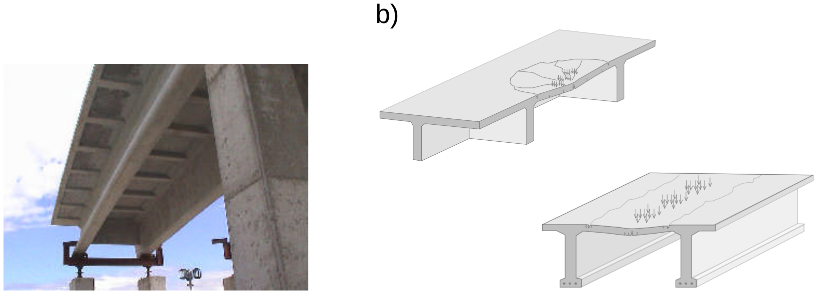
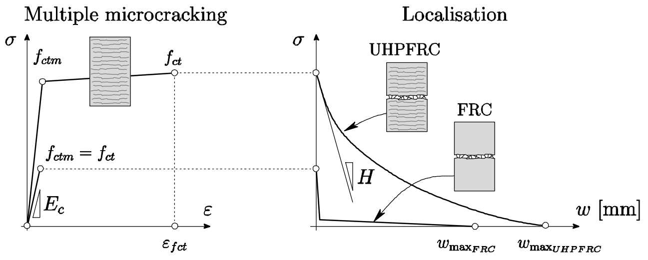


Figure 1: Thin UHPFRC slabs: a) deck of Seonyu footbridge (with 3 cm thick slabs[5]); b) local bending failure modes[7]

Since the first structural applications of UHPFRC, thin slabs without conventional reinforcement have been used as promising and efficient elements[8, 5] (Fig. 1 a)). In thin elements, the presence of the fibres provides sufficient bending strength and ductility even if conventional reinforcement is avoided[7]. Thicknesses can be reduced since no reinforcement is present and due to the high durability of the material. This allows minimizing the UHPFRC quantity, with beneficial effects on the cost and the self weight of the structure.
Initially, thin slabs have been mainly used for roofs or as upper slabs in pedestrian bridges[5,8]. More recently, researchers from the Laboratoire Central des Ponts et Chaussées[6] (LCPC) proposed the application of thin slabs in a bridge deck, using a concept of two-way ribbed slabs, known as efficient for ordinary concrete since Nervi's work[9]. In theses structural concepts, slabs must provide sufficient bending and punching shear resistance to prevent local modes of failure (Fig. 1 b)).
In this view, the paper focuses on the behaviour of thin unreinforced UHPFRC slabs in bending. The results of an experimental and theoretical study on the structural response of these elements are presented.

2. UHPFRC: MATERIAL MECHANICAL PROPERTIES

According to the references[2,3], UHPFRC is defined as a cementitious material having compressive strength higher than 150 MPa and sufficient fibre content to achieve a ductile behaviour in tension.



UHPFRC	
f_{ctm}	9 MPa
f_{ct}	9 MPa
E_c	60 GPa
ε_{fct}	0.25 %
H	5 N/mm^3
w_{max}	10 mm

Figure 2: Qualitative comparison between the tensile behaviour of UHPFRC and a conventional fibre reinforced concrete (FRC): *σ(ε)* relationship before crack localisation and *σ(w)* relationship; mechanical properties for the UHPFRC BSI©[10,11], used for the experimental part of the research[7]

Qualitatively, the compressive behaviour of UHPFRC does not differ a lot from that of ordinary concrete. The compressive strength of UHPFRC is, however, much higher and the brittleness characterising the typical response of high strength concretes is overcome by the use of fibres. The tensile behaviour, on the contrary, is significantly different from that of other concretes (Fig. 2): after cracking of the matrix, fibres in UHPFRC can carry a larger tensile force than the matrix itself. As a consequence, a large number of cracks develops in UHPFRC and the first matrix cracking is not directly followed by strain localisation (Fig. 2). This phenomenon, often designated multiple microcracking, produces a strain hardening response characterized by a slightly increasing or constant stress value with development of large tensile strains[12]. In this paper, this phase is designated pseudo-plastic phase and described with a stress-strain relationship, *σ(ε)*. The softening response after crack localisation can be described with a stress-crack opening, *σ(w)*, relationship[13]; the crack characterised by softening behaviour is named macrocrack in this paper. UHPFRC is characterized by fracture energies G_F up to several hundred times that of an OC and by an initial slope of the *σ(w)* law, *H*, much smaller than that of OC and FRC (Fig. 2).
The UHPFRC used in this research is the BSI© from Eiffage[10,11]. It is reinforced with 2.4% in volume of high strength steel fibres with a length of 20 mm and a diameter of 0.3 mm. The average compressive strength of BSI is 190 MPa [14]. The values of its characteristic tensile behaviour are listed in the table in Fig. 2.

3. EXPERIMENTAL PROGRAM

Two test series on thin UHPFRC slabs have been performed by the authors of the paper at the Structural concrete laboratory of the EPFL. Tests aimed at investigating the structural response in service and up to failure for UHPFRC slabs under central point load (Fig. 3). The first test series was conceived to study bending response, while the second series was designed to study punching shear failure. As for ordinary concrete members, an interaction between the bending and punching responses exists[7]. However, this paper only focuses on the bending behaviour. A very limited number of test results on thin slabs, failing in bending or in punching, has been published up to present[15,16].

3.1 Test set-up and specimens

Six UHPFRC slabs were tested up to failure. All of the slabs had the same square geometry in plane (Fig. 3), but different thicknesses. Thicknesses, h, of 40, 50 and 60 mm were chosen to cover the range of interest for structural application without conventional reinforcement. Tests were carried out under central point load, with eight support points, free to rotate in the radial direction. This support disposition provides the same axisymmetric boundary conditions as in the case of a circular slab of radius $r_b = 450$ mm, which allows a straightforward results interpretation. The load was introduced over a 30 x 30 mm load area and controlled in displacement. To retrace the displacement field of the slabs, vertical displacements at the central point and at twelve other measurement points were also monitored with LVDTs fixed to the tensile slab side (Fig. 3).

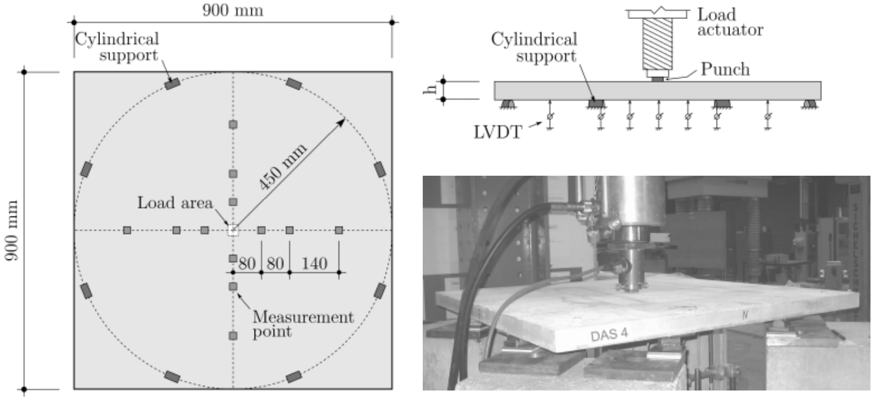


Figure 3: Test set-up, specimen geometry and boundary conditions

3.2 Measured bending response

All the tested slabs failed in bending in a similar manner (Fig. 4). A typical force-central point displacement curve (P- δ, Fig. 4a) is linear only for a small initial part of the pre-peak response, up to less than 1/3 of the maximal force, while the major part of the curve is non-linear. The displacements at peak are significant, 20 to 25 times their values at the end of the elastic phase. For increasing deformations in the post-peak phase, the force decreases slowly.

A failure crack pattern consisting of four radial macro cracks (Fig. 4b) characterizes all the tested slabs. It is interesting to notice that the visible cracks appeared only at high force levels of approximately 85÷90 % of the peak force.

This is in agreement with another observation, relevant for design at service states: the secant stiffness of the slabs decreases very slowly after the loss of linearity and up to a significantly high force levels (Fig. 5b).

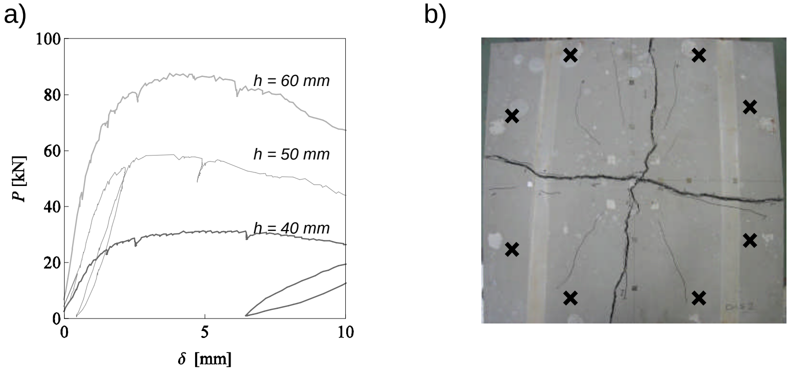


Figure 4: Bending response of UHPFRC slabs: a) measured force-displacement curve at the mid-span point; b) failure crack pattern

4. BENDING RESPONSE: MODELLING POSSIBILITIES

To the knowledge of the authors, only few theoretical works have been published on the modelling of UHPFRC slabs and are mainly based on numerical FEM analysis. For conventional FRCs, an approach based on softening hinge is also proposed [4].

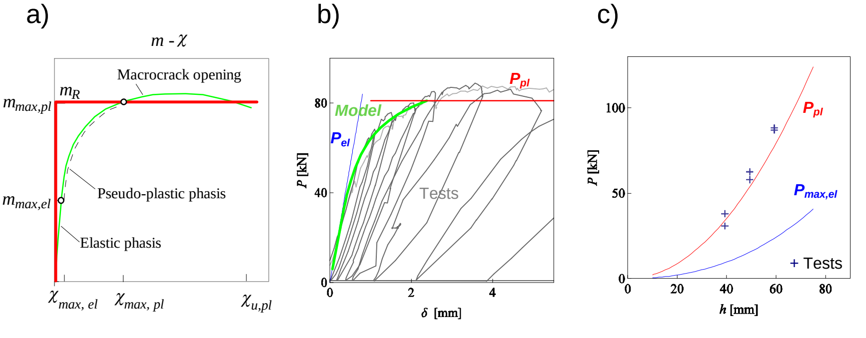


Figure 5: Modelling of the bending response: a) *m*-χ diagram of a section; b) simulated and measured prepeak response of the slab during multi-microcracking (*h* = 60 mm); c) actual and predicted ultimate bending load

The behaviour in the first phase of the non-linear response of a slab under symmetric boundary conditions can be analyzed more easily by numerically solving a set of analytical equations of the continuum, based on the moment-curvature response of the section (Fig. 5 a)). The latter can be expressed analytically, in the elastic and pseudo-plastic phases[7]. A comparison of the simulated and measured response is shown in Fig. 5b. In addition to the fact that no visible cracks appeared for these force levels, the good agreement between the simulated and the measured response confirms that a pseudo-plastic stress-strain relationship can be used to model the multiple-microcracking phase in tension (for other slabs, see[7]).

Once the maximal bending moment in the slab reaches the moment corresponding to the beginning of macrocrack opening (Fig. 5.a)), localisation of deformations takes place in radial macrocracks (Fig. 4 b)) and the continuum model described above can no longer be used. The structural response approaches that of rigid blocks rotating between the discrete macrocracks, with a limited variation of force while deformations increase significantly (Fig. 4 a)). The rotational capacity along macrocracks is governed by the non-linear *M*-χ relationship (green line in Fig. 5 a)). As shown in [7], the *M*-χ relationship can be simplified with an elastic-perfectly-plastic relationship (red line in Fig. 5 a)). Thank to this simplification, the bending failure force for a critical crack pattern can be easily calculated using the yield line method[17]:

$$\iint_A \delta(x,y)dxdy = P \cdot \delta \tag{1}$$

For the concentrated point load and radial crack pattern, as shown in Fig. 4 b):

$$P = 6.123 \cdot m_R \tag{2}$$

where m_R is the resistant plastic moment and is defined as the bending moment at the end of the pseudo-plastic phase (Fig. 5 a)). The advantage of the method is that the value of m_R can be analytically expressed as a function of material properties and sectional geometry[7]:

$$m_R = n_{fct} \cdot f_{ct} \frac{bh^2}{6} = \left(3 - \frac{2\sqrt{2} f_{ct}}{\sqrt{f_{ct}\left(E_c \varepsilon_{fct} + \sqrt{f_{ct}\left(2E_c \varepsilon_{fct} - f_{ct}\right)}\right)}}\right) \cdot f_{ct} \frac{1 \cdot h^2}{6} \tag{3}$$

The values of bending failure force obtained using Equations 2 and 3 are represented by the red line in Fig. 5 c) as a function of slab thickness, *h*. The actual failure loads of tested slabs are also presented in the same figure, showing good correlation with theoretically predicted values. A comparison with other test results with different boundary conditions can be found in [7].

It is important to underline that the final crack pattern and the possibility to develop a plastic mechanism are related to the deformational capacity of the sections. The important rotation capacity of thin UHPFRC elements explains the high redistribution of internal forces and the experimentally observed fact that all the tested slabs develop the same failure mechanism. Moreover, due to the small initial slope of UHPFRC stress-crack opening relationship, *H*, (Fig. 2), similar levels of ductility and moment bearing capacity can be achieved in thin elements even if the pseudo-plastic phase is not present[18].

For UHPFRC, the values that characterize the pseudo-plastic tensile phase (Fig. 2) can vary as a function of fibres distribution. The results of a parametric study on the influence of the tensile properties on the bending failure force are presented in Fig. 6 a) and b). The same boundary conditions as those of the tested slabs (Fig. 3) are considered. The value of the ultimate force is only slightly influenced by a variation of the deformation ε_{fct} (Fig. 2) between 0.15% and 0.35% (nominal value = 0.25%), and slightly more affected by a variation of ±1 MPa in the tensile strength f_{ct} (nominal value = 9 MPa). Variations in the span length only influence the value of the force at the end of elastic phase, $P_{el,max}$, but not the theoretical plastic solution, as known for this boundary condition.

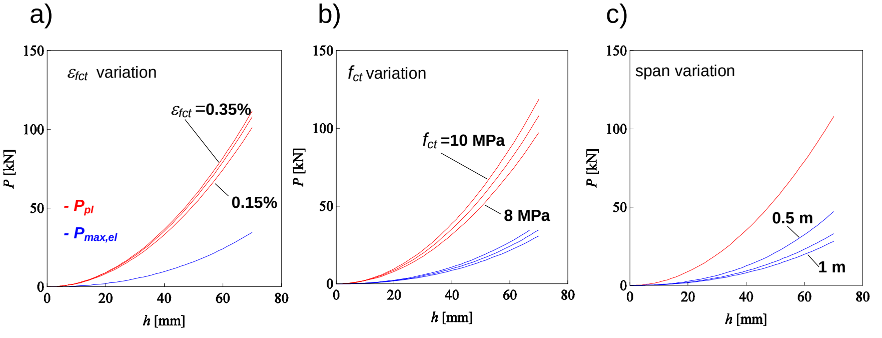


Figure 6: Influence of variations of UHPFRC tensile properties and slab span on the bending failure force predicted with the yield line method (red lines).

5. CONCLUSIONS

Thin UHPFRC slabs are studied in this paper as structural elements that enable an efficient exploitation of the advanced UHPFRC material properties. The paper presents some aspects related to the behaviour and modelling of thin UHPFRC slabs, supported by the results of an experimental program.

It is experimentally and theoretically shown that a significant redistribution of internal forces takes place in thin slabs due to multiple-microcracking and to macrocracks opening; this leads to a high increase in force-bearing capacity beyond the end of the elastic region; a ductile failure and the same failure crack pattern is observed for all tested slabs.

A major part of the load-bearing capacity is achieved with multi-microcracking behaviour; this phase can be well modelled using elastic-pseudo-plastic tensile stress-strain relationship, allowing good prediction of behaviour at service states.

The ultimate load bearing capacity of thin UHPFRC slabs can be well assessed based on the yield line method, using the proposed formulation for the resistant plastic moment. The approach is experimentally validated for thin slabs, with dimensions of interest for structural application without conventional reinforcement (40-60 mm).

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