

FLEXURAL BEHAVIOUR OF UHPC BEAMS REINFORCED WITH ORGANIC FIBRES AND STEEL BARS

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Abstract

The research program has been launched by Lafarge Research Centre in order to better understand behaviour of UHPC members reinforced with fibres and reinforcing bars. This program is divided into two parts: an experimental program and a numerical program. The experimental results seem to demonstrate that UHPC beams reinforced with fibres and reinforcing bars works well as a composite where all participants are effectively used. The numerical part assesses different numerical tools with a focus on their efficiency for prediction capacities and also for design purposes (easy to use). LCR numerical tool is validated with the help of experimental results. Afterwards contribution of fibres is parametrically studied. The main benefits of using UHPC beams reinforced with fibres and reinforcing bars are emphasized.

Résumé

Un programme de recherche visant à mieux comprendre le comportement de BUHP à fibres organiques renforcés par des armatures métalliques a été lancé au Centre de Recherche de Lafarge (LCR). Il comprend une partie expérimentale et une partie numérique. Les résultats expérimentaux semblent démontrer que les BUHP renforcés à la fois par des fibres et des armatures travaillent en composite avec une participation effective des deux modes de renforcement. La partie numérique propose d'évaluer différentes stratégies numériques en termes de prédiction des capacités résistantes et de facilité d'utilisation pour les concepteurs. L'outil numérique LCR a été développé grâce à l'analyse des résultats expérimentaux et a permis dans un second temps d'étudier de manière paramétrique la contribution nette des fibres. Les principaux avantages de l'utilisation de BUHP armés de fibres et d'armatures sont présentés dans cette contribution.

1. RESEARCH SIGNIFICANCE

For ten years now, a second family of Ultra High Performance Fibre-Reinforced Concrete (UHPFRC) along the one dedicated to structural applications (bridges, footbridges, repairing) has been developed for architectural applications (cladding, decorative lattices). Recent developments have enabled a production of large and slim elements with complex forms for building envelopes. These elements combine several functions: aesthetics, water tightness and self-bearing.

The structural applications mainly use metallic fibres (with eventually prestressing), whereas this new type of elements use organic fibres in order to ensure a better aesthetics; in addition, they may need additional reinforcement (most often steel bars) depending on load and geometry of panels (Fig. 1). The current reference document for a design of structural members made of UHPFRC is the “interim recommendations” of AFGC-SETRA [1]. Although the combination of fibres and rebar has already been investigated [2-4], there is not yet a generally admitted way of designing composite structures of this kind. In order to better understand the behaviour of UHPC members reinforced with fibres and steel reinforcing bars, Lafarge Research Centre has started a research program. This study is a part of the research program and is divided into two parts: an experimental program and a numerical program.



Figure 1: Precast elements in Ductal® FO reinforced with steel bars

2. EXPERIMENTAL PROGRAM



Figure 2: Experimental setup for three-point bending test

Six rectangular beams made of UHPFRC and reinforced with one steel bar were precast by Lafarge. The six beams are one meter long. The dimensions of the sections are given in Table 1. The beams were tested in three-point bending tests with simple supports and were loaded under deflection control until failure (Fig. 2). Instrumentation consisted of a strain gauge on the steel bar and another one on the lateral surface at the mid-section of each beam.

Table 1: Dimensions of the beams

beam number	span length [mm]	section dimensions [mm]	reinforcement bar diameter [mm]	cover of reinforcing bar [mm]
1	900	40×60	8	15
2	900	40×80	8	15
3	900	40×100	8	15
4	900	40×120	8	15
5	900	40×160	8	15
6	900	60×160	10	15

3. MATERIAL PROPERTIES

3.1 Fibre reinforced concrete

In the case of normal strength concrete, the design code EN 1992-1-1 [5] (among others) proposes a list of “standard concretes” which are referred by their compressive strength (C25/30, etc). Once the compressive strength is given, almost all other properties (tensile strength, Young modulus, creep, shrinkage, etc) are deduced by use of empirical relations. In the case of UHPFRC, knowing the compressive strength does not allow deducing other properties. In particular, the tensile behaviour needs to be precisely characterized by specific tests. In addition, once the material itself is known (type and dosage of fibres) its real performances also depend significantly on the fibres distribution and orientation which are influenced by the placement method and the geometry of the structure (K factor approach in AFGC recommendations).

The material that was used in this study is an ultra-high performance concrete reinforced with organic fibres (4.3 %). It has been characterised by three-point and four-point flexural tests on prisms (70x70x28mm) in accordance with the AFGC recommendations (Table 2).

Table 2: Parameters for AFGC-SETRA softening law

	E_{cm} [GPa]	f_{cm} [MPa]	f_{ftm} [MPa]	$\sigma_{0.3mm}$ [MPa]	l_c [mm]	$\epsilon_{0.3}$ [‰]	$\epsilon_{u1\%}$ [‰]	ϵ_{lim} [‰]
Beam 1 - 6	35	120	9.7	5.0	$\frac{2}{3}h$	$\frac{w_{u0.3}}{l_c} + \frac{f_{ctk}}{E_{cm}}$	$\frac{w_{1\%}}{l_c} + \frac{f_{ct,el}}{\gamma_{cf}E_{cm}}$	$\frac{l_f}{4l_c}$

3.2 Steel

The beams were precast with standard steel bars (according to EN 10080) and no material characterization was carried out before bending tests. Nevertheless, the results of monitoring points allow estimating material properties for the modelling phase. As the objective of this

study is to support the development of design codes, the bi-linear model proposed in EN 1992-1-1 (§ 3.2.7) with strain hardening ($K=1.08$) was used (Table 3). The real behaviour of steel rebar reveals a quite high scattering, and therefore, it is expected that simulations will under-estimate the capacity of beams 5 and 6, because of real tensile strengths were 680 MPa and 642 MPa, respectively.

Table 3: Model parameters for reinforcing bars

	E_s [GPa]	f_{yk} [MPa]	K [-]
Beam 1 - 6	210	550	1.08

4. ANALYSIS OF EXPERIMENTAL RESULTS

Figure 3a shows a typical example of experimental results (Beam n°3) and figure 3b completes this example with the numerical study of different levels of contribution. From these figures is easy to see different stages of fibre contribution. The first level (A) starts after reaching the tensile strength of the matrix (in our case around $f_{ctm} = 9.7$ MPa), where the same matrix without fibres (green curve) would start to converge to the solution without concerning tensile contribution of concrete (red curve). The second part (B) starts with the beginning of steel yielding (dashed vertical line) and represents the real contribution of the fibres to the ultimate strength capacity. This plateau is defined by steel yielding (B) and beginning of fibres damage (C). The descending part (C) – (D) is caused by diminishing contribution of fibres to the overall capacity and the following plateau represents capacity of yielding steel in tension and the matrix in compression (ordinary reinforced concrete). This plateau will end up with reaching the ultimate strain either of the matrix or of the steel reinforcement in tension.

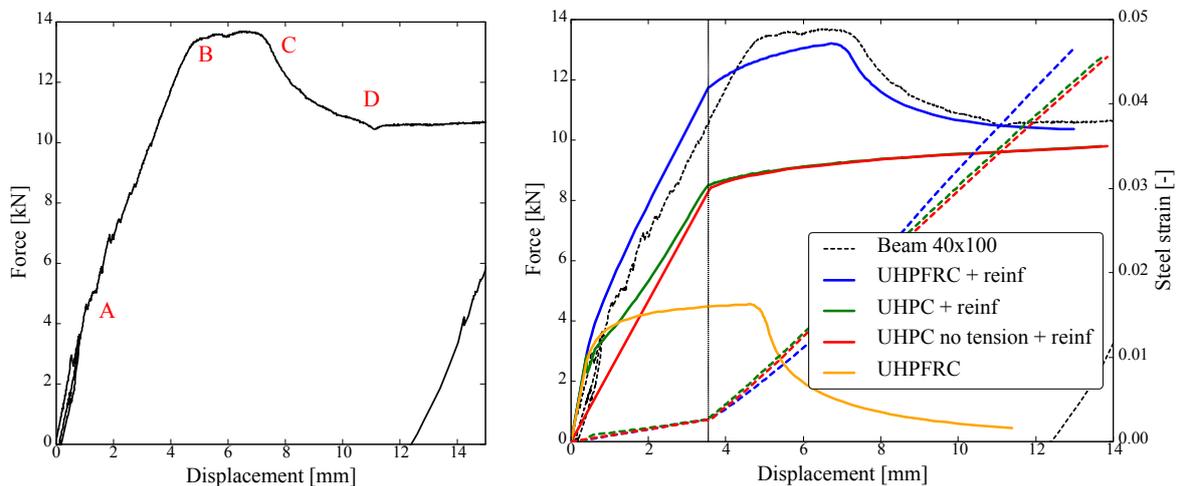


Figure 3: Typical response for UHPFRC reinforced with steel rebar (Beam n°3);
a) Identification of main stages b) Parametric study (LCR tool)

5. NUMERICAL MODELLING

One of the objectives of this combined program is to assess the efficiency of different numerical models used by design offices. Two external companies with two different numerical tools were asked to perform numerical modelling of the experiment. Besides, the experiment was modelled with a tool developed in LCR especially for the purpose of this study.

The numerical modelling was further divided into two parts. The first part represents modelling based on the AFGC-SETRA recommendations, without knowing the experimental results prior to simulation. Input data for the modelling was taken from table 1, 2 & 3. The second part is based on the numerical modelling of the beams with knowledge and input data obtained during a reverse analysis from one selected beam.

5.1 Numerical tools

Two different tools of external companies were used in this study. First one is based on fibre beam elements, which is described in the frame of the Euler-Bernoulli beam theory [6]. For each beam, the section is divided into several fibres. Each fibre behaves then like a beam of Euler. Several materials can be affected on only one finite element support (steel + concrete, for example). Considering that one objective of this study is to assess the efficiency of simple numerical models for engineering purpose, two series of simulations have been carried out with forced-based approach (the descending branch, which leads to numerical difficulties, is not considered) and displacement-based approach.

The second external model is based on 2D isoparametric elements [7]. Compared to the previous modelling technique, this one is more expansive (it requires more expertise and it takes around 20-30 minutes per simulation) but it is able to account for: non-linear behaviour in compression and in tension including hardening, softening and cracking description based on the nonlinear fracture mechanics.

The model developed in LCR is similar to the first model, as it represents Euler-Bernoulli beam. The model is based on “moment curvature approach” and incorporates two main steps (Figure 4). The first step (multi-fibre approach) links stress-strain (S-S) relationship with moment-curvature (M-C) relationship and the second step (multi-element approach) links (M-C) relationship with (F-D) force-deflection relationship.

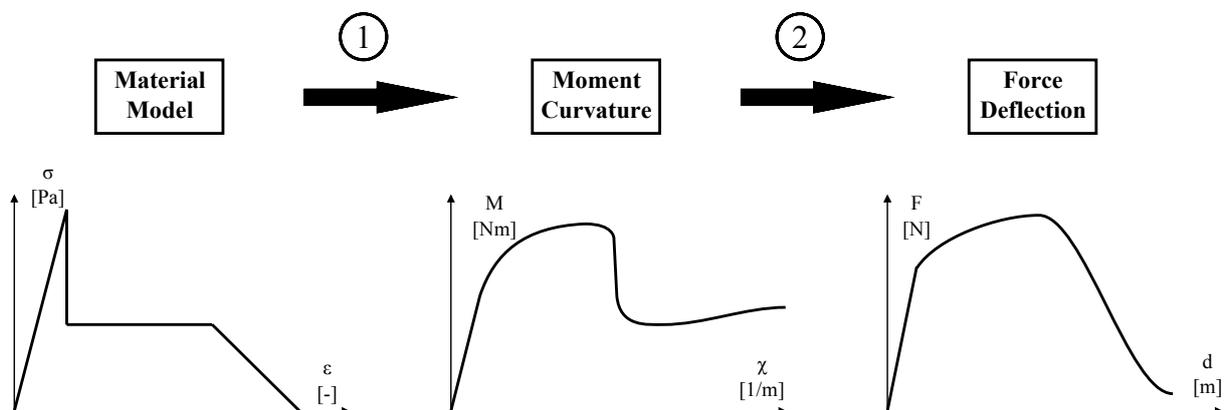


Figure 4: Theoretical overview of LCR tool

5.2 Numerical results

As it was mentioned above the numerical modelling was divided into two parts. Figure 5 shows results from the first part, where the inputs from tables 1, 2 & 3 were used. The main difference between experimental and numerical results is in initial stiffness (from beginning to the first plateau), which is mainly caused by theoretical (design) dimensions (Table 1). Another interesting difference is in post-peak behaviour, where the localization problem appears. This phenomenon is discussed in conclusion.

Table 4: Updated parameters after reverse analysis

	LCR model			2D Plane stress			Fibre Beam	
	B1	B2	B3	B1	B2	B3	B3	
f_{ftm}	8.5	8.0	9.7	5.6	4.0	6.3	9.7	[MPa]
$\sigma_{0.3mm}$	4.8	5.2	5.0	4.5	3.2	5.0	5.0	[MPa]
$\epsilon_{0.3}$	0.5	2.0	1.8	0.01	0.045	0.045	0.48	[-]
ϵ_{lim}	5.0	7.0	2.2	0.3	1.3	1.3	4.5	[-]

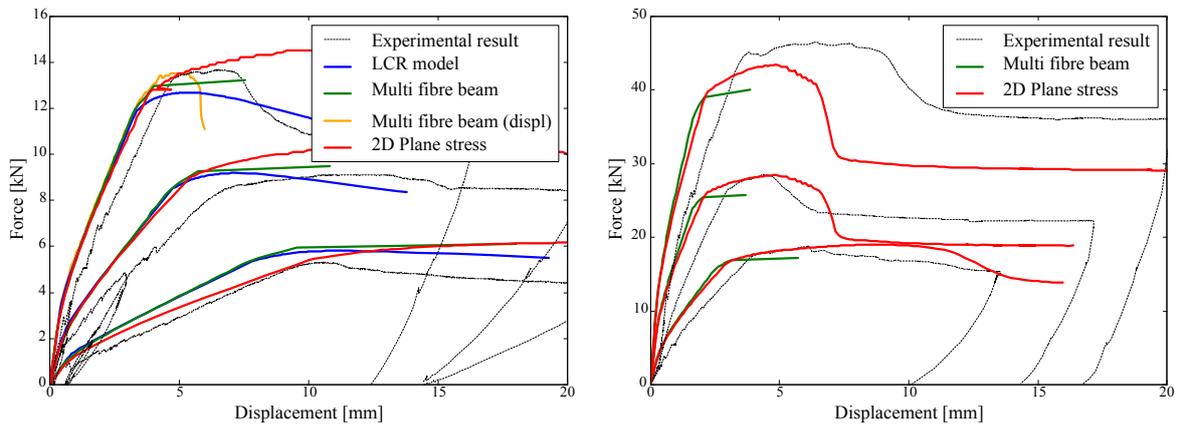


Figure 5: Numerical simulation based on SETRA recommendation (Beams 1 -6)

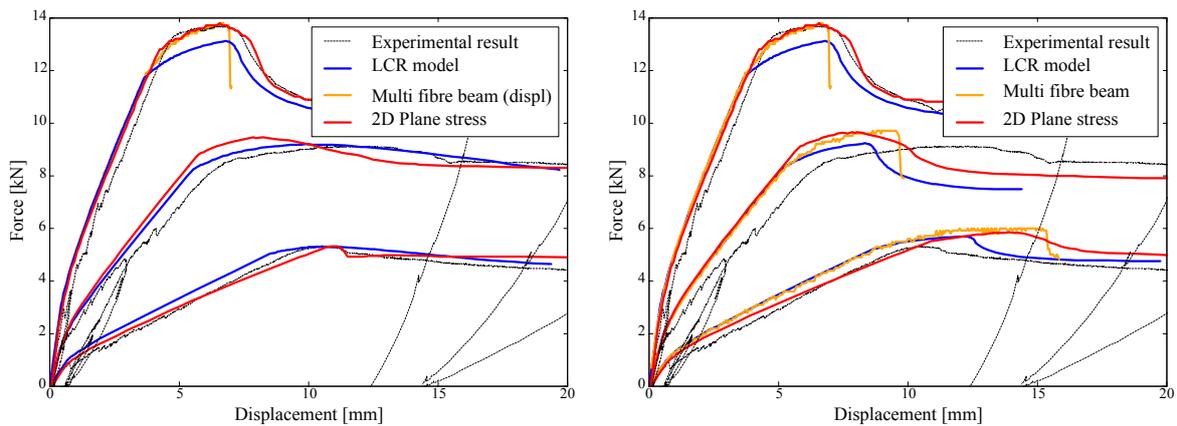


Figure 6: Reverse analysis
(Beams 1-3)

Figure 7: Numerical simulation based on
beam n°3 (Beams 1-3)

Figure 6 and table 4 shows results from the reverse analysis. These reverse analyses were performed only with the displacement-based approach for every single beam separately. The numerical results for beams based on inputs from reverse analysis of the beam n°3 are shown in figure 7.

5.3 Validation of LCR tool

The validation of the LCR tool was done with a help of the first two beams. The reverse analysis was performed to fit force displacement diagram with the minimum adjustment of steel reinforcement and afterwards strains in the steel were plotted against displacement. Figure 8 shows a good conformity between the experimental and the numerical results. Figure 5 also shows a good conformity with other numerical tools (stiffness and ultimate capacity). The difference in ultimate capacity for beam n°3 (top left curve) is explained as overstepping limit of applicability. The Euler-Bernoulli theory for pure bending is used in the LCR model, however the beam n°3 has length-depth ratio equal to 9. For this reason other beams were not modelled with this tool.

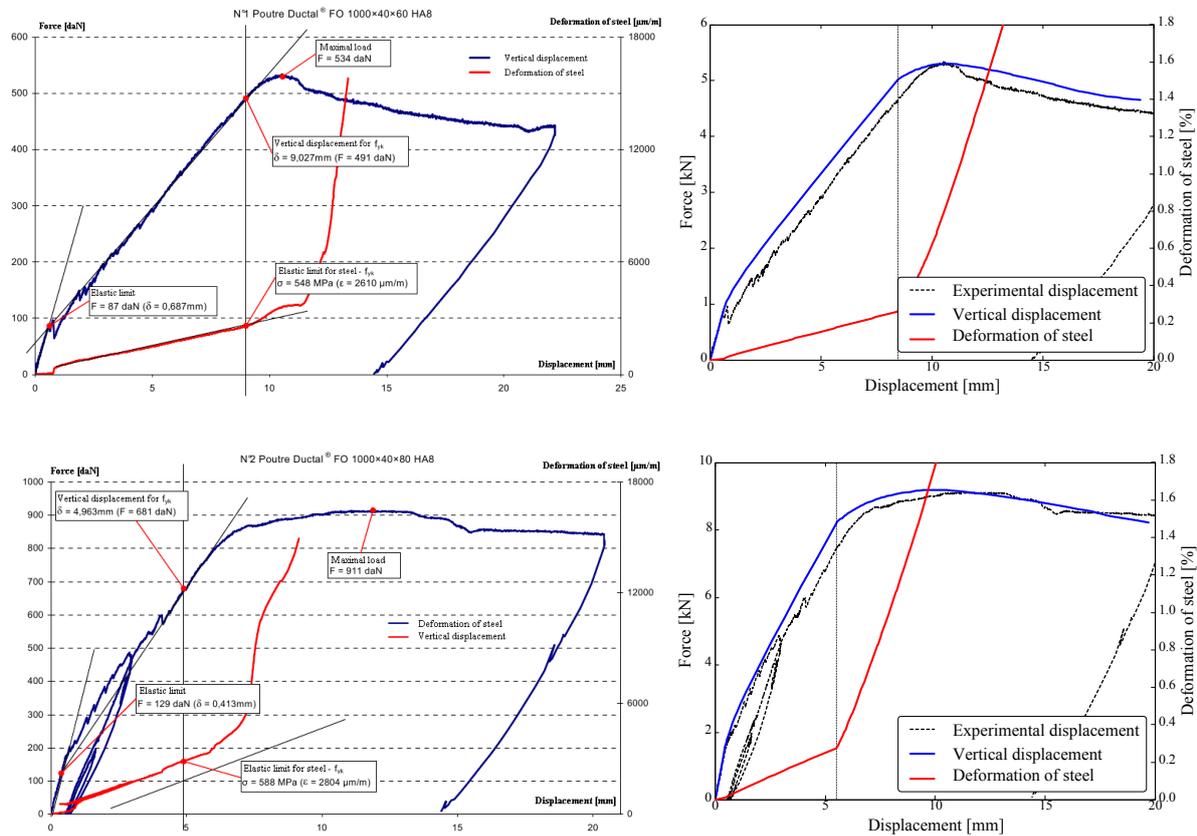


Figure 8: Validation of numerical tool (Beam n°1 & 2)

6. ULTIMATE LIMIT STATE (ULS) DESIGN

The objective of this paragraph is to focus on the design criteria for structural members made of UHPC. The European standard EN 1990 (Basis of structural design) [5] stipulates in § 3.3-(4) that excessive deformation shall be avoided. According to EN 1992-1[6], for steel in

tension, the strain should not be greater than $\epsilon_{ud} = 0.9 \epsilon_{uk} = 4.5 \%$. In concrete, two criteria are considered, elastic limit for compression ($\epsilon_{cl} = 3.43 \%$) and 0.3 mm crack width for tension (AFGC [1], characteristic length equal to $2/3 h$). Figure 9 shows development of strains in concrete and steel versus displacement. These graphs show that even for relatively higher ratios of discrete reinforcements (8 %, 6 % & 5 %) the compression failure is avoided. The graphs also show that designing those kinds of structures for maximal usage of steel (4.5 %) leads to uneconomical design as the ultimate capacity is reached before this limit.

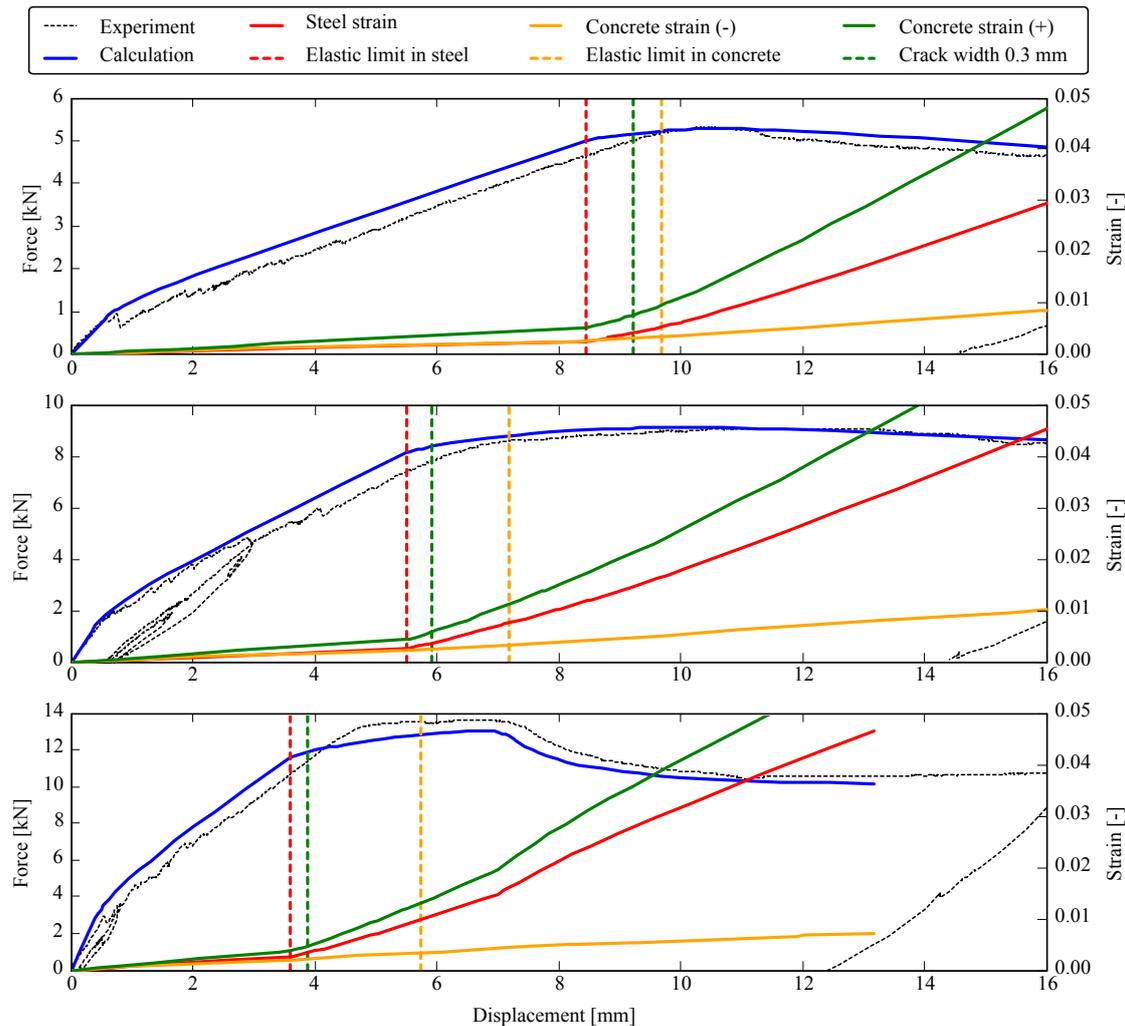


Figure 9: ULS design study; force and strains vs deflection (Beams 1 -3)

7. CONCLUSIONS AND PERSPECTIVES

As said before, this study is a part of an ongoing research program. The first experimental and numerical results seem to demonstrate that the UHPC reinforced with organic fibres and reinforcing bar works well as a composite where all participants (UHPC, fibres and reinforcing bar) are effectively used. Figure 10 & Table 5 show that adding fibres into the matrix helps to significantly increase ultimate performance in terms of limit states

(SLS & ULS). For example; beam 40 / 90 / 900 mm produced from the same material as beam n°3 with steel reinforcement (\varnothing 8 mm), would have higher ultimate capacity (143 %) and lower deflection (64 %) than the same beam without considering fibres. From the other side; adding reinforcing bar to the UHPFRC improve multi-crack distribution along the beam (figure 11).

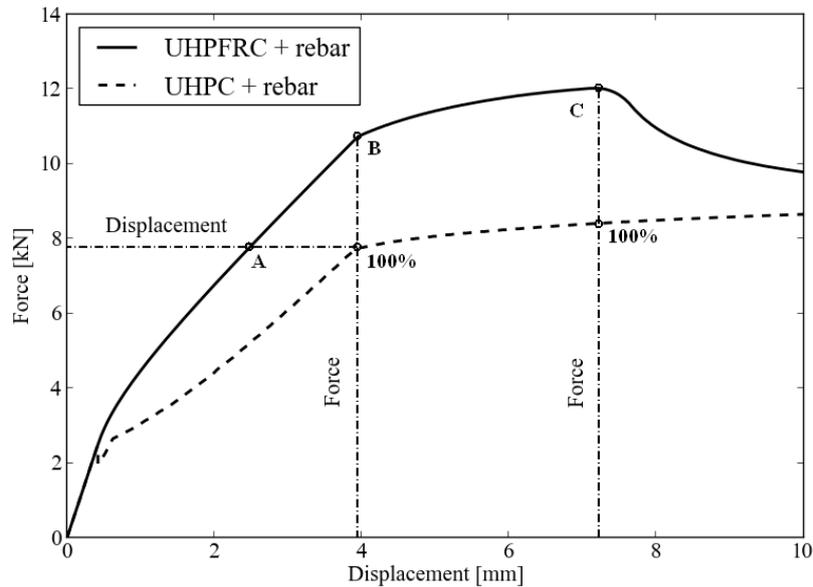


Figure 10 & Table 5: Parametric study of fibre contribution for SLS and ULS – LCR tool (Material properties obtained from the reverse analysis of the beam n°3; 40/depth/900 mm)

Depth [mm]	Displacement A [%]	Force B [%]	Force C [%]
60	70	131	132
70	69	134	135
80	66	136	139
90	64	139	143



Figure 11: Crack pattern on beams after testing

On the numerical part, the first results show that even if different models are used, the similar results are obtained (figure 5). Although table 4 shows a higher variation of the tensile strains in concrete after the reverse analysis for different numerical models, the good results are obtained (figure 6). Once models are calibrated on one experiment, it improves their predictive capacities for other experiments (figure 7). All models have a good conformity up to the ultimate capacity. The further modelling is affected by a localization phenomenon. In this study (LCR model, Multi fibre beam), a characteristic length according to AFGC-SETRA recommendation [1] was used as length of the localization, nevertheless this value needs to be proved by other investigation, as it has major influence on a post peak behaviour.

Albeit the complex numerical modelling of UHPFRC reinforced with steel bars requires higher level of knowledge and still needs further investigation, the benefits of this composite system show new potentials for all design aspects. Furthermore these obstacles appear in post-peak behaviour and therefore they do not have to be included in commercial design. This study proves efficiency of standard design software for simulation of UHPFRC reinforced with steel bars up to the ultimate capacity.

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