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Thin UHPFRC plates stiffened by reinforced ribs represent an efficient conceptual use of UHPFRC, as demonstrated in some outstanding applications. Optimization of the ribs reinforcement and of the UHPFRC fibre ratio, which has significant economic and technical relevance, is critically related to guaranteeing ductile failure modes of such structures and components, taking into account the effects of the scatter of local material properties and post-cracking fibre contribution. To this aim, flexural tests on ribbed triangular UHPFRC plates have been carried out at IFSTTAR Structures Laboratory, with Lafarge as a partner, in a joint project with Laval University. The fibre content and the preferential orientation of the steel fibres due to the casting process were varied, as well as the loading configuration, so that the possible structural redundancy could be checked. The results of these tests are described and analytically analysed in relation to the material properties derived from both moulded samples and specimens sawn from companion plates.

Keywords: UHPFRC, UHPC, steel fibers, ribbed plates, yield lines method.

1 Introduction

Ultra High Performance Fibre-Reinforced Concrete (UHPFRC) refers to a class of materials with a cementitious matrix, a characteristic compressive strength in excess of 130 MPa, and containing steel fibres in order to achieve ductile behaviour under tension [1], and represents an important breakthrough for structural design. Indeed the UHPFRC behaviour under tension is a fundamental constitutive property that modifies the use of conventional reinforcement [2]. Thus extremely light but durable elements can be made with it, either prestressed or even made of plain UHPFRC for shorter spans. Moreover, UHPFRC plates stiffened by reinforced ribs represent a conceptual efficient use of UHPFRC, as demonstrated in some previous applications, e.g., Villa Navarra roofing, Jean Bouin arena renovation, etc. [3-4], with probably promising diffusion. However, some aspects of this design trend appear as critical either due to a limited experimental validation of the design provisions, or due to the specific geometry of the structure. In fact, 2D deck mechanisms have not been extensively documented for UHPFRC, for which a number of present applications have been based on beams. Moreover, optimization of the ribs reinforcement and of the UHPFRC fibre ratio, which has significant economic and technical relevance, is critically related to guaranteeing ductile failure modes of such structures and components, including effects of the scatter of local material properties and post-cracking fibre contribution. Therefore, an experimental program was defined to analyse the flexural behaviour of reinforced ribbed triangular UHPFRC plates taking into account the actual orientation of fibres, as a supporting basis for better understanding of such structures.

2 Flexural Tests

Specimens and parameters

All specimens were fabricated in a precast factory (Bonna Sabla, Vendargues, France), using UHPFRC mixes with two fiber ratios (V_f = 1% and V_f = 2%), with main features presented in Table

1. Two days after casting, the specimens heat treated during 48 hours in a climate-conditioned box at about 90°C with a relative humidity of about 100 %. The intent of this step is to rapidly increase the mechanical properties and to complete maturation of the UHPFRC mix: the total further shrinkage is zero and the creep is significantly reduced after the heat treatment. The main parameters studied in this experimental program were: (i) the fiber ratio; (ii) the casting process; and (iii) the loading configuration. Ten UHPFRC plates stiffened by reinforced ribs were tested. An overview of specimens characteristics is given in Table 2.

Table 1: UHPFRC mix characteristics

Concrete Mix	f_c cylinders After steam treatment (MPa)	Young's Modulus After steam treatment (GPa)	Steel straight fibers L_f – Φ_f (mm)	V_f (%)
UHPFRC-1%	229	56.9	13 – 0.2	1.0
UHPFRC-2%	234	58.4	13 – 0.2	2.0

Table 2: Parameters of the flexural tests

Specimen	Fiber ratio	Casting process	Loading configuration
2%-A-4pts-01	2%	Process A	4 point bending
2%-A-4pts-02	2%	Process A	4 point bending
1%-B-4pts-01	1%	Process B	4 point bending
1%-B-4pts-02	1%	Process B	4 point bending
2%-A-centred-01	2%	Process A	Centred bending
2%-A-centred-02	2%	Process A	Centred bending
1%-A-centred-01	1%	Process A	Centred bending
1%-A-centred-02	1%	Process A	Centred bending
1%-B-centred-01	1%	Process B	Centred bending
1%-B-centred-02	1%	Process B	Centred bending

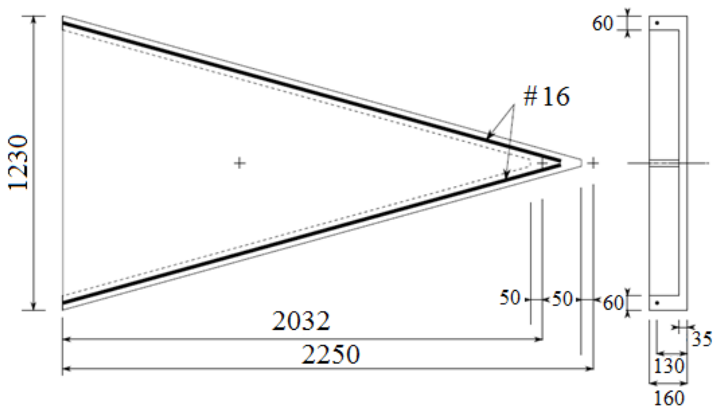


Figure 1 Top view of specimens (Left side) and cross-section (Right side) – Dimensions in mm

The triangular specimens got a total length of 2.25 meters having a span of 2.0 meters and a total depth of 160 mm. Each rib was reinforced thanks to #16 rebar with an effective depth equal to 130 mm. The ribs width was 60 mm. The nominal top flange thickness was 35 mm for all specimens, however 1 or 2 mm-deviation was observed and taken into account in the results interpretation. The full details of dimensions and arrangement of reinforcement are shown in Figure 1.

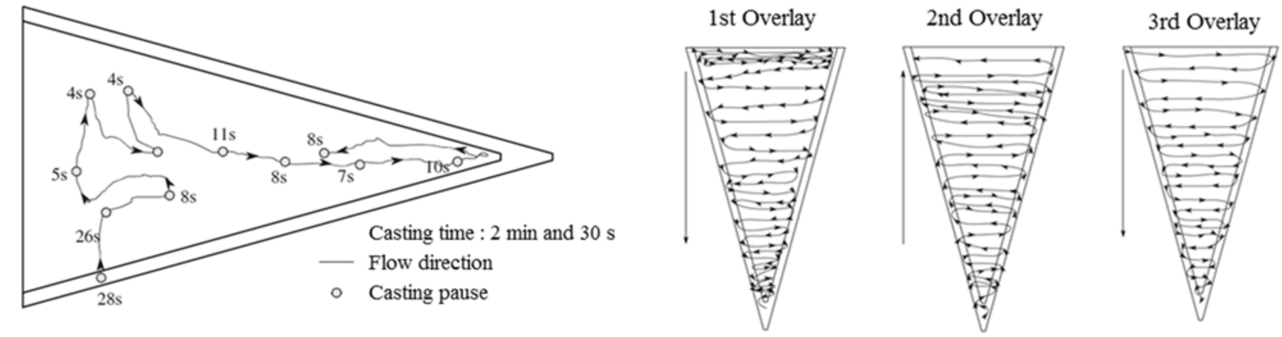


Figure 2 Casting process : process A (left side) ; process B (right side)

Two casting processes have been considered in order to estimate their influence on fiber orientation in the structure : casting process A or B (see Figure 2). The process A aims to obtaining an isotropic fiber orientation in the deck plane. The process B corresponds to a casting method trying to induce preferential fibre orientation (in the deck plane) following the transverse direction.

Two loading configurations have been considered (see Fig. 3). The first configuration is a Four Point Bending Test (4BPT) chosen to grasp the behaviour of reinforced UHPFRC and quantify the possible contribution of the deck in-between the ribs. The position of four loading points has been determined in order to obtain constant stress on the tensile face in-between. The second configuration is a centred bending test which aims to grasp the UHPFRC behaviour under complex loading (concomitance of longitudinal and transversal bending) with identification of forces redistribution after structural localization and yield lines pattern.

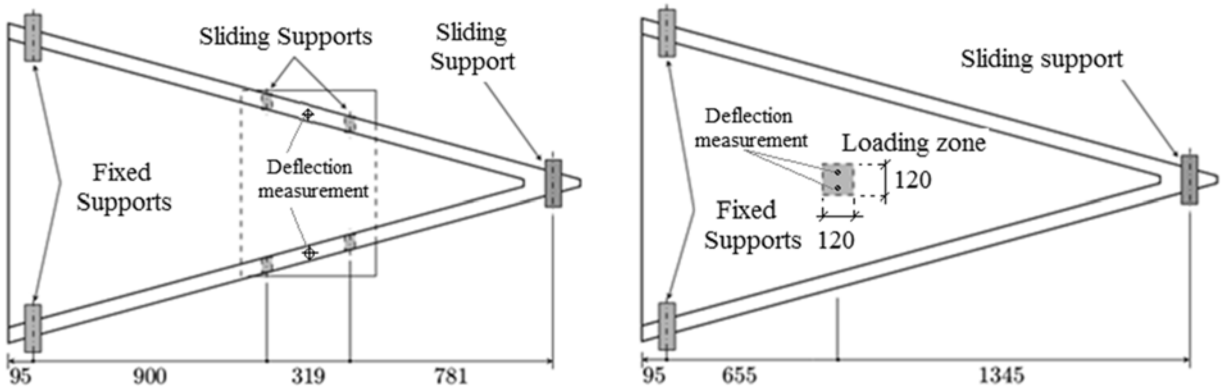


Figure 3 Loading configurations : 4 point bending tests (left side) ; centred bending tests (right side)

Experimental results

Figure 4 shows the experimental load-deflection curves for 4PBT and centred bending tests, respectively. The result of the specimen 2%-A-4pts-02 is omitted since it has been considered as non representative due to problems during casting inducing unexpected fiber distribution.

Considering the 4PBT configuration, for UHPFRC with V_f = 2%, a fine multiple cracking (with a low spacing around ¾ times L_f) develops until reaching structural localization (one failure crack in the maximum bending moment zone) associated to rebars yielding. For UHPFRC with V_f = 1%, several macro-cracks develop with a spacing which reduces gradually until reaching structural localization and a long plateau due to rebars yielding. The specimen made of UHPFRC with V_f = 2% has a 15% higher capacity than triangular plates made of UHPFRC with V_f = 1%. Nevertheless this difference starts reducing after structural localization. Indeed, when the failure crack is rather opened, UHPFRC contribution is low and structural strength is only brought by parts under compression and rebars under tension. An example of bending failure is shown in Figure 5 for both fiber ratios.

Considering centred bending configuration, in order to take into account the influence of deviation in upper deck height among specimens on the real stress field during loading, the curves displayed in Figure 4 show the applied force divided by the squared deck height as a function of the deflection. For each plate, multiple cracking develops on the tensile face of the upper deck following principal tensile stresses distribution. When the maximum load is reached, structural localization appears with identification of a Y-shaped yield lines pattern. An example of bending failure is shown in Figure 5 for each configuration. The specimens strength made of UHPFRC with V_f = 2% is 11% higher than triangular plates 1%-B-centred and 19% higher than specimens 1%-A-centred.

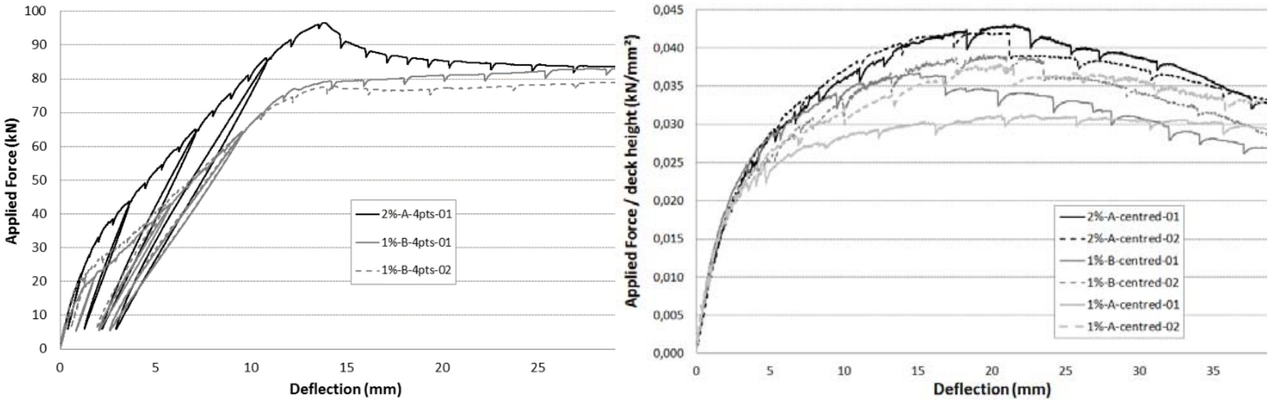
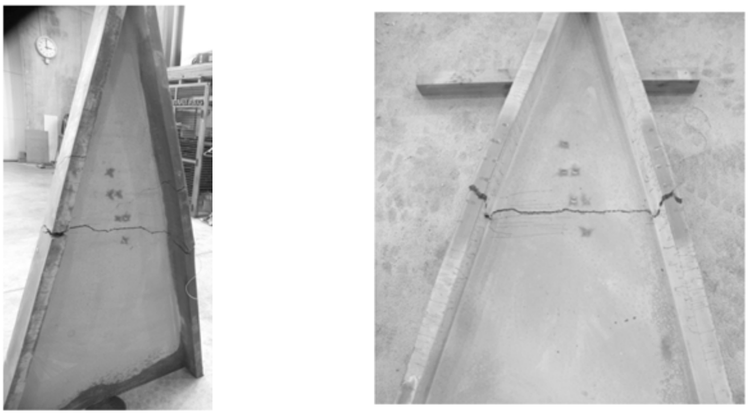


Figure 4 “Load-deflection” curves for four point bending tests (at left) and “Load/h² - deflection” curves for centred bending tests (at right)

1%-B-4pts-01 2%-A-4pts-01



1%-A-centred-01 1%-B-centred-01 2%-A-centred-02

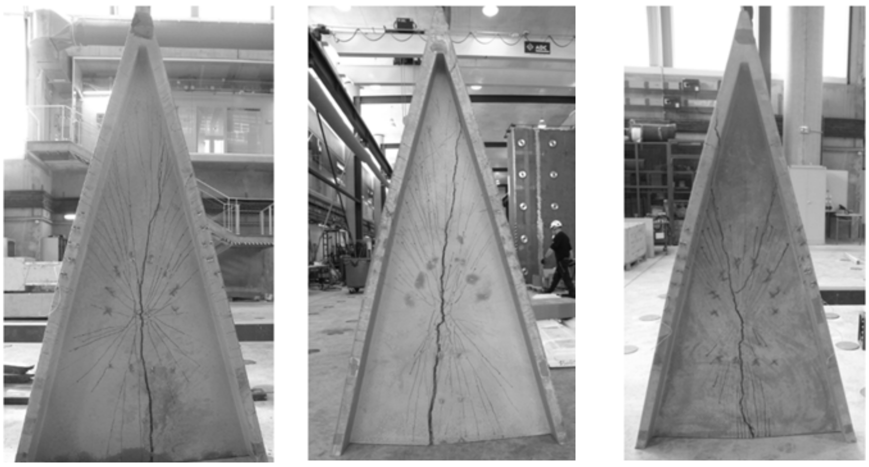


Figure 5 Examples of failure patterns for four point bending tests (1%-B-4pts-01 ; 2%-A-4pts-01) and centred bending tests(1%-A-centred-01 ; 1%-B-centred-01 ; 2%-A-centred-02)

3 UHPFRC Mechanical Characterization

Four point bending tests on moulded prisms

Four point bending tests on six 70mm×70mm×280mm moulded prisms have been carried out for each UHPFRC mix (V_f = 1% and V_f = 2%) in order to identify the limit of elasticity $f_{ct\text{-}el}$ and the UHPFRC post-cracking behaviour under tension. The total span was 210 mm and the distance between upper rollers was 70 mm. For each UHPFRC mix, from six results, an average curve “Bending stress – midspan deflection” is constructed (see Fig. 6 left). Then inverse analysis [5] is applied to obtain the post-cracking “stress-strain” relationship (see Fig. 6 right). Indeed, in this first order analysis, the UHPFRC mix with V_f = 1% is considered as pseudo-strain hardening.

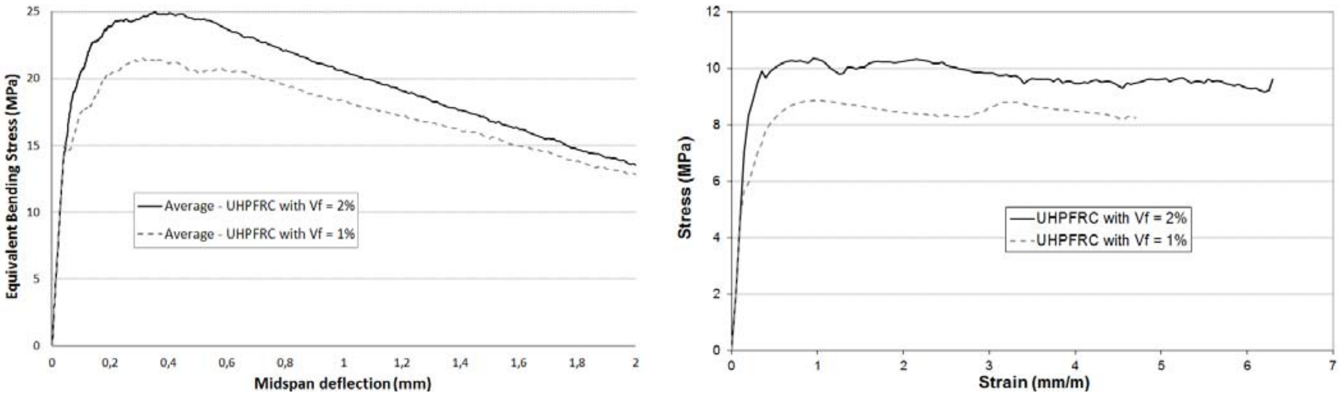


Figure 6 For each UHPFRC mix : Average curve “Equivalent Bending Stress (EBS) – Midspan deflection” obtained from 4 point bending tests on moulded prisms (at left) and corresponding post-cracking “stress-strain” relationship obtained from inverse analysis (at right)

Fibres orientation: four point bending tests on sawn prisms

The UHPFRC tensile behaviour identified from moulded elements does not account for the influence of fibres orientation in the real structure. Thus, since it is necessary for safe and relevant calculations [2], prisms have been sawn out at different angles in the upper deck of additional triangular plates which have been cast with the same process than other specimens. From consideration of the casting process and loading configuration, two zones have been chosen to identify the fibres orientation: the “triangular base zone” and the “triangular top zone” (see Figure 7). For both zones, four inclinations have been studied (0°, 45°, 90° and 135°) from two additional specimens for each configuration (except for 1%-A-centred where only one additional triangular plate had been cast, so only one zone is considered). For each inclination, six prisms 60mm×35mm×240mm have been extracted and tested in four point bending configuration (total span equal to 210 mm and distance between upper rollers equal to 70 mm).

As recommended in [2], for each casting process and zone, an orientation factor has been calculated for each angle (1), from the average curves “Equivalent Bending Stress (EBS) – Midspan deflection” corresponding to the different inclinations. These values are displayed in Table 3.

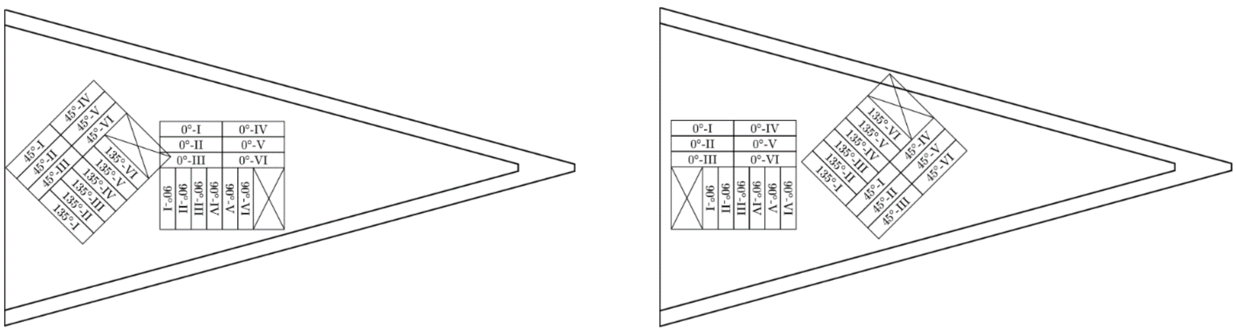


Figure 7 Prisms extraction on additional specimens for a given configuration

$$\text{Orientation factor } \alpha° = \frac{Max("EBS-\delta" - \alpha°)}{Max\left[\ Average("EBS-\delta"\ 0°;"EBS-\delta"\ 45°;"EBS-\delta"\ 90°;"EBS-\delta"\ 135°)\ \right]} \quad (1)$$

Table 3 "Orientation factor" for each inclination and for each configuration

Casting process	Zone	Inclination (°)	Max "EBS-δ" at α° (MPa)	Max Average Curve ("EBS-δ") (MPa)	Orientation factor
2%-A	Triangular base zone	0	25,90	25,89	1,00
		45	22,93		0,89
		90	23,22		0,90
		135	36,58		1,41
	Triangular top zone	0	24,85	24,38	1,02
		45	22,50		0,92
		90	28,47		1,17
		135	22,97		0,94
1%-B	Triangular base zone	0	18,95	19,06	0,99
		45	18,76		0,98
		90	19,12		1,00
		135	20,30		1,06
	Triangular top zone	0	16,51	14,86	1,11
		45	17,16		1,16
		90	13,58		0,91
		135	17,49		1,18
1%-A	-	0	22,77	19,09	1,19
		45	18,47		0,97
		90	16,26		0,85
		135	20,03		1,05

Reference "σ-w" relationship for the upper deck of ribbed triangular plates

The identification of fibres orientation in the upper deck is particular useful to analyse the results of the centred bending loading. For this configuration, the chosen analytical approach (which will be detailed in the next section) is based on the yield lines theory. Thus "σ-w" relationships are necessary as input data. For each casting process and each zone, a reference "σ-*w*" relationship is obtained from the average curves "σ– w" corresponding to the inclinations 0°, 45°, 90° and 135° determined from inverse methods described in [6], see Figure 8.

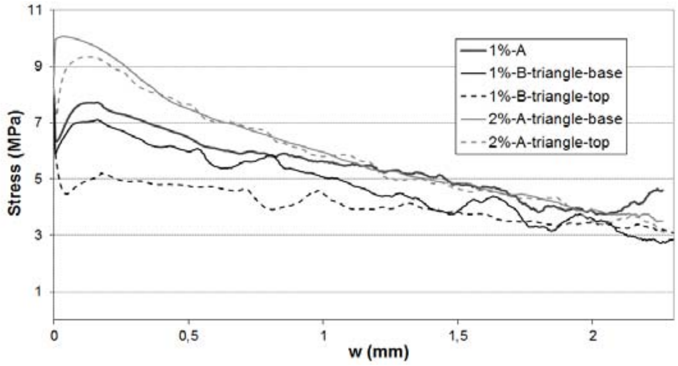


Figure 8 Reference "σ-w" relationships obtained with inverse analysis for each casting process and each zone

4 Comparison with analytical modelling

Four point bending tests on triangular plates

The chosen approach for modelling the 4PBTests is based on "stress-strain" calculation. UHPFRC post-cracking "stress-strain" relationships presented in Figure 6 are used for the calculation. Indeed fibres orientation inside 70mm×70mm×280mm moulded prism is assumed to be similar to fibres orientation inside ribs (width equal to 60 mm) of triangular plates. A perfect bond between UHPFRC and steel bars is assumed. The rebar stress-strain constitutive law is considered as elastic-perfectly plastic with a yield stress derived from uniaxial tests equal to 564 MPa. Comparison of analytical modelling and experimental results is presented in Fig. 9.

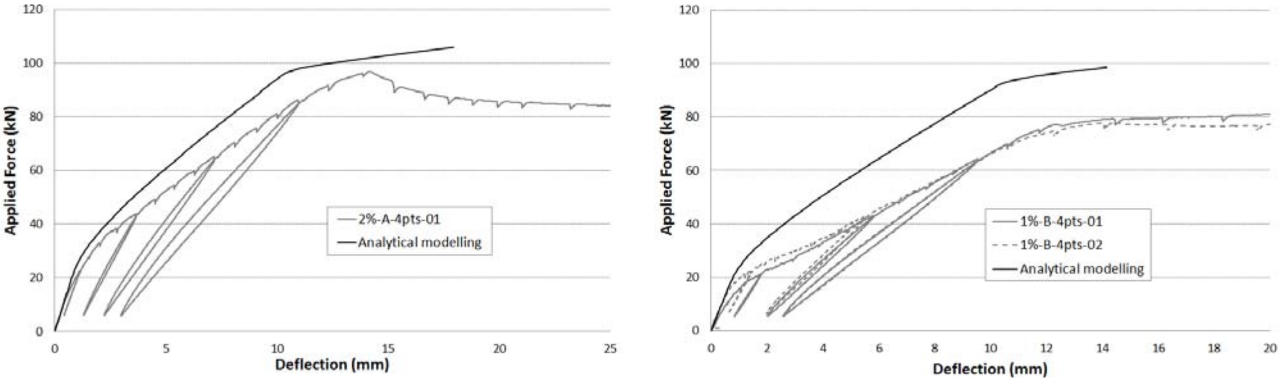


Figure 9 Four point bending tests : comparison between experimental results and analytical modelling : 2%-A-4pts at left and 1%-B-4pts at right

The analytical model overestimates the strength and stiffness of specimens during loading. This difference can be explained by the fact that during casting, rebars inside ribs may have disturbed the fibres flow. As a consequence, the real UHPFRC (in ribs) post-cracking behaviour is worse than the one used for this calculation. The difference between analytical modelling and experimental results is bigger for UHPFRC with V_f = 1%. The assumption of a pseudo-strain hardening behaviour for this UHPFRC does probably not represent its real behaviour. For this UHPFRC mix, it will be necessary to use a “stress-crack opening” approach with a “shear stress – displacement” law between rebar and UHPFRC.

Centred bending tests on triangular plates

The chosen approach for the modelling of centred bending tests is based on yield lines theory, which consists in using the mechanism leading to the collapse of the structure to predict the failure load. The structure is considered as turning progressively into a multi-hinges mechanism. These hinges are created by the material yielding along lines between plates supposed as perfectly rigid. Equalling the work of internal forces (due to the moment and rotation along the yield lines) and the energy of applied external forces enables to obtain the force as a function of the deflection δ at the loading point. Here, the yield lines are directly known from the experimental results. To apply this method, we need to determine the relationship between bending moment M and breaking angle θ, which is directly derived from curves “Bending Moment – Crack opening” obtained with the “stress-crack opening” laws presented in Figure 8, multiplied by the orientation factor associated to the yield lines direction. To this calculation, the elastic deflection and deflection due to longitudinal bending are added in order to compare directly the results of experiments and analytical modelling (see Figure 10).

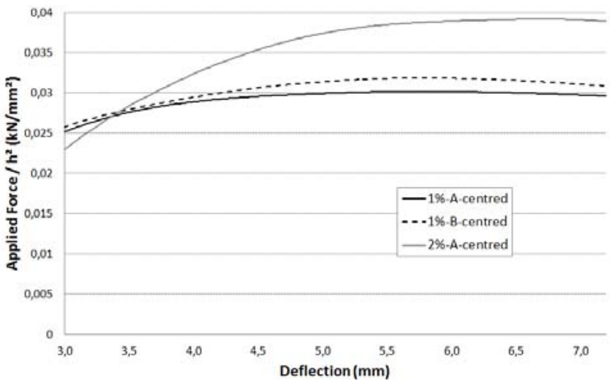


Figure 10 Centred bending tests : curves "Applied Force/h² vs. Deflection" (analytical modelling)

Table 4 gives a synthesis of experimental results compared to the results of this analytical modelling. The maximum load is fairly predicted but the predicted deflection is rather far from experimental results. Indeed, before reaching the maximum force and development of the yield lines pattern, multiple cracking has occurred inducing deformations. This step is not taken into account by the analytical modelling. A similar fair ultimate load prediction associated to stiffness overestimation has already been found by [7] in applying yield lines methods to UHPFRC.

Table 4 Centred bending tests: comparison between experimental results and analytical modelling

		Experimental result		**Analytical modelling**	
		Maximal Applied Force/h² (kN/mm²)	Deflection at max force (mm)	Maximal Applied Force/h² (kN/mm²)	Deflection at max force (mm)
2%-A-centred	2%-A-centred-01	0,04302	21,0	0,03919	6,7
	2%-A-centred-02	0,04196	20,7		
1%-B-centred	1%-B-centred-01	0,03665	15,1	0,03187	5,7
	1%-B-centred-02	0,03915	20,7		
1%-A-centred	1%-A-centred-01	0,03121	21,9	0,03020	5,9
	1%-A-centred-02	0,03785	20,9		

5 Conclusions

Flexural tests have been carried out in a four point bending or centred bending configuration on ten reinforced ribbed triangular UHPFRC plates with different parameters such as fibres ratio (V_f=1% and V_f = 2%) or casting process. In order to identify the real UHPFRC post-cracking behaviour in the structure, prisms have been cut in the upper deck, at different inclinations to determine the real "orientation factors". First analyses of these experimental results, in particular for the centred bending configuration, highlight the importance of taking fibre orientation into account for a precise assessment of the structural capacity and its ductility.

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