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FEEDBACK OF A TEN YEARS ASSESSMENT OF FIBRE DISTRIBUTION USING K FACTOR CONCEPT

Alain Simon (1), Dominique Corvez (2), and Pierre Marchand (3)

(1) Eiffage TP, Noisy Le Grand, France

(2) Lafarge SA, Paris, France

(3) Université Paris-Est IFSTTAR, Champs-sur-Marne, France

Abstract

AFGC SETRA Interim recommendations have proposed in 2002 a way to assess fibre orientation factor in UHPFRC structural members. The method has been then used on most of the major structural UHPFRC projects in France and the aim of this contribution is to present a ten year feedback of it. In a first part, the method principle will be presented extensively through a classical bridge project: Pont de Saint Pierre La Cour. In a second part, key results obtained with projects such Achères shells, Bourg-les-Valence bridge, Pinel bridge and "Pont du Diable footbridge" will be compared and analysed with respect of casting methods employed. In sum, this practical K factor method has shown robustness and reliability that no other non-destructive method has proposed from now.

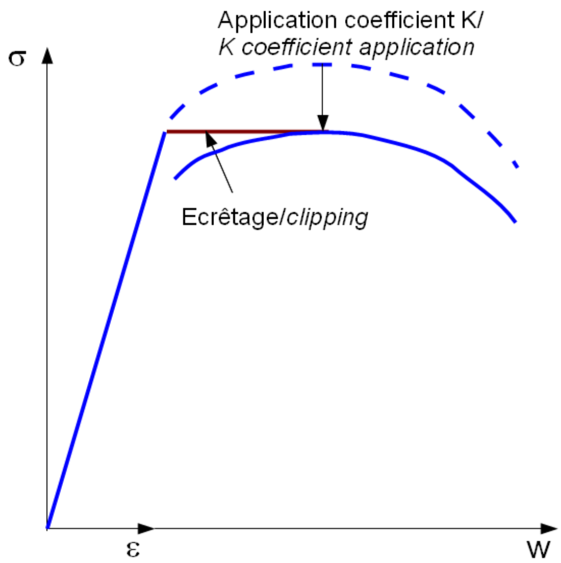
Résumé

Les Recommandations provisoires AFGC SETRA de 2002 ont proposé une manière de déterminer un facteur d'orientation des fibres à prendre en compte dans le dimensionnement de pièces structurelles en BFUP. La méthode utilisée sur la plupart des ouvrages BFUP structuraux fait désormais référence et le but de cette contribution est de présenter dix années de retour d'expérience. Dans une première partie, la méthode et ses particularités seront présentées au travers du projet du Pont de Saint Pierre La Cour. Dans une seconde partie, les résultats clés des projets tels que les coques d'Achères, les ponts de Bourg-lès-Valence, le pont Pinel ou encore le Pont du Diable seront comparés et analysés en fonction des modes de coulage employés. En conclusion, l'accent sera mis sur le caractère pratique de la méthode du coefficient K qui a montré une robustesse que ne sauraient égaler à ce jour, les méthodes non destructives.

1. INTRODUCTION

In UHPFRC, precise determination of the contribution of fibres is key in the assessment of tensile properties in the post cracking state. K factors introduced by AFGC-SETRA Recommendations in 2002, enable to represent distribution and orientation of fibres in different zones of a real structure, compared to a theoretical model where fibres would be randomly equally distributed and with an isotropic orientation. K factors are taken into account directly in the design constitutive law of the UHPFRC. They will affect the non-linear part of the tensile law, which is the domain influenced by the fibres contribution.

At the stage of suitability tests, the K factors previously taken into account in the design of a project must be verified experimentally. In order to do this, several samples have to be taken from a mock-up at full scale (see fig. 1), sufficiently representative of the structure under design, and fabricated in the same conditions (in terms of formwork and concreting process).



Domain on which the K factor is applied

Samples dimensions depend on the fibre length and on the type of test (direct tensile test or bending test), and their location in the prototype depend on the main tensile stresses to be justified in the real structure, where the fibres efficiency will highly contribute. Finally, several effects in the samples can influence more or less the orientation or the anchoring of the fibres located in the vicinity of an edge, and have to be taken into account.

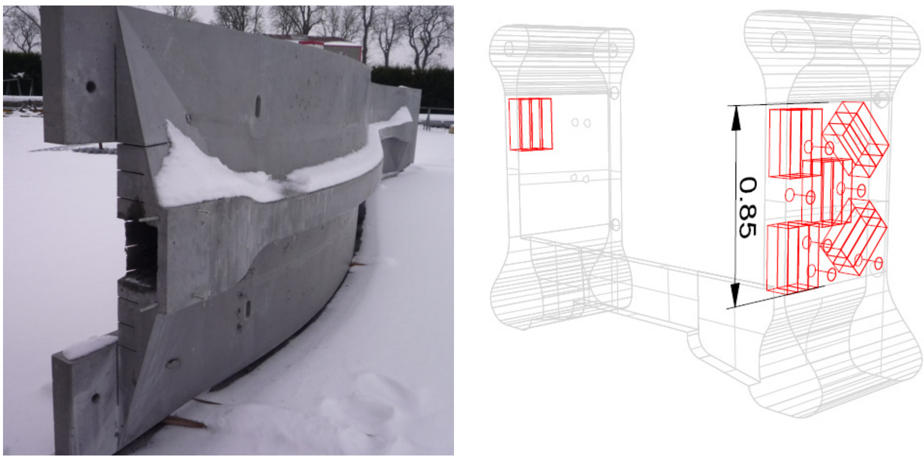


Figure 1: two examples of prototypes subjected to K factor analysis: A shell of Achères plant on the left, a segment of the "Pont du Diable" footbridge on the right

2. METHOD APPLIED

2.1 Edge effects correction

Rules to assess the effect of the different edge effects (formed surface, sawing, notching) are given here. It is supposed that the part which is submitted to compression during the test does not need any correction.

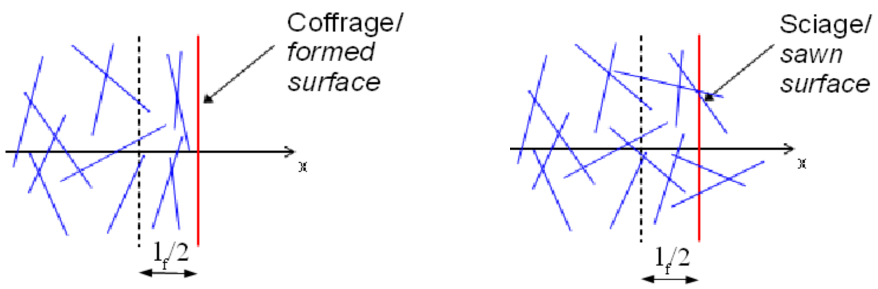


Figure 2: effect of formed and sawn surface

2.1.1 Formed surface

The fibres in the middle of a prism are not disturbed by the formwork. They are assumed to be distributed isotropically in 3D and the orientation factor is equal to α = 0.405 in this zone. The fibres located in the vicinity of a formed wall (see fig. 2), that is to say these whose centre of gravity is inside a $L_f/2$ (where L_f = fibre length) wide band along this formed wall are subjected to the formed wall effect. Those against the form are oriented in 2D (α = 0.637) and those located at a distance higher than $L_f/2$ are oriented in 3D (α = 0.5 in theory, 0.41 for keeping a safe evaluation of edge effects). Taking into account the non-linear variation of α in these bands, we obtain an average value of the orientation factor, equal to α = 0.597

2.1.2 Sawn surface

The fibres in the middle of a prism are not disturbed by the sawing. They are assumed to be distributed isotropically in 3D and orientation factor is equal to α = 0.5 in this zone (a value of 0.41 is taken into account). The fibres whose the centre of gravity is located inside a $L_f/2$ wide band along the sawn surface (see fig. 2) are also distributed isotropically in 3D, but their length has been reduced by sawing. It is therefore considered that a fibre whose centre of gravity is on the sawn face is no longer anchored. Anchoring becomes fully effective only for fibres whose centre of gravity is at $L_f/2$ from the face. In the intervening area [0 ; $L_f/2$], it is assumed that the fibres are 50 % effective.

2.1.3 Notch

Providing a notch enables to localize cracking of a specimen. It is hence easier to measure the crack width evolution during a direct tensile test or a bending test. The notch depth has to be higher or equal to the half-length of fibres ($L_f/2$). The indirect consequence of this notch is to delete any formwork effect on the fibre orientation of this face. As comparison is done on specimens with the same notch dimension, and since the reference area considers the cross-section after deduction of the notch, no correction is required.

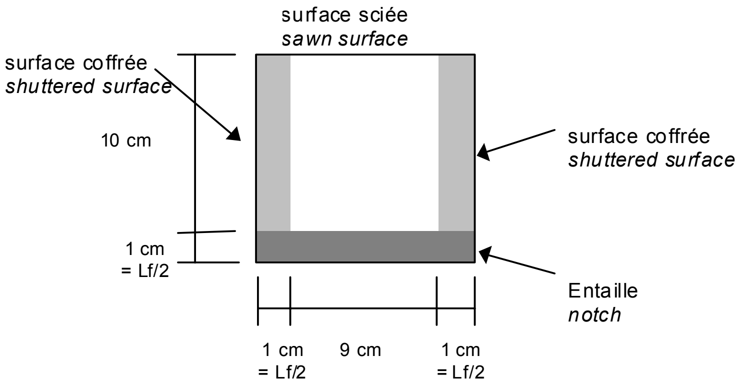
2.1.4 Unformed free-surface

If the free surface is under tension and not notched, then it is necessary to consider it as a formed surface and to apply the corresponding correction. This accounts for the 2D fibre orientation along the free surface. If the free surface is under compression or notched, no correction has to be applied.

2.2 Examples of edge effects

2.2.1 Example for a formed prism

Hypothesis: L_f = 20 mm and prism dimensions 11 cm x 11 cm x 44 cm, to be notched.



As the fibre length is 2 cm, the notch depth is $L_f/2$ = 1 cm.
For the same reason, a 1 cm wide zone of disturbance is taken into account on each side of the cross-section (formed wall effect).
The mean value α = 0.597 in the vertical bands ($L_f/2$ wide) is used.

The orientation factors are used to determine the mean orientation factor for the entire cross-section of a prism: αmean = (0.41 x 9 + 0.597 x 2) / 11 = 0.444

The factor by which the raw results have to be divided, and which enables to overcome the wall effect is therefore: λ = 0.438 / 0.41 = 1.083

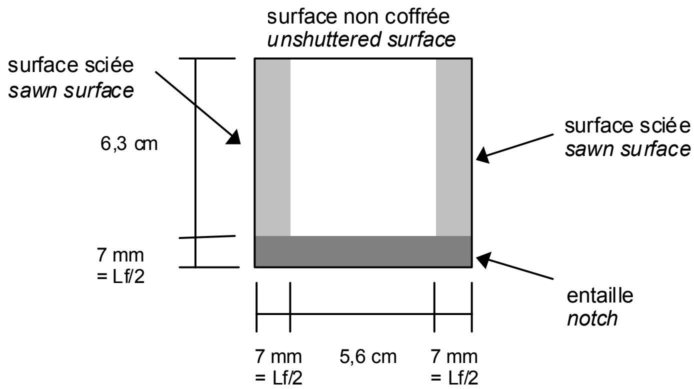
This result means that with a test carried out with such a specimen, the intrinsic UHPFRC bending strength is over-estimated by 8.3 %, because of the edge effects which exist in the tested specimen.

2.2.2 Example for a sawn prism

Hypothesis: L_f = 14mm and prism dimensions 7 cm x 7 cm x 28 cm, to be notched.

The notch depth is $L_f/2$ = 0.7 cm. The fibres are assumed to be 50 % effective in the interval [0 ; $L_f/2$].

The factor by which the raw results have to be divided, and which enables to deduce the edge effect is therefore:



λ = (50 % x (0.7 + 0.7) + 100 % x 5.6) / 7 = 0.9

This result means that with a test carried out with such a specimen, the intrinsic UHPFRC bending strength is under-estimated by 10 %, because of the edge effects which exist in the tested specimen.

2.3 A case study: Saint-Pierre-La-Cour Bridge

The deck of this road bridge built in 2005 is constituted by Ductal® girders and by an ordinary concrete upper slab. A 3 m long beam mock-up was made (see fig. 3) according to the chosen procedure to manufacture the definitive beams. 24 specimens 70 x 70 x 280 mm have been sawn as described below (as the fibre length is L_f = 13 mm, the transversal dimensions are at least equal to 5 L_f = 65 mm):

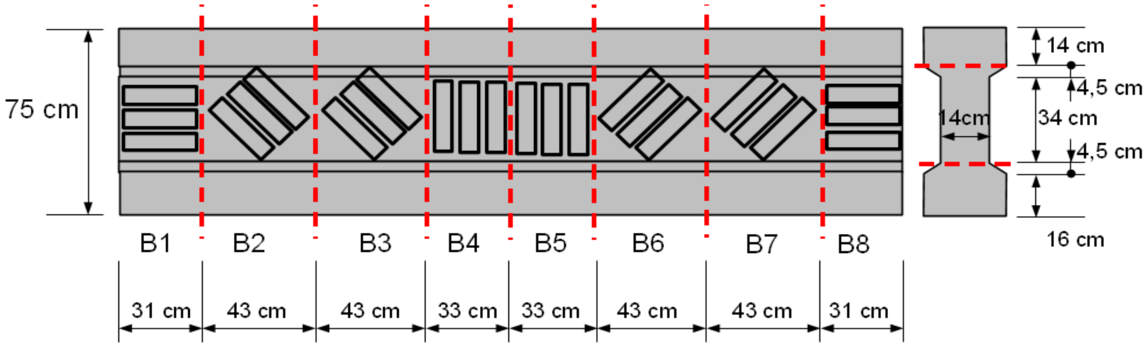


Figure 3: sawing of the mock up for Saint-Pierre-la-Cour project

Each sample has been notched (notch depth equal to 7 mm ≥ $L_f/2$) and then submitted to a 3 points bending test. In the table below the average of the peak values of the curves (stress versus crack opening or deflection), for the specimens sampled in a same zone, are displayed. These values are then corrected to take into account the edge effects (λ = 0.91) and compared to the intrinsic reference previously obtained: 25 MPa for this project (average value of the bending moment peaks, measured on at least 6 formed specimens).

K global factor to be used here for 45° oriented stress is the maximum of the mean values (table 1). Here Kglobal = 0.73 limited to Kglobal = 1.

K local: for each series of specimens, the minimum stress value is considered (table 2). The K local factor to be used is the maximum obtained for all the series. Here: Klocal = 1.36

Table 1: tests results obtained for determination of Kglobal

Zone	Mean stress value	Corrected value	K global
45° : B2 and B7	31.2 MPa	34.4 MPa	0.73→1
45° : B3 and B6	33.3 MPa	36.7 MPa	0.68→1

Table 2: tests results obtained for determination of Klocal

Zone	Minimal stress value	Corrected value	K local
45° : B2 and B7	26.5 MPa	29.2	0.86→1
45° : B3 and B6	16.7 MPa	18.4	1.36

3. EXPERIENCE FEEDBACK ON K FACTORS

Applications in UHPFRC, especially in France, highlighted the necessity to determine the fibre orientation factors during the suitability tests. Among others, one can quote: the 2 bridges on the detour road of Bourg-Lès-Valence (in Drôme department), built with BSI® by Eiffage TP in 2001-2002; Saint-Pierre-la-Cour Bridge (in Mayenne department), built with Ductal®, by Quille (Bouygues group) in 2005; PS34 overpass on the A51 motorway, built with BCV® in 2005 by Campenon Bernard Régions (Vinci group); the Pinel Bridge in Rouen, built with BSI®, in 2007 by Eiffage TP; the “Pont du Diable” footbridge built with Ductal® in 2009 by Freyssinet (Vinci group); and the shells of the water treatment plant of Achères, built with BSI® by Eiffage TP in 2010.

3.1 PS34 Overpass

The structure is a bridge over the A51 motorway, with no intermediate pier. A fully precast bridge deck, lifted with a crane, has been possible due to the lightness of the UHPFRC solution. The deck is made of precast segments built with BCV®, combined and assembled by post-tension. The prisms sawn in a full scale mock-up (see fig. 4) built in Campenon Bernard plant, enabled to validate the structural response in transversal bending of the box girder upper slab (horizontal prisms for positive and negative bending moment), the response in shear of the web (vertical prisms in it) and the response of the lower slab, especially the junction point of the flows during concrete placing (horizontal prism at the centre point of the slab). Due to the shape of the box girder and the way to poor the concrete (from only one fixed point at the top of the formwork) different values for K coefficients were obtained in the different characteristic zones.

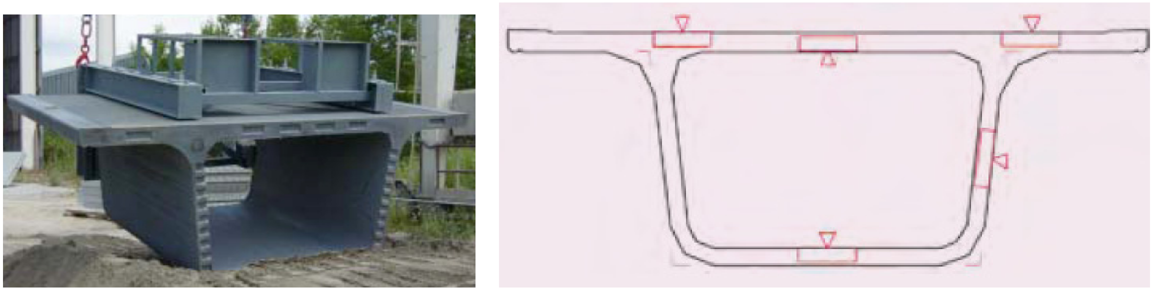


Figure 4: full scale mock-up of a precast segment, with the scheme of extracted samples

3.2 Pinel Bridge

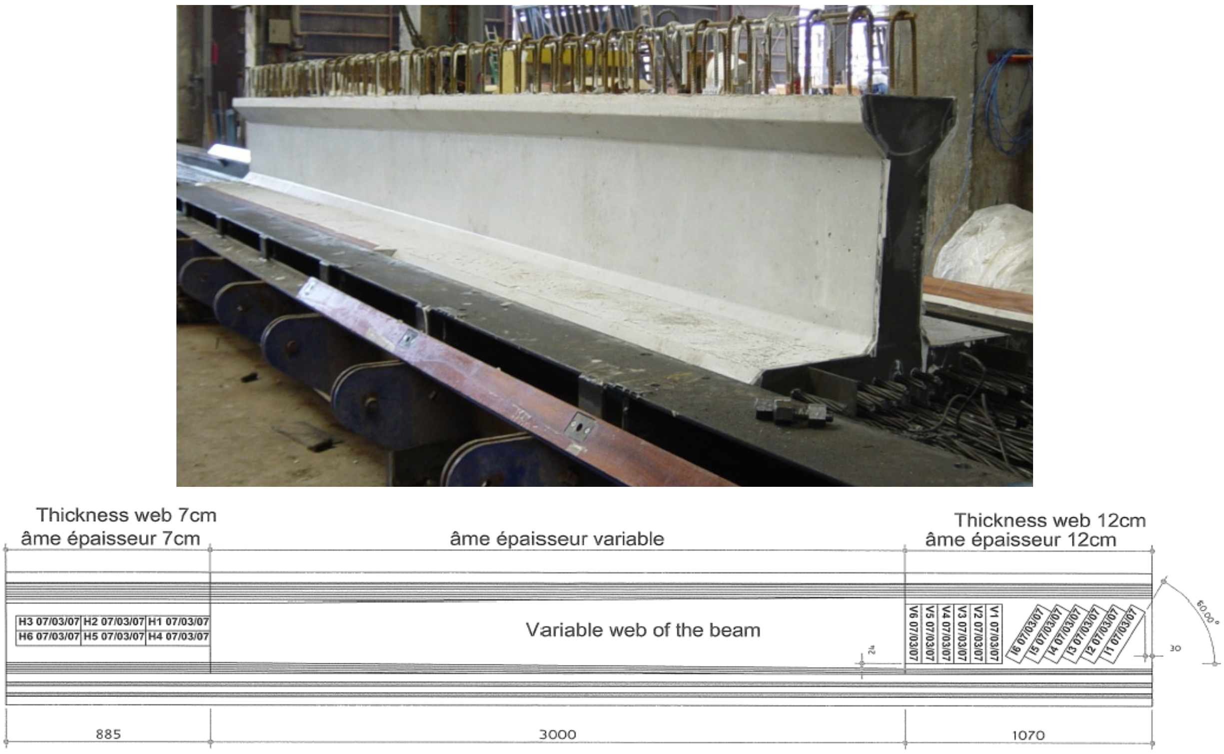


Figure 5: full scale mock-up of a girder with the location of the extracted samples

The girders of the Pinel bridge deck are precast pretensioned inverted T beams called ITE. They are made with UHPFRC, whereas the upper slab is made with ordinary concrete. This combination of two kinds of concrete is a good compromise solution between the minimal thickness of a deck (useful for urban bridges) and the lower cost of it. Suitability tests have been carried out in the Hürks Beton plant, before the start of the manufacturing process of the 27m girders in BSI®. The formwork of the mock-up was identical to what have been chosen for the manufacturing process, with a representative length of 5m taken into account the variable width of the actual beams. Three different zones were subjected to prisms sampling, by sawing (see fig. 5). Due to fibres orientation effects during concrete placement, three successive mock-ups had to be manufactured and tested to calibrate the casting method and obtain results consistent with design hypothesis. At the end of the suitability tests, the values obtained with the 3 points bending tests on notched prisms were : Kglobal = 1.33 and Klocal = 1.75 (maximum values of the 3 zones).

3.3 Bourg-Lès-Valence Bridges

The two bridges of Bourg-Lès-Valence, built in 2001-2002, were the first road bridge decks made of ultra-high-performance concrete, without any rebar. In this project, the girders and the upper slab were made of UHPFRC. π-shaped prestressed beams were precast in BSI® in a plant, carried to the construction site by rail and road, and were jointed together longitudinally with in-situ BSI®. A mock-up of one half of a π-shape beam (see fig. 6) has been casted in the Hürks Beton plant in the Netherlands. Five different sets of samples were made (see Table 3 and fig. 7): three to validate the prestressed girders structural response and two for the upper slab which contained no passive reinforcement.

Figure 6: mock-up of a girder before and after sawing

Table 3: summary of extracted samples

Set	Location	Direction of cut	Prisms
A	web	oriented at 45°	10
B	web	vertical	10
C	web	horizontal	9
D	upper flange	transverse	10
E	upper flange	longitudinal	10

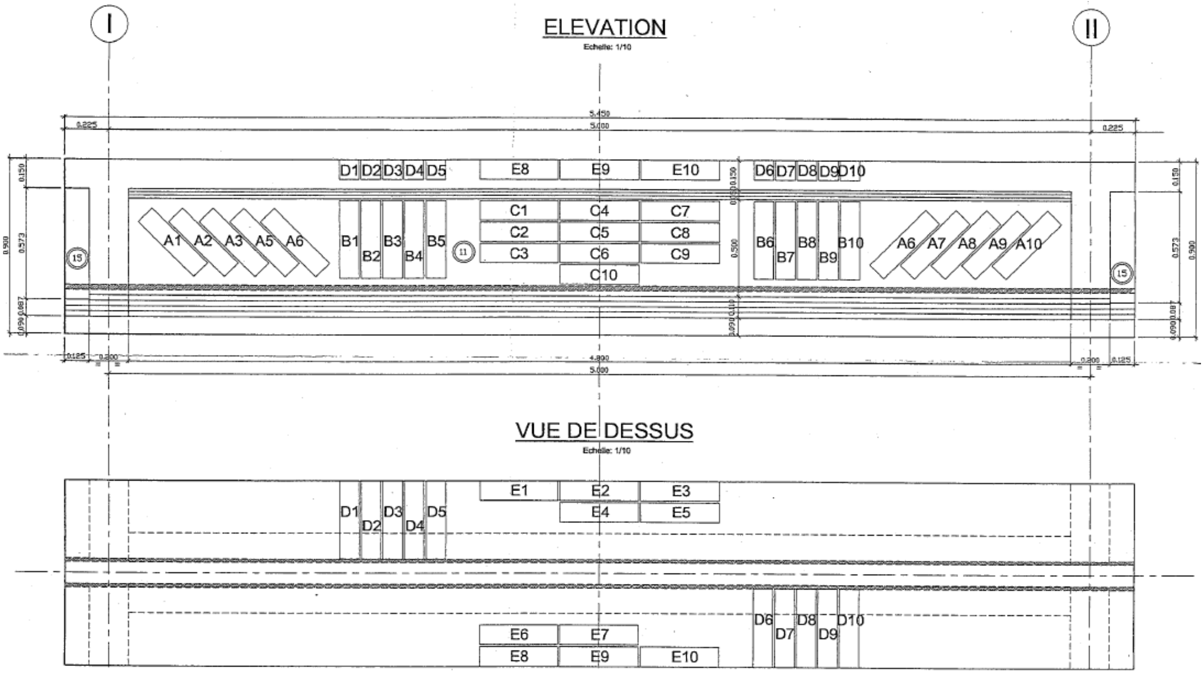


Figure 7: scheme of extracted samples

Table 4: K values obtained

	Zone A	Zone B	Zone C	Zone D	Zone E	Chosen value
Global effects	1.025	0.832→1	1.247	1.089	0.882→1	K = 1.25
Local effects	1.456	1.221	1.722	1.340	1.135	K = 1.75

The results obtained for the K factors in the different zones, are gathered in table 4. For this project, only one value for global effects has been chosen, and one value for local effects (i.e. maximum values of A-B-C-D-E zones). These values have been considered in 2002 French AFGC-SETRA recommendations, as default values for a new project.

3.4 Shells of the water treatment plant of Achères

The elements are precast shells in BSI®, wave shaped, with the following dimensions: height 2.80 m and length 10.60 m. They are prestressed by post-tensioning but contain no passive reinforcements. Prisms were sawn in two characteristic zones of the full-scale mock-up (see fig. 8) built in Eiffage plant: in standard cross-section to validate the bending response of the shells and in the cantilever bearing zone where the prestressing force is introduced.

The results obtained for the K factors in the two zones, are gathered in table 5. In this project two couples of coefficients have been considered in design calculations.

Table 5 : K values obtained

	Mid-span section	Bearing zones
Global effects	K = 1.20	K = 1.35
Local effects	K = 1.65	K = 1.55

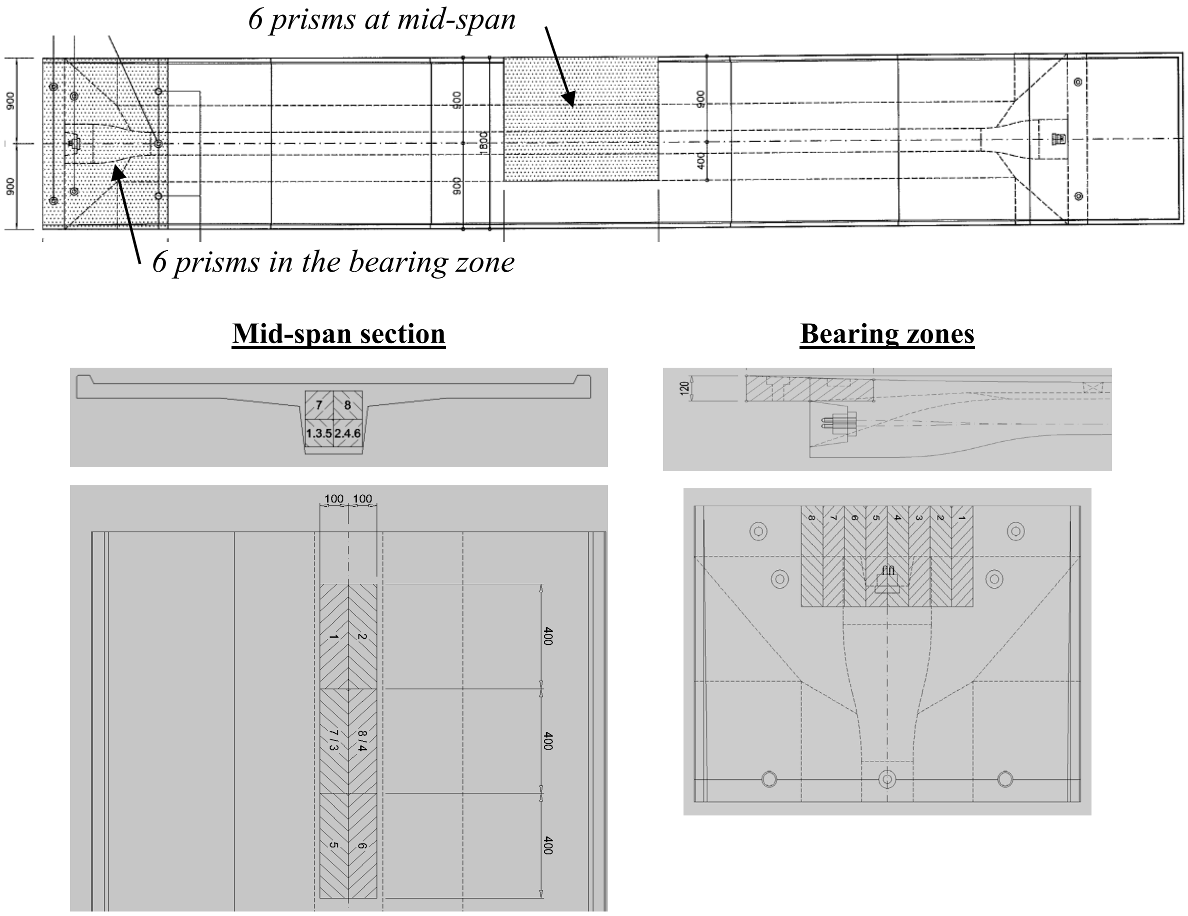


Figure 8: mock-up of a shell, with scheme of extracted samples

3.5 Pont du Diable footbridge

The "Pont du Diable" is a footbridge built in Ductal® in 2009. The deck is made of precast segments combined and assembled by post-tension. A mock-up at full scale in terms of cross-section and with a length of 80 cm (4.6 m for the real segment), was built in the Bonna Sabla plant in Vendargues (see fig. 9).

Samples were extracted from the two webs of the mock-up at different locations and with different inclination angles, 90° (vertical direction), 180° (horizontal direction) and 45° (see fig. 10). The footbridge is a post-tensioned structure. This implies that the tensile strength is not used in longitudinal direction. Hence, only results obtained in the vertical direction and at 45° are important for the resistance of the structure in terms of shear. The results obtained for the K factors are gathered in table 6.

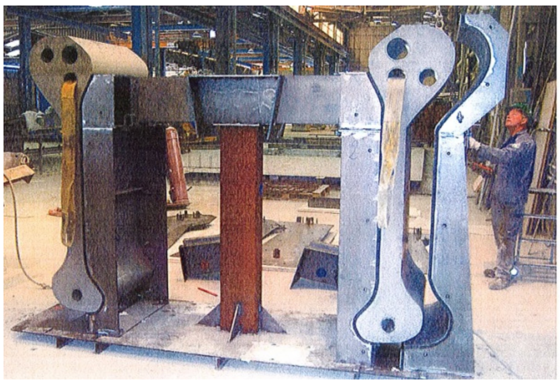


Figure 9: mock-up of a footbridge segment

Consequently, the values to be taken into account for shear design are: Kglobal = 1.26 and Klocal = 2.12 (maximum values of the 4 zones).

Table 6 : K values obtained

Samples inclination	Global effects	Local effects
45° zone 1	0.79→1	0.85→1
Vertical – zone 1	0.93→1	1.04
Vertical – zone 2	1.26	2.12
45° zone 2	1.24	1.37

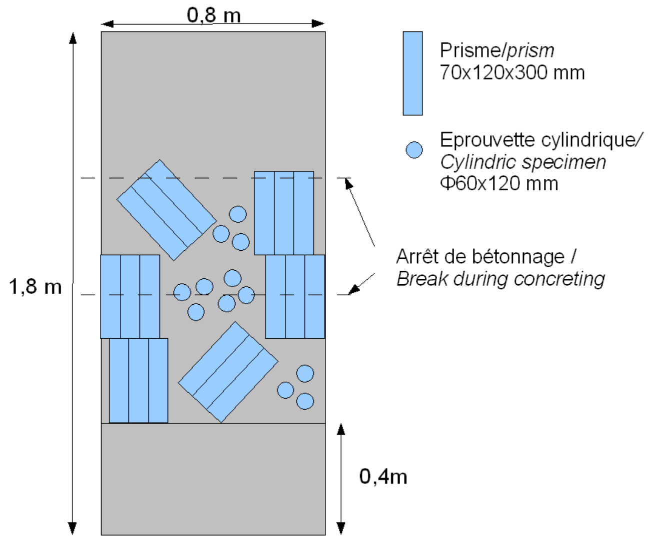


Figure 10: scheme of extracted samples

4. CONCLUSION

The numerous and varied projects with UHPFRC during the last decade, permitted to show the important variability in term of orientation and distribution of the fibres in a structure. This phenomenon depends on many factors, like the shape of the formwork, the way to cast the UHPFRC, the viscosity of it, and many others. To date it is not possible to predict the concrete flow behaviour, and particularly the mix between several layers or the mix at junction points of flows. The practical K factor method, proposed by AFGC-SETRA recommendations has shown robustness and reliability. In many cases it led to modify the way to cast the concrete or the local shape of a formwork, to obtain results consistent with design hypothesis. It means that in several cases, if the K factor method had not been applied, a safety design would not have been obtained. By the way of a conclusion, this method, that has to be applied during suitability tests, must not be neglected. It is one of the most important steps during the building process of a structure in UHPFRC.

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