ADVANCES IN THE DEVELOPMENT OF THE FIRST UHPFRC RECOMMENDATIONS IN SPAIN: MATERIAL CLASSIFICATION, DESIGN AND CHARACTERISATION

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Abstract

With the aim to foster the use of UHPFRC in Spain, the Committee nº1 of the Scientific-Technical Spanish Association of Concrete (ACHE) created in November 2015 the task group 1.6 focused on the development of the first UHPFRC guidelines in Spain. This paper provides a summary of the major issues developed so far regarding of UHPFRC tensile classification, the conceptual design process and characterisation test setup for quality control.

According to the Spanish recommendations, tensile classification of UHPFRC depends on four tensile parameters that can be used to derive the constitutive stress-strain laws in tension proposed for SLS and ULS. These laws must be affected by fibre orientation coefficients to take into account real distribution of fibres in the structural element according to its geometry, fibre length and pouring system. Finally, a quality control programme on four-point bending tests must be carried out to assess that characteristic design tensile parameters are achieved. Standard test and methodology to derive these parameters from it are also described.

Résumé

Dans le but de promouvoir l'usage du BFUP en Espagne, le comité n°1 de l'Association scientifique et technique Espagnole du Béton (ACHE) a créé en novembre 2015 le groupe de travail 1.6 dédié à la mise au point de la première directive sur les BFUP en Espagne. Le présent article résume les principaux sujets traités à ce jour concernant la classification du BFUP en traction, les principes de conception et le type d'essai de caractérisation à utiliser en contrôle.

D'après les recommandations Espagnoles, la classification du BFUP en traction se fait sur la base de quatre paramètres qui peuvent être utilisés pour déterminer les lois de comportement contrainte-déformation en traction proposées pour les vérifications à l'ELS et à l'ELU. Ces lois sont à affecter des coefficients d'orientation des fibres pour prendre en compte la distribution réelle des fibres dans l'élément de structure selon sa géométrie, la longueur des fibres et le mode de coulage. Enfin, un programme de contrôle doit être réalisé sur la base d'essais de flexion quatre points pour vérifier que les valeurs caractéristiques du comportement de traction de calcul sont bien atteintes. L'essai normalisé et la méthodologie permettant d'en déduire ces paramètres sont décrits.

1. INTRODUCTION

Traditionally, the design process of concrete structures has been determined by one single parameter: the compressive strength of concrete. This parameter has been found to be crucial as it correlates with other mechanical parameters required for a project, such as bond strength, tensile strength or flexural strength. That is why compressive strength is the only *strength* parameter in concrete descriptions. However this is not the only parameter required for design. Other required parameters are: (i) exposure environment, which determines the permissible crack opening, covering and durability properties of concrete; (ii) maximum aggregate size, which determines the distance between rebars; and (iii) concrete workability, which determines the casting procedure according to the structure design. Using these parameters is possible to develop any structural concrete project using current codes.

In case of fibre-reinforced concrete (FRC), tensile behaviour cannot be explained using compressive strength, and additional information must be provided to take into account tensile performance in design. This is why MC2010 includes two parameters that correspond to tensile residual strength at two CMOD values obtained from EN-14651. These parameters describe the stress-crack opening behaviour of FRC and allow the consideration of its tensile performance in both ULS and SLS.

When a concrete structure is to be design, design process used must be the same no matter what type of concrete is used. In a first step, design parameters must be established, i.e. concrete type must be defined. In the case of a structure made of conventional concrete these parameters are: compressive strength, exposure environment, maximum aggregate size and concrete workability. If we are dealing with fibre-reinforced concrete, parameters to define tensile contribution of fibres are also required.

It is worth remembering that all strength parameters used to define concrete correspond to strength parameters obtained from a specific standard test. In case of compressive strength, the standard test described in EN-12390 corresponds to a uniaxial compression test. According to the strength value derived from it, structures are design. However, sometimes concrete is not subjected to pure uniaxial forces, but to biaxial or triaxial ones. That is the case of D regions and strut and tie models. In this cases, design guidelines provide correction coefficients to take this effect into account, keeping the same characterisation test. This is the same phenomenon as happens with fibre reinforced concrete. The standard EN-14651 provides the residual strength values in tension in a very specific bending test in which fibres have a specific distribution and orientation. This distribution may differ from fibre distribution in the structural element according to its geometry, fibre length and pouring system. This fact should be considered not in the characterisation phase, but when designing each structural element by means of specific fibre orientation coefficients.

Note that the only purpose of characterisation is to offer a representative value for the mechanical behaviour of concrete. This value must be affected by correction coefficients in the design phase to take into account structural effects. Then, the purpose of the quality control is not to check that correction coefficients used for design (fibre distribution, orientation or biaxial stress state coefficients, etc.) are right, but to check that the concrete used to make the structural elements achieved the characteristic values required, i.e. the parameters originally used to verify the structure. Same principles of conventional and fibre-reinforced concrete must be applied to UHPFRC.

The design process proposed by the Spanish task group in charge of the development of the Spanish guidelines for UHPFRC is according to Figure 1, which agrees with the above-described paragraphs.

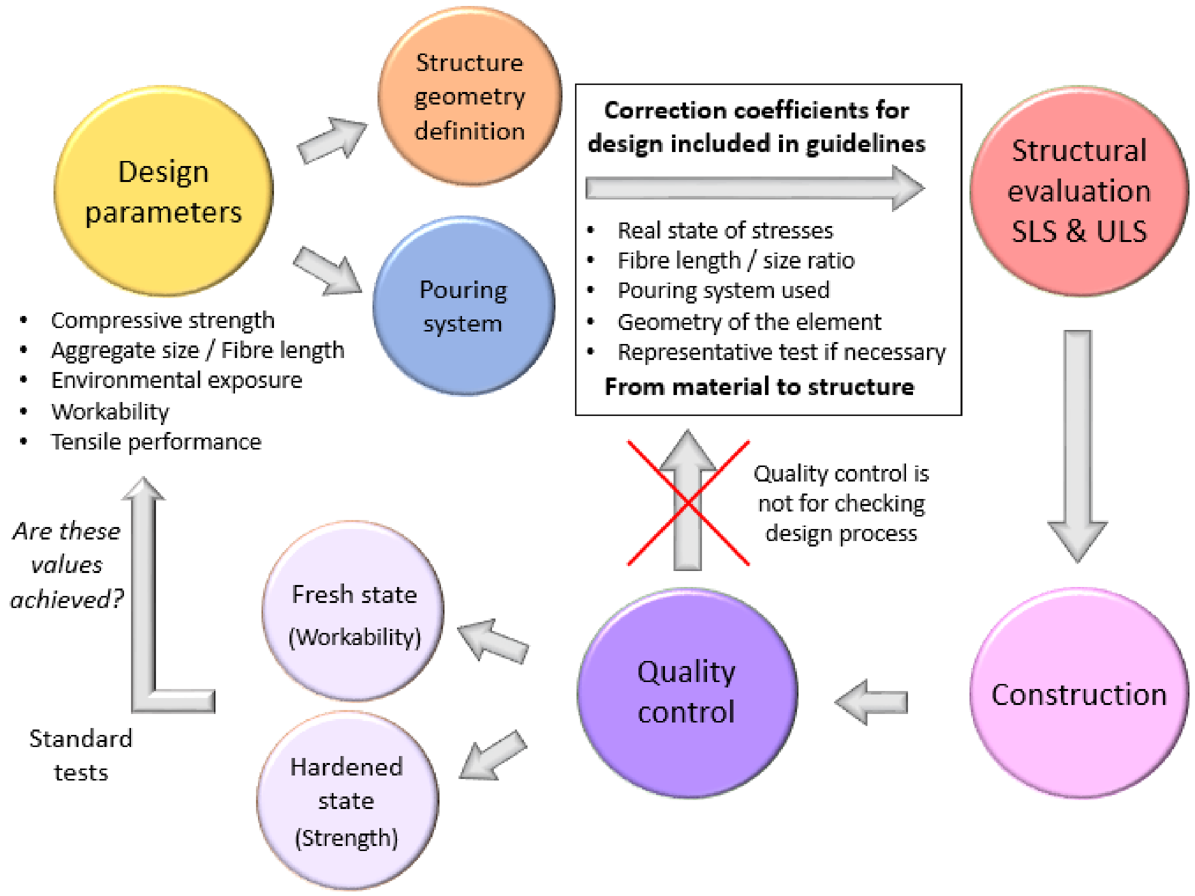

Figure 1. Design and quality control process

2. CLASSIFICATION

It seems reasonable to keep compressive strength, exposure environment and concrete workability as UHPFRC project parameters. However, this may not be the case for maximum aggregate size. According to current UHPFRC codes [1,2], maximum aggregate size is limited to 1-2 mm. Notwithstanding, it is known that certain types of UHPFRC use maximum aggregate sizes of 6-8 mm. A larger aggregate size is not commonly used since the commonest fibre length used is 13, and it would affect the fibre to matrix bond. This is why the distance between rebars and minimum cover should be determined by fibre length instead of maximum aggregate size. Therefore in the specific case of UHPFRC, it seems more convenient to use fibre length instead of maximum aggregate size. This could also be valid for FRC.

As with FRC, it is necessary to identify the UHPFRC tensile properties required for design and which cannot be derived from any other parameter. Figure 2 shows the proposed constitutive law in tension for UHPFRC along with the 6 parameters necessary to define it: (i) elastic modulus (E); (ii) cracking strength (f_t); (iii) hardening ratio (μ); (iv) strain at peak ($\varepsilon_{t,u}$);

(v) crack opening (w_0); fibre length (L_f). Note that the elastic modulus can be derived from compressive strength and fibre length is already a design parameter. A decision was made to keep the crack opening at zero stress at one fourth the fibre length, according to French standard [1]. For simplicity, the stress at the change of the slope in the stress-crack opening law was set at one third the maximum tensile strength. The proposed constitutive tensile law for UHPFRC is consistent with that proposed by CM2010 for plain concrete and fibre-reinforced concrete.

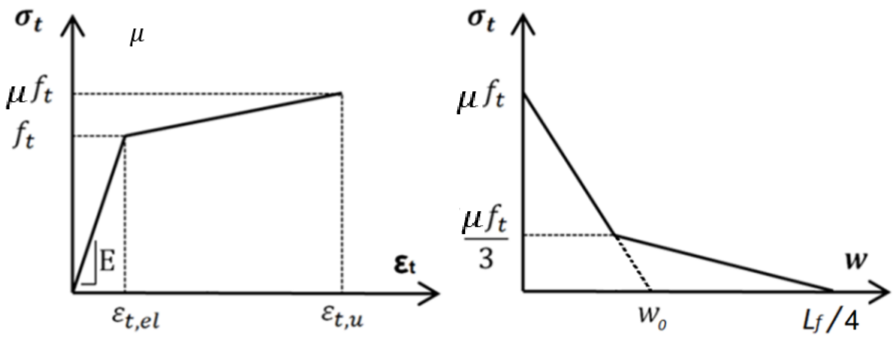

Figure 2. Constitutive law in tension for UHPFRC

According to the above-mentioned, UHPFRC can be defined using the following description:

UHPFRC - $f_{c,k}$ / W / FL / EE
SX -$f_{t,k}$ / μ_k / $\varepsilon_{t,u,k}$ / $w_{0,k}$

where $f_{c,k}$ is the characteristic compressive strength; W is the workability type of UHPFRC; FL is the maximum fibre length; EE is environmental exposure. The definition of these classes does not correspond to this work. Only the UHPFRC classification is dealt with according to its tensile constitutive law. Parameter SX can be either SS, which means strain-softening, or SH, which means strain-hardening, as not all UHPFRC must be strain-hardening materials. If SS comes into play, only $f_{t,k}$ and $w_{0,k}$ are required as μ_k and $\varepsilon_{t,u,k}$ describe the strain-hardening behaviour.

A minimum characteristic cracking strength value of 5 MPa seems reasonable for UHPFRC. It implies an average value of around 6.3 MPa, which is reasonable for a low fibre reinforced - 120 MPa characteristic compressive strength UHPFRC. Spanish recommendations propose this value as the minimum characteristic compressive strength for UHPFRC.

The minimum ductility condition for UHPFRC included in the French standard is shown in Eq. 1. Eq. 1 can be expressed as in Eq. 2, considering only the first line of the stress-crack opening relationship in Figure 2, when w_{lim} equals 0.3 mm, $f_t = 5\ MPa$, $\mu = 0.9$ and K=1.25 in accordance with the French standard. For this specific case, w_0 must be higher than 0.9 mm. Therefore, the minimum material ductility requirement according to the French standard can be accomplished by demanding a minimum $w_{0,k}$ higher than 0.9 mm. A decision was made to set this minimum value in 1 mm to guarantee a minimum ductility condition.

$$\frac{1}{Kw_{lim}} \int_0^{w_{lim}} \sigma(w)dw \geq \max(0.4f_t; 3\ MPa) \quad (1)$$

$$\frac{\mu f_t}{1.25}\left(1-\frac{0.15}{w_0}\right) \geq \max(0.4f_t; 3\ MPa) \quad (2)$$

Establishing minimum $\varepsilon_{t,u,k}$ and μ_k values is no easy task because, in some way, setting them determines the border between a strain-softening and a strain-hardening concrete. Even though the international research community agrees on its qualitative definition, establishing a quantitative criterion is not easy, as concrete behaviour is much more complex than that and the tools used for its determination are not 100% reliable. This is why any criteria assumed for this purpose can be called into question.

The experimental tests performed in four-point bending tests [3] show that a microcracking process is ensured when the $\varepsilon_{t,u}$ value is higher than approximately 2.5‰. The coefficient of variation on its determination is around 20% usinig the method proposed in section 4. Accordingly, it seems reasonable to consider a minimum $\varepsilon_{t,u,k}$ value of 2‰ to guarantee UHPFRC strain-hardening behaviour in that specific test, which implies an average $\varepsilon_{t,u}$ value of around 3‰.

It is commonly assumed that strain-hardening behaviour appears when a specimen exhibits microcracking. In [4], it is proposed that exhibiting strain-hardening behaviour in a four-point bending test requires the formation of *plural* cracks. This term is defined as two independent cracks or more that are visible to the naked eye and occur in the pure bending span before a maximum load is observed. A visual criterion is proposed in [4] which is not desirable for a standard.

The Spanish guidelines propose the following condition: for being considered a strain-hardening material, (i) the average hardening ratio value obtained from the standard four-point bending tests must be at least 0.9 and (ii) $\varepsilon_{t,u,k}$ is higher than 2‰. That is to say, if the characteristic hardening value is not higher than 1, it suffices that the average value is at least 0.9 to consider strain-hardening response in design. The use of a higher hardening ratio in design requires achieving this specific characteristic value in unnotched four-point bending tests.

If after UHPFRC characterisation (or quality control) all the specimens exhibit a deflection hardening response, but either $\varepsilon_{t,u,k}$ is lower than 2‰ or the average μ value is lower than 0.9, then the hardening branch cannot be used and UHPFRC must be treated as a strain-softening material. In this case, UHPFRC would be described according to the following description:

SS - $f_{t,k}$ /$w_{0,k}$

If $f_{t,k}$ is lower than 5 MPa or $w_{o,k}$ is lower than 1 mm, then the material cannot be considered UHPFRC and must be characterised as common FRC following EN-14651. The final UHPFRC proposal according to its tensile performance is summarised in Table 1.

According to previous considerations, the possible variation ranges of these parameters for UHPFRC proposed are:

$f_{t,k}(MPa) \rightarrow [5,6,7,8,9,10,12,14]$
$\mu_k \rightarrow [0.9^*, 1, 1.2, 1.4]$, * means average value
$\varepsilon_{t,u,k}(‰) \rightarrow [2, 4, 6,8,10]$
$w_{0,k}(mm) \rightarrow [1, 1.5,2,3,4]$

These ranges were established by considering the variability expected for these parameters using the characterisation test setup and methodology described in section 4. A 10% coefficient of variation was considered for f_t, μ, and one of 20% was considered for $\varepsilon_{t,u}$, w_0. The average value of a specific class was considered to be between the characteristic values of the next two classes.

Table 1 summarises the tensile classification of UHPFRC proposes by the Spanish recommendations. Qualitative criteria to distinguish between a strain-softening and a strain-hardening UHPFRC are provided. Deflection-hardening condition is required in addition to a minimum $w_{o,k}$ value of 1 mm to ensure minimum ductility in tension.

Table 1 Summarised UHPFRC classification

Parameter	SS-UHPFRC	SH-UHPFRC
$f_{t,k}$	≥ 5 MPa	≥ 5 MPa
$w_{o,k}$	≥ 1 mm	≥ 1 mm
$\varepsilon_{t,u,k}$	-	≥ 2‰
μ	-	≥ 0.9 (average value)
Additional conditions	Deflection-hardening response in bending	
	Point 2 below Point 3 (see section 4)	

3. DESIGN

When a structural engineer faces a UHPFRC design of a structure, first step is to select design parameters of concrete:

$$\text{UHPFRC - } f_{c,k} \text{ / W / FL / EE}$$
$$\text{SX -} f_{t,k} \text{ / } \mu_k \text{ / } \varepsilon_{t,u,k} \text{ / } w_{0,k}$$

In a second step, structure geometry as well as the construction and pouring methods must be defined as structural design is going to be according to them. Their influence is included in parameter fibre orientation factor "K". Figure 3 and 4 shows the design constitutive laws proposed in both SLS and ULS for UHPFRC according to design parameters and K coefficient.

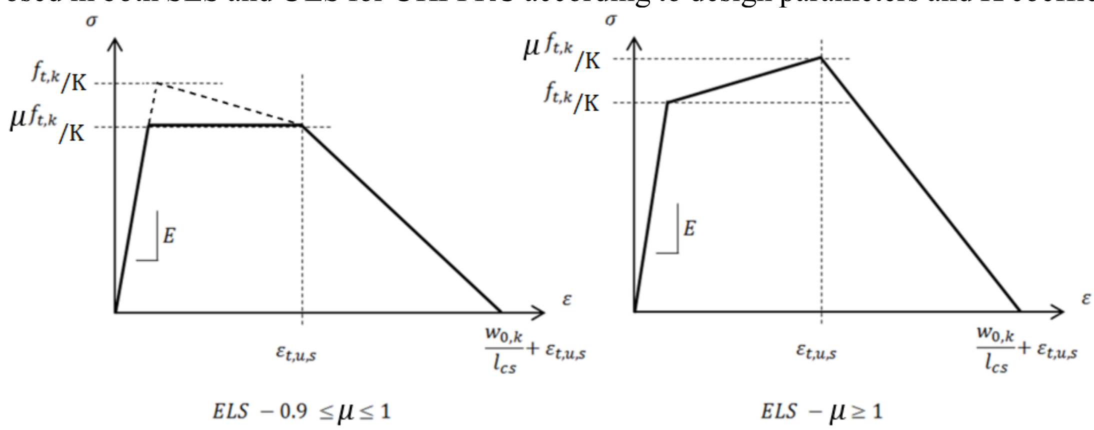

Figure 3. UHPFRC constitutive law in SLS according to the hardening value

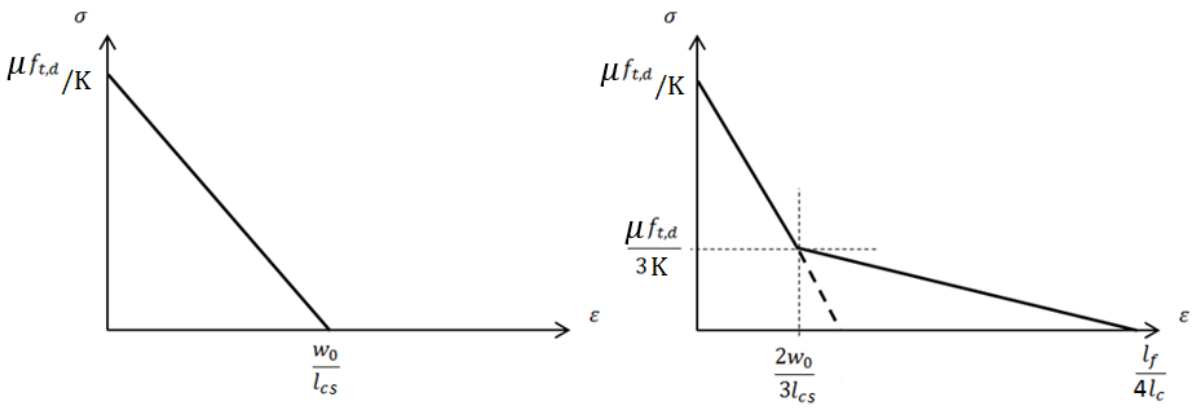

Figure 4. Two UHPFRC constitutive laws alternatives in ULS

Note that in Figure 3 the strength values correspond to characteristic values and in Figure 4 to design values, i.e. already affected by the security coefficient.

The characteristic strain value at peak ($\varepsilon_{t,u,k}$) may be a structural parameter. The use of a strain value at peak in service limit state ($\varepsilon_{t,u,s}$) for the determination of the cracking state of a UHPFRC structure should be affected by a structural length. However, this phenomenon is not clear yet. That is why rules in Eq. 3 are proposed in a first approach when UHPFRC is combined with steel rebars. If only UHPFRC is used, $\varepsilon_{t,u,s}$ coincides with $\varepsilon_{t,u,k}$, but the softening branch cannot be used in design.

$$\varepsilon_{t,u,s} = \begin{matrix} 0.015 \; if \; \varepsilon_{t,u,k} \leq 0.004 \\ 0.002 \; if \; \varepsilon_{t,u,k} > 0.004 \end{matrix} \tag{3}$$

Parameter l_{cs} is the structural characteristic length necessary to transform the stress-crack opening relationship into stress-strain relationship required for sectional analysis check. According to French standard, a structural characteristic length of 66% the element depth can be used as a first approach.

The K factor takes into account all phenomena that make the constitutive behaviour in the structure differs from the constitutive behaviour in the standard specimen, such as (i) fibre length, (ii) fibre length to depth or width ratio, (iii) pouring system, (iv) nature or forces acting in the structure, (v) 1D, 2D or 3D behaviour, etc. These parameters should be provided by the scientific community, but there is a long way to go till it happens. In the meantime, it is quite common that for every structural element in which fibre orientation is expected to be relevant for design, specific tests are carried out to evaluate its associated K coefficient related to the one in the standard test. These tests should be carried out on representative elements of the structure following a similar pouring process. Otherwise, the established K coefficient would not valid.

Nowadays, current French standard proposes a standard K coefficient of 1.25 for global effects and 1.75 for local effects. If different K coefficients are expected, representative test of the structural element should be performed.

Note that representative tests have the main goal to determine suitable K coefficients to be used, while quality control tests (or characterisation tests) have the main purpose of checking that the characteristic properties required in project have been achieved during construction.

4. STANDARD TEST

Despite uniaxial test allows a direct identification of the uniaxial behaviour of UHPFRC without requiring any assumption, this test is complex to be carried out. That is the main reason why a bending test is proposed as a standard test. Conventional FRC uses the standard test described in EN-14651. However this method is not suitable to characterise strain-hardening phase in UHPFRC. In addition, when using the notched three-point bending test in UHPFRC more than one crack appears at the notch [5]. It makes that the CMOD measurement is not right as it corresponds to more than one crack. Generally, this fact is not taken into account [1].

In order to be able to reproduce the strain-hardening behaviour of UHFPRC as well as to make the determination of the stress-crack opening relationship easier, the unnotched four-point bending test is proposed as standard test for UHPFRC. Test geometry is shown in Figure 5, left. The test finishes when a load that equals 75% of the maximum is reached on the unloading branch. Two LVDTs must be placed on each side of the specimen to record the displacement at mid-span using a similar device to that shown in Figure 5. Together with the displacement at mid-span, the distance from the crack to mid-span measured on the top face (d) must also be recorded (see Figure 5, right). The tests in which the crack appears out of the central one third must be eliminated. After the test, the specimen depth and width must be measured at the failure section.

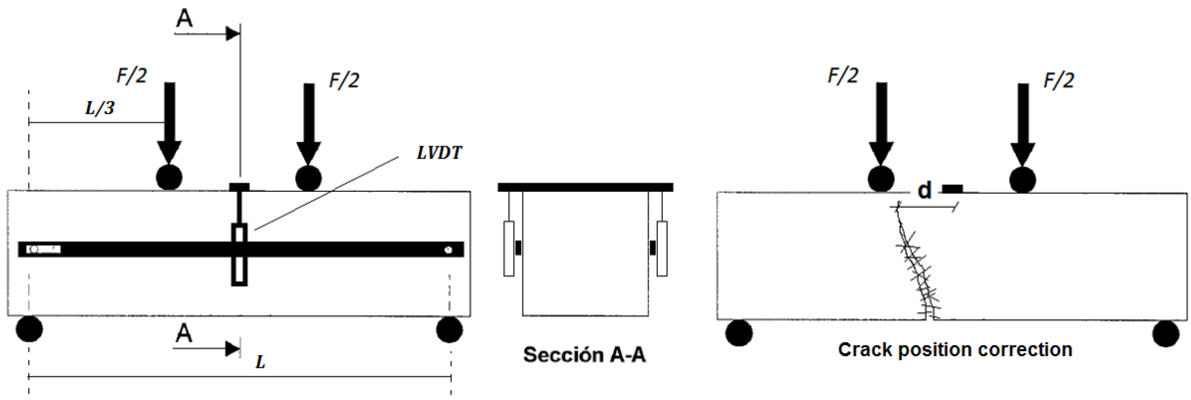

Figure 5. Standard four-point bending test setup proposal and measurement of the distance from the crack to the mid-span

The size and geometry of the standard specimen are not in accordance with structure size, but depend on fibre length. Two different specimens (Type A and B) are proposed according to the fibre length. The span is always 450 mm.

Type A: Prismatic specimen 100 x 100 x 550 mm if $L_f \leq 20\ mm$
Type B: Prismatic specimen 150 x 150 x 600 mm if $20 < L_f \leq 60\ mm$

If UHPFRC is flowable, specimens should be cast using a movable pouring point in order to avoid its longitudinal flow. The process must start on the specimen edge. Then the pouring point is moved to the other edge at a constant speed, which coincides with the concrete flowing speed. This process has to be repeated after reaching the other edge until the specimen is completely filled. With this system concrete is poured in layers. It is absolutely necessary that a new layer does not simply lie in the previous one. It must break the previous layer and blend with it to avoid fibre alignment. The specimen must be tested by turning it 90 degrees from its casting position. If UHPFRC is not flowable, the pouring system shown in EN-14651 must be followed. Neither of these methods guarantee an isotropic fibre distribution of the specimen, but the behaviour obtained from them should be used as a reference to establish the subsequent fibre orientation coefficients (K).

Methodology to derive the tensile properties of UHPFRC from this test is based on the work developed in [3]. After performing the test, load must be converted into an equivalent flexural strength (σ_{fl}), assuming a linear elastic distribution of the stresses in the section. If the extension of the linear elastic slope of the $\sigma_{fl} - \delta$ curve intersects the δ axis at a point that differs from 0, every measured δ value must be corrected. After this correction, the new $\sigma_{fl} - \delta$ is obtained, which is similar to that shown in Figure 6. This curve must be drawn. Next step involves identifying four key points on this curve: P_1, P_2, P_3 and P_4.

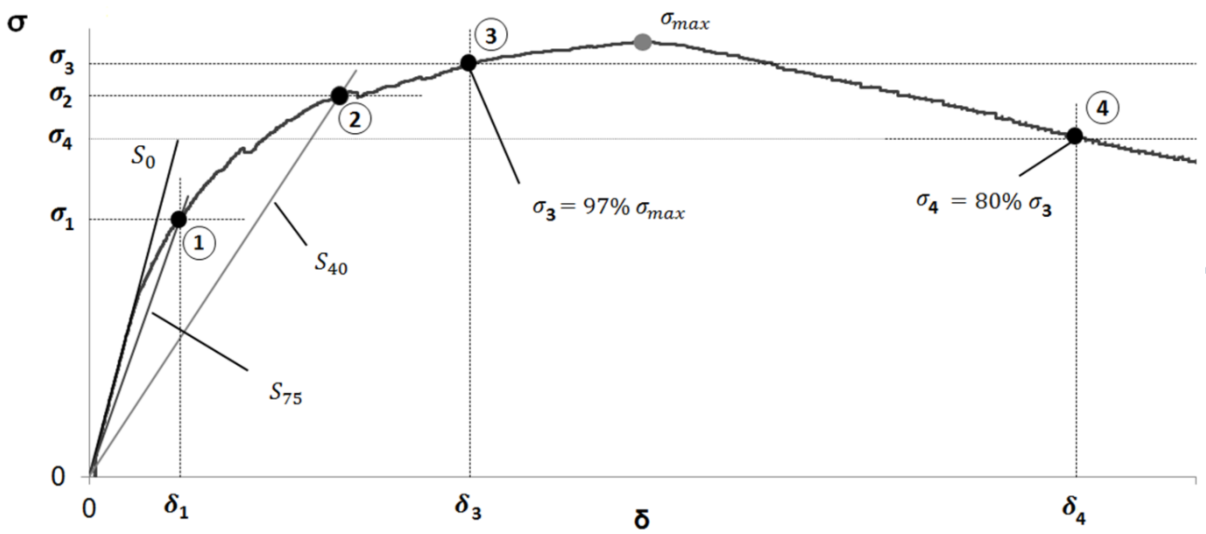

Figure 6. Definition of the four key points on an experimental $\sigma_{fl} - \delta$ curve

P_1 and P_2 are defined as the intersection between S_{75} and S_{40} to the experimental curve, respectively. The slope of the lines S_{75} and S_{40} are a 75% and a 40% the initial slope. P_3 is defined as 97% of the flexural strength on the loading experimental curve. P_4 is defined as 80% the stress at point 3 on the unloading experimental curve. The elastic modulus can be obtained as a function of the specimen depth (h) and the initial slope (m) obtained from the $\sigma_{fl} - \delta$ curve that defines the line S_0, according to formulation in Table 3.

Once these points have been identified and the crack position has been measured (d) (see Figure 5, right), the tensile parameters can be derived using formulation in Table 3 developed in [3]. Note that this methodology can only be applied when point 2 is below point 3. It happens when strain at peak is approximately above 1.5‰.

Parameters derived from this methodology coincide to parameters used to classify UHPFRC. Note that they represent an approximation of the UHPFRC constitutive tensile behaviour showed in that specific standard test under a specific pouring system. As it has been previously mentioned, these values can only be considered as representative values for the tensile response of UHPFRC and additional hypotheses regarding of the fibre orientation expected in structural elements must be taken into account for design.

Table 2 Closed-form formulation for the determination of tensile parameters of UHPFRC from a unnotched four-point bending test.

	$h = 100\ mm$ $L = 450\ mm$	$h = 150\ mm$ $L = 450\ mm$	**Parameters**
$\boldsymbol{E}$	$2.40\ h\, m$	$4.79\ h\, m$	$m = \frac{\Delta\sigma}{\Delta\delta}$
$\boldsymbol{f_t}$	$\frac{\sigma_1}{1.63}\left(\frac{\sigma_1}{\sigma_2}\right)^{0.19}$	$\frac{\sigma_1}{1.59}\left(\frac{\sigma_1}{\sigma_2}\right)^{0.21}$	
$\boldsymbol{\varepsilon_{t,u}}$	$\frac{f_t}{E}\left(7.65\frac{\delta_3}{\delta_1} - 10.53\right)$	$\frac{f_t}{E}\left(6.65\frac{\delta_3}{\delta_1} - 9.40\right)$	
$\boldsymbol{\mu}$	$\alpha^{-0.18}\left(2.46\frac{\sigma_3}{\sigma_1} - 1.76\right)$	$\alpha^{-0.17}\left(2.24\frac{\sigma_3}{\sigma_1} - 1.55\right)$	$\alpha = {\varepsilon_{t,u}E}/{f_t}$
$\varepsilon_{t,d}$	$\mu^{-0.37}\alpha^{0.88}\left(3.00\frac{\delta_4{}^*}{\delta_3} - 1.80\right)\frac{f_t}{E}$	$\mu^{-0.38}\alpha^{0.89}\left(2.82\frac{\delta_4{}^*}{\delta_3} - 1.68\right)\frac{f_t}{E}$	$\delta_4{}^* = \delta_4(1 + \frac{0.6}{L}d)$
$\boldsymbol{w_0}$	$\left(\varepsilon_{t,d} - \varepsilon_{t,u} + \frac{10\mu f_t}{3E}\right)\frac{3h}{2}$	$\left(\varepsilon_{t,d} - \varepsilon_{t,u} + \frac{10\mu f_t}{3E}\right)\frac{9h}{4}$	

5. ACKNOWLEDGEMENTS

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