DESIGNING UHPFRC STRUCTURES WITH ORGANIC FIBRES

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Abstract

Despite their lower performances compared to metallic fibres, the UHPFRC with organic fibres represent roughly 30% of the UHPFRC production. The organic fibres are mainly used for façade and furniture applications. Easier to work and with a better finishing, the organic fibres provide although a greater brittleness in tension. The design methods used for the general UHPFRC can be adapted for organic fibres in such a way to take in account the loss of strength in tension. This paper starts with a description of the differences between the mechanical behaviours of the two UHPFRC. Then it will present the design method with the "brittle approach", in order to define the design rules. That is mostly an adaptation of the existing methods by changing the safety factors and the behaviour laws. For the aesthetic applications, we must often limit or forbid cracking in serviceability limit state. This paper will suggest the stress-strain laws for the design with or without reinforcement.

Résumé

Bien que ne présentant pas les mêmes performances que les BFUP avec fibres métalliques, les BFUP avec fibres organiques représentent environ 30% du marché des BFUP. Les fibres organiques sont utilisées essentiellement pour les applications de façade et de mobilier. Plus faciles à travailler et avec une meilleure finition, les fibres organiques confèrent cependant au béton une plus grande fragilité en traction. Les méthodes utilisées pour le dimensionnement les autres BFUP sont utilisables moyennant quelques adaptations pour tenir compte de la perte de résistance en traction. Cet article présente d'abord les différences de comportement mécanique entre les deux types de BFUP. Il détaille la méthode de dimensionnement dans une approche fragile, afin de pouvoir décrire les méthodes de dimensionnement. Il s'agit essentiellement d'adapter des méthodes existantes soit en modifiant les coefficients de sécurité et les courbes de comportement. Les applications esthétiques nécessitent souvent de limiter la fissuration voire de l'exclure en utilisation de service. Cet article propose les courbes de comportement à prendre en compte pour la conception avec ou sans armatures.

1. MATERIAL DESCRIPTION

1.1 Material Performances

Today in France, the design codes for UHPFRC ([1] and [2]) are taking only in account those with metallic fibres (Type M according to §4.1 of NF P 18_470 [3]). The methods described in these documents can be used for UHPFRC with organic fibres, by adapting the design rules in such a way to take in account the loss of strength [4]. In its own introduction (§1.1), the French standard NF P 18-710 [2] defines the criteria that UHPFRC must fulfil:

- First criterion: 150 MPa ≤ f_{ck} (Characteristic Compressive Strength) ≤ 250 MPa

Today, the Characteristic compressive strength of the UHPFRC with organic fibres is between 100MPa and 130MPa. Although the performance is largely below, the compressive strength is rarely critical for the design. Moreover, the behaviour in compression is very similar for organic fibres and metallic fibres (elasto-plastic). So we can apply the same design methods with the characteristic compressive strength of organic fibres

- Second criterion: 6 MPa ≤ $f_{ctk,el}$ (Characteristic value of limit of elasticity under tension)

Some UHPFRC with organic fibres are reaching this value (like the Ductal B3 FO from LafargeHolcim), and others don't. Although the tensile behaviour class for all is T1 (Strain-softening), the multi-cracking of Organic Fibres is more spaced (less cracks but bigger)

- Third Criterion: In order to guarantee the material will have adequate ductility in bending, the tensile behaviour must respect the minimum ductility condition:

$$\frac{1}{w_{0,3}}\int_0^{w_{0,3}} \frac{\sigma(w)}{1,25} dw \geq \max(0,4 f_{ctm,el}; 3MPa)$$

$w_{0,3}$ = 0,3mm
$f_{ctm,el}$: Mean value of tensile limit of elasticity under tension
$\sigma(w)$: Characteristic post-cracking stress according to the crack opening

Like for the second criterion, some UHPFRC with organic fibres are respecting this condition, when others don't. So, for structural applications (elements that support other), we recommend using the UHPFRC that respect both the second and the third criterion. In all cases, it is necessary to adapt new safety factors for the tensile strength [4]

- Fourth Criterion: 2300 kg/m^3 ≤ γ (Density) ≤ 2800 kg/m^3

The density of the UHPFRC with organic fibres is between 2300 kg/m^3 and 2500 kg/m^3.

Like for those with metallic fibres, the mix-design and the high binder content of the UHPFRC with organic fibres eliminate capillary porosity resulting in good durability of the concrete, and self-healing crack capacity [5]. We can mention, that it is unusual to use heat treatment or prestressing with organic fibres, so we will not talk about it.

1.2 Identity card for UHPFRC with organic fibres

The identity card for UHPFRC with Organic fibres must provide the following characteristics, using the testing methods described in the NF P 18-470 [3]:

<u>Mechanical behaviour:</u> (see annex of NF P 18-470 [3])

- Characteristic compressive strength: f_{ck} (see annex C [3])
- Characteristic value of limit of elasticity under tension: $f_{ctk,el}$
- Mean value of tensile limit of elasticity under tension: $f_{ctm,el}$
- Characteristic value of post-cracking strength: f_{ctfk}

- Mean value of post-cracking strength: f_{ctfm}
- Characteristic value corresponding to a crack opening of 1% of the high of testing prism for thick elements: $f_{ctf,1\%,k}$ (see annex D [3])
- Height of the tested prism associated to $f_{ctf,1\%,k}$: a
- Maximum tensile strain resulting from the tensile tests for thin elements: $\varepsilon_{lim,k}$ (see annex E [3]). For preliminary design, the value of $\varepsilon_{lim,k}$ = 2,5‰ can be assumed (§2.2 of the AFGC recommendations [1])
- Mean value of Young's modulus: E_{cm} (see annex C [3])
- Poisson's ratio: ν (see annex C [3])
- Creep coefficient: $\varphi(\infty,t_0)$

Material Composition:

- Length of fibres: L_f
- Maximum diameter for aggregates: D_{upper}

Physical characteristics

- Density
- Water porosity at 90 days
- Apparent Gas permeability at 90 days
- Apparent diffusion coefficient of chloride ions at 90 days
- Coefficient of thermal expansion at 28 days
- Total shrinkage amplitude at 90 days
- Class associated to reaction to fire

1.3 Tests related to the project

For structural applications with organic fibres, the following tests should be carried out:

- Suitability tests to define the "orientation coefficient" (see annex F of NF P 18-470 [3]). For preliminary design, the following "orientation coefficients" can be taken: K_{Global} = 1,35 and K_{Local} = 1,8
- Control tests scale 1/1 of the whole element or a part with the ultimate loads.

2. HYPOTHESES FOR DESIGN WITH ORGANIC FIBRES

2.1 General description

The aim of this paper is to define the calculation assumptions for the UHPFRC with organic fibres, that means in a large part the stress-strain laws and the strain limits of the material. Then the calculations for design and for verification must be carried out in accordance with the following standards:

- The definition of the limit states and the loads combination according to Eurocode 0 [6]
- The loads definition according to Eurocode 1 [7]
- The characteristics of the UHPFRC according to the French standard NF P18-470 [3]
- The design and check according to French standard NF P18-710 [2] and the Eurocode 2 [8]
- The tolerances and the imperfections according to the French standard NF P18-451 [9]

The Eurocode 0 defines two main limit states:

- The Serviceability Limit State (SLS) which must check durability, appearance, comfort and functionality. The durability is checked by a limitation of the stress and the strain in the material. The ranges of comfort and functionality are defined by a limitation of the deflection and the dynamic behaviour. The appearance is checked both by a deflection limit and by a limitation of the strain (risk of cracking). Consequently, it is necessary to verify two "limit sub-states": SLS-S (Cross-section stress check) and SLS-D (Structure displacements check).

- The Ultimate Limit State (ULS) must check the equilibrium (EQU), the resistance of the foundations (GEO), the structure strength (STR) and the fatigue failure (FAT). The first two conditions, we will not discuss, because the design for the UHPFRC is the same as for the concretes. Accordingly, it is necessary to verify three "limit sub-states": ULS-S (Cross-section stress check), ULS-B (Great displacements and buckling) for the structure strength (STR) and ULS-F (Fatigue check) for the fatigue failure (FAT).

The standards for the design of UHPFRC ([1], [2] and [3]) are defining the stress-strain laws in function of the thickness (Thick elements and thin elements). The reinforcements in the UHPFRC with organic fibres are giving a greater ductility in tension [10]. Moreover, it is not possible to put reinforcements inside the thin elements (maximum thickness: $e_{max} < 3.L_f$) with the minimum cover condition ($C_{min} > 1,5.L_f$). For each limit state, we have three kinds of constitutive law:

- Thin elements (thickness $e < 3.L_f$) never reinforced;
- Thick elements (thickness $e > 3.L_f$) without reinforcement;
- Thick elements (thickness $e > 3.L_f$) with reinforcement.

2.2 Serviceability Limit State - Cross-section stress check (SLS-S)

Both for appearance (no crack opening) and for strength, the behaviour of UHPFRC without reinforcement is elastic-linear at Serviceability Limit State. The stress is then limited to the characteristic value of limit of elasticity in tension divided by the factor of 1,6. This factor is defined by the Eurocode 2 [8], and is safer than the « jurisprudence CSTB » (MOR/3 taken from the ATEC – BETSINOR [11]).

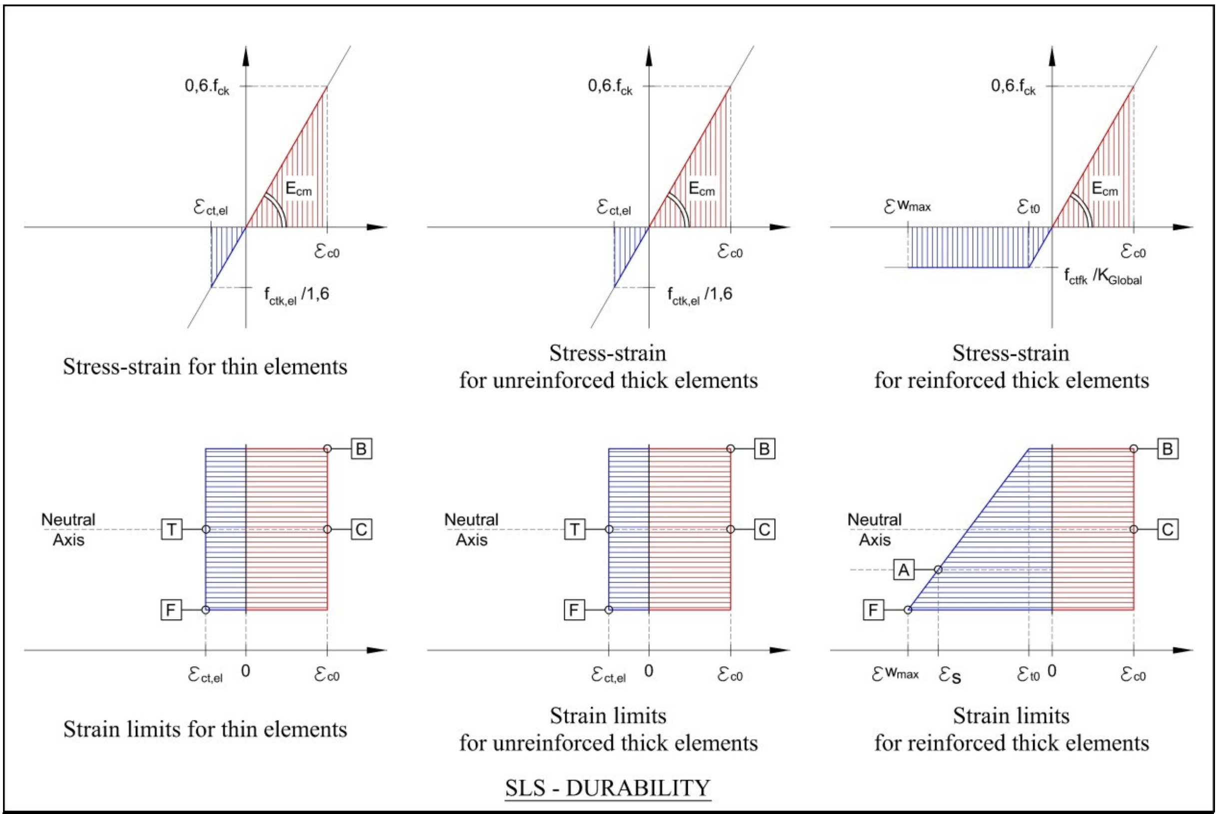
The longitudinal reinforcements are making the crack opening acceptable at the SLS (anyway induced by the endogenous shrinkage blocked by the steel). According to the §7.2 of the French standard NF P18-710 [2], the limitation of stress in the steel reinforcement doesn't replace the check of the crack opening in the UHPFRC. The crack opening is then defined, as for UHPFRC type M, by the table 7.201 in the chapter §7.3.1 of the document. So, we don't recommend using organic fibres with reinforcements in the case the crack opening is visually embarrassing for appearance. The limit of the steel stress is given by the formulas of §7.3.4 of the French standard NF P18-710 [2]. These formulas can be used for verification at the end, but they are not practical for design. The following simplified and conservative formula can be deduced (see Appendix):

$$\varepsilon_{sm,f} \leq (w_{max} /(3,40.c+0,68.ø/\rho_{eff})) + (f_{ctfm} /(K_{Global} \times E_{cm})) + (4,4/E_s .(f_{ctm,el} – f_{ctfm}/K_{Global}))$$

where:
- Value of steel reinforcement Young's modulus: E_s
- Cover: c
- Diameter or the reinforcement bar: ø
- Effective steel ratio: ρ_{eff}

This formula gives conservative results but still acceptable for a first design.

Then the results must be checked with the formulas of §7.3.4. For compression, the criteria are the same as for the metallic fibres (§7.2 of NF P18-710 [2]). These SLS verifications are illustrated Fig. 1.



ε_{c0} = 0,6. f_{ck} /E_{cm} $\varepsilon_{ct,el}$ = $f_{ctk,el}$ /(E_{cm} x 1,6)	ε_{c0} = 0,6. f_{ck} /E_{cm} $\varepsilon_{ct,el}$ = $f_{ctk,el}$ /(E_{cm} x 1,6)	ε_{c0} = 0,6. f_{ck} /E_{cm} ε_{t0} = f_{ctfk} /(E_{cm} x K_{Global}) ε_{Wmax} = w_{max} /L_c + $f_{ctk,el}$ /E_{cm} w_{max} : *see §7.3.1 of NF P18-710* *L_C = 2/3.h* ε_S : *see §7.3.4 of NF P18-710*

Figure 1: Stress-strain laws and limits for Limit Sub-States SLS-S
(Cross-section stress check)

2.3 Serviceability Limit State - Structure Displacements check (SLS-D)

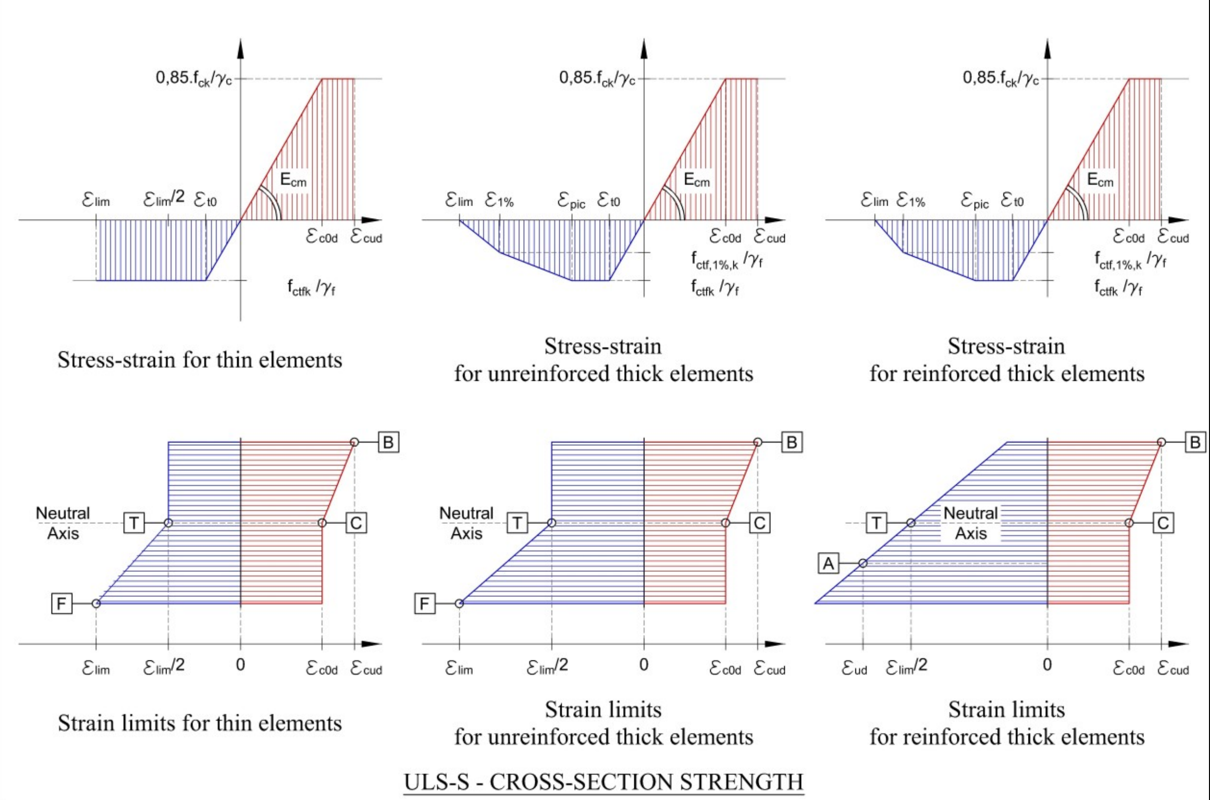
For the SLS-D, we can use the same behaviour laws as for the SLS-S, but including the creep effects: E_{cm} is replaced by $E_{c,eff}$ as defined in §7.4.3 of NF P18-710 [2] :

$$E_{c,eff} = E_{cm} / (1+ (\varphi(\infty,t_0) \times M_{EQP} /M_{ED}))$$

- Creep coefficient: $\varphi(\infty,t_0)$
- Effective bending moment under quasi-permanent combination: M_{EQP}
- Effective bending moment under the design case: M_{ED}

2.4 Ultimate Limit State - Cross-section stress check (ULS-S)

For the thin elements in UHPFRC with organic fibres, the approach developed by S. Bernardi *et al.* [4] gives the new safety factors to apply (γ_ε = 2,0 and γ_f = 2,5). For thick elements, no similar study exists. So, we recommend using the same safety factors for preliminary design (two times safer than for metallic fibres) and then to carry out tests. In the neutral axis, the tensile strain must be limited to ε_{lim}/2, and the compressive strain must be limited to ε_{c0d} (§6.1 of NF P18-710 [2]). For ULS, the shear stress in the cross-section must be checked, using the following limit: $\sigma_{Rd,f} = f_{ctfk} / \gamma_f$. With metallic fibres, the limit of the shear stress takes into account the sum of the resistances of concrete and fibres. The loss of strength in tension with organic fibres forces to consider only the capacity of the fibres (post-cracking state). These ULS verifications are illustrated Fig. 2.



$\varepsilon_{cud} = (1+14.f_{ctm}/(K_{Global} \times f_{cm}).\varepsilon_{c0d}$ $\varepsilon_{c0d} = 0.85.\ f_{ck}/(E_{cm} \times \gamma_c)$ $\varepsilon_{t0} = f_{ctfk}/(E_{cm} \times \gamma_f)$ $\varepsilon_{lim} = \varepsilon_{lim,k} / \gamma_\varepsilon$	$\varepsilon_{cud} = (1+14.f_{ctm}/(K_{Global} \times f_{cm}).\varepsilon_{c0d}$ $\varepsilon_{c0d} = 0.85.\ f_{ck}/(E_{cm} \times \gamma_c)$ $\varepsilon_{t0} = f_{ctfk}/(E_{cm} \times \gamma_f)$ $\varepsilon_{pic} = 0{,}3mm/(L_c \times \gamma_\varepsilon)$ $+ f_{ctk,el}/(E_{cm} \times \gamma_f)$ $\varepsilon_{1\%} = 0{,}01.a/(L_c \times \gamma_\varepsilon)$ $+ f_{ctk,el}/(E_{cm} \times \gamma_f)$ $\varepsilon_{lim} = L_f/(4.L_c \times \gamma_\varepsilon)$ *$L_C = 2/3.h$*	$\varepsilon_{cud} = (1+14.f_{ctm}/(K_{Global} \times f_{cm}).\varepsilon_{c0d}$ $\varepsilon_{c0d} = 0.85.\ f_{ck}/(E_{cm} \times \gamma_c)$ $\varepsilon_{t0} = f_{ctfk}/(E_{cm} \times \gamma_f)$ $\varepsilon_{pic} = 0{,}3mm/(L_c \times \gamma_\varepsilon)$ $+ f_{ctk,el}/(E_{cm} \times \gamma_f)$ $\varepsilon_{1\%} = 0{,}01.a/(L_c \times \gamma_\varepsilon)$ $+ f_{ctk,el}/(E_{cm} \times \gamma_f)$ $\varepsilon_{lim} = L_f/(4.L_c \times \gamma_\varepsilon)$ *$L_C = 2/3.h$* ε_{ud} : *see §3.2.7 of NF P18-710*

Figure 2: Stress-strain laws and limits for Limit Sub- ULS-S (Cross-section stress check)

2.5 Ultimate Limit State – Greats displacements and buckling check (ULS-B)

For the ULS-B, we can use the same behaviour laws as for the ULS-S, but including the creep effects: E_{cm} is replaced by $E_{c,eff}$ as defined in §5.8.4 of NF P18-710 [2] :

$E_{c,eff} = E_{cm} / (1+ (\varphi(\infty,t_0) \times M_{0EQP} / M_{0ED}))$

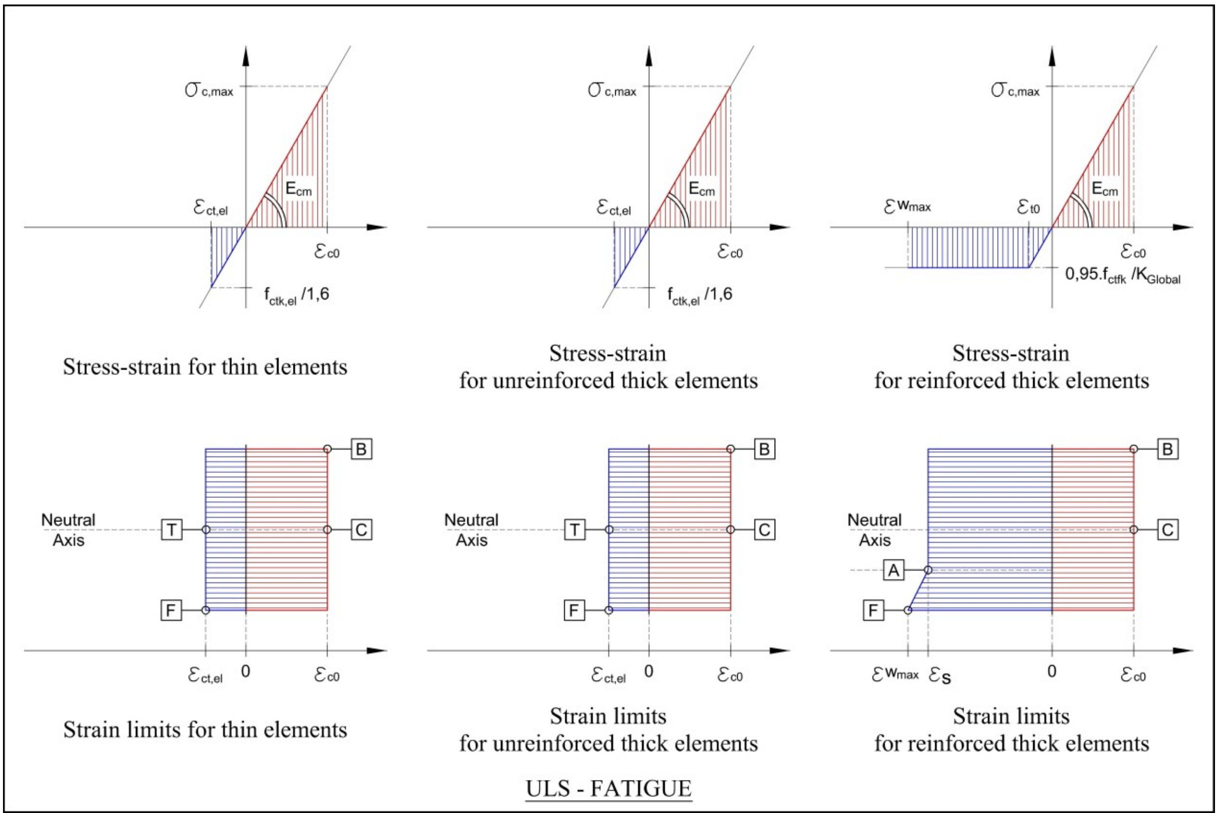
where: - Creep coefficient: $\varphi(\infty,t_0)$

- First order bending moment under quasi-permanent combination: M_{0EQP}
- First order bending moment under the design case: M_{0ED}

2.6 Ultimate Limit State – Fatigue check (ULS-F)

According to §6.8.1 of NF P18-710, the ULS-F can be checked independently of the number of cycles, by limiting the stress in the material (under SLS frequent loads combinations) as follows (Fig. 3):

- Maximum compressive stress of UHPFRC : $\sigma_{c,max} \leq \min(0{,}4.f_{ck} + 0{,}4.\ \sigma_{c,min}\ ;\ 0{,}6.f_{ck})$
- Minimum compressive stress of UHPFRC : $\sigma_{c,min} \geq 0$ (Compression is positive)
- Maximum tensile stress of UHPFRC is limited to $0{,}95.f_{ctfk}/K_{Global}$
- Maximum stress of steel reinforcement is limited to 300 MPa



$\varepsilon_{c0} = \sigma_{c,max}/E_{cm}$ $\sigma_{c,max} = \min(0{,}4.f_{ck} + 0{,}4.\ \sigma_{c,min}\ ;\ 0{,}6.f_{ck})$ $\varepsilon_{ct,el} = f_{ctk,el}/(E_{cm} \times 1{,}6)$	$\varepsilon_{c0} = \sigma_{c,max}/E_{cm}$ $\sigma_{c,max} = \min(0{,}4.f_{ck} + 0{,}4.\ \sigma_{c,min}\ ;\ 0{,}6.f_{ck})$ $\varepsilon_{ct,el} = f_{ctk,el}/(E_{cm} \times 1{,}6)$	$\varepsilon_{c0} = \sigma_{c,max}/E_{cm}$ $\sigma_{c,max} = \min(0{,}4.f_{ck} + 0{,}4.\ \sigma_{c,min}\ ;\ 0{,}6.f_{ck})$ $\varepsilon_{t0} = 0{,}95.f_{ctfk}/(E_{c,eff} \times K_{Global})$ $\varepsilon_{Wmax} = w_{max}/L_c + f_{ctk,el}/E_{c,eff}$ w_{max}: *see §7.3.1 of NF P18-710* $L_c = 2/3.h$ $\varepsilon_s = 300\text{MPa}/E_s$

Figure 3: Stress-strain laws and limits for Limit Sub-State ELU-F (Fatigue failure)

3. CONCLUSION

The development of UHPFRC with organic fibres depends mainly on a better knowledge and better control of its mechanical characteristics. New studies on thick elements and reinforced elements should improve the safety factors and optimize the material.

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APPENDIX

For simplifying the formula (7.204) of chapter §7.3.4 (NF P 18-710), we try to find the minimum value for the steel strain $\varepsilon_{sm,f}$ (mean strain in the steel bar):

Formula (7.204): $w_s = s_{r,max,f} .(\varepsilon_{sm,f} - \varepsilon_{cm,f}) \leq w_{max}$ (defined in table 7.201)

=> $\boxed{\varepsilon_{sm,f} \leq (w_{max} / s_{r,max,f}) + \varepsilon_{cm,f}}$ (1)

Formula (7.205): $\varepsilon_{cm,f} = (f_{ctfm} /(K_{Global} \text{ x } E_{cm})) + (k_t/E_s .(f_{ctm,el} - f_{ctfm}/K_{Global}).(1/\rho_{eff} + E_s/E_{cm}))$

=> $\boxed{\varepsilon_{cm,f} \geq (f_{ctfm} /(K_{Global} \text{ x } E_{cm})) + (4{,}4/E_s .(f_{ctm,el} - f_{ctfm}/K_{Global}))}$ (2)

With $0{,}4$ (*long time load*) $\leq k_t \leq 0{,}6$ (*short time load*)
$0 \leq \rho_{eff} \leq 1/8$ (*a cover at least greater than the diameter of the bar*)
$3 \leq E_s/E_{cm} \leq 5$ (E_s = 200GPa and 40GPa $\leq E_{cm} \leq$ 65GPa)

Formula (7.213): $\delta = 1 + 0{,}4.(f_{ctfm}/(f_{ctm,el} .K'_{Global}) \leq 1{,}5$

=> $\boxed{1 \leq \delta \leq 1{,}5}$ (3)

Formula (7.212): $l_t = 2 \text{ x } [0{,}3.k_2 \text{ x } (1 - f_{ctfm}/(f_{ctm,el} .K_{Global}))/(\delta.\eta) \text{ x } ø/\rho_{eff} \geq L_f /2$

=> $\boxed{L_f/2 \leq l_t \leq 0{,}267.ø/\rho_{eff}}$ (4)

With $0{,}5$ (*Bending moment*) $\leq k_2 \leq 1$ (*tension*)
$0 \leq 1 - f_{ctfm}/(f_{ctm,el} .K_{Global}) \leq 1$ (*UHPFRC type T1: strain-softening)*
$1 \leq \delta \leq 1{,}5$
$\eta = 2{,}25$ (without prestressing)

Formula (7.211): $s_{r,max,f} = 2{,}55 \ (l_0 + l_t) = 2{,}55 \ (1{,}33.c/\delta + l_t)$

=> $\boxed{s_{r,max,f} \leq 3{,}40.c + 0{,}68.ø/\rho_{eff}}$ (5)

With $L_f/2 \leq l_t \leq 0{,}267.ø/\rho_{eff}$
$1 \leq \delta \leq 1{,}5$

From the inequalities (1), (2) and (5), the steel strain ($\varepsilon_{sm,f}$) can be minimised as follow :

$$\boxed{\varepsilon_{sm,f} \leq (w_{max} /(3{,}40.c+0{,}68.ø/\rho_{eff})) + (f_{ctfm} /(K_{Global} \text{ x } E_{cm})) + (4{,}4/E_s .(f_{ctm,el} - f_{ctfm}/K_{Global}))}$$