NEW SEMI-PROBABILISTIC DESIGN METHOD FOR NON-STRUCTURAL ELEMENTS MADE OF UHPFRC

Sébastien Bernardi (1), Vibhu Malik (1), Svatopluk Dobrusky (2), Gilles Chanvillard† (2), Seddik Sakji (3)

(1) Ductal® – LafargeHolcim, France

(2) LafargeHolcim Research Centre, France

(3) Centre Scientifique et Technique du Bâtiment, France

Abstract

Despite the fact that nowadays there many useful documents focused on designing UHPFRC, none of them sufficiently covers a domain of thin non-structural elements (façade panels, sunshades, etc). The French standard NF P18-470 describe a simplified constitutive law for thin elements, three back analyses methods for determining the constitutive law, and a few recommendations on general aspects. Unfortunately, the disunited paragraphs have made the design of thin elements an impractical option. As the result, product certifications for thin elements made of UHPFRC in France were evaluated and certified according to a brittle-failure design. However, the brittle failure is avoided by the fibers. The thin elements mainly used for architectural applications are predominantly loaded in bending. When cracking stress of UHPFRC is reached, the fibers bridge created cracks. Moreover, the elements may resist higher loading when they exhibit deflection-hardening behavior (higher amount of fibers). In the case of UHPFRC, an apparent size effect of thin plates is relatively high. Consequently, a special design method for thin elements should be used to cover all specific characteristics.

In this paper, a semi-probabilistic design method for thin UHPFRC panels (developed by a working group involving CSTB, precasters and contractors) is presented. The method introduces two partial factors to ensure the sufficient safety of designed structures. The partial factors are calibrated by a reliability-based code calibration method considering French loading conditions (NF EN 1991). The new design method with the calibrated partial factors allows better exploitation of UHPFRC without compromising the safety requirements prescribed by EN 1990.

Résumé

Malgré le fait qu'il existe aujourd'hui de nombreux documents sur le dimensionnement des ouvrages en BFUP, aucun d'entre eux ne traite le cas des éléments minces non structuraux (panneaux de façade, brises soleil, etc.). La norme française NF P18-470 donne une loi de comportement simplifiée pour les éléments minces, trois méthodes d'analyse inverse pour déterminer cette loi de comportement ainsi que quelques recommandations générales. Malheureusement, seuls les éléments minces structuraux avec fibres métalliques sont couverts. Faute de méthode reconnue, les éléments non structuraux en BFUP sont aujourd'hui en France, dimensionnés en considérant un comportement fragile en traction, et ce malgré la présence de fibres en quantité importante. Les éléments minces concernés sont destinés à des applications architecturales et sont principalement soumis à des efforts de flexion. Ils ont ainsi la capacité de redistribuer

une partie des efforts en état fissuré, grâce à l'efficacité des fibres. Cette capacité est d'autant plus grande que le pourcentage de fibres est important, permettant d'assurer un comportement écrouissant en flexion. Par conséquent, il est nécessaire de pouvoir utiliser une méthode de dimensionnement spécifique, permettant d'intégrer la ductilité du matériau à l'échelle de l'élément en BFUP.

Dans cet article, nous présentons une méthode de dimensionnement semi-probabiliste pour les éléments minces en BFUP (élaborée par un groupe de travail impliquant le CSTB, des préfabricants et des entreprises). La méthode introduit deux facteurs partiels de sécurité, qui ont été déterminés par une méthode de calibration, conformément à l'approche fiabiliste de l'EN 1990, en considérant les charges de la norme NF EN 1991.

1. INTRODUCTION

Applications of nonstructural elements made of UHPFRC start to be more frequent than in the past, yet no comprehensive design procedure is still available. The lack of the comprehensive design procedure makes a market entry or an introduction of new products difficult and the most of all expensive. Thus, the new design procedure is introduced to facilitate applications of such elements.

The design procedure addresses needs of manufacturers as well as designers. The manufacturers guarantee properties of their material determined according to this procedure and the designers use the properties as the input values for the suggested structural verification. In order to allow a simple communication between the manufacturers and designers, the complete design procedure is presented in two steps: structural verification (calculations) and determination of the material properties (testing methods).

The design procedure was adopted from NF P 18-470 [1], thus it is fully synchronized with Eurocode standard format. All assumptions are based on NF P 18-470 and the Eurocode family [2, 3, 4, 5, 6] except the assumptions mentioned in this chapter.

2. SCOPE OF THE DESIGN PROCEDURE

The design procedure is developed for thin elements (e.g. panels) made of UHPFRC and predominantly loaded in bending and defining as secondary elements which are not considered as part of the main structure (no structural issue or participation to the bracing system). The structural verification includes long-term effects of self-weight, wind, and snow. Supports of the elements should allow axial movements to prevent tensile stresses from thermal expansion and similar effects.

The procedure targets mass production and should be especially used for mostly regular shapes. In the case of irregular elements or exceeding of the target scope, the suggested procedure is not recommended.

2.1 Material

The material must have deflection-hardening behavior (Figure 1) with the minimal material properties defined below:

- Compressive strength $\geq$ 120MPa — Apparent tensile strength $f_{ctf} \geq$ 4MPa
- Ductility ε_{lim} # 0.0008 — Elastic modulus in flexion E_c between 35 and 55 GPa

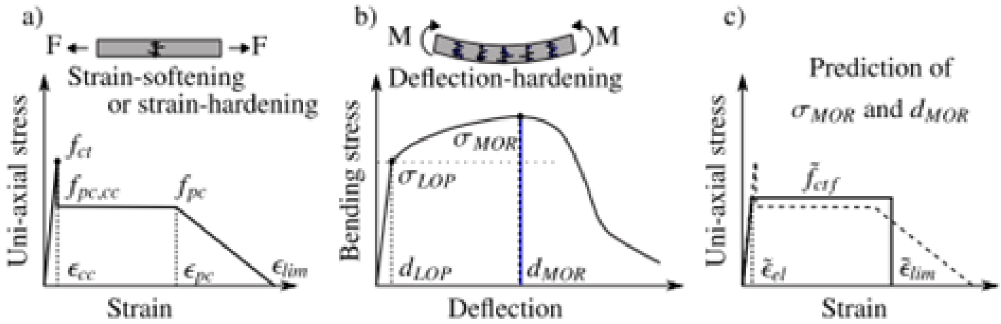


Figure 1: UHPFRC material characteristics: uniaxial tensile response (a), bending response (b), and simplified constitutive law (c)

2.2 Dimensions

Thickness may vary between 10 and 70 mm, but should be smaller than 3 times the fibre length (definition of thin elements). Span may vary between 400 and 2600 mm.

2.3 Loading

The loading is considered according to French versions of Eurocodes [3, 4, 5] and their national annexes. The load combinations are considered according to EN 1990 [2]. The limits were suggested and agreed by a working group chaired by CSTB (Centre Scientifique et Technique du Bâtiment, the French regulatory organization) which involved French precasters and contractors. The limits are assumed to do not affect the indented (normal) field of applications:

- Self-weight: the characteristic value of self-weight is 2475 kg/m^3
- Snow: the maximum snow load is 0.95 kN^2/m and the maximum product of the deterministic coefficients $\mu_i C_e C_t$ is 1.6. The product limits the maximal effects of the design specific coefficients: μ_i shape coefficient, C_e exposure coefficient, and C_t thermal coefficient
- Wind: four wind classes (22, 24, 26 and 28 m/s) can be used and combined with the limiting conditions:

$$c_{dir}\ c_{season}\ c_{pe}\ c_e(z) \leq 3 \text{ for substantially horizontal panels} \quad (1)$$

$$c_{dir}\ c_{season}\ c_{pe}\ c_e(z) \leq 12 \text{ for substantially vertical panels} \quad (2)$$

The products limit the maximal effects of the design specific factors: c_{dir} directional factor, c_{season} seasonal factor, c_{pe} pressure factor and $c_e(z)$ exposure factor.

3. STRUCTURAL VERIFICATION

The structural verification is composed of two steps: verification of SLS and ULS. EN 1990 [2] specifies three serviceability limit states:

- the functioning of the structure or structural members under normal use
- the comfort of people
- the appearance of the construction works

and four ultimate limit states:

- EQU: loss of static equilibrium of the structure or any part of it considered as a rigid body
- STR: internal failure or excessive deformation of the structure or structural members, including footings, piles, basement walls, etc., where the strength of construction materials of the structure governs
- GEO: failure or excessive deformation of the ground where the strengths of soil or rock are significant in providing resistance
- FAT: fatigue failure of the structure or structural members

3.1 SLS - Serviceability limit state verification

Only the last state, the appearance of the construction works, is relevant for facade panels or similar elements. This is why two relevant cases are selected for the SLS verification: cracking and deflection. A purely elastic computation is suggested for both conditions as the cracking must be avoided.

3.1.1 The cracking condition

$$M_{Rk} \geq M_{Ek} \quad (3)$$

$$M_{Rk} = \frac{6\,\tilde{f}_{ctfk}}{bh^2} \quad (4)$$

where M_{Ek} is the moment due to the characteristic combination of loading actions, b and h are the dimensions of the cross section, and f_{ctfk} is the characteristic tensile strength.

3.1.2 The deflection condition

$$d_k \leq d_{lim} \quad (5)$$

$$d_k = \mathrm{f}\,(E_k, E_{cm}, L, b, h, A) \quad (6)$$

where d_k is the deflection due to the characteristic combination of loading actions E_k, d_{lim} is the maximum deflection defined by an investor, E_{cm} is the mean elastic modulus, L is the span of the element and A is the structural coefficient related to the support conditions.

3.2 ULS - Ultimate limit state verification

The ULS verification must secure the safety of people and structures, thus the partial factors are introduced. In the case of facade panels or similar elements, the internal failure condition (STR) is the governing case. The ULS verification is written as:

$$R_d \geq E_d \quad (7)$$

$$M_{Rd} \geq M_{Ed} \quad (8)$$

where E_d is the design loading effect determined according to Eurocodes and R_d is the design resistance of the element. M_{Rd} is the design resistance of the cross-section computed by the suggested design method.

EN 1991-1-4 [5] states that the fatigue failure due to the effects of wind actions (only relevant load actions for facade panels or similar elements) should be considered for susceptible structures. If the verification is required by an investor, the approach described in NF P 18-470 [1] based on the stress limitation can be used instead with the more conservative value of f_{ctfm}.

Nevertheless,it is believed that this limit state should not be governing as the frequent combination of loading actions is considered as the baseline [6].

3.2.1 Simplified method to compute nonlinear resistance of UHPFRC

The simplified method based on Annex E of NF P 18-470 [1] is used. The method was developed for a fast and straightforward estimation of the stress-strain relationship. Figure 2 describes the crosssection analysis. The internal forces are written as:

$$N = bh\tilde{f}_{ctf} - \frac{1}{2} b\,(1-\alpha)^2\, h^2\, \chi\, E_c \tag{9}$$

$$M = \frac{1}{2} bh^2 \tilde{f}_{ctf} - \left(\frac{1}{3} - \frac{\alpha}{2} + \frac{\alpha^3}{6}\right) b\, h^3\, \chi\, E_c \tag{10}$$

where:

$$\chi = \frac{\tilde{\varepsilon}}{\alpha\, h} \qquad \tilde{\varepsilon} = \tilde{\epsilon}_{lim} - \tilde{\varepsilon}_{el} \qquad \tilde{\epsilon}_{el} = \frac{\tilde{f}_{cft}}{E_c} \tag{11}$$

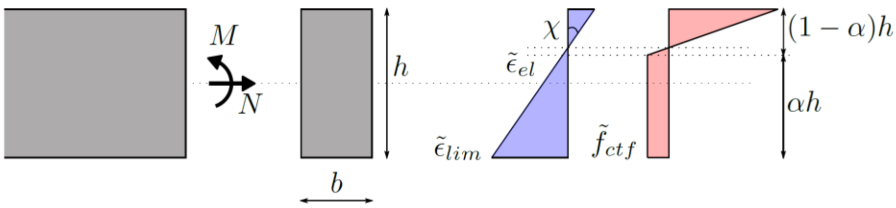


Figure 2: Stress and strain distribution with the simplified constitutive law

Using the equations above and the fact that the axial force is nil, the position of the neutral axis αh is determined as:

$$\alpha_{1,2} = 1 + \frac{\tilde{f}_{cft}}{E_c\,\tilde{\varepsilon}} \pm \sqrt{\frac{2\,\tilde{f}_{ctf}}{E_c\,\tilde{\varepsilon}} + \left(\frac{\tilde{f}_{cft}}{E_c\,\tilde{\varepsilon}}\right)^2} \tag{12}$$

Where only one root is admissible (a must be smaller than one):

$$\alpha = 1 + \frac{\tilde{f}_{cft}}{E_c\,\tilde{\varepsilon}} - \sqrt{\frac{2\,\tilde{f}_{ctf}}{E_c\,\tilde{\varepsilon}} + \left(\frac{\tilde{f}_{cft}}{E_c\,\tilde{\varepsilon}}\right)^2} \tag{13}$$

By knowing the position of the neutral axis and the curvature, the resisting moment is computed from. At the end, the elastic response in compression must be verified:

$$f_c \geq (1-\alpha)\, h\, \chi\, E_c - \tilde{f}_{cft} \tag{14}$$

3.2.2 ULS verification

The new partial factor $\gamma_f = 2.5$ and $\gamma_\varepsilon = 2.0$ are used as mentioned in the paper [7] to secure the safety of people and structures. The design values for the resistance $\tilde{f}_{ctfd}$ and for the ductility $\tilde{\epsilon}_{limd}$ are used instead of $\tilde{f}_{ctf}$ and $\tilde{\varepsilon}$ respectively. Figure 3 illustrates differences between the mean, characteristic and design values.

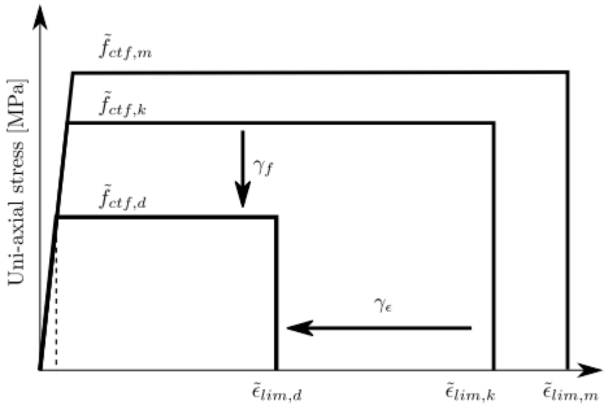


Figure 3: Simplified tensile constitutive law for mean, charateristic, and design values

4. DETERMINATION OF MATERIAL PROPERTIES

The experimental test procedure is described in NF P 18-470 [1] – Annex E. At least 6 samples for each direction and for each face should be tested (i.e., 12 samples if the final elements are to be loaded in one direction only: 6 tests with one face up and 6 tests with another face up; and 24 samples when the final elements are to be loaded in two directions). The aging effects should be taken into account when relevant according to relevant standards and requirements.

Equations (9) and (10) are used to back analyze the simplified constitutive law. $\tilde{f}_{ctf}$ and $\tilde{\varepsilon}_{lim}$ respectively are, however, unknown, and therefore the position of the neutral axis must be computed from the known maximum force F_{MOR}, the corresponding deflection d_{MOR}, and the estimated curvature χ:

$$M = (2\alpha^3 - 3\alpha^2 + 1)\frac{b\,h^3\,\chi\,E_c}{12} \quad (15)$$

$$\chi = \frac{216}{23}\frac{d_{MOR}}{L^2} \quad (16)$$

$$M = \frac{1}{6}\,F_{MOR}\,L \quad (17)$$

where L is the span of the tested element.

Then the values of the simplified constitutive law are:

$$\tilde{f}_{cft} = -\frac{1}{2}\,(1-\alpha)^2\,h\,\chi\,E_c \quad (18)$$

$$\tilde{\varepsilon}_{lim} = -\chi\,\alpha\,h + \frac{\tilde{f}_{ctf}}{E_c} \quad (19)$$

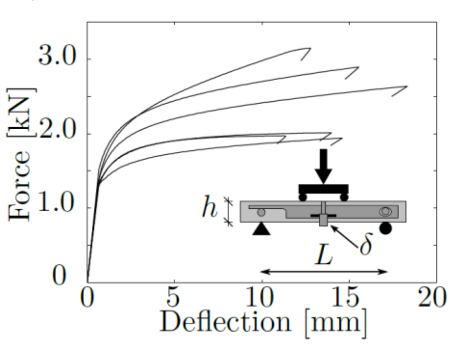
Figure 4 shows the determination procedure for one set of the experimental results (one side and one direction). The maximal force and the corresponding deflection is noted for each sample, and then each couple (F_{MOR}; d_{MOR}) is back analyzed by the equations above.The characteristic values are defined according to EN 1990 [2] as 5% quantiles from the back analyzed values. Each set is treated independently and the final characteristic value is defined as the minimum value:

$$\tilde{f}_{ctfk} = \min\left(\tilde{f}_{ctfk}^{1}, \dots, \tilde{f}_{ctfk}^{n}\right) \tag{20}$$

$$\tilde{\varepsilon}_{limk} = \min(\tilde{\varepsilon}_{limk}^{1}, \dots, \tilde{\varepsilon}_{limk}^{n}) \tag{21}$$

where n is the number of sets (direction, faces, and aging). If two minimums sets come from two different sets, the couple that corresponds to the lower resisting moment should be considered. If the fatigue verification is required, the minimum value from the mean values of each set should be used.

a)



b)

F_{MOR} [kN]	d_{MOR} [mm]
3.2	12.3
1.9	14.2
2	11.9
2.6	17.8
2.9	15.2
2.1	13.9

c)

E_c [GPa]	$\tilde{f}_{ctf}$ [MPa]	$\tilde{\epsilon}_{lim}$ [–]
40	12.9	0.0109
41	7.6	0.0133
42	7.8	0.01
43	10.3	0.0167
45	11.5	0.0139
39	7.9	0.0126

Figure 4: Determination of the simplified constitutive law from the experimental results (a), by noting the measured value (b), and back-analyzing them (c)

5. CONCLUSIONS

The reliability-based code calibration procedure was used for the calibration of partial factors of thin elements made of UHPFRC predominantly loaded in bending.

Economical advantages of the new semi-probabilistic verification compared to the original brittle design approach were significant. The new semi probabilistic approach clearly differentiates between brittle-like and ductile-like behavior. The design resistance of the brittle material was similar to the original brittle design approach whereas the design resistance of the ductile material was significantly increased due to the substantial contribution of fibers. Three interesting features of the semi-probabilistic approach were observed:

- The semi-probabilistic ultimate resistance is proportional to the MOR which is the desired feature, rather than to the LOP, as it is in the case of the original brittle resistance;
- The relative average values of the semi-probabilistic ultimate resistance are always below the LOP which should, in the vast majority of cases eliminate a risk of cracking;
- Although the new partial factors are relatively high, 2.0 for ductility and 2.5 for strength, which is similar to the safety factor of the original brittle approach (FS = 3.0), a significant improvement of the design resistance is obtained.

The results provided compelling evidence of the advantages of the reliability based code calibration and notably the advantages of the modified approach. Indeed, the design method of thin UHPFRC elements with the calibrated partial factors allows better exploitation of the material without compromising the safety requirements.

REFERENCES

[1] NF P 18-470, "Ultra-high performance fibre-reinforced concrete - Specifications, performance, production and conformity, July 2016. AFNOR French standard institute.
[2] EN 1990 Eurocode: Basis of structural design. AFNOR French standard institute.
[3] EN 1991-1-1 Eurocode 1: Actions on structures - Part 1-1: General actions Densities, self-weight, imposed loads for buildings. AFNOR French standard institute.
[4] EN 1991-1-3 Eurocode 1: Actions on structures - Part 1-3: General actions Snow loads. AFNOR French standard institute.
[5] EN 1991-1-4 Eurocode 1: Actions on structures - Part 1-4: General actions Wind actions. AFNOR French standard institute.
[6] EN 1992-1-1. NF EN 1992-1-1 Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings, October 2005. ISSN 0335-3931. AFNOR | French standard institute.
[7] Dobrusky S., Bernardi S., Sakji S., Reliability based calibration of partial factor for thin non-structural elements made of UHPFRC. Proceedings of UHPFRC 2017, October 2017. Montpellier, France.