NEWLY IMPLEMENTED PRODUCTS AND DESIGN STANDARDS FOR UHPFRC IN FRANCE

François TOUTLEMONDE
Paris-Est University / IFSTTAR
Grégory GENEREUX
CEREMA
Michel DELORT
ATILH
Jacques RESPLENDINO
SETEC-TPI

Context and motivation

The standardization process of ultra-high performance fiber-reinforced concrete (UHPFRC, in French "BFUP") was launched in France on the basis of the technical consensus expressed in AFGC Recommendations (AFGC, 2013). Availability of standards is deemed to help acceptability of UHPFRC structures and buildings incorporating UHPFRC by insurance companies. These standards should give provisions for ordering the material, studying and adjusting the mix-design and controlling the production processes, based on more than 15 years of satisfactory experience in France.

Complying with the architecture of existing standards which derives from European standards, three documents had to be elaborated:

- the NF P 18-470 standard for UHPFRC as a construction product, which substitutes to the standard valid for ordinary structural concrete and includes as annexes test protocols or adaptations of standards and test results analysis when applied to UHPFRC;

- One standard for the design of UHPFRC structures, referred to as NF P 18-710, which stands as a national complement to Eurocode 2;

- One standard for the execution of UHPFRC structures, which provides complements, precisions or amendments to the execution standard NF EN 13670/CN.

The first two documents have been published in April 2016, and major features are detailed in this paper. The latter one is expected early 2017.

Scope of the Standards: UHPFRC definition

The NF P 18-470 standard covers UHPFRC with a characteristic compressive strength equal to or greater than 150 MPa and comprising metallic fibers (these UHPFRC mixes are designated « BFUP-S »), since they were addressed by the AFGC Recommendations since 2002. Design of structures to be made with these materials is covered by NF P 18-710 Standard. However, NF P 18-470 also covers UHPFRC materials where the non-brittleness is achieved through the use of other types of fibers (designated "type A UHPFRC") as well as UHPFRC mixes with a lower characteristic strength, yet above 130 MPa, whatever the type of fibers contributing to non-brittleness (see hereafter).

For the moment however, due to lack of documented feedback and experience in real applications, structural design using UHPFRC with non-metallic fibers and/or with a compressive strength lower than 150 MPa is considered as non-traditional, thus out of the scope of the NF P 18-710 Standard, and thus requires dedicated technical approval.

According to NF P 18-470, the standard « BFUP » (UHPFRC) designation is limited to a material with demonstrated non-brittleness which, in addition to the compressive strength performance, meets requirements and reaches or overpasses performance thresholds for a series of characteristics (especially related to durability) detailed hereafter. The required "non-brittleness », i.e. the UHPFRC hardening behavior under pure bending that shall be effective, is one of the most remarkable performance of these materials besides compressive strength. NF P 18-470 provides explicitly the following inequality (1) which must be verified:

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

Where: $w_{0,3}$ = 0,3 mm

$f_{ctm,el}$ is the average value of the elasticity limit under tension, in MPa

σ(w) is the characteristic post-cracking strength as a function of the crack opening w, in MPa. The method for obtaining this function from inverse analysis of bending tests on prisms is detailed in two annexes within NF P 18-470 Standard, adapted from corresponding annexes of the AFGC Recommendations.

The designation « BFUP » also implies that the material fulfills the following requirements:

- *D_{sup} (nominal upper size of aggregates) lower or equal to 10 mm;*
- *Density comprised between 2200 kg/m^3 and 2800 kg/m^3;*
- *Characteristic value of the elasticity limit under tension at 28 days $f_{ctk,el}$ higher or equal to 6,0 MPa;*
- *Water porosity at 90 days ≤ 9,0 % (following NF P 18-459 standard);*
- *Coefficient of apparent diffusion of chloride ions at 90 days ≤ 0,5 10^{-12} m²/s (following XP P 18-462 standard with adaptations described in A.1 (annex A) of NF P 18-470);*
- *Apparent gas permeability at 90 days ≤ 9. 10^{-19} m² (following XP P 18-463 standard with adaptations described in A.2.1 (annex A) of NF P 18-470).*

Classes and required properties

Classes are defined in the NF P 18-470 Standard to make UHPFRC specification easier. They mostly concern compressive strength, tensile constitutive law, workability, the type of thermal treatment possibly applied, and improved potential durability characteristics. The compressive strength class is determined referring to the characteristic strength measured at 28 days on cylinders with nominal dimensions 110 mm in diameter / 220 mm in height. This second number in the designation, corresponding to the cube strength, is indicative only for the class determination. Current classes are BFUP 130/145, BFUP 150/165, BFUP 175/190, BFUP 200/215, BFUP 225/240 and BFUP 250/265, whatsoever intermediate strength levels rounded to the nearest 5 MPa may be used.

The class associated to the tensile behavior of a UHPFRC mix is obtained by comparing the elasticity limit $f_{ct,el}$ with the post-cracking strength f_{ctf}, both for the average response curve and for the characteristic curve. It is determined considering an a priori fixed value of the K_{global} orientation factor which is applied to the post-cracking phase to account for the placement effect of the UHPFRC material in the structure, the postulated value of this factor being 1,25. Conformity to the specified class can thus be evaluated for the material, whatever its structural application. For design validation purpose however, as detailed in NF P 18-710, the value of the K-orientation factor effectively measured during the suitability test is used to determine the design class associated to the tensile behavior, which governs methods of verification. Noticeably, K_{global} is limited to 2,0.

Workability of UHPFRC should be preferably specified using a target value. In absence of such a value, it can be specified using consistence classes. The classes corresponding to improved potential durability are worth being specified in case of a particularly severe exposure (e.g. tidal or splash zone at seashore, or exposure to severe freeze-thaw cycles with deicing salts) or particularly long design service life (over 100 years). Finally, using an RM class adapted to the intensity of the abrasion risk associated to the more or less loaded hydraulic flow should allow dispensing with the sacrificial cover which appears as the default provision for prevention of wear in the design standard NF P 18-710.

The NF P 18-470 standard gives those requirements that conforming UHPFRC have to meet. These requirements concern constituents, mix-proportions, properties of UHPFRC at the fresh state and properties of hardened UHPFRC. Except specified otherwise for a given project, properties of hardened UHPFRC shall be measured at 28 days when UHPFRC production does not include a post-setting thermal treatment, otherwise they shall be measured after completion of this thermal treatment. Some requirements apply to all UHPFRC while some of them are optional, depending on requested characteristics for a given project. The NF P 18-470 standard defines a concept of "identity card", document which, where relevant, gives for each property, the performance value met by a given UHPFRC mix. Placing fresh UHPFRC, curing and possible thermal treatments application belong to operations covered by standards related to the execution of structures, though having a critical influence on the performance to be met by UHPFRC as a material. Therefore NF P 18-470 includes the requirements associated to these processes and associated control (procedure, control parameters, acceptability criteria).

UHPFRC Conformity Evaluation

NF P 18-470 defines the different steps of evaluation and acceptance of UHPFRC supply as well as the part which is responsible for declaring conformity to given requirements. These steps comprise the evaluation of the pre-mix, where relevant, the validation of the design study (adapted where relevant with evaluation of conformity to characteristics and values declared in the identity card), of the suitability test (trial prototype production), of the production control of UHPFRC at the fresh state, and of the production control of UHPFRC when hardened after placing and, where relevant, application of treatments.

NF P 18-470 states that UHPFRC is a "design concrete", i.e. for which required properties are specified. Meeting these requirements by choosing a given UHPFRC material derives from experience documented in the material identity card, or is validated by the results of the design study. The design study is carried out by the producer of UHPFRC or under his responsibility. It consists in verifying that the UHPFRC mix allows meeting the project requirements, taking into account possible deviations in the manufacturing process (thus it includes batches according to the nominal recipe, and liquid / solid deviations). When the identity card exists, the UHPFRC producer may use it to prove that all or part of the specifications are met. When it does not exist or in case of missing information, the design study must include tests associated to the determination of required characteristics that were not previously investigated.

Verifying that the required properties are effectively met in the production conditions of the specific project is the aim of the suitability test (trial production). This suitability test should be carried out by the producer of UHPFRC so that the specifier can validate the choice of the proposed UHPFRC mix, taking into account the effective production, transport, placing, curing and possible treatment processes specified in the execution procedures. This trial testing should also comprise the production of a prototype element, carried out under the responsibility of the user of UHPFRC; this step is required for validating all the execution procedures, especially those associated to placing, curing and thermal treatment, by demonstrating that the specified performances (noticeably K-factors) are met.

NF P 18-470 gives the acceptance criteria for the design study and for the suitability test. Then it gives the objectives to be met in terms of UHPFRC production control, as well as the tests and acceptance criteria to verify that they are met and that the production is under control.

Evaluation of the conformity of UHPFRC to NF P 18-470 is split in several steps:

a) Evaluation of conformity of the pre-mix, when the considered UHPFRC is produced using this pre-mix of constituents (evaluation applies to a potential conformity to the UHPFRC identity card);

b) Initial evaluation of conformity of the UHPFRC by acceptance of the design study, which where relevant includes the results given in the UHPFRC identity card (evaluation applies to the conformity to the specification, without taking into account all specific aspects of the production process);

c) Initial evaluation of conformity of the UHPFRC by acceptance of the suitability test based on the trial production of the prototype element (evaluation applies to the full conformity to the specification, taking full account of the UHPFRC recipe and mixing, transport, placing and possible treatment processes);

d) Evaluation of conformity of the UHPFRC during the production process based on the results of autocontrol testing associated with the UHPFRC production at the fresh state;

e) Evaluation of conformity of the UHPFRC during the production process based on the results of autocontrol testing associated with UHPFRC placing, possible treatments applied, and with specified required characteristics at the hardened state.

Conformity of UHPFRC to NF P 18-470 is established only when conformity at each of these steps has been established, should property transfers have taken place or not.

At step e) described here above, the user of the UHPFRC, who produces the UHPFRC structure, element or product, is responsible for the evaluation and declaration of conformity of the UHPFRC for what concerns application of placing, curing and possible thermal treatment(s), and conformity to specifications of properties determined on hardened placed, cured and treated UHPFRC, such as compressive strength, tensile response, possible additional specified or controlled properties.

Specific Aspects of the Design of UHPFRC Structures

As a complement to Eurocode 2 (part 1-1: General rules and rules for buildings; part 1-2: General rules, structural fire design; and part 2: Concrete bridges, design and detailing rules), the NF P 18-710 Standard focuses on provisions specific to UHPFRC, and indicates direct applicability or non-relevance of other clauses. This format has been deemed to promote use of this new Standard by design engineers having experience with the Eurocodes.

With this format, the major difference consisting in effectively using the tensile contribution of the UHPFRC material is emphasized. This contribution, corresponding to a stress-strain or stress-crack opening design curve, is described in the section 3 "Material" with different admissible degrees of approximation. It is used for ultimate limit state (ULS) verifications, namely in bending, shear and torsion, and also for serviceability limit state verifications especially for crack control. It is also applicable, under certain limitations, for verifications using strut and tie models, and design of tying in buildings.

For the final design justification, the material characteristics determined during the suitability tests and trial prototype production, as well as the effective set of orientation factors, have to be used to calibrate the design curve for tensile UHPFRC contribution, which is indeed a specific feature of UHPFRC structural design process. Since the tensile contribution of UHPFRC is used, and may often result in dispensing with conventional secondary reinforcement, a partial material factor γ_{cf} *for UHPFRC under tension has been defined and calibrated based on present experience of characteristics measured on effective industrial production of UHPFRC.*

Another main specific issue of NF P 18-710 concerns non-brittleness. The minimum reinforcement ratio conditions generally provided in Eurocode 2 Section 9 are replaced by two verifications: first, a condition which is related to the minimum material ductility associated to the post-cracking tensile capacity up to 0.3 mm crack opening, which (including a default orientation factor value of 1.25) has to be higher than 40 % times the limit of linearity in tension (cf. Equation (1)); a second condition has to be verified for cross-sections which are not under full compression, introducing a sufficient margin between the resisting axial force and bending moment, taking into account the contribution of cracked UHPFRC under tension, and the axial force and bending moment corresponding to the limit of linearity of the material constitutive behavior. When this latter condition is verified with the only contribution of UHPFRC, no conventional reinforcement for non-brittleness is required.

Improved UHPFRC properties have a direct influence on reinforced UHPFRC structural design and detailing, especially concerning anchor lengths of reinforcing bars, for which the design provisions have been adjusted, and concerning cover thickness, for which the condition associated to correct placement may become more critical than bar corrosion prevention (in general, the cover thickness has to exceed 1.5 times the fiber length).

Ultimately, it shall be reminded that for UHPFRC, the different useful design characteristics (Young's modulus, tensile characteristics, creep and shrinkage values…) cannot be estimated a priori as functions of the sole compressive strength. For preliminary design, a set of parameters range is provided. And when available, identity cards of UHPFRC mixes can be useful to provide guidance for the first verifications. But for the final design justification, parameter determination based on trial production values is mandatory.

Recent Developments in the Design Provisions

Most of previous specific aspects directly derive from the French experience of design of UHPFRC structures documented in AFGC Recommendations, revised in 2013. The NF P 18-710 Standard preparation however led to formal clarification of requirements, and interaction with NF P18-470 provisions for identification of material requested properties. Moreover, adaptation of the Section 5 "Structural analysis" to the case of UHPFRC structures made it necessary to formally precise the conditions of buckling / instability verifications, taking into account the contribution of UHPFRC under tension, and the conditions for accepting non-linear advanced verifications have been described in a dedicated annex.

The provisions for fatigue verification have been established, including explicit exclusion of the cases where no fatigue risk is to be expected. Verifications for shear, torsion and punching shear have been clarified in better distinguishing the case of reinforced, pre-stressed or plain UHPFRC elements, with detailed and comprehensive provisions for concentrated loads close to bearings. A clear set of partial safety factors corresponding to the case of accidental actions has been made available.

Although quite short in length, the normative annex R corresponding to fire design is critical for the safe implementation of UHPFRC, e.g. in buildings or tunnels. The principles of NF EN 1992-1-2 are kept, except the use of simplified tabulated methods. Determination of material properties at high temperature is to be carried out following NF P 18-470 provisions, which combine values deriving from standard curves and values to be explicitly determined experimentally, *for which the testing protocol is given. It is also reminded that control of thermal instability (spalling), which is generally achieved with a sufficient polypropylene fiber content, is not a material intrinsic property and has to be demonstrated experimentally with sufficient representativeness in terms of specimen geometry, fire scenario and loading conditions.*

The (although short) normative annex U is also a key addition for UHPFRC application, in relation to seismic verification. Since seismic verifications deriving from Euro code 8 national implementation are of regulatory application for buildings, it was necessary to precise how this should be accounted for in the case of UHPFRC structural components. First, material partial factors associated to seismic verifications are given. Moreover, it is admitted that elements be justified if their behavior keeps elastic, assuming non-cracked members inertia and a damping factor equal to 2 %, and the effects of seismic actions being lower than resisting ULS moment / axial force. When a ductility demand is to be satisfied, an experimental demonstration is required. For this demonstration, the representative component must be submitted to at least 5 cycles up to the ultimate demanded displacement, and the corresponding decrease in bearing capacity must not exceed 20 % of the maximum load.

Conclusions

The present paper aimed at highlighting major features of the new NF P 18-470 and NF P 18-710 Standards for UHPFRC, especially those providing a formal clarification or complement to AFGC Recommendations indications. Adoption and implementation of these new Standards, together with associated documents concerning execution of UHPFRC structures, appears as a significant milestone for a wider use of UHPFRC, safeguarding quality and safety.

References

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