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TWENTY YEARS-LONG FRENCH EXPERIENCE IN UHPFRC APPLICATION AND PATHS OPENED FROM THE COMPLETION OF THE STANDARDS FOR UHPFRC

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Abstract

Ultra-high Performance Fibre-Reinforced Concrete (UHPFRC) has emerged as a fruitful result of research efforts based on three main ideas: strength and compactness improvement of cement materials by intense reduction of the water to binder ratio; efficient use of fibers to provide post-cracking tensile capacity and pseudo-ductility; and reduction of natural imperfections due to aggregate in limiting their size and selecting very high quality materials in an optimized grading. From twenty years, UHPFRC has demonstrated outstanding strength and resistance to transfer, so that durability and lightness of prestressed members have been mostly searched in structural applications. Later on, UHPFRC has been adopted to develop attractive façade and roofing components, owing to renewed aesthetic possibilities associated to durable mineral surface quality, lightness, semi-transparency and possible complex shapes.

Based on this experience the standardization process launched in France has resulted in three complementary standards, addressing UHPFRC structural design, material production and control (both documents published in 2016), and execution of structures (to be published by end 2018). Further expected development (deserving significant educational efforts) especially concern civil engineering facilities answering high durability and sustainability demands, light and efficient solutions for protection and structural repair, and architectural achievements in façades and public buildings.

1. INTRODUCTION: WHAT WE UNDERSTAND WITH UHPFRC

Ultra-high Performance Fibre-Reinforced Concrete (UHPFRC) has emerged around 25 years ago [1] as a fruitful result of dedicated research efforts based on the combination of three main ideas:

- Strength and compactness improvement of cement materials by intense reduction of the water to binder ratio, which was made more and more possible and efficient with R&D advances in superplasticizers and mineral additions;
- Use of steel fibers to provide post-cracking tensile capacity and pseudo-ductility (Fig. 1), which was made possible thanks to more than two decades of conceptual and exploratory development of conventional fiber-reinforced concrete, and really efficient as compared to it due to the high quality of the matrix and the possibility to incorporate high amounts of fibers;
- Reduction of natural imperfections due to aggregate in limiting their size and selecting very high quality materials in an optimized grading, which took benefit of aggregate packing models having been developed in the late 80s.



Figure 1: Evidence of ductility, test for approval of UHPFRC beams in view of their application in the renovation of thermal exchange devices in Cattenom plant cooling tower [3]

This concept combination has enabled to produce several industrially controlled patented materials [2] markedly overpassing the highest (very) high-performance concrete available at that time, with 150 MPa-characteristic compressive strength at least, and possibly dispensing with the traditional use of secondary reinforcement due to material non-brittleness and with thick cover in aggressive environment due to much reduced transfer coefficients. This allowed dispensing with keeping systematic continuity with traditional reinforced concrete design provisions. Moreover, mixing, placement, thermal treatment and formwork technology could be kept understood in the continuity of emerging self-compacting concrete.

UHPFRC is indebted to some pioneers in this concept combination: Pierre Richard†, Marcel Cheyrezy, Gérard Birelli, Thierry Thibaux and Gilles Chanvillard†. These people were convinced that it could open the way to new horizons for cement materials. They promoted this combination as an answer to badly answered demands, in order to:

- Reduce local brittleness governed by defects;
- Promote industrial control in constructions processes and products;
- Optimize the use of cement in a high added value material;
- Initiate a trend « less is beautiful » in concrete architecture.

A tens of years later, in parallel with a growing demand for outstandingly slender and attractive architectonic elements, the use of organic and stainless steel fibres in UHPFRC-type materials was developed, the range of mixes was extended addressing the fire-resistance demand and the possibly lower strength requirements, and ribbed plates or shells with passive reinforcement in the stiffeners tended to appear as structurally efficient. Growing interest and economic significance of this development in building components turned out evident from

the first international symposium strictly dedicated to UHPFRC applications, organized in Marseille (France) in 2009 [4].

Five years later, and particularly for the Standardization process intended to ease UHPFRC ordering, clarification of the UHPFRC-type materials designation had become necessary given the ongoing development of these materials, and the request for precise classification associated to the degree of validation for available background in view of structural design, and effective field experience of implementation and durability. The designation established by the recently published French Standard [5] is displayed in Table 1. Although this designation is not universally accepted for the moment, it has been adopted as a reference in the French Standard and is used for common understanding in this paper. UHPFRC (as covered by the NF P18-470 Standard [5]) is thus associated to non-brittleness and compressive strength higher than 130 MPa (which is also related to durability characteristics). Non-brittleness threshold is considered a key issue for possibly dispensing with secondary reinforcement and acceptability by building authorities even for non-strictly structural components. Characterization of the post-cracking UHPFRC capacity (contribution to take tensile forces and provide structural non-brittleness), which turns out for design at least as significant as the (often non-directly critical) compressive strength, (Fig. 2) has thus deserved standing R&D efforts for the justification of the tests and data analysis procedures [6]. And therefore the ‘UHPFRC’ designation of non-brittle materials differs from ‘UHPC’.

Table 1: UHPFRC-type materials designation (in italics, French acronyms)

f_{ck} (MPa)	non-brittle metallic fibres	non-brittle other fibres	Possibly brittle
150 to 250	UHPFRC – <i>BFUP</i> type S	UHPFRC – <i>BFUP</i> Type A	UHPC
130 to less than 150	UHPFRC – <i>BFUP</i> Type Z		
less than 130	VHPFRC		VHPC

UHPFRC as covered
by NF P18-470 [5]

UHPFRC as covered
by NF P18-470 [5]

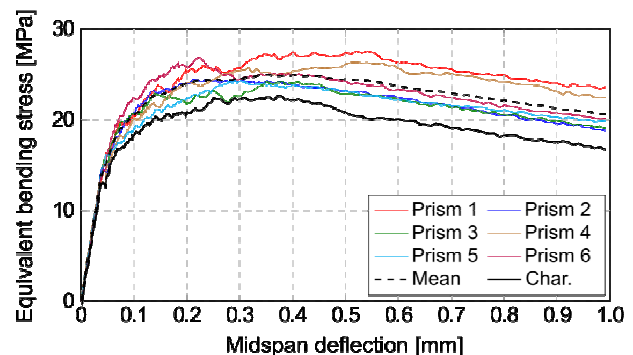
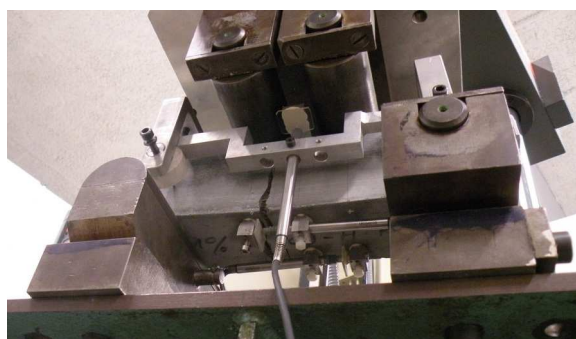


Figure 2: Typical four point-bending characterization on prisms and results [7]

Concerning UHPFRC types designation, type A fiber-reinforcement is related to clear physical differences from metallic fibers e.g. when exposed to high temperatures. The strength limiting values equal to 130 and 150 MPa may appear as somehow conventional thresholds, they are however related to present accepted experience and they determine the accepted design methods. Type S-UHPFRC correspond to the materials first developed and used, for which structural design provisions have been validated, and thus correspond to the scope of the NF P18-710 Standard [8] associated to UHPFRC structural design. Changing the limiting values would require collecting and documenting significant additional background.

It should be mentioned that this technical designation may differ from the commercial (ranges) designation of UHPFRC-type materials.

2. UHPFRC HISTORICAL DEVELOPMENT IN FRANCE

Since implementation of innovative building solutions highly depends on the capacity to convince owners and authorities, regional and national issues and experience are worth being considered although worldwide scientific and technical exchange on UHPFRC technology have been existing for more than 15 years.

2.1 Genesis

Since the first major UHPFRC applications in France concerned a number of prestressed beams for the renovation of the heat exchange zone in a cooling tower of Cattenom nuclear power plant (NPP) (Fig. 3), and an innovative competition for typical bridge crossing over 2 x 2 lanes-highway, implemented at Bourg-lès-Valence in South-Eastern France (Fig. 4), the owners (Power Company and State Highways) and the associated technical authorities requested an extensive documentation on UHPFRC structural behaviour to be collected, supporting the computation files that had to gain contradictory validation. At the same time, companion prospective efforts towards nuclear applications additionally helped demonstrating outstanding strength and resistance to transfer, so that durability and lightness of prestressed members have appeared as main advantages to be searched in structural applications.



Figure 3: UHPFRC beams for thermal exchange devices in Cattenom NPP cooling tower [3]



Figure 4: Bourg-lès-Valence UHPFRC bridge deck made of prestressed Pi-shaped beams.

As a conclusion of this initial implementation period, the first worldwide recommendations for production, characterization of UHPFRC and structural design using these materials, were published in France in 2002 [9]. Drafting of these recommendations had taken full benefit of the owners and contractors involvement in these pioneer applications, with high level of technical supervision and results of R&D efforts. Additional favourable conditions have included the fact that several industrially available materials had been developed, and that stakeholders were convinced of their common interest in scientific advance and development of relevant UHPFRC implementation to face durability and building performance challenges.

2.2 Exploration

Based on a limited number of well-characterized UHPFRC mixes, and considering that fresh UHPFRC technology could be understood in the continuity of that of emerging self-compacting concrete, efforts could be focused from 2002 to 2012 on exploring structurally efficient applications, relying on the AFGC Recommendations [9] design principles for pre-stressed / post-tensioned beams and boxes and non-reinforced thin elements. Application to footbridges as Seon Yu Footbridge (Fig. 5) and Passerelle des Anges (Fig. 6) led to lightness / slenderness records [10]. Effective realization of these projects motivated consistent research efforts to ensure controlled quality of the material produced and placed.



Figure 5: Pi-shaped cross-section of the UHPFRC arch Seonyu footbridge in Seoul.



Figure 6: Passerelle des Anges, post-tensioned braced lateral beams, 1/38 slenderness [10]



Figure 7: ITE® beams. Left) Just handled after precasting for Buthaumont Bridge [11]. Center) Being installed at Pinel Bridge, allowing safe deck completion from above [12]. Right) After completion, deck from below: Pont de la République in Montpellier [13]

For road bridges, optimized shapes, like ITE® beams [12], first applied for Pinel bridge in 2006 (Fig. 7), were demonstrated as favourable for valuable implementation, while cost-efficiency also relied on indirect material savings or lightness benefits for the method of execution. Study of alternative shapes such as post-tensioned box-girders [14, 15] or ribbed slabs [16] turned out technically attractive and led to significant progress in validation of extensive design provisions, yet being scarcely applied due to lack of high-volume application opportunities which would have resulted in cost-effectiveness.

Besides valuable application in structural components, exploration of UHPFRC by architects helped develop attractive façade and roofing components, thanks to new aesthetic possibilities associated to durable mineral surface quality, lightness and possible complex shapes and semi-transparency, with typical examples of Villa Navarra [17] roofing ribbed plates (Fig. 8) and “Les enfants du Paradis” net panels (Fig. 9) in 2007. For such non-structural elements the range of mixes was extended significantly. Plain thin UHPFRC plates or ribbed plates with passive reinforcement in the stiffeners proved structurally efficient. Association of UHPFRC with glass panels, developed for the Jean Bouin Stadium renovation [18] has given a new impulse to semi-transparent roofing components (Fig. 10). Growing interest and economic significance of this development in building applications allowed UHPFRC produced volumes to take off in France from the 2010s, although technically optimized applications like light prestressed bridges (as in Malaysia), or joint fills between

precast beams or deck slabs (as in North American projects of “accelerated bridge (re)construction”) did not find their market here.



Figure 8: Thin UHPFRC roofing panels at Villa Navarra [17].



Figure 9: First UHPFRC net panels

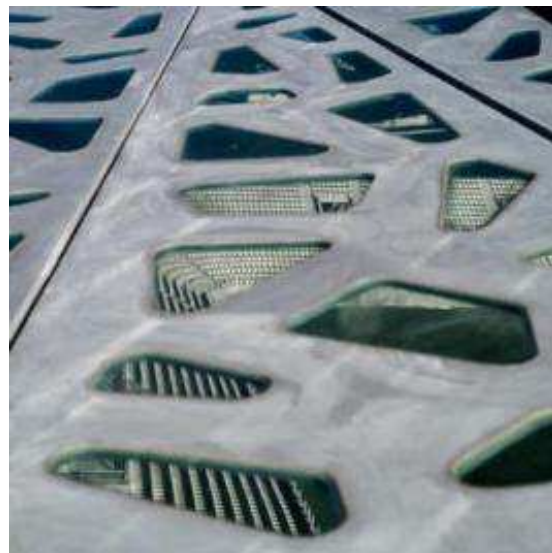


Figure 10: Roofing panels of Jean Bouin Stadium [18]

2.3 Demonstration

The year 2013, associated to the second international symposium on UHPFRC applications organized in Marseille [19] and to the publication of the revised edition of AFGC Recommendations [20], has constituted a significant milestone for UHPFRC in France. Revision of the AFGC recommendations had been motivated by consistency with the format of Eurocode enforced as the reference for structural design, and by taking into account the scientific advances in UHPFRC engineering and gained experience in UHPFRC design and realizations. As a key example of fine-tuned prestressed UHPFRC structural design, these revised recommendations have been applied for the design of the ‘Ring of Memory’ (Fig. 11) at Notre-Dame de Lorette First World War Memorial [21-22].

Two major projects associated to highly visible urban renovation projects, the MuCEM [23-26] in Marseille (Fig. 12) and the Jean Bouin Stadium [18] in Paris (Fig. 13), had been completed the same year, constituting significant industrial achievements for the delivery of high numbers of UHPFRC precast components, and a decisive involvement of designers, checkers and authorities for safety verification of all innovative details. Their completion led to widened awareness of technical and architectural capabilities of UHPFRC among professional (architects, engineers) and for the public, including clients of constructions.



Figure 11: The Ring of Memory, curved UHPFRC post-tensioned structure [21-22].



Figure 12: the MuCEM in Marseille [23-26]: 330 UHPFRC post-tensioned columns, 380 net cladding and roofing UHPFRC panels, two UHPFRC footbridges.



Figure 13: Jean Bouin Stadium [18]. 10,700 m² roofing panels, 1811 façade net panels.

The NF P18-470 and NF P18-451 standards cover 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 [9, 20]. Design of structures to be made with these materials is covered by NF P18-710 Standard. However, NF P18-470 and NF P18-451 also cover 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 Table 1). For the moment however, due to lack of documentation of feedback and experience in real applications, structural design using UHPFRC with non-metallic fibers and/or with a compressive strength lower than 150 MPa has been considered as non-traditional, thus out of the scope of the NF P18-710 Standard, and thus requires dedicated technical approval.

Consistently with effective feedback of implemented materials in technically and economically efficient projects, the scope of these standards is also separated from present standards (NF EN 1992-1-1 [32] and NF EN 206/CN [28], which cover concrete with a maximum compressive strength class of C90/105 and C100/115, respectively). Moreover, while these standards are compatible with *fib* Model Code 2010 [33] principles concerning fiber-reinforced concrete (§ 5.6.1), they give specifically adjusted provisions based on experience of materials associated to a high enough fiber ratio to ensure a minimal ductility.

3.1 Material specification and control

Namely, the required ‘non-brittleness’, i.e. the UHPFRC hardening behavior under pure bending that shall be effective, is one remarkable performance of these materials besides compressive strength. NF P18-470 provides explicitly the Equation (1) to be verified:

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

Where: $w_{lim} = 0,3 \text{ mm}$

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

$\sigma(w)$ 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 or thin plates is detailed in Annexes D and E of NF P18-470 Standard.

The UHPFRC designation also implies that the material fulfils the following requirements: nominal upper size of aggregates lower or equal to 10 mm; density comprised between 2200 kg/m³ and 2800 kg/m³; 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 $\leq 9,0 \%$; coefficient of apparent diffusion of chloride ions at 90 days $\leq 0,5 \cdot 10^{-12} \text{ m}^2/\text{s}$; and apparent gas permeability at 90 days $\leq 9 \cdot 10^{-19} \text{ m}^2$.

Moreover, classes are defined in the NF P18-470 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. The class associated to the tensile behavior of a UHPFRC mix (namely T1: strain softening under direct tension, T2: limited strain hardening or T3: significant strain hardening) 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. This orientation factor is consistent with the definition given in *fib* Model Code 2010 [33] for any type of fiber-reinforced concrete (§ 5.6.7). Conformity to the specified class can thus be evaluated for the material, whatever its structural application.

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 de-icing 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 P18-710.

The NF P18-470 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 P18-470 standard defines a concept of ‘identity card’, document which, where relevant, gives for each property, the performance value met from effective production experience 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 P18-470 includes the target requirements associated to these processes and associated control (procedure, control parameters, acceptability criteria).

NF P18-470 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. UHPFRC is deemed 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 (Fig. 15).

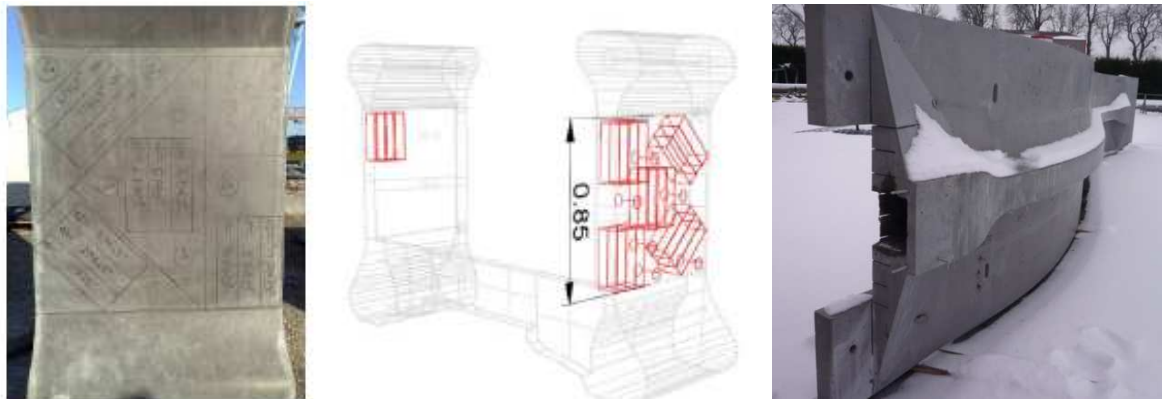


Figure 15: K-factors identification from prisms sawn from prototype elements [26, 34]

Evaluation of the conformity of UHPFRC to NF P18-470 is thus 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 internal inspection testing along with the UHPFRC production at the fresh state;
- e) Evaluation of conformity of the UHPFRC during the production process based on the results of internal inspection testing along with UHPFRC placing, possible treatments applied, and with specified required characteristics at the hardened state.

Conformity of UHPFRC to NF P18-470 is established only when conformity at each of these steps has been established, should property transfers have taken place or not.

3.2 Structural design

As a complement to Eurocode 2 [32], the NF P18-710 Standard focuses on provisions specific to UHPFRC, and indicates direct applicability or non-relevance of other clauses. The major difference with ordinary concrete, consisting in effectively using the tensile contribution of the UHPFRC material, is thus emphasized. This tensile contribution may be described 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. 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 concerns non-brittleness. The minimum reinforcement ratio conditions of Eurocode 2 Section 9 are replaced by two verifications: first, the minimum material ductility characterized by Equation (1); secondly, for cross-sections which are not under full compression, a 20 % margin has to be demonstrated between the resisting bending moment, taking into account the contribution of cracked UHPFRC under tension, and the elastic 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, resulting in reduced anchor lengths of reinforcing bars and cover thicknesses, 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).

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, an informative set of parameters range is provided in Annex T of NF P18-710 [8]. 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.

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 fire design in Eurocode 2 are kept, except the use of simplified tabulated methods. Determination of material properties at high temperature is to be carried out following NF P18-470 provisions, which combine values deriving from standard curves and values to be explicitly determined experimentally, for which the testing protocol is given. Moreover, the 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 (also short) normative annex U related to seismic verification is also a key reference for UHPFRC application in fulfilment with national regulations for prevention of seismic risks. 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 shall be submitted to at least five cycles up to the ultimate demanded displacement, and the corresponding decrease in bearing capacity shall not exceed 20 % of the maximum load.

3.3 Execution

The most recently elaborated NF P18-451 Standard [29] follows the same outline as the NF EN 13670/CN standard [30], so that specific rules for UHPFRC are emphasized. The scope of the standard covers UHPFRC conforming to NF P 18-470 whatever its production conditions, which can be either cast in a place different from the final construction site to produce (structural or non-structural) precast elements, cast in place to produce structural or non-structural members, or cast in place as a joint-fill, coating or repair material along existing members. According to this standard for the execution of the UHPFRC structure or elements, the quality management refers to execution class 2 at least, which implies mandatory inspection – not only self-control – of all important casting steps (Fig. 16).

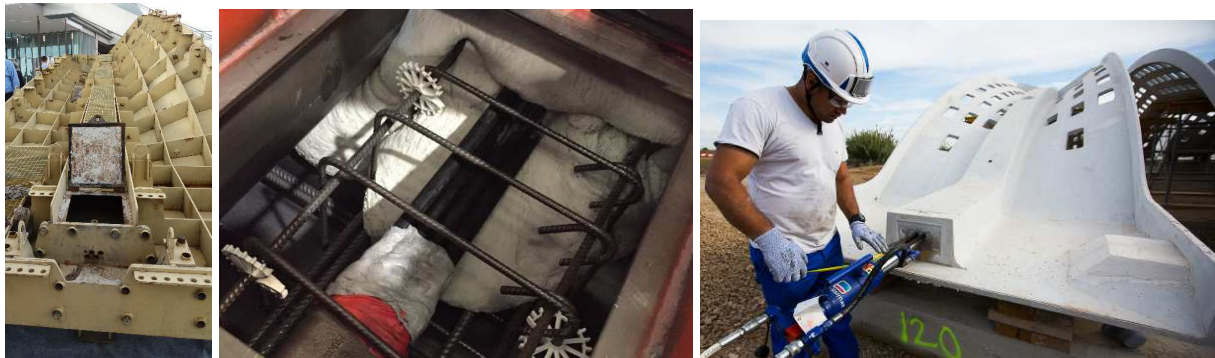


Figure 16: Inspection of UHPFRC placement in a critical zone of post-tensioning anchorage, requiring a window in the formwork and control before prestressing application [35].

As a specific feature of the documentation, the execution specification shall comprise: a detailed UHPFRC mixing protocol; a detailed concreting programme; procedures for the management of early age transient steps, form removal, handling of precast elements; and a procedure for placing and adjustment of precast elements, where relevant.

Concerning falsework and formwork, specific care is requested due to UHPFRC characteristics at the fresh state, during setting and at early age. Tightness and rigidity of the forms shall be ensured. Formworks geometry and surface should promote the UHPFRC flow and avoid fibers blockage (e.g. sharp edges should be avoided). Early age thermal and autogenous deformations shall be anticipated for reaching the requested geometry (e.g. owing to active control of falsework and formworks geometry, using matched joints, etc.). Restraints at early age due to formworks should be avoided (e.g. with appropriate moulds rigidity and/or optimized form removal time). Significance of the formed surfaces and high slenderness of the members make the control of the facings aspect critical. Care is thus requested on the choice of appropriate solutions for the material of the formwork skin, the form release agent, air vents to release entrapped air, etc. (Fig. 17). The control of inserts location requires specific provisions in thin and frequently unreinforced members. Testing the resistance of anchors may be requested.

Since following a documented mixing protocol is part of the conformity of UHPFRC to the NF EN 18-470 Standard, the choice of the appropriate mixer (capacity, precision of dosage, device for fibers introduction) is a sensitive step. Also storage conditions of the constituents are to be mentioned in the protocol. The concreting programme, to be validated from the suitability test and especially from trial application in concreting the scale one mock-up, shall

include: transport, placing and compaction methods (avoid dropping, segregation, cold joints, give indications in case of injection), and for this the tools to be used, the maximum placing duration, the management of flows and layers of fresh UHPFRC, the control tests during this phase, the methods of joint treatment, and the treatment of existing surfaces if UHPFRC is cast against such ones so that a composite structure is realized. It shall also give the finishing provisions, describe the curing method, the thermal treatments if any, the provisions in case of hot weather / cold weather / unexpected casting interruption, the methodology of cooling management if any (prevention of thermal cracking), and the indications concerning form removal (especially aiming to prevention of restraints).



Figure 17: Typical form solutions for UHPFRC elements.
 Left) supply material for the mould of a net panel with numerous inclusions [36].
 Right) Match-casting of thin walled segments to be assembled by post-tension [22].



Figure 18: Typical handling operations of large and thin UHPFRC elements [34, 18, 35].

A specific section of the NF P18-451 standard addresses execution of structures with precast concrete elements. It is confirmed that jointing using UHPFRC is considered as (UHPFRC) concreting. In case of assembling precast UHPFRC elements whatever the method, experience motivates to take special care due to frequent slenderness, deformability and thus possible risk of instability of the elements during handling (Fig. 18). In the case of thin precast UHPFRC members, the risks of mismatch and unexpected loads due to connection are to be prevented with specific provisions related to geometrical (position) control. Given the sensitivity to the quality of execution, and the associated safety issues, the use of glue for jointing UHPFRC elements shall be validated by (type) testing.

The section of the standard dedicated to geometrical tolerances distinguishes class 1 « normal » values, which however comprise reduced tolerances as compared to NF EN 13670 for thin members (less than 50 or 75 mm), and class 2 « reduced » values, which correspond to smaller deviations taken into account for instability verification, mainly for columns, according to the design standard (NF P 18-710) [8]. In any case, stricter tolerance values may be requested for functional requirements (especially for thin or slender members).

4. PRESENT AND PROMISING FIELDS OF APPLICATION

4.1 Civil structures and bridges

As stated in the context of the third international symposium dedicated to UHPFRC organized in France [37], worldwide recognition especially within ACI Excellence in Concrete Construction Awards program has been gained for outstanding UHPFRC projects. Noticeably enough, due to optimization in conceptual design, UHPFRC has made possible competitive solutions not only for tailor-made signature projects (Fig. 19), but also for typical bridge situations exemplified by the Buthaumont Bridge [11] or the footbridge at Le Cannet des Maures [38]. Cost-efficiency of UHPFRC bridges generally also comes from the indirect advantages of a light / slender deck, in case of difficult soil conditions, in association with quicker / cheaper erection methods, or due to lower access embankments with reduced earth works. Such benefits are effectively taken in Malaysia in the context of important new infrastructure needs [39]. They also motivated the development of light prefabricated bridge solutions to be exported to sites with limited possibilities of local resources and workmanship [40]. While the market of new road bridges may keep limited in France and Western Europe, efficient UHPFRC solutions for (urban) rail bridges may still deserve valuable exploration [41]. In this context, compliance with UHPFRC standards is a key condition for acceptability by the clients and the supervisors, and for a sound competition with alternative solutions.



Figure 19 : La République Bridge in Montpellier [13]

Beside new bridges which may require a rather expensive case-by-case approach, optimized series of applications in civil engineering structures and facilities could become an increasing field of UHPFRC usage, especially in relation to the generally high durability-demand. Examples already exist with the industrial buildings at Achères water treatment plant (Fig.

20), or the noise barriers of metro viaducts in Rennes. Opportunities might be found in the field of renewable energies and urban networks. In addition to materials and design standards, documentation of effective UHPFRC field durability and sustainability appears as a key for development of this prospective market.



Figure 20: UHPFRC roofing elements for Achères water treatment plant [34]

4.2 Building components

From 2010 the driving field of UHPFRC application in France has concerned ultra-thin, often highly transparent and architecturally appealing cladding and roofing panels, for buildings as “La Mantilla” residence or ITER headquarters (Fig. 21) as well as for large public infrastructure projects as the new Montpellier high speed railway station (Fig. 22).

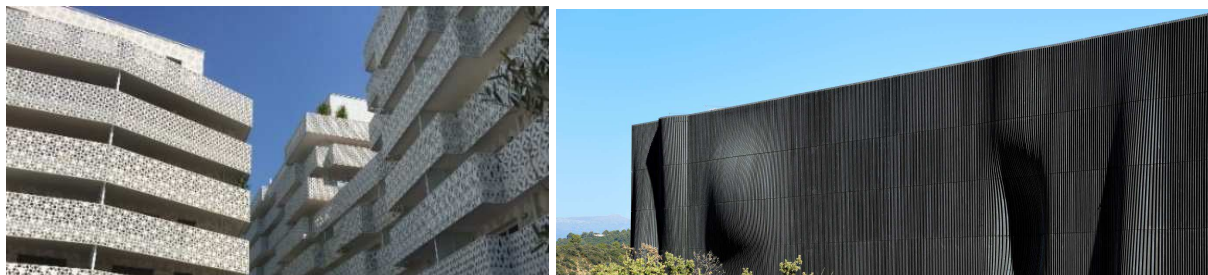


Figure 21: UHPFRC building components. Left) balustrade elements in Montpellier [36].
Right) Cladding elements for ITER Headquarters in Cadarache



Figure 22: UHPFRC roofing components of Montpellier new TGV Station [35]

While answering versatile aesthetical demands, such UHPFRC ‘secondary elements’ of the buildings have gained acceptable cost-efficiency due to their lightness, thus reduced costs for transport, installation and fixation to the main frame of the structure and reduced applied loads on it. Their economical acceptability, promoted when the number of components is high (Fig. 23), has also imposed clever formwork and moulding solutions to allow variations with minimal adaptations of the industrial tools. While the NF P18-451 Standard gives general indications based on the gained industrial experience in this domain, detailed precasters’ skills beyond the standard are clearly associated to the success of such UHPFRC applications, as a result of the material sensitivity to its placing process and early-age treatment and restraints.

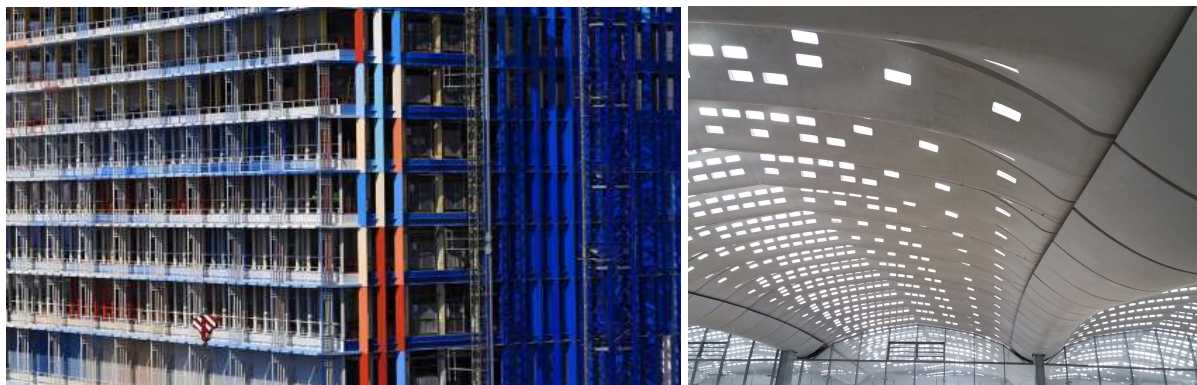


Figure 23: Variations in replication of UHPFRC precast building components.

Left) Façade elements of La Marseillaise high rise building [42].

Right) Roofing palm-shaped shells of Montpellier new railway station [35].

4.3 Repair

With the iconic examples of Chillon viaducts [43] and Hammersmith Flyover [44] (Fig. 24) and progressively also in France especially for maintenance of ancient [45] and/or fatigue-sensitive [46] steel bridges, bridge deck repair or protection using UHPFRC has deserved increasing interest. Repair solutions, for buildings also, are increasingly considering UHPFRC.



Figure 24: UHPFRC applied for rejuvenation of prestressed concrete viaducts [43, 44].

Left) UHPFRC overlay. Right) Small UHPFRC anchor blocks for additional post-tension

Key technical advantages are associated to the possible low intrusiveness of the repair intervention, associated to the limited required material amount with respect to the high bearing capacity. Fire resistance, adaptability to complex geometrical shapes, possible implementation underwater may also be comparative advantages with respect to alternative repair solutions. UHPFRC allow e.g. low overlay or deck slabs thicknesses (Fig. 25) reducing incidence on the supports and foundations. Added mass of anchoring blocks for additional post-tensioning can similarly be very limited [44]. High stiffness, low creep, intrinsic durability and wear resistance of the UHPFRC applied will result in a long expected lifespan for the repaired structure. Even water-tightness may be achieved, provided adequate design, mix and execution provisions are taken.



Figure 25: Thin slabs for redecking the Grand Pont in Thouaré-sur-Loire [45] or the Illzach orthotropic deck [46].

Versatility of the UHPFRC application for repair should thus result in cost-efficiency despite a possibly still high unitary material cost. This however requires a combined optimization of the UHPFRC material, design and execution of the repair operation. Especially important are the methods of execution: How to connect precast elements to the existing structures, what is the geometrical tolerance, how durable is the fixation? Should the UHPFRC be placed by gravity pouring, injected, spread with a finisher? With which consequences on water tightness and fibre orientation / homogeneous distribution?

The combined design-mix-methods optimization may result in reduced time for jobsite operations (which saves money and risks), taking possible advantage of precasting, and/or adaptable fresh UHPFRC rheology then rapid hardening if cast on site. In addition to bridge strengthening, protection of marine structures, seismic retrofitting and external thermal insulation of buildings with UHPFRC-born façades probably constitute promising fields of application. Recently published French standards on UHPFRC are intended to ease the acceptance of UHPFRC in the repair projects and their implementation. However, the effective possibility to combine optimization of design, mix and methods may require an adapted contract and delay organization.

5. PROSPECTS AND FURTHER NEEDS OF EFFORTS

Availability of UHPFRC Standards in France [5, 8, 29, 31] has opened new conditions for easier acceptance of UHPFRC projects and solutions referring to a technical shared background and reference for contracts. However, consolidation and dissemination of design skills, and engineering and industrial know-how is a key condition for further development of UHPFRC applications. Several architects, designers, checkers, engineering offices, and

precasting plants, although quite few, have developed such a UHPFRC expertise. Education associated to the standards dissemination should strengthen these capabilities. Especially from the new NF P18-451 on execution, it can be expected an easier specification of works using UHPFRC, clarification of the critical tasks in UHPFRC works execution, inspection and supervision, clarification of “UHPFRC know how” for the precast industry and for contractors, and anticipation of execution issues, resulting in more reliable costs and delays prevision.

Further research and development efforts should address advanced UHPFRC modelling, seismic design with UHPFRC, development of typical “UHPFRC solutions”, and non-conventional placement process optimization including 3D printing and - with a more immediate promising prospect - sprayed UHPFRC (especially for steel culverts repair [47]) which could widen the scope of cost-efficient UHPFRC implementation. Moreover, dissemination of information related to satisfactory durability and field implementation, and improved laboratory characterization of UHPFRC durability characteristics, still deserve efforts for convincing possible owners and supervisors especially for technically demanding applications.

Finally, given the significance of relevant applications of type-A and type-Z UHPFRCs, extension with possible adaptation of the NF P 18-710 Standard to these materials should be undertaken at short term.

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