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THE UHPFRC REVOLUTION IN STRUCTURAL DESIGN AND CONSTRUCTION

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Abstract

The paper summarizes the development of UHPFRC knowledge and techniques until revision of the AFGC recommendations in 2013, emphasizing the evolutions which benefit from building and design feedback and from research efforts made on the last decade. Recent projects and achievements allow emphasizing the specific points of the design which justified the use of UHPFRC and the critical points of the execution which pass the field of traditional structures. The paper finally lists scientific and technological breaks engendered by UHPFRC which impose the engineers and the designers to think out of the reflexes attached to the traditional reinforced or prestressed concrete structures.

Résumé

L'article présente le développement des connaissances et de la technologie du BFUP jusqu'à la révision des recommandations AFGC en 2013, en mettant en évidence les évolutions liées au retour d'expérience en termes de conception et de réalisation, et aux résultats des recherches réalisées sur la dernière décennie. Des projets et ouvrages récemment construits permettent de mettre en évidence les points particuliers de la conception qui ont justifié le recours au BFUP, et les points sensibles de la réalisation qui sortent du champ des structures en béton traditionnel. L'article se termine par une synthèse des ruptures scientifiques et technologiques engendrées par les BFUP, qui imposent aux ingénieurs et concepteurs de sortir des leurs réflexes attachés aux structures en béton armé ou béton précontraint traditionnel.

1. UHPFRC DEFINITION AND DEVELOPMENT

Following AFGC revised recommendations [2], Ultra High Performance Fibre-Reinforced Concrete (UHPFRC) are materials with a cement matrix, and a characteristic compressive strength between 150 MPa and 250 MPa. They contain steel fibres, in order to achieve ductile behaviour in tension and overcome if possible the use of passive reinforcement.

UHPFRC differ from high performance and very high performance concretes by:

- the systematic use of fibres, which ensures that the material is not brittle and may allow, through the participation of the fibres which provide tensile capacity after the cement matrix has cracked, dispensing with conventional active or passive reinforcements, especially secondary reinforcing bars;
- their compressive strength generally greater than 150 MPa;
- their composition with a high binder content that leads to the absence of any capillary porosity;
- their direct tensile strength of the matrix systematically higher than 7 MPa.

Early researches on UHPFRC were made by Professor Bache in 1970 in Denmark under the development of CRC technology. This technology is still very active. This is a particular technology, which a large percentage of metal fibre implemented in a cement matrix to produce prefabricated building structures (balconies, staircases) which are reinforced by traditional reinforcement calculated without taking into account the participation of mechanical fibres.

In France, the first researches on UHPFRC have been developed in the 1990s under the leadership of Pierre Richard in the context of Reactive Powder Concrete technology (RPC). The design was then optimized at Lafarge Research Centre in partnership with Bouygues and Rhodia and Lafarge developed Ductal®, the first marketed UHPFRC, which was launched in the late 90s [4]. Under the leadership of EDF, BSI / CERACEM ® technology was developed by the group Eiffage in the late 90s [41]. This technology gives rise to the realization of a growing number of applications as a structural landmark in the field of new structures and repair or strengthening of structures. In the 2000s, the cement company Vicat with the support of the Vinci Group has developed the BCV, which gave also significant structural achievements [32]. With this experience, first recommendations on UHPFRC were issued in France in 2002 to formalize methods to characterize performance of these materials and to give rules to design UHPFRC structures without any frame other than reinforcing fibres which constitutes the major innovation of this type of material [1].

From the 2000s, several countries have engaged in the way of UHPFRC application. The Japanese recommendations were published in 2004. From this date, a lot of outstanding structures (footbridges, road and rail bridges, airport runway extension) have been built [39]. In Australia, a significant activity is developed based on the realization of bridge structures [8]. In Switzerland, UHPRC has been mostly applied under the supervision of EPFL to in-situ reinforcement of structures [7]. UHPFRC footbridges have been built in the Netherlands and in Spain. UHPFRC has also deserved a growing application in maintenance and development of US highways infrastructure [14] as well as in China; prototype bridges and structures have been built in Canada, Germany, Austria and Korea. Moreover, Germany was able to launch from 2005 to 2012 an ambitious R & D program on UHPC under the guidance of the University of Kassel [35].

As discussed during the 1st fib-AFGC symposium on UHPFRC held in Marseille (France) in 2009, this growing experience, also gained in France especially with signature architectural achievements, bridges and building façade components, motivated a revision of AFGC interim recommendations [1] to better account for advanced scientific and technological knowledge, and strengthen critical safety provisions. Major items of the background of this revision are highlighted in the following. Although the background of applications in France is more explicitly quoted, it is expected that the lessons drawn can be of worldwide relevance.

2. FROM INTERIM TO REVISED AFGC RECOMMENDATIONS ON UHPFRC

2.1 Control of fibre orientation

Suitability tests

To use UHPFRC structural material, the AFGC 2002 recommendations introduced the concept of suitability tests. These tests shall be carried out on a specimen representative of the real structure, made of the same materials and following the same mixing and casting procedures as proposed for the execution of the actual structure. In the case of precast products, these tests are included in the phase of development of industrial production processes. From experience gained during completion of real structures, it has turned out how this approach was valid and necessary, including when companies in charge of the construction were very experienced in UHPFRC application. Indeed, these suitability tests lead almost invariably to optimization of the casting process initially planned, or to adaptations of the original design when technological and/or economical aspects preventing adjustment of the process. Sometimes suitability tests lead to slightly changing the UHPFRC mix-proportions to better control the rheology of the material.

K-factor

The influence of UHPFRC implementation on tensile strength of the material in an actual structure is dealt with through a coefficient noted K that weights the constitutive laws derived from laboratory tests. This coefficient is determined from the results of flexural tests performed on specimens sawn in the element built for the suitability tests, after preliminary design may have taken the default (K_{global} = 1.25; K_{local} = 1.75) values. As compared to the 2002 version, the revised recommendations [2] state that for thin elements, suitability tests can give values of K different from 1 when the methodology of casting differs from that used for preliminary studies. For security, the recommendations state that the coefficient K should always be taken greater than or equal to 1. Indeed, a K value less than 1 implies that a beneficial effect of preferred orientation of the fibres in a given direction is taken into account. If relevant, then it would be essential to justify the resistance of the structure in all other directions in which K values are generally greater than 1 even though these directions do not correspond to those of the main effort.

This concept of K coefficient validated though suitability test does not exist in Eurocodes, which still do not cover fibre-reinforced concrete, but has been introduced in the last version of the fib Model Code for cases where the structural strength is provided by the fibres. Although K is not a material safety factor, the process of its identification and application helps adjusting the overall safety of UHPFRC implementation in controlling the intrinsic material properties scatter in a distinct operation as from adjusting the effective fibre distribution in the critical parts of the structure.

2.2 Improved material knowledge

Heat treatment vs. shrinkage creep effects

AFGC 2002 recommendations had introduced the concept of a specific heat treatment for UHPC, typically lasting about 48 hours, made after the concrete setting at a temperature of about 90° C and above 90 % relative humidity. This type of treatment dramatically decreases creep and subsequent shrinkage. Research related to UHPFRC application in the prefabrication industry have allowed proposing additional provisions for computing creep and shrinkage for UHPFRC submitted to moderate (early age) thermal curing designed primarily to accelerate the maturation of the concrete [11].

Fire resistance

Many tests have determined for several UHPFRC mixes all the temperature-affected mechanical properties in order to achieve numerical simulations related to fire resistance: thermal conductivity, specific heat, thermal expansion, compression and tensile strength, Young's modulus [26]. The revised recommendations provide a synthesis of these tests and give default values for a preliminary design of a UHPFRC structure subject to precise specifications of stability under fire. However, it is emphasized that the UHPFRC behaviour under high temperatures strongly depends on the material effectively used and on the structure geometry, it is thus reminded that for a final design one must absolutely take into account the actual constitutive law of the material used to build the structure.

Abrasion

The new version of the recommendations provides main results of abrasion tests carried out for execution of hydraulic works. These results confirm the interest of UHPFRC used as a shield for structures submitted to intense wear.

Sustainability

Sustainability of UHPFRC application has been investigated. Since the UHPFRC cement content is about twice that of conventional concrete, it produces twice as much CO_2 and consumes two times more energy to be produced. However, the experience of UHPFRC achievements shows that when used appropriately, it can divide the quantities of material used in a structure by two or three, and savings can be expected for the structural execution. Compared to a conventional reference solution, if relevant, the UHPFRC alternative allows only a slight gain in terms of CO_2 and energy, but offers a significant gain in terms of durability. The standard methods in life cycle analysis should be upgraded for taking better account of this advantage.

2.3 Structural design provisions

Tensile strength

Numerous tests investigating the tensile behaviour of traditionally reinforced UHPFRC [22, 23], with special attention to tension stiffening effects have helped updating the design recommendations. Following UHPFRC types could be distinguished:

- UHPFRC with a hardening characteristic constitutive law in direct tension (only few mixes are of this type, since it requires a very high fibre content),
- UHPFRC with a hardening average constitutive law in direct tension, but with a softening characteristic law (most UHPFRC mixes available in the market are of this type),
- Softening UHPFRC which have a softening average law in direct tension (these mixes have a low fibre content and generally do not meet the non-brittleness criterion required for structural concrete).

Shear and punching shear resistance

For updating design provisions in accordance with the Eurocodes format, a compilation of available international literature on shear and punching shear tests was performed [19, 21, 37, 43], and additional dedicated tests were carried out [3]. Provisions for shear design and punching shear verifications were then complemented and adjusted.

Seismic design

Although UHPFRC has been used in Japan (but with conventional passive reinforcement for ensuring seismic ductility requirements), and investigations have been done in Canada for use of UHPFRC in seismic strengthening of existing structures [24], quantitative data on UHPFRC response under seismic actions are still scarce, which has still not made possible to extend AFGC recommendations as a complementary document to be used with Eurocode 8.

Recommendations are given to assess a structure with reference to Eurocode 8 in dispensing with detailing provisions for ensuring limited ductility, which is a conservative approach valid in areas of low seismicity. For larger seismic hazards, tests are recommended for dedicated structural assessment.

3. EXPERIENCE GAINED IN APPLICATIONS

3.1 New bridges

From the pioneer experience of Sherbrooke and Seon-yu [5] footbridges or Bourg-lès-Valence road bridges [15-16, 30, 40], UHPFRC application in bridges has successfully demonstrated the capability of making slender structures possible with architectural versatility and high potential durability [4, 8, 27]. Most recently, the “Passerelle des Anges” footbridge (1/38 height/span ratio) [25] as well as footbridges between the MUCEM roof, Fort Saint-Jean and Marseille old district confirm this demonstration (Fig. 1). Control of vibrations, possibly requiring a tuned mass damper, turns out critical in such structures as well as for steel solutions.

Figure 1: Passerelle des Anges and MUCEM footbridges, Rudy Ricciotti (architect)

Additional steps of the demonstration of UHPFRC interest in bridge structures are emphasized hereafter. With La Chabotte box-girder Bridge for example [9], the geometry of the cross section has been specially adapted to UHPFRC, with curved surfaces to facilitate casting. This project also demonstrated that it is possible to eliminate any watertight and pavement layer on an UHPFRC structure, provided roughness of the top surface is given by the formed faces to ensure adhesion of vehicles, and special care is taken in joint execution between prefabricated components. The ability of UHPFRC to constitute precast elements assembled by prestressing without any match-casting during manufactory had also been shown with the Claye-Souilly channel bridge [17, 41]. This design proved highly cost-efficient since it permitted a very significant weight gain compared to the traditional reinforced concrete solution; it needed only particular care to geometric tolerance and rigidity of the formwork masks used for precasting (Fig. 2).

Similarly at Saint-Pierre-la-Cour Road bridge [19], the weight gain of the UHPFRC structure compared to a traditional solution could be quantified as a factor of 2.2. Moreover, the design fully utilizes UHPFRC for its durability performance. Indeed, all surfaces of the deck in contact with ambient air are either made of UHPFRC (beams and underside of the slab) or protected by watertight layer (upper slab).

Structural efficiency had been optimized with the development of ITE ® beams [10, 33]. Their performance in terms of slenderness constitutes an alternative to filler beam decks but their implementation has additional benefits: 40 % reduction of the deck weight, shape and stiffness of the beams make them insensitive to lateral torsional buckling which significantly simplifies implementation.

Figure 2 : UHPFRC channel bridge along Fast Railway line, Claye-Souilly

Figure 3: Repair of Illzach Bridge steel deck using precast UHPFRC thin slabs

3.2 Structural retrofitting

Protective overlay, shells and panels

First developed within the framework of the European project SAMARIS, UHPFRC has been used in a thin overlay to repair reinforced or prestressed concrete bridge decks. It thus increases the rigidity of the structure, its mechanical strength and its durability, while dispensing with any waterproofing membrane and its further maintenance. Application is currently growing on Swiss infrastructures [7]. Extension of this concept has been applied on steel bridge decks (Fig. 3) and on concrete slabs of buildings. For these applications, restrained shrinkage shall be controlled by a sufficiently high fibre content and control of early age desiccation is critical.

Repair and protection of structures subject to torrential flows and abrasion have found very efficient solutions using UHPFRC. First reference cases concern Valabres pier protection, a canal bridge over the access road to the Fréjus tunnel (Fig. 4), or repair of the River Tunnel

Hosokawa in Japan [28]. UHPFRC is used in thin and smooth elements which is favourable for the hydraulic constraints, while abrasion resistance proves excellent.

a)  b) 

Figure 4: Before a) and after repair and protection b) of a canal bridge by an UHPFRC slab.

Columns and highly compressed members

Direct worthwhile application of UHPFRC capacity in compression has been found with strengthening or retrofitting works [42], which shall limit additional volumes of materials, e.g. to accommodate larger interior volume, while additional bearing capacity is required. This may have led to pure UHPFRC (fire-resisting) columns for the retrofitting of Albi Museum or rue Volney building [13], UHPFRC jacketing of columns in the parking of the building in Perpignan, or steel tube columns filled with UHPFRC (rue Volney, Reina Sofia Museum) [31, 33, 42]. Similarly the favourable ratio of design compressive stress to weight has been used first historically in the prestressed UHPFRC girders of the Cattenom power plant cooling tower [41, 44], which constituted an additional thermal exchange bearing structure and should thus be light enough. It was also applied with retrofitting of the bridge over Huisne River in Le Mans, the beams of which had to be thickened and strengthened with additional prestressing. In such applications, high Young's modulus, low creep and no necessity of passive rebars are decisive advantages [42].

3.3 Recent trends

Large shell structures

As one of the first iconic examples, the roof over Millau bridge tollgate [18] has highlighted UHPFRC ability to be used in complex shapes and constitute thin membranes. Since UHPFRC materials are generally hardening in bending, but softening in pure tension, this structure highlighted the design case of parts submitted to direct tension (tensile membranes), which require prestressing or significant reserves in the design stress as compared to the tensile strength. Moreover, the production of large UHPFRC segments has proved requiring perfect control of the rheology, rigorous follow-up of early-age thermal effects and thermal gradients due to thickness variations [36], special provisions for handling and assembling elements in order to control deflections and stresses during the erection process.

Such lessons have been useful for the shell structures covering Achères plant for water treatment (Fig. 5).

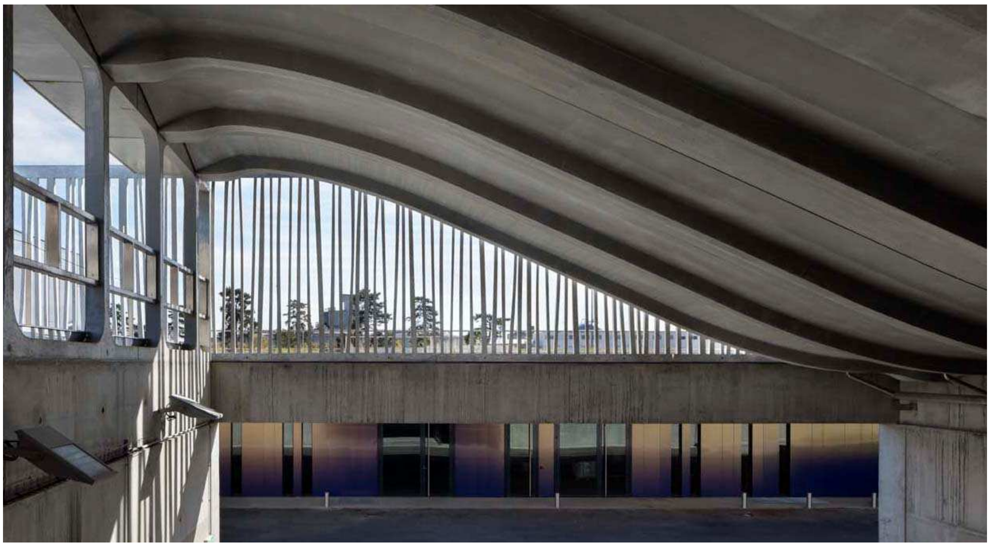
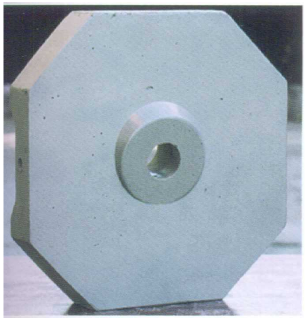


Figure 5: UHPFRC shells covering Achères plant for water treatment

Optimized infrastructure components and equipments

The largest UHPFRC project realized today (Fig. 6-a) has concerned the extension of Haneda Airport in Japan, consisting in the construction over the sea of a huge slab of Ductal® based on steel piles [39]. This slab is made of precast elements, prestressed in both directions and built in a factory on site. Compared to a conventional solution, UHPFRC has made it possible to reduce the weight of the structure (which is significant in a highly seismic zone) and ensure the durability of the structure subjected to a particularly aggressive atmosphere.

a)



b)

Figure 6: UHPFRC applications in marine environment a) extension of Haneda airport b) anchor plates for an embankment along the sea, La Réunion Island

This achievement, confirming the success of retaining wall plates at La Réunion Island (Fig. 6-b) or the recent protection of a marine signal in Brittany, shows that the maritime sector is certainly one of the most relevant to the use of UHPFRC. Indeed marine structures are generally subjected to intense dynamic loadings, chemical attacks, abrasion and mechanical shocks. Conventional solutions are very massive and pose significant maintenance problems associated with accelerated aging of traditional materials. UHPFRC should allow changing significantly the design of these structures by providing much lighter solutions, mechanically efficient and durable. These solutions should present economical and environmental interest since the initial investment stage, and strengthen their interest in time through a significant reduction in maintenance costs.

Optimized waffle deck structures could find application in harbour facilities. They have been widely studied for bridges [43] and have first been applied in Iowa for a road bridge deck. For a successful retrofitting of existing highways infrastructures, the Federal Highway Administration (FHWA) in the USA has carried out an important program on UHPFRC connections of such precast ribbed UHPFRC deck elements to steel or traditional prestressed concrete beams. Several guidance documents clearly show the interests of using UHPFRC to simplify the connections and make them more durable. Such applications represent an important development in Northern America.

Building façades, components and equipments

In France, the field of building and architectural components has been representing a leading domain of UHPFRC application for the last decade. In sunshades, cladding or roof components, UHPFRC solutions compete with steel or aluminium alloy and can produce very slender, durable, aesthetic, and durable structures.

a) b)

Figure 7: UHPFRC net panels a) Galleries of MuCEM b) Jean Bouin Stadium roofing

From its first application at the Theater “Les enfants du paradis” in Chartres, net panels have gained a growing interest [38]. UHPFRC advantages are directly related to the finesse and variety of geometrical shapes allowed by the absence of passive reinforcement. The UHPFRC net panels constitute on of the signatures of the MuCEM project (Fig. 7-a), where UHPFRC has been used for all peripheral support structures made of treelike-shaped columns, for the perforated panels of the south-east and the south-west facades and above the roof, for the peripheral gateway and its support structure [12].

The roof and façade of the Jean Bouin stadium in Paris [34] constitutes a three-dimensional shell composed of large triangular ribbed slabs (up to 9 m long) made of UHPFRC (Fig. 7-b), some of them with glass inclusions (these elements are supported by a steel support structure).

Practical execution has shown that the inclusion of glass panels in a UHPFRC slab imposes to provide flexible joints at the interface between glass and UHPFRC to ensure sealing and avoid the risk of cracking of the glass panels as a result of UHPFRC shrinkage and contact pressure at the interface.

4. FUTURE OF UHPFRC TECHNOLOGY

4.1 Potential of worthwhile application

While precasting UHPFRC elements may be particularly appropriate for constituents, geometry and process control, UHPFRC use on site is possible and can be fully relevant.

The preferred areas of application, which take cost benefit of possible repetitive application, may include:

- Structures or parts of structures subjected to aggressive environments (abrasive effects, structures in marine environment or submitted to chemical attack) [6, 44],
- Structures or structural parts for which weight gain is interesting (seismic zone, foundation problems, slender structures, structures to be built in remote zones ...),
- Structures submitted to shock effects (waste storage containers, shields...) [29],
- Structures in which high facings quality and unconventional moulded shapes are searched
- Composite structures: UHPC has a high strength over elastic modulus ratio, which is attractive for use in combination with steel or carbon fibre; limited creep and drying shrinkage makes their use in composite structures particularly relevant,
- Structures or structural parts for which the complexity and density of the traditional passive reinforcement lead to very difficult design and proper casting.

4.2 Designing and building with UHPFRC: a necessary revolution

Even though UHPFRC structures evolution is still in front of us, some significant features can be emphasized as requiring major changes in the design practice. First, volumes are modified with thicknesses that can become very small, which can disturb uninitiated designers, but which is often very relevant: the thickness reduction tends to favour fibres orientation and increases material strength. The production of very slender parts requires being vigilant, to reduce and check geometric tolerances, to control stresses and distortions in transient phases of handling and assembly. The shape of the forms must be completely revisited. In a traditional structure one prefers angles allowing the shaping of the reinforcement frames. With UHPFRC one should avoid any corner and prefer curved surfaces that facilitate casting of the fresh material and avoids discontinuities of flow.

The absence of reinforcement allows considering all structural shapes as long as the geometry is consistent and relevant with the stresses in the structure, and compatible with efficient moulding. The adequacy of UHPFRC with precasting often requires rethinking the overall design of a structure: for a large structure with a complex geometry, a study should be conducted on how to build the overall structure from an assembly of reduced size elements which present a redundant geometry, allowing an optimal resistance to external forces and an easy implementation. This requires an unconventional new way to design and build structures. The development of precasting is consistent with investigations on connections between elements to achieve most efficient forces transmission, sealing and durability of the assembly.

Formwork technology evolves, with the development of 3D formwork solutions: moulded plastic or polystyrene cut automatically to allow any three-dimensional shapes.

With increasing concrete performance, special care and controls of execution are all the more required, which comprises: validation of processes through suitability tests; monitoring and control of the rheology depending on weather conditions; strict limitations of the deviations of the material performance (consistency, strength...); and compliance with dimensional tolerances and geometric requirements.

Design methods for UHPFRC structures differ from traditional provisions of reinforced and / or prestressed concrete well controlled by consultants: namely, resistance calculations use theories developed for fibre-reinforced concrete that are still hardly known. Test methods for flexural tensile strength are not well known by laboratories and require specific numerical processing tools (inverse method). One of the main obstacles to the current development of UHPFRC is thus related to the lack of specific skills in design offices, architects, laboratories and companies.

In fact, UHPFRC requires an important intellectual precondition investment. To date, the market has been relatively small, and only a few engineering offices, firms and authorities have been involved. Since a certain taking off of these materials can be observed (particularly in Japan, but also in Europe and in France) it is likely that a larger number of consulting firms and companies will develop skilled teams to meet demand. This should strengthen the development of UHPFRC and lead to the emergence of a growing number of UHPFRC solutions alternatively to traditional ones.

5. CONCLUSIONS

Even if UHPFRC design recommendations derive from Eurocode 2 format, and even if UHPFRC development has capitalized lots of advances of general concrete science and engineering, the design and construction of UHPFRC structures require thinking out of the reflexes attached to traditional reinforced or prestressed concrete structures. Since UHPFRC cost of production and implementation is still high, an optimization effort is necessary to ensure a significant financial gain. Niches exist and worthwhile applications tend to increasingly grow as far as durability, aesthetics, timely opportunities for erection, possible series savings and material gains are concerned. In a growing number of highly constrained projects UHPFRC can bring real innovative responses. Significant achievements worldwide in the last few years testify that relevant cost-effective and technically feasible, durable and sustainable uses of UHPFRC may be found in wider fields than anticipated.

Much research on UHPFRC has been conducted in recent years, with higher or lesser fibre content, active and/or passive reinforcement, that has led to better describing the combined effects of fibre and active or passive reinforcement, and to better define the conditions for obtaining a sufficient ductility. This opens the way to further optimized structural solution.

Research should also be continued with a high priority on fresh UHPFRC flow modelling, to optimize the casting processes and the control of fibres orientation; optimization of mixes to control and / or limit the effects at the early age (autogenous shrinkage); and methods of evaluation and development of globally sustainable UHPFRC solutions.

Researches and ongoing projects will thus further strengthen UHPFRC; development and contribute to demonstrate their structural and architectural potential.

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