A TYPE OF UHPC NOT QUITE UP TO STANDARDS

Bendt K. Aarup (1)

(1) Hi-Con A/S, Hjallerup, Denmark

Abstract

CRC (Compact Reinforced Composite) is the designation of a special type of UHPFRC (Ultra High Performance Fibre Reinforced Concrete) developed in Denmark in 1986. CRC has been used in structural applications since 1995. Hi-Con A/S has used CRC exclusively since 2001 - typically for smaller precast structural elements such as balcony slabs, staircases, beams and columns and mostly on the Danish market. Over the last 5-6 years new products have been introduced - and to new markets, with applications in Holland, England, Sweden, Norway and Finland. The applications of CRC have been relatively successful with more than 70,000 tons of structural elements produced over the years but while the Eurocode does not cover CRC, applications of CRC also fall short of the requirements in the new standards being developed for UHPFRC. Examples show how it is possible to achieve good design without meeting these standards – and some of the challenges are described.

Résumé

Le CRC (Compact Reinforced Composite) désigne un type de BFUP (Béton Fibré à Ultra hautes Performances) développé au Danemark en 1986. Le CRC a été utilisé pour des applications structurelles depuis 1995. Depuis 2001, la société Hi-Con A/S utilise exclusivement le CRC, généralement pour des éléments structurels préfabriqués de taille réduite tels que des dalles de balcon, des escaliers, des poutres et des colonnes, principalement sur le marché danois. Au cours des 5 à 6 dernières années, de nouveaux produits ont été créés pour de nouveaux marchés, avec des applications en Hollande, en Angleterre, en Suède, en Norvège et en Finlande. Les réalisations en CRC ont été relativement réussies avec plus de 70 000 tonnes d'éléments structurels produits au cours de ces années bien que l'Eurocode ne couvre pas le CRC et que ses applications ne répondent pas aux exigences des nouvelles normes développées pour les BFUP. Des exemples montrent comment il est possible de réaliser une bonne conception sans pour autant respecter ces normes et certains de ces défis sont décrits.

1. INTRODUCTION

(UHPFRC) Ultra High Performance Fibre Reinforced Concrete - concrete with a high degree of ductility combined with compressive strengths of 130 MPa or higher - was first introduced as CRC (Compact Reinforced Composite) was developed in 1986 – more than 30 years ago [1]. Since then a number of other types of UHPFRC have been developed such as Ductal® (Lafarge), SMART-UP® (Vicat) and BSI® (Eiffage), but only in the last 10-15 years interest in these materials has really intensified as evidenced by large research projects around the world and many workshops and conferences on this particular topic. While the first tentative applications of UHPFRC were carried out in the late 90s, it is within the past 5-6 years that this type of concrete has really found increasing application, not only in Europe and USA but also in the Middle East, China, Australia and Japan. Architects and engineers have started to design projects specifically with UHPFRC in mind [2] and standards for UHPFRC have become available [3-5]. The Swiss standard [5] is relatively short and not very restrictive, but as the French standards are much more comprehensive – and seem to be in line with what is being considered for the preparation of equivalent German standards – they are considered indicative (at least in the present paper) of what could become a more general standard for UHPFRC in Europe.

The French standards on UHPFRC – as long as they deal with structural applications – cover fibre reinforced concrete with a minimum characteristic compressive strength of 150 MPa. UHPFRC with a characteristic compressive strength of 130 MPa is covered by [3], but is generally considered as non-structural, and the design guide [4] does not consider UHPFRC with a characteristic compressive strength below 150 MPa. The standards are primarily aimed at structures where no reinforcing steel is necessary, but recognizes that to produce certain structures UHPFRC may contain prestressing steel (prestressed UHPFRC) or reinforcing steel (reinforced UHPFRC). CRC falls into the latter category, as fibre reinforcement is always combined with passive reinforcing bars. However, as CRC is typically designed with a characteristic compressive strength of either 110 or 120 MPa it is covered neither by the Eurocode nor by the new standards. This is not so different from how things have been since the first applications of CRC in 1995, but it is important to note that it is possible to produce very good concrete in this “grey area” between standards. Hi-Con – a small precast producer in Denmark – started production of CRC in 2001 and has had extensive experience operating without being covered by standards as they only produce elements in CRC – no conventional concrete is used.

2. TYPICAL APPLICATIONS OF CRC

CRC was originally developed with an emphasis on combining the strength and ductility of structural steel with the durability, fire resistance and formability of concrete. However, the first applications did not specifically address these properties, but instead exploited the aesthetical potentials gained from the possibility of creating slender and minimalistic concrete elements – primarily balconies and staircases.

The first staircases and balconies were produced in 1997 and since then more than 70,000 tons of different structural elements made in CRC have been produced for projects in Denmark, Sweden, Norway, England, Holland and Belgium (fig. 1). Especially some of the staircases present challenges to the design, where it is necessary to fully utilize the material (fig. 2). For most of these applications durability (low cover to the rebar), ductility (crack control) and stiffness (small deformations) rather than compressive strength are the most important factors in the design. Increasing characteristic strength would not have much influence on the design, which is governed more by fire resistance, long term deformations and vibrations. Increasing compressive strength would require using different aggregates, grading or curing which would increase the price of the concrete and make it more difficult to compete with steel or conventional concrete. However, if necessary for a specific project, a higher compressive strength can be used by having a stricter quality control as the properties of CRC are not much different from other similar types of UHPFRC as shown in comparative testing [6].

Figure 1: Examples of balconies and staircases for projects in Denmark.

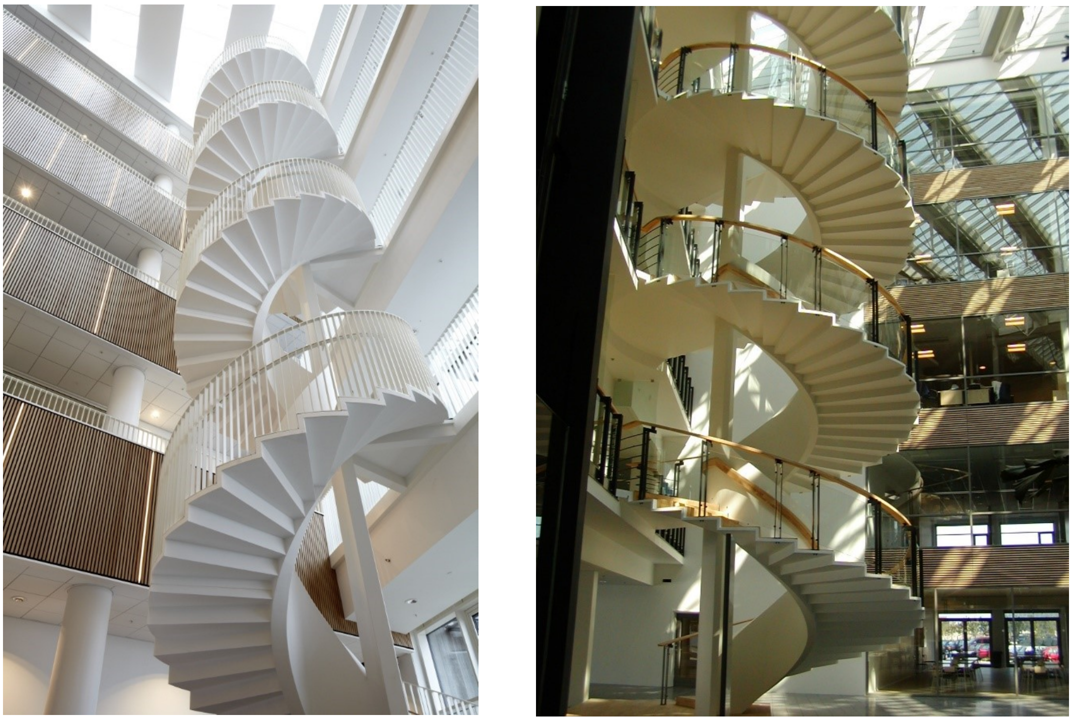

Figure 2: Examples of helical staircases.

Figure 3: Installation of CRC façade elements for Odense University, Denmark.

While the bulk of the applications of CRC have been for balconies and staircases, other products include small bridges or façade elements (fig. 3). While these types of applications are relatively new for CRC, façade elements and bridges have been one of the first areas to demonstrate the possibilities of UHPFRC and architects have designed projects specifically based on the properties of UHPFRC, such as for the Peace Bridge in Seoul, MuCem in Marseille, Stade Jean Bouin in Paris, Louvre Abu Dhabi and the US Embassy in Maputo, Mozambique.

3. DESIGN IN CRC

As CRC always includes conventional reinforcement the design is basically performed according to the Eurocode (or similar standards), but in specific areas (such as compressive strength, brittleness, cover to the reinforcement) the CRC design deviates from the standards, and in those cases it is necessary to ensure that thorough and valid documentation is made available to support these deviations.

Over the years, a sufficient number of references have been accumulated so that it is typically not necessary to go through all this documentation with the building authorities for a specific project, but special requirements will often be made for the first projects in new countries. This was e.g. the case for the first project in Holland, where a special assessment of the calculating principles was made together with a full scale test.

This full-scale test was carried out to validate the calculations with regard to deformations (fig. 4). The first projects in Finland were also accompanied by full-scale loading tests as well as a full-scale fire test. For subsequent projects or for projects in other countries (fig. 5) it has not been necessary to repeat these tests. As mentioned earlier compressive strength is not really the most important property of the concrete because of the very slender elements. The design is determined by fire resistance, long-term deformations or vibration limits, which means that the carrying capacity of the elements is often at least 3 to 4 times higher than the design load.

Figure 4: Test loading of a balcony section with 8 × design load (Poptahof, NL).

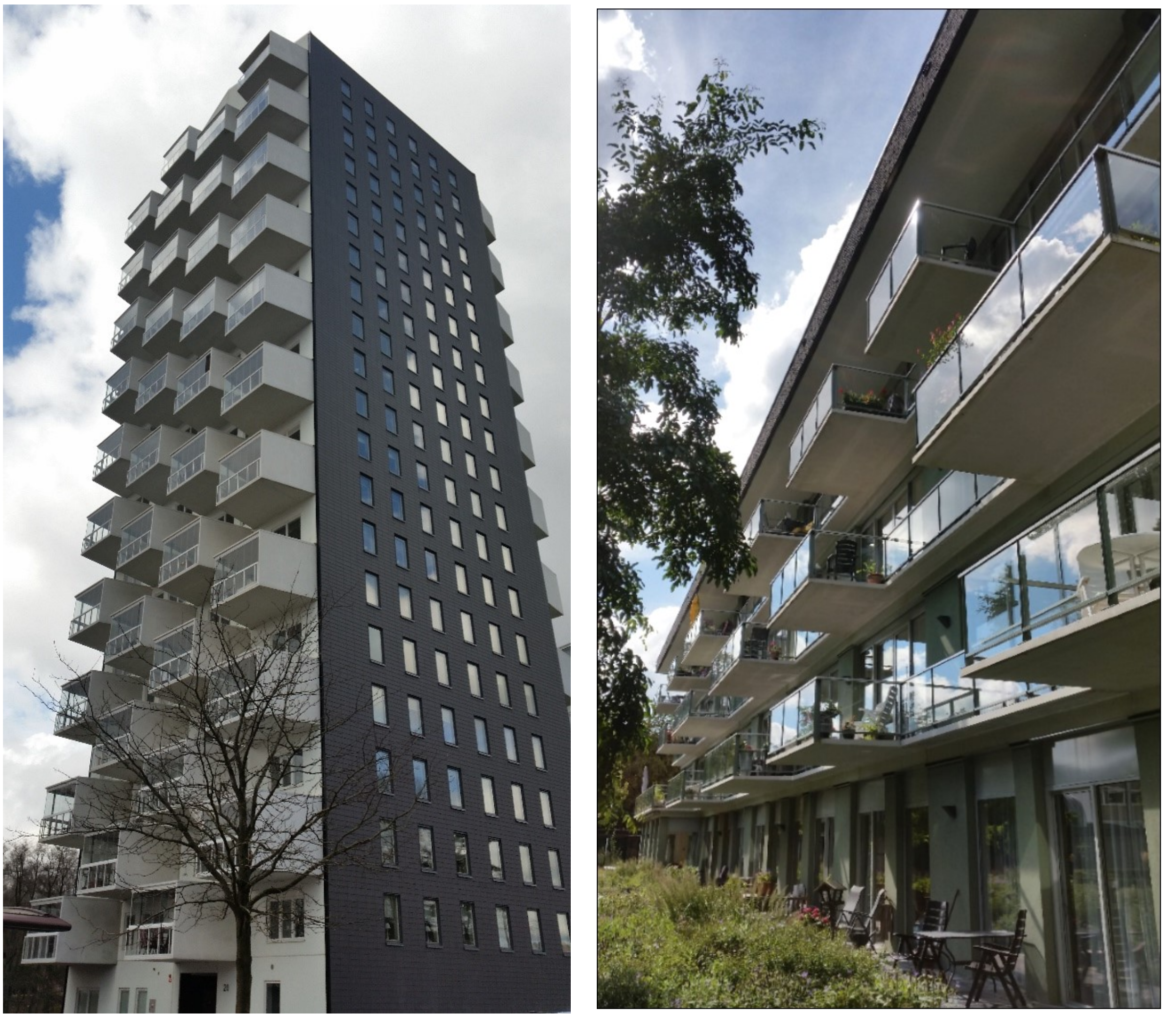

Figure 5: Balcony projects in Sweden and Holland

4. AREAS OF SPECIAL IMPORTANCE WHEN DESIGNING WITH UHPC

The new standards for UHPFRC attempt to cover all areas that could present problems, but presently they are only in effect for France and Switzerland. Even if the standards are used as guidelines outside of these countries, some concretes – such as CRC – fall between the Eurocode and these guidelines. As CRC is always used with conventional reinforcement, some aspects such as fibre distribution and fibre orientation are not as critical as for UHPFRC, but there are still a number of properties that need to be assessed carefully. UHPFRC is typically characterized by very high strength and stiffness, but unless the concrete is specifically designed for ductility and high performance in other areas such as durability, the finished structure may perform less than optimal. It is therefore necessary for any manufacturer to be aware of the pitfalls of UHPFRC design, production and application – even if the material is not covered by standards. Examples of areas where special documentation is needed are shown below.

4.1 Compressive strength

The Eurocode [7] covers concretes with compressive strength (based on 150 x 300 mm cylinders) up to 90 MPa, but includes a penalty factor to account for brittleness at higher strength. If for instance a concrete with 90 MPa characteristic compressive strength is considered, the strength is reduced by 20 % in the design because of this factor. Special documentation demonstrating ductility also in compression is required if it is elected to deviate from this reduction factor η.

4.2 Durability

UHPFRC is often used in slender structural designs, where the high compressive strength is utilized to reduce the cross section dimensions. To achieve the most effective design, and hence best utilization of the concrete, it is often required to reduce the cover layer thickness compared to the values stated in [7]. To avoid reinforcement corrosion it is necessary to have a very dense concrete, with the associated documentation demonstrating that both carbonation and chloride penetration in the loaded state is suitably slow. With slender structures with a comparatively high live load where the structure is exposed to significant bending tension, it is also necessary to document effective crack control and to document how micro cracks affect carbonation and chloride penetration, something that is not typically achieved with standard testing [8].

4.3 Fire

In several aspects, UHPFRC may exhibit inferior performance in fire-exposed condition compared to ordinary concrete. One of these aspects is explosive spalling, as it was observed on projects like the Great Belt Link and the English Channel Tunnel with dense concretes. When dense concrete is heated, steam is generated that cannot easily escape, and consequently very high internal pressure may build up, that can lead to explosive spalling. If the tensile strength of the material is high, the pressures that can be reached before steam is released may be high enough to generate powerful explosions. Consequently, it is very important to have sufficient knowledge about parameters such as critical moisture content, permeability and tensile strength for a particular concrete under fire exposure conditions [9, 10].

Some types of UHPFRC exhibit such low porosity, that even at very low moisture contents, it is not possible to document sufficient resistance to explosive spalling. In those cases – if the structures are to be used where there is risk of fire – an option is to include polypropylene fibres or to produce a special version of UHPFRC reducing mechanical properties.

Very dense concretes with low water/powder ratios and containing steel fibers typically conduct heat more easily than ordinary concrete and have a lower heat capacity. On the other hand, they often exhibit better tensile and compressive strengths at elevated temperatures. This underlines the necessity to properly document the material properties through fire testing before using the material in the structural fire design.

5. CATHARINABRIDGE IN LEIDEN

Most of the elements produced in CRC are relatively small – typically weighing less than 10 tons each – and are used in housing, but over the last few years CRC has also been used for bridges. This has mainly been in Holland where design is handled by a Dutch engineering firm – Pieters Bouwtechniek (PBT) – together with Hi-Con Netherlands. A recent project – from the spring of 2016 - was a very slender bridge designed for light traffic in Leiden (figs. 6 and 7).

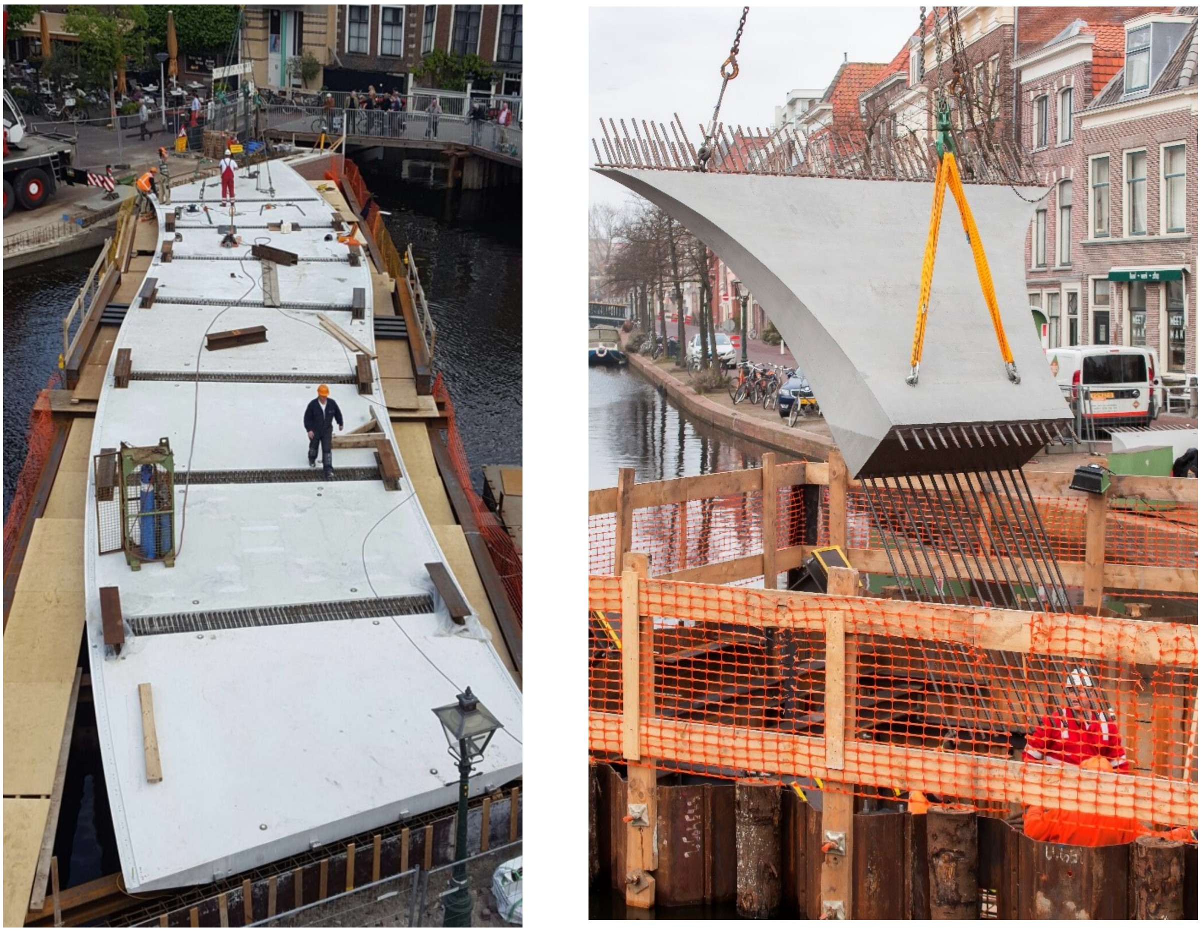

Figure 6: Deck elements and pile element being placed [Gerda van Ekris].

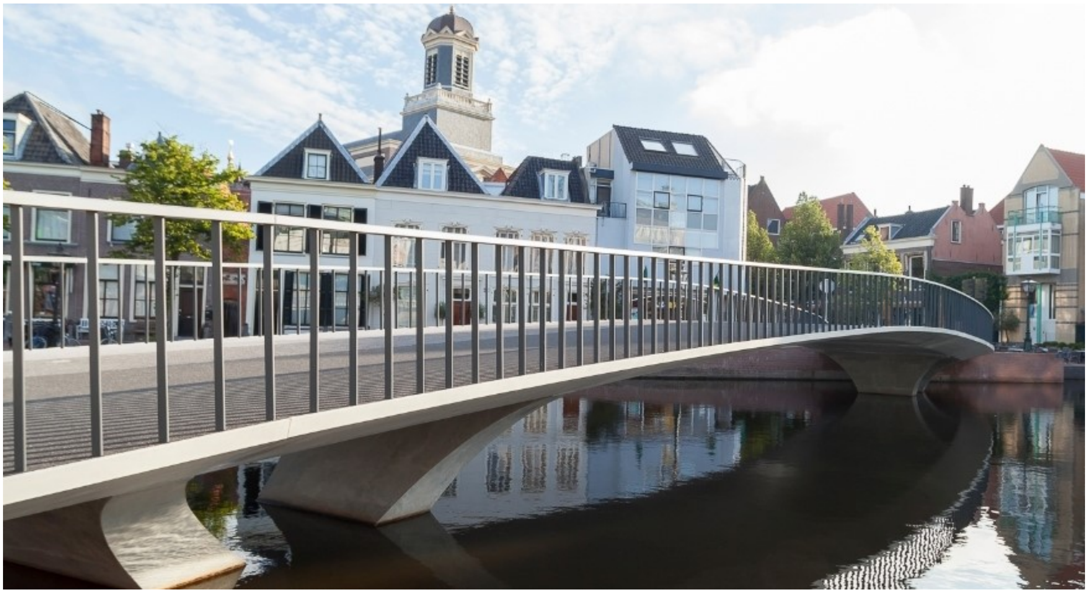

Figure 7: Catharinabridge in Leiden with slenderness of 1:81 [Gerda van Ekris].

The bridge was designed by PBT together with architects DP6 architectuurstudio [11]. The slenderness ratio of the bridge is 1:81, only passive reinforcement is used and EPS (Expanded Polystyrene) blocks were placed in the deck-elements to reduce weight. A total of 8 deck-elements were used for the bridge – produced at Bruils factory in Weert. The deck elements – and the foundation piles - were joined using a UHPFRC dry-mix called CRC JointCast, a system similar to what has been used for more than 100 bridges in the US and Canada [12]. The width of the bridge is 6 meters, the total length 36 meters and the span in the middle is 22 meters.

The bridge was designed based on a characteristic strength of 120 MPa – with a mix including granite aggregate to a maximum size of 8 mm, but the most important parameters (besides durability and ductility to ensure crack control) was a Young's modulus of 45 GPa and a cracking strength of 6.5 MPa. This ensured that the deformations of the bridge were within specifications and when vibration measurements were performed on the bridge the Eigen frequency was measured to 5.4 Hz.

6. CONCLUSION

In the case of the Catharinabridge, increasing the characteristic strength from 120 to 180 MPa (as an example) would have changed the bridge design very little and the same is true for a number of other projects using reinforced UHPFRC. Using conventional quartz sand in available gradings and with no special curing helps to achieve a cost-competitive concrete mix, but makes it difficult to achieve a characteristic strength of at least 150 MPa. This means that a concrete of this type will not be covered by the future standards. That is fine, as it will be difficult to produce standards that cover every type of concrete, but it is important to note that a concrete that "is not quite up to standards" can be the best choice for a particular project – and that there are still some design issues that should be considered carefully.

REFERENCES

[1] Bache, H.H., "Compact Reinforced Composite, Basic Principles". CBL Report No. 41, Aalborg Portland, 1987, Aalborg, Denmark

[2] Resplendino, J. & Toutlemonde, F., "The UHPFRC revolution in structural design and construction, Designing and Building with UHPFRC", Proceedings of the RILEM-fib-AFGC International Symposium on UHPFRC, Marseille, France, 2013, pp. 791-804.

[3] NF P18-470 Concrete – Ultra-high performance fibre-reinforced concrete – Specifications, performance, production and conformity, AFNOR, Paris, 2016.

[4] NF P18-710, Design of concrete structures: specific rules for Ultra-High Performance Fibre-Reinforced (UHPFRC), AFNOR, Paris, 2016.

[5] SIA 2052:2016 Béron fibré ultra-performant (BFUP) – Matériaux, dimensionnement et exécution, SIA, Zürich, 2016.

[6] Varga, Igor De la *et al.* "Material Property Evaluation of Different Commercially-Available UHPC-Class Materials", First Int Interactive Symposium on UHPC, July 2016, Des Moines, USA.

[7] European Union, EN 1992-1-1 (2004), Design of concrete structures - Part 1-1: General rules and rules for buildings.

[8] Andrade, M.C., Frias, M. & Aarup, B., "Durability of Ultra-High Strength Concrete: Compact Reinforced Composite". BHP96 Fourth International Symposium on Utilization of High-Strength/High-Performance Concrete, 1996, Paris, France.

[9] Khoury, G et al, "Scientific summary of the HITECO research BRITE programme", ACI Int. Conference on "State-of-the-art in high performance concrete", 1999, Chicago, USA.

[10] Rom, L. & Ellegaard, P. & Aarup, B, "Slender CRC Columns", Nordic Concrete Research no. 34, 2nd issue, 2005.

[11] Nalta, Rogier v. & Graaff, Mirte d., "The Catharinabridge in Leiden", High Tech Concrete: Where Technology and Engineering Meet, fib Symposium 2017, June 12-14, Maastricht.

[12] Graybeal, Benjamin A., "Ultra-High Performance Concrete Connections: Design and Performance of robust, constructible Solutions", Proceedings of Hipermat 2016 – 4th International Symposium on Ultra-High Performance Concrete and High Performance Construction Materials, Kassel, 2016.