RILEM-*fib*-AFGC Int. Symposium on Ultra-High Performance Fibre-Reinforced Concrete,
UHPFRC 2013 – October 1-3, 2013, Marseille, France

REJUVENATION OF MARITIME SIGNALISATION STRUCTURES WITH UHPFRC

Emmanuel Denarié (1), Damien Jacomo (2), Nicolas Fady (3), Dominique Corvez (4)

(1) Division of Maintenance and Safety of Structures (MCS-ENAC), Ecole Polytechnique Fédérale de Lausanne (EPFL), GC B2-402, Station 18, CH-1015 Lausanne, Switzerland

(2) Lafarge Ciments, 5, bld Louis Loucheur, B.P. 302, F-92214 Saint-Cloud Cédex

(3) CETMEF - DT/TSMF/PIE, Technopôle Brest Iroise B.P. 5, 155, Rue Pierre Bouguer, F-29280 – Plouzané

(4) Lafarge SA, Direction Technique BFUP/Ductal®, 61, rue des Belles Feuilles, F-75116 Paris Cedex 16

Abstract

The extremely low permeability of UHPFRC, associated to their outstanding mechanical properties makes them especially suitable to rejuvenate maritime signalization turrets or lighthouses at sea. Those structures have a very severe environment and very limited access due to tide and weather conditions. They require extremely efficient intervention methods. Similarly to what is done on existing bridge decks or building slabs, UHPFRC provide in this case a unique and robust solution with a vision to simplify and shorten the rehabilitation process with long term durability. In this context, an existing turret, off the south Brittany coast nearby Lorient (France), was reinforced with a 60 mm UHPFRC layer. The UHPFRC was cast in place by a helicopter in a formwork around the existing masonry structure.

The UHPFRC mix was specifically tailored to this application with a tensile strain hardening response, limited shrinkage, and an optimized rheology (self-leveling) for a fast filling of the formwork to minimize the use of helicopter time.

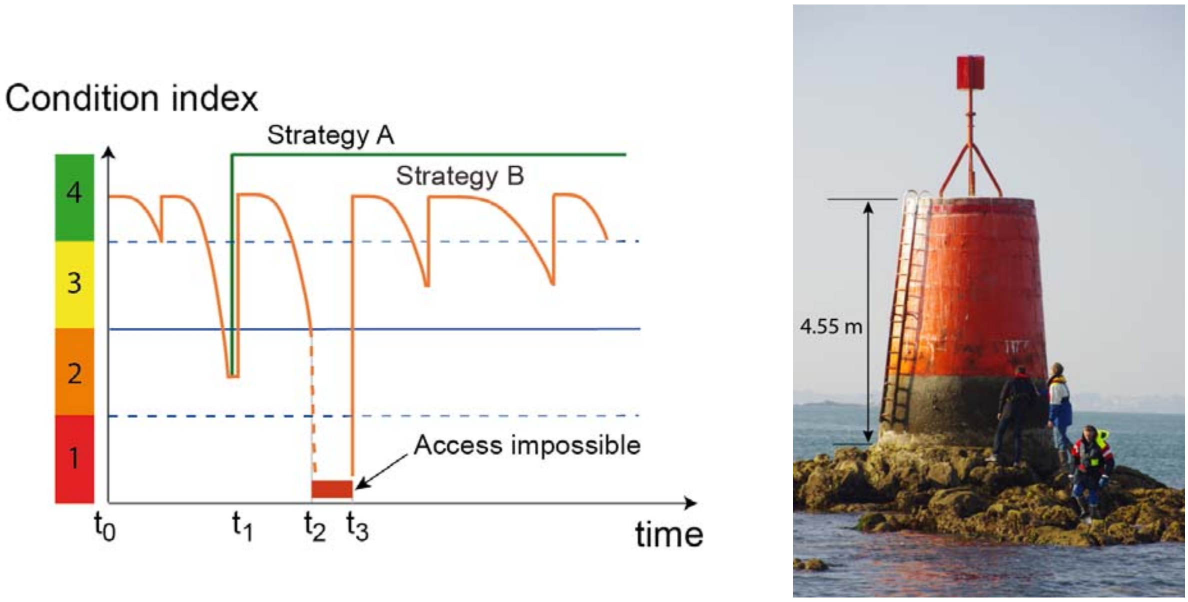
Résumé

La très faible perméabilité des BFUP, associée à leurs propriétés mécaniques exceptionnelles sont particulièrement adaptées pour le rajeunissement de tourelles de signalisation maritimes ou de phares en mer. Ces structures exposées à un environnement très agressif ont un accès très limité sous l'influence des marées et de la météorologie. Elles requièrent des méthodes d'intervention très efficaces. Comme pour les ponts existants ou les dalles de bâtiments, les BFUP procurent dans ce cas une solution unique et robuste permettant de simplifier et réduire la durée des réhabilitations, avec une perspective de durabilité à long terme. Dans ce contexte, une tourelle existante en mer, sur la côte sud bretonne près de Lorient (France) a été renforcée par l'application de 60 mm de BFUP, coulés en place par hélicoptère dans un coffrage autour de la structure existante en maçonnerie. La formulation du BFUP a été optimisée avec: un comportement écrouissant, un retrait limité, et une rhéologie adaptée pour un remplissage rapide limitant le temps de présence de l'hélicoptère.

1. INTRODUCTION

Over le last 10 years, under the impulse of MCS/EPFL, the applications of thin layers of Strain Hardening Ultra High Performance Fibre Reinforced Concretes (SH-UHPFRC), with or without rebars, for cast on site rehabilitation works or reinforcement of structures has demonstrated its advantages in terms of durability, cost efficiency and site duration [1-4]. The main motivation of this strategy for road structures or buildings is to limit the costs and annoyances induced by construction sites on users. Interventions have to be as fast and as long lasting as possible. The same approach can be followed for maritime structures, subjected to environmental classes XS 1, 2, 3 (exposure to sea water) for new [5] or existing structures. In the latter case, the time available for the interventions is also very limited (typically only a few days per year), not because of the users of the structure, but because of the very limiting tide and weather conditions, as illustrated on Figure 1a). The vertical axis represents the condition index according to the VSC system used in the conservation of maritime structures, [6]. Classes 1 and 2 mean preventative maintenance. Class 3 means severe disorders but no immediate risk of collapse. Class 4 indicates a high risk of sudden collapse and needs immediate intervention. At time t_1, reinforcement is required. At this stage (condition 2), it can be realized within the next 2 years. At time t_2, a major reinforcement is immediately necessary but cannot be performed until time t_3. This latency time with a high risk of collapse is avoided with Strategy A, contrarily to Strategy B based on a less durable method. In this perspective, the strategy used for the rehabilitation of road structures with SH-UHPFRC appears to be also optimal for maritime structures at sea.

The global vision of this approach is the conservation of lighthouses at sea. In a first step, signalisation turrets are used as a prototype. The Turret "Le Cabon", in the harbour of Lorient (France), Figure 1b) needed strengthening. This paper describes the methodology and the rehabilitation works performed in 2013 to strengthen it with a 60 mm UHPFRC shell cast in-place in a formwork by helicopter (first time on-site application of UHPFRC at sea).



a) b)

Figure 1: a) Strategy of conservation for maritime structures, b) Turret "Le Cabon"

2. TURRET "LE CABON"

The Turret "Le Cabon" is located in the **Lorient** harbour bay, Brittany, France (3° 21' 40" W – 47° 42' 08.2" N) at the entrance of the so called "little sea of Gâvres", between Gâvres and Port Louis, Figure 2.

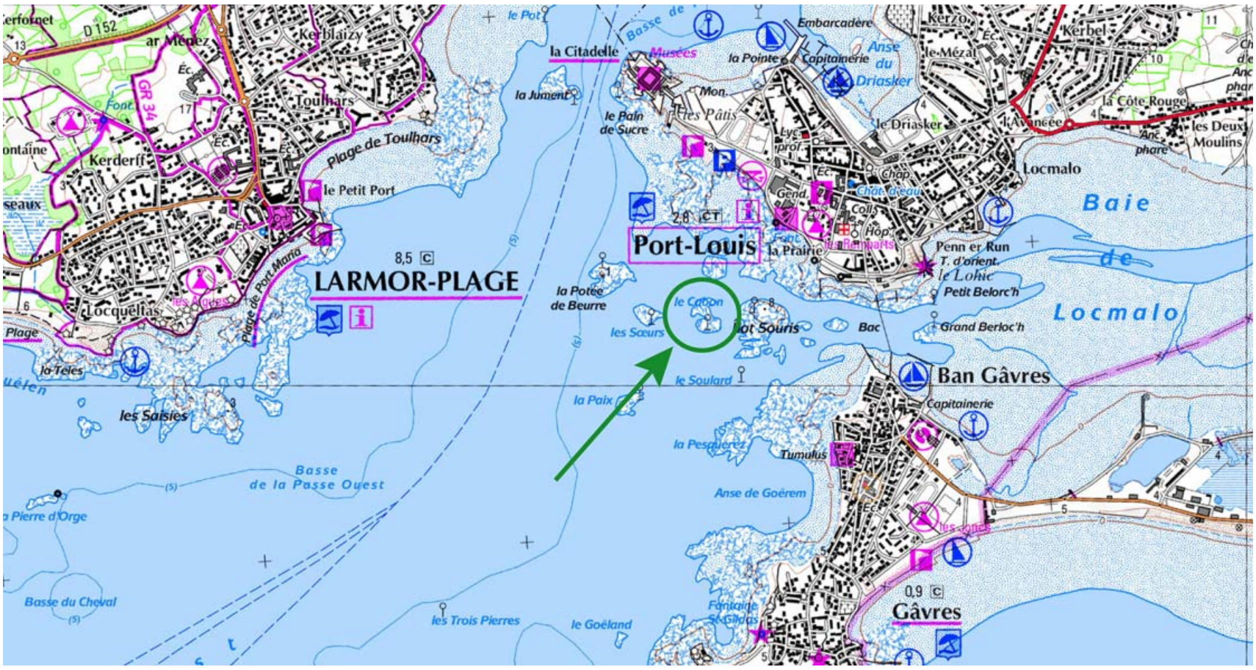


Figure 2: geographical location of the Turret Le Cabon, Lorient, Brittany, France, adapted from "Geoportail" maps [7]

It is a very common type of turret made out of a coarse concrete masonry (base diameter = 3.25 m, height = 4.55 m). Its age is around 70 years. The access time of the turret for rehabilitation works is very limited due to tide and weather conditions. The day of casting (June 26, 2013), the total sea level height difference between low and high tide was 4.7 m, comparable to the height of the Turret. At low tide the rock subgrade platform is accessible and can be used to circulate around the turret. At high tide it is totally submerged and half of the turret too, all this within 6 hours.

3. MATERIALS AND METHODS

3.1 UHPFRC

The general requirements for concretes at sea are described in details in [8]. With their very dense and impervious microstructure, UHPFRC fulfill these without difficulties.

The additional requirements to the UHPFRC for this site were the following:

- Minimization of autogenous shrinkage, to limit eigenstresses and leave most of the tensile hardening potential of the material to resist residual swelling reactions (after 70 years age of the Turret) that were suspected such as AAR, Sulfate attack.
- Self-compacting (class SF2 according to EN 206-9), i.e. slump flow between 660 and 750 mm and workability to be maintained over 2 to 3 hours (transport from plant to helicopter landing site: up to 1 hour).
- Strain hardening response under tension, target value of the deformation at peak stress ε_U: on average between 1 and 2‰ for specimens cut out of square plates (700/700/60 mm) cast horizontally. Tensile strength $\mathbf{f_{ut}} \geq 10$ MPa on average.

The material NaG3 SR FM 3.25 % was developed by LAFARGE for this site. It has 3.25 % vol. straight smooth steel fibres (length 13 mm, diameter 0.185 mm) and a water/cement ratio between 0.21 and 0.23. It has no accelerator and uses a superplasticizer optimized to offer a workability range of 2 to 3 hours. A shrinkage reducing admixture is also used to mitigate to a very large extend the autogenous shrinkage and minimize eigenstresses.

3.2 Fabrication and processing of the UHPFRC

The steel formwork was designed to support the high pressure of the very liquid UHPFRC over a height of 4.6 m (fully hydrostatic pressure with ρ_{UHPFRC}=26 kN/m^3) and remain watertight to avoid fresh UHPFRC leakages. It was firmly attached by dowels to a concrete footing anchored at the base of the turret.

The casting took place on June 26, 2103. The formwork was installed on the turret the day before. The UHPFRC was produced at the Keryado Lafarge concrete production plant in a concrete mixer of 2 m^3 capacity. Batches of 1.25 m^3 UHPFRC were selected to optimize processing. The UHPFRC matrix (premix + water + admixtures) was mixed for 10 to 13 minutes before fibre addition. Total mixing time was 13 to 17 minutes for each batch. Two batches were realized consecutively and fed into a concrete truck.

After a first control of the workability at the concrete plant, the fresh UHPFRC was transported by truck to Gâvres (37 km, 1 h on average). From there it took 4 to 5 minutes for the helicopter to load it into a skip, deliver 300 litres UHPFRC (750 kg) to the Turret, and come back. Total 4.2 m^3 UHPFRC were used with 2 truck rotations and 18 helicopter runs. Total time for UHPFRC delivery to the Turret was around 2 hours. Seven days curing were guaranteed before the formwork was removed. No compaction was applied on the UHPFRC. The free surface of the fresh UHPFRC on the top capping of the turret was covered with a plastic foil held in place by gravel for 7 days.

3.3 Workability

The UHPFRC workability was determined first at the plant, before the departure of the concrete truck, then on the helicopter landing site at the time of truck arrival.

It was also determined before loading the skip attached to the helicopter, for several helicopter runs. Table 1 summarizes the results obtained [9]. The measured values of slump flow were initially lower than the requirements (SF2), most probably because of the relatively high fresh UHPFRC temperature (30°C). However, after 5 minutes fast stirring by the concrete truck at the helicopter landing site, a satisfactory workability could be reached. The material was homogenous with no fibre segregation and the workability was maintained over more than two hours, which is perfect for this type of application.

Table 1: workability test results

At concrete plant (before truck departure)

Truck N°	Batch n°	Air temp. [°C]	UHPFRC temperature [°C]	Slump flow [mm]	T500 [s]	Time
1	1	19	26.5	575	5	10 h 40
	1+2	18.5	30	610	4.5	11 h 15

At truck arrival on helicopter landing site or later

Truck N° / (Batches)	Helicopter Run (over 9)	Air temp. [°C]	UHPFRC temperature [°C]	Slump flow [mm]	T500 [s]	Time
1/(1+2)	1	20	30	590	n.a.	12 h 15
	7	n.a.	n.a.	660	6	12 h 45

At truck arrival on helicopter landing site or later

Truck N° / (Batches)	Helicopter Run (over 9)	Air temp. [°C]	UHPFRC temperature [°C]	Slump flow [mm]	T500 [s]	Time
2 /(3+4)	1	22	32	670	4	13 h 27

3.4 Mechanical properties of the UHPFRC

The compressive strength f_{Uc} of the UHPFRC was determined at 28 days on: (1) 6 cylinders diameter 70 mm, height 140 mm, and (2) 3 cylinders diameter 113 mm, height 226 mm, all cast on the site and cured at 20 ± 2 °C. The results are shown in Table 2.

Table 2: compressive strength test results

Cylinders [mm/mm]	f_{Uc} [MPa]	
	Average	Standard deviation
70/140	135.0	6.8
113/226	136.8	4.2

As no special requirements were set to the compressive strength for this application, those values are satisfactory, in the lower range of typical values for this type of specimens.

The tensile response of the UHPFRC was evaluated indirectly by means of the inverse analysis with a Non Linear Finite Element code (MLS) of 4PT bending tests results. Two test series were used for comparison:

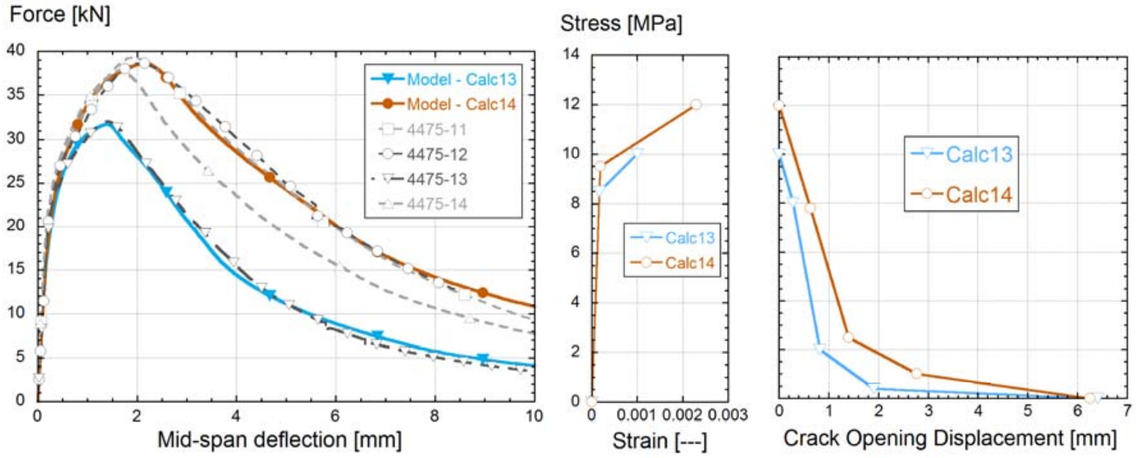
- Series A: 4 prisms 600/150/62 mm (span: 420 mm) cut out of large plates (700/700/62 mm) cast during preliminary material tests in Septembre 2012, and kept at 20°C, 95 % RH before testing at 28 days.

- Series B: 2 prisms 70/70/280 mm (span: 210 mm), cast in steel forms on the site and kept at 20°C, 95 % RH before testing at 28 days.

Figure 3a) shows the results of test series A (specimens 4475-12 and 13) with the model (best fit for highest/calc 14 and lowest/calc 13 observed flexural responses on a series of 4 specimens). Figure 3b) and c) show the tensile laws obtained by the inverse analysis of bending test results 4475-12 and 4475-13. The FEM software used was MLS [10].

The bases of the model (Smeared Crack Model with bulk energy dissipation) and verifications of mesh size objectivity are described in details in [11-12]. The elastic modulus of 50 GPa was determined from the analysis of the 4 PT being tests results. The tensile laws are shown in stress vs strain Figure 3b), resp. crack opening axes Figure 3c).

<u>Bending tests - Series A</u>



a) b) c)

Figure 3: a) 4 PT bending tests results series A and fitted models, b) and c) fitted tensile laws

Bending tests - Series B

Figure 4 shows the results of test series B (specimens 4660-6 and 9) with the predictions of the models calibrated from test series A. The correspondence is excellent. This means that the materials used on the site have a similar tensile response as those used for the preliminary tests. One can further notice that, as expected from orientation effects of fibres, the response observed on the 70/70/280 prisms cast in forms is close to the highest bending response observed from the 600/150/60 prisms cut out of larger plates (model Calc 14). Table 3 gives the Modulus of rupture (MOR) for the two test series. From test series A and B and from the inverse analyses, one can assume that the tensile hardening response of the UHPFRC cast on the Turret will be on average between the two boundaries defined by models Calc 13 and 14, summarized in Table 4. This fully satisfies the requirements.

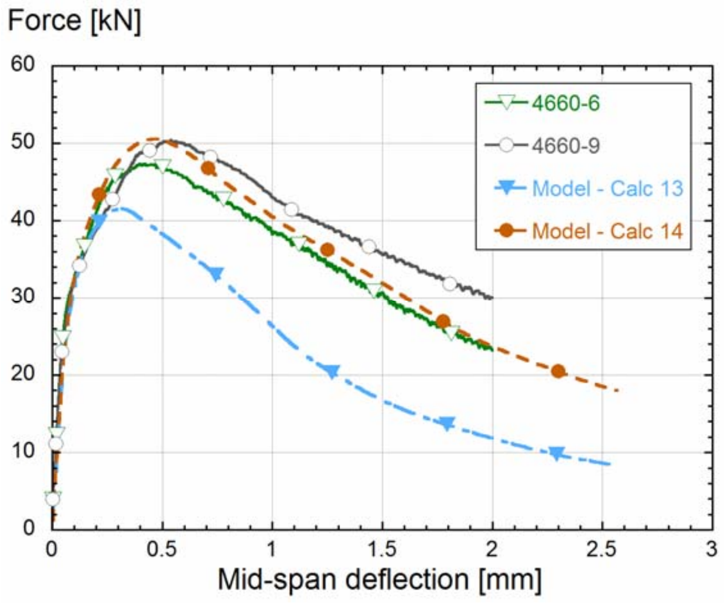


Figure 4: 4 PT bending tests series B and models

Table 3: MOR from bending tests

Test series	MOR [MPa]	
	Average	Standard deviation
A	26.4	2.3
B	29.0	1.6

Table 4: Tensile properties of the models determined by inverse analysis

Model	End elastic range f_{ute} [MPa]	Tensile strength f_{ut} [MPa]	End hardening ε_U [‰]	End softening w_2 [mm]
Calc 13	8.5	10	1.0	6.5
Calc 14	9.5	12	2.3	6.5

4. APPLICATION ON THE TURRET

Figure 5 illustrates the conditions on the site during application of the UHPFRC with the helicopter. The sea was not particularly rough at the date of casting (swell less than 1 m).

a)

b)

c)

Figure 5: a) installation of the formwork, b) delivery of the skip with UHPFRC, c) pouring of the UHPFRC into the formwork

5. CONCLUSIONS AND OUTLOOK

- SH-UHPFRC cast in place was applied for the first time for the reinforcement of a maritime structure.
- The UHPFRC recipe was specially tailored for this cast-in place application with a high degree of restraint, with a targeted tensile strain hardening response, limited autogenous shrinkage, and a self-compacting, fluid character with a workability range of up to 3 hours that were achieved as planned.
- Very fluid UHPFRC impose very high requirements to the tightness, resistance and deformability of formworks (hydrostatic pressure).
- The inverse analysis of bending test results on UHPFRC specimens cast during the site confirmed their strain hardening response according to the requirements (between 1 and 2 ‰ on average – without favorable fibre orientation).
- The application of the UHPFRC on the Turret by a helicopter was fast and efficient.
- This successful application opens the way to the cast in place reinforcement of heritage lighthouses at sea, in most difficult conditions of access.

ACKNOWLEDGEMENTS

The authors wish to thank: (1) the "Subdivision des Phares et Balises" from Lorient, Mr Ronan Goavec and his team (Christophe Le Mouel, Pascal Conan, Michel Le Roux) for having accepted to test UHPFRC on one of their structures at sea and for their major contribution to the success of this application, (2) Mrs Binse from the Keryado Lafarge concrete production plant in Lorient for making her facilities available for UHPFRC production, (3) Michel Menguy (CETE OUEST/DLRB, St Brieuc) for his advices on production and quality control of cementitious materials, and (4) Nicolas Bourneton (CETE OUEST/DIMER, Nantes) for the design of the formwork. Finally, the support from LAFARGE for the UHPFRC (development, raw components for the site, and technical support) is gratefully acknowledged.

REFERENCES

[1] Brühwiler E., Denarié E., 'Rehabilitation of concrete structures using Ultra-High Performance Fibre Reinforced Concrete', *UHPC-2008: The Second International Symposium on Ultra High Performance Concrete, Kassel*, Germany, March 05 – 07, 2008, 895-902.

[2] Denarié E., Brühwiler E., 'Strain Hardening Ultra-high Performance Fibre Reinforced Concrete: Deformability versus Strength Optimization', *International Journal for Restauration of Buildings and Monuments*, Aedificatio, Vol. 17, n° 6, 2011, 397-410.

[3] Šajna A, Denarié E, Bras V., 'Assessment of a UHPFRC bridge rehabilitation in Slovenia, two years after application', 3rd International Symposium on Ultra-High Performance Concrete - *HiPerMat, Kassel*, Germany, 2012, 937-944.

[4] Habert, G., Denarié, E., Šajna, A., Rossi, P., 'Lowering the global warming impact of bridge rehabilitations by using Ultra High Performance Fibre Reinforced Concretes', *Cement and Concrete Composites*, 38, 2013, 1-11.

[5] Kubwimana T., Bourneton N., Rouxel N., Hauchecorne A., 'Utilisation des bétons fibrés à ultra hautes performances en site portuaire', *XIèmes Journées Nationales Génie Côtier – Génie Civil*, Les Sables d'Olonne, France, 22-25 juin 2010, http://www.paralia.fr/jngcgc/11_79_kubwimana.pdf, 685-692.

[6] CETMEF, 'Visites Simplifiées Comparées - Méthode d'aide à la gestion de patrimoines - Etablissements de Signalisation Maritime, Guide d'utilisation', CETMEF - CETE de l'OUEST CETE NORD-PICARDIE, 2007.

[7] Geoportail Maps, http://www.geoportail.gouv.fr/accueil, 2013.

[8] CETMEF – CIRIA, 'The use of concrete in maritime engineering - a guide to good practice', http://www.ciria.org, Guidelines ref (C674), 2010.

[9] Menguy M., 'Bétons Fibrés Ultra Performants pour le renforcement d'ouvrages en mer, Réparation de la tourelle du CABON, Coulage du 26 Juin 2013', test report on production of UHPFRC, *CETE OUEST/DLRB*, St Brieuc, 2013.

[10] FEM Code MLS, ver. 8.4, FEMMASSE, http://www.femmasse.com/, The Netherlands, 2006.

[11] Sadouki H., Denarié E., 'D26 - Modelling of UHPFRC in composite structures', Deliverable D26, *European project 5th FWP / SAMARIS* – Sustainable and Advanced Materials for Road Infrastructures – WP 14: HPFRCC, http://samaris.zag.si/, 2006.

[12] Bazant Z.P., Planas J., 'Fracture and Size Effect in Concrete and Other Quasibrittle Materials', *CRC Press LLC*, 1998, 220-227.