UHPFRC for the cast-in place reinforcement of offshore maritime signalization structures

Emmanuel Denarié [(1)]

[(1)] Maintenance, Construction et Sécurité des ouvrages, (MCS-ENAC), École Polytechnique Fédérale de Lausanne (EPFL), GC B3-435, Station 18, CH-1015 Lausanne, Suisse.

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ABSTRACT
Offshore lighthouses are a remarkable historical heritage often over 100 years old. The management of their aging is a challenge. The extremely low permeability of Ultra-High-Performance Fiber Reinforced Concretes (UHPFRC), combined with their outstanding mechanical properties (robust tensile Strain Hardening (SH) for specific mixes) are particularly suitable for the reinforcement of this type of structures and more generally offshore maritime signalization structures. These structures under the influence of tides and weather, exposed to a very aggressive environment, have very limited access. As for existing bridges, SH-UHPFRC provide in this case a robust, effective, and very durable reinforcement solution, making it possible to simplify and reduce the duration of interventions. In this context, an existing turret at sea, on the south coast of Brittany, was reinforced by the application of a 60 mm UHPFRC hull, cast in place by helicopter in a formwork around the existing masonry structure. This application paves the way for the reinforcement with the same materials of lighthouses at sea exposed to extreme weathering conditions, such as "La Jument" nearby the island of Ushant (Brittany, France).

KEYWORDS: UHPFRC, Strain-Hardening, Reinforcement, Lighthouses, Offshore.

1.- INTRODUCTION
Over the last 14 years, under the impulse of MCS/EPFL, the application of thin SH-UHPFRC layers, with or without passive reinforcement, cast in place on existing structures (bridges and buildings), has demonstrated its many advantages in terms of durability, sustainability, cost-efficiency, and reduction of the duration of sites [1, 2]. The same approach applies for structures in the marine environment (exposure classes XS 1, 2, 3), whether they are new, to guarantee their durability, or existing, for an efficient, fast and durable reinforcement adapted to the very severe constraints of the marine environment. The timeframe available for interventions on offshore structures is extremely limited, not because of traffic constraints such as for terrestrial traffic routes, but because of meteorological and tidal constraints (typically only a few days access per year). In this

perspective, the strategy of targeted interventions with UHPFRC used for road structures and buildings is also optimal for structures in the marine environment, especially for those, such as signalization structures at sea (turrets and lighthouses), subjected to the most severe conditions. Since 2011, a collaboration between MCS/EPFL and CEREMA Brest has matured this concept and implemented it for the first time in 2013 on a turret in the bay of Lorient in Brittany.

The application of UHPFRC to new structures in a marine environment has already been the subject of several achievements and conceptual or feasibility studies. Without being exhaustive, one can cite: (1) the Sakata-Mirai footbridge (variable height box girder cross section, wide circular openings, span 50 m) in Japan, prefabricated externally post-tensioned box-girder UHPFRC segments, located at the mouth of a river by the sea [3] ; (2) the extension in 2008 of the Haneda airport in Japan (Tokyo harbor), with 24,000 m^3 UHPFRC in the form of prefabricated pre-tensioned ribbed slabs attached to a metallic frame [4]; (3) the completion in 2012 of one of the 4 multi-span bridges with 6 spans planned for the extension of a container unloading terminal at Port Klang in Malaysia with a locally developed and produced UHPFRC [5] for 102 12.1 m long prestressed beams, without passive reinforcement; (4) the feasibility study for the application of prefabricated elements in UHPFRC for a harbor dock in Lorient, France [6]; (5) the proposal of prefabricated UHPFRC elements for the replacement of polder flood barriers in the Netherlands, [7]; (6) the proposal for the use of UHPFRC for offshore wind turbines [8] and then for the construction of their foundations [9], and finally prefabricated UHPFRC elements assembled by post-tensioning for the towers [10]; (7), the project of wave power plants using UHPFRC floats, with a prototype plant was installed in 2005 in the North Sea as part of the "Wavestar" project [11]; (8) the UHPFRC deep sea housings developed at university of Dresden [12] currently under testing in the arctic sea, 2500 m deep; (9) the emblematic MUCEM building and footbridge in Marseille, with structural members and filigree cladding lattices made of UHPFRC, exposed to the seaside environment [13]; (9) the footbridge “Las Ovejas” in Alicante (span: 45 m), on the Mediterranean seaside, made of post tensioned UHPFRC segments (FORMEX® mix using local components) with an organic shape and transparent colored inserts, [14]; and finally (10) the very original use for offshore mussels farms of a UHPFRC grid resting on floaters, (FORMEX® mix), [15].

Regarding the strengthening with UHPFRC existing structures in marine environment, Buitelaar [16] cited: (1) the case of the Puerto Cabello port jetty in Venezuela with the application between 1991 and 1992 of 30 mm of UHPFRC pumped in a formwork around 254 tubular pillars (thickness of 100 mm) made of prestressed concrete, damaged and corroded in the tidal zone; (2) reinforcement with UHPFRC and UHPC grouting of oil rig structural members, first in Venezuela in 1992 and 1993 on Lake Maracaibo, then in the North Sea in 1995 and following (Ekofisk platform) among others. This type of reinforcement using injected UHPC grouts is since then widely used. Tanaka et al., [17] validated the application of synthetic fiber-based UHPFRC (UHP-SHCC) for the reinforcement of piers in harbor sites. Finally, the use in 1998 of 6000 "Reactive Powder Concrete" (with synthetic fibers) support plates of ground anchors for the reinforcement of a retaining wall on the coast of Reunion Island [18] is also representative.

The detailed study of the archives on the design, construction and evolution of two lighthouses in the Iroise Sea: "La Jument" off the island of Ushant, and "Ar-men" off the island of Sein, allowed to model in three dimensions with finite elements, the evolution of these structures more than one hundred years old, [19, 20]. The effect of the multiple reinforcements applied during the life of these structures has been studied, and their effectiveness evaluated. The dynamic response of "La Jument" lighthouse was modeled and characterized in place, using an ambient vibration sensor. These measurements helped validate the choice of elastic materials properties used for numerical modeling. Finally, the three-dimensional numerical model was used to develop the basics of an intervention project by applying UHPFRC to reinforce and confine the basement of the lighthouse and the existing Reinforced Concrete ring around the tower base.

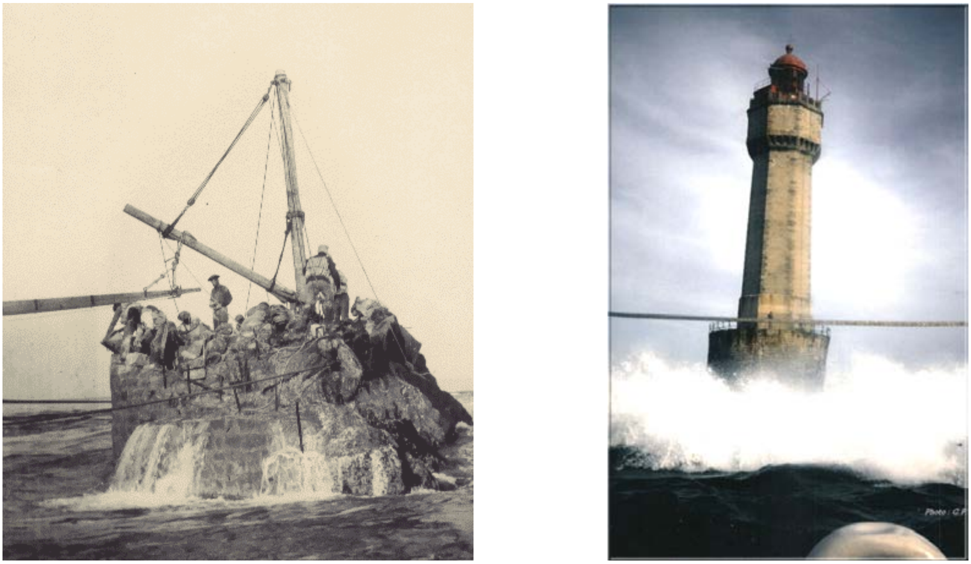
This paper first presents the particular context of lighthouses at sea and the challenges associated with their construction and reinforcement, based on the example of the "La Jument" lighthouse. In a second step, the concept of reinforcement intervention with UHPFRC is set forward. Finally, the first intervention of this type successfully carried out on the turret "Le Cabon" in Lorient, France in 2013 with a self-compacting UHPFRC is presented and discussed.

2.- LA JUMENT LIGHTHOUSE

2.1.- Context and historical background

Even if the generalization of the use of GPS has made the means of visual navigation (diurnal and nocturnal) less decisive, they remain very used and present with the lighthouses at sea, an important cultural and patrimonial value which must be preserved in a rational way as part of the state's legal obligation to ensure the maintenance of maritime signalization structures. To date, there are about 70 lighthouses classified or listed "Heritage Historic Monuments Ministry of Culture" in France, among which "La Jument", off the coast of Ushant Island in Brittany.

The construction of lighthouses at sea has always been a challenge calling for extraordinary tenacity, courage, and patience. The construction of the lighthouse of "La Jument" lasted seven years between 1904 and 1911, maximum duration imposed by the legacy used to fund the project. The first year of construction, access was possible only 52 hours, then between 150 and 400 hours the following years, for a total of 2037 hours or 85 days over seven years. It is now 117 years old and still resists despite the extreme stresses it undergoes: local configuration of the seabed favoring the formation of breaking waves of more than 20 m in height, extreme local pressures greater than 20 to/m^2 (extreme cases of 60 to/m^2 were reported), under the action of the most powerful. Figure 1a) illustrates the beginnings of the construction of the lighthouse with the substrate rock on the right. Metal rods anchored in the rock to serve as points of support are visible. Figure 1 (b) shows the lighthouse in the 1980's, taken from the boat during a staff rotation of lighthouse keepers. In both cases, the access conditions were particularly difficult.



a) b)

Figure 1. "La Jument" lighthouse, a) construction, b) lighthouse keepers staff rotation in the 1980's. Photos a) Michel Cloâtre fund, b) George Pennec.

The Fresnel lens of the lighthouse had a range of 22 nautical miles until the 2014 storms, marking the entrance to the "Fromveur" channel, south of Ushant, which was the source of many shipwrecks until to the construction of the lighthouse. Since 2015, its range is reduced to 10 miles with the upcoming installation of a LED light source to replace it.

Figure 2 after (Loraux, 2013a) presents the 3D FEM modeling (DIANA) of the main successive phases of the service life of the structure. Its total height from the beginning of the bedrock to the level of the lantern platform is 40 m above sea level "CM 0" (low water coefficient 120). The peculiarities of this lighthouse at sea are: (1) its larger upper part to shelter the engine room, resulting in an unfavorable distribution of masses regarding the dynamic stresses, and (2) an octagonal cross-section of the tower that gives more grip to the forces applied by the waves than a cylindrical shape (case of the Ar-men lighthouse).

Originally, the free height of the tower from the basement was 29.7 m, reduced to 26.2 m after raising the basement. The original base, completed in 1911, was 3.5 m lower than the current upper level and was much narrower, almost contiguous to the base of the tower over a large part of its perimeter.

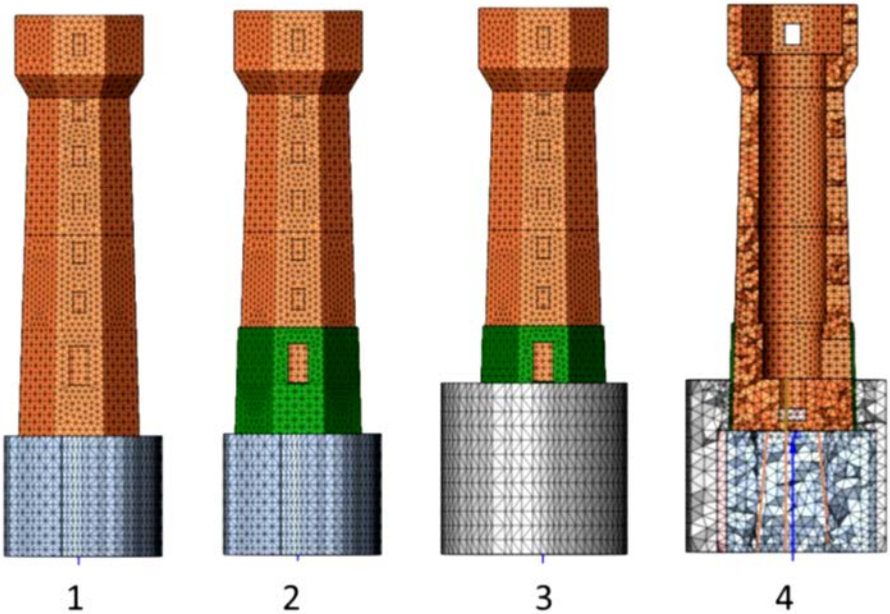


Figure 2. "La Jument" lighthouse, 3D finite element modeling of the successive steps of the life of the structure: (1) original condition (1911), (2) reinforced concrete strapping at the foot of the lighthouse and reinforcement of the tank (1917-18), (3) successive enlargements and basement elevation (1919-1928), (4) prestressed anchors (1936-1941), taken from [19].

Shortly after the commissioning of the structure in 1911, following strong storms, various reinforcements had to be undertaken to (1) stabilize the structure which exhibited very strong vibrations reported by the keepers (this lighthouse was automated in 1991), and (2) remedy to the cracks found at the base of the tower. The basement was progressively widened and raised 3.5 m between 1912 and 1928, and the base of the tower was confined between 1917 and 1918 with a reinforced concrete ring that extends down to the level of the old basement, 3.5 m below the current platform level and up to 4 m from the current platform level. Finally, between 1936 and 1941, three anchors inclined 1/10 to the outside were placed at the foot of the tower to apply stabilization efforts related to the mass of the tower (Coyne system applied to dams as early as 1931). Of these three anchors, at most 1058 tons (probably 2 of 3 anchors) could be activated compared to the planned 3 x 1000 tons, compared to the total weight of the tower of about 4800 tons. Given the very aggressive salty environmental conditions and doubts about their anchorage, it is unlikely that these anchors still perform any function after more than 75 years.

Figure 3a) and b) illustrate the condition of the basement in 2013. One can distinguish its heterogeneous nature following the multiple reinforcements carried out in the past, and the state of corrosion and cracking of the RC ring at the base of the tower.

The most significant positive effect of all the interventions carried out in the past is certainly the raising of the basement and its widening, and the confinement of the base of the tower, as shown by the finite element model, [19].

a) b)

Figure 3. "La Jument" lighthouse, Ushant, France, condition in 2013: a) basement, b) Reinforced concrete reinforcement ring at the base of the tower, made in 1918, photos E. Denarié.

Dry-Mix shotcrete was applied locally to the basement in 2010. Heavy storms in winter 2014 tore materials apart from the top of the basement and damaged 70% of the platform surface, revealing existing radial cracks. However, there was no significant increase in these visible surface cracks compared to archive documents. A wide crack visible between the foot of the tower and the basement indicates that the tower is not clamped in the basement over its full height. The tower did not show an apparent increase in cracking patterns after the 2014 storms. Ambient vibration measurements made on the structure before and after the 2014 storms [19-21] did not show significant differences in the response of the structure at rest. Dry-mix shotcrete was applied in 2015 to fill the voids left after the 2014 storms on the upper part of the basement and to prepare the ground for wider interventions. Comprehensive monitoring of the action of waves is currently ongoing, [22].

2.2.- Concept of reinforcement with UHPFRC

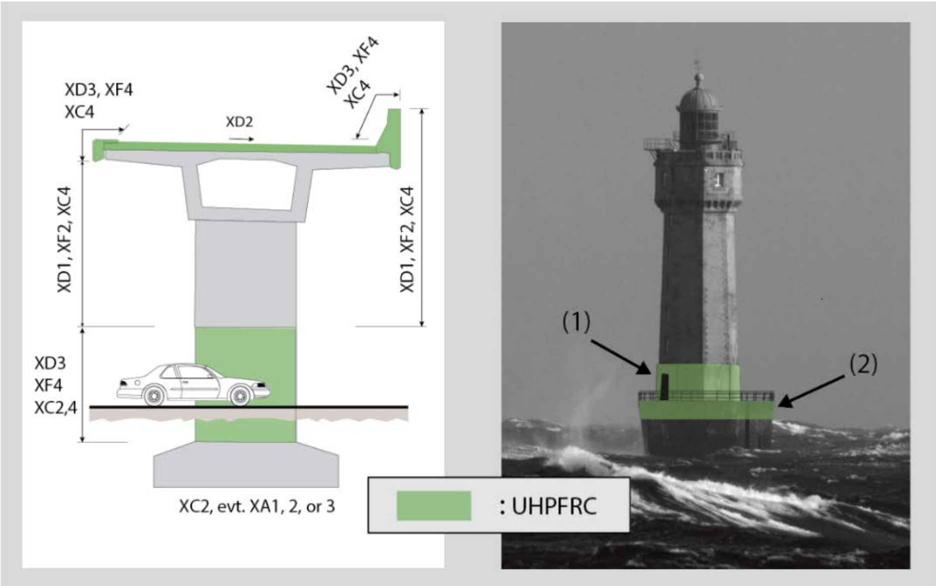
The concept of reinforcement of the structure is inspired by the technique of protection/reinforcement of road structures using cast-in-place SH-UHPFRC, combined if necessary with passive reinforcement, fig. 4a), successfully applied since 2004 in Switzerland, [1, 2].

According to the information available, and subject to additional ongoing studies, the reinforcement of the structure shall have two main objectives fig. 4 b):

(1) strengthen the reinforced concrete ring around the base of the tower, which is heavily damaged,

(2) confine the upper part of the heterogeneous basement and seal it to prevent water penetration and hinder the pressure of the breaking waves to avoid the widening of the existing radial cracks.

Finally, the interaction of the base of the tower and the upper part of the basement will have to be analyzed to determine if the reinforcement will have to be continuous and tightly connect these two parts (with the advantage of blocking definitively water infiltrations) or let the tower oscillate more or less freely in the space of the current cavity (opening of 20 mm, about 3 m deep, along 2 contiguous faces of the octagonal perimeter of the tower) as it is apparently the case currently.



a) b)

Figure 4. Concept of application of UHPFRC for: a) bridge reinforcement and protection proposed by Brühwiler in 1999; and (b) reinforcement of lighthouses at sea (La Jument Lighthouse, Ushant, France) proposed by Denarié in 2011: (1) reinforcement of the reinforced concrete rim dating from 1918, at the base of the tower, (2) confinement and protection of the upper part of the basement.

3.- FIRST APPLICATION – TURRET "LE CABON"

3.1.- Context

The Turret "Le Cabon" is located in the Lorient harbor bay, Brittany, France (3° 21' 40" W – 47° 42' 08.2" N). 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 submerged and half of the turret too, all this within 6 hours.

Reinforcement consisted of applying a 60 mm thick layer of UHPFRC on the entire surface of the turret including the upper platform, forming a continuous hull.

3.2.- Materials

General requirements for marine concrete are given in [23]. UHPFRC meet these requirements by far. Given the configuration of reinforcement equivalent to a ring test with a 92% degree of restraint, the additional requirements imposed on the UHPFRC for this project were as follows:

- Strain hardening tensile response in uniaxial tension, target value of deformation at the end of strain hardening ε_{Utu} on average between 1 and 2 ‰ for specimens cut in square plates (700/700/60 mm) poured horizontally. Tensile strength $f_{Utu} \geq 10$ MPa on average.

- Limitation of the shrinkage to prevent most of the eigenstresses under restraint and leave most of the tensile hardening behavior to resist the residual effects after 70 years of suspected still ongoing swelling reactions in the masonry substrate.

- Self-compacting character (class SF2 after EN 206-1), i.e. a spread between 660 and 750 mm and workability maintained over 2 to 3 hours (transport from the concrete plant to the base of the departure of the helicopter was 1 hour).

The "NaG3 SR FM" UHPFRC [24], was adapted by Lafarge for this application to achieve tensile strain hardening. It contained 3.25% vol. of straight steel fibers (length 13 mm, diameter 0.185 mm) and had a water/cement ratio between 0.21 and 0.23. It did not contain any accelerator and used an optimized superplasticizer to maintain workability over 2 to 3 hours. A proprietary shrinkage reducing technology helps offset to a large extent (autogenous shrinkage not more than 100 µm/m) the shrinkage induced eigenstresses of this particular UHPFRC mix.

The properties of the UHPFRC used were determined during the suitability trials in 2012 and during the construction site [25, 26]. All the objectives were achieved both regarding workability (self-compacting class SF2), as well as of the tensile response of the UHPFRC with a tensile hardening varying between 1 and 2.3 ‰ and a tensile strength between 10 and 12 MPa (at 28 days), determined by inverse analysis of prism flexural tests.

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, [27].

It was also determined before loading the skip attached to the helicopter, for several helicopter runs, Table 1.

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, satisfactory workability could be achieved througout the casting. The material was homogenous with no fiber segregation, and the workability was maintained for more than two hours, which is perfect for this type of application.

Table 1. Workability test results at truck arrival at helicopter landing site or later

Truck N° / (Batches)	*Helicopter Run (over 9)*	*Air temp. [°C]*	*UHPFRC temperature [°C]*	*Slump flow [mm]*	*T500 [s]*
1/(1+2)	1	20	30	590	n.a.
	7	n.a.	n.a.	660	6
2/(3+4)	1	22	32	670	4

It should be noted that the compressive strength of the UHPFRC was on average (for six cylinders 70/140 mm tested at 28 days) 135 MPa (121 MPa for the fractile of 5%). These values are in the low range of those usually obtained for UHPFRC. This could be explained by the specific composition of the UHPFRC mix. It is however not an issue in this structural application for which the tensile response and protective properties prevail.

3.3.- Execution

The steel formwork was designed to withstand the hydrostatic pressure of the fluid UHPFRC, at the height of 4.6 m (UHPFRC density of 26 kN/m^3) and to prevent leakage of fresh UHPFRC. It was fixed at the foot by anchors to a concrete wall itself anchored at the base of the turret.

The pouring took place on June 26, 2013. The metal formwork had been installed on the turret the previous day, figure 5a). The UHPFRC was produced at the LAFARGE concrete plant in Keryado, in a mixer with a capacity of 2 m^3. Batches of 1.25 m^3 of UHPFRC were chosen to optimize the production line and the on-site transport according to the rate of rotations of the helicopter. The UHPC matrix (premix, water, adjuvant) was mixed between 10 and 13 minutes before adding the fibers. The total mixing time was 13 to 17 minutes for each batch. Two batches were mixed consecutively and poured into a concrete truck.

After a first control of the workability at the plant, the fresh UHPFRC was transported by truck to Gâvres (37 km, 1 hour on average). From there, it was only 4 to 5 minutes to load the skip attached under the helicopter with an average of 300 liters of UHPFRC (750 kg), transport them to the turret, dump them into the formwork figure 5b), and return to the truck. A total of 4.2 m^3 of UHPFRC were cast with two rotations of the truck and 18 rotations of the helicopter over a total duration of 2 hours. No compaction was applied to the UHPFRC during casting.

The free surface of the UHPFRC on the upper platform of the turret was covered with a plastic sheet covered with gravel left in place during seven days of curing. The formwork was removed after seven days.

a)

b)

Figure 5. a) Installation of the metal formwork on the turret, b) casting of the UHPFRC by helicopter, photos E. Denarié.

3.4.- Feedback and perspectives

Figure 6a) shows the condition of the turret in September 2013, three months after casting. No crack was visible, at most microcracking on certain zones. The surface finish of the UHPFRC was excellent and suitable for the application of the final red paint, Figure 6b). The visual appearance of the painted turret and its surface rendering resemble a metal structure.

According to the owner of the structure (Service des Phares et Balises Lorient), the intervention with the help of UHPFRC has significantly reduced the quantity of materials required compared to a conventional solution with cast in place concrete. This significantly reduces the intervention time and the necessary means.

The intervention costs between the two variants have comparable values with a decisive advantage for the UHPFRC solution regarding durability and resistance to the extreme forces and abrasion regularly imposed by the swell.

- A second intervention on another turret at sea (Men er Houteliguet) of comparable size to that of Le Cabon, located near the island of Houat in Brittany, at sea, was realized successfully in 2017, with a similar mix, with the additional challenge of producing the UHPFRC on site, on a barge near the turret, using on-board mixers, [28]. Further projects are currently under development.
- Recent developments on sprayed UHPFRC with steel fibers, [29, 30] open the way to other modes of application to fulfill the same goals of reinforcement of offshore structures.

a) b)

Figure 6. a) turret condition in September 2013, b) condition in September 2015 after final paint application and two winters. Pictures E. Denarié.

4.- CONCLUSIONS

- The concept of application of cast in place UHPFRC for the reinforcement of existing offshore structures with difficult access has been validated for the first time successfully on a turret in Brittany.

- The strain hardening UHPFRC recipe developed for this application has been very satisfactory both from the point of view of the workability (self-compacting SF 2), and for the mechanical performance in tension (tensile strength between 10 and 12 MPa, tensile strain hardening between 1 and 2.3 ‰ on specimens sawn in a square plate without preferential orientation).

- The application of the UHPFRC on the Turret by a helicopter was fast and efficient.

- This successful application paves the way for the reinforcement of heritage lighthouses at sea in most difficult conditions of access, such as that of "La Jument", taking benefit of the outstanding properties of UHPFRC.

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