Field Demonstration of UHPFRC Durability

Girders shown to perform well in a cooling tower

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The Cattenom nuclear power plant in eastern France was built during the 1980s. It has crossflow cooling towers, in which hot water is cooled as it falls through a crossing air flow. As with cooling towers at other sites, the aggressive exposure damaged the devices supporting the splash fill early in the life of the structure. This led Electricité de France (EDF) to repair the fill and its supporting structure.

The restoration, initiated in the mid-1990s, consisted of dividing the splash fill into two levels. This required designing and installing an additional mezzanine superstructure that had to be integrated within the existing structure. To increase durability and to minimize the additional weight (and potential settlement due to the low soil-bearing capacity at Cattenom), this additional superstructure was constructed as a grill of precast, prestressed ultra-high-performance fiber-reinforced concrete (UHPFRC) beams and girders. This constituted a pioneering large-scale industrial application of UHPFRC in France.[1,2]

The girders were fabricated between 1996 and 1998, partly using Béton de Poudres Réactives (reactive powder concrete, or RPC®), a UHPFRC developed in partnership by Bouygues, Lafarge, and Rhodia and presently marketed under the Ductal® trademark, and partly using Béton Spécial Industriel®, a UHPFRC material developed by Quillery and presently distributed by Eiffage under the trademark BSI Ceracem®. The beams were installed above the empty cold water basin in the cooling tower (Fig. 1) while the plant was shut down for maintenance.

In 1996, two UHPFRC witness (durability warning) girders were also installed to allow monitoring of the aging process in the aggressive environment. The girders were installed near the ground level, above the water level in the cold water basin of cooling tower No. 1. The girder ends are supported on a tripod resting in the cold water basin and on the concrete wall at the edge of the cold water basin. The setup includes a sustained loading created by stainless steel rods used to clamp the beams together at midspan, inducing 14 MPa (2000 psi) tension stress at the extreme fibers of the flanges. Several small, short beam elements are attached to the top girder, allowing inspection of the effectiveness of different corrosion protective systems at the ends of the strands.

The girders were made of RPC and were cast at the end of May 1996 in the Sablons factory at Longjumeau, close to Paris. A compressive strength of about 200 MPa (29 ksi) was obtained using a water-cement ratio (*w*/*c*) of 0.19, with the cement content representing 30.6% of the material, excluding fibers. The fiber content was 161 kg/m^3

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Fig. 1: Installation of the UHPFRC beams in 1997

(271 lb/yd^3) or 2.1% in terms of volumetric content. At casting, the slump was 160 mm (6.3 in.).

The girder cross section is shown in Fig. 2. The web thickness is 50 mm (2 in.). Each strand was tensioned to 180 kN (4 kips). The minimum cover is 22 mm (0.9 in.) (relative to the inclined flange side).

Except during operational breaks, the girders are constantly subjected to hot, dripping water. The average water temperature is 35°C (95°F), and the surrounding relative humidity is practically 100%. During winters, the cold water basin is maintained at a temperature of at least 10°C (50°F). Because the witness girders are close to the basin, their temperature in winter can be estimated at about 10°C (50°F). Yet, because the girder ends at the edge of the basin are close to the outer edge of the cooling tower (Fig. 3), they are at the limit of the zone subjected to water splash. Depending on the winter conditions, ice can form at that location.

The circulating cooling tower water has a pH level between 7 and 7.5 and leaves deposits. The girders, reinforced concrete piers supporting the external superstructure, and cooling tower shell have been entirely and rapidly covered by a layer of scale (Fig. 4). Analysis indicates that the water has a maximum chloride content between 1 and 2 g/L and a sulfate content of about 500 mg/L. For comparison, the water of the nearby Moselle River has a pH of 7.8 and concentrations of about 400 mg/L for chlorides and 100 mg/L for sulfates.

Fig. 2: Girder cross section

In application of the NF EN206-1 standard,[3] these environmental characteristics correspond to exposure classes XD2 (exposure to waters containing industrial chlorides) and XA1 (sulfate content between 200 and 600 mg/L). It can be assumed that the standard refers to calm waters at temperatures ranging from 5 to 25°C (41 to 77°F). EDF policy is to overclassify the exposure for the cooling towers because the water is at high temperatures and is continuously renewed. This would lead to exposure classes of XD3 and XA2 in the present case. The girders are entirely covered by scale, however. This certainly serves as a barrier against diffusion and protects the girders from external attack, so the mentioned exposure classes seem excessively severe.

Moreover, an XD2 exposure class would call for protective measures equivalent to those required for structures immersed in seawater (that is, in water with a minimum chloride content of 20 g/L), which seems overconservative. With respect to the initiation of corrosion due to chlorides, it seems preferable to refer instead to the 6.7 g/L criterion provided in Reference 4 for regular reinforced concrete. Given the constant high relative humidity conditions, this appears to be more representative.

INVESTIGATIONS AFTER 10 YEARS' EXPOSURE

Core sampling

During a break in plant operations in 2004, a visual inspection helped confirm the absence of corrosion of the fibers at the UHPFRC surfaces, the development of the scale layer, and the ongoing corrosion of external metallic elements. The plant operator, EDF experts, and the AFGC task group for UHPFRC agreed to take advantage of a plant shutdown in February 2008, about 10 years after the restart of the retrofitted cooling tower. They planned to inspect and take core samples to help quantitatively characterize the in-place aging of the UHPFRC structures—among the oldest available for evaluation (Fig. 5).

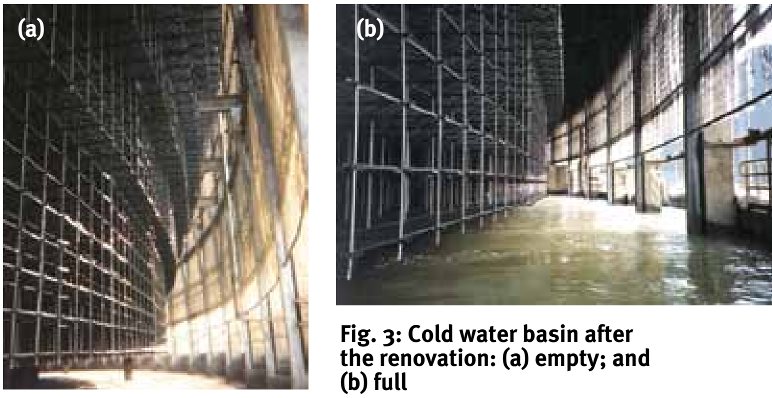

Fig. 3: Cold water basin after the renovation: (a) empty; and (b) full

Given the presence of prestressing strands and to preserve the mechanical setup for in-place creep characterization, sampling consisted of drilling a limited number of cores through the webs of both girders. Eight cores, distributed within the zones subjected to the highest tensile stresses, were extracted by the on-site maintenance contractor using a 52 mm (2 in.) outside diameter bit. Investigations of these samples allowed for evaluation of some of the mechanical characteristics of the concrete, provided quantitative confirmation of the durability characteristics of UHPFRC, and determined if there was corrosion of either steel fibers or tendons.

Observations and durability indicators

Inspection of the ends of the core samples and the external surfaces of the girders confirmed the presence of a scale layer. Unprotected tendons were corroded at their ends, but a thorough examination of drilled surfaces showed that fibers in the UHPFRC were sound, except when they extended out of the surface at angles or at unformed surfaces. The porosity accessible to water and capillary water absorption were measured on core No. 5, using methods recommended in Reference 4. The values obtained were 4.3% and from 0.025 to 0.035 g/cm^2, respectively.

The water absorption is about one-tenth that normally measured for high-performance concrete. Concerning porosity, which is one of the most fundamental durability indicators for cementitious materials, if the entrapped air (about 2.5% measured during casting and representing a significant content of noninterconnected air bubbles) is subtracted, the expected order of magnitude corresponding to the intrinsic porosity of hydrates is found.[5] Altogether, this value complies with known measures indicated in AFGC recommendations.[6]

Risk of corrosion induced by possible carbonation

The depth of carbonation was first evaluated with a phenolphthalein indicator on core sample No. 6, which

Fig. 4: Photo of girders taken during the inspection in 2000, showing scaled deposits and no visible corrosion

Fig. 5: External appearance during the 2008 inspection: (a) the unprotected end of the girder; and (b) the formed side surface

had been split transversely in two parts. On the first side, corresponding to the girder web face with the greatest scale thickness, an external 1 mm (0.04 in.) thick zone had a pH lower than 9. On the other side, the carbonated depth was not measurable. A more quantitative evaluation was attempted, using slices sawn from the samples. Along the height of sample No. 8, 6 mm (0.25 in.) thick slices were cut, except for the first (thicker) one.

Each piece was ground to obtain about 15 g (0.5 oz) of material, from which pH was determined following the method described in Reference 7 using 10 mL (0.6 in.^{3}) of a solution obtained with 15 g (0.5 oz) of the ground material and 15 g (0.5 oz) of water. The pH meter was calibrated using reference solutions with pH values of 7 and 12.45. The results are shown in Table 1. The pH value of each slice is close to 12.3 and variations along the thickness of the web are insignificant. This value characterizes sound (noncarbonated) concrete.

Because significant carbonation was not observed deep in the specimen, and to precisely assess the surface scale deposit, pieces of samples No. 2 and 3 (freshly broken from the compressive tests described in the following) were examined using a scanning electron microscope and X-ray diffractometry. Scale samples from the UHPFRC girder surface, from one of the conventional reinforced concrete piers supporting the cooling tower and from a UHPFRC core sample, were also examined. In all cases, the most abundant element obtained from specimens representative of the inner parts of the UHPFRC girder was found to be quartz. Conversely, calcite was found to be the major component of the scale obtained from the girder surface or from the regular reinforced concrete pier.

To complement these local investigations, a combined thermochemical analysis with X-ray diffractometry was carried out on slices sawn from the edge and the inner part of core sample No. 1 (Table 2). The very low CO_2 content of inner specimens (C and E) may be the result of an unexpected side effect related to sample preparation.

Thus, calcite appears as clearly due to either surface carbonation or to the combination of CO_2 of the surrounding air with calcium contained in the circulating water in the cooling tower, which may itself be enriched by leached concrete elements. If the calcium of this calcite comes from hydrates at the surface of the UHPFRC member, the concerned depth can be evaluated. Referring to regular cement pastes subjected to carbonation, where calcite mass content may represent 23% (that is, 10% for CO_2), according to Reference 8, the values obtained for A and G slices correspond to carbonation limited to a depth lower than 1.73/10 or 1.98/10 times the slice thickness value (5 mm [0.2 in.]). This is less than 1 mm (0.04 in.), confirming the phenolphthalein indication.

On the contrary, if calcite is assumed to represent an outer layer, which is more consistent with a mechanism corresponding to supply by covering and dripping water, the inner side of A and G slices is considered to have the same CO_2 content as the inner slices (C and E), and the obtained thickness of "pure scale" is about 0.2 mm (0.008 in.). This low thickness seems to make better sense given the fact that none of the fibers of the UHPFRC material appear to be corroded along the girder.

In fact, the outer scale layer prevents diffusive penetration of CO_2, either for the UHPFRC girders or for the surrounding regular reinforced concrete structures, which show no significant visible signs of reinforcement corrosion. Even so, the atmosphere surrounding the splash fill in the cooling towers, which combines dripping water, intense air flow, and rather mild temperature, is favorable to carbonation and would correspond to XC4 exposure class.[3] The obtained results tend to confirm that, due to their high internal compactness, and possibly also with nonhydrated particles able to rapidly combine in a protective calcite layer, the UHPFRC members studied in this program are preserved from carbonation-induced damage in a durable way, despite the severe environmental exposure.

TABLE 1:
pH MEASUREMENTS TAKEN ALONG THE LENGTH OF SAMPLE No. 8

Slice designation	Depth, mm	pH	Temperature, °C
A	0 to 11.5	12.35	23.5
B	12.6 to 18.6	12.32	23.2
C	19.7 to 25.7	12.35	23.7
D	26.8 to 32.8	12.38	23.4
E	33.9 to 39.9	12.37	23.7
F	41 to 46	12.32	23.9
Average		12.35	23.57
Standard deviation		0.02	0.25

Note: 1 mm = 0.039 in.; °F = °C × 9/5 + 32

Risk of corrosion induced by possible chlorides ingress

To quantify the possible penetration of chlorides, which are present at a relatively high content in the circulating water, a chemical dosage procedure was used on the material sawn at the surface or the inner core of sample No. 1 (Table 2).

The chloride ion dosage was evaluated according to a potentiometric method using a 0.01 mol/L solution of silver nitrate. The procedure for free chloride dosage derives from works described in Reference 9. It is required to obtain 5 g (0.2 oz) of ground material containing no fibers. No corrosion of the fibers thus removed was observed. Slices A, B, C, E, and G were first studied, with 22 chemical determinations performed (four per slice on average).

In all cases, the quantity of chloride ions was found to be less than 0.1 g Cl^- per 100 g of cement, which is the precision limit of the method due to the low material quantities available. This limit is to be compared to the threshold generally allowed for initiation of reinforcement corrosion, namely 0.4 g Cl^- per 100 g of cement. It can thus be concluded that there is insignificant chloride penetration within these UHPFRC members.

The risk of chloride-induced corrosion is low because the circulating water has a relatively low chloride content and the UHPFRC materials have low transfer coefficients. Therefore, to better document UHPFRC durability with respect to the risk of chloride-induced corrosion, it would be interesting to carry out similar investigations on structural elements subjected to an aggressive marine environment. Examples could include anchor plates of some reinforced earth retaining walls at La Réunion Island.[5]

Mechanical properties

Three specimens were used to quantify the possible evolution over time of UHPFRC mechanical characteristics. Core No. 2, 3, and 4 were chosen because each had satisfactory cylinder geometry (Fig. 6). They were, however, drilled again to avoid eccentricity-induced errors during the compressive tests. The final diameter was 36 mm (1.4 in.). After grinding the ends to provide adequate bearing, the specimens were 48 mm (1.9 in.) long. The resulting aspect ratio, 1.33, is slightly lower than the generally admitted geometrical range needed to avoid strength overestimation with respect to uniaxial compression (size effect due to end confinement). To determine Young's modulus and Poisson's ratio, cylinders were instrumented with three pairs of longitudinal and transverse strain gauges, each with 10 mm (0.4 in.) gauge lengths, glued at 120-degree increments along the perimeter. Strain data was successfully obtained for two specimens, whereas compressive strength was measured for three cylinders.

Material characterization had been carried out 7 days after casting (which is also after the thermal treatment) on 70 mm (2.8 in.) diameter cylinders. Direct comparison with data measured on drilled specimens at 10 years should thus take into account a possibly favorable size effect for the smaller specimens.

The initial compressive strength, Young's modulus, and Poisson's ratio were 207.8 MPa, 56.0 GPa, and 0.21, respectively. These values are the averages of three measurements. The related standard deviation for the strength was 2.2 MPa, and Young's modulus ranged from 54.8 to 56.8 GPa.

Results for the core samples are shown in Table 3. For the loading cycles between 5 and 30% of the expected maximum load, the linearity of the longitudinal and transverse strain versus the stress curves was excellent.[10,11] This indicates the absence of internal material damage and that the quality of the determined Young's modulus and Poisson's ratio values is good. Although the strength values indicated by the cores are greater than the initial

TABLE 2:
QUANTITATIVE CARBONATION DETERMINATION

Slice designation	Depth, mm	% CO_2
A	0 to 5	1.73
B	6.1 to 13.1	—
C	14.2 to 21.2	0.17
D	22.3 to 29.3	—
E	30.4 to 37.4	0.28
F	38.5 to 45.5	—
G	46.6 to 51.6	1.98

Note: 1 mm = 0.039 in.

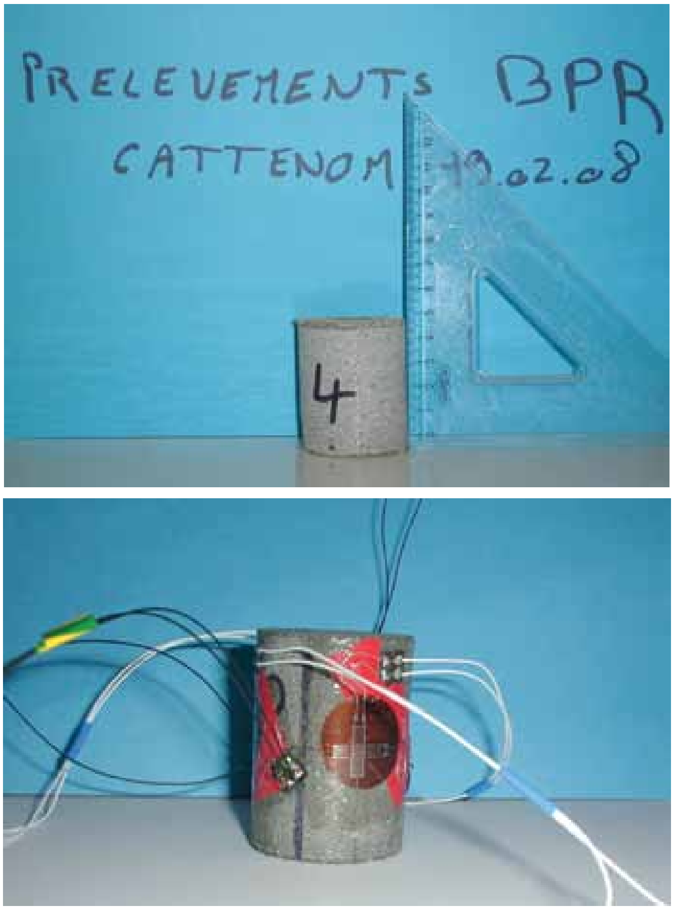

Fig. 6: Sample preparation for determination of mechanical characteristics

values, a long-term increase is not likely. The difference can be attributed to the difference in size and aspect ratio of the two series of specimens, but it can still be said that the mechanical characteristics are sufficiently stable with time and that the design values were used safely.

CONCLUSIONS

Microscope observations, as well as chemical and mechanical measurements, carried out on core samples taken from UHPFRC girders set in the Cattenom No. 1 cooling tower provided results consistent with what was expected:

- Young's modulus and compressive strength values are stable, indicating stability of the hydrates;
- The ingress of chlorides is too small to be measured;
- The girders exhibit possible carbonation in only a thin outer layer, and this is probably associated with external scale deposits; and
- With the exception of fibers extending out of the facings, there is no visible fiber corrosion.

These indications support the expectation that the prestressing strands in the girders are protected from corrosion, except at exposed ends. The high durability of these UHPFRC structural members is thus confirmed.

During this investigation, it was also confirmed that some measurement techniques are at the limit of appropriate sensitivity for materials with low permeability to aggressive agents. Due to the low quantity of specimens and material taken, it was also not possible to carry out additional investigations to verify chemical durability (such as mercury intrusion porosity, electrical resistivity determination, and exhaustive analysis of the hydrates) and mechanical durability (particularly long-term stability of the tensile behavior, which is an indication of the participation of the fibers).

These data would be valuable for confirmation of the members' structural safety.

Given the well-controlled and documented aggressive environment of the cooling tower, it would thus be all the more important to carry out similar surveys and investigations after another 10 years and thereafter. Moreover, it would be important to get appropriate information characterizing the resistance of UHPFRC to chloride penetration in a marine environment (more severe than the one studied herein) to confirm the excellent properties obtained in laboratory investigations.[12]

TABLE 3:
MECHANICAL CHARACTERISTICS AT 10 YEARS

Core No.	Strength, MPa	Young's modulus, GPa	Poisson's ratio
2	236.8	—	—
3	230.9	53.9	0.184
4	253.5	54.9	0.191
Average	240.4	54.4	0.19

Note: 1 MPa = 145 psi; 1 GPa = 145 ksi.

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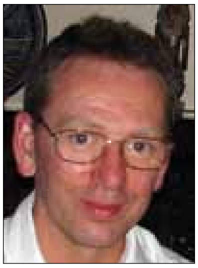

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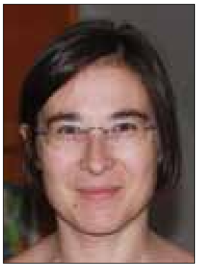

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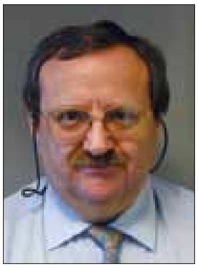

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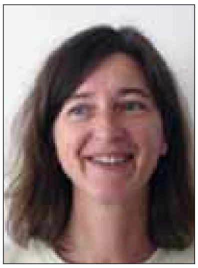

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