FATIGUE BEHAVIOR OF ULTRA-HIGH PERFORMANCE CONCRETE (UHPC) UNDER COMPRESSIVE LOADING

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Abstract

Fatigue behavior of Ultra-High Performance Concrete (UHPC) under compressive loading is investigated in this paper. For suitable design of tower structure of wind turbines, fatigue properties are keys factor to be considered. Two main types of mechanical tests were carried out in this study: static tests for the compressive strength evaluation and fatigue tests under compressive loading. At the applied stress level for the fatigue test (upper stress = 0.6 and lower stress = 0.1), the results show that the UHPC specimens withstand to 10 million cycles of loading. The static tests carried (after fatigue tests) show no deterioration or damage of the specimens and no drop of the maximum compressive stress values compared to specimens tested before fatigue tests. These results lead to conclude that the wind turbines made of UHPC might withstand to the fatigue for 20 years of operating time.

Résumé

Le comportement en fatigue du béton à ultra-hautes performances (BUHP) sous chargement de compression est l'objet de cet article. Pour une conception convenable de mâts d'éoliennes, les propriétés en fatigue des matériaux sont un facteur clef à prendre en compte. Deux types de tests mécaniques ont été utilisés dans cette étude : des essais statiques pour l'évaluation de la résistance en compression, et des essais de fatigue sous charge de compression. Pour le niveau de contraintes appliquées lors de l'essai de fatigue (contrainte maximale 0.6 et contrainte minimale 0.1), les résultats montrent que les échantillons de BFUP supportent jusqu'à 10 millions de cycles. Les essais statiques (effectués après les essais de fatigue) montrent qu'il n'y a pas eu de détérioration des éprouvettes ni de chute des valeurs de résistance en compression par rapport aux éprouvettes testées avant les essais de fatigue. Ces résultats permettent de conclure que les éoliennes faites en BFUP devraient résister à la fatigue pendant une durée d'activité de 20 ans.

1. INTRODUCTION

Advances in the science of concrete materials have led to the development of a new class of cementitious composites, namely ultra-high performance concrete (UHPC). Over the last 20 years Lafarge (LafargeHolcim) was one of the main companies that pioneered the development of this innovative material. UHPC was applied successfully on many projects worldwide [4, 8]. One promising field of application is the use of UHPC for the tower structure of wind turbines. Wind turbines are usually designed for a service life of 20 years during which the tower structure can be subjected to as many as 10^9 load cycles [5, 7, 11].

Fatigue is one of the governing criteria in the design of tower structures for wind turbines and consequently capability of assessing the fatigue behavior of UHPC is critical. Fatigue behaviour of UHPC has been studied by many researchers [1, 2, 3, 6, 8, 9, 10, 12] but UHPC behavior as wind turbine construction materials need deeper understanding.

The main objective of this study is to determine the fatigue resistance of UHPC material (Ductal®-FM) under uniaxial compressive loading. Material is described in more detail in the chapter 2. To achieve this objective, a large experimental campaign of static tests and fatigue tests under compressive loading were carried out partially at LafargeHolcim company (for static tests) and at Klokner Institute (for fatigue and static tests).

2. EXPERIMENTAL INVESTIGATION

Fatigue behavior of UHPC was studied under compressive loading. Experimental program consists of two main parts – static tests (evaluation of compressive strength) and fatigue tests under compression. In the second part, cylindrical specimens were exposed to cyclic loading with loading frequency of 10 Hz. Before this experimental campaign started the preliminary tests in order to validate the robustness of Klokner Institute (KI) experimental devices were performed. After the validation of gained values of compressive strength between KI and LafargeHolcim the experimental campaign should start. Before fatigue test, compressive strength tests were first carried out in order to define the level of axial stress for the fatigue tests. Fatigue behavior was studied under compressive loading with the defined stress level. The upper stress level and lower stress level are noted respectively S_o and S_u.

Cumulative damage calculation using Eurocode model, Model Code MC2010 and Palmgren Miner law were realized before the experimental campaign (this calculation is not presented in this paper). The cumulative damage calculation (value close to zero) indicated no substantial damage of the UHPC wind tower over 20 years of operating time. In this cumulative damage calculation, we used real data from 2.5 MW turbine at 100 m height. The maximum upper stress was 45 % of the mean compressive strength.

In this study three different scenarios of the tests were considered for the fatigue campaign. The passing from one scenario to another depended on the number of cycles at failure, as shown in the Table 1 – all scenarios are presented in order to show that at a certain stress level of fatigue, it is not necessary to carried out fatigue tests. If the failure of the specimens occurred at Scenario 1 during Step 1 (S_o=0.6 : S_u=0.1, during $<10^7$ cycles), Step 2 would follow. The upper/lower level would be changed to 0.4 and 0.1 respectively and fatigue test will continue. If the failure of the specimens occurs at Scenario 2 during Step 2 (S_o=0.4 : S_u=0.1, during 10^7 cycles), Step 3 will follow. The 60 % upper limit was selected to conservatively cover all loading scenarios. In the case of wind energy 10^7 cycles are needed to be done for the evaluation of the fatigue impact to final compressive strength of the UHPC.

Table 1: Scenario of the fatigue tests

	Number of Step	**Applied stress level $S_o : S_u$**	**Number of test**	**Results: Number of cycles at failure**	**Action to be done**
Scenario 1	1	0.6 : 0.1	4	$\geq 10^7$	**Stop**
Scenario 2	1	0.6 : 0.1	4	$< 10^7$	Continuing
	2	0.4 : 0.1	4	$\geq 10^7$	**Stop**
Scenario 3	1	0.6 : 0.1	4	$< 10^7$	Continuing
	2	0.4 : 0.1	4	$< 10^7$	Continuing
	3	0.3 : 0.1	4	$\geq 10^7$	**Stop**

For this experimental campaign a cylindrical UHPC specimens were used. The test specimens were prepared by Ductal Team at LafargeHolcim Research Center. The UHPC used for the experimental investigation was "Ductal®-FM Gris Formulation" from LafargeHolcim. The steel fibers had a length of 14 mm and a diameter of 0.185 mm and were added at a ratio of 2.0 % by volume. Test specimens were prepared from two batches. The first batch was prepared for the first part of tests and the second batch for second part of the experimental campaign.

The moulds were removed approximately 20 hours after casting. The test specimens were then put into a water tank for heat treatment. The water temperature was slowly increased from approximately 15 °C to about 90 °C and kept constant for at least 48 hours. The specimens were removed from the water tank after the water temperature had slowly dropped to approximately 20 °C.

The test specimens had a height of 180 mm and a diameter of 60 mm, i.e. a height to diameter ratio of 3. With this ratio, it is justified to assume that the compressive strength in the middle region of the test specimen is equal to the uniaxial compressive strength. This is relevant as the fatigue tests aim at determining the basic fatigue behavior of Ductal®-FM for its structural use. The same test specimen size was also chosen by other researchers [10].

The loading surfaces of the test specimens were grinded and polished before the test to ensure that the surfaces were flat and coplanar. To ensure that each specimen is equally loaded on the each side during the tests a resistive strain gauges were installed to the each specimen.

3. TEST PROGRAM

Part of the static tests of compressive strength of UHPC were performed in Klokner Institute and in LafargeHolcim and all of the fatigue tests were after performed in Klokner Institute. The results gained from these static tests were compared and used for calculation of a stress levels in the fatigue tests. The tests were performed in two different laboratories in order to validate the reproducibility and the repeatability of the tests. Before the start of the experimental campaign, a preliminary fatigue test was performed in Klokner Institute to evaluate which Scenario would be optimal and fit for this material. The test could be finished by three possible ways – specimen withstands 10^7 cycles without any deterioration, specimen withstands 10^7 cycles with visible deterioration with impact on final compressive strength and specimen does not withstand the cyclic loading. For these reason the worst scenario (Scenario 1) was chosen (Table 1). When the specimen not withstand prescribed 10^7 cycles a scenario 2 will be performed.

The total number of tests performed during whole experimental program is presented in Table 2. Two different loading devices were used in KI for each type of the test. Loading devices for static and fatigue tests in Klokner Institute are shown in Figure 1.

Table 2: Test program

Type of tests	Number of specimens	Company
Static compression tests	11	LafargeHolcim
	10	Klokner Institute
Fatigue tests	4	

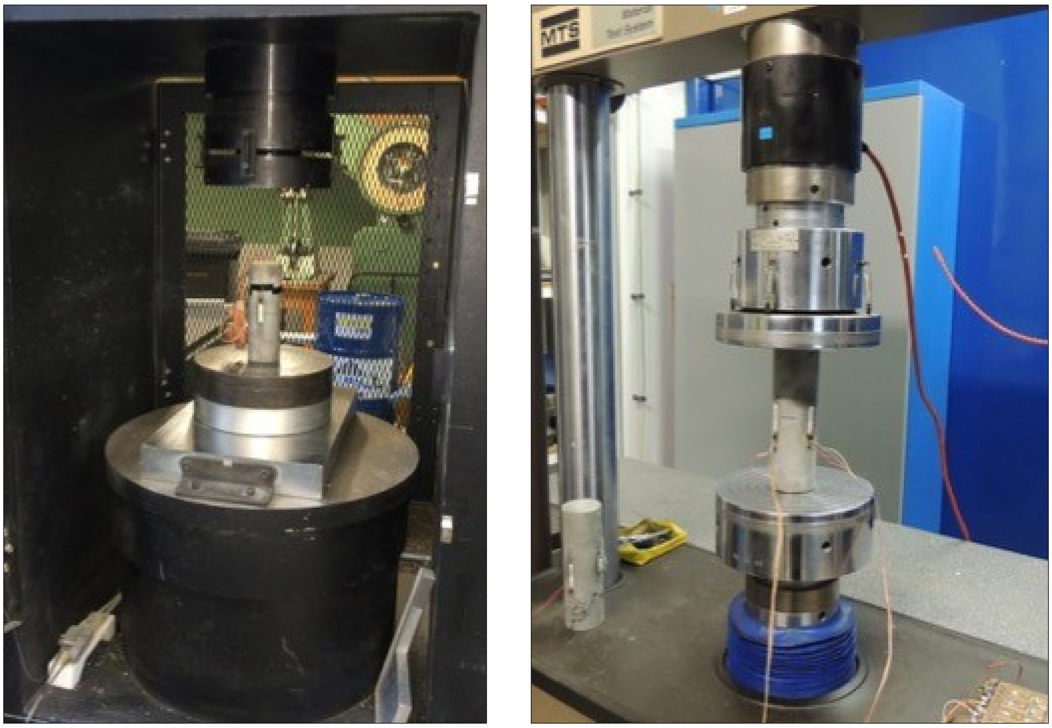

Figure 1: Loading device Instron 3000 kN SATEC – static tests (left), Loading device MTS 500 kN B262 – fatigue tests (right), cylindrical specimens with four resistive strain gauges installed on sides in the middle of the specimen

3.1 Static compression tests

Static tests were carried out in both laboratories because of comparison of conformity of the results obtained in LafargeHolcim Company and Klokner Institute and also for validation of the repeatability and reproducibility of the tests. Static tests of the UHPC cylinders were determined by using 11 specimens tested in LafargeHolcim laboratory and 10 specimens tested in the laboratory of KI. Specimens for static test were measured, weighed and four resistive strain gauges for stress - strain measurement during static test were installed for each specimen. The arrangement of resistive strain gauges is shown at Figure 1.

The experimental measurement stress-strain relations were performed in KI at a loading machine with a maximum loading capacity of 3000 kN. The specimens were preloaded in the beginning by stress level of 0.8 MPa. Three preload cycles (0.8 – 68 MPa estimated 1/3 of the maximum loading force) were performed before final loading. The loading was continually graded to the maximum force. The loading speed rate (0.8 MPa/s ≈ 2,26 kN/s) was hold after the reaching the maximal loading force. Typical scheme of the static test is presented in Figure 2.

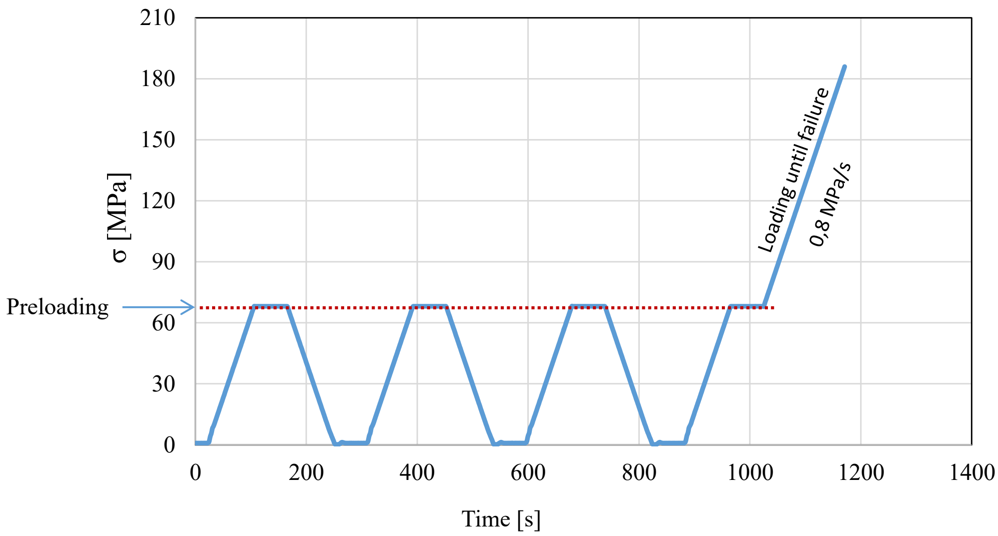

Figure 2: Static tests (compressive strength tests) procedure

3.2 Fatigue tests

For the fatigue test the same cylindrical specimens as for static compression tests were used. The fatigue tests were conducted on a servo hydraulic (MTS) testing machine with a maximum load capacity of 500 kN. Four resistive strain gauges for stress strain measurement were installed for each specimen (same as specimen for static test). In the fatigue load test, the strain gauges and stress-strain measurement were used only at the beginning of the fatigue test for equal loading of the cylindrical specimen, which is a crucial factor. Therefore, each specimen was put into an exact position regarding equal stress - strain values on each strain gauges. Indeed, the strain gauges confirmed the equal loading. After this preliminary measurement, the resistive strain gauges have no function during fatigue test because they are not able to withstand 10 million cycles of continual loading. After the end of fatigue load tests, they had to be replaced by new set of resistive strain gauges for stress-strain measuring during static tests. In the lab, 10 million cycles of loading are enough of evaluated fatigue behavior (compromised time and realistic). 10 million fatigue cycles were chosen because it is a realistic number for representing life time of wind tower turbine, and it is also considered as a lower bound of the very high cycle fatigue domain. Fatigue testing is very time consuming process – this experiment focused on 20 years life time of wind turbine. In case to represent scenario with more than 10 millions cycles a higher stress level (0.6) than the real maximum stress (0.45) were applied.

Each specimen was exposed to sinusoidal loading between 0.6 and 0.1 level of stresses of maximum compressive stress gained from the static test (Table 3). The tests are carried with this frequency in order to be in the security area. If the material withstand to 10Hz, it will resist to lower frequency of loading. One continual dynamic load test took approximately 12 days. After 10 million cycles specimens were removed from the fatigue loading machine and prepared for static tests in a other loading machine.

Table 3: Characterization of the fatigue tests

Number of tests	$S_o : S_u$ [-] : [-]	$\sigma_o : \sigma_u$ [MPa] : [MPa]	$F_o : F_u$ [kN] : [kN]
1 (3)	0.6 : 0.1	128 : 21 (131 : 22)	360.4 : 59.4 (367.1 : 60.8)

4. RESULTS

4.1 Static compression tests

Table 3 presents the results of compression tests performed during the experimental campaign. The tests were carried out with axial stress control. The mean ultimate compressive strength gained from static tests performed in LafargeHolcim laboratory was 212.1 MPa, with a standard deviation of 10.3. Compressive strength of 217.8 MPa with a standard deviation of 11.3 was obtained from tests performed in KI laboratory. Final value 214.8 MPa with a standard deviation of 10.9 was calculated taking account the results from both laboratories. Characteristics in more detail are presented in Tables 4 and 5. All test performed showed good conformity, repeatability and very good material properties of UHPC material.

For the fatigue test at the experimental campaign, only, the mean value of compressive strength obtained by KI was used to define the applied upper and lower stresses.

Table 4: Results of static compression tests – LafargeHolcim, all results

Company	Specimen name/number	Diameter [mm]	Height [mm]	Weight [g]	Bulk density [kg/m³]	Ultimate compression force **F** [kN]	Compressive strength of the concrete **f** [MPa]
LafargeHolcim	LH P - 1	59.8	180.0	1279	2529	598.8	213.2
	LH P - 2	59.8	179.6	1280	2537	598.2	213.0
	LH P - 3	59.7	179.2	1290	2571	601.0	214.0
	LH P - 4	59.7	179.1	1275	2534	570.1	203.0
	LH-1	59.7	179	1274	2543	583.9	206.5
	LH-2	59.7	179	1274	2543	553.9	195.9
	LH-3	59.7	181	1296	2558	645.7	228.4
	LH-4	59.8	179	1274	2534	560.6	198.3
	LH-5	59.8	182	1301	2545	627.8	222.0
	LH-6	59.7	179	1273	2541	614.2	217.2
	LH-7	59.8	180	1283	2538	627.5	221.9
Mean value LafargeHolcim results					**2543**		**212.1**
Standard deviation					7.5		10.3

Table 5: Results of static compression tests – Klokner Institut, all results

Klokner Institute (KI)	KI P - 1	59.7	180.1	1282	2543	631,7	224.9
	KI P - 2	59.7	180.3	1281	2539	615.9	219.3
	KI P - 3	59.7	180.4	1283	2541	561.2	199.8
	KI P - 4	59.7	179.2	1274	2540	634.7	226.0
	KI-1	59.7	180.8	1285	2540	594.4	212.3
	KI-2	59.7	180.8	1285	2539	648.6	231.7
	KI-3	59.8	179.2	1273	2535	604.5	215.6
	KI-4	59.7	179.2	1271	2535	620.5	221.7
	KI-5	59.7	180.0	1280	2541	638.6	228.1
	KI-6	59.7	179.8	1273	2531	556.5	198.8
Mean value KI results					**2538**		**217.8**
Standard deviation					3.6		11.3
Mean value with all results					**2541**		**214.8**
Standard deviation					**9.1**		**10.9**

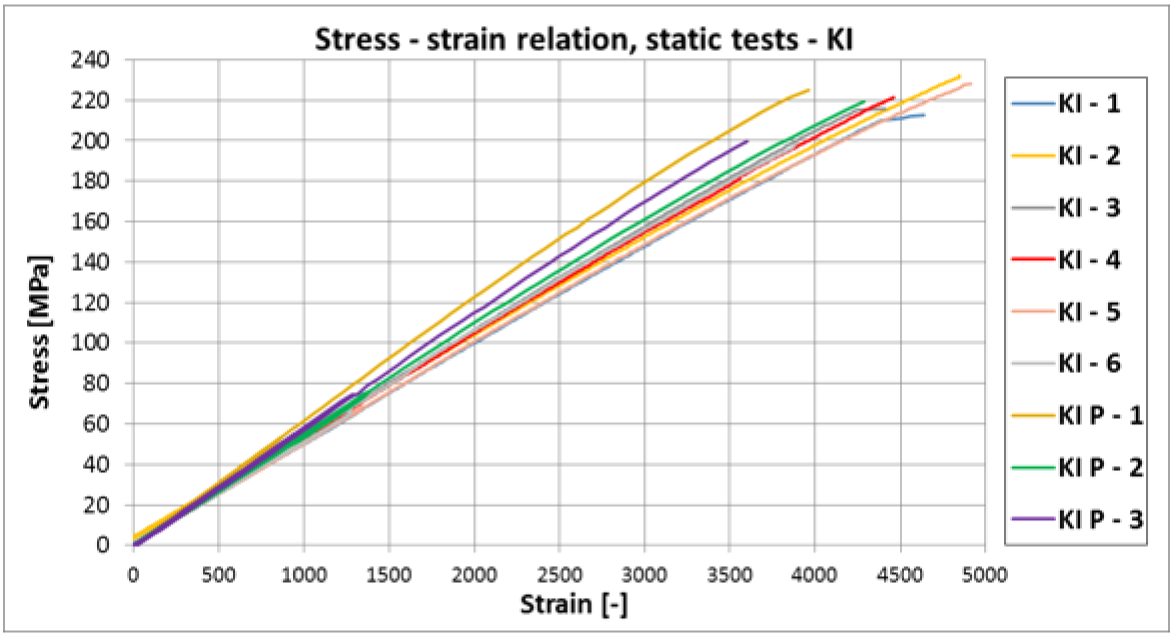

Figure 3: Stress – strain diagram of static tests

Typical damage pattern of cylindrical specimens after static tests is shown at Figure 4. Because of very high stress at the end of the test a very sudden and explosive drop of force was observed. This is the reason why almost linear lines of stress – strain dependence are presented at Figure 3. The differences between the observed curves are because different loading speed of two sets were tested (preliminary and final sets). High values of final compressive stress could be achieved by equal loading of each sides of the specimen.

Figure 4: Typical damage pattern – specimens after static tests

4.2 Fatigue tests

Four cylindrical specimens were tested on fatigue resistance. One specimen was used for the first fatigue test. The experimental campaign continued with 3 more specimens. Only a lower and uppers stresses were a little bit different. The applied lower /upper stresses (or force) are presented in Table 3. This was caused by different average compressive stress of specimens after static tests. For the last three specimens, the limits were calculated from average compressive strength achieved in Klokner Institute. The used lower stress in all tests was Su = 0.1 and the upper stress was So = 0.6. This was the worst chosen scenario of the fatigue test, because there is difference of 50% of final compressive strength value – almost 109 MPa (306 kN).

The main results from the fatigue tests were that specimens widtstand cycling without deterioration and measured compressive strength was the same as strength carried out from thre static tests. Results of the static tests after the fatigue tests are presented in Table 6. Very promising compressive strength results were obtained. No significance drop of final values of compressive strength was observed compared to specimens tested only in static compression. Mean compressive strength results from static tests of specimen after fatigue test were 220.9 MPa with standard deviation 7.9. Very good conformity (stress – strain relation) of the all static tests performed is presented in Table 6.

No deterioration or damage of cylindrical specimens was observed. Only small delamination zones of concrete on the bottom and upper edges during dynamic loading were noted. This delaminated zone has no effect to final compressive strength. Average values of stress - strain relationship were calculated from static and fatigue tests carried out in KI and these average relationships are shown in Figure 5.

Table 6: Results of compression tests (after fatigue tests)

Specimen No.	Diameter of the specimen	Height of the specimen	Weight of specimen	Bulk density of the specimen	Ultimate compression force **F**	Compressive strength of the concrete $\mathbf{f_c}$
	[mm]	[mm]	[g]	[kg/m^3]	[kN]	[MPa]
KI F- 1	59.9	179.2	1278.0	2531	636.0	225.0
KI F- 2	59.8	179.3	1276.4	2539	620.6	221.3
KI F- 3	59.8	179.5	1271.6	2527	596.5	212.7
KI F- 4	59.8	180.3	1272.6	2518	640.5	228.4
Mean value				**2528**		**220.9**
Standard deviation				10.5		7.9

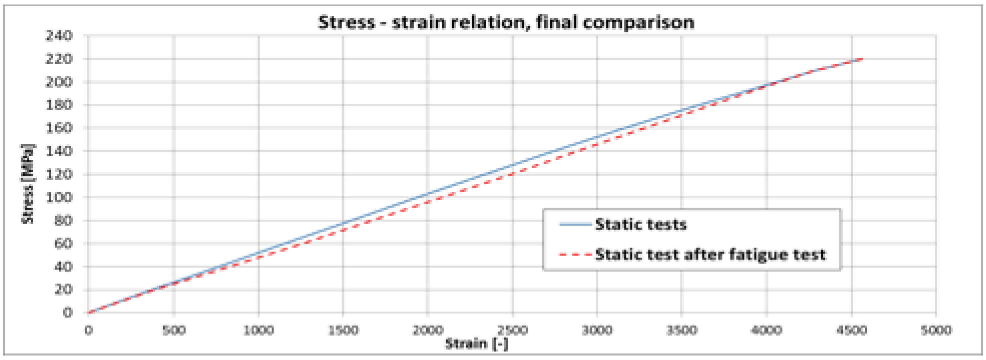

Figure 5: Stress – strain diagram of all static tests

5. CONCLUSION

Fatigue behaviour of Ultra High Performance Concrete (UHPC) was studied in this paper. Two different types of tests were carried out (static and fatigue tests). The compressive strength tests (static tests) were realized in order to obtain the stresses levels for the fatigue tests and to determine the effect of cyclic loading on the specimens after the fatigue test. The main conclusions of this study are:

- The mean ultimate compressive strength gained from static tests performed in LH laboratory was 212.1 MPa (standard deviation of 10.3) and 217.8 MPa (standard deviation of 11.3) in KI laboratory. Final value 214.8 MPa with a standard deviation of 10.9 was calculated taking account the results from both laboratories.
- Static tests carried out show the repeatability and the reproducibility of the results obtained in the two laboratories.
- UHPC specimens withstand 10 million cycles (a representing life time of wind tower turbine – realistic value) of fatigue (So = 0.6 and Su = 0.1, frequency = 10 Hz). No deterioration or damage of cylindrical specimens was observed after the fatigue tests. Only small delamination zones of the concrete on the bottom and upper edges were noted.
- The mean value of compressive strength before and after the fatigue tests shows, very close results. Mean compressive strength gained from static tests of specimen after fatigue test were 220.9 MPa with standard deviation 7.9.

- Obtained result is very promising and enables to state that, at the applied stresses levels, the UHPC wind tower may resist to the fatigue loading and can withstand to the loading for long time (approximately 20 years) of operation.
- If UHPC is applied this way production control testing is desirable to verify and confirm this statement.

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