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EXPERIMENTAL INVESTIGATION OF THE FATIGUE BEHAVIOR OF 3D PRINTED STEEL FIBER REINFORCED CONCRETE

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Abstract: Currently, the development of innovative production methods for concrete structures is progressing rapidly. As an example, the state-of-the art on 3D printing of cementitious materials has progressed from the pioneering work of printing mortars to printing with conventionally proportioned concretes at structural scale. Recent advances have even enabled printing of concrete reinforced with steel fibers. With the rapid development, including the improvement of material toughness from the addition of fibers, the road is paved for advanced applications, including utilization of 3D printed concrete as the sole load bearing system of larger structures. With increasingly complex structures, an increased need for documentation of material properties at certain load conditions follows.
This paper presents an experimental investigation of the fatigue behavior of 3D printed fiber reinforced concrete in compression. The experimental program is to be considered as a preliminary test program, providing indications on the question if the fatigue life of the fiber reinforced 3D printed concrete material can be compared to the fatigue life of conventional concrete, e.g. as predicted by the Eurocode provisions. The results are compared with similar tests on 3D printed concrete without fibers to demonstrate that the inclusion of fibers does not impact the fatigue behavior negatively. From the experiments conducted, it is found that the behavior of the 3D printed materials exposed to fatigue loading, is comparable to the prediction models for fatigue life of conventional concrete.

1 INTRODUCTION

In recent years, advances in technology have introduced 3D printing techniques of different materials, including cementitious materials. The potentials of 3D printing are typically the possibility of creating an optimized structure using less material, with a decreased labor requirement, resulting in increased construction speed among several benefits [1]. The optimized structures may lead to an increase in strength-to-weight ratio [2], and for similarly performing structures, the environmental impact can be smaller [3].

Due to the unconventional requirements for workability and early age properties to obtain an intermediate state where additional layers can be added on top within a short period of time, the challenges in creating a well-performing structure from design-phase, through construction-phase to the use-phase are several and there is a general need for experimental evidence and education [4] to promote 3D concrete printing (3DCP) as a viable alternative to traditional reinforced concrete structures.

The early generation of 3D printers designed for printing with concrete were limited by small nozzle heads, narrow supply pipes etc., essentially allowing printing with cementitious mixtures designed with a small maximum aggregate size – i.e. a mortar. The benefit is primarily the improved flexibility in design, however, the drawbacks are several and for load bearing applications, challenging the structural engineer on which design methods to rely on when performing structural analysis. Is it possible to use design methods developed for conventional concrete?

One step forward in comparing with conventional concrete is the upscale from a mortar material to printing mixtures containing larger aggregate sizes, comparable to what is used in conventional concrete. This paper aims to investigate experimentally the fatigue life of fiber reinforced 3D printed concrete. The research is motivated by an ambition to print a wind turbine tower solely by use of 3D printed concrete technology. The increased flexibility for geometrical design enabled by use of 3DCP compared to conventional prefabricated solutions (steel or concrete), outperforms the conventional methods in terms of geometrical footprint and transportation restrictions of large prefabricated elements, eventually making 3DCP a viable alternative to prefabrication methods.

Considering the typical loading scenarios of a wind turbine tower, where e.g. large bending moments are imposed on the structure (in combination with shear forces and torsional moments) from the wind load acting on the blades, the fatigue life of the material becomes a relevant material property to validate as the wind load is random and of dynamic nature. The experimental program presented in this paper intends to validate that the fatigue life of the fiber reinforced 3D printed concrete can be reliably assessed by use of code provisions for conventional concrete.

1.1 Eurocode provisions for fatigue life

The latest generation of Eurocode [5] provides the following formulas for verification of the number of cycles a concrete material can sustain before fatigue failure (Formula E.7):

$$N_i = 10^{k_i} \tag{1}$$

Where the exponent ki is calculated from: (simplified version of Formula E.8 [5]):

$$k_i = C \cdot \frac{1 - \frac{|\sigma_{c,max}|}{f_c}}{\sqrt{1 - \left|\frac{\sigma_{c,min}}{\sigma_{c,max}}\right|}} \tag{2}$$

The number of cycles is hence dependent on the maximum and minimum stress levels the concrete is exposed to and an empirical determined factor, $C = 14$. The relation is based on the linear damage theory or Palmgren-Miner Rule. To test if the relation can be safely adopted for 3D printed fiber reinforced concrete, a set of experiments were designed and tested, adopting a minimum stress level of 0.1 f_c (compression considered positive) and varying the maximum stress levels, see tested points compared to Equation (1) in Figure 1. As opposed to the provision in Eurocode, the experimental program was designed using mean strengths and not design fatigue strengths. Additionally, 10% extra cycles were added along with 100 cycles to allow the test machine to run in on the programmed frequency and load levels.

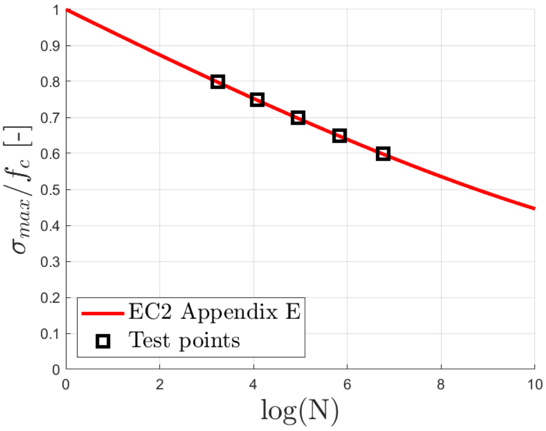

Figure 1: Eurocode relation for fatigue life verification of concrete and test points used for validation.

2 EXPERIMENTAL CAMPAIGN

The experimental campaign comprised 25 specimens, all a part of a larger experimental program designed to determine a variety of material properties (compressive strength, flexural strength, creep performance and similar) from a print trial of 3D printing conducted during the fall of 2024.

2.1 Test program

The test specimens were prepared from a larger structure printed as a wall element with a thickness of 22-25 cm and a length of several meters. Figure 2 shows how a slice of the printed wall was cut out by wet-sawing and prepared to a prismatic geometry as close as possible to 100 mm x 100 mm x 400 mm (B x L x H) for application of compression perpendicular to the print direction.

Figure 2: Printed material with indication of a typical specimen size, cut out from the 3D printed block.

The approach of the campaign was to first determine the static strength of the specimens, as an average of four samples, followed by initiation of the fatigue campaign with varying maximum stress levels (see Figure 1).

Specimens from two different prints were tested, one containing 0.8 vol% steel fibers (Specimens P16-P30) and a second mixture of similar proportions without steel fibers (Specimens P31-P40).

Figure 3: Specimen equipped with strain gauges, installed in test machine.

2.2 Experimental setup

All specimens were tested in a servo-hydraulic test machine with a capacity of 5 MN [6]. Most specimens were equipped with two strain gauges on two opposite facing surfaces, see example of a specimen installed in the machine in Figure 3. The tests were conducted at a frequency between 1 Hz and 4 Hz. The tests were conducted in DTU Structural Lab, part of the Center for Advanced Structural and Material Testing (CASMaT) at the Technical University of Denmark.

3 RESULTS

Table 1 contains the results of the static compression tests. In this relation, it should be noted that the results of Specimens* P17, P31, and P32, have been left out from average result used to define the load levels in the fatigue test. The average strength of the remaining specimens aligns with similar results of compression test on cylindrical specimens prepared from the same prints.

Table 1: Overview of specimens for static test of the uniaxial compression strength (prior to fatigue testing).

ID	B [mm]	L [mm]	f_c [MPa]
P16	99	102	62.5
P17	100	104	56.1*
P18	98	104	63.7
P19	100	101	67.5
P31	98	101	27.2*
P32	98	102	36.0*
P33	98	102	50.5
P34	98	100	51.9

Table 2 contains the geometry of the specimens tested in fatigue, including the maximum stress level ($S_{max} = \sigma_{c,max} / f_c$), the number of cycles applied and the residual strength of the specimens tested post fatigue. In this relation, it should be noted that for the higher stress levels, some specimens failed after a low number of cycles (< 100 cycles). This happened both for fiber reinforced specimens and specimens without fibers.

Table 2: Overview of specimens testing in fatigue, including number of cycles and the residual strength determined after fatigue loading.

ID	B [mm]	L [mm]	S_{max}	N	$f_{c,residual}$ [MPa]
P20	99	100	0.80	1183	69.1
P21	99	100	0.80	Failed	-
P22	101	104	0.80	Failed	-
P23	100	106	0.75	6424	67.8
P24	98	100	0.75	6424	68.2
P25	102	108	0.70	37937	65.0
P26	95	100	0.70	37937	69.4
P27	99	100	0.65	233582	61.2
P28	100	100	0.65	233582	66.8
P29	96	102	0.60	1499389	67.2
P30	98	105	0.60	1499389	70.7
P35	100	103	0.80	1183	60.2
P36	100	102	0.80	Failed	-
P37	98	99	0.75	Failed	-
P38	99	99	0.75	6424	57.40
P39	97	101	0.70	37937	58.18
P40	100	103	0.65	233582	53.8

The remaining specimens did not fail from application of the full number of cycles, including the 10 % extra compared to the predictions of Equation (1).

During the tests, the strain values measured at peak and valley points by the strain gauges were recorded synchronized with the applied load. From these values, an indicative value of the elastic modulus, E_c, can be calculated. Figure 4 contains results of two specimens, demonstrating that the elastic modulus decreased slightly within the first few thousand cycles to obtain a stable value for the rest of the test. In general, the strain values increased slightly in magnitude, however, the calculations of the elastic modulus did not indicate any further accumulated damage in the material. At a specified number of cycles, the full strain curve in five cycles were recorded with data collected at a frequency of 256 Hz. Results of full cycles confirmed the (simplified) calculated values of the elastic modulus presented in Figure 4.

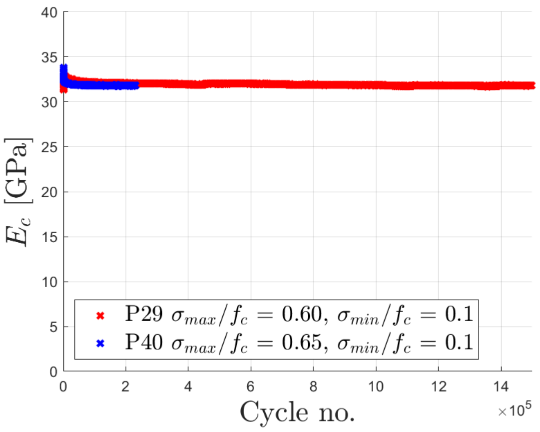

Figure 4: Development in calculated elastic modulus using peak and valley results.

In general, the calculated values of the elastic modulus for the non-fiber reinforced prints were smaller than the values calculated for the fiber reinforced mixture, which corresponds well with expectation considering the difference in compressive strength. Nevertheless, the values of the stabilized elastic modulus (mean of all cycles) of the printed concretes (in the range of 29 to 32 GPa) appear smaller than the expectation for a conventional concrete with a comparable compressive strength.

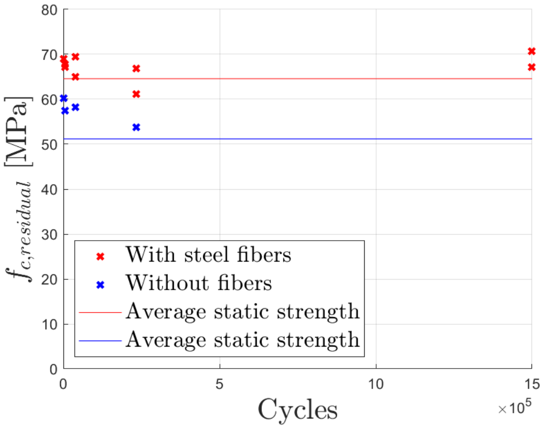

Figure 5: Residual uniaxial strength of specimens tested post fatigue testing.

In Figure 5, the residual compressive strength of the fatigue tested specimens can be seen. It appears that most specimens tested a higher strength than the equivalent static strength. The reason for this in unknown, however, may be related to the general scatter in results that can be expected for such a material, since it is not expected that the material will harden during fatigue loading and the difference in age was small compared to the age of the specimens (approximately 3 months hardening time at the time of testing).

4 DISCUSSIONS AND CONCLUSIONS

From the experimental evidence presented in the paper, there are no indications that the fatigue life of a 3D printed concrete with or without steel fiber reinforcement cannot be safely predicted by use of the provisions given in the latest version of Eurocode 2. The experimental results also demonstrate that the inclusion of steel fibers in the concrete mixture do not negatively impact the fatigue life when comparing to the results of fatigue tests on a similar 3D printed concrete mixture without steel fibers.

However, a concerning trend was identified for some specimens that visually appeared without defects or other reasons to disregard the specimens, as failure was observed at either a very low load level for static testing or within a low number of cycles for the fatigue test.

Despite no visual defects observed, the apparent significantly lower strength can potentially be explained by the quality of the printed material, assuming that a local defect in a single interface between adjacent printed layers may cause loss of capacity. During the handling and preparation of the specimens for the experimental campaign, a variation in print quality was observed. One of the severe flaws is shown in Figure 6, where the lack of coherence with the layers can be detected visually. This is a concerning observation, as there is a potential risk for one weak interface being decisive for the structural integrity of the entire structure. For the case of a wind turbine tower, there is no possibility of designing a structural redundancy to accommodate potential low cycle fatigue failures of the concrete.

A way to mitigate this, however, would be mapping of print parameters combined with an extensive experimental investigation to establish a set of acceptance criteria for the quality of 3D printed concrete structures. With this information, potential risks of collapse may be identified and mitigated already during the print process. This requires coordination between developers of software, materials and structural testing to work together to identify needs and solutions for collection of meaningful data.

Figure 6: Example of significant flaw originating from issues in the print process.

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