FLEXURAL FATIGUE OF HIGH AND ULTRA HIGH STRENGTH FIBRE REINFORCED CONCRETE

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Abstract
This paper presents the results of an experimental study on the bending behaviour of two concrete mixtures. A high strength fibre reinforced mortar, with a maximum aggregate size of 2 mm and 1.6% by volume of 13 mm long, 0.16 mm in diameter steel fibres and an ultra high strength concrete, with a maximum aggregate size of 7 mm and 2.5% by volume of 20 mm long, 0.3 mm in diameter steel fibres were used. The bending behaviour was tested with a four point bending test under static and fatigue loading on small beams (125/125/1000 mm.) The static bending performance highly depends on the fibre distribution in the beam; the more fibres are present, the higher the load bearing capacity. The way fibres are distributed and orientated depends on the casting method. Even though the fibres increase the maximum flexural tensile strength and improve the post-peak static behaviour, their contribution to the fatigue resistance is not very pronounced. The fatigue performance of both mixtures can be compared with conventional concrete, though fatigue results are difficult to evaluate due to the high scatter. The scatter, however, can be reduced by improving the workability and flow ability in the fresh state of a concrete mixture, in combination with an appropriate production technique.

1. INTRODUCTION
An important advantage of ultra high strength fibre reinforced concrete is that this material allows lighter structures. A consequence of the weight reduction is, however, that fatigue becomes an important design criterion in structures subjected to dynamic loads, for example in bridges. Ultra High Performance Fibre Concrete is not only an interesting material for new bridges, but as well for the repair of old bridge decks. First experiences were gained with substituting the asphalt topping of bridge decks by a high
performance steel fibre reinforced concrete layer bonded to the steel deck [1]. Better knowledge of the fatigue behaviour of high performance fibre concrete is therefore, in all respects, required.

This paper presents the experimental results on two different mixtures tested at Delft University of Technology. Static and fatigue tests were performed, with due attention to the fibre orientation and distribution. Image analysis was used to count the fibres and obtain information on their distribution in cross-sections of beams close to their fracture surface at the tests. The study is part of a PhD research project on fatigue of high performance cementitious composites.

2. CONCRETE MIXES AND TEST SETUP

The results presented in this study refer to two different concrete mixtures. One is a high strength fibre reinforced concrete, and will from now on be denoted by the acronym HSFRC. The other is an industrial ultra high strength fibre reinforced concrete, developed by the companies Eiffage and Sika. It will be referred to as BSI/CERACEM in this paper. The material ingredients of the two mixtures, the mixing and casting procedure and their general mechanical characteristics are presented briefly in this section.

The HSFRC is a self-compacting mixture that contains the following materials [2]: 358 kg/m$^3$ of a Portland cement CEM I 52.5R, 555 kg/m$^3$ of a blast furnace slag cement CEM II/A 52.5, 61 kg/m$^3$ of microsilica added as a slurry containing 50% of water, 1067 kg/m$^3$ of sand with a maximum aggregate size of 2 mm, 17.9 kg/m$^3$ of a polycarboxylic-ether based superplasticiser, 207 kg/m$^3$ of water and 125 kg/m$^3$ (a percentage of 1.6% by volume) of steel fibres. The fibres were 13 mm long, straight with a diameter of 0.16 mm. In the casting process, the cement and sand were first mixed together, after that the water and superplasticiser were added, followed by the microsilica and the steel fibres. The fresh state properties were controlled mainly by the slump spread from a 300 mm high cone, aiming at a spread of approximately 700 mm. The hardened state properties were checked by compressive and splitting tensile tests on 100 mm cubes. The mean compressive strength was 146 MPa; 20 MPa for the splitting tensile strength.

The BSI/CERACEM is a self-compacting mixture developed and patented by the industry [3], therefore only indicative values of its components and the mixing process will be given. 2355 kg/m$^3$ of a dry premix containing Portland cement (47%), microsilica (7%) and aggregates (45%) are mixed with 195 kg/m$^3$, that is 2.5% by volume, of steel fibres, 195 kg/m$^3$ water and 44.6 kg/m$^3$ polycarboxylic-ether superplasticiser. Also here, the fresh state properties were mainly controlled by a slump spread using a slightly different 200 mm high cone. The spread should be around 650 mm. The hardened state properties were tested on 100 mm cubes also. The mean compressive strength was 217 MPa and the splitting tensile strength was 28 MPa.
2.1 Test specimens and experimental set-up

The test specimens for the static and fatigue bending tests were small beams of dimension 125/125/1000 mm. They were cast separately into steel moulds. Six beams were prepared at one time, cast in two separate batches of three. The HSFRC beams were always cast by placing the concrete into the narrow side of the mould, and allowing it to flow to the other end. Most of the BSI/CERACEM beams were also cast in that way. Only a small number of them was produced by reducing the flow of the fresh concrete: it was placed in patches all along the mould length. These beams were tested only under static loads and the intention was to determine whether the production method influences the bending performance, and whether there is a preferential method to cast small beams with regard to a reduction of the scatter in the static flexural strength.

A four point bending test was used as the testing method for the static and fatigue tests. The same testing apparatus and an identical number of LVDTs were used for both loading types. The beams were tested at a span of 750 mm, loaded at their third points, which implies that the distance between the loading points was 250 mm. Two LVDTs were placed at midspan at the front and backside of the beam to measure the deflection. Eight LVDTs were placed at the bottom fibre of the beam over a total distance of 450 mm to measure the longitudinal deformation and therefore indirectly the crack openings. The static tests were performed with the average signal of the two LVDTs that measured the deflection functioning as control parameter. The fatigue tests were load-controlled. A sinusoidal load that ranged between two pre-set load levels was applied at a frequency of 10 Hz. The upper load was a certain percentage of the previously determined mean value of the static maximum load, while the lower load level was always 20% of the upper load.

3. RESULTS

The results of the static bending tests are presented as stress-deflection curves in Figure 1. Each curve is the average of six beams. Two curves are presented for the BSI/CERACEM mixture. The one shown in black is the average of six beams that were cast by letting the concrete flow from one end of the mould. This curve reaches the highest loads and has a pronounced deflection hardening branch. The other, grey curve, is the average of six beams cast without allowing the concrete flow. It indicates a different, less efficient bending performance. The average curve for the HSFRC is the average of six beams cast from one side into the mould, therefore allowing concrete to flow. Since the mixture has a weaker matrix and contains less fibres these beams have a lower strength than the BSI/CERACEM beams cast identically. They also show a lower stiffness but their ‘hardening’ branch is longer.
The two curves of the BSI/CERACEM in Figure 1 already show that mixtures can behave quite differently and further emphasise the importance of the casting method. The fibre distribution and alignment are mainly responsible for the differences. All beams were sawn at a cross-section close to their fracture surface after testing and pictures were taken. The fibres were reflected by the camera flash, providing a contrast to the cement matrix and aggregates. The fibres in the cross-sections were counted with image analysis tools. Results are presented in Figure 2. For the BSI/CERACEM, a direct relation between the number of fibres in the critical cross-section and the static strength could be observed. The same holds for the HSFRC, although the relation is not as pronounced. This is attributed to two facts. On the one hand, the scatter in the HSFRC was significantly less, especially since all beams were cast identically for that mixture while both casting methods were taken into account for the BSI/CERACEM mixture. On the other hand, the fibre diameter is smaller for the HSFRC (0.16mm instead of 0.3 mm), and the quality of the pictures and the software had reached their limit during the analysis, contributing to less accurate results. The results of the image analysis for the BSI/CERACEM are presented in detail in [4], and more general information regarding fibre orientation and fibre count is given by Grünwald [5] and Akkaya et al. [6].
Tables 1 and 2 show the results of individual beams tested at five different upper load levels for both mixtures. It is evident that the interpretation of the results is difficult due to the high scatter. The scatter is smallest for the HSFRC mixture, which is most obvious when comparing the logarithms of the numbers of cycles to failure. The HSFRC is the better workable mixture that results in lower scatter in the static material strength. The beams that did not fail at ten million load cycles are listed in the table too. They were treated as run-outs and their values are not regarded for the determination of the average number of cycles at each stress ratio. The average number was not calculated for the HSFRC tested at an upper load level of 70%, since all beams except one did not fail at ten million load cycles. The beams that had not failed were either tested under fatigue loading until failure, by increasing the upper load, or tested statically up to failure, but these results are not listed here.

Table 1: Fatigue tests results of the BSI/CERACEM ; number of cycles to failure.

<table>
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<tr>
<th>Stress ratio</th>
<th>0.55</th>
<th>0.65</th>
<th>0.70</th>
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</table>

Average 1969593 21675 174307 102089 6944
Table 2: Fatigue results of the HSFRC; number of cycles to failure

<table>
<thead>
<tr>
<th>Stress ratio</th>
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The direct results from the fatigue tests can in the present stage not provide reliable S-N lines since even more test results for each load level are needed. However, Figure 3 shows that for both composites a direct relation (on a logarithmic scale) between the slope of the deflection and the number of cycles to failure exists. This slope refers to the typical second part of a fatigue experiment when the deflection increase is constant. It is mostly the longest part of the total fatigue life of a specimen. In the figure, the results of the HSFRC are marked with circles and the ones of the BSI/CERACEM in squares.

Parant [7] also observed a relation between the slope in the deflection at the second stage of a fatigue experiment and the initial deformation, i.e. the deflection reached at the end of the first load cycles, when the load is gradually applied before the sinusoidal load cycles begin. The initial deformation was also related to the number of cycles to failure. Moreover, there seemed to be a deformation threshold since beams that showed an initial deformation below a certain value did not fail, at least not until two million load cycles. Parant performed experiments with a high performance composite containing a total of 11% of steel fibres in three different fibre lengths. The same procedure was applied for the two mixtures in this study. Only for the HSFRC a similar relation appears to be valid; the deformation threshold was not found for the BSI/CERACEM. The relation between the initial deformation and the number of cycles to failure is shown in Figure 4. The HSFRC beams that had not failed after ten million load cycles are also included to visualise the deformation threshold.
4. DISCUSSION

The static tests show the effect of the production method, which influences fibre distribution and alignment, as well as the scatter in strength. The average peak strength of the BSI/CERACEM cast with the flow method was 29.9 MPa with a coefficient of variation (average value divided by the standard deviation) of 11%, while the beams cast by restricting the flow not only had a much lower average value of the peak strength, namely 19.1 MPa, but also had a twice as high coefficient of variation of 22%. That was the main reason that led to the decision to keep the flow method as the preferred production method used for the test specimens for the fatigue tests, thus keeping the scatter in the material strength as low as possible. The HSFRC was only cast with the flow method and had an average static flexural strength of 23.9 MPa (coefficient of variation of 8%). It is evident that the use of a different production method alters the
mechanical characteristics and fibre distribution. This has been confirmed in a previous study [2], where beams were cast with the flow method and with a shovel, as described in RILEM regulations for fibre reinforced (but not self-compacting) concrete. The beams were notched, had dimensions of 150/150/600 mm and were tested in a three point bending tests at a span of 500 mm. The beams cast with the flow method showed the highest flexural strengths, namely 24.9 MPa, whereas 16.8 MPa was the average for the ones cast with a shovel.

The fatigue results are difficult to interpret due to the high scatter. This is a common problem in these kind of tests, also for plain concrete. One of the contributing factors is the scatter in the static material strength; since fibre reinforced concrete normally has higher scatter compared to plain concrete, the scatter in fatigue results is also expected to be higher compared to plain concrete. The average numbers of cycles to failure per load level shown in the Tables 1 and 2 should decrease with increasing load level, but this was not the case for the results presented. This view changes when the run-outs, the specimens that had not failed after ten million load cycles, were included in the mean value. This is only indicative since their actual number of cycles to failure, if it exists, was not obtained. For the BSI/CERACEM at a stress ratio of 0.55 and 0.65 this mean value would change into 4461954 and 2516256, respectively. The modified values for the HSFRC would be 3177716 and 2577654 for the stress ratios of 0.75 and 0.80 respectively (at a stress ratio of 0.70 the average would be 9103101 since only one beam of the seven tested did actually fail before ten million cycles). Probably more test specimens are needed for each load level in order to get better interpretable results. Also the load levels, especially for the HSFRC, were chosen quite close to each other with a 5% difference. This was done because almost no beam failed at a ratio of 0.70. Therefore, it was decided not to investigate lower load levels in the following tests. The applied levels then had to range between 0.75 and 0.90.

A statistical analysis was performed on both mixtures to evaluate the results, but also here more tests specimens were probably needed at each load level in order to get more reliable predictions. A detailed explanation of the performed statistical operations is given by Singh and Kaushik [8]. In the analysis, the stress ratios 0.70, 0.75 and 0.80 were merged into a stress level of 0.75 for the BSI/CERACEM mixture, and the ratios 0.75, 0.80 and 0.85 were merged into a level of 0.80 for the HSFRC since the numbers of cycles to failure were almost similar for these levels. The two parameter Weibull distribution was found to fit the results and the values of these parameters were calculated using (1) the graphical method, (2) the method of moments and (3) maximum likelihood estimates and the average values of all three methods were used as final values. The applicability of the Weibull distribution was checked with a Kolmogorov-Smirnov goodness-of-fit test. With these parameters, probabilistic predictions of the number of cycles to failure for the applied stress levels were determined, see Table 3. The results were rounded by a multiply of hundred.
Table 3: Probabilistic fatigue lives for different failure probabilities.

<table>
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<tr>
<th>Pf</th>
<th>S=0.55</th>
<th>S=0.70</th>
<th>S=0.80</th>
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<td>2918500</td>
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5. CONCLUSIONS

- The production method influences fibre alignment and distribution and also the flexural mechanical properties, of the two high performance fibre reinforced composites used in this study.
- Fatigue results show high scatter and are difficult to interpret. However, the fatigue performance of the HSFRC was in relative terms better compared to the CERACEM, partly due to its better workability and lower scatter in material strength. This implied that more load cycles to failure could be endured at higher percentages of the static mean flexural strength. In absolute terms, the CERACEM had a better fatigue performance; since the mixture has a flexural strength 10 MPa higher than the HSFRC, so it can be subjected to higher loads.

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