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Fatigue behaviour of strain-hardening cement-based composites (SHCC)

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ABSTRACT

The safe use of strain-hardening cement-based composites (SHCC) in structural and non-structural applications often requires a solid knowledge of the mechanical performance of this novel material under cyclic loading. The article at hand presents the findings of a comprehensive experimental investigation focusing on fatigue behaviour and failure mechanisms of SHCC made with polyvinyl-alcohol fibre and subject to various loading regimes. Uniaxial tests were performed both as tension-swelling tests and alternating tension-compression cyclic tests. While the upper reversal point was controlled – depending on the chosen regime – either by a given deformation increment or load level, the lower reversal point was always controlled by a given load value. The experiments revealed a pronounced decrease in the number of load cycles to failure with increasing upper stress level, smaller applied strain increments and with transition from purely tensile loading to alternating tension-compression regime. Furthermore, the effects of these tests parameters on strain capacity and other material properties of SHCC were investigated. On the basis of the test results, evaluation of the crack patterns and microscopic analysis of the conditions of the fracture surfaces, four various failure modes were identified, each of them typical for particular cyclic loading scenarios.

1. Introduction

Strain-hardening cement-based composites (SHCC), also often called engineered cementitious composites (ECC), are a particular type of fibre reinforced concrete (FRC), which exhibits a tensile strain capacity of several percent [1]. The name SHCC highlights a specific stress-strain behaviour of this material in monotonic, uniaxial tension tests. After a linear-elastic stage prior to first cracking, the stress-strain curve changes its inclination dramatically due to the gradual formation of a large number of fine cracks bridged by polymeric fibres. The increase in stress and the formation of new cracks continue until the crack-bridging capacity of the fibres in the "weakest" crack is reached. Then the localisation of failure occurs and the material exhibits the strain-softening behaviour characteristic of most types of FRC. This softening behaviour is caused by fibre pull-out and fibre rupture in the final crack.

While the mechanical performance of SHCC under monotonic, quasi-static and partly dynamic loading has been extensively investigated over the last two decades, see, for example [2,3,4,5], only little research has been performed on the behaviour of SHCC subject to cyclic loading. This is a serious limiting factor with respect to prospective practical applications of SHCC, since knowledge of fatigue behaviour is obviously absolutely necessary for structural design, specifically in estimating the service life of many objects of modern infrastructure such as bridges, railway structures, roads, windmills etc. The use of new materials like SHCC could considerably extend the service life of such structures and reduce costs for their maintenance and repair [6,7,8]. Furthermore, knowledge of cyclic behaviour is needed for seismic design, even though the number of cycles is very low under seismic loading when compared with the loading cases mentioned above; see, for example [9,10].

First experiences with the fatigue behaviour of SHCC were gained from load-controlled bending tests. Zhang and Li [11] observed a pronounced increase in bearable number of cycles with decreasing load level, the behaviour known also for other materials. Suthiwarapirak, Matsumoto and Kanda [12,13] confirmed these findings. Additionally, they observed a reduction in number of cracks with decreasing fatigue stress level. In that experimental work up to 2 million load cycles could be reached in tensile regimes [13].

In the deformation-controlled tension-compression experiments by Fukuyama et al. [9] only about five cycles were applied until the strain capacity was exhausted. The envelope curve for the cyclic tension took a very similar course to that of the curve obtained from the corresponding monotonic tension tests. In contrast, Douglas and Billington [10] found that the envelope of the stress-strain curve from the cyclic tests was below the corresponding relationship measured in the monotonic regime. The difference was particularly pronounced in the experiments with high strain rates. Jun and Mechtcherine [14] performed uniaxial cyclic tension tests and did not observe any pronounced effect of tensile cyclic loading on material performance in terms of stress-strain response. However, because of the relatively large deformation increment

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of 0.1% chosen, the number of loading cycles to failure was very moderate. The analysis of the hysteresis of the stress-strain curves showed a decrease in the material stiffness with an increasing number of loading cycles. The hysteresis further revealed a considerable partial inelastic deformation in every loop. Mechtcherine and Jun [15] reported the results of load-controlled cyclic tension test on pre-cracked SHCC specimens. The strain capacity was not negatively affected in that test series in comparison to monotonic tension loading. However, the maximum number of loading cycles in the experiments was about two thousand only. Similar to other investigations cited in which the cycle numbers were even smaller, this is not representative of most structural and non-structural applications with cyclic loading as the relevant scenario.

The article at hand reports on experimental investigation intended to enhance the knowledge of the performance of SHCC subject to cyclic loading. Specifically, the effect of alternating tension-compression loading as well as behaviour under a high number of loading cycles must be studied both in deformation-controlled and load-controlled testing regimes. Additionally, cracking patterns as well as the conditions of fracture surfaces need to be studied closely in order to obtain information on cracking processes and mechanisms for various loading scenarios.

2. Experimental program

2.1. SHCC composition and processing

For the experimental work in this research project a well established SHCC composition developed at the TU Dresden was chosen as in [14, 16], see Table 1. The binder was a mix of Portland cement type 42.5 R-HS and fly ash. Only very fine aggregates, quartz sand with particle sizes ranging from 0.06 mm to 0.20 mm, were used. Such small grain sizes were necessary to achieve a uniform distribution of fibres. The mixture contained 2% by volume of polyvinyl-alcohol (PVA) fibre with a length of 12 mm and a diameter of 40 μm. Adequate workability was achieved by using a superplasticizer and a viscosity agent.

When producing the SHCC under investigation, first, all dry components were homogenized in a mixer. Subsequently, the water was added and the components were mixed until a plastic consistency of the mix was achieved. Next, the fibres were added during continuous, relatively slow mixing, followed by the intensive mixing needed for good fibre distribution. Finally, the superplasticizer was added to achieve the required consistency of the mix.

All specimens were cast horizontally in dumbbell shaped metal forms of dimensions 24 mm (40 mm at the ends) × 40 mm × 240 mm, see also [14]. After casting, the moulds were covered with plastic plates and stored for two days in a room at controlled temperature of 22 °C. Following de-moulding, the specimens were placed in plastic boxes and stored under a controlled temperature of 20 °C until testing. Because of the fibres, a perfect plane levelling of the fresh mix in the mould was not achievable. In order to produce flat surfaces, the superfluous material was cut off with a circular saw after the SHCC had hardened.

The specimens were prepared in different batches. To prevent the influences of some possible variations in the quality of the individual mixes, specimens from several batches were used for each parameter combination under investigation. All specimens subject to cyclic tests were age approximately 56 days.

The cyclic tests were performed in a testing machine under stable climatic conditions of 20 °C and 65% RH with non-rotatable boundaries, achieved by using stiff metal adapters and special fast-hardening glue. Two LVDT's attached to two opposite sides of the specimen were used to measure the deformation of the specimen at a gauge length of 100 mm, see also [14]. Additionally, the data for force, crosshead displacement and time were recorded.

Table 1
Composition of SHCC under investigation, in kg/m^3.

Cement CEM I 42.5 R-HS	Fly ash	Water	Quartz sand 0.06/0.20	Super-plasticizer	Viscosity agent	PVA fibres
505	621	338	536	8.5	3.2	26.0

2.2. Testing procedures

2.2.1. General information

The experimental program consisted of three different testing series. Each production batch consisted of 12 specimens. The first series, reference and control, consisted of uniaxial, monotonic tensile tests at a specimen age of 28 days. For this, three specimens were randomly chosen from each batch so that the production quality could be controlled on the one hand, and representative reference stress-strain diagrams could be obtained on the other. Batches which yielded strain capacities below 2.5% in these control tests were excluded from testing in cyclic regimes. The strain rate was 10^{-2} s^{-1} in this test series. The control value for the steering of the machine was its crosshead displacement. The displacement rate was chosen on the basis of preliminary tests so that the given strain rate for SHCC specimens could be reached. This arrangement was chosen because the testing machine allowed only one LVDT to be used for the test control, which was considered inappropriate for the experiments performed.

Cyclic tests were performed in two different regimes constituting two further testing series, namely, deformation-controlled cyclic tests and load-controlled cyclic tests.

2.2.2. Deformation-controlled regimes

All deformation-controlled uniaxial tension and tension-compression tests were performed using a strain rate of 10^{-2} s^{-1} which corresponds to low-speed dynamic regime characteristic for traffic loads. Note that in comparison to quasi-static testing at lower strain rates a lower strain capacity and a higher tensile strength can be expected for testing at the chosen strain rate [14,17].

The machine-control software enables the setting of upper and lower reversal points independent of one another. As a result, chosen deformation values could be set as reversal point criteria during the tensile part of the cycle, while load-controlled reversal points were used for the compressive part. The lower reversal point was load-controlled. Three different load levels were investigated: $\sigma = 0$ MPa, $\sigma = 25\%$ of the compressive strength of SHCC under investigation and $\sigma = 50\%$ of the compressive strength.

The upper reversal point was deformation-controlled. A particular incremental increase in strain in each cycle, starting from the very first one, was chosen and kept constant over the entire experiment. Three different deformation increment sizes were used: a large one of 0.2%, a medium one of 0.002% and a small one of 0.00002%. Fig. 1 shows an

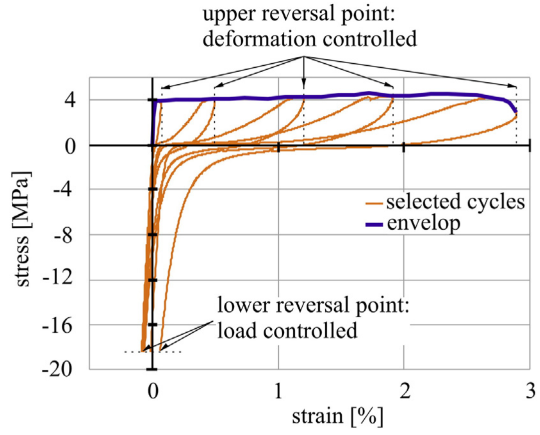

Fig. 1. Schematic presentation of deformation-controlled testing regimes.