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Fatigue behaviour of high-strength concrete with respect to strain and stiffness

Nadja Oneschkow *

Institute of Building Materials Science, Leibniz Universität Hannover, Appelstraße 9A, 30167 Hannover, Germany

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ABSTRACT

The fatigue behaviour of concrete, and especially of high-strength concrete, has become more important for the design of structures due to more slender structures, which are more sensitive to fatigue loading, or due to wind turbines, which are typically exposed to high-fatigue loading. The fatigue behaviour of a high-strength concrete was investigated within a research project with respect to the influence of maximum stress level, loading frequency and waveform. The investigations were focused on low-cycle-fatigue. The influence on numbers of cycles to failure and on the developments of strain and stiffness were systematically analysed. Selected results are presented in this paper. For the three influences investigated the results show certain systematologies in the change of strain and stiffness parameters with respect to the change in number of cycles to failure.

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1. Introduction

Conventional reinforced and prestressed concrete constructions are characterised by massive cross-sections. Permanent loads are usually higher than variable loads for these constructions and, therefore, fatigue loading relevant for the design rarely exist. However, developments in concrete technology in recent decades have led to high-performance concretes with increasing strength and very good flow properties. These high-performance concretes enable structural engineers to draft more slender reinforced and prestressed concrete constructions. The permanent loads and, therefore, the ratio between permanent and variable loads become smaller due to the related reduction of the cross-section. Such constructions are more sensitive to oscillations and, thus, fatigue verification becomes relevant for the design. Furthermore, structures such as wind turbines are characteristically exposed to high fatigue loading. In addition, the fatigue verification currently applied includes significantly higher reductions in fatigue resistance for high-strength concretes than for normal-strength concretes [1].

The fatigue behaviour of concrete has been investigated for about 100 years, but the documented investigations are mostly restricted to the analysis of numbers of load cycles to failure in order to characterise the point of failure. The developments of strain and stiffness as two properties describing the fatigue behaviour in the sense of material behaviour have rarely been investigated to the extent of the work described in the following. In literature some investigations including the development of strains and stiffness are documented but often only a few selected parameters are analysed. Furthermore, there are only a few and often single results available concerning the possible influence of the maximum stress level, the loading frequency and the waveform on the developments of strain and stiffness, e.g. [2–4]. Coincidently, there are significantly fewer results documented for high-strength concretes, also with respect to numbers of cycles to failure, than for normal-strength concretes. Thus, even today, only a little knowledge is available concerning the process of material degradation in concrete due to fatigue loading.

The fatigue behaviour of a high-strength concrete under pure compressive fatigue loading was investigated intensively within the scope of a research project [5,6] focusing on low-cycle-fatigue. Thereby, influences of the maximum stress level $S_{c,max}$, the loading frequency f_P and the waveform (sinusoidal or triangular) were considered. Instead of numbers of cycles to failure, the developments of strain and stiffness were focused on as a first step towards a more mechanism-orientated analysis of concrete fatigue. Of course, the numbers of cycles to failure were also determined, especially for analysing the possibility of existing relationships between the influences on the number of cycles to failure and the influences on the developments of strain and stiffness. Additionally, investigations were conducted with respect to sustained loading and monotonically increasing loading with high rates of loading in relation to fatigue behaviour [5].

* Tel.: +49 (0)511 7625341.
E-mail address: n.oneschkow@baustoff.uni-hannover.de
URL: http://www.baustoff.uni-hannover.de

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Nomenclature

Meaning of symbols

d	diameter [mm]
$\bar{E}^{II}_{S,N}$	gradient of development of stiffness in phase II (MPa)
$\Delta E_S^{0.0-1.0}$	percentile loss of stiffness (%)
F_{cm}	mean value of maximum compressive load (kN)
$f_{cm,cube150}$	compressive strength for 150 mm cube (MPa)
f_P	loading frequency (Hz)
h	height (mm)
N_f	number of cycles to failure (–)
$S_{c,max}$	maximum stress level (–)
$S_{c,min}$	minimum stress level (–)
t_U	duration until failure (s)

Meaning of Greek letters

ε^f	strain at failure (‰)
$\varepsilon^{1.0}_{max}$	end strain at maximum stress (in the last complete cycle) (‰)
$\Delta\varepsilon^{0.0-1.0}_{max}$	overall growth of strain at maximum stresses (‰)
$\Delta\varepsilon^{0.0-1.0}_{min}$	overall growth of strain at minimum stresses (‰)
$\bar{\varepsilon}^{II}_{max,N}$	gradient of development of strain at maximum stresses in phase II (–)
$\bar{\varepsilon}^{II}_{min,N}$	gradient of development of strain at minimum stresses in phase II (–)

Meaning of abbreviations

HPC	high-strength concrete investigated
PVC	polyvinyl chloride
R.H	relative humidity
sin	sinusoidal
tr	triangular
wf	waveform

This was one reason for considering triangular waveform in the fatigue investigations. The most important results of the fatigue tests are presented in this paper.

2. Concrete and specimens

The experimental investigations were conducted on a high-strength concrete with an average 28-day compressive strength of $f_{cm,cube150}$ = 116 MPa after water storage. The high-strength concrete was classified in concrete class C80/95. The maximum grain size was 8 mm. The mixture contained the following constituents:

Cement CEM I 52,5 R HS/NA, crushed stone 2/8 (granite), sand 0/2, fly ash, silicafume-slurry, super-plasticiser (PCE), defoamer and water.

The experimental investigations were conducted using cylindrical specimens with the dimensions d/h = 60/180 mm. PVC tubes, which were braced between two wooden plates, were used as formwork. The concrete was filled into the formwork in two layers and each was compacted. The specimens were cast to a height of $h \approx 250$ mm. Subsequently, they were cut at both ends to the required height of 180 mm in order to ensure the necessary concrete quality at the upper and lower ends of the specimens. The PVC formwork was removed after 48 h and the cylinders were stored in standardized conditions (20 °C/65% R.H.) until testing. Before testing, the loading surfaces of the cylinders were firstly plane-parallel ground and afterwards, polished, to achieve more centric loading and more uniform stress distribution. Additionally, cubic specimens with an edge length of 150 mm were included in each batch of concrete for testing the 28-day compressive strength. About 31–36 cylindrical specimens were available in each batch for the fatigue investigations.

3. Fatigue tests

3.1. Experimental set-up

A servo-hydraulic universal testing machine was used for the fatigue tests (see Fig. 1). This machine can be used with either a 1 MN or a 10 MN actuator. The 1 MN actuator was used in this research project. This configuration enables cyclic loading with different waveforms and loading frequencies up to f_P = 10 Hz and above.

The test set-up used is shown in Fig. 2. It can be seen that the specimens were tested using an external calotte, which was place underneath the specimens. The upper pressure plate is fixed. The load is applied upwards and, therefore, the load cell is placed on the immovable upper side. The actuator stroke and force were measured during the tests. In addition, the axial deformations of the specimens were measured using three laser distance sensors which were positioned at 120° from one another. Thereby, the measuring length corresponded to the height of the specimens. Furthermore, the temperature of the specimens surface was also measured using an infrared sensor.

The data was measured continuously, whereby the sampling rate was chosen with respect to the loading frequency with the

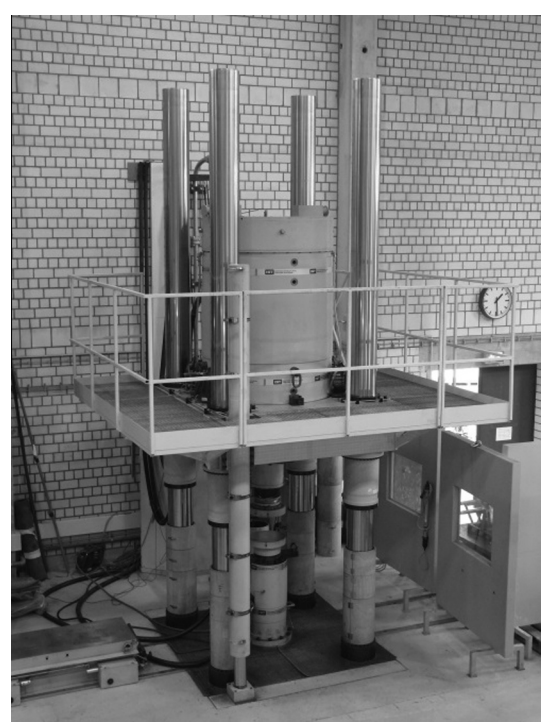

Fig. 1. Servo-hydraulic universal testing machine [7].

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