Fracture Mechanics of Concrete Structures
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EXPERIMENTAL INVESTIGATIONS ON FRACTURE AND DAMAGE OF CONCRETE DUE TO FATIGUE

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Abstract
A series of deformation controlled three-point bend tests on notched beams were performed to determine the fatigue behaviour of concrete. In these tests an improved experimental set-up allowed to investigate both the ascending and the descending branches of the load-crack opening relation and the load-deflection curve, respectively, even for high cycle fatigue loading (up to 10^6 cycles). As a result a significant decrease of the net flexural strength $f_{tn,fl}$ and an increase of the critical crack mouth opening displacement $CMOD_0$ with increasing number of load cycles were observed. The fracture energy G_F appears to a large extent to be independent of this test parameter.
Keywords: Fracture energy, fatigue, cyclic damage, bend tests

1 Introduction

Fracture and damage of concrete under static and dynamic loading are characterized by the development and spreading of microcracks. While suitable models to describe the material behaviour of concrete under static tensile loading are available, a corresponding approach for failure under cyclic tensile loading is still missing. Until now, in research studies mostly so called Wöhler tests were performed. These experiments provide a relation between maximum stress or stress amplitude and the number of load cycles to failure. However, they do not allow to describe the softening behaviour of concrete because of the applied force control, which consequently leads to an instable crack propagation.

This experimental study aims to create a basis for the derivation of new models for fatigue of concrete using a fracture mechanics approach. To derive the fracture mechanical properties of concrete, in particular the fracture energy G_F and the critical crack mouth opening displacement $CMOD_0$ as well as the net flexural strength $f_{tn,fl}$ a series of deformation controlled three-point bend tests were performed. Hereby, in contrast to previous experimental investigations by means of low cycle tests (see e.g. Duda (1990) and Hordijk (1991)) the number of load cycles to failure was chosen as the main test parameter varying in a broad range. Based on these tests, the influence of the number of load cycles on the crack development in concrete should be studied.

2 Experimental investigations

2.1 Concrete composition and preparation of specimens

The concrete was mixed using an ordinary Portland cement CEM I 32,5 R. The mix proportions by mass of water/cement/aggregate were 0.63/1/6.5. As aggregates quartzite sand and gravel with a maximum aggregate size of 16 mm were used. The average compressive strength of the concrete obtained from tests on cube specimens (size 150 mm) at an age of 28 days was found to be 33.5 MPa.

For the tests beams with a length l = 860 mm, a height d = 200 mm and a width b = 100 mm have been used. The span of the beams s was fixed to 800 mm. A 100 mm deep notch (relative notch depth = 0.5) was sawn in the middle of the span in order to obtain a stable crack propagation and to minimize the energy dissipation outside the notched cross-section.

For the preparation of the specimens first large concrete slabs (860×500×200 mm³) were cast. After demoulding, the slabs were cured 7 days under water before a part of them was sealed to prevent loss of moisture. The other part was cured unsealed in a climatic chamber at a relative humidity of 65% and a temperature of 20 °C. At an age higher than 28 days the specimens were sawn out of the concrete slabs and were stored under the corresponding conditions. The age at testing varied between 20 and 27 months. Further details may be found in a report by Müller et al. (1998).

2.2 Test set-up

The tests were carried out as three-point bend tests on a general-purpose hydraulic machine. The machine had a very stiff set-up and therefore only small deformations of its own could occur. The deflection of the concrete beams was measured by linear variable differential transducers (LVDTs) which were attached directly to the specimens by means of a special frame device in order to eliminate the effect of settings of the boundaries on the result of the deflection measurement.

The deformation control was achieved by an analogous PID (proportional, integral, derivative) controller. Besides the deflection δ, the crack mouth opening displacement CMOD was measured and used as control signal in order to maintain a constant crack mouth opening displacement rate (dCMOD/dt = const.). Therewith it was possible to obtain a stable crack opening and subsequently a stable crack propagation.

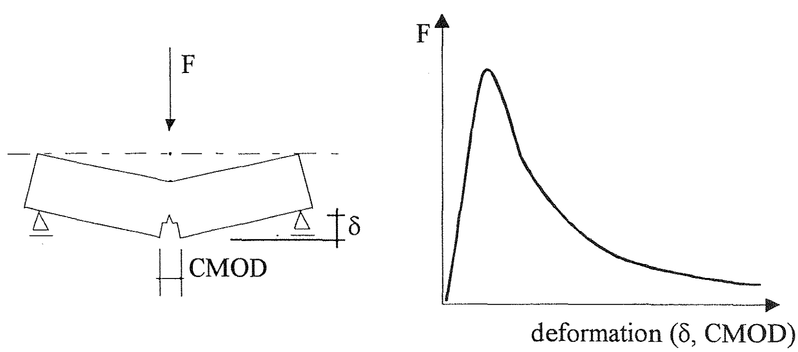

Fig. 1. Schematic view of the tested specimens and a typical load-deformation relation

A schematic view of the loaded specimens and a typical obtained load-deformation relation are shown in Fig. 1. For more details concerning the test equipment see e.g. Krupke (1995) and Müller et al. (1998).

2.3 Experimental programme

The main test parameters in the experiments on fatigue were the number of cycles to failure, the crack opening rate and the curing conditions. Hereby the number of load cycles varied from 1 (static tests) over 10 (low cycle fatigue tests = LCF) and 100 (medium cycle fatigue tests = MCF) up to 1 million (high cycle fatigue tests = HCF). A series of HCF tests were carried out by using a crack opening rate, which was 4 times lower than the original crack opening rate dCMOD/dt = 0.14 mm/s. The sealed and unsealed specimens were used to investigate the influence of the curing conditions on the fatigue behaviour of concrete.

The fatigue tests were accompanied by a comprehensive programme of further experiments, in particular static loading tests, Wöhler tests and short-time creep tests. The results of these experiments were published in a report by Müller et al. (1998).

3 Experimental results

Typical load-deflection curves for a static and a medium cycle fatigue test with 100 load cycles on unsealed specimens are shown in Fig. 2. The F-δ curve for the MCF test shows a shape of its envelope curve being similar to the curve of the static test. Furthermore a continuous stiffness degradation can be seen by the decreasing gradients of the loading as well as the unloading cycles.

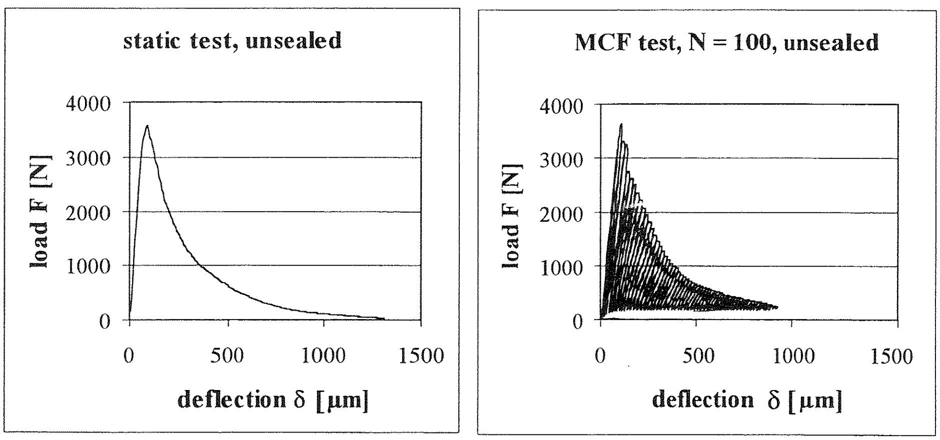

Fig. 2. Typical load-deflection curves for a static test (left) and a MCF test with 100 load cycles (right)

The net flexural strength $f_{tn,fl}$ was calculated considering the material behaviour as linear-elastic, see equation (1).

$$f_{tn,fl} = 1.5 \cdot \frac{\left(F_m + \frac{m\,g}{2}\right)s}{b(d-a_0)^2} \tag{1}$$

In equation (1) F_m is the maximum load and $m \cdot g$ is the weight of the beam. The geometric dimensions are explained in Fig. 3.

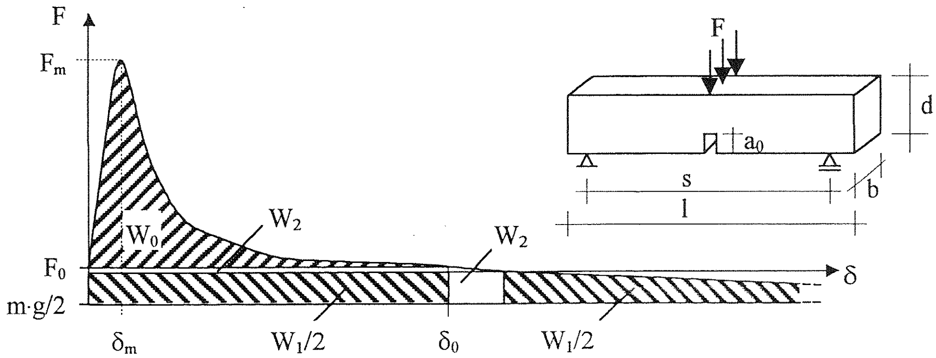

Fig. 3. Decomposition of the fracture energy and geometric dimensions of the specimens

The values for the fracture energy according to the RILEM recommendation (RILEM TC 50-FMC, 1985) were calculated by equation (2).

$$G_F = \frac{W_0 + W_1 + 2 \cdot W_2}{b(d-a_0)} \tag{2}$$

In equation (2) W_0 denotes the area under the load-deflection curve, W_2 results from the difference between the log-off load F_0 and the zero load $F = 0$. The log-off load $F_0 = 25$ N was chosen to obtain a defined end of each test. W_1 considers the dead weight with $W_1 = 2 \cdot (mg/2 \cdot \delta_0)$, see Fig. 3. The used decomposition of the fracture energy G_F follows the conception introduced originally by Petersson (1981). For the specimens under cyclic loading, the fracture energy G_F was determined using the obtained envelope of the load cycles.

The maximum load F_m, the critical deflection δ_0 as well as the critical crack mouth opening displacement $CMOD_0$ were measured directly. The main results of the performed three-point bend tests are summarized in Table 1.

Table 1. Average results for the static and the cyclic tests

number of load cycles	curing condi-tion	maximum load F_m [N]	net flexural strength $f_{tn,fl}$ [MPa]	fracture energy G_F [N/m]	critical deformation δ_0 [μm]	critical crack opening $CMOD_0$ [μm]
1	s	3143	3.92	119.5	1056	1143
10	s	3840	4.73	136.1	1182	1265
100	s	3569	4.36	128.5	1109	1171
1000	s	3264	4.03	135.1	1330	1507
10000	s	2892	3.48	129.7	1374	1557
100000	s	2596	3.33	166.7	2110	2242
1000000	s	1965	2.71	142.5	1901	1977
1	u	3613	4.50	161.3	1324	1441
10	u	3544	4.46	168.1	1456	1561
100	u	3633	4.61	152.6	1255	1295
1000	u	3449	4.20	216.2	2005	2102
10000	u	3082	3.78	134.9	1402	1518
100000	u	2915	3.57	154.4	1697	1809
1000000	u	2861	3.58	172.4	2045	2250

legend: s = sealed specimens, u = unsealed specimens.

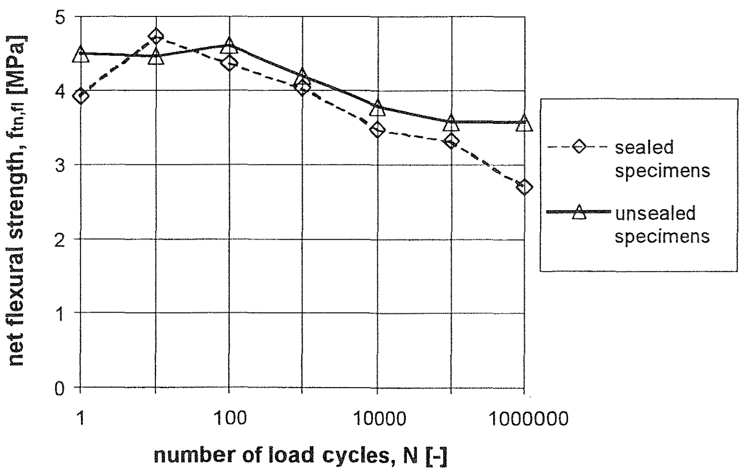

Fig. 4. Influence of the curing conditions and the number of load cycles to failure on the net flexural strength $f_{tn,fl}$

It was found that for HCF tests an increase of the number of cycles leads to a decrease of the maximum load F_m, the net flexural strength $f_{tn,fl}$

and the deflection δ_m (see Fig. 4). However, the corresponding values obtained from the low cycle fatigue tests ($n = 10^1$) for sealed specimens and from the medium cycle fatigue tests ($n = 10^2$) for unsealed specimens were higher than the values from the tests under static loading.

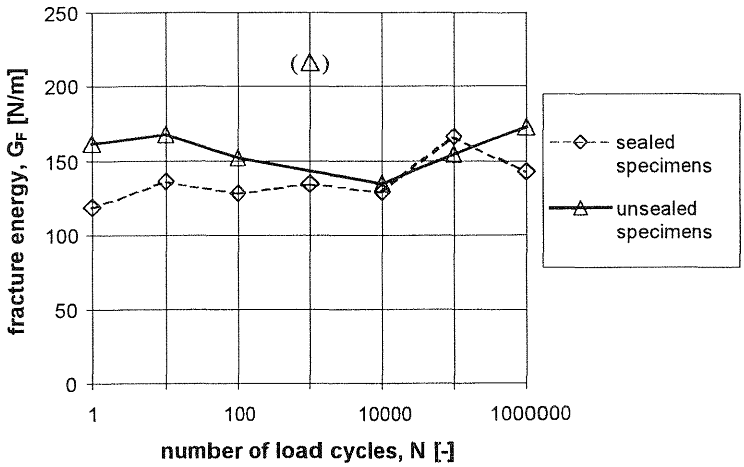

Fig. 5. Influence of the curing conditions and the number of load cycles to failure on the fracture energy G_F

The tests on sealed specimens provided a slight increase of the fracture energy G_F with increasing number of load cycles (Fig. 5). In contrast to this, the value of G_F remained approximately constant for unsealed specimens, if the value for 1000 load cycles is neglected which, however, was obtained from just one experiment.

The critical crack mouth opening displacement $CMOD_0$ at the end of the descending branch in the F-CMOD-relation showed an increase with increasing number of load cycles both, for unsealed and sealed specimens (Fig. 6). A similar tendency was observed for the critical deflection δ_0.

The curing conditions had obviously no significant effect on the observed general trends with increasing number of load cycles, but the individual test values for the unsealed specimens are somewhat higher in most cases (Figs. 4, 5 and 6). Such higher values for $f_{tn,fl}$, G_F and $CMOD_0$ have also been observed in other investigations, see e.g. Hordijk (1991).

The lower crack opening rate exerted no significant effect on the above mentioned test parameters.

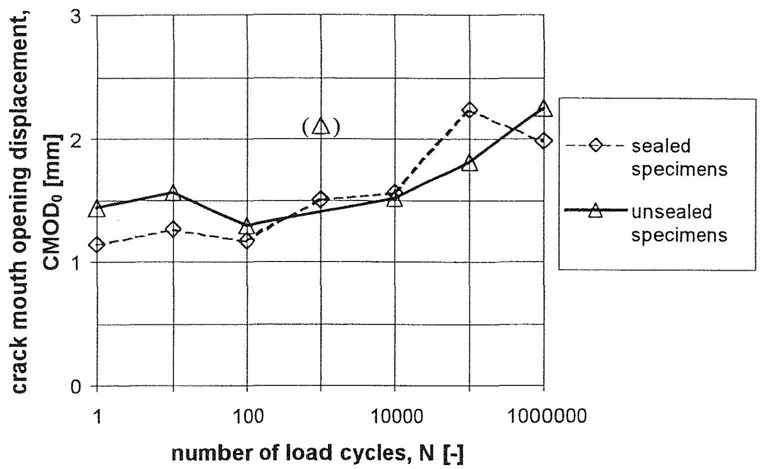

Fig. 6. Influence of the curing conditions and the number of load cycles to failure on the critical crack mouth opening displacement $CMOD_0$

4 Discussion of the experimental results

The observed tendency of the G_F-values with increasing number of load cycles may result from different, sometimes contrary influences. The energy supply by each load cycle results in a continuous separation of the aggregates from the matrix and therefore in an enlargement of the process zone and in a further crack propagation, respectively. In case of unloading a crack cannot close completely because of the unlocked or pulled out aggregates. This phenomenon leads to tensile stresses, especially in the vicinity of the crack tip, and reduces the maximum load F_m.

On the other hand the increasing number of load cycles to failure requires a higher loading frequency which causes higher values of the critical crack mouth opening displacement $CMOD_0$ and the critical deflection δ_0.

As a result of these effects, the shape of the envelope curves changes with increasing number of load cycles as it is obvious from Fig. 7. This observation clearly shows that the assumption of a unique envelope curve for the fatigue behaviour of concrete (see e.g. Duda (1990) or Hordijk (1991)) is correct only for low and medium cycle fatigue, but cannot be maintained for high cycle fatigue.

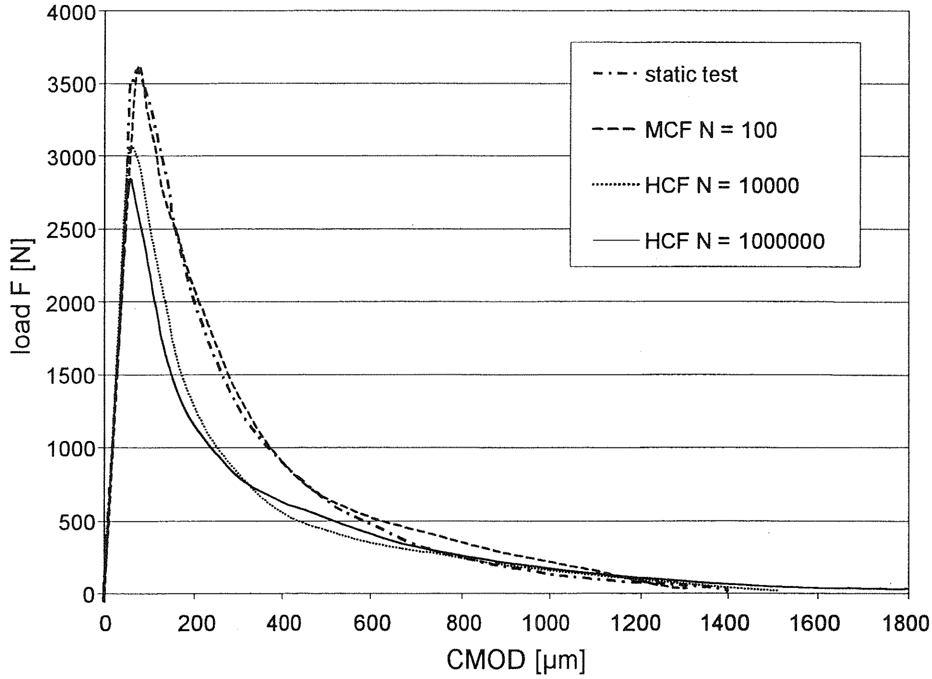

Fig. 7. Envelope curves of the F-CMOD relations for a static test and fatigue tests with N = 100, 10000 and 1000000 on unsealed specimens

The ascending branch shows approximately the same shape for all tests up to 80% of the peak load. The peak load decreases for increasing number of load cycles. As a result, the envelope curves for the first, steeper part of the descending branch from HCF tests are below the corresponding curves from the static and the medium cycle fatigue tests. The second, shallow part of the descending branch of the envelopes from HCF tests mostly intersects the static curve. Thus, the contribution of the second part of the descending branch to the value of the fracture energy G_F is higher for HCF tests than for static tests.

5 Summary and conclusions

Three-point bend tests on notched beams were performed under deformation control to investigate the behaviour of concrete under cyclic tensile

loading. As a result for HCF tests it was found that an increase of the number of load cycles leads to a decrease of the maximum load F_m, the net flexural strength $f_{tn,fl}$ and the deflection δ_m at the load F_m, and to an increase of the critical crack mouth opening displacement $CMOD_0$ and the critical deflection δ_0, respectively.
Furthermore it could be shown that for increasing number of load cycles the envelope curves differ from the static curve. However, no clear tendency for the influence of the number of load cycles on the fracture energy G_F could be observed. It might be possible, that the fracture energy G_F is independent of the cyclic load history. Further experimental and theoretical studies are necessary to validate or to reject this assumption.

Future work will also be concentrated on developing a constitutive material law to describe the behaviour of concrete under cyclic tensile loading.

6 References

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