Numerical and Experimental Investigation into the Fatigue Behavior of Plain Concrete

by D.A. Hordijk and H.W. Reinhardt

ABSTRACT—Fatigue of concrete has received considerable attention in the last 15 years. The investigations, however, have been mainly phenomenological. Therefore, the knowledge about the cause and mechanism of concrete fatigue is still limited. This paper reports about a research project in which fatigue of concrete is studied by applying nonlinear fracture mechanics. With a description of the crack cyclic behavior of concrete, crack growth could be studied numerically. Qualitatively promising results have been found. A number of fatigue experiments are described in which the development of deformations with the number of cycles is followed as accurately as possible. For that purpose, a data-acquisition system was specially designed.

Introduction

In the last 15 years, the fatigue behavior of concrete has received considerable attention from investigators in the field of concrete structures. There are several reasons for the interest in this loading type for concrete. Firstly, the use of new types of structures, like offshore platforms, that are subjected to dynamic loading. Secondly, the use of higher strength concrete and lightweight concrete, as well as reductions in safety margins, have resulted in more slender structures in which the dead load forms a smaller part of the total load. Thirdly, it is recognized that the material properties may be affected by repeated loading. Despite all this, the importance of fatigue of the concrete in reinforced concrete structures is sometimes doubted, mainly because no clear concrete-fatigue failures are known from the literature. However, in a study by CEB General Task Group 'Fatigue of Concrete Structures,'[1] it was concluded that, although no fatigue collapses of concrete structures were found, fatigue was a contributory factor in the progressive deterioration observed in most of the cases studied.

Codes for concrete structures comprise more and more design rules for concrete-fatigue calculations. These rules are based on the Palmgren-Miner hypothesis[2, 3] in which the supposition is that damage accumulates linearly with the number of cycles applied at a particular stress level. The material input in the analyses are the so-called S-N curves. From these curves the number of cycles until failure for each relative stress level can be obtained. In the past, concrete-fatigue research activities have mainly been addressed to the determination of S-N curves. Although these investigations were very valuable from a practical point of view, they did not explain the cause and mechanism of concrete-fatigue behavior. In order to gain more insight in the mechanism, it is necessary to study the fatigue phenomenon on a theoretical basis.

Fatigue investigations for steel structures deal with crack growth. Cracks initiate at points of stress concentration which may be due to flaws present in the material or may be caused by discontinuities in the geometry of the structure. After the crack is initiated, its propagation is studied with the aid of fracture mechanics. In the research project that is described in this paper, a similar local approach is also applied to fatigue of concrete. Here only some principal results will be presented. For more detailed information the reader is referred to Ref. 4.

Concrete-fatigue Behavior

For a comprehensive review of the fatigue behavior of concrete, the reader is referred to Refs. 5 and 6. Here, some main findings for concrete-fatigue behavior will be presented, with emphasis on the observed tendencies rather than on quantitative descriptions. Like in the case of static loading, a distinction can be made between the different loading types, as there are compression, tension, bending and bond between concrete and steel. It appeared, however, that qualitatively more or less the same results were found for these different loading types.

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The main characteristic of fatigue behavior of concrete, but also of other materials, is that the number of load cycles, N, that can be performed before failure occurs, increases for a decreasing upper load level. When the relative upper load (or stress) level is plotted against the logarithm of the number of cycles to failure, then a linear relation will be found [see Fig. 1(a)]. These types of curves are known as Wöhler curves or S-N curves. If the deformations are recorded during a fatigue test on concrete and plotted against the number of cycles performed then a curve will generally be obtained that is known as a cyclic creep curve [(Fig. 1(b)]. This curve is characterized by three specific parts. In the secondary branch the increase of deformation per cycle is constant. Just before failure occurs, the deformations increase rapidly. A similar relation, but turned upside down, is found for the development of the secant modulus of elasticity in a compression test[8] [(see Fig. 1(c)]. Finally, it can be mentioned that there is a strong relation between the increase of strain per cycle in the secondary branch of the cyclic creep curve and the number of cycles to failure. This indicates that there may be a fatigue failure criterion for concrete that is based on ultimate strain or deformation.

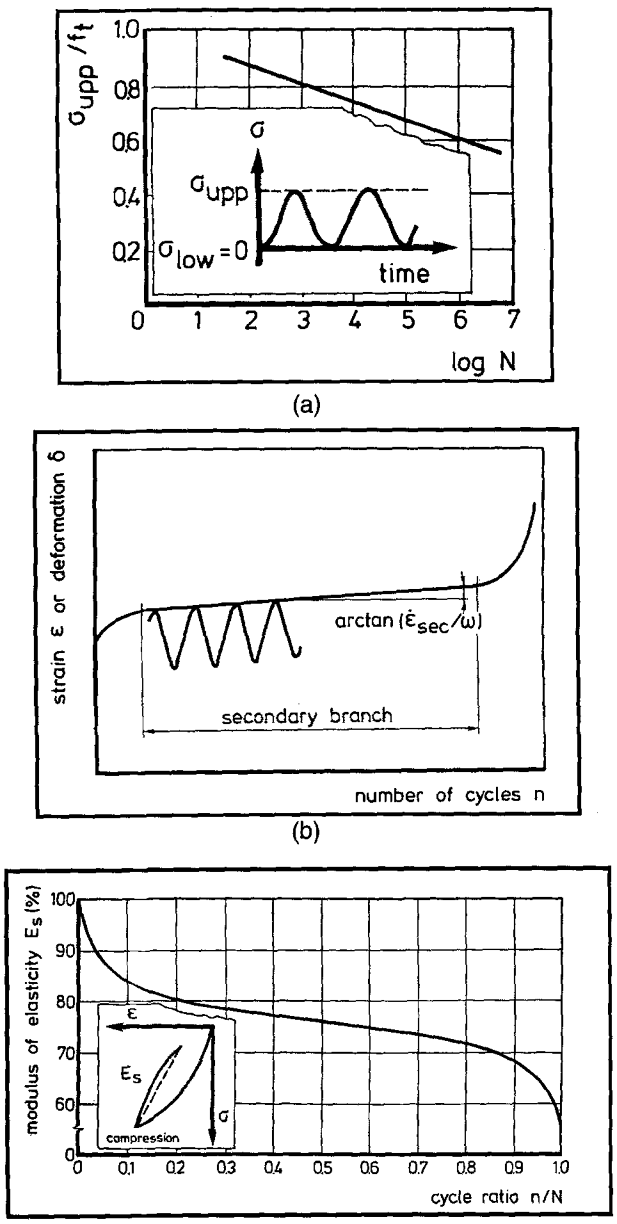

Fig. 1—Concrete fatigue results; (a) S-N curve,[7] (b) cyclic creep curve and (c) development of the secant modulus of elasticity with n/N

Approach for the Concrete Fatigue Study

General

In this investigation an attempt is made to explain concrete-fatigue behavior based on crack growth due to cyclic loading. For this local approach the knowledge of fracture mechanics for concrete is applied. Concrete is a heterogenous material for which is has been demonstrated that conventional fracture-mechanics approaches cannot be applied for normal-sized structures. In 1976, Hillerborg and coworkers[9] proposed the fictitious crack model in which it is assumed that there exists a fictitious crack (also called 'softening zone') ahead of a visible crack (see Fig. 2). In the fictitious crack stresses can still be transferred, depending on the crack opening. With this model it became possible to analyze the behavior of different types of concrete structures properly. A very important material property of concrete is the relation between stress and crack opening in the softening zone. This relation can be determined in deformation-controlled uniaxial tensile tests (Fig. 3). For these tests it is known that fracture occurs very locally. Therefore crack openings can be obtained directly

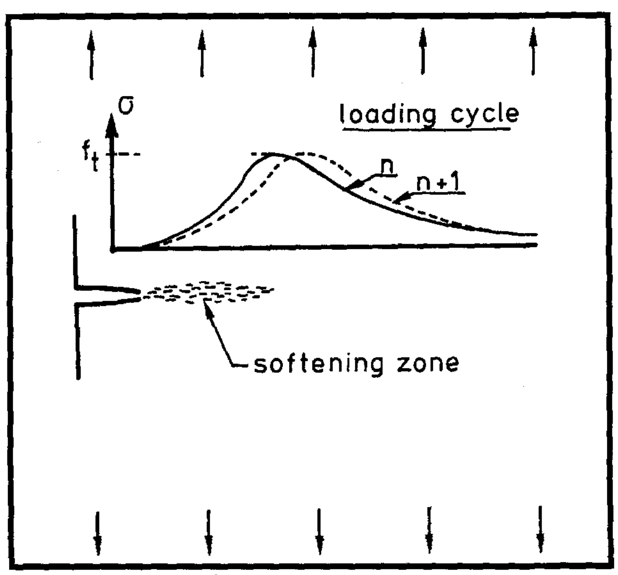

Fig. 2—Stress distribution according to the 'fictitious crack model'[9]

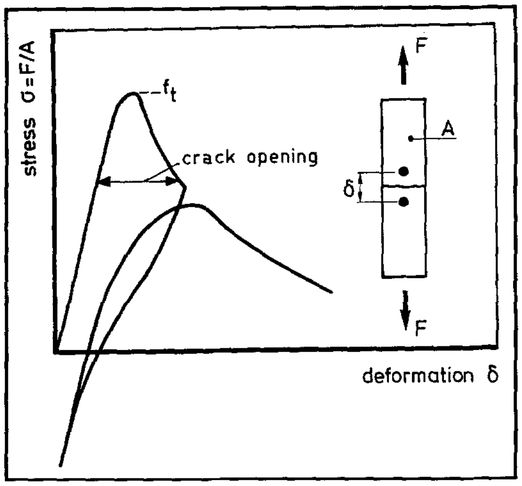

Fig. 3—Concrete tensile behavior

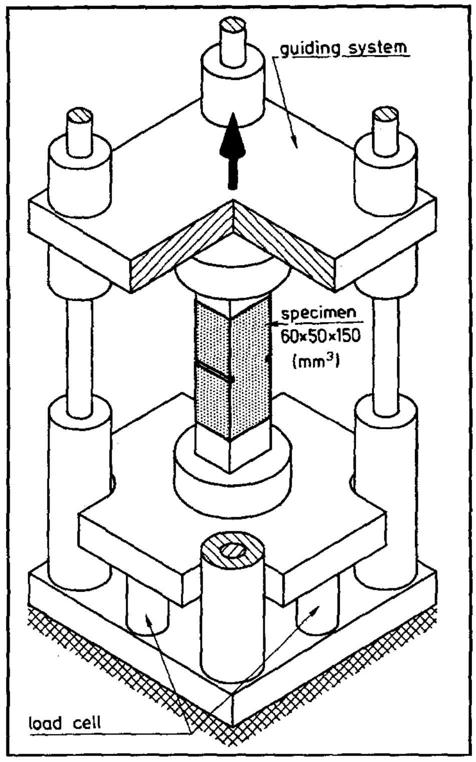

Fig. 4—Schematic representation of the applied testing rig

from the measured stress-deformation relation. By now, the stress-crack opening relation for concrete is reasonably well known.[4]

If, in a deformation-controlled uniaxial tensile test, a load cycle is performed in the descending branch, then a result as sketched in Fig. 3 is found. The fact that after such a load cycle the maximum attainable stress is lower than the stress at the start of the load cycle, is the basic material behavior for the concrete-fatigue approach in this study. If the solid line in Fig. 2 represents the stress distribution after n loading cycles ($n \geq 0$), then by the observed post-peak cyclic tensile behavior it is known that the stresses in the softening zone will be lower after the next loading cycle. Since the external maximum load will be the same, a stress redistribution has to take place which causes the length of the softening zone to increase.

Numerical Investigation

In order to study crack growth numerically with the above presented approach, it is necessary to describe the complete post-peak tensile behavior of concrete and to implement it in a numerical program. Based on a great number of experiments, such a complete constitutive model 'continuous-function model' for the tensile behavior of concrete was proposed.[4] The structure that was chosen for the investigation of crack growth is a notched four-point bending specimen, while a multi-layer model was applied for the analyses. With these analyses it was intended to investigate to what extent results from cyclic loading correspond with results that are usually found in fatigue experiments.

Experimental Investigation

In the past, the increase of deformation with the number of cycles, as measured in tensile fatigue tests, was mostly assumed to be the result of increased strains. By now it is known that in a static tensile test fracture occurs locally. In this research project the intention was to investigate to what extent fracture in tensile fatigue tests also occurs locally and to investigate whether the descending branch in a static test is the failure envelope in a fatigue test. Therefore a number of fatigue experiments were performed in which deformations were measured very accurately. With these tests it was furthermore intended to study the development of the shape of the loops with the number of cycles. Some details about the applied measuring technique will be given in the next section.

Experiments

A limited number of tensile-tensile and tensile-compressive fatigue tests were performed. For these tests as well as for the accompanying deformation-controlled uniaxial tensile tests a very stiff testing rig was applied (Fig. 4). Initially, it was intended to use unnotched specimens. However, due to the fact that fracture mostly occurred near a glue platen, this proved to be impossible. Nevertheless, two experiments on unnotched specimens, one loaded statically and one loaded dynamically, were successful. For the rest of the experiments, notched specimens were applied. The middle cross-sectional area of the specimens was 50 × 50 mm, while the length was 150 mm. A normal-weight concrete with an 8-mm maximum aggregate size and a cube compressive strength equal to 47 MPa, was applied. For the deformation measurements, eight LVDTs (linear variable differential transducers) were applied with a base of 35 mm and 110 mm, respectively. Four 50-kN load cells placed under the lower loading platen were used for the load measurement. For more information about the testing rig and the procedure for deformation-controlled uniaxial tensile tests, the reader is referred to Ref. 4.

The test ran load controlled with cycles between an upper and lower load level that could be chosen freely. For measuring the deformations at different loading points in a loop, it is necessary to have a measuring system which is able to measure very accurately. This is understandable if it is realized that for a measuring length of 35 mm, the deformations of the unloading and reloading curves in a loop differ less than 1 μm. On the other hand, the measuring system must be very fast. In order to get some idea about the shape of a loop, the number of measuring points in such a loop must not be too small. It is very hard to meet these two requirements at the same time: a measuring system that is accurate as well as fast. New data acquisition equipment was specially built for these experiments.

In the data-acquisition system a fast A/D-converter was chosen for the analog-digital conversion. The resolution and accuracy that could be attained with that converter was not enough. Therefore, for each measurement, eight samples were averaged. The frequency of the fatigue loading was 6 Hz. This means that every second, six loops are performed [see Fig. 5(a)]. The principle of the data-acquisition system is such that the first half of each second is used to sample and the second half of the second is used to process the data. In the three loops that are recorded, 75 measuring points are available. For each measuring point, the deformation of eight LVDTs and the load in the four load cells are recorded. Consequently, 900 (= 75 × 12) measurements are taken in 0.5 seconds (sampling frequency: 14400 Hz). As an example, an experimental result is shown in Fig. 5(b). So far, the procedure for measurements at regular intervals is described.

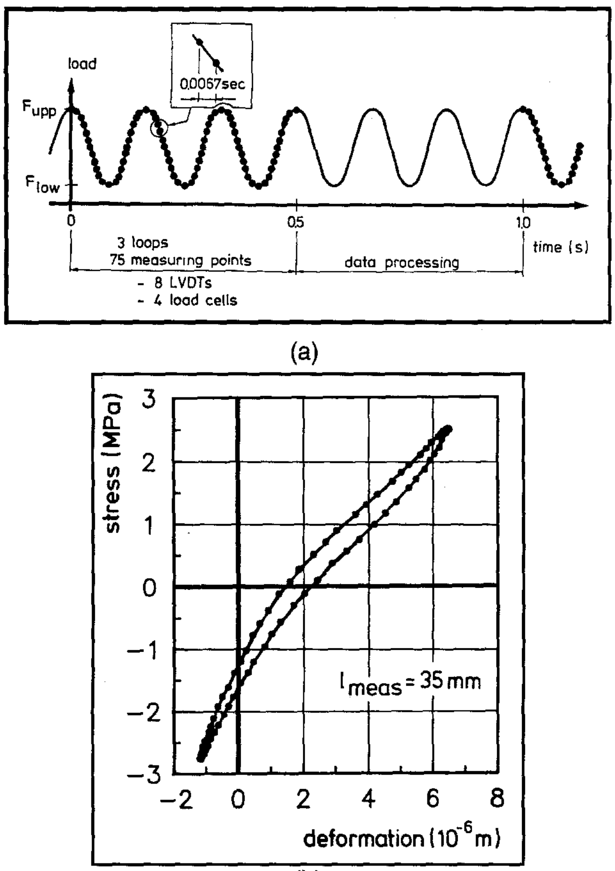

Fig. 5—(a) Principle of the data-acquisition for the fatigue tests and (b) an example of an experimental result

The most interesting part of the experiment is certainly the last part. In that part, the deformations increase strongly. Since it was intended to compare deformations at the envelope curve in a static test and at failure in a fatigue test, it was necessary to record data near failure. For that reason a buffer is used, in which the data of the last 20 seconds are stored. This buffer is updated in each second half of a second in which data processing takes place and therefore contains 20 times the data of three loops. As soon as the test is stopped, the data in the buffer can be read and stored in a data-file. In order to detect the ending of the experiment, the recorded load at the upper load level is checked. After failure of the specimen, the upper load level will no longer be reached. When this had occurred a preset number of times, the test and measurements were stopped.

As far as the above-described measurements are concerned, the following remarks can be made. It is not claimed that the data-acquisition system is able to measure reproducible deformations of less than 0.1 μm. It was only intended to improve the measurements in such a way that the unloading and reloading curves in a loop do not cross each other. It is realized that some hysteresis may be present in the measurements. Nevertheless, the development of loops can very well be studied. Furthermore, a difference in temperature between day and night, as well as a difference in temperature due to an open door, may influence these measurements significantly. Therefore, an environmental chamber was built around the specimen, in which the temperature could be kept more or less constant during the experiment.

Numerical Analyses

By applying a multilayer model (for details see Ref. 4) and the constitutive relation for the crack cyclic behavior, it was possible to study the behavior of a notched four-point bending specimen. For a continuously increasing deformation, a load-deflection curve with a maximum of 1403.6 N was found (Fig. 6). Then the analysis was repeated until a load level equal to 94 percent of the maximum load was reached, whereafter the structure was unloaded to a zero load level. Because a softening zone exists at the upper load level, it could be expected that crack growth occurs with cyclic loading (see also Fig. 2). That indeed was observed when more loading cycles were performed. Besides the growth of the length of the softening zone (crack) with the number of cycles, a change in shape and position of the loops could be observed. After 146 cycles were performed, the maximum load level could no longer be reached and the descending branch, as found in the static analysis, was then followed. As could be

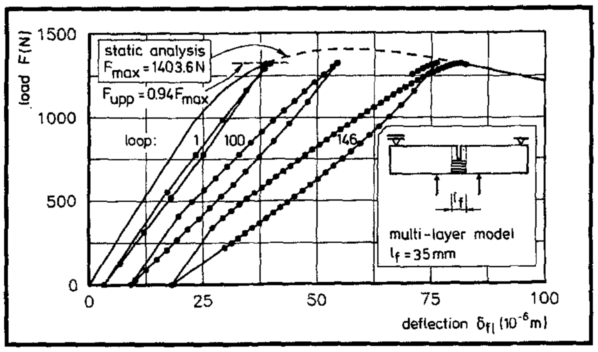

Fig. 6—Load-deflection relations obtained with the numerical analyses

expected, the descending branch acted as a failure criterion. Whether the development with the cycle ratio of parameters like deflection and secant stiffness shows a curve as usually found in experiments (Fig. 1) could not be said in advance. Therefore it is very promising that such curves were indeed found in the analysis [see Figs. 7(a), 7(b) and 7(c)]. Furthermore, a number of analyses with different upper and lower load levels were performed. The results of these analyses plotted in S-N diagrams showed qualitatively good similarity with experimental results.[4] Although the proposed model could so far only be applied for low-cycle high-amplitude fatigue, the obtained preliminary results are very promising.

Experimental Results

With the uniaxial tensile fatigue tests it was mainly intended to compare deformations in a static test with those in a fatigue test and to get an answer to the question of whether the descending branch in a static test is also the failure envelope in a fatigue test. Initially, it was intended to use unnotched specimens. The reason for that was that the process of localization in a fatigue test was also to be investigated. Notches in the specimens cause such a local increase in stress that one may not draw conclusions on the phenomenon of localization when notched specimens are used. Tests on unnotched specimens, however, are very difficult to perform. In most of the experiments, fracture occurred near a glue platen. Nevertheless, one fatigue experiment and one static experiment were successful. Furthermore, a number of fatigue experiments were performed on notched specimens. The applied upper and lower stress levels and the number of cycles to failure, can be obtained from Table 1. Additionally, four specimens were loaded under a continuously increasing deformation (denoted as static tests). The results of these tests were used as a reference for the fatigue tests.

In the experiment on the unnotched specimen, fracture fortunately occurred within the base of the 35-mm LVDTs. In Fig. 8(a), the stress-deformation relation for a number of loops is plotted, while deformation is the average of the four 35-mm LVDTs. In the same figure the stress-deformation relation for the static test on the unnotched specimen is plotted. As can be seen, the deformation at the upper stress level for the last loop that was recorded more or less coincided with the descending branch of the static test. However, two remarks need to be made. First of all, it is not known whether the last recorded loop is also the last loop that was performed. There is a possibility that three more loops were performed. Since the increase in deformation is the greatest in the last loops, this may have a

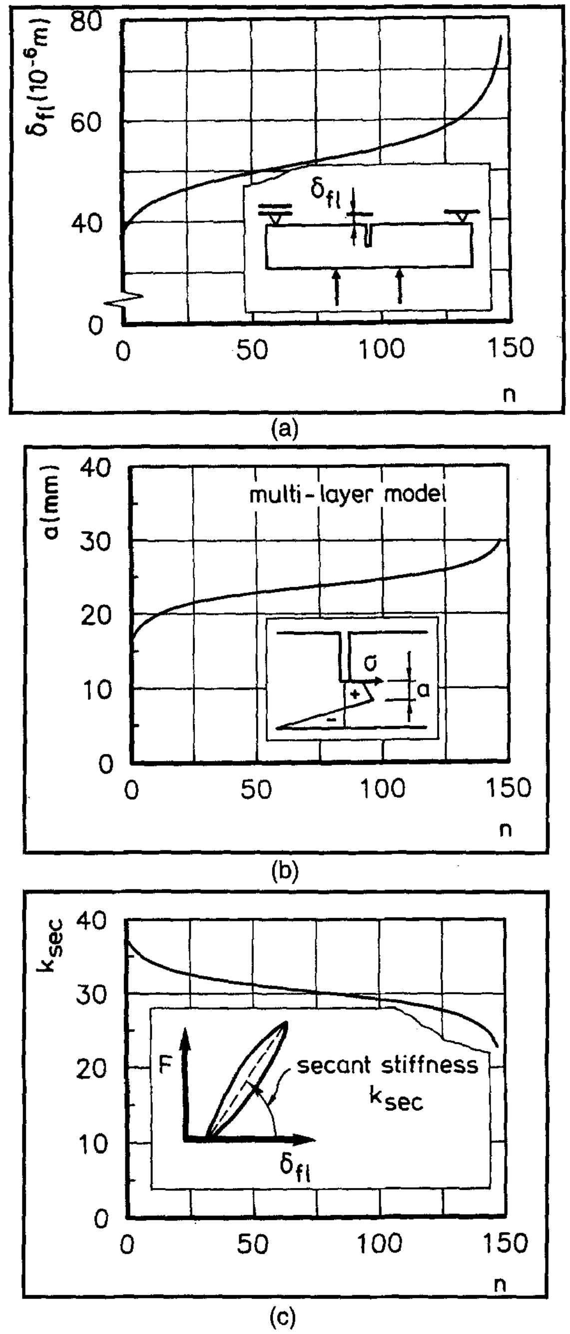

Fig. 7—The variation of (a) the deflection, (b) length of the softening zone and (c) secant stiffness with the number of cycles as found in the fatigue analysis.

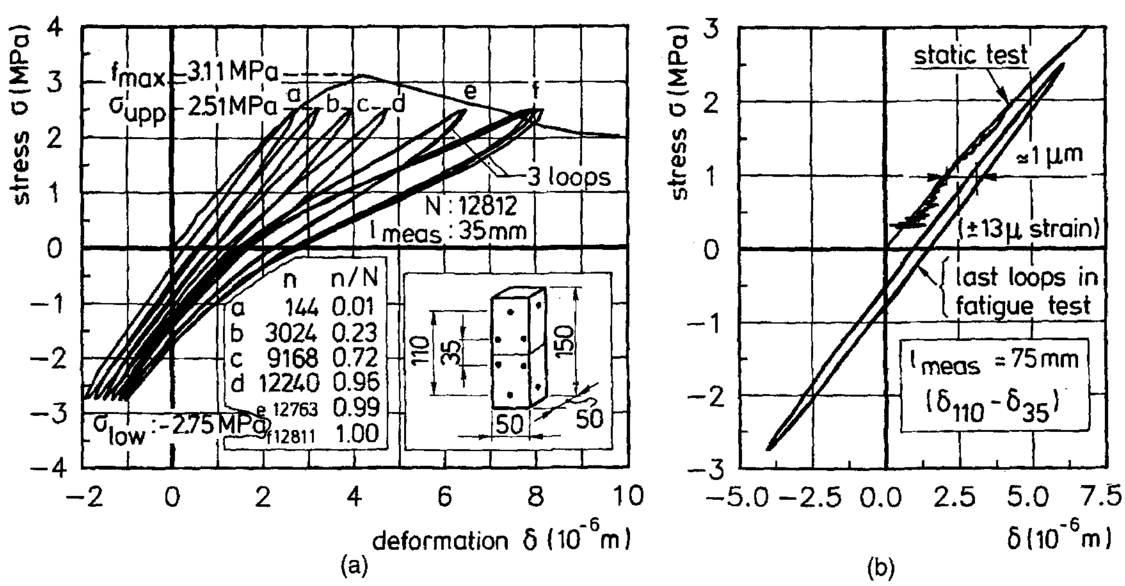

Fig. 8—Stress-deformation relation from static and fatigue tensile experiments with unnotched specimens

significant effect on the measured deformation at failure. In actual fact the real value for the deformation at failure is equal to or larger than the last one recorded. The second remark concerns the result of the static test. Here, only the result of one experiment is shown. It should be borne in mind, however, that due to scatter, the position of the descending branch may vary.[4]

In order to quantify the damage that occurred outside the final fracture zone, the deformations obtained with the 35-mm LVDTs were subtracted from the deformations obtained with the 110-mm LVDTs. This results in a deformation pertaining to a measuring length of 75 mm (two parts of 37.5 mm each), which does not encompass the final fracture zone. It appeared that the shape of the stress-deformation curve of a loop varied only a little in the beginning of the test, while it remained more or less the same during the subsequent cycles to failure. The shape of the last cycles is shown in Fig. 8(b). The irreversible deformation is about 1 μm, which is equal to about 13 μstrain. This result shows that also in a tensile fatigue test, fracture mainly occurs in a small zone. This can also be seen when the deformations at the upper stress level in a cycle are plotted versus the cycle ratio *n/N* [see Fig. 9(a)]. The result of the experiment on the unnotched specimen has also been used to calculate the development of the secant stiffness and the energy within a cycle respectively, with the cycle ratio. In Figs. 9(b) and 9(c), it can be seen that the obtained relations show good similarity with those found in the fatigue analyses.

In order to show the relation between deformations in a fatigue experiment and in a static test, results are plotted in one diagram (see Fig. 10). In the upper part of Fig. 10, the average σ-δ relation for the static experiments is plotted, while in the lower part of the same figure, the cyclic creep curve for fatigue test 7 is plotted in such a way that the axes for the deformation correspond. Characteristic points in the cyclic creep curve denoted as B, C and D are projected in the σ-δ diagram. Similarly, the points B, C and D for all the fatigue experiments are plotted in Fig. 11. No distinct relation can be obtained from the results. Except

TABLE 1—UPPER AND LOWER STRESS LEVELS IN THE FATIGUE TESTS AND NUMBER OF CYCLES TO FAILURE

Experiment	Notched/ Unnotched	Upper Stress (MPa)	Lower Stress (MPa)	*N*
1	unnotched	2.51	-2.75	12812
2	notched	3.18	-5.30	86
3	notched	3.00	0.67	13026
4	notched	3.00	0.05	1951
5	notched	2.75	-5.20	2378
6	notched	2.69	-5.14	10784
7	notched	2.50	-4.82	50720

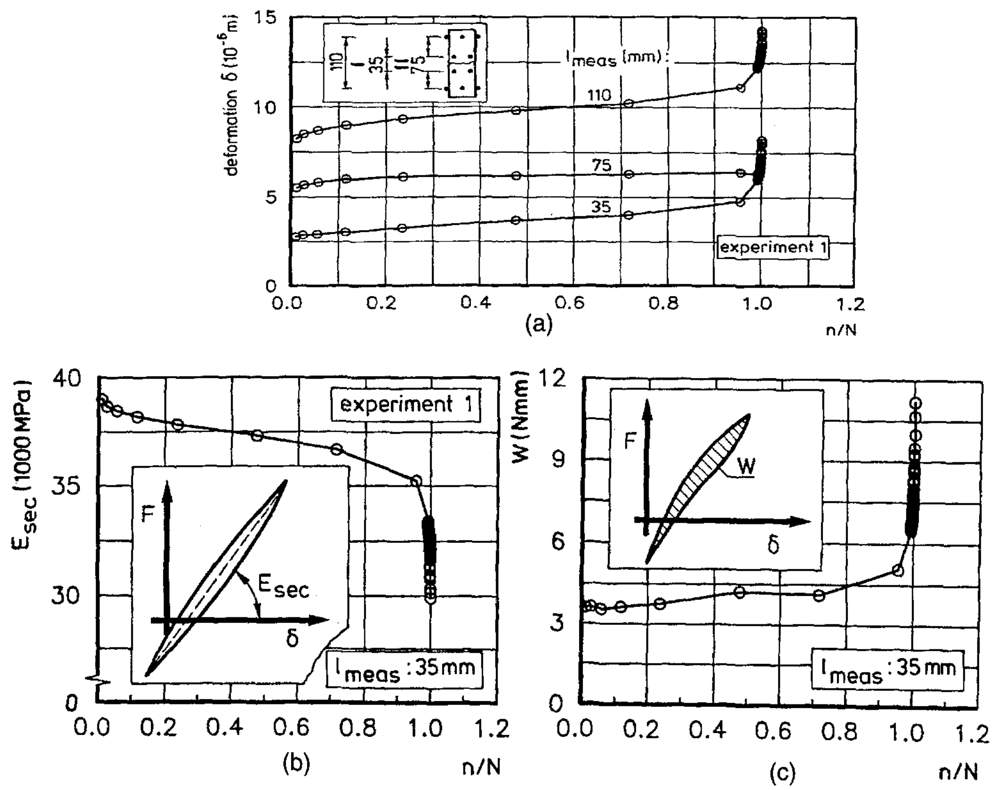

Fig. 9—Variations of (a) deformations at the upper stress level, (b) secant stiffness and (c) energy within a cycle with cycle ratio

for the result of the unnotched specimen, the deformation for the upper stress level at failure in the fatigue experiments is larger than the deformation at the descending branch in the static experiments, even if the scatter in the static experiments is taken into account. So far, possible explanations for this observed result deal with the influence of the notches and distributed cracking due to compressive loading in the lower parts of the loops (see also Ref. 4). Although the authors believe that a failure criterion based on ultimate deformations exists, further research along the presented lines is necessary to prove it.

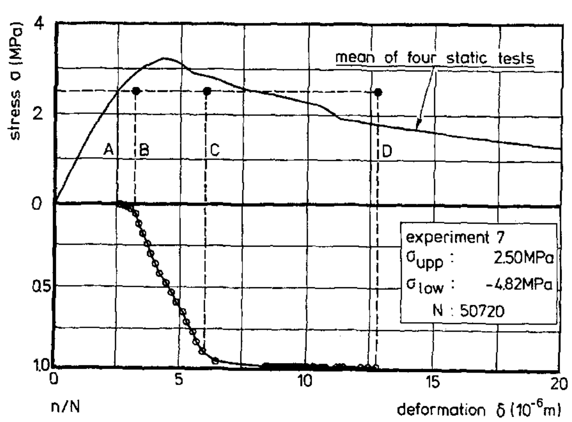

Fig. 10—Average stress-deformation relation of the static tests and the cyclic creep curve for fatigue test 7

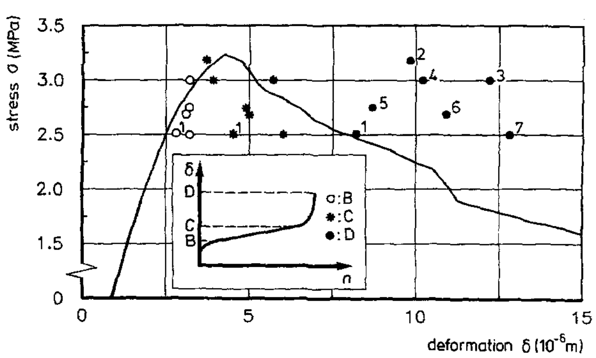

Fig. 11—A comparison of characteristic points in the cyclic creep curves of fatigue tests with the average σ-δ relation from the static tests

Concluding Remarks

From the analyses and experiments the following main conclusions can be drawn. The local approach to fatigue of plain concrete showed very promising results and offers good prospects for further research in this direction. The specially developed data-acquisition system is suitable for studying the tensile fatigue behavior more thoroughly. Tensile fatigue failure is a local phenomenon like tensile failure in a static experiment. As regards a failure criterion based on deformation, more research is required before conclusions can be drawn.

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