Shear transfer across a crack in concrete subjected to repeated loading

Experimental results: Part I

Ir. A.F. Pruijssers/Ing. G. Liqui Lung

Department of Civil Engineering
Stevin Laboratory
Concrete Structures

Delft University of Technology
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by

Ir. A.F. Pruijssers
Ing. G. Liqui Lung

Mailing address:
Delft University of Technology
Concrete Structures Group
Stevin Laboratory II
Stevinweg 4
2628 CN Delft
The Netherlands

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This research relates to the behaviour of cracked concrete under repeated shear loading. Pre-cracked monolithic specimens were subjected to a repeated shear load. The normal restraint stiffness was applied by means of embedded reinforcing bars with a diameter of 8 mm. The variables of the tests were the concrete grade, the steel grade, the reinforcement ratio, the number of cycles, the applied shear stress level and the initial crack width. The maximum applied shear stress was in the range of 50%-90% of the static shear strength. The experimental program on reinforced specimens comprised 42 tests with repeated load and four tests with an increasing static shear load. The repeated tests were so-called 'high-cycle low-amplitude' experiments, i.e. the number of cycles exceeded 1,000. The displacements of the crack faces were measured by scanning the electronic signal nine times per load cycle. The load was sinusoidal.

The experimental results are represented by the relations between the displacements of the crack faces and the number of cycles, the crack-opening path and the behaviour of the crack in a cycle.

In the second part of the research program tests were performed on similar specimens without embedded reinforcing bars. The normal restraint stiffness was governed by four external steel bars having no bond with the concrete. The force normal to the crack face was measured by means of strain gauges glued to the steel bars.
1 INTRODUCTION

The experimental study forms part of the research program 'Concrete Mechanics part 2'. This project focuses on fundamental behaviour of concrete under various loading conditions, especially under offshore conditions. The aim of the project is implementation of the models into advanced numerical programs. These models describe the fundamental physical behaviour. Implementation of a model requires a good understanding of the physical mechanism and a suitable formulation of the quantitative result of this mechanism.

Reinforced concrete structures are assumed to be cracked under service conditions. In order to analyse concrete structures by means of finite element programs, such programs must cope with nonlinear elastic behaviour of the material due to cracking.

Extensive investigations give a thorough understanding of the behaviour of cracked reinforced concrete in the case of bending. In the case of shear forces due to earthquakes, wave attack, etc there is a lack of knowledge about the behaviour of the cracked concrete. Until now experimental and theoretical studies have focused on static shear loads. A theoretical and experimental study carried out by Walraven [5], which forms part of the project 'Concrete Mechanics part 1', gives a good understanding of the mechanism of aggregate interlock for static loading conditions. Experiments with cyclic load, including those conducted by White and Holley [1], Laible, White and Gergely [2], Jimenez et al [3] and Mattock [4] were tied to the behaviour of nuclear reactor vessels, i.e. a relatively large crack width (w > 0.5 mm), a small number of cycles (N = 15-25) and a high shear stress in proportion to crack width. These tests are so-called "high-amplitude low-cycle"-tests.

The lack of information in respect to shear load is restricted to the behaviour of cracked concrete subjected to a relatively low shear stress, but during at least a few thousand cycles, i.e. the "high-cycle
low-amplitude"-tests. These tests focus on wind and wave attack on offshore structures. This report deals with these tests.

A qualitative understanding of the crack behaviour shows that the transmission of forces across a crack in concrete depends on the unevenness of the crack surfaces (aggregate interlock), dowel action and axial restraint stiffness of the reinforcement crossing the crack. Moreover, the interaction between these mechanisms can play an important role.

These mechanisms are reasonably well understood for static loading conditions. The experimental study described in this report deals with tests on push-off specimens with embedded reinforcement, representing real structural conditions.

Apart from these tests a smaller test series is performed to study the mechanism of aggregate interlock in transferring dynamic shear load. In these test series the normal restraint stiffness is obtained by means of steel plates at each half of the specimen interconnected by four external restraint bars. These bars cross the shear plane perpendicularly. In [6] the experimental results are analysed on basis of the static mechanisms. As a result of this analysis further experimental work is conducted. The results of that study are given in [17].

The experimental study reported here is subdivided into two parts. In the first part tests on specimens with embedded reinforcing bars are performed, in the second part results of specimens with external restraint bars are presented. In this report both test series are reported separately.
2. AIM OF THE INVESTIGATION AND JUSTIFICATION OF THE RESEARCH PROGRAM

2.1 Introduction

The scope of the research project is stated in the literature survey [7]. The variables which require further investigation are listed in that survey. In this report a short enumeration of all the important parameters is given. This chapter focuses on the specimens with embedded reinforcing bars.

2.2 Aim of the investigation

The aim of the investigation is modelling the behaviour of cracked concrete, subjected to repeated and reversed shear load with a low amplitude with respect to the crack width. The number of cycles must be 1,000-1,000,000 to represent offshore conditions. Crack widths in offshore constructions must remain very small (less than 0.10-0.25 mm).

Shear stress in cracked reinforced concrete is transferred by the following mechanisms:
  - aggregate interlock
  - dowel action
  - axial restraint stiffness of the reinforcement
  - interactions between the given mechanisms.

The main object of this study is the adaptation of the static aggregate interlock model of Walraven [5] to the case of dynamic load. However, the mechanism of dowel action and the axial restraint stiffness will be studied in detail if necessary for a good description of the actual structural behaviour.
2.3 Justification of the research program

As stated earlier, it is necessary to conduct experiments on specimens with embedded reinforcement. In structures the reinforcement is quite a complex system; it may consist of several layers, bar diameters and directions. The inclination between bar and crack surface may vary from 0° to 180°. Reinforcement webs may cross a crack at different inclinations. All these possibilities interfere with a clear interpretation of the test results.

The inclination between the bars and the crack face has been studied by several investigators. Mattock [8] conducted static tests on push-off specimens (see Fig. 2.1) with parallel as well as with orthogonal reinforcement. Both test series show an obvious influence of the inclination between bar and crack face. The interpretation of the results of the tests with orthogonal bars is far more complex than the interpretation of the tests with parallel bars. The last mentioned tests show a maximum shear stiffness for a bar inclination of 120-130°.

![Fig. 2.1 Typical push-off specimens with orthogonal and parallel reinforcement used in Mattock's experimental study [8]](image-url)
White et al. [9,12] carried out dynamic experiments on shear panels with biaxial reinforcement (see Fig. 2.2). The inclination between the bars and the crack face was 45°. The maximum number of cycles applied was limited to ten. The aim of the research program of White was the formulation of design codes for nuclear reactor vessels.

Fig. 2.2 White's specimen geometry and loading system [9,12].

Fig. 2.3 Comparison between calculated (dotted) and experimental (solid) stress-displacement relations for Walraven's tests.
The experimental and theoretical study carried out by Walraven [5] was limited to static tests. In this program a series of tests with inclined bars was conducted. The inclination varies from 45° to 135° (see Fig. 2.3). A model based on the mechanism of aggregate interlock and the transfer of stress by means of concrete struts influenced by axial steel stress in the reinforcement was adopted. This model describes the experimental results reasonably well. However, for bars with an inclination perpendicular to the crack face the model gives a qualitative rather than a quantitative representation of the experiment.

In the case of orthogonal reinforcement the bars in the weakest direction can be suspended by the bars in the stiffest direction. This phenomenon depends on the diameter of the bar and the angle between bar and crack face. Moreover, the mesh size plays a role; the distance of the point of suspension to the crack face is influenced by the mesh size.

Mattock's test results [8] show that an increase of shear stiffness due to the bars in the stiffest direction can be concealed by a decrease in the shear stiffness in the weakest direction. The aim of the research program is the modelling of fundamental crack behaviour under shear load. Because of this fundamental character of the study only reinforced specimens with parallel bars will be used. Except for these bars no reinforcing bar, inclined or parallel to the crack face, is apparent. Therefore the inclination of the bars is examined only in the theoretical study [6].
The parameters, which are investigated in the experimental study, will be discussed here:

a. The reinforcement ratio $\rho$

The normal restraint stiffness is directly influenced by the reinforcement ratio $\rho$. In an actual structure the normal restraint stiffness varies locally. The reinforcement ratio can be varied by changing the diameter of the bar and/or the number of bars. For a straightforward interpretation the combination of the two possibilities is unfavourable. Variation of the diameter of the bar may change the influence of the cover on the bond characteristics. Hence the reinforcement ratio is varied by a change in the number of bars:

$$\rho = 1.12 \%, \text{i.e.} \ 4 \text{ stirrups with a diameter of} \ 8 \text{ mm.}$$
$$\rho = 1.68 \%, \text{i.e.} \ 6 \text{ stirrups with a diameter of} \ 8 \text{ mm.}$$

b. The initial crack width $d_{no}$

As already stated (Chapter 1), the initial crack width $d_{no}$ varies between 0.01-0.10 mm to ensure a crack width which is smaller than 0.25 mm under service conditions. On precracking the specimen it was found that the initial crack width could not be adjusted; the measured crack width after precracking of the specimen varies from 0.01 to 0.08 mm. Attempts to produce a larger initial crack width led to bond failure of the reinforcement, resulting in a marked reduction of the normal restraint stiffness. In that case the measured crack width was 0.20 mm, but the ultimate shear stiffness was too low for this experimental study. Hence the initial crack width was not an adjusted, but a measured parameter.
c. The concrete grade $f_{ccm}$

High-strength concretes are applied in offshore constructions; 28-day cube crushing strengths of 60-70 N/mm$^2$ are no exception. This is caused by a high cement content (400-450 kg/m$^3$) and a low water-cement ratio of approximately 0.40. In gravel concrete the high compressive strength can cause an increase in the number of particles fractured and a decrease of the number of interfacial bond fractures. The mechanism of aggregate interlock is strongly influenced by the amount of particles with interfacial bond fracture.

In order to investigate the influence of the fracture of particles on the mechanism of aggregate interlock two concrete qualities were used:

- **Mix A:** $f_{ccm} = 50$ N/mm$^2$
  \[ w.c.r. = 0.50 \]
  
  Maximum particle size $D_{\text{max}} = 16$ mm

- **Mix B:** $f_{ccm} = 70$ N/mm$^2$
  \[ w.c.r. = 0.375 \]
  
  Maximum particle size $D_{\text{max}} = 16$ mm

Mix A had a compressive strength representing the lower limit for concrete used in offshore structures. Interfacial bond fracture predominated over fracture of the particles. In mix B fracture of the particles was assumed to occur for a large amount of particles.

Both mixes almost complied with the Fuller grading curve. Detailed information is given in Appendix I.
d. The number of cycles $N$

To simulate offshore conditions the experiments were 'high-cycle fatigue'-tests. For plain concrete Hsu, et al [15], formulated the boundary between 'high-cycle' and 'low-cycle':

$$\log(N_f) = 3 - 0.353 \times \log(T)$$  \hspace{1cm} (2.1)

in which $N_f$ = number of cycles till failure

$T$ = time per cycle (s/cycle)

If the frequency is 60 cycles/min the boundary between 'low' and 'high' is 1,000 cycles. For the current research program the duration of a cycle will be one second, mainly because this frequency fits in with the testing equipment; a shorter duration is hardly possible, a lower frequency leads to a long test period per specimen. With a test range of 1,000 - 1,000,000 the test period varies between 20 minutes and 12 days. In general a maximum of 200,000 cycles was applied; after this number of cycles has been endured, the maximum shear stress is raised or the specimen is brought to shear failure by means of an increasing static shear load. The decision either to raise the shear load or to apply a monotonically increasing static shear load was made on the basis of the displacement after the first 200,000 cycles. In several cases it was decided to continue the experiment at the same stress level; in an exceptional case shear failure occurred after more than 900,000 cycles.

The large number of cycles up to shear failure interfered with good planning: in general it was not possible to start the experiment at an age of 28 days. The concrete strength at the start of the experiment was deduced from the 28-day strength (see Section 2.3f concerning the applied shear load)
e. The steel grade $f_{sy}$

The normal restraint stiffness of the specimen is influenced by the Young's modulus of steel and the bond characteristics of the bars. In the event of yielding of the bars the steel grade is an important parameter. The use of two steel grades provides an opportunity to investigate whether the reinforcement yields or not. The steel grades used in the current research program were: (see Fig. 2.4)

Steel L(ow): $f_{sy} = 460 \text{ N/mm}^2$
Steel H(igh): $f_{sy} = 550 \text{ N/mm}^2$

The bars were ribbed, with rib coefficient $f_R = 0.050$ for the low steel grade and $f_R = 0.059$ for the high steel grade.

Fig. 2.4 Stress strain diagrams for the steel grades used in the tests.
f. The applied shear stress level $\tau_m/\tau_u$

In fatigue tests the maximum applied stress is referred to the static strength. For the static shear strength the results of the experimental work of Walraven [5] are used. By means of a regression analysis Frenay [15] derived the following relation between the concrete strength, reinforcement ratio and the measured ultimate shear strength by means of a regression analysis:

$$\tau_u = a \times (\rho f_{sy})^\beta$$

(2.2)

in which $a = 0.822 \times f_{ccm}^{0.406}$

$\beta = 0.159 \times f_{ccm}^{0.303}$

$f_{ccm}$ in [N/mm$^2$]

$f_{sy}$ in [N/mm$^2$]

$\rho$ in [10$^{-2}$ %]

average value $\tau_u, exp/\tau_u, cal = 0.99$

coefficient of correlation = 6.9%

When eq. (2.2) is used no additional static tests are necessary. The ultimate shear stress in Walraven's experiments was reached at a crack width of 0.25 - 0.45 mm, depending upon concrete grade and reinforcement ratio. In the current research the crack width is limited to a maximum of 0.25 mm under service conditions. To ensure that the crack width remains smaller than 0.25 mm during the first cycles the maximum shear stress $\tau_m$ is referred to the static shear stress at a crack width of 0.25 mm. Again Walraven's experimental results were used. In the literature survey [7] a relation between concrete quality, reinforcement ratio and shear stress at a crack width of 0.25 mm is derived:

$$\tau_{0.25} = 2.9065 + 0.1033 f_{ccm} + 1.5708 \rho$$

(2.3)

with $r = 0.96$
In general the ratio between the ultimate shear stress $\tau_u$ and the shear stress at a crack width of 0.25 mm $\tau_{0.25}$ is about 1.05–1.10 (see Fig. 2.5). Initially the range for $\tau_m/\tau_{0.25}$ was 0.3–0.6, but during the preliminary tests it appeared that for this range no measurable increase in the displacements of the crack occurred. The final range was chosen: 0.6–0.9.

\[
\begin{align*}
\text{shear stress [N/mm}^2\text{]} & \\
\tau_u & \\
\tau_{0.25} & \\
\text{static experiment} & \\
0 & 0.25 0.50 0.75 1.00 \\
\text{crack width [mm]} & \\
\end{align*}
\]

Fig. 2.5 Typical static experiment of Walraven.

In eq. (2.2) and (2.3) the cube compressive strength taken at the instant of starting the test must be substituted. As already stated, in general this strength deviates from the 28-day strength. For both mixes the increase in strength is measured as a function of time [14]. The relations derived by Frenay [15] are normalised to the strength at an age of 28 days:

Mix A: $f_{ccm}(t_0) = (t_0 * f_{ccm}(28)) / (3.92 + 0.86 * t_0)$ \hspace{1cm} (2.4)

Mix B: $f_{ccm}(t_0) = (t_0 * f_{ccm}(28)) / (2.52 + 0.91 * t_0)$ \hspace{1cm} (2.5)
The equations (2.4) and (2.5) are represented in Fig. 2.6.

![Graph](image_url)

**Fig. 2.6.** The relation between the cube compressive strength and the age of the concrete.

The stress level during an experiment is calculated with eq. (2.3). In practice the measured maximum stress differs slightly from the calculated stress. In the coding of the experiments (see Section 3.3) the ratio between the measured shear stress and the ultimate static shear strength has been adjusted.
Synopsis

The parameters investigated in this study are:

a. reinforcement ratio $\rho$; 1.12% and 1.68%, i.e. 4 and 6 stirrups 8 mm.

b. steel grade $f_{sy}$; 460 and 550 N/mm$^2$

c. concrete grade $f_{c,m}$; 50 and 70 N/mm$^2$

d. shear stress level $\tau/\tau_{0.25}$: 0.60 - 0.90

$\tau_m/\tau_u$ : 0.55 - 0.90

The number of cycles varies from 1,000 to 200,000-900,000 at a loading frequency of one cycle per second. The initial crack width after precracking the specimen is a measured parameter.

Definition of shear failure

An experiment ended due to shear failure when the crack failed in transferring the applied shear force. The parallel displacement of the crack face exceeded 2 mm in a few cycles.
3. TYPE OF SPECIMEN AND TEST PROGRAM.

3.1 Type of specimen

A test specimen of the push-off type is quite suitable for experiments with shear load. This type of specimen was often used in earlier research programs. In consequence, test results can be compared without scale-factors. The geometry of the test specimen used in this research (see Fig. 3.1) is closely related to the specimen type used by Walraven [5].

![Fig. 3.1 Geometry of the test specimen](image)

The shear plane of the specimen is 36000 mm² (300 mm x 120 mm). For the specimen with embedded bars the reinforcement perpendicularly crossing the shear plane was in the form of closed stirrups, overlapped on one of the short sides to ensure good anchorage (see fig. 3.2). The specimens were cast in a steel mould placed horizontally, so that at the time of casting the shear plane was in a vertical position.
During the preliminary tests secondary cracking occurred in the cantilevers, hence initiating preliminary failure. To avoid this type of failure the cantilever is prestressed in the transverse direction (see Fig. 3.3).
3.2 Test program of reinforced specimens

Fatigue tests are characterised by significant scatter of the results. The dynamic tests on a push-off specimen subjected to a shear load will show such scatter. Moreover, another reason for scatter is the fact that the transmission of forces is influenced not only by the shear stiffness of the shear plane, but also by the normal restraint stiffness of the reinforcement. To minimize this scatter the test program is divided into a few parts.

Table 3.1 Test program of reinforced specimens.

<table>
<thead>
<tr>
<th>$\tau_n/\tau_u$</th>
<th>Mix A</th>
<th>Mix B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4 stirrups</td>
<td>6 stirrups</td>
</tr>
<tr>
<td>55%</td>
<td>n+n</td>
<td>n</td>
</tr>
<tr>
<td>60%</td>
<td>n</td>
<td>n+f</td>
</tr>
<tr>
<td>65%</td>
<td>n+f</td>
<td>n+n</td>
</tr>
<tr>
<td>70%</td>
<td>f+f+f</td>
<td>n</td>
</tr>
<tr>
<td>75%</td>
<td>f+f+f</td>
<td>f+f</td>
</tr>
<tr>
<td>80%</td>
<td>f+f+f</td>
<td>f+f</td>
</tr>
<tr>
<td>85%</td>
<td>f+f</td>
<td></td>
</tr>
<tr>
<td>90%</td>
<td>f</td>
<td></td>
</tr>
</tbody>
</table>

n = no shear failure during cycling  
f = failure during cycling

In each part of the program listed in Table 3.1 just one or two parameters are varied and two or three experiments are conducted under the same loading conditions. The test program is listed in Table 3.1. The test program should represent reality. In practice the shear stress
level has a normal distribution, which is represented in Fig. 3.4 by a straight line. By plotting the data of Table 3.1 in the same diagram it is shown that the test program indeed represents a normal distribution. It must be noted that the stress level used in the test series is much higher than according to the real structural conditions. This was necessary to obtain crack displacements in a measurable range.

Fig. 3.4 Normal distribution of the test program.
3.3 Coding of the experiments.

All specimens have been assigned an identifying code. This code indicates the type of experiment. For the tests with reinforced specimens the following code is used:

\[
A / 4 \quad L / 0.70 / 6.7 / 0.05
\]

(1) (2a) (2b) (3) (4) (5)

with

(1) = concrete grade:  
  A = Mix A  
  B = Mix B

(2) = (a) number of stirrups  
  (b) steel grade:  
    L = Low  
    H = High

(3) = maximum shear stress level during cycling: \( \tau_m / \tau_u \)

(4) = maximum applied shear stress \( \tau_m [N/mm^2] \)

(5) = (measured) initial crack width \( \delta_{no} \)
Test specimen and test program
4 TEST EQUIPMENT AND DATA-AQUISITION SYSTEM

4.1 Test set-up and equipment

All the tests were performed on precracked specimens. Prior to the actual test the crack was made in a special splitting frame (see Fig. 4.1). In a three-point bending test the crack was formed by pushing a steel knife-edge into a V-shaped groove along the shear plane. The crack opening was measured with displacement transducers placed on small steel plates stuck to the surface of the concrete. Interactively with the measured displacements recorded by a Commodore 8032 micro-computer a bending moment up to approximately 4 kNm was applied (see Fig. 4.1a). After a crack-opening of more than 0.05 mm (at maximum splitting force) had been removed the load was removed and then the rear face of the specimen was split as shown in Fig. 4.1b.

Fig. 4.1 Combined splitting and bending arrangement.
The average crack width recorded after removal of the splitting arrangement varies between 0.01 and 0.08 mm. This so-called initial crack width is the last part of the identifying code of the specimens (see Section 3.3). The measuring devices were removed before transfer of the specimen to the testing rig.

To prevent secondary cracking the cantilevers were prestressed in the transverse direction by means of a single 3/8 inch tendon providing an initial concrete compressive stress of approximately 1 N/mm².

Figure 4.2 Testing rig used for the repeated tests.
After prestressing of the cantilevers the specimen was placed in the testing arrangement for the actual test. In Fig. 4.2 the testing arrangement is shown schematically. The specimen was supported by a roller bearing to prevent restraining forces being transmitted from the test frame after crack opening. A 1000 kN jack placed on the foot of the frame provided the load, which was measured by a load cell placed between the cross head and the hinge. The hinge induced the load at the top of the specimen. This testing arrangement is almost identical with the one used by Walraven [5]. The results of his static experiments will be in good agreement with the results of the current study.

The applied shear stress during the test alternated between the adjusted maximum and minimum levels (see Fig. 4.3.). The time per cycle was one second.

![Graph of applied shear stress](image)

Fig. 4.3. Applied shear stress

Schenk electrical equipment was used for load control. As appears from the schematic overall view of the loading system (see Fig. 4.4) the electric signal from the servo controller was transformed into a hydraulic signal of the oil jack. The loading frequency signal was
obtained from a Hewlett-Packard function generator (sinusoidal signal). On the servo controller the static value and the amplitude could be adapted to the shear stress according to eq. (2.3). A minimum shear stress of 0.33 N/mm² was applied in all the tests.

Fig. 4.4. Schematic overall view of the loading system.
4.2 The data acquisition system

The data acquisition system was used for both the precracking of the specimen and the actual test (see fig. 4.4). It consisted of:

- Commodore 8032 micro-computer (8-bits).
- Commodore 8050 dual floppy disk drive (1 Mbyte)
- Commodore 4022 dotmatrix printer
- HDAS-16 channel - 12-bits Analog Digital Converter; range set to 
  +10 V
  system error of the converter is 0.025% of full scale range. [16]
- 16 channel DC amplifier with user selectable gain of 1 or 1000
- 20 channel extension board.

The linear displacement transducer, Hewlett-Packard type 7-DCDT-100, had 0.01 mm measuring accuracy at 5 mm range and 6 V power supply. The displacement transducers and the load cell were connected to the amplifier via the extension board. The amplified signals were converted by the 16 channel A/D-converter and led to the micro-computer for storage and display on the monitor screen.

In order to reproduce the signal each measured cycle was scanned nine times (see Fig. 4.5). During each scan the converted values of all sampled signals were put into a buffer.

![Fig. 4.5. Method of scanning the signal.](image-url)
The control of the A/D-converter was performed by a machine language routine called by a basic main program. The machine language routine permitted sampling at a rate of approximately 20,000/second. By means of a special circuit a trigger level was adjusted to the maximum load. By sampling this trigger level it was possible to start the first scan after each call on the peak value of the applied load.

In the main program the interval between two measurements was set on the basis of the increase in the displacements of the crack face. The interval was in the range of 30 seconds–4 hours.

4.3 Test procedure

After the specimen had been centred in the testing frame the measuring system (see Fig. 4.6) was attached to the steel footings glued on the concrete. These footings were attached close to the shear plane in order to reduce the elastic deformation of the concrete between the measuring points on both sides of the crack.

![Fig. 4.6 The measuring system](image-url)
This deformation was also measured and was about 0.02 mm at maximum shear load. For small displacements of the shear plane this elastic deformation caused serious problems in the analysis of the results; see Walraven [18].

Prior to the start of the experiment the zero measurement of the transducers and load cell was performed. The zero measurement of the crack width reflects the initial crack width. Before interpretation of the test results the initial crack width must be added.

The static shear stress and the amplitude were adjusted before setting the frequency. Immediately after the start of the test the trigger level was set and all measuring channels were scanned. Due to the time delay caused by physical and mechanical inertia during the adjustment of the trigger level, the first measurement obtained was for cycle 10 or even cycle 50. Therefore the displacements were not recorded during the first few cycles.
5 RESULTS OF THE EXPERIMENTS ON SPECIMENS WITH EMBEDDED REINFORCING BARS

5.1 Introduction

The experiments on the specimens with embedded reinforcing bars are subdivided according to the concrete grade and the number of reinforcing bars. A review of the experiments is given in the Tables 5.1-5.4. In addition to the experiments with repeated shear loading four tests were performed with a static increasing shear load. Three of these specimens were tests at an old age in order to try out the testing rig and the measuring devices. The details are listed in Table 5.5. A total of 42 repeated and four static tests was performed. The results of the experiments with repeated shear loading are presented in a series of plots as shown in Fig. 5.1.

Fig. 5.1. Results of a test with repeated shear loading.
The series of plots consists of:

a. $\delta_n - \log(N)$ - relation for $\tau_m$  
$\delta_t - \log(N)$ - relation for $\tau_m$  
$\delta_n - \log(N)$ - relation for $\tau_0$  
$\delta_t - \log(N)$ - relation for $\tau_0$  
Fig. ....(a)

b. $\delta_n - \delta_t$ - relation for $\tau_m$  
$\delta_n - \delta_t$ - relation for $\tau_0$  
Fig. ....(b)

c. $\delta_n - \tau/\tau_m$ - relation  
Fig. ....(c)

d. $\delta_n - \tau/\tau_m$ - relation  
Fig. ....(d)

The definitions of $\tau_m$ and $\tau_0$ are given in Fig. 5.2.

Fig. 5.2. The definitions of $\tau_m$ and $\tau_0$.

$\tau_m$ = maximum applied shear stress  
$\tau_0$ = minimum applied shear stress

Due to the large number of cycles during an experiment there is no possibility of showing the displacements of the crack in each cycle. In the Figs. .... (c) and .... (d) a few cycles are drawn to show the behaviour of the crack in a specific cycle.
Table 5.1 Specimens of mix A with four 8 mm diameter stirrups.

<table>
<thead>
<tr>
<th>Code</th>
<th>batch</th>
<th>$t_0$</th>
<th>$f_{cm}$ [N/mm²]</th>
<th>$t_a$</th>
<th>$t_a$</th>
<th>$t_a/t_0$</th>
<th>No. of cycles</th>
<th>failure during cycling</th>
<th>remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/4L/6.1/0.03</td>
<td>200683</td>
<td>31</td>
<td>54.47</td>
<td>10.00</td>
<td>6.1</td>
<td>0.610</td>
<td>455000</td>
<td>no</td>
<td>static push-off</td>
</tr>
<tr>
<td>A/4L/6.6/0.06</td>
<td>250783</td>
<td>42</td>
<td>50.20</td>
<td>9.47</td>
<td>6.0</td>
<td>0.634</td>
<td>263337</td>
<td>no</td>
<td>static push-off</td>
</tr>
<tr>
<td>A/4L/6.7/0.06</td>
<td>171084</td>
<td>31</td>
<td>54.30</td>
<td>10.97</td>
<td>7.0</td>
<td>0.638</td>
<td>388000</td>
<td>no</td>
<td>static push-off</td>
</tr>
<tr>
<td>A/4L/6.6/0.01</td>
<td>008883</td>
<td>38</td>
<td>46.83</td>
<td>9.29</td>
<td>6.0</td>
<td>0.646</td>
<td>340000</td>
<td>no</td>
<td>preliminary failure of cantilever</td>
</tr>
<tr>
<td>A/4L/6.6/0.02</td>
<td>230184</td>
<td>28</td>
<td>50.99</td>
<td>10.50</td>
<td>6.9</td>
<td>0.657</td>
<td>550000</td>
<td>no</td>
<td>preliminary failure of cantilever</td>
</tr>
<tr>
<td>A/4L/7.0/0.01</td>
<td>100783</td>
<td>43</td>
<td>54.49</td>
<td>10.99</td>
<td>7.0</td>
<td>0.700</td>
<td>241000</td>
<td>no</td>
<td>preliminary failure of cantilever</td>
</tr>
<tr>
<td>A/4L/7.3/0.05</td>
<td>300983</td>
<td>29</td>
<td>53.70</td>
<td>9.90</td>
<td>7.2</td>
<td>0.727</td>
<td>140000</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>A/4L/7.4/0.01</td>
<td>010883</td>
<td>42</td>
<td>49.86</td>
<td>9.42</td>
<td>7.0</td>
<td>0.743</td>
<td>435000</td>
<td>no</td>
<td>preliminary failure of cantilever</td>
</tr>
<tr>
<td>A/4L/7.6/0.02</td>
<td>260983</td>
<td>33</td>
<td>48.20</td>
<td>9.20</td>
<td>7.0</td>
<td>0.761</td>
<td>592550</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>A/4L/7.7/0.03</td>
<td>311083</td>
<td>32</td>
<td>48.50</td>
<td>10.15</td>
<td>7.7</td>
<td>0.759</td>
<td>476200</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>A/4L/7.7/0.04</td>
<td>010883</td>
<td>39</td>
<td>49.48</td>
<td>9.38</td>
<td>7.2</td>
<td>0.768</td>
<td>178500</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>A/4L/7.8/0.04</td>
<td>311083</td>
<td>37</td>
<td>49.30</td>
<td>10.26</td>
<td>8.0</td>
<td>0.780</td>
<td>519800</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>A/4L/7.9/0.02</td>
<td>171083</td>
<td>28</td>
<td>53.47</td>
<td>10.86</td>
<td>8.6</td>
<td>0.792</td>
<td>895000</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>A/4L/8.0/7.3/0.03</td>
<td>020983</td>
<td>28</td>
<td>47.20</td>
<td>9.09</td>
<td>7.3</td>
<td>0.803</td>
<td>115200</td>
<td>yes</td>
<td>static push-off</td>
</tr>
<tr>
<td>A/4L/8.0/7.5/0.05</td>
<td>250783</td>
<td>37</td>
<td>49.60</td>
<td>9.39</td>
<td>7.5</td>
<td>0.799</td>
<td>299450</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>A/4L/8.2/7.4/0.05</td>
<td>080883</td>
<td>35</td>
<td>46.43</td>
<td>8.99</td>
<td>7.4</td>
<td>0.823</td>
<td>996000</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>A/4L/9.0/7.0/0.05</td>
<td>180783</td>
<td>43</td>
<td>54.50</td>
<td>10.00</td>
<td>9.0</td>
<td>0.900</td>
<td>118000</td>
<td>yes</td>
<td></td>
</tr>
</tbody>
</table>

*) These specimens are not listed in table 3.1

Table 5.2 Specimens of mix A with six 8 mm diameter stirrups.

<table>
<thead>
<tr>
<th>Code</th>
<th>batch</th>
<th>$t_0$</th>
<th>$f_{cm}$ [N/mm²]</th>
<th>$t_a$</th>
<th>$t_a$</th>
<th>$t_a/t_0$</th>
<th>No. of cycles</th>
<th>failure during cycling</th>
<th>remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/6L/5.1/6.0/0.04</td>
<td>270683</td>
<td>35</td>
<td>51.37</td>
<td>11.89</td>
<td>6.0</td>
<td>0.505</td>
<td>509000</td>
<td>no</td>
<td>static push-off</td>
</tr>
<tr>
<td>A/6L/5.6/6.7/0.05</td>
<td>140383</td>
<td>72</td>
<td>51.41</td>
<td>11.90</td>
<td>6.7</td>
<td>0.563</td>
<td>386000</td>
<td>yes</td>
<td>only measurements for R-88017-386000</td>
</tr>
<tr>
<td>A/6L/5.8/6.8/0.01</td>
<td>270683</td>
<td>30</td>
<td>50.40</td>
<td>11.73</td>
<td>6.8</td>
<td>0.578</td>
<td>194000</td>
<td>no</td>
<td>static push-off</td>
</tr>
<tr>
<td>A/6L/6.1/7.2/0.04</td>
<td>060883</td>
<td>22</td>
<td>51.30</td>
<td>11.88</td>
<td>7.2</td>
<td>0.606</td>
<td>168000</td>
<td>no</td>
<td>static push-off</td>
</tr>
<tr>
<td>A/6L/6.2/7.0/0.04</td>
<td>190983</td>
<td>30</td>
<td>57.30</td>
<td>12.89</td>
<td>8.0</td>
<td>0.621</td>
<td>410760</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>A/6L/6.6/7.9/0.03</td>
<td>101083</td>
<td>28</td>
<td>45.10</td>
<td>11.84</td>
<td>7.9</td>
<td>0.663</td>
<td>175000</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>A/6L/6.6/8.6/0.02</td>
<td>190983</td>
<td>36</td>
<td>58.60</td>
<td>13.10</td>
<td>8.6</td>
<td>0.656</td>
<td>407220</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>A/6L/6.7/8.2/0.09</td>
<td>050983</td>
<td>29</td>
<td>53.20</td>
<td>12.20</td>
<td>8.2</td>
<td>0.672</td>
<td>210900</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>A/6L/6.8/8.0/0.05</td>
<td>100383</td>
<td>64</td>
<td>51.01</td>
<td>11.63</td>
<td>8.0</td>
<td>0.676</td>
<td>100000</td>
<td>yes</td>
<td></td>
</tr>
</tbody>
</table>
### Table 5.3 Specimens of mix B with four 8 mm diameter stirrups

<table>
<thead>
<tr>
<th>Code</th>
<th>batch</th>
<th>t0</th>
<th>fccm [N/mm²]</th>
<th>to</th>
<th>fcm [N/mm²]</th>
<th>No. of cycles</th>
<th>failure during cycling</th>
<th>remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>B/4L/.57/.7/.0/.03</td>
<td>110483</td>
<td>53</td>
<td>73.54</td>
<td>12.27</td>
<td>7.0</td>
<td>665000</td>
<td>no</td>
<td>initial crack width = 0.20 mm</td>
</tr>
<tr>
<td>B/4L/.59/.7/.0/.20</td>
<td>110783</td>
<td>43</td>
<td>69.90</td>
<td>11.85</td>
<td>7.0</td>
<td>512660</td>
<td>yes</td>
<td>static push off</td>
</tr>
<tr>
<td>B/4L/.60/.7/.0/.06</td>
<td>110783</td>
<td>43</td>
<td>69.46</td>
<td>11.74</td>
<td>7.0</td>
<td>22500</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>B/4L/.60/.7/.4/.02</td>
<td>250583</td>
<td>40</td>
<td>72.54</td>
<td>12.27</td>
<td>7.4</td>
<td>603</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>B/4L/.61/.7/.3/.04</td>
<td>250583</td>
<td>28</td>
<td>70.80</td>
<td>11.95</td>
<td>7.3</td>
<td>611</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>B/4L/.61/.8/.5/.04</td>
<td>211183</td>
<td>38</td>
<td>75.34</td>
<td>13.89</td>
<td>8.5</td>
<td>612</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>B/4L/.62/.7/.3/.04</td>
<td>220883</td>
<td>31</td>
<td>67.89</td>
<td>11.61</td>
<td>7.3</td>
<td>629</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>B/4L/.66/8.0/.0/.07</td>
<td>110483</td>
<td>52</td>
<td>73.47</td>
<td>12.26</td>
<td>8.0</td>
<td>653</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>B/4L/.69/.9/.0/.04</td>
<td>211183</td>
<td>30</td>
<td>74.00</td>
<td>13.69</td>
<td>9.0</td>
<td>657</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>B/4L/.75/8.4/.0/.05</td>
<td>031083</td>
<td>30</td>
<td>65.10</td>
<td>11.28</td>
<td>8.4</td>
<td>745</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>B/4L/.79/9.0/.0/.08</td>
<td>250893</td>
<td>37</td>
<td>63.80</td>
<td>11.11</td>
<td>8.8</td>
<td>792</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>B/4L/.81/9.1/.0/.04</td>
<td>031083</td>
<td>28</td>
<td>64.70</td>
<td>11.23</td>
<td>9.1</td>
<td>810</td>
<td>yes</td>
<td></td>
</tr>
</tbody>
</table>

*) This specimen is not listed in Table 3.1

### Table 5.4 Specimens of mix B with six 8 mm diameter stirrups

<table>
<thead>
<tr>
<th>Code</th>
<th>batch</th>
<th>t0</th>
<th>fccm [N/mm²]</th>
<th>to</th>
<th>fcm [N/mm²]</th>
<th>No. of cycles</th>
<th>failure during cycling</th>
<th>remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>B/6L/.46/6.9/.0/.04</td>
<td>040783</td>
<td>39</td>
<td>70.70</td>
<td>15.11</td>
<td>6.9</td>
<td>550000</td>
<td>no</td>
<td>static push-off</td>
</tr>
<tr>
<td>B/6L/.52/7.9/.0/.02</td>
<td>120993</td>
<td>32</td>
<td>71.68</td>
<td>15.26</td>
<td>7.9</td>
<td>290000</td>
<td>no</td>
<td>t0 = 8.0; 10.0 [N/mm²]</td>
</tr>
<tr>
<td>B/6L/.53/8.0/.0/.06</td>
<td>040783</td>
<td>46</td>
<td>71.40</td>
<td>15.21</td>
<td>8.0</td>
<td>250000</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>B/6L/.56/9.0/.0/.02</td>
<td>050583</td>
<td>35</td>
<td>75.10</td>
<td>15.81</td>
<td>8.9</td>
<td>325900</td>
<td>no</td>
<td></td>
</tr>
</tbody>
</table>

### Table 5.5 Specimens subjected to an increasing static shear load

<table>
<thead>
<tr>
<th>Code</th>
<th>batch</th>
<th>to</th>
<th>fccm [N/mm²]</th>
<th>to</th>
<th>fcm [N/mm²]</th>
<th>No. of cycles</th>
<th>failure during cycling</th>
<th>remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/6L/st/10.9/.05</td>
<td>140383</td>
<td>92</td>
<td>62.08</td>
<td>12.01</td>
<td>10.92</td>
<td>10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A/6L/st/10.9/.04</td>
<td>140383</td>
<td>95</td>
<td>52.16</td>
<td>12.02</td>
<td>10.93</td>
<td>10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A/6H/st/15.2/.01</td>
<td>101093</td>
<td>28</td>
<td>45.10</td>
<td>11.84</td>
<td>10.20</td>
<td>10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A/6L/st/10.4/.01</td>
<td>301083</td>
<td>191</td>
<td>56.79</td>
<td>14.96</td>
<td>10.40</td>
<td>10.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.2 Test results

The results of the experiments with repeated shear loading are represented in the figs. 5.3 - 5.44. A few remarks are listed in tables 5.1-5.4. In addition to these remarks some observations made during the experiments will be discussed here.

No secondary cracking is observed during the experiments. Therefore, the whole crack plane of a specimen contributed to the shear transfer. In general the displacements of the crack on the front side of the specimen differ from these displacements on the rear side. The displacements on the rear side (this at the bottom during casting) are in general larger than the displacements on the front side. This is in contrary to what can be expected on the basis of compaction and hydration shrinkage. The differences between the deformations on the front - and rear side can cause problems in the theoretical explanation of the experiments [6]. Hence, in Appendix II the $\delta_n - \delta_t$ relations for both the front and rear side of the specimens are represented.

The age of a specimen $t_o$ at the start of the experiment differs from the age of 28 days at which the concrete strength is determined. The concrete strengths listed in Tables 5.1 - 5.5 have been calculated with equations (2.4) and (2.5) for $t_o$. The concrete strengths at 28 days are listed in Appendix III relating to the standard tests on concrete.

Specimens Nos. A/4L/.65/6.0/.05, A/4L/.70/7.0/.04 and A/4L/.74/7.0/.06 failed due to preliminary failure of the non-prestressed cantilever. These specimens were cast for experiments with reversed loading; see [17]. They had a slightly different configuration as reported in [17], so that the cantilever could not be prestressed.

Specimen No. B/4L/.59/7.0/.20 had an initial crack width of 0.20 mm. For this specimen an attempt was made to adjust an initial crack width of 0.10 mm. Due to bond failure of the reinforcement on the rear side
of the specimen the crack width exceeded the chosen value of 0.10 mm. The resulting normal restraint stiffness was very low and shear failure occurred within only 1331 cycles.

The shear stress level applied in the experiment on specimen A/4L/.90/9.0/.05 was rather high. Large deformations of the crack face occurred even during application of the shear load. The number of cycles to shear failure ($N_f = 118$) was not in the range of the high-cycle experiments with which this report is more particularly concerned.
5.2.1. Displacement during cycling

Experimental results

figure: 5.3
specimen: A/4L/61/61/03

\( N \)
- \( \bullet = 75 \)
- \( \circ = 50200 \)
- \( x = 450000 \)
crack displacements $[\text{mm}]$

- separation $\delta_n$
- slip $\delta_t$

Experiment results

figure: 5.4
specimen: A/4L/63/6.0/06

- $N$
  - $\bullet = 5$
  - $\circ = 29135$
  - $\times = 263337$
Experimental results

Figure 5.5
Specimen: A14H.64/70.06

\( \tau / \tau_m \)

\( \tau / \tau_m \)

(c) Separation \( \delta_n \) [mm]

(d) Slip \( \delta_t \) [mm]
crack displacements [mm]

- separation $\delta_n$
- slip $\delta_t$

(a) log $N$ [cycles]

(b) separation $\delta_n$ [mm]

(c) separation $\delta_n$ [mm]

(d) slip $\delta_t$ [mm]

figure: 5.6
specimen: A/4L/65/6.0/05

N
- $= 10$
- $= 64000$
- $= 25600$
Experimental results

Figure 57
specimen: A/4H.66/6.9/.02

\[
N = \begin{cases} 
10 & \tau = 7.1 \text{ N/mm}^2 \\
542580 & \tau = 8.1 \text{ N/mm}^2 \\
250 & \tau = 600000 \text{ N/mm}^2
\end{cases}
\]
crack displacements [mm]

- separation $\delta_n$
- slip $\delta_t$

(a) log N [cycles]

(b) separation $\delta_n$ [mm]

(c) separation $\delta_n$ [mm]

(d) slip $\delta_t$ [mm]

figure: 5.9
specimen: A/4L/73/72/05

$\tau/\tau_m$

- $\bullet$ = 100
- $\square$ = 5000
- $\times$ = 12200
Experimental results

Figure: A/3/L/74/70/06

N = 5
o = 351
crack displacements [mm]

- separation $\delta_n$
- slip $\delta_t$

slip $\delta_t$ [mm]

$\frac{\tau}{\tau_m}$

(c) separation $\delta_n$ [mm]

(d) slip $\delta_t$ [mm]

figure: 5.11
specimen: A/4L/76/70/02

N
- $= 50$
- $= 2020$
- $= 3600$
- $= 5590$
figure: 5.12
specimen: A/4H/76/77/03

N
○ = 50
● = 1630
□ = 4750
Experimental results

Graph (a) shows crack displacements versus log N (cycles), with curves for separation $\delta_n$ and slip $\delta_t$.

Graph (b) illustrates the relationship between slip $\delta_t$ and separation $\delta_n$.

Graphs (c) and (d) depict the ratio $\tau/\tau_m$ for separation $\delta_n$ and slip $\delta_t$, respectively.

Figure: 5.13
Specimen: A/4LI.77/72/04

Parameters:
- $\bullet = 10$
- $\circ = 1035$
- $\times = 1575$
crack displacements [mm]

- separation $\delta_n$
- slip $\delta_t$

log $N$ [cycles]

figure: 5.14
specimen: A/4H/78/80/4
Experimental results

Figure 5.15
specimen: A/4H/79/8.6/02

- $\tau / \tau_m$
- $\tau / \tau_m$
- $\delta_n [\text{mm}]$
- $\delta_t [\text{mm}]$

N
- $= 5$
- $= 530$
- $= 770$
Figure 5.17
specimen: A/4L/80/75/05

N
● = 10
○ = 1000
x = 32440
□ = 295000
Experimental results

Figure: 5.18
Specimen: A/4L/82/74/05

\[ \frac{\tau}{\tau_m} \]

Log N [cycles]

Separation \( \delta_n [\text{mm}] \)

Slip \( \delta_t [\text{mm}] \)

Separation \( \delta_n [\text{mm}] \)

Validation: 10

- = 10
- = 360
- = 740
Experimental results

Figure: 5.19
specimen: A1/L/90/00/05

- N = \infty
- o = 85
- o = 110
Experimental results

(c) separation $\delta_n$ [mm]  

(d) slip $\delta_t$ [mm]

figure: 5.20  
specimen: A/6L/51/6.0/04
Experimental results

Figure 5.21
specimen: A/6L/56/67/05

N
- = 100
- = 4100
- = 22000
- = 104000
- = 244000
- = 386000

(c) separation δn [mm]
(d) slip δt [mm]
crack displacements [mm]

- separation $\delta_n$
- slip $\delta_t$

log $N$ [cycles]

separation $\delta_n$ [mm]

slip $\delta_t$ [mm]

$\frac{\tau}{\tau_m}$ vs. separation $\delta_n$ [mm]

$\frac{\tau}{\tau_m}$ vs. slip $\delta_t$ [mm]

figure: 5.22
specimen: A/6L/58/6.8/02

$N$

$\circ = 88817$
$\bullet = 193725$
Experimental results

figure: 5.23
specimen: A/6L/61/72/04

\[ N = 72 \]
\[ \tau = 7.2 \]
\[ \tau = 8.2 \]

\[ \bullet = 100 \]
\[ \circ = 160\,300 \]
\[ \triangle = 10 \]
\[ \circ = 27\,000 \]
\[ \times = 109\,800 \]
\[ \blacksquare = 318\,100 \]
crack displacements [mm]

\[ \text{separation } \delta_n \]
\[ \text{slip } \delta_t \]

log N [cycles]

separation \( \delta_n [mm] \)

\( \tau/\tau_m \)

\[ N \]
\[ N = 50 \]
\[ N = 410000 \]
crack displacements [mm]

- separation $\delta_n$
- slip $\delta_t$

log $N$ [cycles]

slip $\delta_t$ [mm]

separation $\delta_n$ [mm]

$\tau / \tau_m$

(c) separation $\delta_n$ [mm]

(d) slip $\delta_t$ [mm]

figure: 5.26
specimen: A/6L/66/86/02

N
- O = 25
- $\bullet$ = 10800
- $\square$ = 35280
crack displacements [mm]

(a) log N [cycles]

(b) separation δ_n [mm]

(c) separation δ_n [mm]

(d) slip δ_t [mm]

 Experimental results

figure: 5.27
specimen: A/6L/67/8.2/08

<table>
<thead>
<tr>
<th>N</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>4400</td>
</tr>
<tr>
<td>□</td>
<td>13500</td>
</tr>
<tr>
<td>▲</td>
<td>21000</td>
</tr>
</tbody>
</table>
crack displacements [mm]

- separation δₙ
- slip δₜ

slip δₜ [mm]

separation δₙ [mm]

τ/τₘ

separation δₙ [mm]

slip δₜ [mm]

figure: 5.28
specimen: A/6L/68/8.0/03

N
- □ = 100
- • = 320
- ○ = 500
- □ = 1000
crack displacements [mm]

- - - separation δn
- - - - slip δt

log N [cycles]

(a)

slip δt [mm]

(b) separation δn [mm]

$\tau / \tau_m$

(c) separation δn [mm]

(d) slip δt [mm]

figure: 5.29
specimen: B/4L/57/70/03

N

- = 100 $\tau = 7.0 \text{ N/mm}^2$
- = 433000
- = 10
- = 16500 $\tau = 8.0 \text{ N/mm}^2$
- = 88500
crack displacements [mm]

- separation $\delta_n$
- slip $\delta_t$

- $\tau_m$
- $\tau_o$

log $N$ [cycles]

(a)

(b)

separation $\delta_n$ [mm]

figure: 5.30
specimen: B/4L/59/70/20

(c) separation $\delta_n$ [mm]

(d) slip $\delta_t$ [mm]

$\tau/\tau_m$

- $N = 50$
- $N = 800$
- $N = 1160$
crack displacements [mm]

(a) separation $\delta_n$
(b) slip $\delta_t$

$\log N$ [cycles]

separation $\delta_n$ [mm]

slip $\delta_t$ [mm]

$\tau/\tau_m$

separation $\delta_n$ [mm]

slip $\delta_t$ [mm]

figure: 5.31
specimen: B/4L/60/70/06

$N$

= 50

o = 512660
figure: 5.32
specimen: B/4H/60/74/08

N
* = 100
□ = 37400
× = 81400
Experimental results

Figure: 5.33
Specimen: B/4/L.61/73/04

1. Crack displacements [mm]
   - separation $\delta_n$
   - slip $\delta_t$

2. Slip $\delta_t$ [mm]

3. $\tau / \tau_m$ vs. $N$ [cycles]

4. $\tau / \tau_m$ vs. $\delta_n$ [mm]

5. $\tau / \tau_m$ vs. $\delta_t$ [mm]

Note: $N = 200, 9100, 23500$
crack displacements [mm]

- separation $\delta_n$
- slip $\delta_t$

$\tau / \tau_m$

$\tau / \tau_m$

$N$

- $N = 100$
- $N = 345925$

figure: 5.34
specimen: B/4H/61/8.5/04
crack displacements [mm]

- separation $\delta_n$
- slip $\delta_t$

log $N$ [cycles]

figure: 5.35
specimen: B/4L/63/73/04

N
- $\circ = 100$
- $\bullet = 919500$
- $\square = 931200$

(c) separation $\delta_n$ [mm]

(d) slip $\delta_t$ [mm]
Experimental results

Figure 5.36
Specimen: B/4L/65/80/07

N
- = 50
o = 10516
x = 57316
□ = 62000
Experimental results

(c) separation $\delta_n$ [mm]

(d) slip $\delta_t$ [mm]

Figure: 5.37
Specimen: B/4H/66/90/04

$\tau/\tau_m$

$N$

- $\circ = 10$
- $\bullet = 720$
- $\square = 1800$
crack displacements [mm]

- separation $\delta_n$
- slip $\delta_t$

log N [cycles]

separation $\delta_n$ [mm]

slip $\delta_t$ [mm]

figure: 5.39
specimen: B/4L/79/8.8/08

(c) separation $\delta_n$ [mm]

(d) slip $\delta_t$ [mm]

$\tau/\tau_m$

$N$

- $\circ = 190$
- $\bullet = 890$
- $\square = 1150$
crack displacements [mm]

separation $\delta_n$

slip $\delta_t$

log $N$ [cycles]

separation $\delta_n$ [mm]

$\frac{\tau}{\tau_m}$

$\frac{\tau}{\tau_m}$

figure: 5.40
specimen: B/4L/81/9.1/04

N
○ = 110
● = 1020
□ = 1410
crack displacements [mm]

- separation $\delta_n$
- slip $\delta_t$

log $N$ [cycles]

separation $\delta_n$ [mm]

figure: 5.41
specimen: B/6L/46/6.9/04

$N$
- $\bullet = 50$
- $\circ = 550000$
Experimental results

(c) separation $\delta_n$ [mm]

(d) slip $\delta_t$ [mm]

Figure: 5.42
Specimen: B/6L/52/79/02

$N$
- $\circ = 100$
- $\bullet = 290000$
crack displacements [mm]

- separation $\delta_n$
- slip $\delta_t$

log $N$ [cycles]

(a)

slip $\delta_t$ [mm]

$\tau_0$, $\tau_m$

(b)

separation $\delta_n$ [mm]

$\tau_0$, $\tau_m$

(c) separation $\delta_n$ [mm]

$\tau/\tau_m$

(d) slip $\delta_t$ [mm]

$\tau/\tau_m$

figure: 5.43
specimen: B/6L/53/80/06

$N$

- $\bullet = 20 \{ \tau = 80 \text{ N/mm}^2 \}$
- $\circ = 250000 \{ \tau = 80 \text{ N/mm}^2 \}$
- $\square = 5150 \{ \tau = 10 \text{ N/mm}^2 \}$
- $\blacksquare = 20120 \{ \tau = 80 \text{ N/mm}^2 \}$
- $\times = 20600 \{ \tau = 10 \text{ N/mm}^2 \}$
crack displacements [mm]

- separation $\delta_n$
- slip $\delta_t$

log $N$ [cycles]

separation $\delta_n$ [mm]

figure: 5.44
specimen: B/6L/56/89/02

$N$
- $o = 100$
- $* = 325832$
5.2.2. Load-displacement relations in static experiments

In this section the results of the experiments with increasing static shear load are presented. For each specimen two graphics are given representing the relation between the increasing shear stress and the displacements $\delta_n$ and $\delta_t$ of the opposing crack faces. The graphics are represented in the Figs. 5.45 - 5.48.

5.2.3. Load-displacement relations in static experiments after removal of repeated load.

Table 5.6 Specimens subjected to an increasing static shear load after enduration of a repeated load.

<table>
<thead>
<tr>
<th>Code</th>
<th>batch</th>
<th>$f_{ccm}$</th>
<th>$\tau_0$</th>
<th>$\tau_{u,exp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[days]</td>
<td>[N/mm²]</td>
<td>[N/mm²]</td>
<td></td>
</tr>
<tr>
<td>A/4L/.61/6.1/.03</td>
<td>200683</td>
<td>31</td>
<td>54.47</td>
<td>10.00 10.17</td>
</tr>
<tr>
<td>A/4L/.63/6.0/.06</td>
<td>250783</td>
<td>42</td>
<td>50.20</td>
<td>9.47 10.10</td>
</tr>
<tr>
<td>A/4H/.64/7.0/.06</td>
<td>171083</td>
<td>31</td>
<td>54.30</td>
<td>10.97 11.77</td>
</tr>
<tr>
<td>A/4H/.66/6.9/.02</td>
<td>230184</td>
<td>28</td>
<td>50.99</td>
<td>10.50 12.44</td>
</tr>
<tr>
<td>A/6L/.51/6.0/.04</td>
<td>270683</td>
<td>35</td>
<td>51.37</td>
<td>11.89 12.10</td>
</tr>
<tr>
<td>A/6L/.58/6.8/.01</td>
<td>270683</td>
<td>30</td>
<td>50.40</td>
<td>11.73 11.21</td>
</tr>
<tr>
<td>A/6L/.61/7.2/.04</td>
<td>060683</td>
<td>22</td>
<td>51.30</td>
<td>11.88 12.30</td>
</tr>
<tr>
<td>A/6L/.62/8.0/.04</td>
<td>190983</td>
<td>30</td>
<td>57.30</td>
<td>12.89 12.48</td>
</tr>
<tr>
<td>B/4L/.60/7.0/.06</td>
<td>110783</td>
<td>43</td>
<td>69.46</td>
<td>11.74 10.60</td>
</tr>
<tr>
<td>B/4H/.61/8.5/.04</td>
<td>211183</td>
<td>38</td>
<td>75.34</td>
<td>13.89 12.66</td>
</tr>
<tr>
<td>B/6L/.46/6.9/.04</td>
<td>040783</td>
<td>39</td>
<td>70.70</td>
<td>15.11 13.50</td>
</tr>
<tr>
<td>B/6L/.52/7.9/.02</td>
<td>120983</td>
<td>32</td>
<td>71.68</td>
<td>15.26 14.27</td>
</tr>
<tr>
<td>B/6L/.56/8.9/.02</td>
<td>050983</td>
<td>35</td>
<td>75.10</td>
<td>15.81 15.99</td>
</tr>
</tbody>
</table>

The experiments with repeated shear loading, which did not fail during cycling, were subjected to a higher stress level or unloaded and then pushed off in a static test. The results of the static tests are represented in the Figs. 5.49 - 5.61. The specimens pushed off in a static test are listed in Table 5.6.
Experimental results

\[ \tau [N/mm^2] \]

\[ 15 \]

\[ 12.5 \]

\[ 10 \]

\[ 7.5 \]

\[ 5 \]

\[ 2.5 \]

\[ 0 \]

\[ 0 \]

\[ \delta_t [mm] \]

\[ 0 \]

\[ 0.2 \]

\[ 0.4 \]

\[ 0.6 \]

\[ \delta_n [mm] \]

\[ 0 \]

\[ 0.2 \]

\[ 0.4 \]

\[ 0.6 \]

figure: 5.45
specimen: A/6H/ST/102/01

figure: 5.46
specimen: A/8L/ST/102/05
Experimental results

\[ \tau [\text{N/mm}^2] \]

\begin{align*}
\begin{array}{c}
\text{figure: 5.47} \\
\text{specimen:} \\
A/6L/ST/10.9/05
\end{array}
\end{align*}

\begin{align*}
\begin{array}{c}
\text{figure: 5.48} \\
\text{specimen:} \\
A/6L/ST/10.9/04
\end{array}
\end{align*}
Experimental results

\[ \tau [\text{N/mm}^2] \]

\[ \delta_t [\text{mm}] \]

\[ \delta_n [\text{mm}] \]

Figure 5.49: Specimen; A/4L/61/61/03

Figure 5.50: Specimen; A/4L/63/60/06
Experimental results

Figure 5.51
Specimen: A/4H/64/70/06

Figure 5.52
Specimen: A/4H/66/69/02
Experimental results

\begin{figure}
\centering
\begin{tabular}{cc}
\begin{tikzpicture}
\begin{axis}[
    title={$\tau [N/mm^2]$},
    xlabel={$\delta_t [mm]$},
    ylabel={$\tau [N/mm^2]$},
    xmin=0, xmax=0.65,
    ymin=0, ymax=15,
    xtick={0,0.2,0.4,0.6},
    ytick={0,2.5,5,7.5,10,12.5,15},
    grid=both,
]
\addplot[mark=none] coordinates {
(0,0) (0.2,10) (0.4,12.5) (0.6,15)
};
\end{axis}
\end{tikzpicture} & \begin{tikzpicture}
\begin{axis}[
    title={$\tau [N/mm^2]$},
    xlabel={$\delta_n [mm]$},
    ylabel={$\tau [N/mm^2]$},
    xmin=0, xmax=0.65,
    ymin=0, ymax=15,
    xtick={0,0.2,0.4,0.6},
    ytick={0,2.5,5,7.5,10,12.5,15},
    grid=both,
]
\addplot[mark=none] coordinates {
(0,0) (0.2,10) (0.4,12.5) (0.6,15)
};
\end{axis}
\end{tikzpicture}
\end{tabular}
\caption{Specimen: A/6L/61/72/04}
\end{figure}

\begin{figure}
\centering
\begin{tabular}{cc}
\begin{tikzpicture}
\begin{axis}[
    title={$\tau [N/mm^2]$},
    xlabel={$\delta_t [mm]$},
    ylabel={$\tau [N/mm^2]$},
    xmin=0, xmax=0.65,
    ymin=0, ymax=15,
    xtick={0,0.2,0.4,0.6},
    ytick={0,2.5,5,7.5,10,12.5,15},
    grid=both,
]
\addplot[mark=none] coordinates {
(0,0) (0.2,10) (0.4,12.5) (0.6,15)
};
\end{axis}
\end{tikzpicture} & \begin{tikzpicture}
\begin{axis}[
    title={$\tau [N/mm^2]$},
    xlabel={$\delta_n [mm]$},
    ylabel={$\tau [N/mm^2]$},
    xmin=0, xmax=0.65,
    ymin=0, ymax=15,
    xtick={0,0.2,0.4,0.6},
    ytick={0,2.5,5,7.5,10,12.5,15},
    grid=both,
]
\addplot[mark=none] coordinates {
(0,0) (0.2,10) (0.4,12.5) (0.6,15)
};
\end{axis}
\end{tikzpicture}
\end{tabular}
\caption{Specimen: B/4L/60/70/06}
\end{figure}
Experimental results

\begin{align*}
\tau [N/mm^2] & \quad \delta_t [mm] \\
15 & \quad 0.2 \quad 0.4 \quad 0.6 \\
12.5 & \\
10 & \\
7.5 & \\
5 & \\
2.5 & \\
0 & \\
\end{align*}

\begin{align*}
\tau [N/mm^2] & \quad \delta_n [mm] \\
15 & \quad 0.2 \quad 0.4 \quad 0.6 \\
12.5 & \\
10 & \\
7.5 & \\
5 & \\
2.5 & \\
0 & \\
\end{align*}

\begin{align*}
\tau [N/mm^2] & \quad \delta_t [mm] \\
15 & \quad 0.2 \quad 0.4 \quad 0.6 \\
12.5 & \\
10 & \\
7.5 & \\
5 & \\
2.5 & \\
0 & \\
\end{align*}

\begin{align*}
\tau [N/mm^2] & \quad \delta_n [mm] \\
15 & \quad 0.2 \quad 0.4 \quad 0.6 \\
12.5 & \\
10 & \\
7.5 & \\
5 & \\
2.5 & \\
0 & \\
\end{align*}

Figure 5.53: specimen:
A/6L/51/60/04

Figure 5.54: specimen:
A/6L/58/68/02
Experimental results

\begin{align*}
\tau \text{[N/mm}^2\text{]} & \quad \delta_\tau \text{[mm]} \\
\tau \text{[N/mm}^2\text{]} & \quad \delta_\tau \text{[mm]}
\end{align*}

figure: 5.57
specimen: B/4H/61/85/04

figure: 5.58
specimen: B/6L/52/79/02
Experimental results

\[ \tau [N/mm^2] \]

\[ \delta_t [mm] \]

\[ \delta_n [mm] \]

Figure: 5.61
Specimen: B/6L/46/6.9/04
5.3 Relation between the stress level and number of cycles to shear failure

One of the most interesting relations in an experimental study concerning fatigue is the relation between the number of cycles to failure and the stress level in comparison to the static strength. A total of 24 specimens failed during cycling. These specimens are listed in Table 5.7.

Table 5.7 Specimens which failed during cycling

<table>
<thead>
<tr>
<th>Code</th>
<th>batch</th>
<th>( t_0 )</th>
<th>( f_{ccm} )</th>
<th>( \tau_u )</th>
<th>( \tau_m )</th>
<th>( \tau_m/\tau_u )</th>
<th>No. of cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/4L/.73/7.2/.05</td>
<td>200683</td>
<td>29 53.70</td>
<td>9.90 7.2</td>
<td>.727</td>
<td>14000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A/4L/.76/7.0/.02</td>
<td>260983</td>
<td>33 48.20</td>
<td>9.20 7.0</td>
<td>.761</td>
<td>5925</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A/4H/.76/7.7/.03</td>
<td>311083</td>
<td>32 48.50</td>
<td>10.15 7.7</td>
<td>.759</td>
<td>4762</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A/4L/.77/7.2/.04</td>
<td>010883</td>
<td>39 49.48</td>
<td>9.38 7.2</td>
<td>.768</td>
<td>1785</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A/4H/.78/8.0/.04</td>
<td>311083</td>
<td>37 49.30</td>
<td>10.26 8.0</td>
<td>.780</td>
<td>5198</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A/4L/.79/8.6/.02</td>
<td>171083</td>
<td>28 53.47</td>
<td>10.86 8.6</td>
<td>.792</td>
<td>895</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A/4L/.80/7.3/.03</td>
<td>609832</td>
<td>28 47.20</td>
<td>9.09 7.3</td>
<td>.803</td>
<td>1192</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A/4L/.80/7.5/.05</td>
<td>250783</td>
<td>37 49.60</td>
<td>9.39 7.5</td>
<td>.799</td>
<td>299450</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A/4L/.82/7.4/.05</td>
<td>080883</td>
<td>35 46.43</td>
<td>8.99 7.4</td>
<td>.823</td>
<td>996</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A/4L/.90/9.0/.05</td>
<td>180783</td>
<td>43 54.50</td>
<td>10.00 9.0</td>
<td>.900</td>
<td>118</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A/6L/.56/6.7/.05</td>
<td>140383</td>
<td>72 51.41</td>
<td>11.90 6.7</td>
<td>.563</td>
<td>386000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A/6L/.66/7.9/.03</td>
<td>101083</td>
<td>28 45.10</td>
<td>11.84 7.9</td>
<td>.663</td>
<td>1750</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A/6L/.66/8.6/.02</td>
<td>190983</td>
<td>36 58.60</td>
<td>13.10 8.6</td>
<td>.656</td>
<td>40722</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A/6L/.67/8.2/.06</td>
<td>060683</td>
<td>28 53.40</td>
<td>12.20 8.2</td>
<td>.672</td>
<td>21000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A/6L/.68/8.0/.03</td>
<td>140383</td>
<td>64 51.04</td>
<td>11.83 8.0</td>
<td>.676</td>
<td>1000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B/4L/.59/7.0/.20</td>
<td>110783</td>
<td>43 69.90</td>
<td>11.85 7.0</td>
<td>.591</td>
<td>1331</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B/4L/.60/7.4/.08</td>
<td>250583</td>
<td>48 73.54</td>
<td>12.27 7.4</td>
<td>.603</td>
<td>82500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B/4L/.61/7.3/.04</td>
<td>250583</td>
<td>28 70.90</td>
<td>11.95 7.3</td>
<td>.611</td>
<td>23500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B/4L/.63/7.3/.04</td>
<td>220883</td>
<td>31 67.99</td>
<td>11.61 7.3</td>
<td>.629</td>
<td>931731</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B/4L/.65/8.0/.07</td>
<td>110483</td>
<td>52 73.47</td>
<td>12.26 8.0</td>
<td>.653</td>
<td>62000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B/4L/.66/9.0/.04</td>
<td>211183</td>
<td>30 74.00</td>
<td>13.69 9.0</td>
<td>.657</td>
<td>2224</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B/4L/.75/8.4/.05</td>
<td>031083</td>
<td>30 65.10</td>
<td>11.28 8.4</td>
<td>.745</td>
<td>219029</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B/4L/.79/8.8/.08</td>
<td>290883</td>
<td>37 63.88</td>
<td>11.11 8.8</td>
<td>.792</td>
<td>1150</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B/4L/.81/9.1/.04</td>
<td>031083</td>
<td>28 64.70</td>
<td>11.23 9.1</td>
<td>.810</td>
<td>1441</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Some specimens endured the applied shear load for more than 200,000 cycles without shear failure. These specimens were subjected to a higher repeated shear load. Now the specimens sheared off during cycling. The specimens are listed in Table 5.8.

Table 5.8 Specimens which failed during cycling at higher stress level

<table>
<thead>
<tr>
<th>Code</th>
<th>batch</th>
<th>$t_0$</th>
<th>$f_{ccm}$</th>
<th>$\tau_u$</th>
<th>$\tau_m$</th>
<th>$\tau_m/\tau_u$</th>
<th>No. of additional cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>[days]</td>
<td>[N/mm²]</td>
<td>[N/mm²]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B/4L/.57/7.0/.03</td>
<td>110483</td>
<td>53</td>
<td>73.54</td>
<td>12.27</td>
<td>8.0</td>
<td>.652</td>
<td>88500</td>
</tr>
<tr>
<td>B/6L/.53/8.0/.06</td>
<td>040783</td>
<td>46</td>
<td>71.40</td>
<td>15.21</td>
<td>10.0</td>
<td>.657</td>
<td>20631</td>
</tr>
</tbody>
</table>

In Fig. 5.62 the $\tau_m/\tau_u - \log(N_f)$ relation is represented. In the figure the specimens listed in Table 5.7 are marked with a ◆-mark. The specimens listed in Table 5.8 have a ⦿-mark. The specimens, which did not fail during cycling, have a ••-mark.

Fig. 5.62 $\tau_m/\tau_u - \log(N_f)$ relation
The last mentioned specimens include the specimens listed in Table 5.8. The results represented in figure 5.61 can be approximated with a straight line. The following relation is derived from the experimental results by means of a regression analysis:

$$\frac{\tau_m}{\tau_u} = 1.00 - 0.0736 \log(N_f)$$  \hspace{1cm} (5.1)

The results represented in Fig. 5.62 show that despite the scatter of the experimental results the specimens listed in Table 5.8 fit the relation (5.1). Obvious the pre-loading with the repeated shear stress had no measurable influence on the crack behaviour at higher stress levels.
Experimental results
6 EXPERIMENTS ON SPECIMENS WITH EXTERNAL REINFORCING BARS

6.1 Introduction

The scope of the research program for reinforced specimens is given in Chapter 2. This review holds true for the test series reported in this Chapter. In contrary to the fore-going part of the investigation the normal restraint stiffness was not applied by means of embedded reinforcement, but by means of four external restraint bars with a bar diameter of 20 mm. Because of the absence of embedded bars dowel action could be neglected. These tests concentrated on the mechanism of aggregate interlock. The test series comprised 14 repeated - and one static tests.

6.2 Type of specimen.

For these tests the dimensions of the specimen were the same as in the series with the specimens with the embedded reinforcing bars. At the small sides of the specimen steel plates were placed interconnected by four 20 mm steel bars (see Fig. 6.1).

Fig. 6.1 Specimen with external restraint bars.
In contrary to the experiments conducted by Walraven [13] the steel restraint plates were not connected to the concrete by means of bolts screwed in plugs in the concrete. Hence there was no possibility to enlarge the initial crack width $\delta_0$ after removal of the splitting force.

A thin layer of rapidly hardening sand-cement paste placed between the restraint plates and the concrete surface of the specimen ensured an almost linear interaction between crack-opening and restraint force, though the restraint stiffness remained low compared with the specimens with embedded reinforcement. To ensure a small crack width during the first cycles all the specimens were prestressed with an initial normal stress $\sigma_0 = 1.0-2.0$ [N/mm$^2$].

6.3 Testing arrangements and instrumentation.

All the specimens were pre-cracked in the same manner as the reinforced specimens. The first specimens were pre-cracked by applying line loads to the grooves on the front - and rear side of the specimen. This technique provided too much energy, which led to a large initial crack width. Even with a high normal stress it was not possible to close the crack afterwards. The rest of the specimens were cracked as described in Chapter 4.1.

For all the specimens the cantilevers were prestressed according to Fig. 3.3.

The instrumentation used in this part of the investigation was nearly the same as used for the experiments with embedded reinforcing bars and is described in chapter 4. The addition made for this series was a pair of amplifiers for amplification of the signals taken from the strain gauges stuck on the steel restraint bars. The four signals were compensated for bending of the bar, so the measured signal represented the real axial strain.
6.4 Coding of the specimens.

The identifying code of the specimens with external restraint bars differ from the code used for the specimen with embedded reinforcement. For the reinforced specimens the maximum applied shear stress $\tau_m$ could be compared with the shear strength $\tau_u$. This shear strength was determined on basis of Walraven’s experimental work [13] and showed close agreement with the static experiments performed in the current research program; see Tables 5.5-5.6.

The same analysis was made on the static experiments of Walraven, for which the normal restraint stiffness was applied by means of external bars. The following relation was derived by means of a regression analysis:

$$\tau_u = 1.792 + 0.042 f_{ccm} - 13.718 \delta_{no} + 0.598 \sigma_0 \quad [N/mm^2] \quad (6.1)$$

with $\delta_{no} = \text{initial crack width} [\text{mm}]$

$\sigma_0 = \text{initial normal stress} [N/mm^2]$

This relation appeared to underestimate the real measured ultimate stress up to 300 percent. This was probably due to the fact that most experiments conducted by Walraven were not prestressed in contrary to the specimens in the current program. Because of this the coding of the specimens with external restraint bars is as follows:

$$A / 1.12 / 6.70 / .05$$

(1) (2) (3) (4)

with

(1) Concrete grade: $A = \text{Mix A}$

$B = \text{Mix B}$
(2) Initial normal stress $\sigma_o \ [N/mm^2]$

(3) Maximum applied shear stress $\tau_m \ [N/mm^2]$

(4) Initial crack width $\delta_{n0} \ [mm]$

In contrary to the experiments on specimens with embedded reinforcing bars the maximum applied shear stress $\tau_m$ was not the initial applied stress. Due to the fact that for low stress levels no displacements of the opposing crack faces were recorded the applied shear stress at which significant shear slip occurred, was in the coding of the specimens.
7 RESULTS OF THE EXPERIMENTS ON SPECIMENS WITH EXTERNAL RESTRAINING BARS

7.1 Introduction

The experiments on the specimens with external restraining bars are subdivided according to the concrete grade. A review of the experiments subjected to a repeated shear load is given in the Tables 7.1-7.2. In addition to the experiments with repeated shear loading one test was performed with a static increasing shear load. The information about this test is listed in Table 7.3. A total of 14 repeated - and one static tests was performed.

Fig. 7.1. Results of a test with repeated shear loading. -relations with the number of cycles-

The results of the experiments with repeated shear loading are presented in two series of plots according to the Figs. 7.1-7.2
The series of plots in Fig. 7.1 consists of:

a. $\delta_n - \log(N) - \text{relation for } \tau_m$

$\delta_t - \log(N) - \text{relation for } \tau_m$

$b. \frac{\delta_n}{\delta_t} - \tau/\tau_m - \text{relation}$

$\delta_n - \log(N) - \text{relation for } \tau_0$

$\delta_t - \log(N) - \text{relation for } \tau_0$

c. $\delta_t - \tau/\tau_m - \text{relation}$

Fig. 7.2. Results of a test with repeated shear loading.

-relations between the displacements and the normal stress-
The series of plots according to Fig. 7.2 consists of:

a. $\delta_n - \delta_t$ relation for $T_m$
   $\delta_n - \delta_t$ relation for $T_o$  
   Fig. ....(a)

b. $\delta_t - \sigma$ relation  
   Fig. ....(b)

b. $\delta_n - \sigma$ relation  
   Fig. ....(c)

The definitions of $T_m$ and $T_o$ are given in Fig. 5.2.

$T_m =$ maximum applied shear stress
$T_o =$ minimum applied shear stress

According to the representation of the behaviour of the crack faces during a cycle for the experiments on specimens with internal reinforcing bars just a few specific cycles are shown. In the Fig. 7.1 (b) and 7.1 (c) a few cycles are drawn to show the behaviour of the crack in a specific cycle.

The specimens listed in Tables 7.1-7.2 are represented in the Figs. 7.3 - 7.29 (See Section 7.2.1).

The specimens listed in Table 7.3 are represented in the Figs. 7.2 - 7.29 (See Section 7.2.2).
Table 7.1 Specimens for mix A with external restraint bars.

<table>
<thead>
<tr>
<th>Code</th>
<th>batch</th>
<th>$t_a$</th>
<th>$f_{ccm}$ [N/mm$^2$]</th>
<th>$v_o$</th>
<th>$f_a$ [N/mm$^2$]</th>
<th>No. of cycles</th>
<th>failure during cycling</th>
<th>remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/1.3/4.0/.12</td>
<td>121283</td>
<td>40</td>
<td>61.53</td>
<td>1.30</td>
<td>4.0</td>
<td>30800</td>
<td>yes</td>
<td>$t_a = 2 - 7$ N/mm$^2$; static push-off</td>
</tr>
<tr>
<td>A/1.2/5.0/.01</td>
<td>051283</td>
<td>39</td>
<td>52.06</td>
<td>1.22</td>
<td>5.0</td>
<td>20326</td>
<td>no *)</td>
<td></td>
</tr>
<tr>
<td>A/1.3/5.0/.01</td>
<td>260384</td>
<td>52</td>
<td>54.60</td>
<td>1.27</td>
<td>5.0</td>
<td>30800</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>A/1.9/5.0/.19</td>
<td>071082</td>
<td>55</td>
<td>48.40</td>
<td>1.30</td>
<td>6.9</td>
<td>9756</td>
<td>yes</td>
<td>bad fitting restraint plates</td>
</tr>
<tr>
<td>A/0.8/5.5/.01</td>
<td>160182</td>
<td>28</td>
<td>49.56</td>
<td>0.89</td>
<td>5.5</td>
<td>1520</td>
<td>yes</td>
<td>$t_a = 5$ N/mm$^2$</td>
</tr>
<tr>
<td>A/2.1/6.1/.01</td>
<td>190384</td>
<td>45</td>
<td>54.53</td>
<td>2.14</td>
<td>6.1</td>
<td>8640</td>
<td>yes</td>
<td>no displacements recorded after $N = 63800$</td>
</tr>
<tr>
<td>A/1.3/6.2/.01</td>
<td>300184</td>
<td>35</td>
<td>48.09</td>
<td>1.34</td>
<td>6.2</td>
<td>283549</td>
<td>yes</td>
<td>$t_a = 5$ N/mm$^2$</td>
</tr>
<tr>
<td>A/1.3/6.2/.02</td>
<td>081283</td>
<td>43</td>
<td>52.57</td>
<td>1.26</td>
<td>6.2</td>
<td>3120</td>
<td>yes</td>
<td></td>
</tr>
</tbody>
</table>

*) No plots according to Fig. 7.2 available.

Table 7.2 Specimens for mix B with external restraint bars.

<table>
<thead>
<tr>
<th>Code</th>
<th>batch</th>
<th>$t_a$</th>
<th>$f_{ccm}$ [N/mm$^2$]</th>
<th>$v_o$</th>
<th>$f_a$ [N/mm$^2$]</th>
<th>No. of cycles</th>
<th>failure during cycling</th>
<th>remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>B/1.1/5.0/.04</td>
<td>281183</td>
<td>38</td>
<td>71.64</td>
<td>1.07</td>
<td>5.0</td>
<td>254369</td>
<td>no *)</td>
<td>large displacements after load application</td>
</tr>
<tr>
<td>B/1.2/6.0/.01</td>
<td>191283</td>
<td>35</td>
<td>68.36</td>
<td>1.15</td>
<td>5.6</td>
<td>89600</td>
<td>no *)</td>
<td>failure on application of $t_a = 8.9$ N/mm$^2$</td>
</tr>
<tr>
<td>B/1.0/6.2/.04</td>
<td>281183</td>
<td>43</td>
<td>72.25</td>
<td>0.99</td>
<td>6.0</td>
<td>2736</td>
<td>yes</td>
<td>$t_a = 3.5$ N/mm$^2$</td>
</tr>
<tr>
<td>B/2.0/6.5/.01</td>
<td>120384</td>
<td>47</td>
<td>69.14</td>
<td>2.02</td>
<td>6.5</td>
<td>343</td>
<td>yes</td>
<td>$t_a = 3.5$ N/mm$^2$</td>
</tr>
<tr>
<td>B/3.6/6.9/.19</td>
<td>071183</td>
<td>28</td>
<td>70.20</td>
<td>3.58</td>
<td>6.9</td>
<td>82378</td>
<td>no *)</td>
<td>$t_a = 2.7$ N/mm$^2$; static push-off</td>
</tr>
<tr>
<td>B/1.5/7.7/.01</td>
<td>120384</td>
<td>33</td>
<td>67.54</td>
<td>1.99</td>
<td>7.7</td>
<td>3970</td>
<td>yes</td>
<td>$t_a = 5$ N/mm$^2$ $t_m = 7.5$ N/mm$^2$</td>
</tr>
</tbody>
</table>

Table 7.3 Specimens with external bars subjected to an increasing shear load.

<table>
<thead>
<tr>
<th>Code</th>
<th>$t_o$</th>
<th>$f_{ccm}$ [N/mm$^2$]</th>
<th>$v_o$</th>
<th>$f_a, exp$ [N/mm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B/1.30/ST/.07</td>
<td>071082</td>
<td>412</td>
<td>59.20</td>
<td>1.30</td>
</tr>
</tbody>
</table>

The following specimens are pushed off after removal of the repeated shear loading; see tables 7.1-7.2

<table>
<thead>
<tr>
<th>Code</th>
<th>batch</th>
<th>$t_a$</th>
<th>$f_{ccm}$ [N/mm$^2$]</th>
<th>$v_o$</th>
<th>$f_a$ [N/mm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/1.2/5.0/.01</td>
<td>051283</td>
<td>39</td>
<td>52.06</td>
<td>1.22</td>
<td>7.30</td>
</tr>
<tr>
<td>B/3.6/6.9/.19</td>
<td>071183</td>
<td>28</td>
<td>70.20</td>
<td>3.58</td>
<td>9.72</td>
</tr>
</tbody>
</table>
7.2 Results of the experiments with repeated shear loading - observations during the tests.

The results of the experiments with repeated shear loading are represented in the Figs. 7.3 - 7.33. A few remarks are listed in the Tables 7.1-7.2. In addition to these remarks some observations made during the experiments will be discussed here.

In Chapter 5.2 it is mentioned that for the reinforced specimens the displacements of the crack faces on the front side of the specimen differed from the displacements on the rear side. In general the same observation is made for the specimens with external restraining bars, but in contrary to the reinforced specimens there was no preference which side of the specimen had the largest crack width. This was probably due to the fact that the crack opening was restraint by the external bars. A bad fitting of the restraint plates to the surface of the specimen might cause a low restraint stiffness. This was mainly depending upon the quality of the layer between the steel plates and the concrete surface of the short sides of the specimens. As for the reinforced specimens the difference in crack-opening of the front- and rear side of the specimens could cause problems in analysing the experiments. Hence, in Appendix IV the $\delta_n - \delta_t$ relations for both the front and rear side of the specimens are represented.

The age of a specimen to at the start of the experiment differs from the age of 28 days at which the concrete strength is determined. The concrete strengths listed in the Tables 7.1 - 7.2 were calculated with equations (2.4) and (2.5) for to. The concrete strength at 28 days is listed in Appendix III relating to the standard tests on concrete.

Specimens with the embedded reinforcing bars failed at when the applied shear stress exceeded the shear strength of the crack plane according
to the static envelope of the strength. The external specimens discussed here failed by exceeding the defined 'failure slip' of 2 mm. Several specimens were still capable of bearing the applied shear stress. This type of shear failure was probably caused by the increasing normal stress (due to the crack opening) supplied by the external bars, for which no bond failure could occur.

Specimen No. A/0.8/5.5/.01 had a rather low initial normal stress $\sigma_0$. This was caused by the bad fitting of the steel restraining plates to the surface of the specimen. Due to this, one of the external bars was not strained at the start of the experiment. During the experiment this bar was strained by the increasing crack width.

Specimen No. A/1.3/6.2/.01 failed after enduration of an applied shear stress $\tau_m$ of 6.2 N/mm$^2$ for $N = 283,549$ cycles. Due to a malfunctioning of the data-acquisition system no displacements were recorded after cycle $N = 68,400$.

Specimen No. B/1.1/5.0/.04 sheared off on application of the shear force. Despite of this the crack plane was still capable of bearing the applied shear force. For a shear slip $> 1.3$ mm the shear stress was transferred up to $N = 250,000$ cycles. Very large displacements of the crack faces were recorded, but no actual shear failure occurred.
7.2.1 Displacements during cycling.
crack displacements [mm]

- separation $\delta_n$
- slip $\delta_t$

(a) log $N$ [cycles]

(b) separation $\delta_n$ [mm]

(c) slip $\delta_t$ [mm]

figure: 7.4
specimen: A/12/50/01
$N_0 = 10$
$\sigma = 20326$
crack displacements [mm]

- separation $\delta_n$
- slip $\delta_t$

(a) log N [cycles]

$\frac{\tau}{\tau_m}$

(b) separation $\delta_n$ [mm]

(c) slip $\delta_t$ [mm]

figure: 7.6

specimen: A/1.9/5.0/19

N
- 10
- 2340
- 3080
Experimental results

Figure 7.8
specimen, A/21/61/01

N

\( \tau = 5.0 \text{ N/mm}^2 \)

\( \tau = 5.1 \text{ N/mm}^2 \)

\( \tau = 6.0 \text{ N/mm}^2 \)

\( \tau = 8.0 \text{ N/mm}^2 \)

\( \tau = 10.0 \text{ N/mm}^2 \)
Experimental results

figure 79

specimen: A/362/01

\[ \tau = 5.0 \text{ N/mm}^2 \]

\[ \tau = 6.2 \text{ N/mm}^2 \]

\[ N = 1000 \]

\[ N = 4000000 \]

\[ N = 684000 \]

\[ \delta_n \text{ [mm]} \]

\[ \delta_t \text{ [mm]} \]

\[ \tau/\tau_m \]

\[ \tau/\tau_m \]

\[ \log N \text{ [cycles]} \]

\[ \text{crack displacements [mm]} \]

\[ \text{separation } \delta_n \]

\[ \text{slip } \delta_t \]
Experimental results

(a) Crack displacements [mm]
- separation $\delta_n$
- slip $\delta_t$

(b) Separation $\delta_n$ [mm]

(c) Slip $\delta_t$ [mm]

Figure 710
Specimen A/13/6.2/02

$N$
- $= 10$
- $= 59322$
- $= 10$
- $= 2820$

$\tau = 5.1 \text{ N/mm}^2$
$\tau = 6.2 \text{ N/mm}^2$
Experimental results

Figure 7.11

Specimen B41/50/04

\[ N = 50 \]

\[ \delta_n \] (mm)

\[ \delta_t \] (mm)

\[ \log N \] (cycles)

\[ \text{crack displacements \ [mm]} \]

\( \frac{\tau}{\tau_m} \)

\( T \)
Experimental results

Figure 7.2
Specimen: BNF6/601

- \( \tau = 5.6 \) N/mm²
- \( \tau = 8.9 \) N/mm²

\[ N = 10 \]

\[ N = 99500 \]

- \( \square \)

\[ \delta_n \text{ [mm]} \]
\[ \delta_t \text{ [mm]} \]

\[ 10^6 \]
\[ 10^5 \]
\[ 10^4 \]
\[ 10^3 \]
\[ 10^2 \]
\[ 10^1 \]

\[ 10^0 \]
crack displacements [mm]

(a) log N [cycles]

(b) separation $\delta_n$ [mm]

(c) slip $\delta_t$ [mm]

**Experimental results**

<table>
<thead>
<tr>
<th>N</th>
<th>$\tau = 5.2$ N/mm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$86611$</td>
<td>$\tau = 5.2$ N/mm$^2$</td>
</tr>
<tr>
<td>$10$</td>
<td>$\tau = 6.2$ N/mm$^2$</td>
</tr>
<tr>
<td>$1960$</td>
<td>$\tau = 6.2$ N/mm$^2$</td>
</tr>
</tbody>
</table>
Experimental results

Figure 7.14
specimen B/20/6.5/01

\( N = 20 \)
\( \bullet = 270 \)
\( \square = 330 \)
crack displacements [mm]

- separation $\delta_n$
- slip $\delta_t$

(a) $\log N$ [cycles]

(b) separation $\delta_n$ [mm]

(c) slip $\delta_t$ [mm]

Figure: 715

Specimen: B/3.6/69/19

$N_0 = 5 \tau = 69 \text{ N/mm}^2$

- 82378

Experimental results
Experimental results

(b) separation $\delta_n$ [mm]

(c) slip $\delta_t$ [mm]

Figure 7.16

Specimen BA5/77/01

$N = 10^6$

$\tau = 7.2$ N/mm$^2$

$D = 80.60$

$T = 38.90$

20 crack displacements [mm]

separation $\delta_n$

slip $\delta_t$

log N [cycles]
Experimental results
Experimental results

Figure: 7.18
specimen:
A/1.3/5.0/01
Experimental results

Figure 7.22
specimen:
A/13/62/01
Experimental results
Experimental results

\[ \sigma [N/mm^2] \]

\[ \delta_n [mm] \]

\[ \delta_t [mm] \]

Figure: 725

Specimen: B/20/65/01
Experimental results

Figure 7.26
specimen: B15/77/01
7.2.2 Load-displacement relations in static experiments.
Experimental results

Figure: 7.28
Specimen: A/125/01
Experimental results

Figure 729
specimen
B/36/69/19
7.2.3. Close examination of the crack plane

Micro-cracking

The physical model of Walraven [5] is based on the deformation of the rigid-plastic matrix material by the stiff aggregate particles, which are embedded in the opposing crack face. The matrix material, in which the particles are embedded, will deform too. This deformation is a pure plastic deformation according to the theory. To check whether or not this deformation is an elastic - or a plastic deformation a cross-section perpendicular to the crack face was examined on a scale 20 : 1: See Fig. 7.30. [19].

Fig. 7.30. Cross-section of specimen no. B/1.50/7.7/.01

Close to the crack plane a total of 173 observations was made. In Fig. 7.31 24 points are represented. The normal distribution and orientation of the micro-cracks between the particles indicated that this micro-cracking was not caused by high stress-concentrations. The
existence of these micro-cracks was probably caused by shrinkage of the concrete. Therefore, the observations did not contradict the theoretical assumption that the displacements of the crack faces are caused by local plastic deformation of the matrix material.

Fig. 7.31. Observations on scale 20 : 1

In 125 of the 178 observations matrix-material between the particles was examined. For 83 observations one or more micro-cracks were present.
As discussed in Section 2.3c the mechanism of aggregate interlock is strongly influenced by the amount of particles with interfacial bond fracture. For eight specimens the number of particles fractured during pre-cracking and load-application is determined. The results are listed in Table 7.4. In the Figs. 7.32 - 7.33 the particles fractured are represented for two specimen subjected to repeated shear loading.

<table>
<thead>
<tr>
<th>specimen No.</th>
<th>fractured [% total shear plane]</th>
<th>fractured [% particles]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/1.3/5.0/.01</td>
<td>17.8</td>
<td>23.7</td>
</tr>
<tr>
<td>A/2.1/6.1/.01</td>
<td>12.9</td>
<td>17.1</td>
</tr>
<tr>
<td>B/1.5/6.5/.01</td>
<td>22.2</td>
<td>29.6</td>
</tr>
<tr>
<td>B/2.0/7.7/.01</td>
<td>15.4</td>
<td>20.5</td>
</tr>
<tr>
<td>A/10/2.50/9.61/0.02/1st</td>
<td>21.0</td>
<td>28.0</td>
</tr>
<tr>
<td>A/10/2.01/6.50/0.02/5su</td>
<td>16.9</td>
<td>22.5</td>
</tr>
<tr>
<td>A/10/1.02/4.00/0.02/6su</td>
<td>16.3</td>
<td>21.7</td>
</tr>
<tr>
<td>B/10/0.35/0.65/0.01/2st</td>
<td>20.1</td>
<td>26.8</td>
</tr>
<tr>
<td>B/10/0.50/3.17/0.03/3st</td>
<td>16.8</td>
<td>22.4</td>
</tr>
<tr>
<td>B/10/1.02/5.00/0.02/8su</td>
<td>19.1</td>
<td>25.5</td>
</tr>
</tbody>
</table>

The results presented in Table 7.4 show a larger amount of particles fractured in specimens with mix B compared with specimens with mix A. This is in good agreement with the theory, although the amount of
particles fractured in mix A is larger than expected. The mean values for both mixes are:

Mix A : 16.98 % (22.63 %)
Mix B : 18.72 % (24.95 %)

The difference between the results of the two mixes is not significant.

Fig. 7.32 Fractured particles for specimen A/2.1/6.1/.01 (black area)

Fig. 7.33 Fractured particles for specimen B/1.5/6.5/.01 (black area)
7.3 Relation between stress level and number of cycles to shear failure

In Section 6.4 it is mentioned that for specimens with external restraint bars formula (6.1) underestimated the real shear strength in the current research. This was due to the low initial normal stress used in Walraven's experiments [13]. However, combination of the work of Walraven and the experimental work of Dasschner [20] yields a relation between normal stress and ultimate shear stress for high normal stresses; see Fig. 7.34 [21]

The following relation is derived by means of regression analysis:

\[ \tau_u = 1.647 f'_{cc}^{0.321} G_0^{0.427} \]  \hspace{1cm} (7.1)

Although the type of specimen used by Dasschner differs from the type used in the current investigation, relation (7.1) is used to determine \( \tau_u \) for the experiments listed in the Tables 7.1-7.3. The results are listed in Table 7.5.
Table 7.5. The shear strength according to (7.1) and the stress level

<table>
<thead>
<tr>
<th>Code</th>
<th>$\tau_0$ [N/mm²]</th>
<th>$\tau_s/\tau_0$</th>
<th>No. of cycles</th>
<th>Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/1.3/4.0/.12</td>
<td>6.53</td>
<td>.61</td>
<td>30650</td>
<td>yes</td>
</tr>
<tr>
<td>A/1.2/5.0/.01</td>
<td>6.38</td>
<td>.78</td>
<td>20226</td>
<td>no</td>
</tr>
<tr>
<td>A/1.3/5.0/.01</td>
<td>6.59</td>
<td>.76</td>
<td>3090</td>
<td>yes</td>
</tr>
<tr>
<td>A/1.9/5.0/.19</td>
<td>7.53</td>
<td>.66</td>
<td>9756</td>
<td>yes</td>
</tr>
<tr>
<td>A/0.8/5.5/.01</td>
<td>5.24</td>
<td>1.05</td>
<td>1520</td>
<td>yes</td>
</tr>
<tr>
<td>A/2.1/6.1/.01</td>
<td>8.23</td>
<td>.74</td>
<td>8840</td>
<td>yes</td>
</tr>
<tr>
<td>A/1.3/6.2/.01</td>
<td>6.47</td>
<td>.96</td>
<td>235549</td>
<td>yes</td>
</tr>
<tr>
<td>A/1.3/6.2/.02</td>
<td>6.48</td>
<td>.96</td>
<td>3120</td>
<td>yes</td>
</tr>
<tr>
<td>B/1.1/5.0/01</td>
<td>6.68</td>
<td>.75</td>
<td>254369</td>
<td>no</td>
</tr>
<tr>
<td>B/1.2/6.5/01</td>
<td>6.79</td>
<td>.82</td>
<td>89500</td>
<td>no</td>
</tr>
<tr>
<td>B/1.0/6.2/04</td>
<td>6.48</td>
<td>.93</td>
<td>2736</td>
<td>yes</td>
</tr>
<tr>
<td>B/2.0/6.5/.01</td>
<td>8.66</td>
<td>.75</td>
<td>343</td>
<td>yes</td>
</tr>
<tr>
<td>B/3.6/6.9/01</td>
<td>11.11</td>
<td>.62</td>
<td>82778</td>
<td>no</td>
</tr>
<tr>
<td>B/1.5/7.7/.01</td>
<td>8.54</td>
<td>.90</td>
<td>3970</td>
<td>yes</td>
</tr>
<tr>
<td>B/1.3/8/.07</td>
<td>6.83</td>
<td>7.10</td>
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<td></td>
</tr>
</tbody>
</table>

The relation between the stress level and the number of cycles till shear failure is shown in Fig. 7.35.

![Fig. 7.35 The relation between the stress level and the number of cycles to shear failure.](image-url)
It must be noted that the experimental work of Dasschner was performed with a constant normal stress. For the current tests the normal force increased due to the crack opening. For that case the ultimate shear stress is not defined, although eq. (7.1) provides a rough estimation of the shear strength. Despite the large scatter of the results, it appeared that most of the specimens with external restraint bars endured more cycles till failure than the specimens with embedded bars at the same shear stress level. In Fig. 7.35 this is shown by the straight line representing eq. (5.1).
8. NOTATION

\( f_{ccm} \) = cube compressive strength \([N/mm^2]\)

\( f_{sy} \) = yield strength of steel \([N/mm^2]\)

\( n \) = number of observations \([-]\)

\( p \) = probability \([-]\)

\( r \) = coefficient of correlation \([-]\)

\( t_0 \) = age of concrete at start of test \([\text{days}]\)

\( w_{cr} \) = water cement ratio \([-]\)

\( D_{max} \) = maximum particle size \([\text{mm}]\)

\( \delta \) = displacement \([\text{mm}]\)

\( \delta_n \) = crack width \([\text{mm}]\)

\( \delta_t \) = shear slip \([\text{mm}]\)

\( \rho \) = reinforcement ratio \([-]\)

\( \tau \) = shear stress on the crack plane \([N/mm^2]\)

\( \tau_m \) = maximum shear stress on the crack plane during cycling \([N/mm^2]\)

\( \tau_0 \) = minimum shear stress on the crack plane during cycling \([N/mm^2]\)

\( \tau_u \) = ultimate shear strength \([N/mm^2]\)

\( \tau_{u,\text{exp}} \) = ultimate shear strength measured in experiment \([N/mm^2]\)

\( \tau_{0.25} \) = shear stress at a crack width of 0.25 mm \([N/mm^2]\)

\([\text{]}\) = refers to literature (chapter 7)
9 REFERENCES


6. Pruijssers, A.F., Shear transfer across a crack in concrete subjected to repeated load, analysis of results, Delft Univ. of Technology (to be reported in 1985).


16. Liqui Lung, G., Meetsysteem Vakgroep Betonconstracties, (in Dutch, to be reported in 1985), Delft Univ. of Techn.
17. Pruijssers, A.F., Liqui Lung, G., Shear transfer across a crack subjected to repeated loading, Experiments part II, (to be reported in 1985), Delft Univ. of Techn.


Appendix I

APPENDIX I. Mix proportions

Mix code B1632550 strength $f'_{cc} = 51\text{N/mm}^2$

(mix A)

<table>
<thead>
<tr>
<th>Components</th>
<th>$[\text{kg/m}^3]$</th>
<th>Sieve analysis of aggregate</th>
</tr>
</thead>
<tbody>
<tr>
<td>sand</td>
<td>877.2</td>
<td>8 - 16</td>
</tr>
<tr>
<td>gravel</td>
<td>1065.0</td>
<td>4 - 8</td>
</tr>
<tr>
<td>cement-B</td>
<td>325.0</td>
<td>2 - 4</td>
</tr>
<tr>
<td>water</td>
<td>162.5</td>
<td>1 - 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5 - 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.25 - 0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.10 - 0.25</td>
</tr>
<tr>
<td></td>
<td>2429.7</td>
<td></td>
</tr>
</tbody>
</table>

Mix code B1642037.5 strength $f'_{cc} = 70\text{N/mm}^2$

(mix B)

<table>
<thead>
<tr>
<th>Components</th>
<th>$[\text{kg/m}^3]$</th>
<th>Sieve analysis of aggregate</th>
</tr>
</thead>
<tbody>
<tr>
<td>sand</td>
<td>857.3</td>
<td>8 - 16</td>
</tr>
<tr>
<td>gravel</td>
<td>1018.5</td>
<td>4 - 8</td>
</tr>
<tr>
<td>cement-B</td>
<td>420.0</td>
<td>2 - 4</td>
</tr>
<tr>
<td>water</td>
<td>147.0</td>
<td>1 - 2</td>
</tr>
<tr>
<td>superpl.2½%</td>
<td>10.5</td>
<td>0.5 - 1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.25 - 0.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.10 - 0.25</td>
</tr>
<tr>
<td></td>
<td>2453.3</td>
<td></td>
</tr>
</tbody>
</table>

Sieve analysis of aggregate

<table>
<thead>
<tr>
<th>cum.%</th>
<th>mix A</th>
<th>mix B</th>
<th>Fuller</th>
</tr>
</thead>
<tbody>
<tr>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>67.9</td>
<td>68.2</td>
<td>70.7</td>
<td>4 - 8</td>
</tr>
<tr>
<td>45.2</td>
<td>45.7</td>
<td>50.0</td>
<td>2 - 4</td>
</tr>
<tr>
<td>29.1</td>
<td>29.8</td>
<td>35.4</td>
<td>1 - 2</td>
</tr>
<tr>
<td>17.7</td>
<td>18.5</td>
<td>25.0</td>
<td>0.5 - 1</td>
</tr>
<tr>
<td>9.7</td>
<td>10.6</td>
<td>17.7</td>
<td>0.25 - 0.5</td>
</tr>
<tr>
<td>4.0</td>
<td>5.0</td>
<td>12.5</td>
<td>0.1 - 0.25</td>
</tr>
</tbody>
</table>
For a good mix the Netherlands concrete code recommends a minimum quantity of fine material $D < 250 \ \mu m$.
For a maximum particle size of 16 mm at least 140 liters/m$^3$ of concrete is specified.

![Cumulative weight graph](image)

**Actual values:**

$\text{mix A} : \frac{325}{3.1} + \frac{77.7}{2.65} = 134.2 \ \text{m}^3$

$\text{mix B} : \frac{420}{3.1} + \frac{93.5}{2.65} = 170.8 \ \text{m}^3$
APPENDIX II DISPLACEMENTS OF THE CRACK FACES - REINFORCED SPECIMENS

Figure II2
specimen: A/4/L/63/60/05

Figure II1
specimen: A/4/L/61/61/03
figure: II.3
specimen: A/4H/64/70/06

figure: II.4
specimen: A/4L/65/60/05
figure: II.7
specimen: AI4L173/72/05

figure: II.8
specimen: AI4L174/70/06
**Figure II.9**

Specimen: A/4L/76/70/02

**Figure II.10**

Specimen: A/4L/76/77/03
figure: II.11
specimen: A1/4L/77/7.21.04

figure: II.12
specimen: A1/4H/78/8.01.04
\[\delta_f [\text{mm}]
\]

\[\delta_n [\text{mm}]
\]

- \(\theta = \text{front side}\)
- \(\bullet = \text{rear side}\)

**Figure II.13**
Specimen: A/4/1/79/8.6/02

**Figure II.14**
Specimen: A/4/L/80/7.3/03
Figure II.15
specimen: A/41/80/75/05

Figure II.16
specimen: A/41/82/74/05
Figure II.17
Specimen: A/4L/90/90/05

Figure II.18
Specimen: A/6L/51/60/04
\( \delta_t [\text{mm}] \)

- \( \circ \) = front side
- \( \bullet \) = rear side

**Figure II.19**

specimen: A/6L/56/67.05

**Figure II.20**

specimen: A/6L/58/68.02
figure: II.27
specimen:
B/6L/46/69/04

figure: II.28
specimen:
B/6L/52/79/02
figure: II.33
specimen: A/6H/ST/10.2/01

figure: II.34
specimen: A/8L/ST/10.4/05
Figure II.35
Specimen: B/4L/57/8.0/03

Figure II.36
Specimen: B/4L/59/7.0/20
Figure II.37
Specimen: B/4L/60/70/06

Figure II.38
Specimen: B/4H/60/74/08
APPENDIX III. STANDARD TESTS ON CONCRETE

III.1 Introduction

The push-off specimen were cast in steel moulds. Synthetic moulds were used for the cubes. Immediately after casting all the specimens and the cubes were kept wet and were covered with plastic sheets. After two days the specimens were demoulded and stored in a fog room (20°C, 99% RH). At an age of 28 days the specimens were placed in the test rig.

III.2 Standard tests

Table III.1 Tests on 150 mm cubes for mix A

<table>
<thead>
<tr>
<th>batch</th>
<th>to [days]</th>
<th>compressive strength $f_{ccm}$ number</th>
<th>$[N/mm^2]$</th>
<th>v.c. [%]</th>
<th>tensile strength $f_{cml}$ number</th>
<th>$[N/mm^2]$</th>
<th>v.c. [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>140383</td>
<td>28</td>
<td>3</td>
<td>47.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>060683</td>
<td>28</td>
<td>3</td>
<td>53.20</td>
<td>3.2</td>
<td>3</td>
<td>3.59</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td>58</td>
<td>3</td>
<td>60.15</td>
<td>6.9</td>
<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td>84</td>
<td>3</td>
<td>61.67</td>
<td>3.6</td>
<td>-</td>
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<td>-</td>
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<tr>
<td></td>
<td>119</td>
<td>3</td>
<td>65.01</td>
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<td>84</td>
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<td>3.04</td>
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<td>51.75</td>
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<td>3</td>
<td>3.14</td>
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</tr>
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<td>3.10</td>
<td>7.3</td>
</tr>
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<td>3</td>
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<td>3.28</td>
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<td></td>
<td>21</td>
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<td>45.79</td>
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<td>-</td>
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<td>-</td>
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<td>28</td>
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<td>38.83</td>
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</table>
Table III.2 Tests on 150 mm cubes for mix B

<table>
<thead>
<tr>
<th>batch</th>
<th>t_o [days]</th>
<th>compressive strength $f_{ccm}$ number [N/mm²] v.c. [%]</th>
<th>tensile strength $f_{csp}$ number [N/mm²] v.c. [%]</th>
</tr>
</thead>
<tbody>
<tr>
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Appendix IV

APPENDIX IV DISPLACEMENTS OF THE CRACK FACES
- SPECIMENS WITH EMBEDDED BARS

Figure IV.1
specimen: A/1.3/4.0/12

Figure IV.2
specimen: A/1.2/5.0/01
Figure IV.5: Specimen A/0.8/5/5/01

Figure IV.6: Specimen A/2/6/1/01
Appendix IV

Figure IV.9
Specimen: B/1.1/5.0/04

Figure IV.10
Specimen: B/1.2/5.6/01
figure: IV.13
specimen: B/3.6/69/19

figure: IV.14
specimen: B/1.5/77/01
figure: IV.15
specimen: B/1.30/ST/07
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