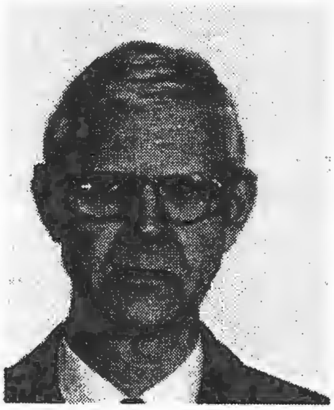
STATIC, FIRE AND FATIGUE TESTS OF ULTRA HIGH-STRENGTH FIBRE REINFORCED CONCRETE AND RIBBED BARS



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ABSTRACT

A new building system has been developed during the last 10 years. This new system consists of a column / slab system with 6 x 6 m distance between the columns. The slabs are precast concrete elements of size 2.9 x 5.9 m connected through joints of ultra high strength fibre reinforced concrete - Densit Joint Cast ®. Also the connections between the columns and the slabs are made of this very strong concrete material.
The paper describes some of the static tests carried out as well as some fire tests. Further, 2 chapters deal with some fatigue tests of the reinforcing bars as well as some fatigue tests of tensile specimens consisting of reinforcing bars embedded in Densit Joint Cast ®. The objective of these fatigue tests is to show that the system / connection can presumably also be used in structures subjected to dominant time- varying loads and thus for example in earthquake regions.

Key words: Ultra-high-strength fibre reinforced concrete, anchorage of reinforcing bars, fire resistance, fatigue.

1. INTRODUCTION

During the last 10 years, a new building system has been developed by the architect firm Dall and Lindhartsen in co-operation with the Danish consulting engineers Carl Bro as. The new building system has been applied to some new buildings at Aalborg University. Part 1 was built during 1995 - 1996 and was ready for use in the summer of 1996. Part 2 was built during 1998 - 1999 and was ready for use in the summer of 1999. A photo of some parts of the buildings is shown in figure 1.

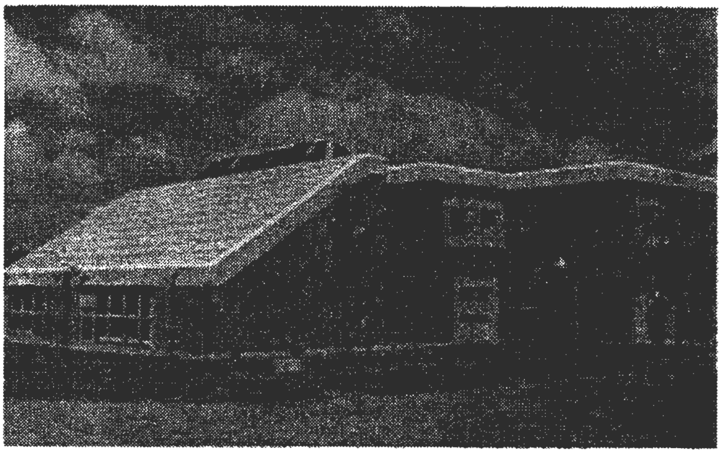


Figure 1. Part of the new buildings at Aalborg University completed in 1996 and 1999.

A very important part - or the main idea - of this building system is the joints between the prefabricated concrete slabs. These joints - 100 mm in width - are made of ultra high strength fibre reinforced concrete - Densit Joint Cast ® - developed by the Cement and Concrete Laboratory at Aalborg Portland, Aalborg, Denmark. Before it was decided to use this new building system for the new buildings at Aalborg University, some essential parts of the system were tested for static loads at the Structural Laboratory at the Department of Building Technology and Structural Engineering, Aalborg University. Further, some small elements were subjected to a combination of static load and fire exposure.

In the last 2 years some further fatigue investigations have been applied. The ribbed reinforcement bars have been tested using different load levels with a harmonic, time varying load. These tests are further described in chapter 5. In chapter 6 some fatigue tests with tensile specimens consisting of reinforcement bars embedded in Densit Joint Cast ® are described. The reason for making these tests is a first step to prove that the principle used in the new building system presumably has some further applications with other types of structures and other types of loads than the loads dominating for buildings in Denmark.

The principle of the new building system is outlined in figure 2.

The building system consists of slabs and columns only. This means that no beams are used in the system. The slabs are cast as 2.9 x 5.9 m slabs and are made from normal strength concrete with a thickness of 200 mm and reinforced with a mesh (100 x 100 mm) of 8 mm reinforcement in the upper and lower side of the slab. 80 mm of this reinforcement is protruding from the slab and thus represents the anchorage length. The columns are circular with a diameter of 350 mm and are placed in a square net of 6 x 6 m. This system gives the architects a freedom to create the plan for the rooms of the building and it is easy to arrange the technical installations between the slabs and non- bearing ceilings.

As mentioned above, the slab elements are 2.9 x 5.9 m resulting in an opening of 100 mm between the slabs. The first operation is to erect the columns and then place the slabs on the columns at provisional supports. Some longitudinal reinforcement bars are placed in the joints and then the very important part of the system, namely the casting of the joints with Densit Joint Cast ®, can take place.

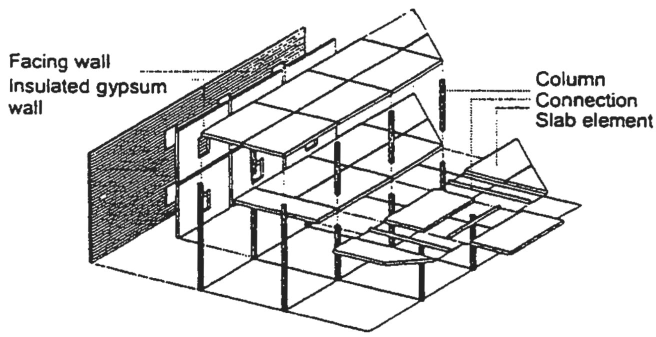


Figure 2. Outline of the new building system

After hardening, the slabs now act as continuous slabs and it is possible to transfer moments and forces from one slab to another. The extremely short anchorage length can be used because the Densit Joint Cast ® gives the joint a very good load-bearing capacity.

Of course other types of slabs, geometry and load bearing system can be applied to the principles as descibed above. More information about the building system can be found in [1], [2] and [3].

2. DENSIT JOINT CAST

In this chapter, a short description of the Densit Joint Cast ® is given. The development goes back to 1987 and the basic principles are reported by H. H. Bache in [4]. Later the material has been tested in several research projects including Eureka and Brite-Euram projects.

In ultra-high-strength concretes, the binder is often composed of Portland cement powder and fine and ultra-fine particles. Such binders are very dense and strong resulting in an ultra-high-strength concrete. However, such types of concrete are brittle and are thus not appropriate for structural applications. By adding for example steel fibres to the concrete, the problem with the brittleness can be solved.

In the concrete the water / powder ratio is 0.15 - 0.18, the silica fume content is 20 - 25 % and the compressive strength can be chosen in the interval of 100 - 200 MPa. The steel fibres have a length of 12 mm and a diameter of 0.4 mm. The steel fibre content is 6% by volume.

The water absorption and the air permeability are very low and the chemical resistance is remarkably good. No damages were detected by freeze / thaw tests according to the RILEM Recommendation No. 117 - FDC. The fire resistance is briefly described in chapter 4, where some fire tests on beams are reported.

The failure criterion for such a material has been reported by C. V. Nielsen in [5] and one of the conclusions is that the theory of plasticity can be used in the ultimate state and the design can thus be made according to modern theories as for example described in national or European codes.

The price for the material is of course higher than for normal strength concrete and a general substitution will not take place. For joints transmitting forces and moments from one structural element to another the material is excellent. This is due to the very good anchorage properties between the concrete and the reinforcing bars.

3. STATIC TESTS

In this chapter, only a few of the results from a great deal of static load tests are mentioned and more information can be found in [2], [3], [6] and [7]. The static load tests can be divided into 3 groups:

- Anchorage tests
- Beam and slab tests
- Column - slab tests

Further, a combination of static load and fire exposure is described in chapter 4.

3.1 Anchorage tests

Some tests have been carried out at the Cement and Concrete Laboratory at Aalborg Portland with specimens subjected to pure tensile loading. The diameter of the reinforcement was 8 mm, 12 mm and 16 mm, respectively. At the Structural Research Laboratory at Aalborg University these tests were continued with 16 mm and 20 mm reinforcement together with some fatigue tests described in chapter 6. The results from the static anchorage tests form the basis of the design of the beam and slab connections and the column - slab connections.

A sketch of the test specimen is shown in figure 3. Y denotes a ribbed bar. The load is pure tension of the main reinforcement.

The volume of the Densit Joint Cast ® is 500 mm x 300 mm x 100 mm and 2 bars of reinforcement - in this case 16 mm bars - are embedded in the concrete as shown. Further, some other bars are applied. The anchorage length for the 16 mm ribbed bars is only 170 mm corresponding to approximately 11 times the diameter. The material properties for the reinforcement was an average yield strength of 598 MPa and an average ultimate strength of 683

MPa. A typical load- displacement curve for pure tension is shown in figure 3 to the right. It can be noticed that there is a clear yield plateau. The average yield force was 113 kN corresponding to a stress in the bar of 561 MPa and an average ultimate force of 133 kN corresponding to a stress in the bar of 661 MPa. These values are very close to the values obtained for the bars alone. All the failures were in the bars and no slip failure between the bars and the Densit Joint Cast ® occurred. The same specimens were used for the fatigue tests described in chapter 6.

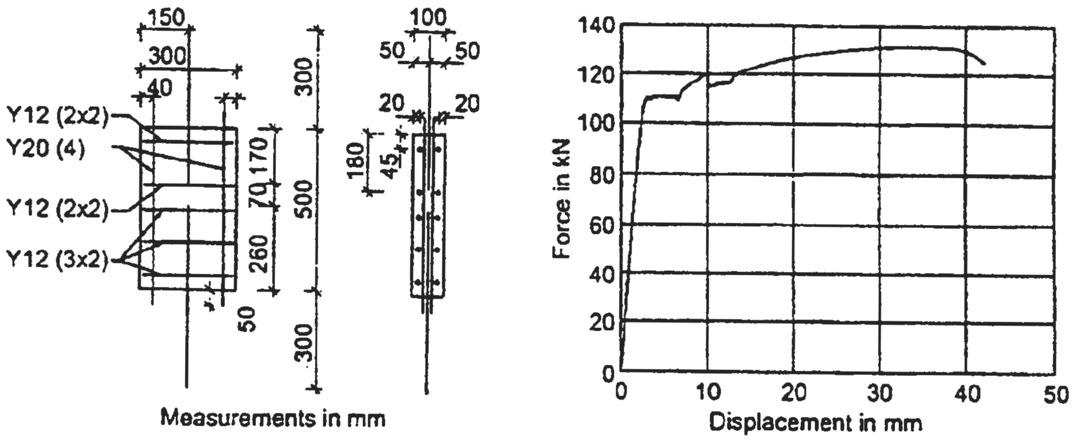


Figure 3 Sketch of pure tensile test specimen and load-displacement curve.

3.2 Beam and slab tests

As described in chapter 1 no beams are used in this new building system. Only slab elements and column elements are used. In this context the word "beam" signifies a slab element with a width of only 300 mm.

Several beam and slab elements were tested. Only one example will be shown here. The loading was a four point loading with two forces and two simple supports as shown in figure 4.

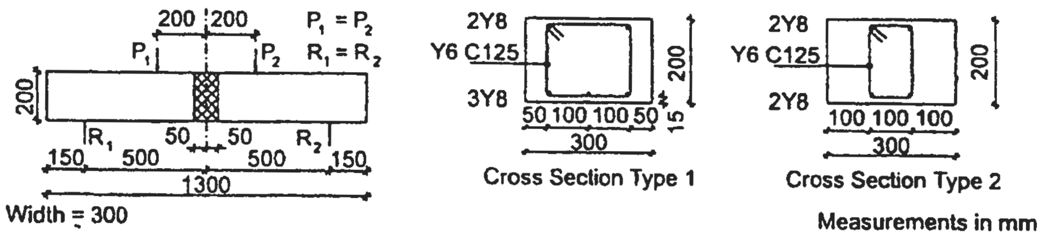


Figure 4 Sketch of beam test.

In figure 4, the joint is the hatched area made of Densit Joint Cast ®. The two parts of the beam are made of normal strength concrete. Different types of joints were tested to develop a connection where the reinforcement is not pulled out of the Densit Joint Cast ®. This means that the connection acts as if the beam is a "normal" concrete beam with respect to strength and stiffness. The tests also gave an estimate of the sensitivity for the anchorage length and the influence of horizontal reinforcement perpendicular to the principal reinforcement in the beam axis direction. The tests showed that an anchorage length of 60 mm was sufficient but in the building system an 80 mm anchorage length was used. In these load tests, forces, displacements, strains and crack widths were measured. All the specimens behaved in a plastic and ductile manner as shown for the load-displacement curve in figure 5.

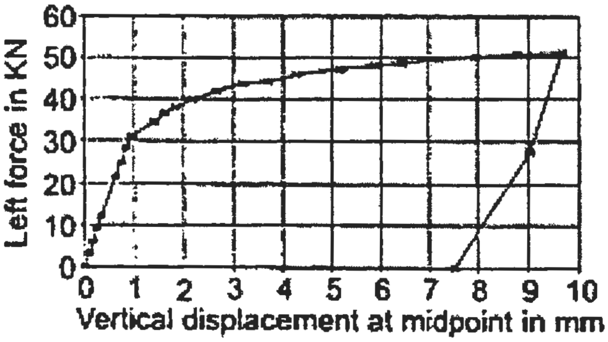


Figure 5 Load-displacement curve for beam test.

The conclusion for these beams tests was that an 80 mm anchorage length for an 8 mm reinforcement bar and a total length of the joint of 100 mm was a practical, reasonable and in static sense a good connection. The measured values for the ultimate moments were in close agreement with the calculated values.

Other beam tests focused on the combination of bending and shear in the joint and with different surfaces (rugged and smooth) between the normal concrete beam parts and the connection made with Densit Joint Cast ®. Different upper and lower bound solutions according to the plasticity theory have been calculated and the measured values in the tests were found to lie in the interval between these bounds both for the yield state and the ultimate state.

In connection with the 1994 / 95 constructions at Aalborg University, four different types of slabs were tested. The slabs were constructed as part of greater slabs and were loaded to simulate some typical load cases and support conditions. All these slab tests were in close agreement with the expectations and calculations. For further details, see [2]. Also in connection with the 1998 / 99 constructions, some slab tests were carried out where the action on the joints was a combination of bending and shear. Both rugged and smooth surfaces were applied. For further details, see [3].

The conclusion for all these slab tests was that the usual theory of plasticity can be used and that the joints are able to transfer the forces and moments as calculated.

3.3 Column - slab tests

One difference between the 1994 / 95 construction and the 1998 / 99 construction is that the stability of the building against horizontal forces (for example wind) in the 1998 / 99 construction is obtained only by means of the columns. In the 1994 / 95 construction there was a need for stabilizing concrete walls but these walls were not necessary in the 1998 / 99 construction. To be sure that the columns were able to transfer the forces from the slabs to the columns, a series on both inner and outer columns were tested. The column/slab connection was subjected to both vertical and horizontal loads. The direction of the horizontal loads was changed to simulate wind forces in different directions. A sketch of the test for an inner column/slab connection is shown in figure 6. For practical reasons the connection was tested with the column above, and not below, the slab.

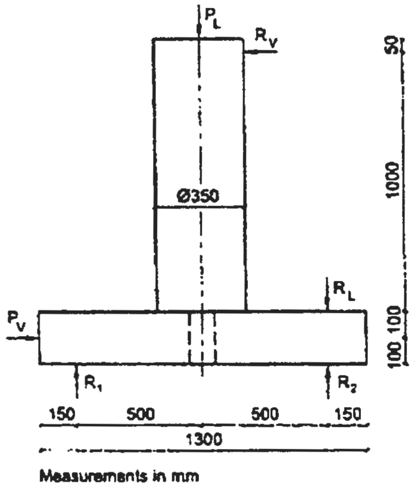


Figure 6 Sketch of testing inner column/slab connection.

The conclusion of the column/slab tests was that it was possible to use the building system without stabilizing walls. The horizontal forces (for example the wind forces) can be transferred through the column / slab connection.

4. FIRE TESTS

Six beams were subjected to a combination of static load and fire exposure. In addition, further two similar beams were tested only for static loads at room temperature. The test setup for the fire testing is shown in figure 7.

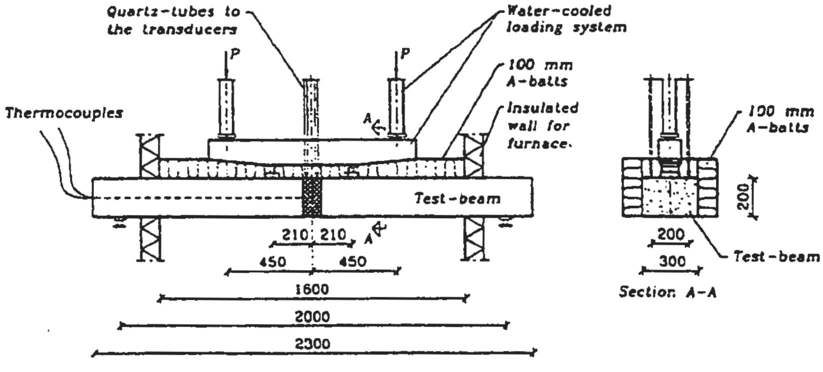


Figure 7 Test setup for fire testing of beams. Measurements in mm.

The inner dimensions of the furnace were like a cube with side lengths of 1.6 m and the furnace was heated by six gas burners at the bottom of the furnace. The vertical loads were transferred to the beam through water-cooled rods. Quartz tubes were arranged between the displacement transducers and the beams.

Two of the beams were tested only for static load at room temperature and showed the same type of load-displacement curve as the beams mentioned in chapter 3, and the load-bearing capacity corresponded to P = 21 kN for each of the two forces. These beams were used as reference beams.

Six beams were tested for static loads and thermal exposure according to the standard temperature curve in the Danish code DS1051.1 (ISO 834), see figure 8. For these six beams, a load of 2 x 11.5 kN was applied one hour before the tests were started. The load was maintained during the entire fire exposure and was not removed until the temperature inside the beam was decreasing. The value of the load of 11.5 kN can be related to the ultimate load at room temperature for the beam of 21 kN. The load is thus a little more than half of the ultimate load. After the fire exposure and the necessary cooling, the beams were loaded again to find the residual load-bearing capacity.

The temperature in the furnace was about 900°C and the temperature inside the beam was approx. 350°C as seen in figure 8.

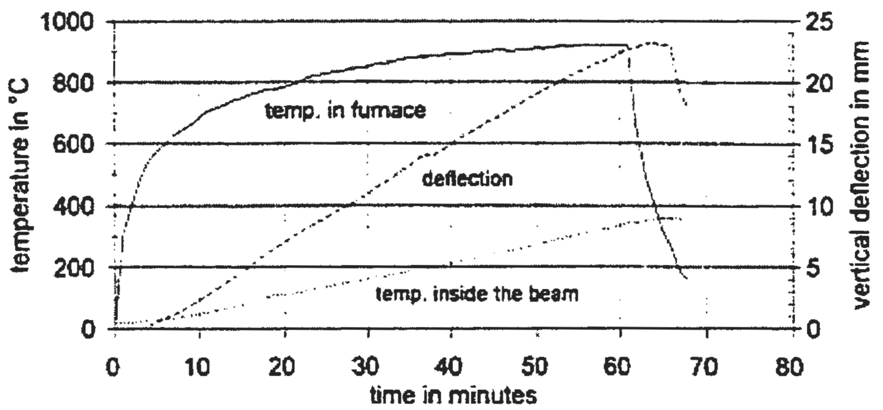


Figure 8 Thermal fire load and vertical deflection for beam D2-3.

A result from these tests is shown in figure 9, where the beam named D1-2 is a beam tested for static load only and the beam named D2-3 is a beam first loaded with 11.5 kN, exposed to fire and then loaded again after cooling. The curve shows the residual load-bearing capacity.

From figure 9 it is seen that the load-bearing capacity is approximately 19 kN for beam D2-3, which is approximately 90 % of the load-bearing capacity for beam D1-2. The load-displacement curve for beam D2-3 showed less ductility than beam D1-2.

The conclusion for the fire testing was that the joints can be classified as fire resistant for at least 60 minutes (time specied in standards). After a fire exposure for 60 minutes the residual load-bearing capacity is minimum 75% of the original capacity.

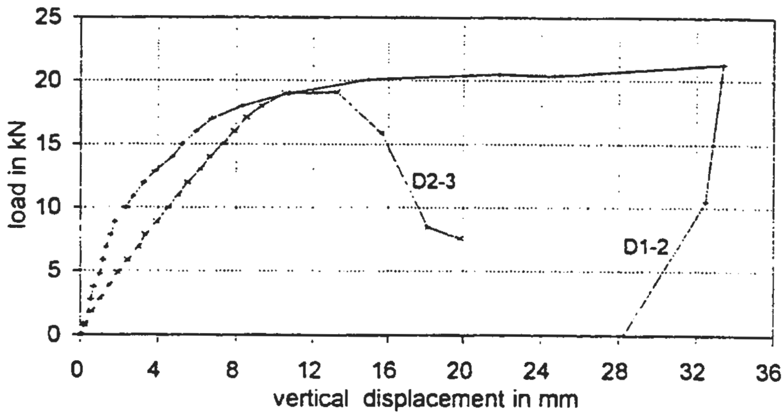


Figure 9 Comparison of load-bearing capacities for normal beam (D1-2) and beam exposed to fire (D2-3).

5. FATIGUE TESTS OF RIBBED REINFORCING BARS

This chapter deals with the fatigue tests of reinforcing ribbed bars (rebars) - New Tentor - manufactured as hot-rolled and accelerated cooled steel bars (AC). As a result of the tests the relationship between the number of cycles N and the stress range $\Delta\Phi = \Phi_{max} - \Phi_{min}$ of constant magnitude, which under the given conditions leads to fatigue failure, is found and shown in S-N curves. S denotes here the stress range.

5.1 Test specimens

The tests include 29 rebars with the diameter N = 10 mm and the length 590 mm and 33 rebars with the diameter N = 16 mm and the length 600 mm. All the rebars are marked with a number. To avoid failure in the rebars where the grips of the testing machine clutch the rebars all the rebars were equipped with aluminium tubes at either end. For rebars N 10 and N 16, the aluminium tubes have the dimensions $l \times d_y \times d_i$ = 100 x 18.0 x 11. 8 mm and $l \times d_y \times d_i$ = 85 x 23.8 x 18.0 mm, respectively, where l, d_y, d_i are the length, the outer and the inner diameter, respectively. The cavity between the rebar and the aluminium tube was filled with a two component glue, Araldite 2011 (AVV106) + Araldite 2011B (HV 953U).

5.2 Material properties

To obtain the material properties of the rebars, static tests were performed with 3 bars of each diameter. The mean values of the properties are shown in table 1.

Table 1 Material properties for the reinforcement

Diameter [mm]	Initial modulus of elasticity [MPa]	Yield strength [MPa]	Ultimate strength [MPa]	Non-proportional elongation at maximum force [%]
10	220×10^3	628	722	10.2
16	188×10^3	628	714	10.4

5.3 Test equipment

A 600 kN Mohr-Federhaff universial testing machine (MF) and a 500 kN servohydraulic testing machine (MTS) was applied for the static and the fatigue testing of the rebars, respectively. The latter is shown i figure 14. The MF and the MTS testing machines are equipped with mechanical and hydraulic fastening grips, respectively.

5.4 Testing

Static testing

The test specimens were instrumented with inductive displacement transducers and during the test corresponding values of force and elongation were measured and data-acquisition was applied. Stress, strains and modulus of elasticity were calculated in a MATLAB programme. The static tests were force controlled corresponding to at constant stress increase of approximately 7 MPa/sec. An example of a representative stress-strain diagram for the rebars is shown in figure 10.

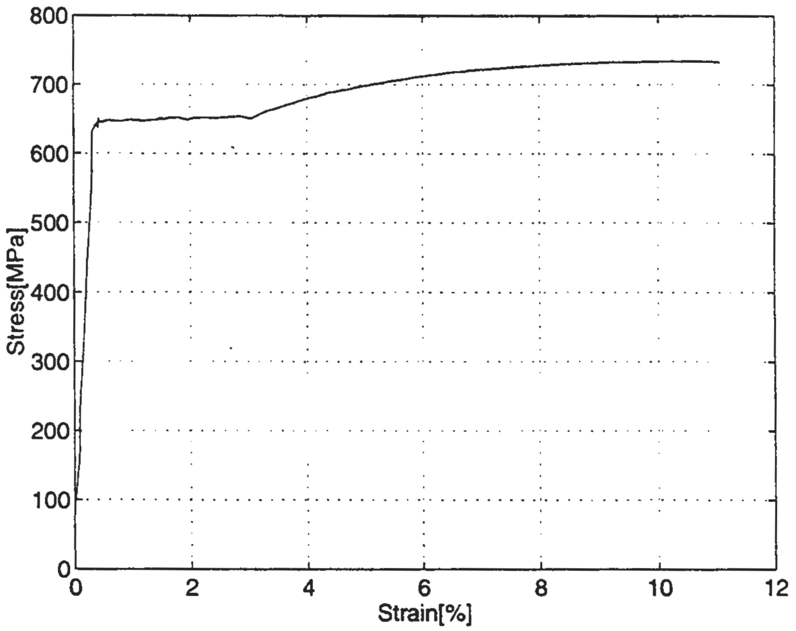


Figure 10 Representative stress-strain diagram of a rebar N=10 mm.

Fatigue testing

All the fatigue tests were force controlled. The variation of the force was harmonic and the stresses were oscillating between constant values of Φ_{max} and Φ_{min}. In many of the tests the test machine was stopped for a few minutes once or a couple of times to correct the force influence. During the fatigue testing, values of the minimum force, the maximum force, the minimum and maximum grip stroke were measured for every 1000 cycles.

Rebars N= 10 mm: For all rebars, the test frequency was 10 Hz, the average stress $\Phi_m = 0.5(\Phi_{max} + \Phi_{min})$ was within the interval 299 MPa < Φ_m < 322 MPa and the stress range ♠$\Phi = \Phi_{max} - \Phi_{min}$ in the interval 259 MPa # ♠Φ # 564 MPa.

Rebars N = 16 mm: For this diameter, frequencies of 5, 10 and 15 Hz were used. With so low frequencies, the frequency seems to have no influence on the result. For these rebars the average stress Φ_m was within 4 different intervals, see table 2.

Table 2 Intervals for the average stress Φ_m = 0,5(Φ_{max} + Φ_{min}) for rebars N = 16 mm

Number of specimens	Intervals for $\Phi_m = 0,5(\Phi_{max} + \Phi_{min})$ [MPa]	Symbols
3	257 MPa # Φ_m # 283 MPa	(
22	300 MPa # Φ_m # 315 MPa	+, o and x
6	317 MPa # Φ_m # 337 MPa	~
2	392 MPa # Φ_m # 395 MPa	∉

In more of the tests the failure occurred very close to the grips. Only results from tests where the failure occurred at a distance of more than 2N from the grips are included in this chapter.

5.5 Test results and discussion

Rebars N = 10 mm
As an example on the accumulated test results the variation of Φ_{max} , Φ_{min} , ♠$\Phi = (\Phi_{max} - \Phi_{min})$, and $\Phi_m = 0,5 (\Phi_{max} + \Phi_{min})$ during the test are shown in figure 11.
In figure 11, it is seen that the test machine was stopped at about N_1 = 29000 and N_2 = 55000 cycles in order to correct the force influence. After the last correction it is seen that the stresses are nearly constant until failure in the test specimen at N_u = 330048 cycles.

In figure 12 the fatigue strength curve (S-N curve) for rebars N = 10 mm is shown. In the test series failure in the rebars did not occur for values of $(\Phi_{max} - \Phi_{min})$ lower than 286 MPa. Test specimens no. 45 with $(\Phi_{max} - \Phi_{min})$ = 259 MPa reached N = 10,000,003 cycles without failure and test specimens no. 46 with $(\Phi_{max} - \Phi_{min})$ = 277 MPa reached N = 12,257,540 cycles without failure. These two test results are indicated by o in figure 12.

29 test results are shown in figure 12 and by linear regression a straight line for these tests (except for the two tests without failure) is calculated. The equation for the straight line in figure 12 is

$$\log (\Phi_{max} - \Phi_{min}) = 3.796 - 0.2264 \log (N) \quad (1)$$

The equation for a straight line where all the test results are above the line is

$$\log (\Phi_{max} - \Phi_{min}) = 3.818 - 0.2403 \log (N) \quad (2)$$

The equation for the S-N curve given for reinforcing bars in the Danish code DS 411 [8] is

$$\log (\Phi_{max} - \Phi_{min}) = 3.49 - 0.2 \log (N) \quad (3)$$

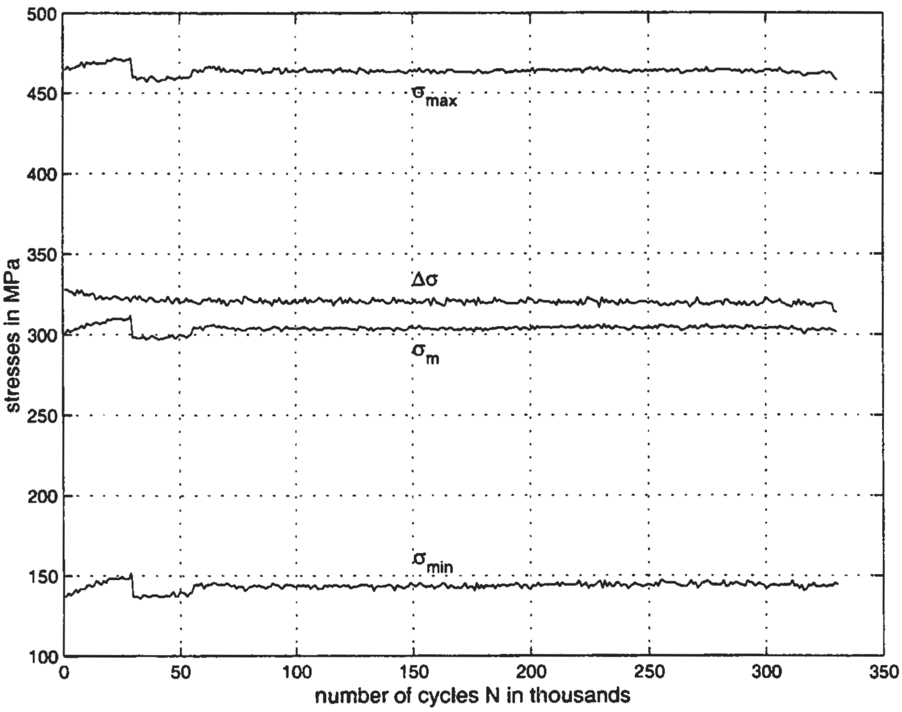


Figure 11 Stress curves from the fatigue test with rebar N = 10, test specimen no. 42

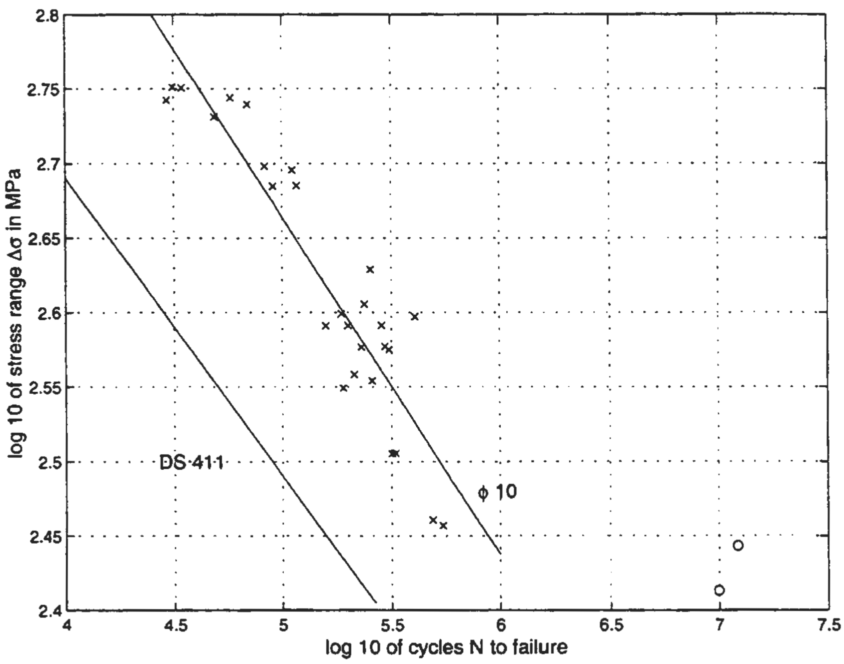


Figure 12 Fatigue strength curve (S-N curve) for rebars N = 10 mm.

It is seen that the lower bound for the test results is above the S-N curve given for reinforcing bars in the Danish code DS 411.

Rebars N = 16 mm
In figure 13, the fatigue strength curves (S-N curves) for rebars N = 16 mm are shown. In this test series failure in the rebars did not occur for values of $\Delta\Phi = (\Phi_{max} - \Phi_{min})$ lower than 388 MPa The test specimens no. 43, 44 and 45 with $\Delta\Phi$ equal to 340 MPa, 341 MPa and 388 MPa, respectively reached N = 4,418,891, N = 7,851,619 and N = 3,864,523 cycles, respectively, without failure. In test specimens no. 61 with Φ_m = 307 MPa and $\Delta\Phi$ = 395 MPa indicated by + in figure 13 failure occurred at 8,749,622 cycles.

33 test results are shown in the figure and by linear regression, a straight line for these tests exclusive the test results indicated by + and o are calculated. Last-named (3 test results) indicate tests where failure did not occurred. The equation for the straight line in figure 13 is

$$\log(\Phi_{max} - \Phi_{min}) = 3.5604 - 0.1686 \log(N) \qquad (4)$$

As seen in table 2, four intervals for the average stress Φ_m were used in this test series. It looks like the values of the stress range $\Delta\Phi = (\Phi_{max} - \Phi_{min})$ at failure are independent of the average stress Φ_m except for very high values of Φ_m, where the tendency is that higher values of Φ_m will give lower values of $\Delta\Phi$ for the same value of number of cycles N, see the two test results indicated by ↔ in figure 13 and table 2.

Ignoring the two test results indicated by ↔, the equation for a straight line, where all the test results are above the line is

$$\log(\Phi_{max} - \Phi_{min}) = 3.5966 - 0.1802 \log(N) \qquad (5)$$

It is seen that this lower bound for the test is above the S-N curve given for reinforcing bars in the Danish code DS 411, see equation (3)

6. FATIGUE TESTS OF RIBBED BARS EMBEDDED IN DENSIT JOINT CAST

This chapter deals with the fatigue testing of 35 specimens. These specimens were of the same type as used for the anchorage tests described in section 3.1, see figure 3. In addition 2 specimens were tested for static loading. For more details about the fatigue testing, see [9].

6.1 Test specimens

As mentioned above, the test specimens were of the same type as described for the anchorage tests. The main reinforcement had a nominal diameter of 16 mm and a nominal yield strength of 550 MPa, see below.

The Densit Joint Cast ® mix was identical for all the test specimens, but there was a little variation in the material properties from specimen to specimen. From one batch of the Densit Joint Cast ®, it was possible to cast 3 test specimens, see figure 3, and 6 cylinders - d/h =100mm /200 mm. A total of 13 batches were made corresponding to 39 test specimens and 78 cylinders. The numbering of the test specimens was x - y, where x is the batch number (1 to 13) and y is a number of the specimen in the batch (1 to 3).

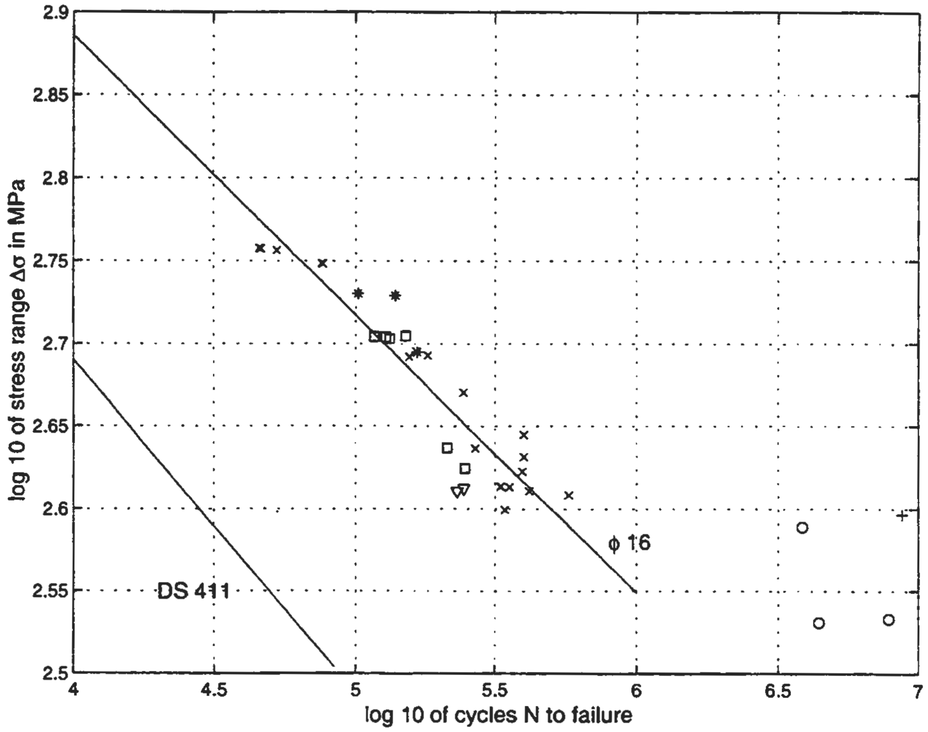


Figure 13 Fatigue strength curves (S-N curves) for rebars N = 16 mm

6.2 Material properties

Reinforcement

As seen in figure 3, three different diameters for the reinforcement were used. The main reinforcement embedded in the Densit Joint Cast® had a diameter of 16 mm and also reinforcement with diameter 12 mm and 20 mm were used. For each diameter 3 specimens were tested to obtain some material parameters for the reinforcement. The results are shown in table 3.

Table 3 Material properties for the reinforcement

Diameter [mm]	Initial modulus of elasticity [MPa]	Yield stress [MPa]	Ultimate strength [MPa]	Ultimate strain [%]
12	189×10^3	613	704	13.4
16	189×10^3	623	705	12.7
20	190×10^3	605	695	16.5

Initial modulus of elasticity:	Mean value:	53.9×10^3 MPa
	Standard deviation:	2.6×10^3 MPa
	Variation coefficient:	0.048
Compressive strength:	Mean value:	159.9 MPa
	Standard deviation:	8.7 MPa
	Variation coefficient:	0.054
Density:	Mean value:	2813 kg/m^3
	Standard deviation:	30 kg/m^3
	Variation coefficient:	0.011

6.3 Test equipment

A 500 kN servohydraulic testing machine was applied to both the static and the fatigue testing, see figure 14 showing the testing machine and one specimen. The testing machine was equipped with hydraulic grips which is a very simple and quick way to fasten the test specimen to the testing machine. But a problem may arise during the fatigue testing especially when ribbed reinforcement is applied. If no precautions are taken the failure will in nearly all tests occur very close to the hydraulic grips. The hydraulic grips will destroy the surface material and the result can be a crack. These cracks will during the fatigue testing develop into larger cracks and the result is that the fatigue properties will depend on these cracks.

To avoid this situation both ends of the reinforcement were equipped with aluminium tubes with a length of 85 mm, an outer diameter of 23.8 mm and an inner diameter of 18.0 mm. The pressure from the hydraulic grips was determined corresponding to the instructions from the manufacturer. In spite of the aluminium tubes some of the specimens failed near the grips, see section 6.4.

During the testing no considerable slip was observed between the reinforcement and the aluminium tubes.

6.4 Testing

Static testing

As mentioned, 2 static tests were applied. These tests were displacement controlled corresponding to a constant velocity for the stroke of the cylinder. The velocity was approximately 1 mm stroke per 20 seconds. Data acquisition was applied for the force and the stroke every second. The stress-stroke curve for the first static test with bar diameter 16 mm is shown in figure 15.

It is seen by comparing this curve with the material properties for reinforcement with d = 16 mm in table 3 that the values from figure 15 correspond to the values from table 3. This means that the 16 mm reinforcement has been embedded and bonded very well in the Densit Joint Cast® and that the failure has been in the reinforcement and not in the zone between the reinforcement and the Densit Joint Cast ®.

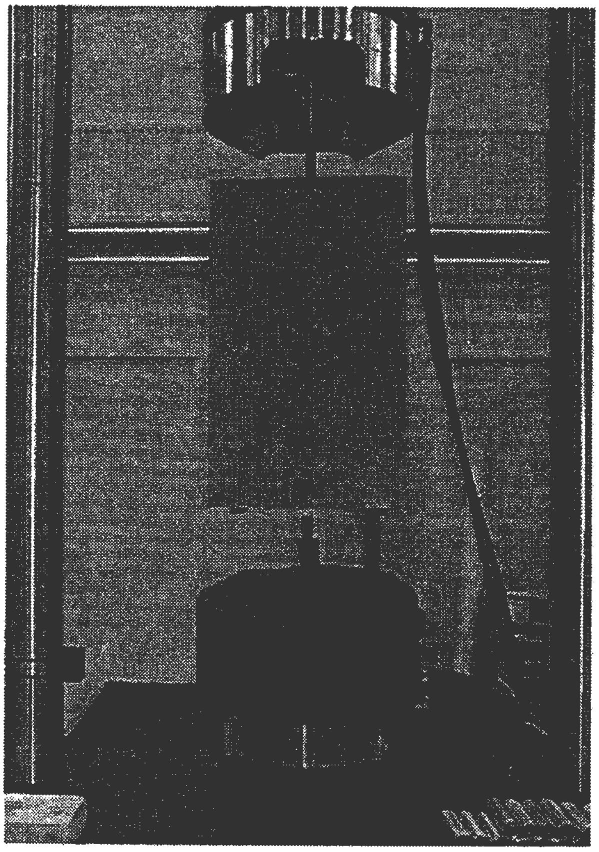


Figure 14 500 kN hydraulic testing machine with test specimen.

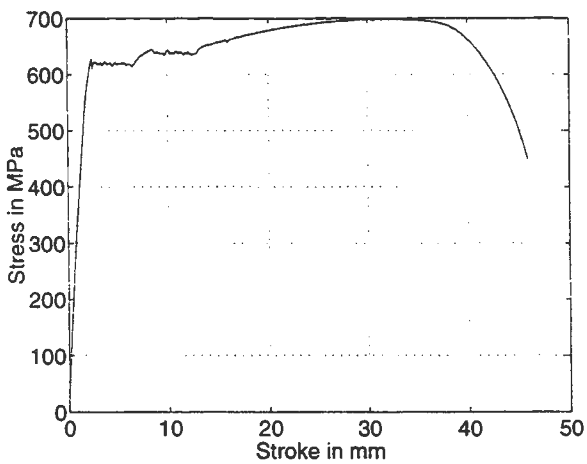


Figure 15 Stress - stroke curve for static test with diameter 16 mm, no. 1.

Fatigue testing
As mentioned, 35 fatigue tests were conducted corresponding to 7 different levels for the applied force. All the fatigue tests were force controlled. The variation of the force was harmonic and the minimum force for all the tests was approximately 10 kN. The maximum

force for the 7 different load levels was: 50 (9) - 60 (6) - 70 (4) - 75 (3)- 80 (4) - 90 (4) - 100 (5) kN, where the numbers in parentheses are the number of tests for the level concerned. The test frequency was 10 Hz.

In some cases there was a failure in the reinforcement near the ends and this was an unwanted situation. The test was then automatically stopped by the testing machine. The test specimen was then equipped with a new aluminium tube and the testing machine was started again. For some of the tests there have thus been some idle periods. These idle periods could have different length. If the failure was in the daytime, a new aluminium tube was installed quickly but if the failure was for example in the night or in the week-ends, the idle periods could be much longer.

For 11 of the 35 specimens tested for fatigue it was not possible to obtain a failure in the concrete embedment zone for the reinforcement or in the reinforcement embedded in the Densit Joint Cast® because 2, 3 or 4 failures occured in the reinforcement near the grips. It was thus impossible to continue the fatigue testing simply because it was not possible to fasten the test specimen to the testing machine. Such a specimen is here called a "run-out" specimen. For such a specimen the fatigue properties are better than given by this fatigue testing as the number of cycles to failure is greater than the number of cycles when the test had to be stopped.

During the fatigue testing, data acquisition was applied for the minimum force, the maximum force, the minimum stroke and the maximum stroke for every 1000 cycles, and all these data are used for calculations in a MATLAB programme.

6.5 Test results

As an example of the test results some of the data from test 1-1 are shown in figure 16. Test 1-1 had a maximum force of approximately 50 kN and a minimum force of approximately 10 kN.

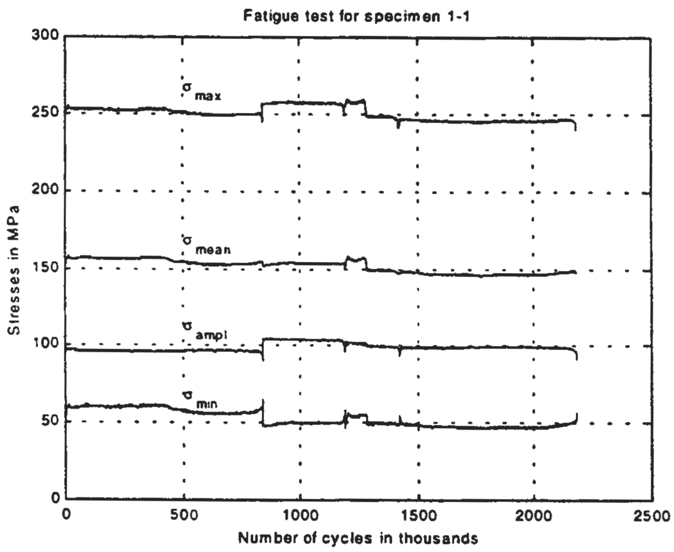


Figure 16 Stress curve from fatigue test 1-1.

The curves shown in figure 16 show the maximum stress, Φ_{max}, the mean stress, Φ_{mean}, the amplitude stress, Φ_{ampl}, and the minimum stress, Φ_{min}. The test has been stopped because of failure in the reinforcement near the lower grip at N = 837300 cycles. Again stopped at N = 1195200 cycles because of failure in the reinforcement near the upper grip and again at N = 1424400 cycles because of failure near the lower grip. The final failure was a failure in the reinforcement embedded in Densit Joint Cast® approximately 20 mm from the lower concrete surface at N = 2186100 cycles. A photo after such a failure is shown in figure 17.

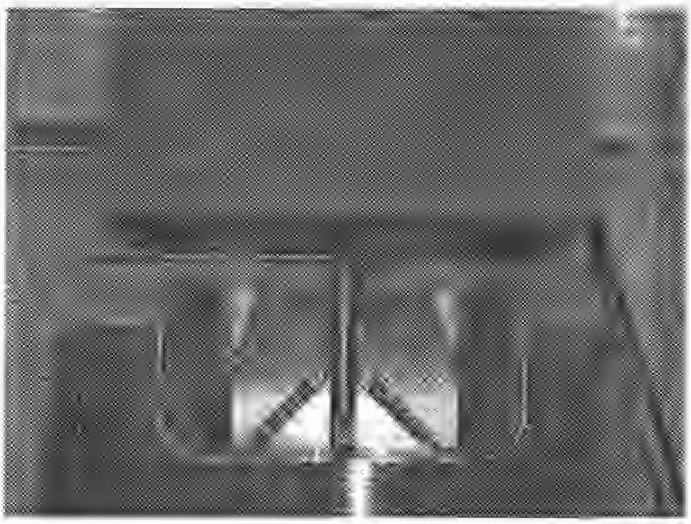


Figure 17 Test specimen after final failure.

The fatigue test results are shown in figure 18 . Only the results from 24 specimens are shown as only these specimens showed a "correct" failure in the reinforcement embedded in the Densit Joint Cast ®. It is important to notice that all the failures were in the reinforcement embedded in the Densit Joint Cast ® and not in the embedment zone between the reinforcement and the Densit Joint Cast ®. The ordinate axis is the logarithm with base 10 of Φ_{max}-Φ_{min} and the abscissa axis is the logarihtm with base 10 of the number of cycles to failure, N.

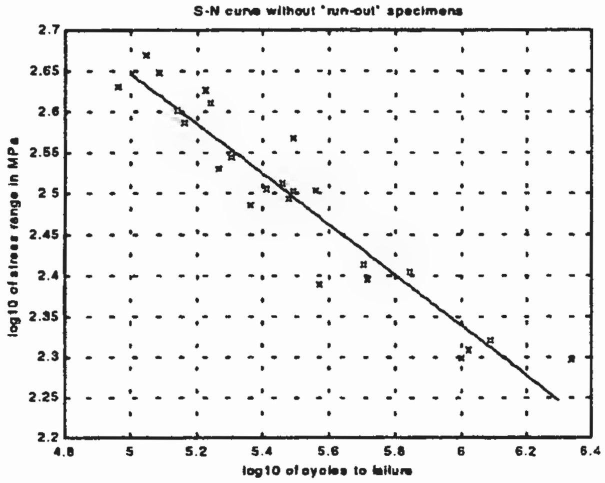


Figure 18 S-N curve for 24 specimens.

For the last 11 specimens - the "run-out" specimens - a failure occured outside the embedded part of the reinforcement which is due to the problems with the grips. These specimens are included in figure 19 showing results from all 35 specimens. The x corresponds to the specimens from figure 18 to the left and the o corresponds to the "run - out" specimens.

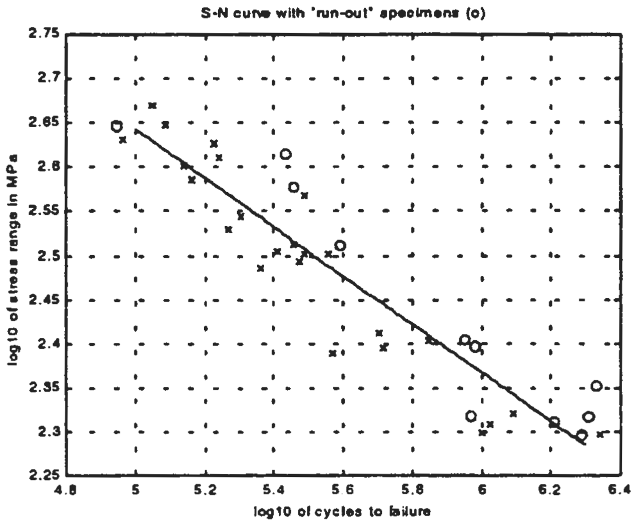


Figure 19 S-N curve for 35 specimens.

By linear regression a straight line for these tests is calculated. Corresponding to figure 18 the equation is:

$$\log(\Phi_{max} - \Phi_{min}) = 4.186 - 0.308 \log(N) \quad \text{for } 5 < \log(N) < 6.3 \qquad (6)$$

and corresponding to figure 19 the equation is:

$$\log(\Phi_{max} - \Phi_{min}) = 4.020 - 0.275 \log(N) \quad \text{for } 5 < \log(N) < 6.3 \qquad (7)$$

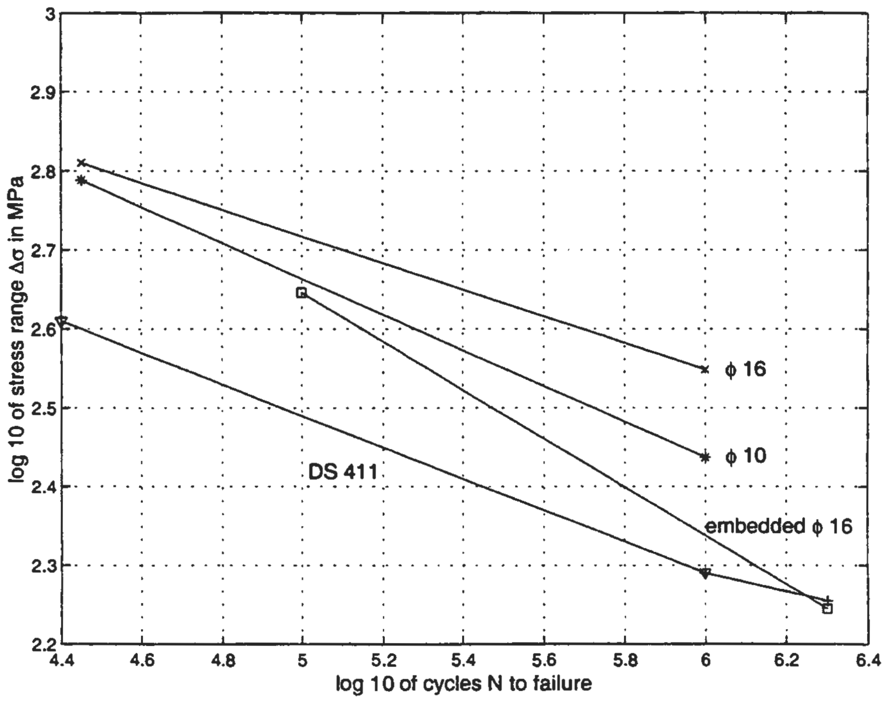
7. CONCLUSIONS

From the test series described in this paper and the practical experience at the construction site the following can be concluded from the first 4 chapters:

1. Casting with Densit Joint Cast ® turns out to be easy to do in this type of joints.
2. The joints make the slab act as a ductile structure with a strength, which can be calculated according to the traditional methods.
3. It is possible to use the building system without stabilizing walls.
4. The joints can be classified as fire resistant for at least 60 minutes. After a fire exposure for 60 minutes and cooling the residual load-bearing capacity is approximately 75% of the original capacity.

For the fatigue testing described in chapters 5 and 6 the conclusion can be seen in figure 20.

Figure 20 shows the S-N curves for New Tentor rebars N = 10 mm, N = 16 mm, the S-N curve for the embedded rebars, see figure 17 and the S-N curves given in DS 411. It is seen that the S-N curve for rebars N = 16 mm is situated above the S-N curve for rebars N = 10 mm and both of them are situated above the S-N curve for the rebars embedded in the Densit Joint Cast and the S-N curve given in DS 411.



Figur 20 *Fatigue strength curves (S-N curves) for New Tentor rebars N=10mm, N=16 mm, N=16 mm embedded in Densit Joint Cast ® and the S-N curve given in DS411.*

ACKNOWLEDGEMENT

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