BEAMS AND SHELL IN HIGH-STRENGTH CONCRETE 8

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SYNOPSIS

A new type of cement-based materials (DENSIT) with compressive strength 160-200 MPa has been investegated with regard to civil engineering applications.

Tests on beams and shells have been carried out in order to evaluate the applicability of known calculation methods on such strong materials, and in order to evaluate the application of steel fibres to increase the ductility of the materials.

Key words: Beams, shell, high-strength concrete, steel fibers, microsilica.

1. INTRODUKTION

A new cement-based material has lately been developed by the Danish cement producer Aktieselskabet Aalborg Portland-Cement-Fabrik and marketed under the trade mark DENSIT [1]. This material or rather this group of materials has in many respects unusual properties which might endow the material with a wide specter of applications.

Very few material data are available at the present. It was therefore decided to set up a number of preliminary tests to become acquanted with the material and to get a first estimate of some of the material parameters.

The material migth find applications in the field of civil engineering though the cost is startling. But a new design together with a rational production could eventually make the material attractive for a production of elements.

In this paper tests on the material and simple beams are reported together with a test on a cylindrical shell.

2. THE MATERIAL

Compared with usual concrete the DENSIT material has a very dense material structure. This has in part been achieved by adding 5-50% ultra-fine microsilica (silica fume) homogeneously arranged in the spaces between the cement particles.

The microsilica consists of extremely fine, amorphus silica particles. The particles are spherical in shape and have a diameter in the interval of only 0.005-0.5μm.

Such small grains exhibit strong surface forces which are prohibitive to a dense compaction unless a small amount of superplasticizers is added.

The material used in the tests was delivered as a ready-mix including aggregates of bauxit (1-4 mm). Marketed by Densit A/S under the trade name Densit® Wear Resistant II. It was mixed with water in a 150 l plan-type power mixer for as much as 30 minutes.

In some batches a small amount (1.5% by volumen) of steel fibers (WIREX-stahlfaser) were added without any tendency of bundling.

The water requirement was very small with a water/cement plus microsilica ratio w/c+s in the interval 0.13-0.20.

The workability was favourable in the upper part of this interval while a great deal of heavy mechanical compaction was required at the lower - especially when steel fibers were added.

In none of the castings bleeding was observed but the low content of water required on the other hand that the free surfaces were protected as soon as possible against evaporation. This was done either with a thin film of polyvinyl cloride or by a curing compound.

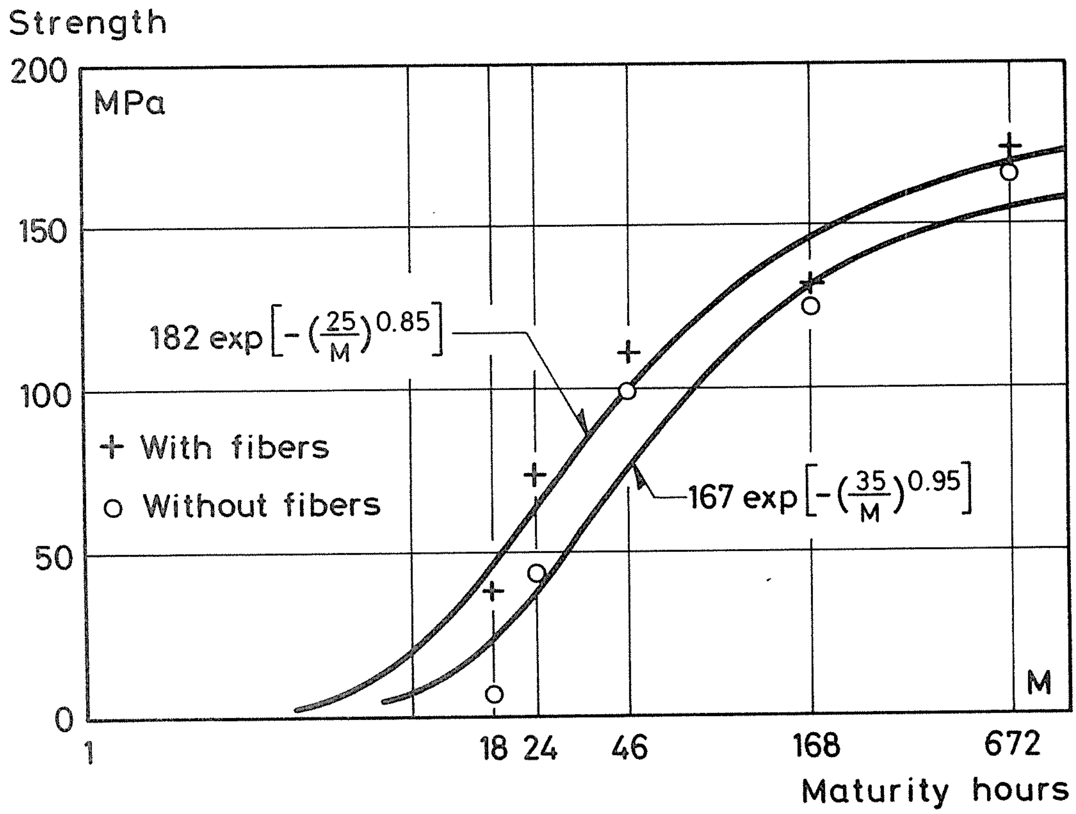


FIG. 1. Strength development by time for a water/cement+silica - ratio of 0.16. Maturity hours is curing time transformed to curing time at 20^oC.

The heat evolution during hydration of the Densit material with w/c+s = 0.16 was measured by adiabatic calorimetry. The measurements were stopped after roughly 500 maturity hours where it turned out that the total amount of heat produced was 198 kJ/kg cement. This is about half the heat created by a concrete with 325 kg/m^3 rapid hardening portland cement.

The development of strength is a little slow at start compared to ordinary concrete but relatively fast later on, see figure 1. This is advantageous in case of a difficult casting but has of course also disadvantages.

If a high early strength is required a moderate temperature curing is needed.

The compressive strength at 28 days will depending of the strength of aggregates lie in the interval 120-280 MPa /1/. Furthermore it depends on the w/c+s ratio as shown in figure 2.

The stress-strain curve is a straight line up to failure with a compressive E-modulus of 50-100 GPa /1/. This was confirmed by our tests where Young modulus was found ranging from 70.7 to 76.1 GPa for different w/c+s ratios (0.13-0.16).

The compression tests were conducted on 100 by 200 mm cylinders in a 300 t testing machine (Mohr & Federhaff). The failure was very sudden and fragile in all the unreinforced specimens while it was less abrupt for the fiberreinforced specimens.

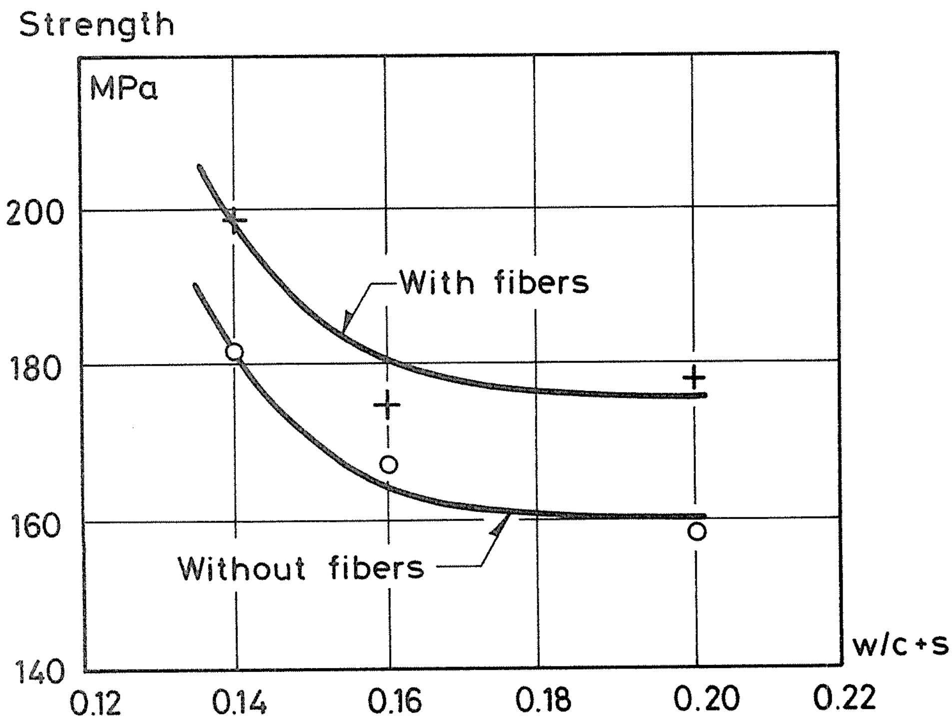


FIG: 2. Compressive strength as function of the water/cement+microsilica - ratio.

The tensile strength is about 10% of the compressive strength but increases to 25% with a small fiberreinforcement /2/. New tests, however, indicate that this strength might increase considerable with different types of fibers.

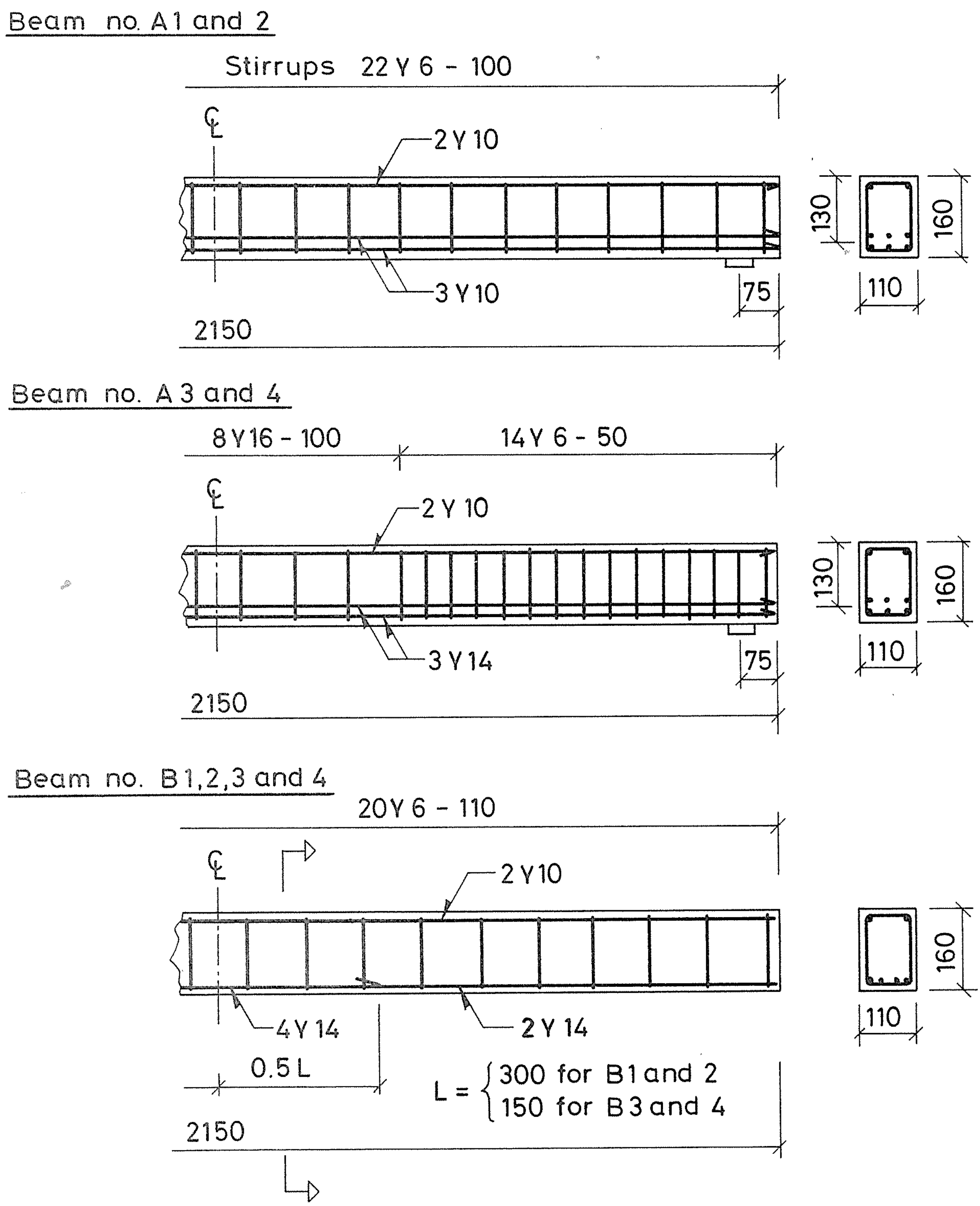


FIG. 3. Testspecimens. The yield stress is 420 MPa and 470 MPa for Y10 and Y14 respectively. For the stirrups the yield stress is 520 MPa.

3. BEAM TESTS

In this experiment 8 beams with different reinforcement were tested in order to investigate the influence of ordinary reinforcement and fiber reinforcement. Moreover the anchorage of the reinforcement in a lap was tested.

The experiments were divided into two parts A and B. One (A) with through reinforcement and the other (B) with a lap in the middle of the beams.

Beams with an even number are reinforced by 1.5% by volumen steel fibers while beams with odd numbers do not have such a reinforcement.

All beams have the same dimension but different reinforcement, see figure 3.

The flexural testing equipment consisted of a rigid frame provided with two hydraulic jacks placed at equal distances (1/3xspan) from the fixed ends. The load was increased step by step and the deflections were recorded automatically by transducers at the ends, the loading points, and at the middle point.

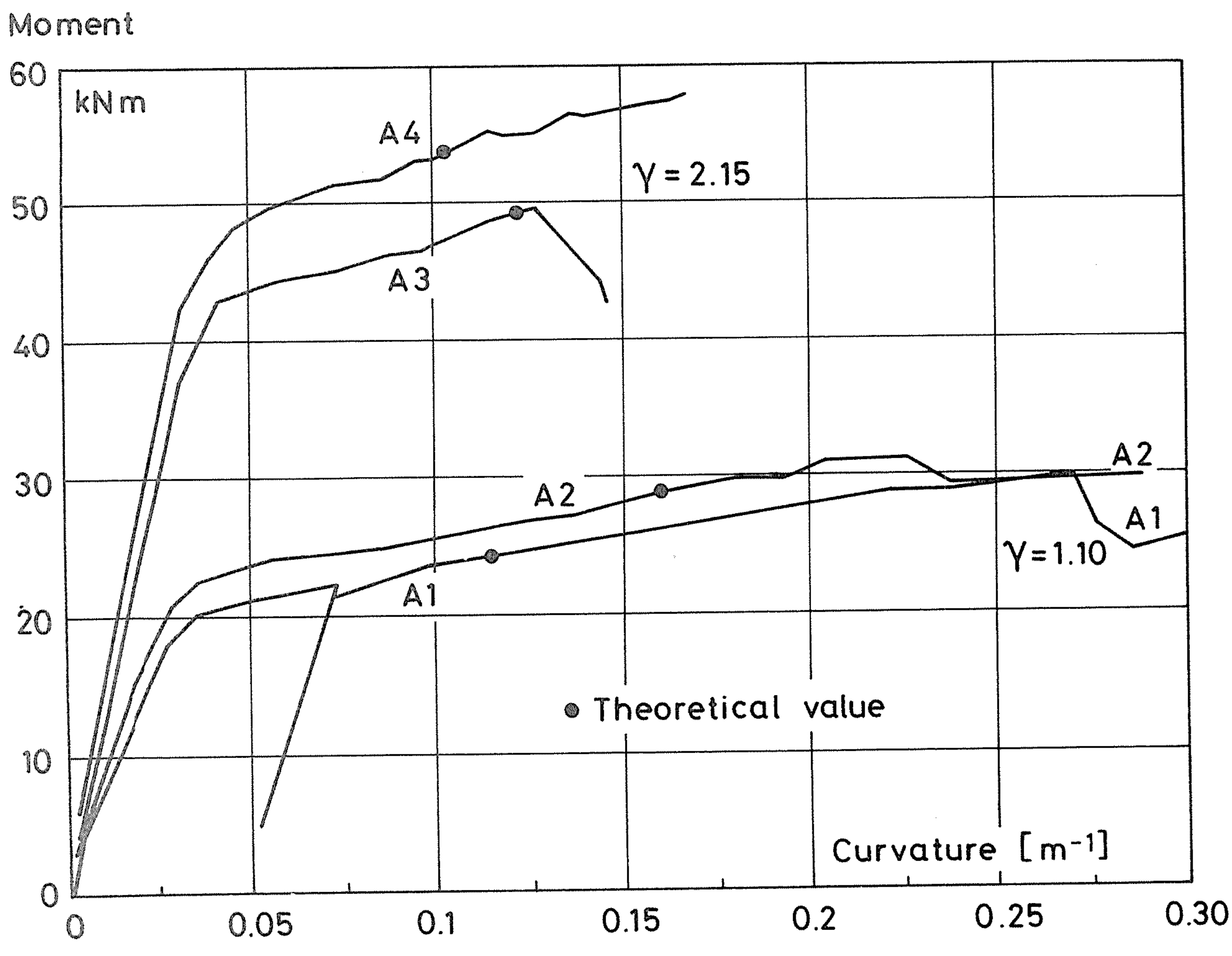


FIG. 4. Curvature versus bending moment for beams with 100 A_s/bd = 1.10 and 2.15.

The found relation between moment and curvature at the middle section of the beam is shown in the figures 4 and 5. The curvature being defined as $10\ u/L^2$ where u is the midpoint deflection and L the span.

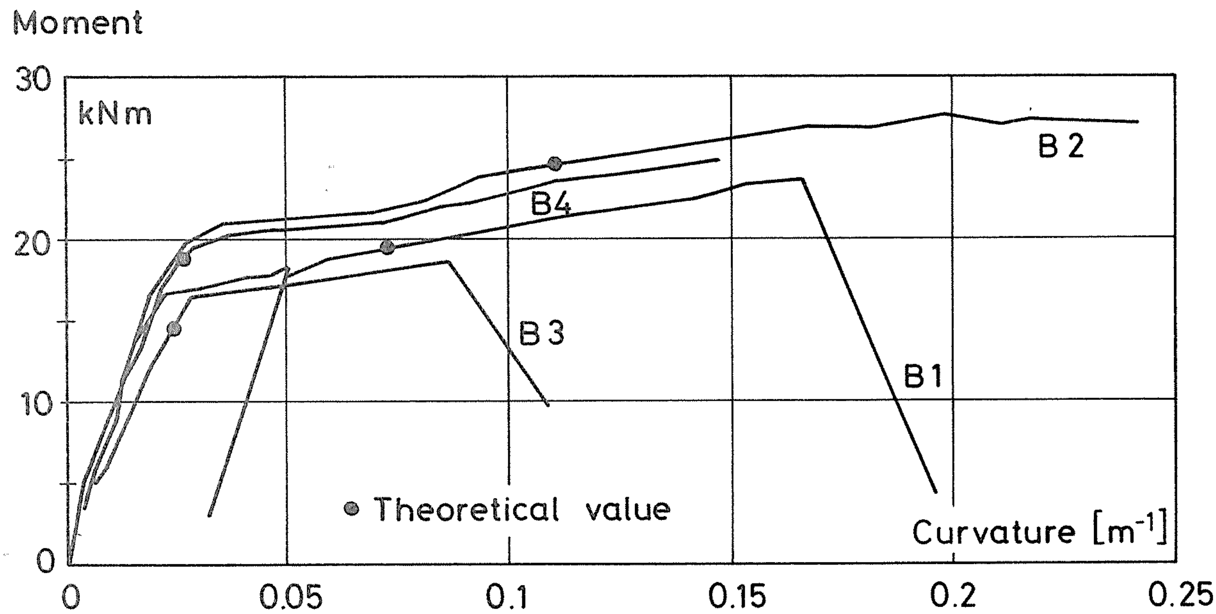


FIG. 5. Curvature versus bending moment for beams with lap joints.

At each loading step the crack pattern was recorded. Figure 6 shows an example of the cracks formed in beam no. A1 for a deflection of 20 mm.

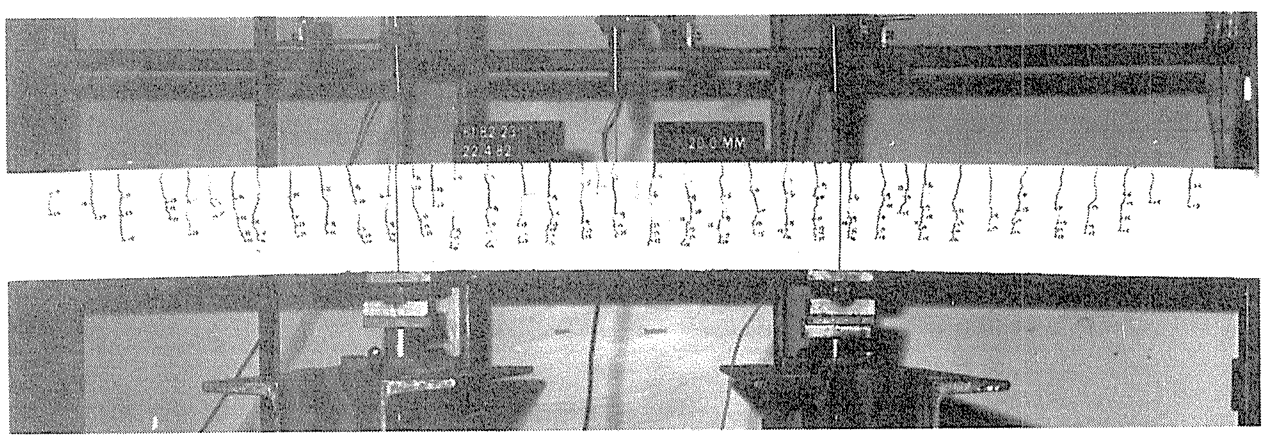
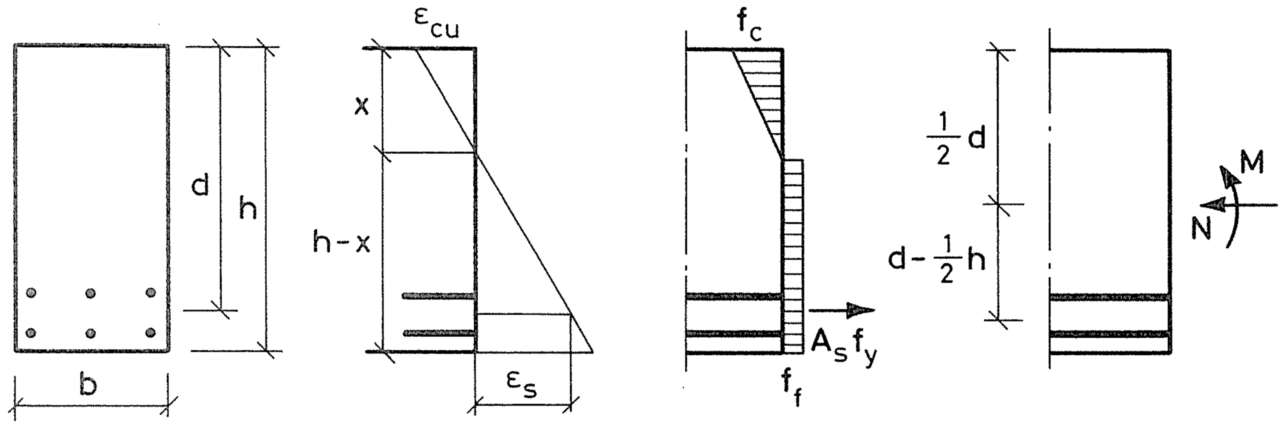


FIG. 6. Crack pattern in beam A1 for a deflection of 20 mm at the midpoint.



f_f: Strength of fibers per square unit

FIG. 7. Stress and strain distribution.

Assuming a linear stress distribution in both the tension and compression zones of the beam, see figure 7, the yield-moment is

$$M_y = \left[d + \frac{h}{2}\left(\frac{x}{x_o} - 1\right) - \frac{x}{6}\left(3 - \frac{x}{x_o}\right)\right]A_s f_y$$

where

$$x = \frac{2(A_s f_y + b\,h\,f_f)}{b(f_c + 2f_f)}$$

$$x_o = \frac{2A_s f_y}{b\,f_c}$$

The actual theoretical values are shown in figure 4.

For the lap it is assumed that the failure takes place in the slab containing the reinforcement the length being equal to the length of the lap. The stirrups are assumed to reinforce the slab in the transverse direction. See figure 8.

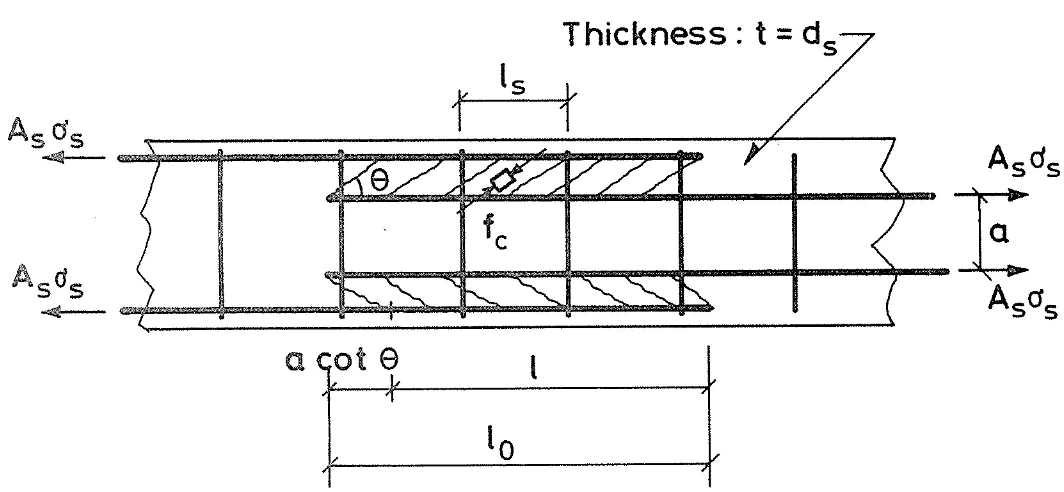


FIG. 8. Model for a lap in a beam.

The lap fails when either the reinforcement or the stirrups yield or the strength of the concrete is exceeded /3/. Analytically this can be expressed by

$$\frac{A_s f_y}{l_o t f_c} = \lambda\beta \sin\theta\cos\theta$$

$$\frac{A_{st} f_{yst}}{l_o\, t\, f_c} = \frac{\lambda\beta}{n}\sin^2\theta$$

$$\beta = 1$$

where

$$\lambda = l/l_o \;;\quad \beta = \sigma_c/f_c \;;\qquad n = l/l_s$$

These expressions show that the required length of a lap is inversely proportional with the compressive strength of concrete f_c why a highstrength concrete anchors the reinforcement better than a low strength concrete.

The test results are in reasonable good agreement with the theoretical values as shown in figure 5.

As the results are not contradicting the results in /4/ it can be concluded, that

i) Moderately reinforced beams cast in DENSIT-material yield under large plastic deformations. A small amount of steel fibers increases the yield moment.

ii) Even short laps are well anchoraged in DENSIT-material and deforms plasticly. A small amount of steel fibers increases the plastic deformation noticeable.

4. CYLINDRICAL SHELL

This test served a dual purpose. Firstly to test a fiber reinforced shell element and secondly to try out a casting process with double formwork.

The shell element was designed to serve as a deck in apartment blocks the design also facilitating a simple production process. The special choice of primary reinforcement could simplify both the production and the coupling of two elements.

The net weight of the element is relatively small (1.3 kN/m^2) which might cause sound problems. But a calculation shows that it is possible to solve these problems in both a technical simple and economic acceptabel way.

The dimensions of the shell was found using a beam model and the stresses were later checked by a FEM analysis.

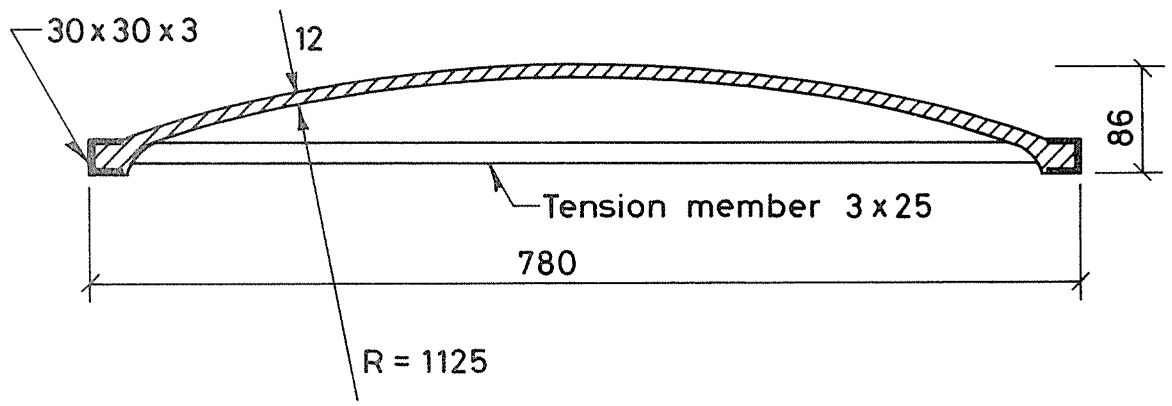


FIG. 9. Cross section of test specimen

To test the element a scala model (1:2.31) was produced. The dimensions are shown in figure 9.

The test specimen was cast in a DENSIT material with w/c+s=0.19 and a fiber content of 1.5% by volumen. The fibers were straight steel fibers with a length of 12 mm and a diameter of 0.4 mm.

The consistency of the material became rather liquid under vibration so pouring from the crown of the shell the material ran down between the boards filling the form from the bottom. After striking of formwork the specimen was cured for 26 days.

The test program was divided into three parts as follows:

Part I : 0- 5.0 kN/m^2, distributed load all over.
Part II : 0-10.0 kN/m^2, distributed load over 0.6×0.6 m^2.
Part III: 0-14.7 kN/m^2, distributed load all over.

During the test the element was turned up-side-down and loaded from below by means of an air bag. The element was supported at all the four corners by steel frames.

In the two cases I and III where the specimen was loaded all over it was further loaded by a line load along the two sides. The total load divided by the projected surface area is referred to as the equivalent load.

Deformations and strains were recorded in several points by transducers, strain-gages and photogrammetry while the element was loaded step by step.

In figure 10 curves are shown for the deflections in the three cases of loading. The residual deflection caused by the first loading is neglected in the following two loadings.

The code of practice demands a deflection less than or equal to the span divided by 400 (i.e. 6.0 mm) at the design load. So with a deflection of 5.8 mm the shell element fulfill this demand.

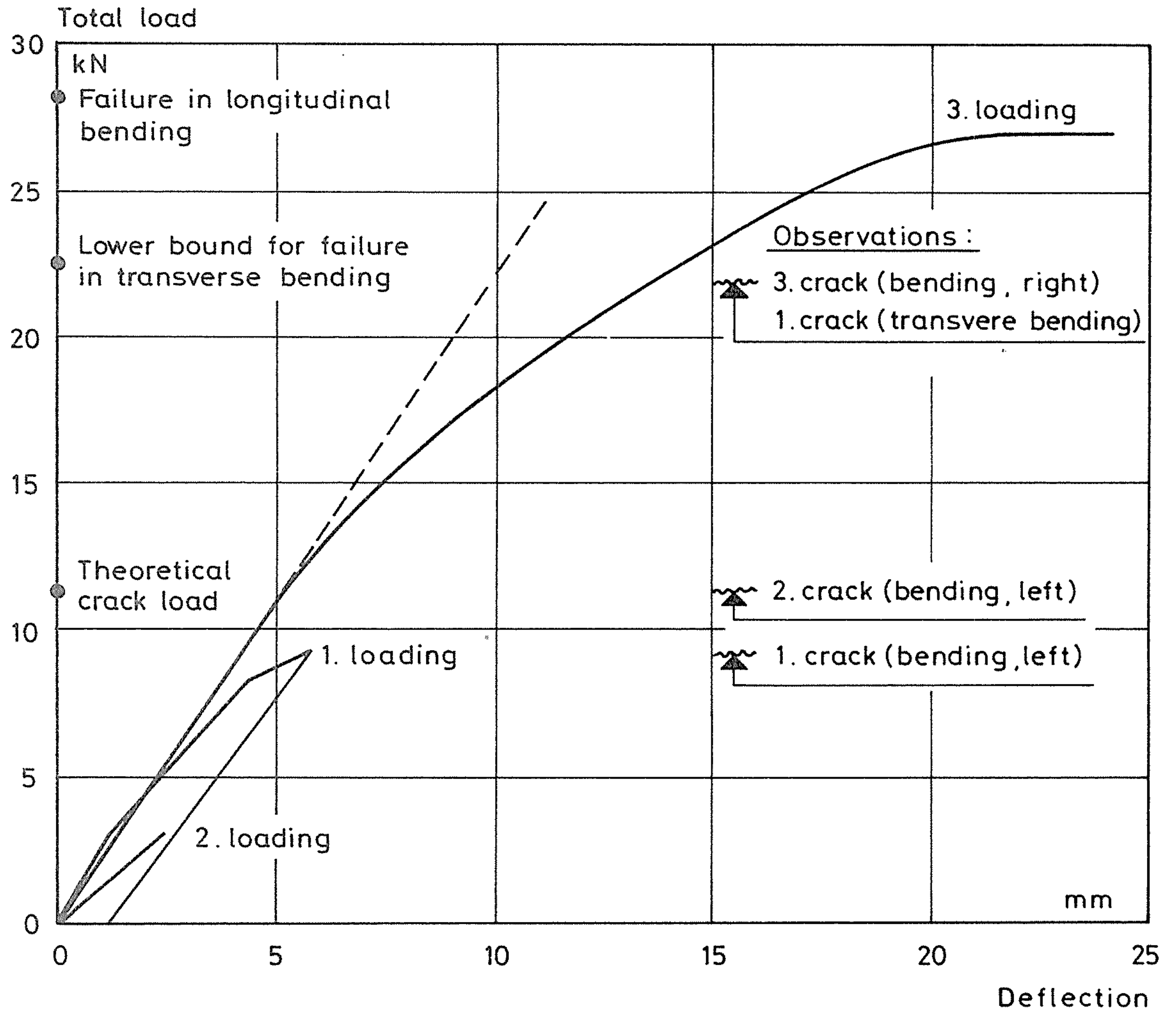


FIG. 10. Curves showing deflections at the middle of the shell for different loads.

At the design load the first crack was observed close to the longitudinal reinforcement.

During the second loading only an area of 0.6×0.6 m^2 was loaded with a uniformly distributed load. Neither more cracks nor residual deflection was recorded.

Finally the load was increased from zero to failure at 27.7 kN. Two new cracks due to longitudinal bending were observed at 11.4 and 22.0 kN while the first crack caused by transverse bending was observed at the latter. The final crack pattern shown in figure 11 developed progressively when the total load exceeded 22-23 kN.

The crack pattern shows that the failure mode is a combination of both longitudinal and transverse bending the latter being predominant. This is supported by the fact that yielding took place in (at least) one of the tension members placed at the ends. And further by the fact that the horizontal transverse displacements at the ends exceeded those at the middle of the shell.

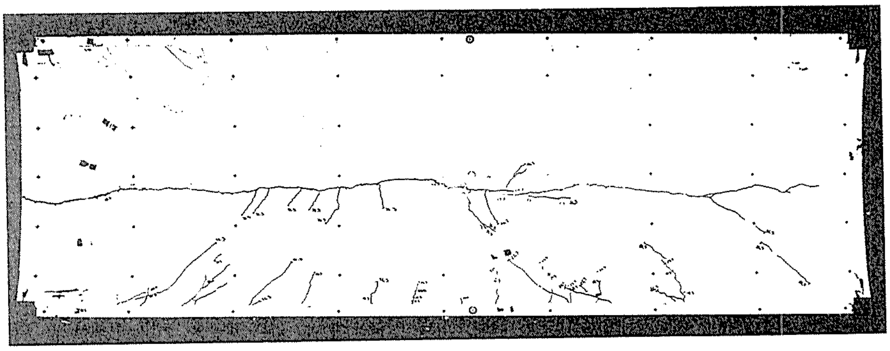


FIG. 11. Crack pattern at failure.

Calculations of both the crack load and the failure load for two different failure modes (longitudinal and transverse bending) are in reasonable accordance with the values found in the test.

In conclusion it can be noted that

i) the general behavior of the shell element is elastic-plastic.

ii) practically no cracks are formed at the design load or even at the double design load.

iii) there is a reasonable agreement between calculations and tests.

Thus a light-weight fiber reinforced shell element in high strength Densit-material might become an attractive solution in the future.

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