

ANCHOR BOLTS IN REINFORCED CONCRETE FOUNDATIONS

SHORT TIME TESTS

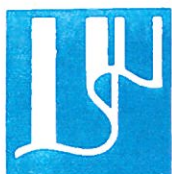
by

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PREFACE

This study was initiated by the Swedish mill and paper industry. The industry had for a long time felt the need for design rules for anchor bolts in reinforced concrete foundations.

After discussions between representatives from the consulting firm AB Jacobson & Widmark and from the Division of Structural Engineering, University of Luleå, a research proposal was submitted to the Swedish Council for Building Research in June 1978. The proposal was accepted, a grant was allowed, and tests were started in 1979.

In this first report, results from static tests are presented.

From AB Jacobson & Widmark, the following persons have been engaged in the study: Carl Erik Broms, projekt leader (planning and supervision); Kent Brusquini, Olle Humble, and Bo Westerberg, consultants (initial literature survey).

From the University of Luleå, the following persons have been engaged in the study: Krister Cederwall, professor and head of the Division of Structural Engineering (general supervision), Lennart Elfgren, projekt leader (planning, testing, analysis, and writing of report); Arne Rehnström (1979) and Håkan E. Johansson (1980), research engineers (planning of and performance of tests); Kent Gylltoft, and Larsgunnar Nilsson, consultants (test programs, analysis); Ingvar Holm, Håkan V. Johansson, Roger Ylinenpää and Lars Åström, laboratory engineers (testing); Mats Oldenburg and Hans Åke Häggblad, research engineers (finite element analysis); Thomas Hedlund, student (diploma work [3-1], testing and analysis); Monica Lövgren and Maj-Britt Anttila, drawers (drawing), and Kerstin Gatu, Jonny Backe and Karin Ericson secretaries (typing and editing of report).

II

The Board of the University of Luleå has allowed a grant corresponding to a half-time position as research fellow during 1980 to Lennart Elfgren. Part of the time has been spent on this investigation.

The cement and grout required for the test specimen have been provided free of charge by CEMENTA AB (Standard Portland Cement) and by Master Builders (Embeco 636 Grout).

Stockholm and Luleå in December 1980

Carl Erik Broms Lennart Elfgren

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NOTATION

The notation follows in principle the standard notation established by ISO (the International Organization for Standardization) in [2-12]. Guidance regarding notations is also given by CEB-FIP in [2-13].

A	area
D	diameter
E	modulus of elasticity
F	axial force
P	prestress force
c	vertical displacement of concrete foundation
d	effective depth
f	failure stress
m	mean value
p	pressure
r	radius
u	horizontal displacement of concrete foundation
v	vertical anchor head displacement (measured relative to the concrete foundation)
α	inclination
ϵ	strain
σ	stress, standard deviation
ν	Poisons ratio
ρ	density
μ	micro = 10^{-6} e.g. $\mu\text{m} = 10^{-6}\text{m}$ coefficient of friction

Indices

c	concrete, compression
r	radial
s	steel
t	tension
u	ultimate
v	vertical shear
y	yield

1 INTRODUCTION

1.1 Background

Machines are often anchored to reinforced concrete foundations by means of anchor bolts. It is desirable that these anchor bolts meet the following specifications:

- They are able to withstand static and cyclic loading
- They are able to anchor a load within a short anchor length even when the load is situated close to the edges of the concrete foundation
- They are easy to install in the foundations even a long time after the foundation was cast.

These requirements have led to the development of various types of anchor bolts. The following main types are most common:

- (a) Anchor bolts which are cast-in-place in the foundation from the beginning (Fig 1.1a)
- (b) Anchor bolts which are taken through the whole foundation in a hole. The bolts are then anchored on the opposite side of the foundation (Fig 1.1b)
- (c) Anchor bolts which are placed in a recess or a drilled hole in the concrete foundation. The anchors are fixed in position by grouting of concrete in the recess or by injection of some kind of mortar (Fig 1.1c).

Types (a) and (b) are used when a very high capacity and quality of the anchor is needed. They are used for the anchorage of turbines and paper making machines, for example. Ample knowledge of the design of these types

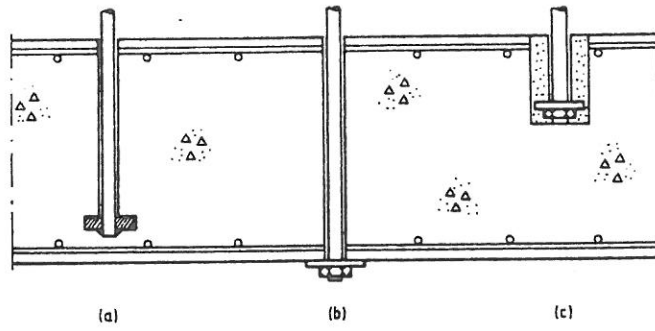


Fig 1.1 Different types of anchor arrangement for bolts

(a) A bolt cast-in-place in the foundation

(b) A bolt anchored at the rear side of the foundation

(c) A bolt anchored in a drilled hole or in a recess in the foundation

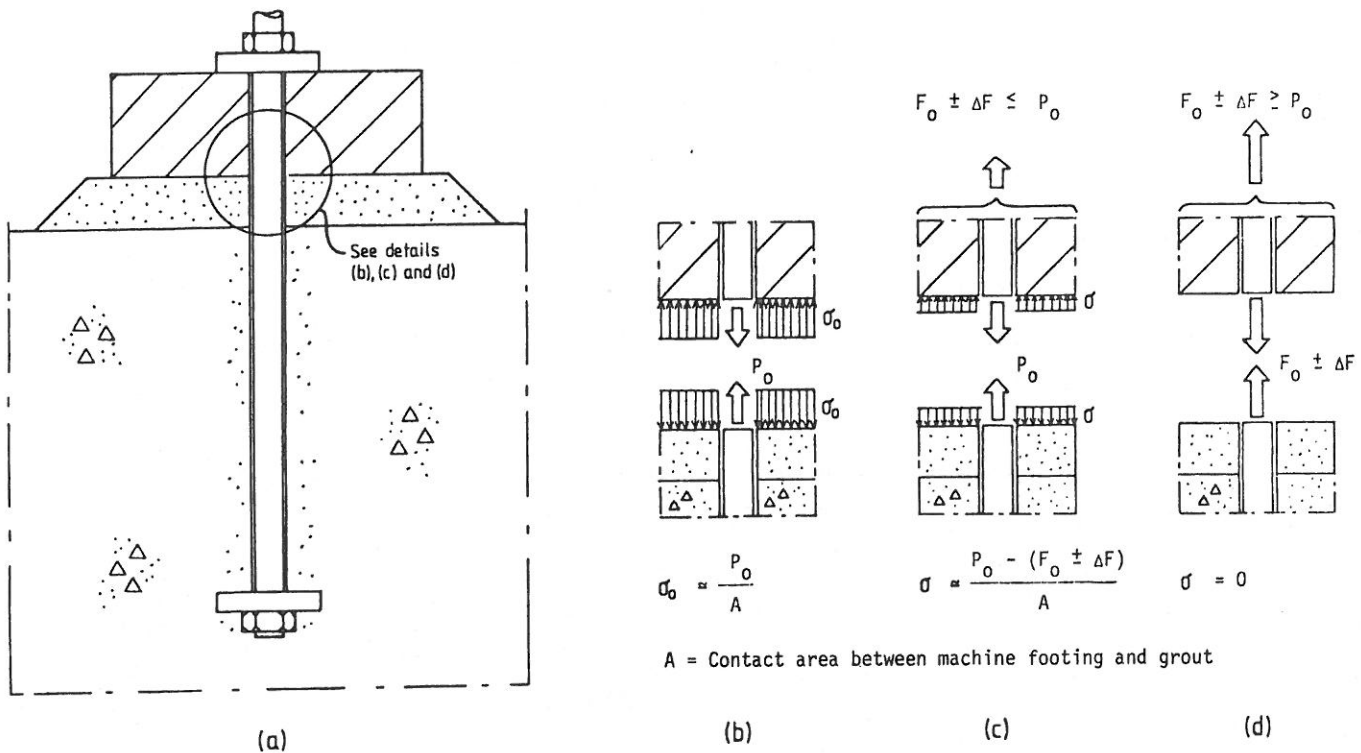


Fig 1.2 Function of a prestressed anchor bolt. In (a) a general view is shown, in (b)-(d) details are given of the forces in the anchor bolt and of the stresses between the machine footing and the foundation grout. Detail (b) illustrates the case when only the prestress force P_0 is acting. In detail (c) the applied load $F_0 \pm \Delta F$ is smaller than P_0 . Only a slight stress variation occurs in the bolt. In detail (d) the applied force $F_0 \pm \Delta F$ is greater than P_0 . The load variation $\pm \Delta F$ must then be carried by the bolt alone. See Appendix A for further details

of anchors is available in the literature (see e.g. [1.1] - [1.4]).

Type (c) is the most common type of anchor. A lot of different bolts and fixings are available. This leads to uncertainty regarding which type to use in a specific case.

In this report anchors of type (c) will be treated. Anchor bolts for the loading range of 50 to 300 kN will be discussed. Fixings for smaller loads are easier to arrange and various methods are discussed in the literature e. g. expanding metal anchors, drive-in-nails and adhesive anchors ([1.3] - [1.8]).

The fatigue capacity of bolts is generally low. The capacity is to a large extent dependent on the stress range σ_r (the difference $\sigma_{\max} - \sigma_{\min}$ in the bolt). According to the Swedish code for bolted connections ([1.9] connection No 16, p. 34) the allowable stress range σ_r is only 13.4 MPa for a bolt with cut threads loaded in tension during 10^7 cycles. This is less than 5 per cent of the yield stress for ordinary steel qualities used for high strength bolts. This implies that very heavy bolts are required to withstand even relatively small cyclic loads.

One way to reduce the cyclic stress variation in a bolt is to prestress it. If the prestressing force P_0 is chosen to be higher than the applied cyclic load $F_0 \pm \Delta F$, the bolt will be only slightly influenced by the cyclic load, see Fig 1.2 and Appendix A. Only minor stress variations will result, which are not detrimental for the fatigue capacity of the anchor bolt.

To be able to withstand cyclic loading, it is thus advisable to use prestressed bolts. Thereby the following provisions ought to be fulfilled by the anchor bolt design:

- The bolt is made of a high quality steel
- The anchorage zone is sufficiently long so that there will be no punching failure in the concrete
- The concrete compression zone at the top of the bolt is designed so that it can carry the prestressing force.

1.2 Aim and scope of the investigation

The main object of this investigation is to provide background results for a design guide for anchor bolts. Special interest is given to the effects of sustained and cyclic loading.

Two major types of anchor bolt arrangements are tested.

In the first one, the recess for the anchor bolt is provided by drilling a hole in the cast foundation, see Fig. 1.3a. This type of recess has two main advantages. No special arrangements are required during the design and the casting of the foundation and there is a complete freedom of where to drill the hole. On the other hand, this type of anchorage is likely to have a rather poor capacity for sustained load due to shrinkage of the mortar grouted in the drilled hole.

In the other type, the recess for the anchor bolt is provided by a conical shell, which is placed in the foundation before casting, see Fig 1.3b. The cone is provided with a spiral reinforcement which helps to carry the splitting forces in the concrete. This type is likely to have a good ability to carry sustained and cyclic loading although some more effort is required during construction.

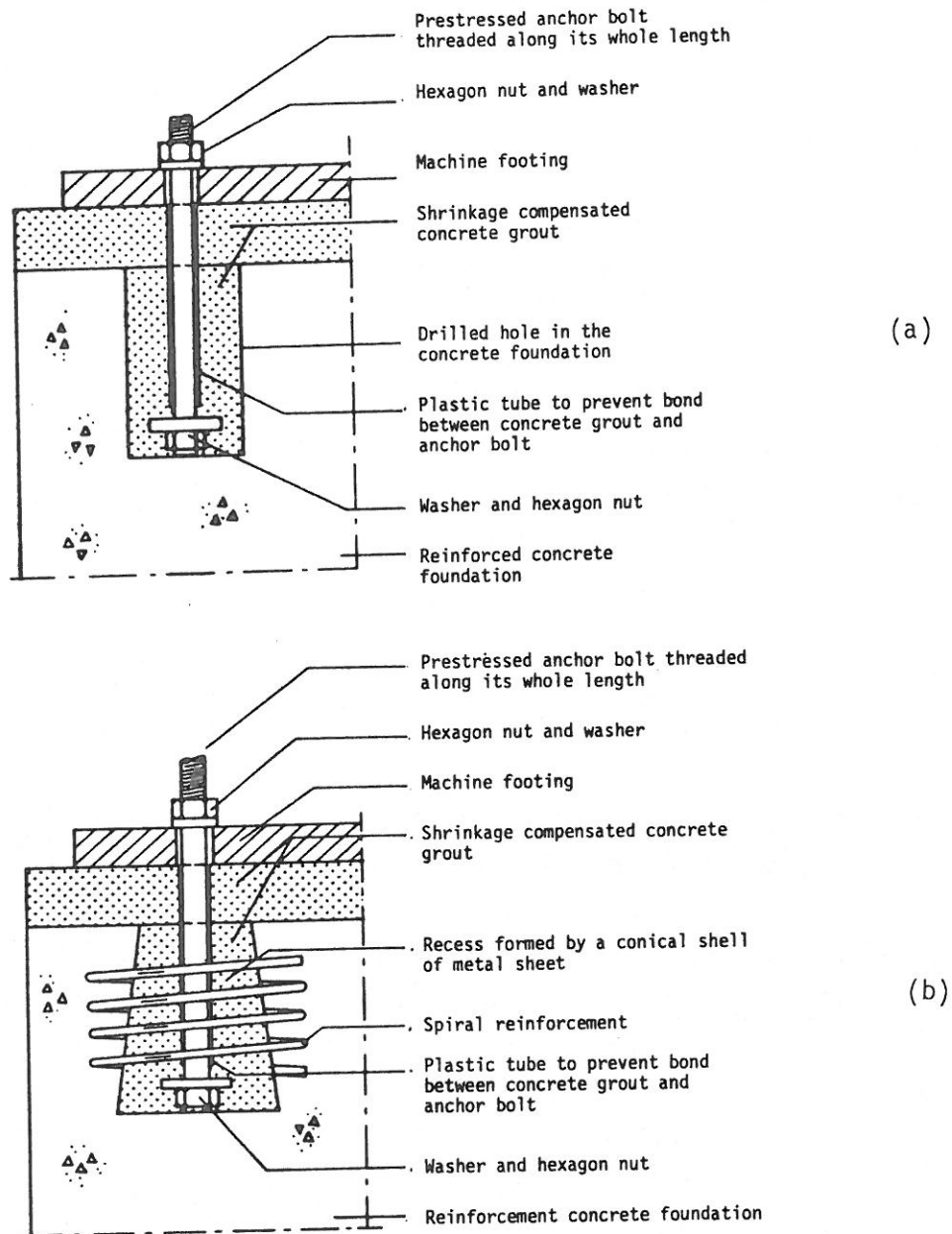


Fig 1.3 Two tested major types of prestressed anchor bolt arrangements

(a) A bolt placed in a cylindrical hole drilled into a reinforced concrete foundation

(b) A bolt placed in a conical recess in a reinforced concrete foundation. The recess is formed by a metal sheet

1.3 Review of literature

1.3.1 General notes

The embedment requirements for anchorage steel were earlier largely left to the discretion of the design engineer. It was not clearly defined by any codes.

During the last decades the problems with anchorage have become more important. Dynamic forces have become more common causing fatigue failures in bolts and anchorage zones. Accordingly the need for research has grown.

In the following some test reports are presented as well as some recent codes and design specifications.

Most of the reports deal with anchors for small loads as, for example, expanding metal anchors and adhesion anchors. However, some of the reports also treat cast-in-place anchors and anchors grouted-in-place. For the grouted anchors, it is important to have a non-shrinking grout. Some references dealing with grout properties are also included for that reason.

1.3.2 Test reports

Ancient work with non-shrinking grout for sealings is reported by Vitruvius [1 11] and Malinowski 1979 [1-12].

American experiences and test results are presented in the following reports and papers.

Adams 1955 [1-21]. Tests of expansion bolt anchors.

Kennedy - Crawley 1955 [1-22]. Tests of cast-in-place anchors.

Nordlin - Ames - Post 1968 [1-23]. Tests of cast-in-place bolts, epoxied-in-place and grouted-in-place

threaded anchor rods and reinforcing steel, and friction type concrete anchorage devices.

American Concrete Institute (ACI) 1969 [1-4]. A Symposium on "Mechanical fasteners for concrete". It contains 13 papers on various aspects on anchoring devices as well as a selected reading list with abstracts of another 36 papers.

Conrad 1969 [1-24]. Tests on grouted anchor bolts.

Mc Mackin - Slutter - Fisher 1973 [1-25]. Tests on cast-in-place headed steel anchors under combined loading.

Reichard - Carpenter - Leyendecker 1972 [1-26]. Tests of cast-in-place inserts embedded in reinforced concrete.

Stowe 1974 [1-27]. Tests on reinforcing bars which are grouted or epoxied in diamond-drilled holes.

American Concrete Institute (ACI) 1973 [1-28]. A Symposium on "Expansive cement concretes". It contains 20 papers on various aspects of expansive cements.

Cannon - Burdette - Funk 1975 [1-29]. Tests on cast-in-place inserts, studs and bolts; on grouted bolts; and on expanding anchors. Tensile pullout tests, shear tests and tests in combined tension and shear.

Bailey - Burdette 1977 [1-30]. Tests on cast-in-place bolts located near an edge being loaded with large shear forces directed towards the edge.

English experiences and test results are presented in the following reports.

Launchbury 1971 [1-3]. A handbook of fixings and fasteners (Nails, Masonry fixings, In situ fixings, Rivets and self-tapping screws etc).

Paterson 1973 [1-31]. An appraisal of present knowledge regarding cast-in-fixings, grout bonded systems and expansion anchors.

Paterson 1976 [1-32]. Tests on expanding, cast-in, and resin capsule fixings.

Paterson 1977 [1-6]. A Guide for selection of expanding fixings.

German and Swiss experiences and test results are presented in the following books and papers.

Rausch 1959, 1960 [1-1]. A classic handbook on the design of machine foundations.

Leonhardt 1974 [1-2]. A text book giving basic principles for the arrangement of reinforcement in concrete structures.

Lang 1979 [1-5]. A paper on epoxied-in-place anchors.

Hilti Symposium 1979 [1-41]. Seven papers on fastening systems with expanding and adhesive anchors.

Scandinavian experiences and test results are presented in the following reports and papers.

Chalmers Provningsanstalt 1963 [1-51]. Tests on anchor bolts grouted in rectangular recesses of corrugated plastic.

Chalmers Provningsanstalt 1971 [1-52]. Tests on anchor bolts grouted in cylindrical recesses of corrugated plastic.

Statens Provningsanstalt 1969 [1-53]. Tests on anchor bolts in cylindrical holes grouted with ordinary concrete and with expanding mortar.

Lorentsen 1971 [1-54]. Tests on anchor bolts in conical and cylindrical recesses grouted with ordinary concrete. A theoretical model is also proposed which is presented in chapter 2 of this report.

Bergvall - Johnson 1975 [1-7]. Tests on deformed reinforcing bars grouted in drilled holes.

Berntsson 1976 [1-55]. Tests on expanding mortar and grouts.

AB Jacobson & Widmark 1978 [1-8]. A handbook on how to repair and strengthen concrete structures.

1.3.3 Codes and Standards

Test methods for anchors and expanding fittings are presented in the following papers.

American Society for Testing Materials (ASTM) 1976 [1-61]. Standard test methods for strength of anchors in concrete and masonry elements.

Statens Planverk (Sweden) 1978 [1-62]. Approval rules for expanding fittings.

Design rules are presented in the following references.

Deutsche Industrie Normen 1970 [1-71]. Tee-headed bolts with large heads (cast-in-place anchors).

Union Carbide (USA) 1974-75 [1-72]. Standards for expansion anchors and for post-tensioned anchor bolts for machinery and process columns.

Tennessee Valley Authority (USA) 1976 [1-73]. Design standards manual.

American Concrete Institute (USA) 1978 [1-74]. Steel embedments for nuclear safety related concrete structures.

2 THEORETICAL MODELS

2.1 Introduction

It is difficult to establish a correct model of the behaviour of an anchor bolt in a reinforced concrete foundation. The reinforcement and the cracking of the concrete complicate the situation. In the following some attempts to find a model will be discussed.

First elastic stresses around the anchor bolt will be discussed in Section 2.2. Then an analogy with punching of slabs will be dealt with in Section 2.3. Finally a model proposed in 1971 by Mogens Lorentsen [1-54] will be reviewed in Sections 2.4 and 2.5.

2.2 Elastic models

The elastic stresses in the vicinity of an anchor bolt can be calculated with the finite element method. A case with rotational symmetry has been studied, see Fig 2.1. A program called FEMP has been used. The program has been developed by Larsgunnar Nilsson and Mats Oldenburg at the Division of Structural Engineering at the University of Luleå [2-1]-[2-3]. The element mesh which has been used is shown in Fig 2.2. Isostress curves for the principal stresses are presented Fig 2.3.

From the plot of the first principle stress σ_1 (Fig 2.3a) it can be seen that the tensile stress has its maximum at the top edge of the washer. The maximum stress has an inclination of about 45° to a horizontal plane. Cracks in the concrete will be initiated here.

From the plot of the second principle stress σ_2 (Fig 2.3b) it can be seen that very high compressive stresses occur at the top of the washer.

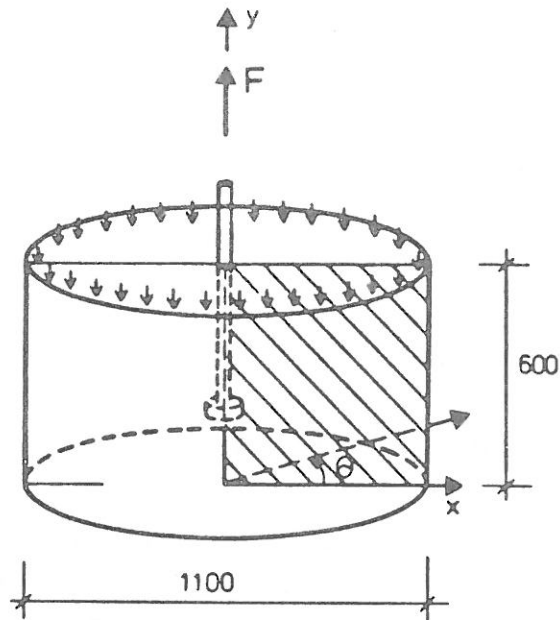


Fig 2.1 Dimensions and loads for anchorage zone analysed with finite element method [2-1]-[2-3]

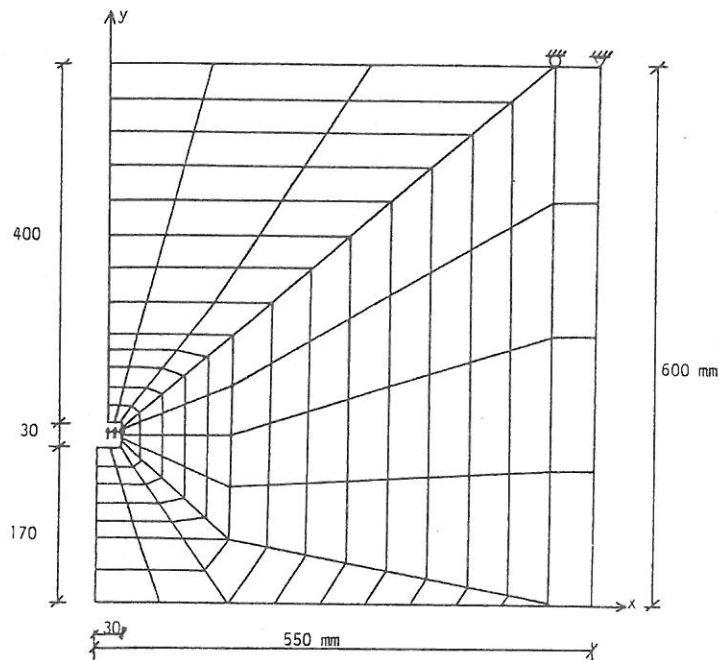


Fig 2.2 Element mesh used in finite element analysis of anchorage zone (123 elements and 147 nodal points). The following material properties for concrete were used $E_c = 25 \text{ GPa}$, $\nu_c = 0$, and $\rho_c = 0$. The load from the bolt is applied directly to the concrete elements situated on top of the washer

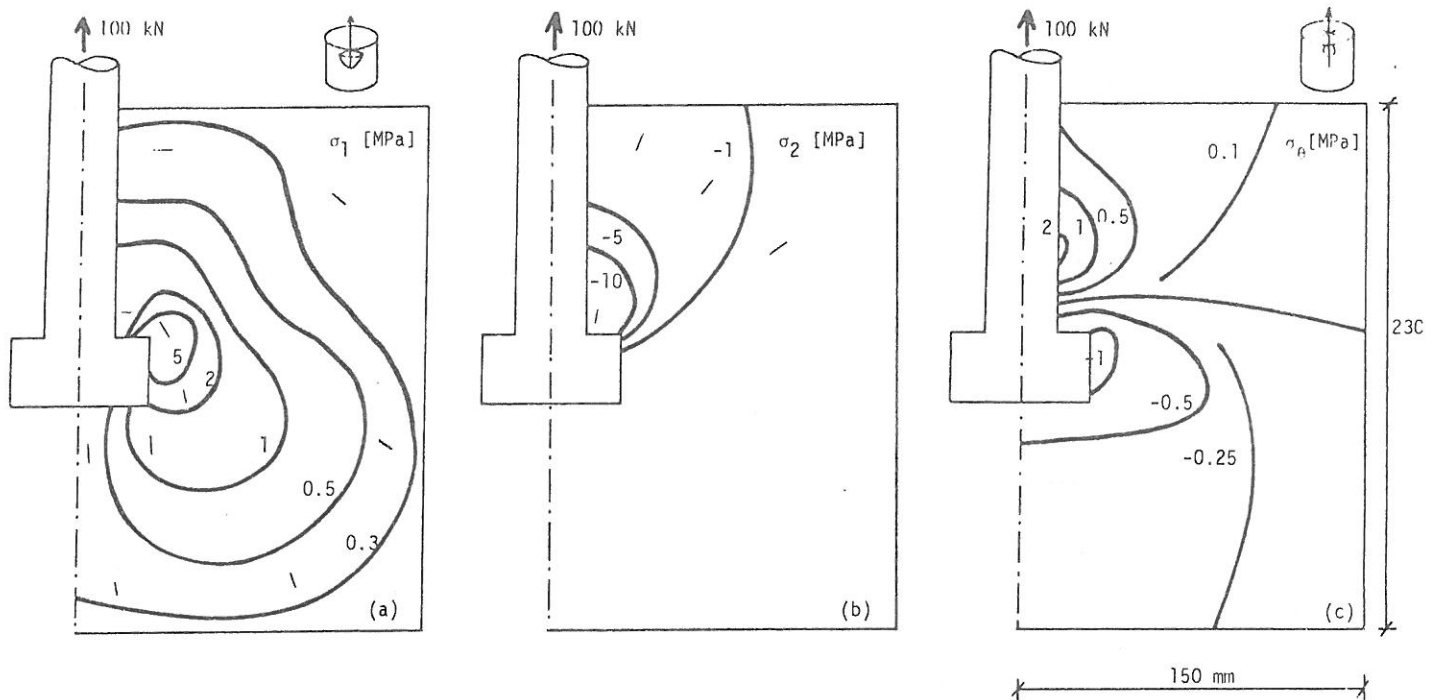


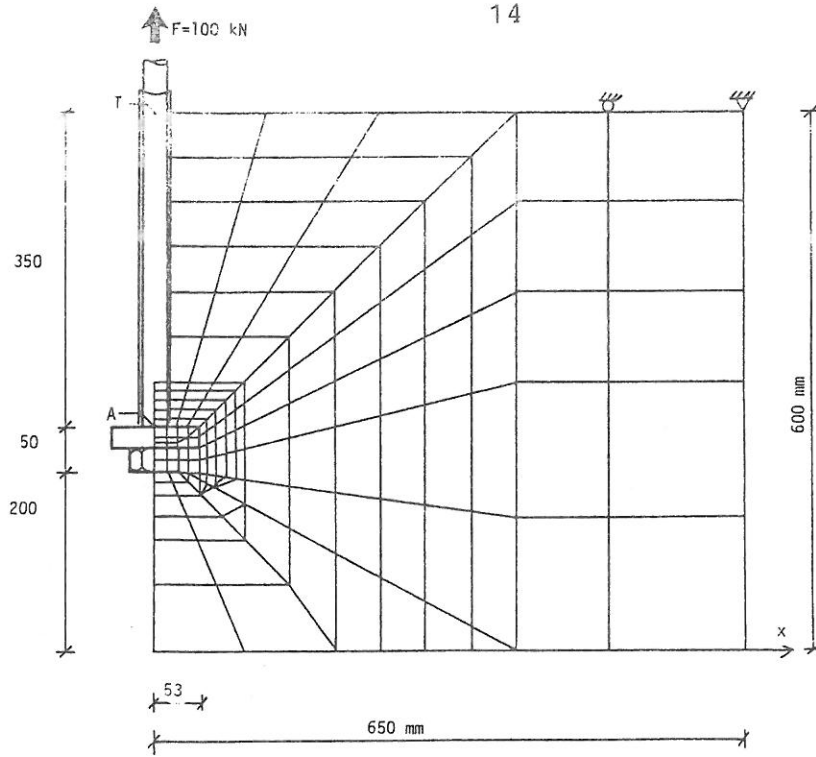
Fig 2.3 Plots of isostress curves for the principal stresses of the finite element model in Figs. 2.1 and 2.2. Small inserted figures above the diagrams indicate possible cracking due to the stresses.

- (a) First principal stresses σ_1 (maximum tensile stress)
- (b) Second principal stress σ_2 (maximum compressive stress)
- (c) Tangential stress σ_θ

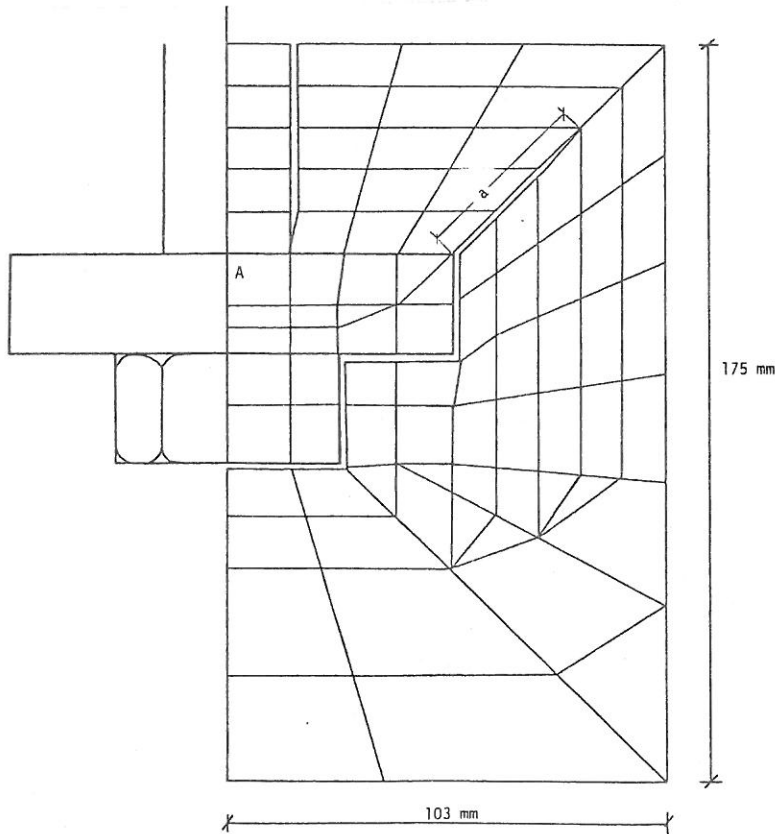
From the plot of the tangential stress σ_θ (Fig 2.3c) it can be seen that tensile stresses occur at some distance above the washer. These stresses will probably cause radial cracks in the concrete when a higher load is applied.

An attempt has also been made to study the stresses around the first inclined crack in the concrete. The element mesh used is shown in Fig 2.4 and some results are illustrated in Figs 2.5 and 2.6.

Three different values of the length a of the crack is studied i.e. $a_0 = 0$ mm, $a_1 = 14,1$ mm, and $a_2 = 42,4$ mm.



(a)



(b)

Fig 2.4 Element mesh used in finite element analysis of cracked anchorage zone (148 elements and 195 node points). The following materials properties for concrete and steel were used $E_c=30$ GPa, $\nu_c=0.2$, $\rho_c=0$, $E_s=210$ GPa, $\nu_s=0.3$, and $\rho_s=0$. In Fig (a) the whole mesh is outlined. In Fig (b) a detail is given of the central part of the mesh when the crack has a length of 42.4 mm.

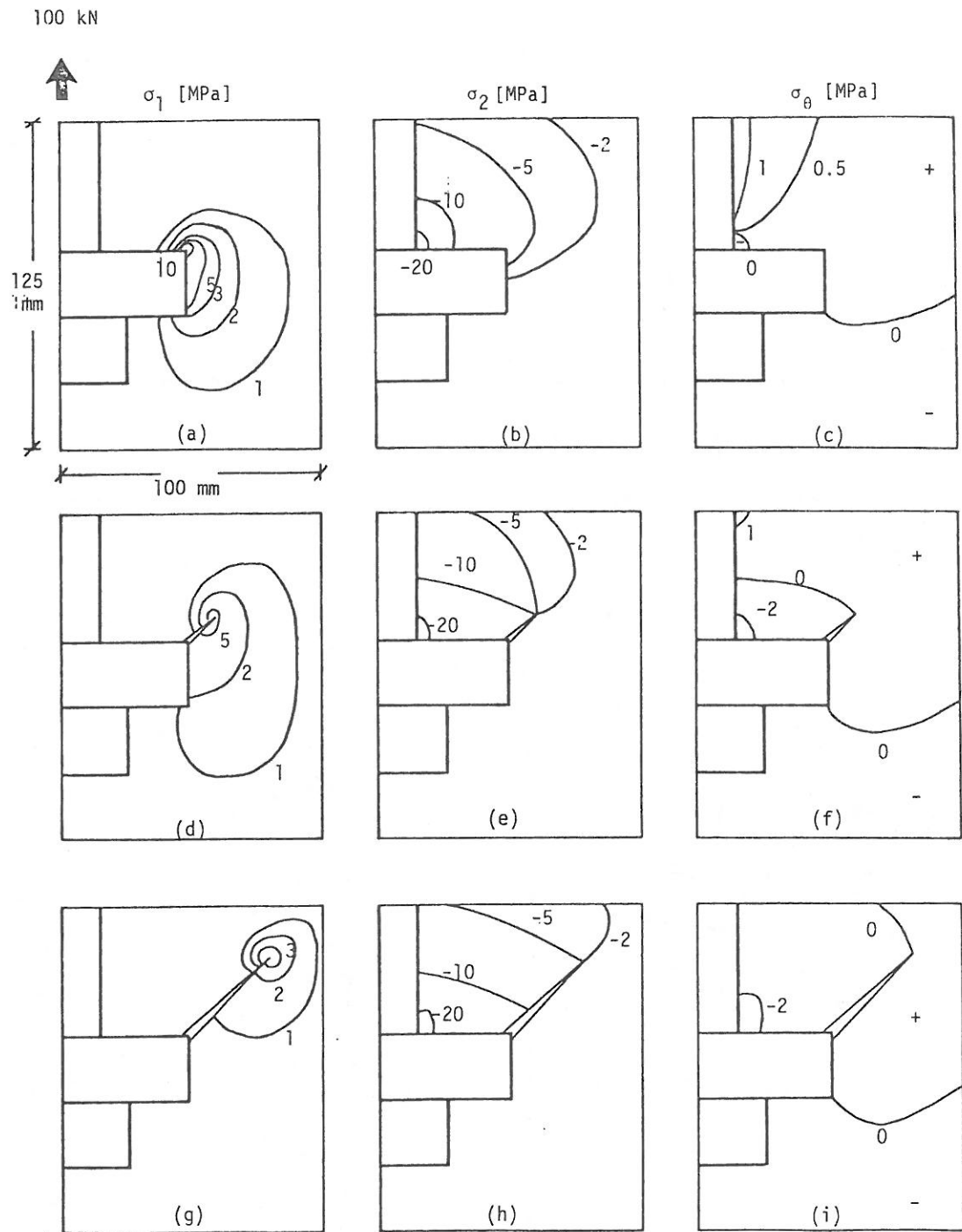


Fig 2.5 Plots of isostress curves for the principal stresses of the finite element model in Fig 2.4

(a), (b), (c) Stresses σ_1 , σ_2 , and σ_3 for zero crack length

(d), (e), (f) Stresses σ_1 , σ_2 , and σ_3 for a crack of length 14.1 mm

(g), (h), (i) Stresses σ_1 , σ_2 , and σ_3 for a crack of length 42.4 mm

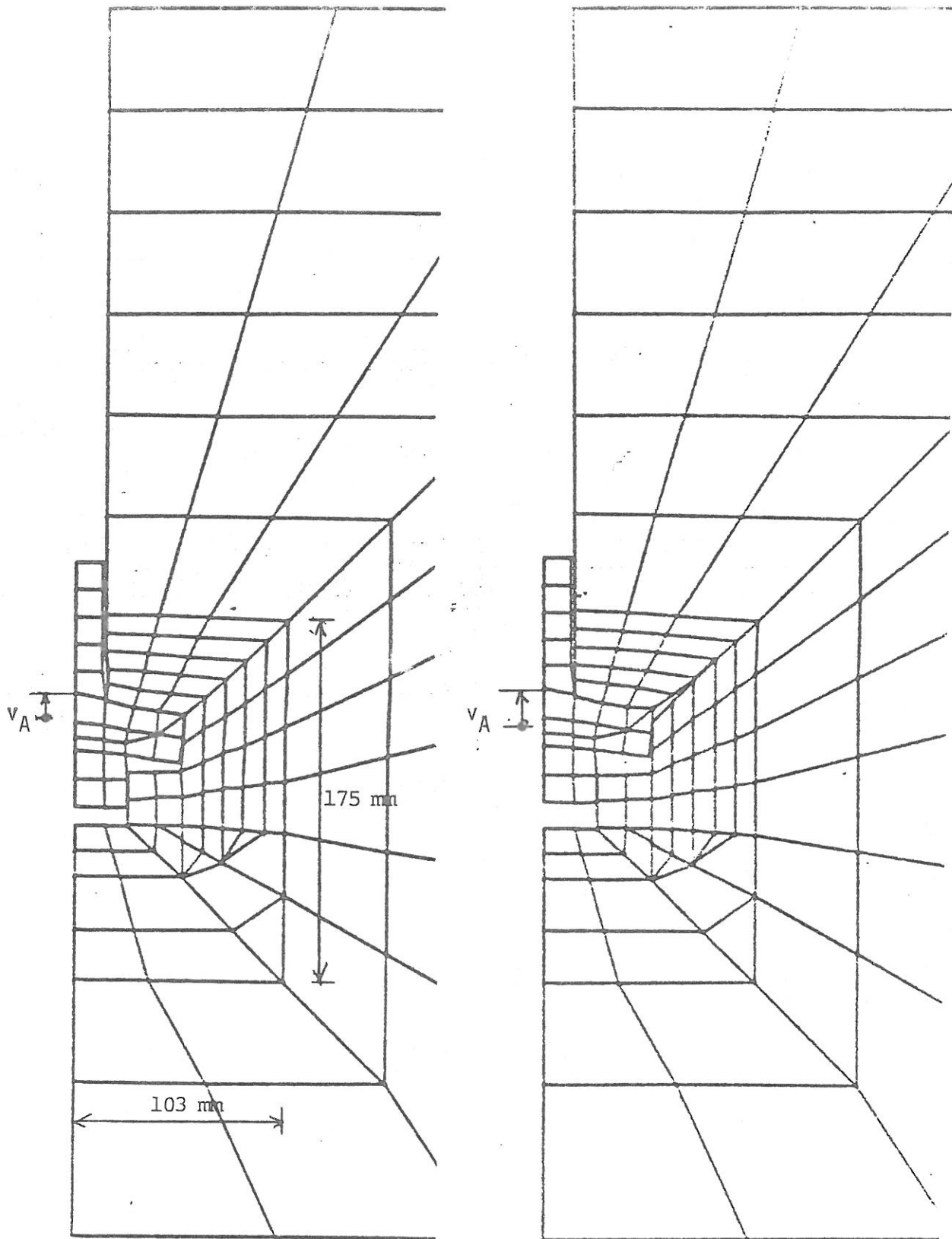


Fig 2.6 Plots of the deformed shape of the area around the anchor bolt for the finite element model in Fig 2.4

(a) No crack ($a_0 = 0$ mm)

(b) Crack length $a_2 = 42.2$ mm

From the plot of the first principle stress σ_1 (Fig 2.5a, d, g) it can be seen that the maximum tensile stress decreases for the given load $F = 100$ kN as the crack length increases. The numerical values of the stresses is to a certain degree dependent on the size and shape of the finite elements, so caution should be exercised when the results are interpreted. However, there is a clear tendency that the applied load must be increased in order to increase the length of the crack.

From the plot of the second principle stress σ_2 (Fig 2.5b, e, h) it can be seen that the maximum concrete stresses do not vary much when the crack propagates. The plot of the tangential stress σ_θ (Fig 2.5c, f, i) shows that the region with tensile stresses moves upwards as the crack propagates.

In Fig 2.6 two plots are shown of the deformed shape of the area around the washer for a load of $F = 100$ kN. In Fig a is visualized the case with no crack ($a_0=0$) and in Fig b is visualized the case with a crack length $a_2 = 42,4$ mm. It can be seen that the bolt is lifted up and that the washer is deformed. It can also be seen that large deformations occur in the concrete just above the top of the washer. In Fig b it can be observed that the crack is quite wide at the root.

In Table 2.1 the displacement v_A is given for a point A (see Fig 2.4) in the middle of the anchor bar and at the same level as the top of the washer. The displacement v_T is also given for a point T (see Fig 2.4) in the top of the anchor bolt. From the table it can be seen how the stiffness of the anchor is reduced with increasing crack length.

Table 2.1 Vertical elastic deflection v in mm for model in Fig 2.4

Deflection v (mm) at load $F = 100$ kN	Length of crack a (mm)		
	0	14.1	42.4
Point A	0.0379	0.0407	0.0438
Point T	0.2737	0.2765	0.2796

2.3 Punching

The anchorage failure of a bolt is related to punching of slabs, see Fig 2.7. There has been many investigations on the punching problem and there is a vast literature on the subject see for example [2-4]-[2-11].

In codes, it is common to use a simplified calculation model for punching. An idealized failure cone is assumed, which is inclined 45° degrees to the horizontal plane. The area A of the cone is, see Fig 2.7

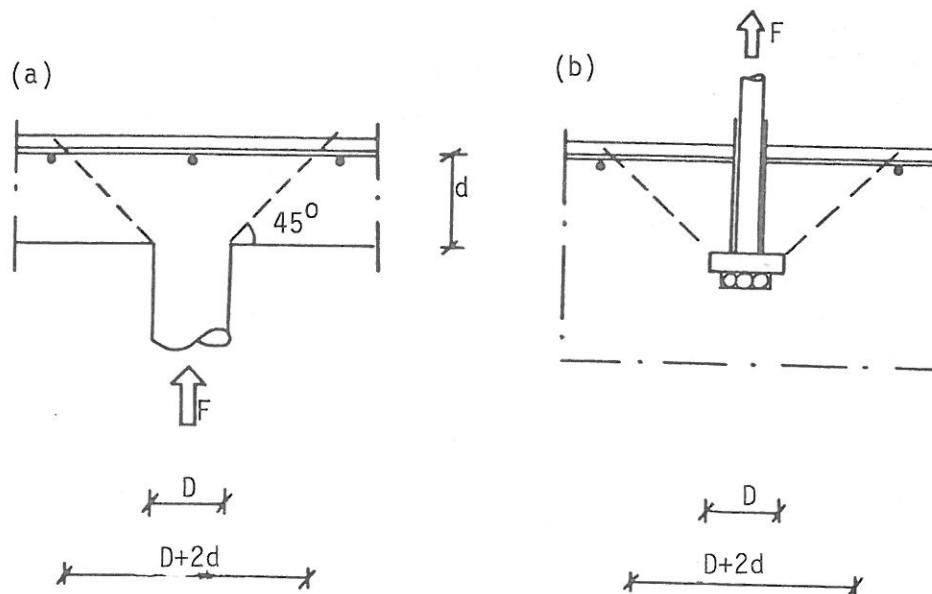


Fig 2.7 Comparison between punching of a slab (fig. a) and failure of an anchor bolt (fig. b). The failure surface is idealized to a cone with an inclination of 45° to the horizontal plane

$$A = \pi \cdot 0,5 (D+D+2d) d\sqrt{2} = \pi (D+d) d\sqrt{2} \quad (2-1)$$

where

D = diameter of column or washer

d = effective depth of slab or foundation

The shear stresses along the cone is often given a constant value f_v at failure. A vertical projection equation then gives

$$F = Af_v/\sqrt{2} = \pi (D+d) d f_v \quad (2-2)$$

In the 1978 CEB-FIP Model Code [2-13] and in the 1979 Swedish Code [2-14] the value of f_v depends on the concrete strength, the depth d , and the amount of reinforcement in the top of the slab.

Analytical models for punching based on the theory of plasticity has recently been presented in 1976-78 by Braestrup - Nielsen [2-8]-[2-10] and in 1980 by Marti [2-11].

2.4 Analogy with thick walled cylinder

For a thick-walled cylinder with the internal pressure p the stresses can be illustrated as in Fig 2.8.

In the walls there are circumferential tensile stresses σ_t and radial compressive stresses σ_r . The stresses have their maxima at the inner surface of the cylinder. According to the theory of elasticity they can be written as (see e.g. Timoshenko [2-15], p 236 or Hellan [2-16], p 56).

$$\sigma_t^{\max} = p \frac{r_0^2 + r_i^2}{r_0^2 - r_i^2} \quad (\text{tensile stress}) \quad (2-3)$$

$$\sigma_r^{\max} = p \quad (\text{compressive stress}) \quad (2-4)$$

When an anchor bolt embedded in concrete is subjected to a tensile force F , stresses are induced in the surrounding concrete. If the bolt is grouted in a recess formed by a conical shell, see Fig 2.9, the surrounding concrete will be subjected to compressive stresses σ and to frictional stresses $\mu\sigma$. The factor μ is the coefficient of friction. If we assume that the stresses are evenly distributed along the surface of the shell, the following equilibrium equation can be written, see Fig 2.9.

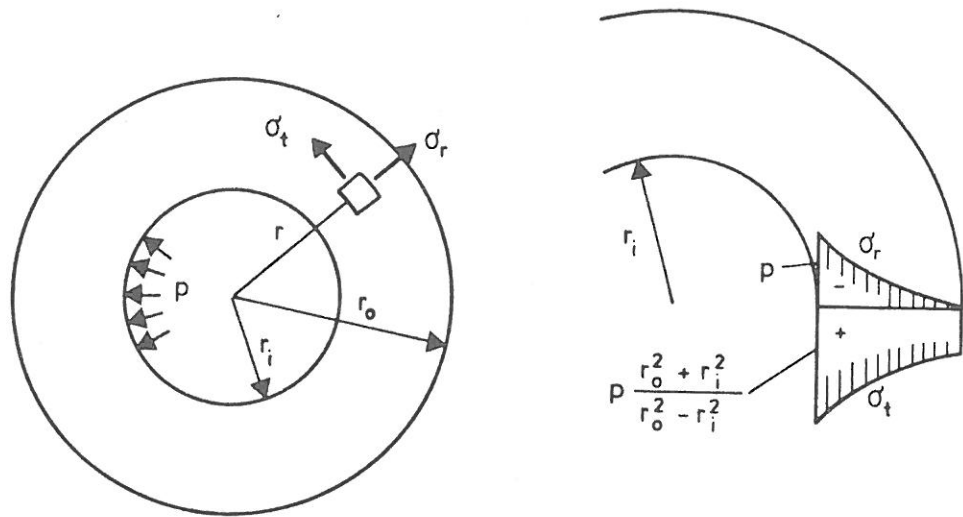


Fig 2.8 Radial and circumferential stresses in thick-walled cylinder

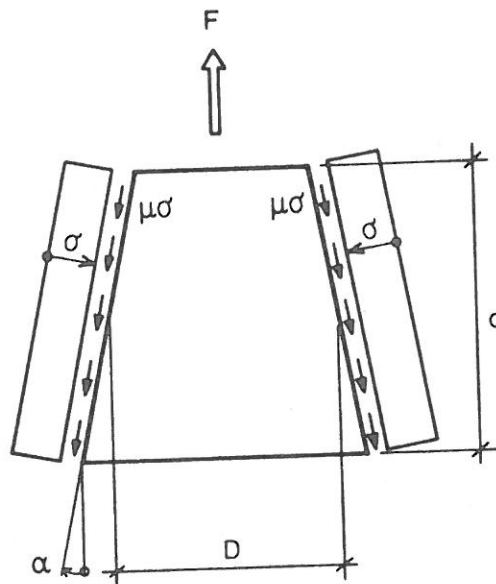


Fig 2.9 The surface of the conical shell is acted on by a contact pressure σ and a friction stress $\mu\sigma$

$$F - \sigma(\sin\alpha + \mu\cos\alpha)\pi D \frac{d}{\cos\alpha} = 0 \quad (2-5)$$

where F = the tensile force in the anchor bolt

σ = the compressive stress on the conical recess shell

α = the inclination of the conical recess shell

μ = the coefficient of friction between the recess shell and concrete

D = the mean diameter of the recess shell

d = the height of the recess shell

From Eq. (2-5) the concrete compressive stress σ can be calculated as

$$\sigma = \frac{F}{\pi D d (\tan\alpha + \mu)} \quad (2-6)$$

In order to use the analogy with the thick-walled cylinder we calculate the horizontal component p of the concrete compressive stress σ and the friction stress $\mu\sigma$, see Fig 2.9.

$$p \, dA - \sigma(\cos\alpha - \mu\sin\alpha) \cdot dA / \cos\alpha = 0$$

$$p = \sigma(1 - \mu\tan\alpha) \quad (2-7)$$

The stress p can now be used as the internal stress acting on a thick walled cylinder. If the concrete tensile strength f_t is inserted in Eq. (2-3), an expression of the internal pressure p required for cracking of the concrete can be obtained,

$$p_{cr} = f_t \frac{r_0^2 - r_i^2}{r_0^2 + r_i^2} \quad (2-8)$$

Using Eqs (2-6) to (2-8) the corresponding tensile force F_{cr} can be obtained

$$\begin{aligned}
 F_{cr} &= f_t \frac{r_0^2 - r_i^2}{r_0^2 + r_i^2} \cdot \frac{1}{1 - \mu \tan \alpha} \pi D d (\tan \alpha + \mu) = \\
 &= f_t \pi D d \frac{\tan \alpha + \mu}{1 - \mu \tan \alpha} \cdot \frac{r_0^2 - r_i^2}{r_0^2 + r_i^2} \quad (2-9)
 \end{aligned}$$

This expression for the cracking load is, of course, of a very approximative nature. The assumption of evenly distributed stresses can also be questioned. However, the equation gives a value which can be used when discussing different test results, see chapter 6.

2.5 Influence of ring reinforcement

When a crack has been formed, the load on the anchor bolt has reached its maximum unless reinforcement or other restraints provide a mean to carry the circumferential tensile forces. If a ring-formed reinforcement is used as indicated in Fig 2.10, the internal pressure p in the thick-walled cylinder can be increased to the value p_y . This corresponds to yielding in the ring reinforcement. If the ring reinforcement has the cross sectional area A and the yield stress f_y the following equation can be written, see Fig 2.10,

$$\begin{aligned}
 2A f_y - p_y \cdot D \cdot d &= 0 \\
 p_y &= 2A f_y \frac{1}{Dd} \quad (2-10)
 \end{aligned}$$

Using Eqs (2-7) and (2-6) the corresponding tensile force F_y can be obtained as

$$\begin{aligned}
 F_y &= 2A f_y \frac{1}{Dd(1 - \mu \tan \alpha)} \pi D d (\tan \alpha + \mu) = \\
 &= f_y \pi 2A \frac{\tan \alpha + \mu}{1 - \mu \tan \alpha} \quad (2-11)
 \end{aligned}$$

This equation is also of an approximative nature. It is assumed that the ring reinforcement will reach its yield point before other types of failure occur. Specifically it is important that the vertical forces along the cone can be anchored in the foundation.

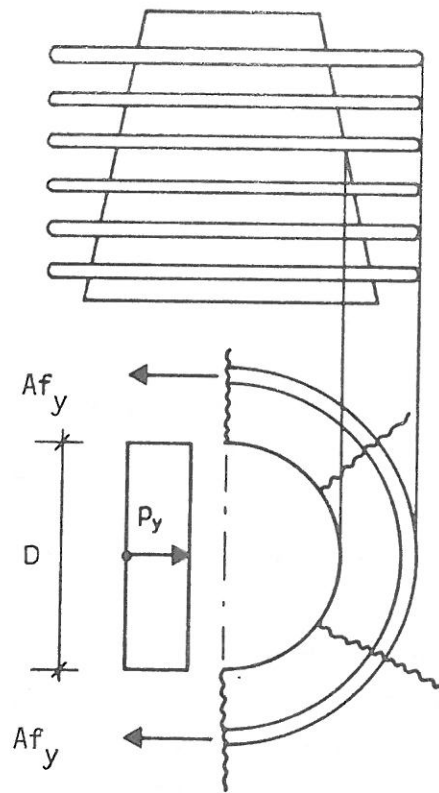


Fig 2.10 Ring reinforcement resisting the concrete pressure in the cone after formation of radial cracks

3 TEST PROGRAM

3.1 Introduction

The test program is divided into three parts

- (1) Basic static tests performed under short time
- (2) Long-time tests under sustained load to check the influence of creep and shrinkage
- (3) Tests with cyclic loading to test the fatigue properties

In this report, results from the basic static tests are presented.

3.2 Static tests

3.2.1 General

The aim of the static tests was to provide basic information about the general behaviour of the anchor bolts and about the influence of such parameters as

- dimension of anchor bolt and size of washer
- depth of anchor bolt and distance of bolt to the edges of the foundation
- amount of reinforcement in the foundation

The program consisted of tests of conical and cylindrical recesses and of drilled holes.

All anchor bolts were made of quality 8.8 i.e. the minimum ultimate stress R_m is 800 MPa and the ratio between the yield stress $R_{p0.2}$ and the minimum ultimate stress R_m is

$$R_{p0.2}/R_m = 0.8$$

All reinforcement was of quality Ks 400 with a minimum yield stress f_y of 400 MPa.

The concrete was aimed to be of grade C 25 with a compressive strength f_{ck} of 25 MPa.

3.2.2 Drilled holes

The test program consisted of twelve anchor bolts grouted in drilled holes. The main variables in the tests were

- the dimension of the anchor bolt and the size of the washer (bolt M27 with washer $\phi 45 \times 3$ mm or bolt M30 with washer $\phi 52 \times 6$ mm or $\phi 105 \times 24$ mm).
- the depth of the drilled hole (200 or 400 mm)
- the distance of the anchor bolt to the edge of the foundation (150 or 300 mm)
- the amount of reinforcement in the foundation ($\phi 10 \# 200$ mm or $\phi 10 \# 100$ mm)

The tests were carried out on three reinforced concrete foundations SD 1, SD 2, and SD 3 (Static Drilled hole tests). Each foundation had four holes SD 1:1, SD 1:2, SD 1:3, and SD 1:4 etc. The anchor bolt arrangement is illustrated in Fig 3.1 and an outline of the variables is given in Table 3.1.

The reinforcement in the foundations is illustrated in Figs 3.3 and 3.4. Photos of the reinforcement cage are shown in Fig 3.7.

3.2.3 Conical and cylindrical recesses

The test program consisted of sixteen anchor bolts with conical or cylindrical recesses. The main variables in the tests were:

- the dimension of the anchor bolt and the size of the washer (bolt M27 with washer $\phi 45 \times 3$ mm or bolt M30 with washer $\phi 52 \times 6$ mm or $\phi 105 \times 24$ mm).
- the diameter and the depth of the recess (cone $\phi 120/170$ mm with 200 mm depth, cone $\phi 120/200$ mm with 250 mm depth, or corrugated cylinder $\phi 150$ mm with 250 mm depth)
- the distance of the anchor bolt to the edge of the foundation (150, 160, or 300 mm).
- the amount of spiral reinforcement and the length of the anchorage hoops (with or without 4 turns of $\phi 10$ spiral reinforcement and with anchorage hoops of 0, 200, 300, 500, or 550 mm depth).

The tests were carried out on six reinforced concrete foundations SW 1- SW 3 and SC 1 - SC 3 (Static Washer size tests and Static Cone tests). Each foundation had four recesses SW 1:1, SW 1:2 etc. The anchor bolt arrangement is illustrated in Fig 3.2 and an outline of the variables is given in Table 3.2.

The reinforcement in the foundations is illustrated in Figs. 3.5 and 3.6. Photos of the reinforcement are shown in Figs. 3.8 and 3.9.

The testing of foundation SC2 was carried out by as a diploma work by Thomas Hedlund [3-1].

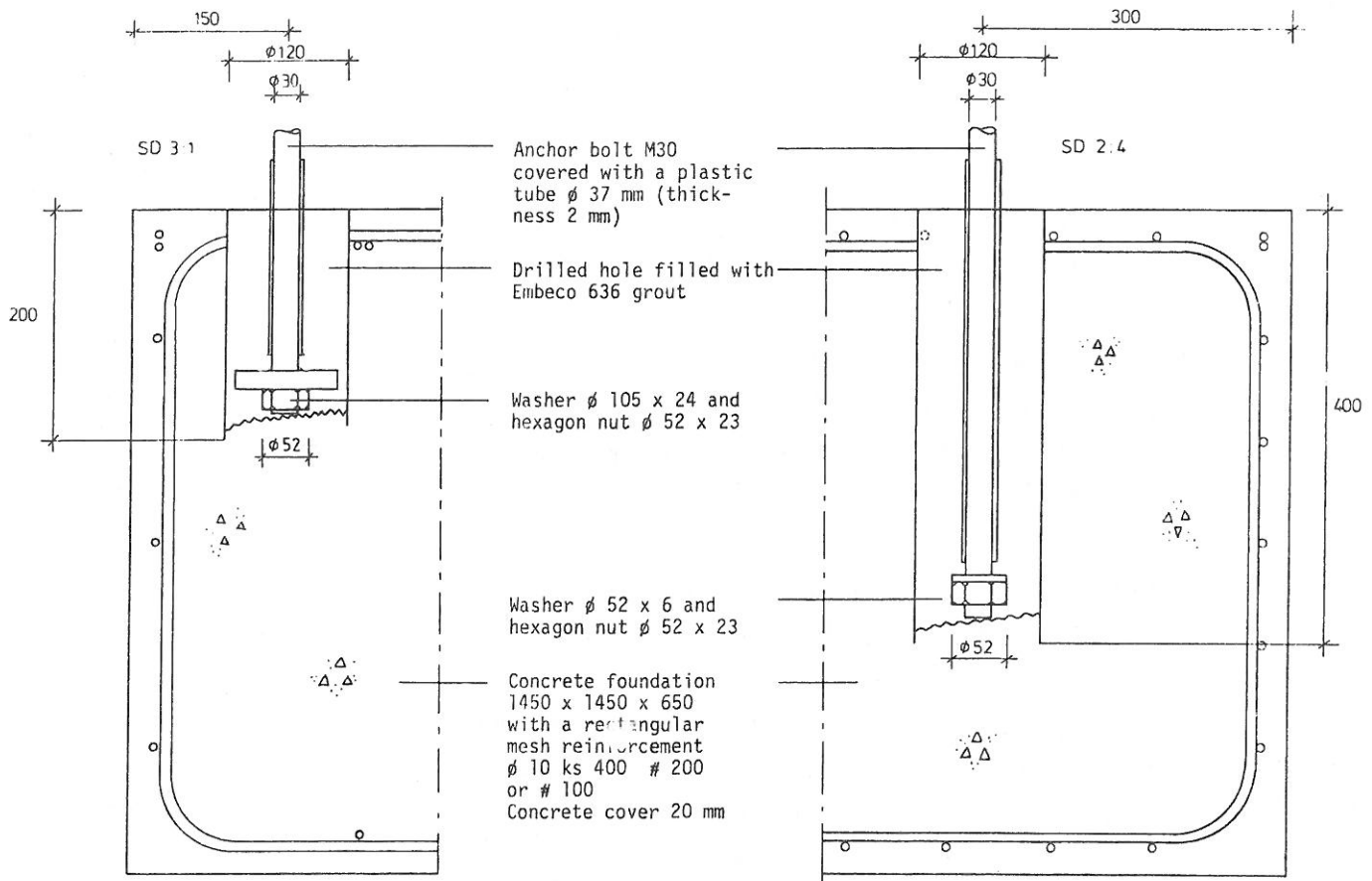
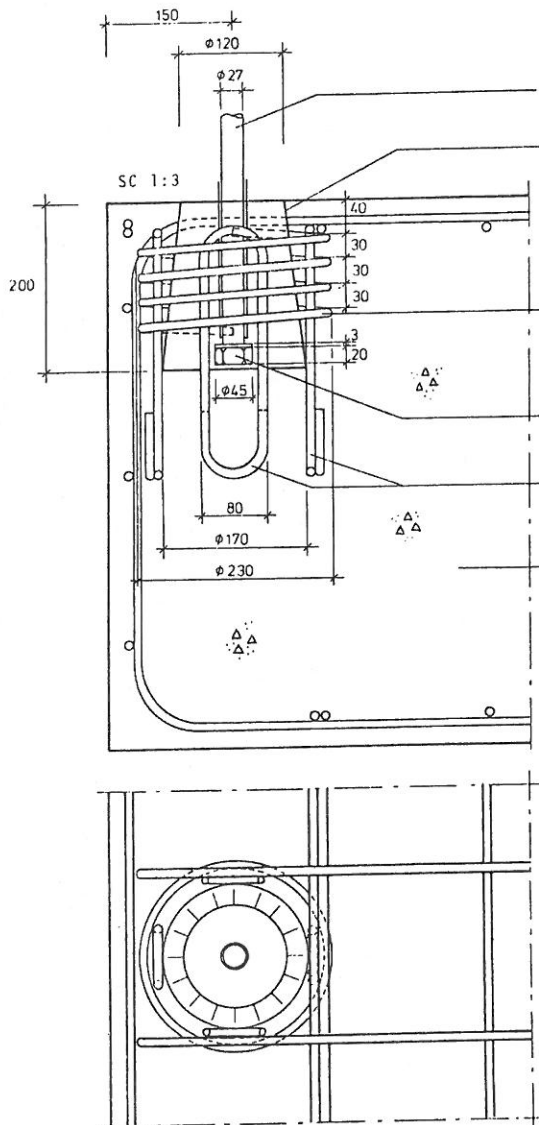


Fig 3.1 Anchor bolt arrangement in static tests of drilled holes No SD 3:1 and SD 2:4



Anchor bolt M27 or M30 covered with a plastic tube $\phi 32$ (M27) or $\phi 37$ (M30) of 2 mm thickness

Conical shell of 0.5 or 1.0 mm steel filled with Embeco 636 grout

Spiral reinforcement $\phi 10$ Ks 400 with inner radius 105 or 125 mm

Washer $\phi 45 \times 3$ or $\phi 105 \times 24$ and hexagon nut $\phi 45 \times 20$ or $\phi 52 \times 23$

Vertical anchorage hoops $\phi 10$ or $\phi 12$ Ks 400 tied to spiral reinforcement

Concrete foundation 1300 x 1300 x 650 or 1450 x 1450 x 650 with a rectangular mesh reinforcement $\phi 10$ Ks 400 # 200. Concrete cover 20 mm

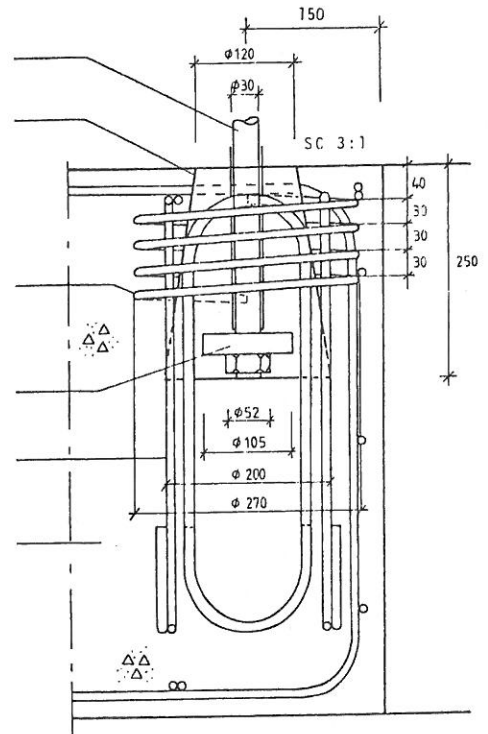


Fig 3.2 Anchor bolt arrangement in static tests on cones

Table 3.1 Outline of tests with drilled holes

Test No	Anchor bolt dimension	Washer size	Hole diameter	Hole depth	Distance to edge of foundation	Foundation reinforcement mesh
	mm	mm	mm	mm	mm	mm
SD 1:1	$\phi 27$	$\phi 45 \times 3$	$\phi 120$	200	150	$\phi 10 \# 200$
1:2	"	"	"	"	300	"
1:3	"	"	"	400	150	"
1:4	"	"	"	"	300	"
SD 2:1	$\phi 27$	$\phi 45 \times 3$	$\phi 120$	200	150	$\phi 10 \# 100$
2:2	"	"	"	"	300	"
2:3	$\phi 30$	$\phi 52 \times 6$	"	400	150	"
2:4	"	"	"	"	300	"
SD 3:1	$\phi 30$	$\phi 105 \times 24$	$\phi 120$	200	150	$\phi 10 \# 200$
3:2	"	"	"	"	300	"
3:3	"	"	"	400	150	"
3:4	"	"	"	"	300	"

Table 3.2 Outline of tests with conical and cylindrical recesses

Test No	Anchor bolt dimension	Washer size	Recess diameter	Recess depth	Anchorage hoop		Notes
					Dimension	Depth	
	mm	mm	mm	mm	mm	mm	
SW 1:1	$\phi 30$	$\phi 52 \times 6$	$\phi 120/170$	200	-	-	
2:1	"	$\phi 75 \times 12$	"	"	-	-	
3:1	"	$\phi 105 \times 24$	"	"	-	-	
3:2	"	"	"	"	-	-	
SC 1:1	$\phi 27$	$\phi 45 \times 3$	$\phi 120/170$	200	$\phi 10$	0	
1:2	"	"	"	"	"	200	
1:3	"	"	"	"	"	300	
1:4	"	"	"	"	"	500	(a)
SC 2:1	$\phi 30$	$\phi 52 \times 6$	$\phi 120/200$	250	$\phi 12$	550	
2:2	"	"	"	"	"	"	(b)
2:3	"	"	"	"	"	"	(a)
2:4	"	"	$\phi 150$	"	"	"	(c)
SC 3:1	$\phi 30$	$\phi 105 \times 24$	$\phi 120/200$	250	$\phi 12$	550	
3:2	"	"	"	"	"	"	(d)
3:3	"	"	"	"	"	"	(d)
3:4	"	"	$\phi 150$	"	"	"	(e)

Notes

- (a) Prestressed bolt
- (b) No spiral reinforcement. All other bolts have spiral reinforcement of four turns of $\phi 10$ Ks40
- (c) Cylindrical recess made of steel
- (d) Distance to edge of foundation is 300 mm (150 mm in the other tests in series and in SC1; 160 mm in series SC2)
- (e) Cylindrical recess made of plastic

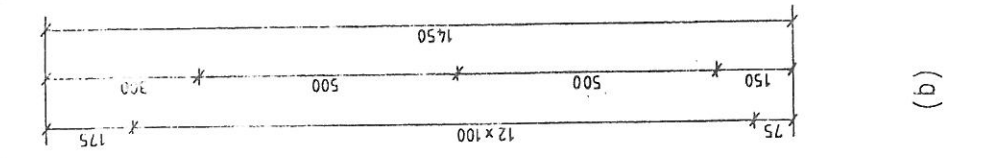
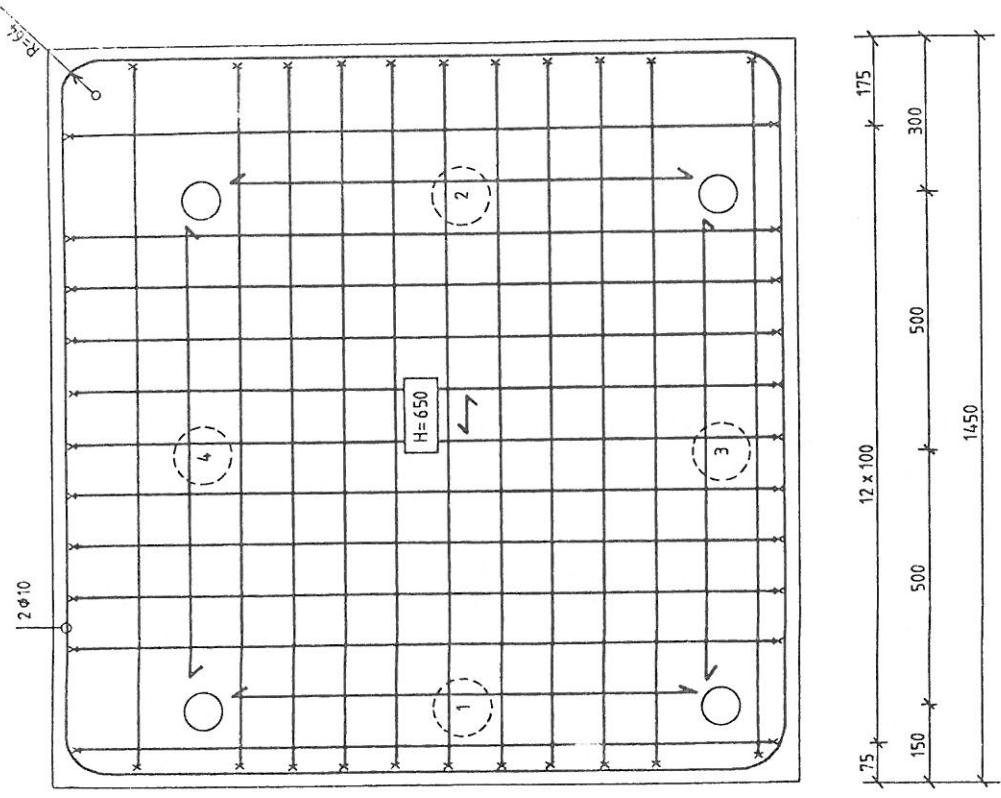


Fig 3.3 Reinforcement arrangement for foundation SD 1 and SD 3 in fig (a) and for SD 2 in fig (b). Reinforcement mesh of $\phi 10$ Ks 400 # 200 in fig (a) and # 100 in fig (b)

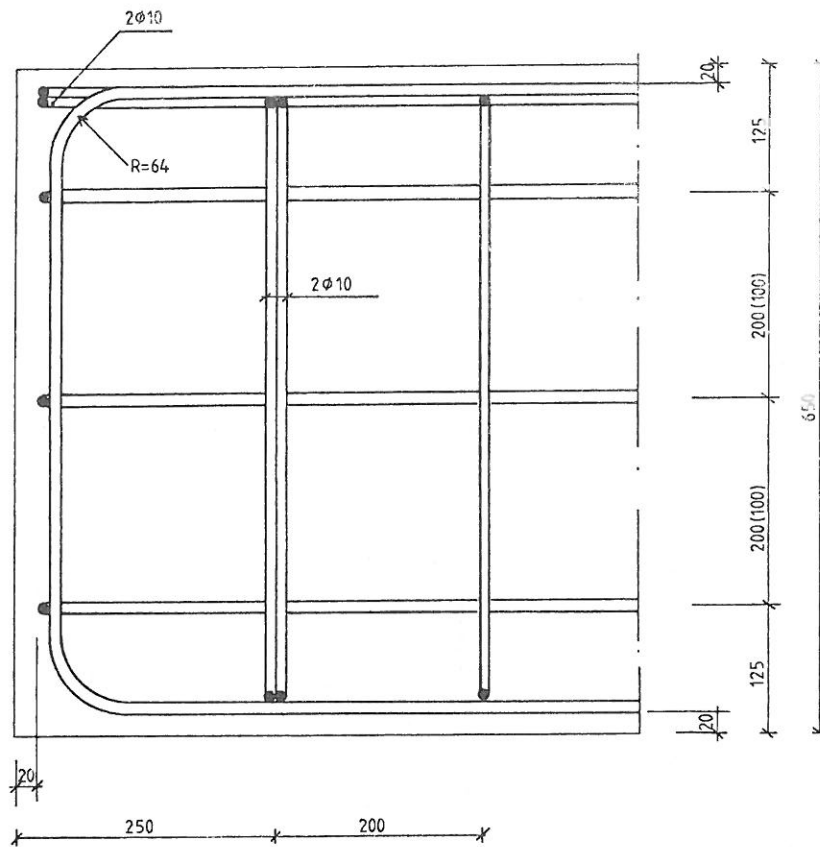


Fig 3.4 Detail of the reinforcement arrangement in the vertical sides of the foundations

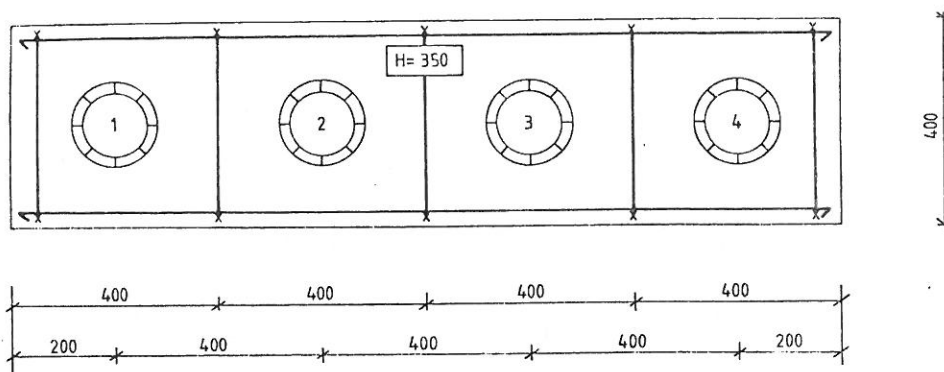

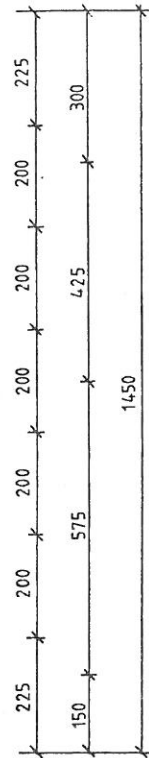
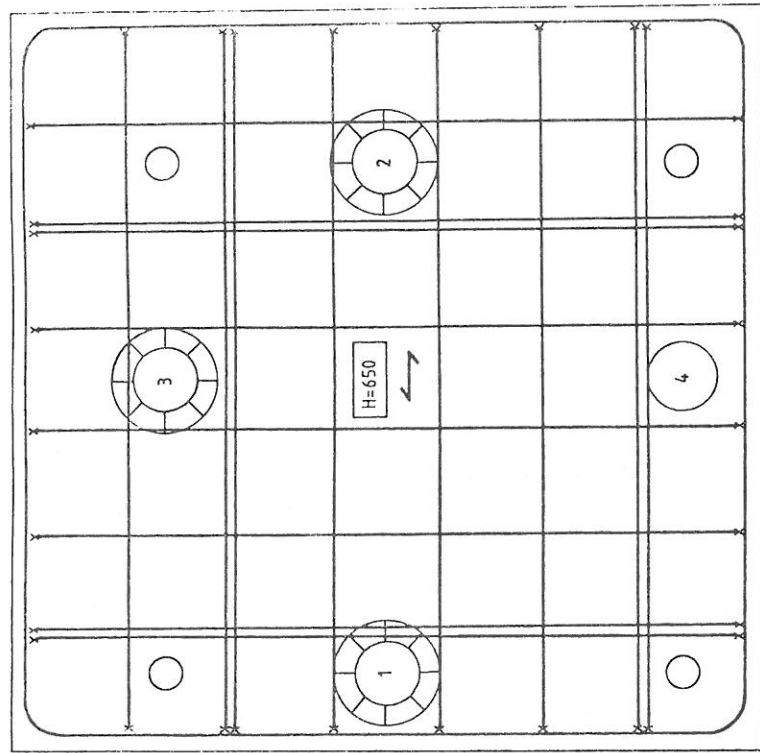
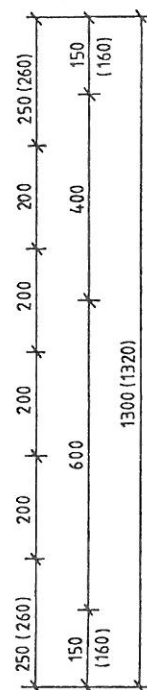
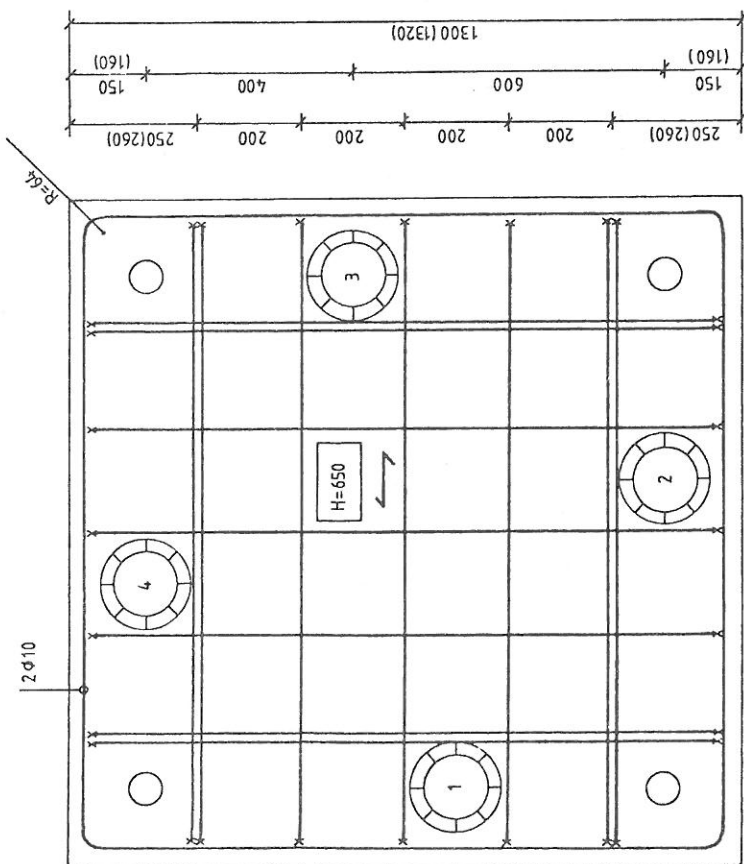


Fig 3.5 Reinforcement arrangement for foundation SW1 - SW4. Horizontal reinforcement of $\phi 10$ Ks 400. Stirrups of $\phi 6$ Ss 220. Conical recesses with top diameter $\phi 120$ mm and bottom diameter $\phi 170$ mm surrounded by spiral reinforcement $\phi 10$ Ks 400 with radius 105 mm



Cylindrical recess with diameter ϕ 150 mm



Plastic pipe \varnothing 70 mm surrounded by spiral reinforcement \varnothing 10 Ks 400 with inner radius 120 mm. The foundation was here fastened to the floor, see section 3.3

Conical recess with top diameter ϕ 120 mm and bottom diameter ϕ 170 mm (ϕ 200 mm)

Fig 3.6 Reinforcement arrangement for foundation SC 1 and SC 2 (in brackets) in fig (a) and for SC 3 in fig (b). Reinforcement mesh of $\phi 10$ Ks 400 # 200



Fig 3.7 Reinforcement for foundation SD 2

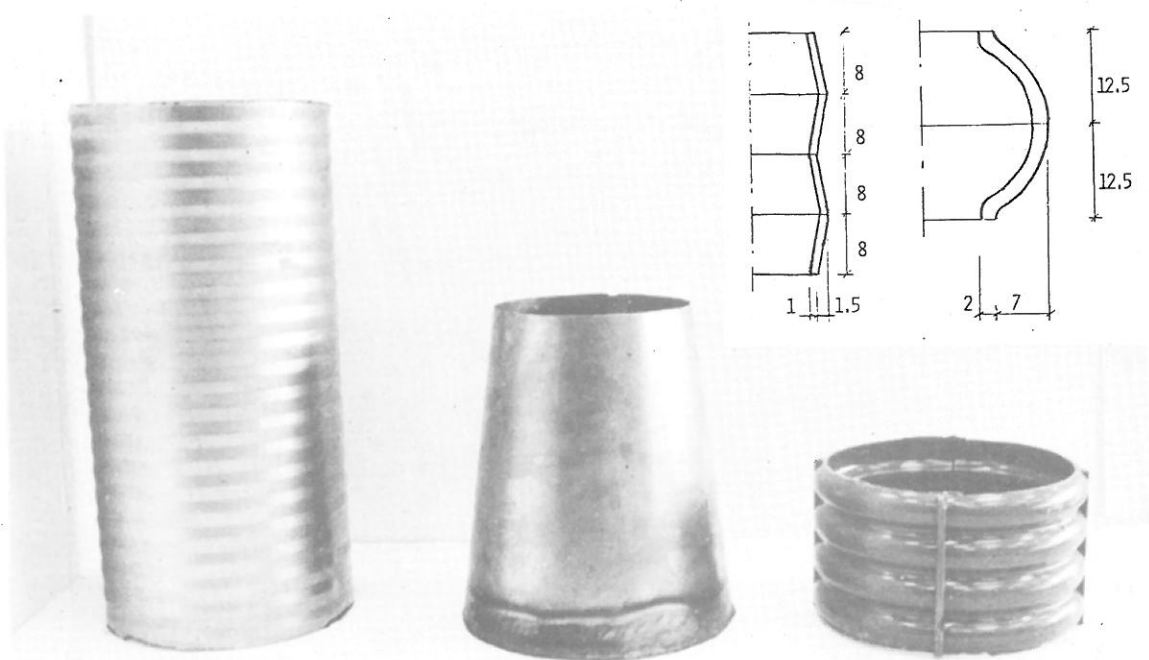


Fig 3.8 Cylindrical and conical recesses. From left to right: Sample of corrugated steel cylinder used for bolt SC 2:4; conical recess used in foundations SC 2 and SC 3; sample of corrugated plastic cylinder used for bolt SC 3:4

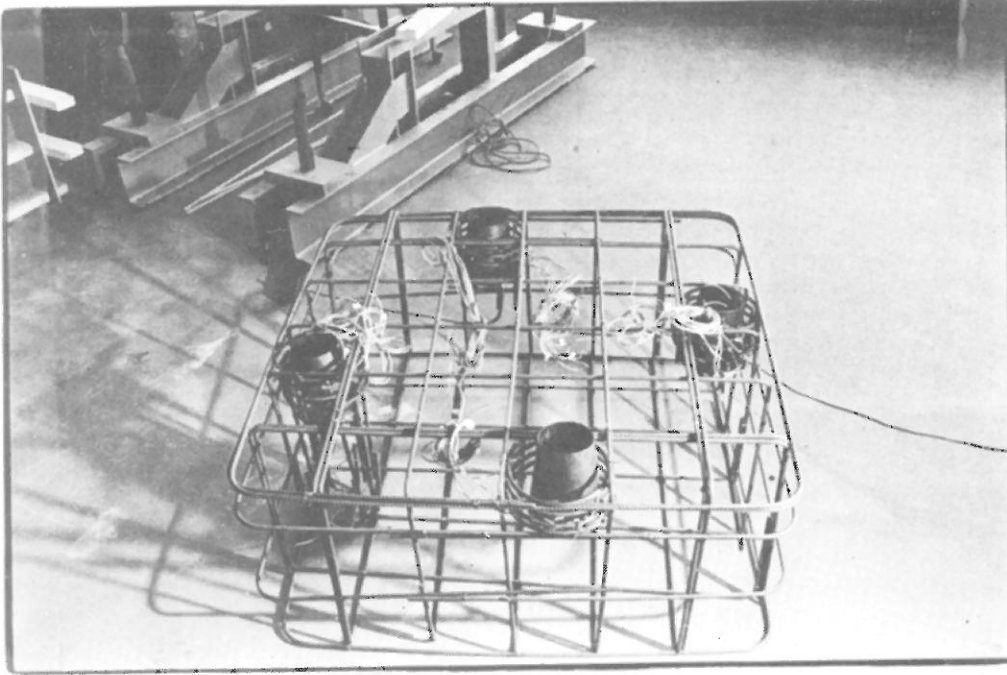


Fig 3.9 Reinforcement for foundation SC 1

3.3 Test Procedure

The tests were carried out in the laboratories of the Division of Structural Engineering at the University of Luleå during 1979 and 1980.

A general view of the test set-up is given in Fig 3.10.

The foundations were bolted to the floor of the Structural Laboratory and the load was applied with a 280 kN or a 1000 kN INSTRON servohydraulic actuator [3-2]. The tests were run in position control. Position control means that the position is controlled for the hydraulic piston connected to the bolt head. This position was changed with a constant velocity during the tests. The time to load one anchor bolt to failure was about two hours. The displacement rate for the anchor head was typically $2.5 \cdot 10^{-6}$ m/sec \approx 9 mm/hour in the beginning of a test (corresponding to a loading rate of approximately 3 kN/minute). At the end of a test the velocity was increased up to $25 \cdot 10^{-6}$ m/sec \approx 90 mm/h (\approx 0.3 kN/min) as the stiffness of bolt was decreasing.

The displacement of the anchor head was recorded with one or two linear potentiometers (Shaevitz Engineering Pennsauken, New Jersey, Type GCD-121-1000) with a maximum error of ± 0.03 mm. The load was recorded with a dynamic load cell (Instron, Type 2513-501 and 2513-511) with a maximum error less than $\pm 1\%$.

Besides the displacement of the anchor head and the load acting on it, other measurements were taken as well, see Fig 3.11. The vertical displacement of the top of the foundation was registered with the same kind of linear potentiometer as the anchor head deflection. Sometimes, the horizontal displacement of the foundation wall was also measured. There were also strain gages mounted close to the bottom of the anchor bolt as well as on various places on the reinforcement cage. The strain gages had a length of 6 mm and a resistance of $120.0 \pm 0.2\%$ (Hottinger Baldwin Messtechnik GmbH, Type 6/120 LY 51).

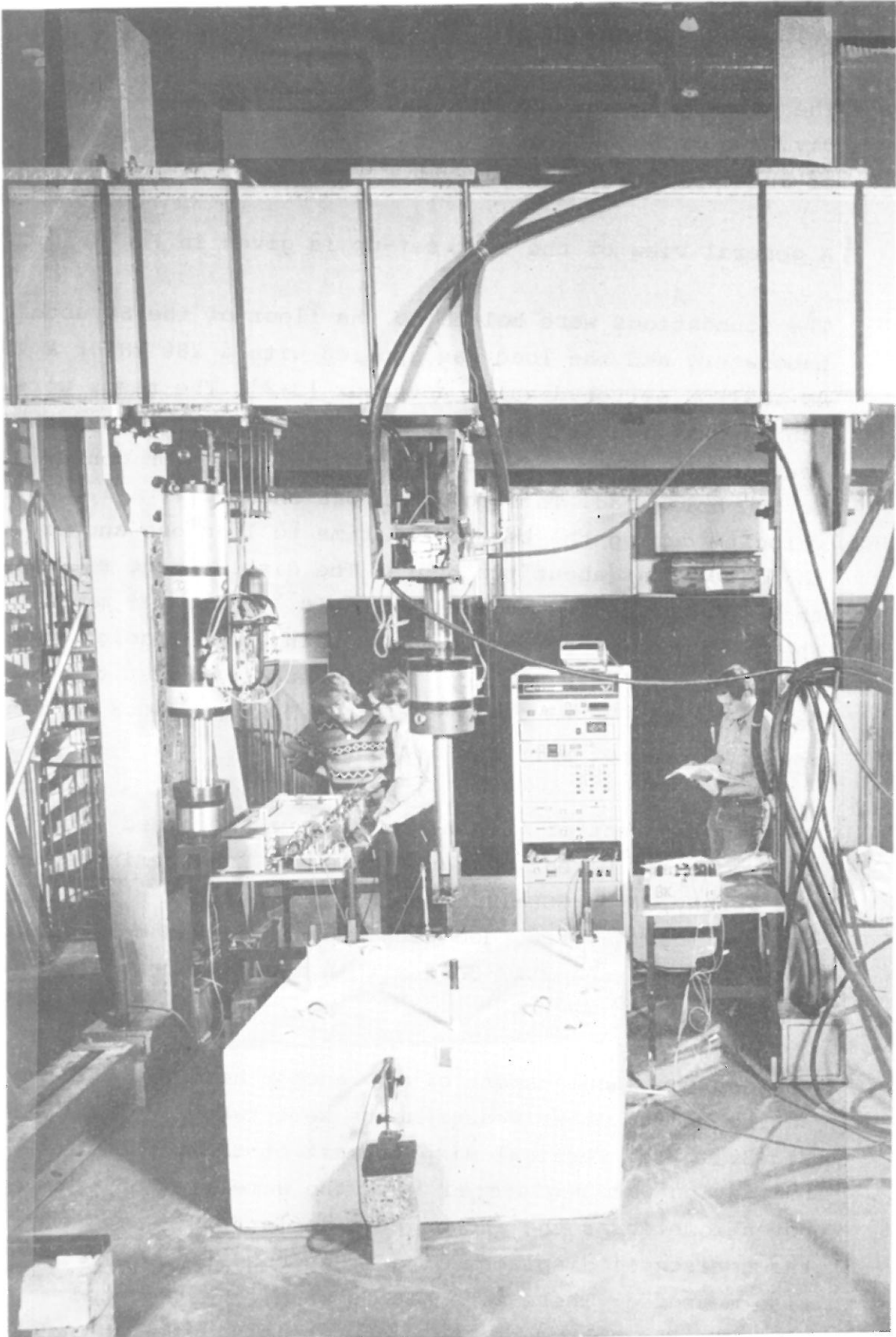


Fig 3.10 General view of test set-up

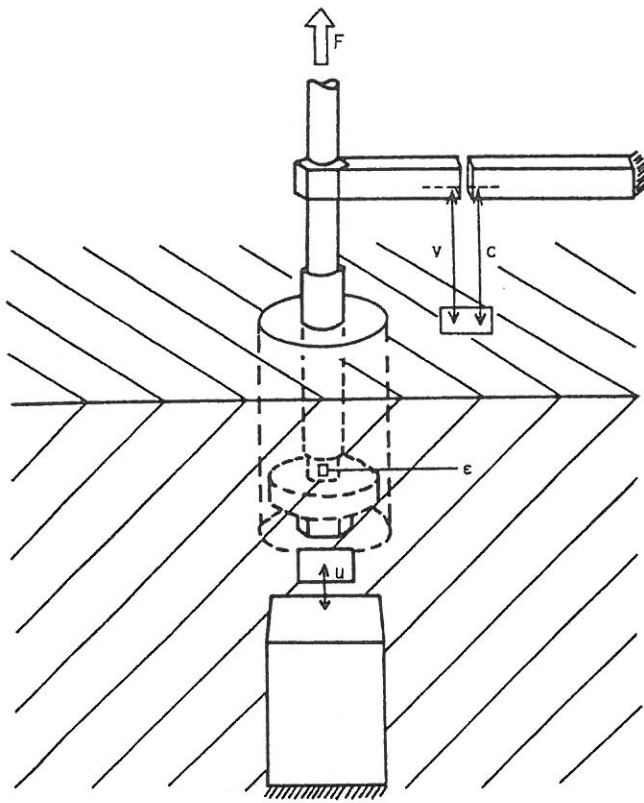


Fig 3.11 Standard measurements. F = applied anchor load, v = anchor head displacement relative to concrete foundation, c = vertical displacement of concrete foundation, u = horizontal displacement of concrete foundation, and ϵ = strain in anchor bolt

4. MATERIAL PROPERTIES

4.1 Concrete

The concrete for the foundations was provided by a local factory (Kallax Betong och Grus AB). It was made of standard portland cement, local sand and gravel with 16 mm maximum diameter. The concrete was proportioned for grade C 25 and it had a semi-fluid consistency. For every foundation three or six cubes were cast. (150 x 150 x 150 mm). Plastic coated plywood forms were used for the foundations and steel moulds for the cubes. The concrete was vibrated in the forms and outside the forms with a vibrating rod of 4.5 cm diameter and with a frequency of about 165 periods per second.

The beams and cubes were stripped after 2 - 5 days and were then kept under wet blankets for another five days. From then on they were stored in the laboratory until testing. The average temperature was 18°C and the average relative humidity 40 to 60%. Date of testing, age of foundation and age of grout are summarized in Table 4.1.

One to three of the test cubes from every foundation were used to determine the tensile strength f_t with the split-cube test [4-1]. All cubes from the foundation were then tested in compression to determine the compressive strength f_c [4-2], [4-3]. The concrete strength properties are summarized in Table 4.2.

4.2 Grout

The grout used in the casting of the conical recesses and in the drilled holes was EMBECO 636 GROUT, a shrinkage compensated grout manufactured by Master Builders. The dry powder was mixed with 4.5 litres of water per 25 kg in a Sandby 75 litres mixer for about three minutes before placing in saturated bolt

Table 4.1 Date of testing
Age of concrete and grout

Anchor Bolt No	Testing Year Month Date	Age of foundation	Age of grout
		Days	Days
SD 1:1	790410	41	5
	1:2 790427	58	4
	1:3 790423	54	4
	1:4 790424	55	5
SD 2:1	790517	78	3
	2:2 790518	79	3
	2:3 790607	99	9
	2:3A 790926	210	6
	2:4 790607	99	9
	2:4A 790926	210	6
SD 3:1	800111	207	4
	3:2 800414	301	26
	3:3 800213	240	8
	3:3A 800926	466	234
	3:4 800925	465	105
SW 1:1	791221	170	9
	2:1 791221	170	9
	3:1 791221	170	9
	3:2 800102	182	21
SC 1:1	790502	47	5
	1:2 790508	53	11
	1:3 790509	54	12
	1:4 790516	61	19
SC 2:1	791003	37	13
	2:2 791003	37	13
	2:3 791010	44	20
	2:4 791004	38	14
SC 3:1	800513	43	18
	3:2 800509	39	14
	3:3 801003	186	161
	3:4 800512	42	17

Table 4.2 Strength of concrete

Founda- tion No	Casting Date	Age at testing Days	Compressive strength				Tensile strength			
			Cube No			Mean value	Cube No			Mean value
			1	2	3		1	2	3	
			MPa	MPa	MPa	MPa	MPa	MPa	MPa	MPa
SD 1-2	790228	41	30.2	31.1	31.3	30.9	2.6	2.6	2.6	2.6
		82	29.6	33.3	32.6	32.1	2.5	3.3	3.1	3.0
		82	33.3	32.0	32.0		3.3	2.8	2.9	
		468	35.6	34.2	34.9	36.1	2.6	3.2	2.7	2.9
		468	38.0	35.8	37.8		3.1			
SD 3	790618	242	37.8	38.2	37.8	37.4	3.1	3.2	2.5	2.9
SW 1-3	790704	170	37.8	38.2	37.3	37.8	-	-	-	-
		321	35.6	38.0	34.2	36.2	2.6	2.8	2.5	2.6
		321	37.1	37.3						
SC 1	790316	67	37.3	39.6	35.8	37.6	3.9	4.0	4.0	4.0
		452	48.0	48.2	48.4	47.9	3.3	3.5	3.2	3.3
		452	46.7	48.2						
SC 2	790827	28	26.4	26.1	26.0	26.2	-	-	-	-
SC 3	800401	39	36.0	35.1	34.2	35.1	2.7	3.2	3.4	3.1

Table 4.3 Strength of grout

Anchor bolt No	Casting Date	Age at testing Days	Compressive strength					Tensile strength				
			Cube No			Mean value	MPa	Cube No			Mean value	MPa
			1	2	3			1	2	3		
			MPa	MPa	MPa	MPa	MPa	MPa	MPa	MPa	MPa	MPa
SD3:1	800107	4	34.2	-	-	34.2	-	2.9	-	-	2.9	
		37	48	55	-	51.5	-	2.9	3	6	3.3	
SD3:2-3	800205	10	51.6	-	-	51.6	-	2.2	-	-	2.2	
		71	57.8	55.6	55.9	56.7	-	3.0	2.8	-	2.9	
SD3:4	800612	69	53.3	60.9	58.2	57.5	-	2.4	2.5	3.0	2.6	
SC2:1-4	790920	0.5	5.3	-	-	5.3	-	-	-	-	-	
		1	15.3	-	-	15.3	-	-	-	-	-	
		2	29.3	-	-	29.3	-	-	-	-	-	
		5	32.4	33.3	-	32.9	-	-	-	-	-	
		14	44.0	-	-	44.0	-	-	-	-	-	
		28	50.0	-	-	50.0	-	-	-	-	-	
SC3:1,2,4	800425	14	52.2	49.8	51.6	51.2	-	4.0	3.8	4.1	4.0	
		19	54.0	-	-	54.0	-	2.5	-	-	2.5	

holes. Cubes of the grout were tested in the same way as the concrete cubes. Test results are summarized in Table 4.3.

4.3 Reinforcement

All reinforcement steel in the foundations was Swedish deformed bars of type Ks 400. The notation Ks stands for "kamstång" (a bar with vertical ribs, literally a bar with crests). The number after Ks denotes the nominal yield strength in MPa. A typical stress-strain diagram is shown in Fig 4.1 and test values for spiral reinforcement are summarized in Table 4.4. The tests were carried out by Statens Provningsanstalt in Borås in accordance with Swedish Standard SS 11 21 37 [4-4].

Table 4.4 Properties of reinforcement

Dimension	Area	Yield stress	Ultimate stress	Deformation
	S_0	R_{el}	R_m	A_{10}
mm	mm ²	MPa	MPa	%
φ10	91	440	690	20
φ10	91	450	700	21
φ10	91	440	690	20

4.4 Anchor bolts

All anchor bolts were made of quality 8.8 i.e. the minimum ultimate stress R_m is 800 MPa and the ratio between the yield stress $R_{p0.2}$ and the minimum ultimate stress R_m is $R_{p0.2}/R_m = 8$.

One bolt of 30 mm diameter was tested by Statens Provningsanstalt i Borås in accordance with Swedish Standard SS 11 21 13 [4-5]. The bolt diameter was reduced to 20 mm through turning. The following results were obtained.

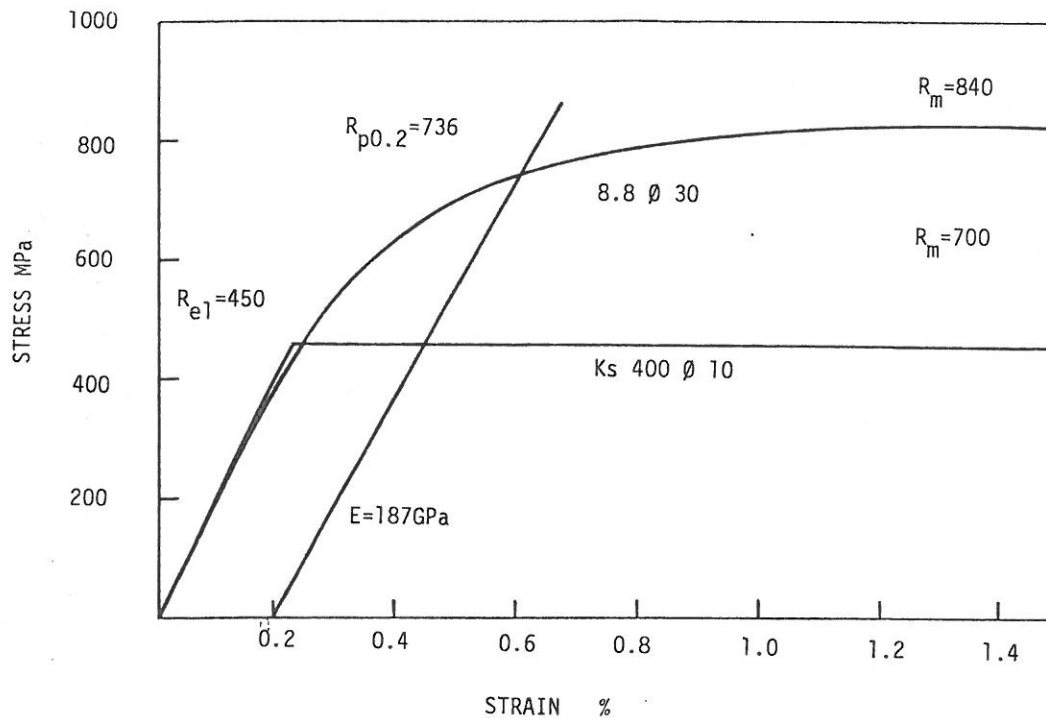


Fig 4.1 Stress-strain curves for reinforcement bar $\phi 10$ Ks 400 and for anchor bolt M30 8.8

Diameter	$d = 20,0 \text{ mm}$
Area	$S_0 = 314 \text{ mm}^2$
Stress to obtain 0,2% rest deformation	$R_{p0.2} = 736 \text{ MPa}$
Ultimate stress	$R_m = 840 \text{ MPa}$
Deformation	$A_5 = 11\%$

The corresponding stress strain diagram is given in Fig 4.1. From the diagram the modulus of elasticity E can be estimated to 187 GPa. Yield forces F_y and ultimate forces F_m for bolts M27 and M30 are given in Table 4.5. The table is based on nominal values and on values obtained in the test by Statens Provninganstalt.

Table 4.5 Yield forces F_y and ultimate forces F_u
for tested anchor bolts

Anchor bolt	M 27	M 30
Stress Area A_s (mm^2)	459	561
<u>Yield force</u> F_y (kN)		
Based on $R_{p0.2} = 640$ MPa	294	359
Based on $R_{p0.2} = 736$ MPa	338	413
<u>Ultimate force</u> F_u (kN)		
Based on the nominal value $R_m = 800$ MPa	367	449
Based on $R_m = 840$ MPa	386	471

4.5 Recesses

The conical recesses were welded together from sheets of steel with a thickness of 0.5 mm (SW and SC 1) or 1.0 mm (SC 2 and SC 3). The stress to obtain 0.2% rest deformation was $R_{p0.2} = 350$ MPa and the ultimate stress was $R_m = 425$ MPa.

5. TEST RESULTS

5.1 General

Two typical load-displacement curves are shown in Fig 5.1. The anchor bolts usually had a stiff behaviour for loads F between 0 - 100 kN. Displacements v of the anchor head relative to the concrete foundation were of the order 1 mm. For loads higher than 100 - 150 kN the bolts gradually started to deform at an increasing rate, indicating cracking of the concrete. The washer size had a marked influence on the stiffness and a larger washer provided a stiffer anchorage.

Ultimate loads for anchors in drilled holes of the depth 200 mm varied between 147 - 206 kN; for holes of the depth 400 mm they varied between 266 - 408 kN. For conical recesses the ultimate load varied between 170 - 254 kN for small washers ($\phi 45 \times 3$) in recesses of 200 mm depth and between 385 - 425 kN for big washers ($\phi 105 \times 24$) in recesses of 250 mm depth. For recesses of corrugated cylinders the ultimate load varied between 307 - 345 kN.

As a comparison it can be mentioned that the nominal yield load F_y is 294 kN for bolt M27 and 359 kN for bolt M30 (see Table 4.5).

The ultimate loads for the tests with drilled holes are summarized in Table 5.1 and the ultimate loads for the tests with conical and cylindrical recesses are summarized in Table 5.2.

Photos of anchorage failures are presented in Fig 5.2 for a drilled hole and in Fig 5.3 for a conical recess. Photos are also presented in Appendix C.

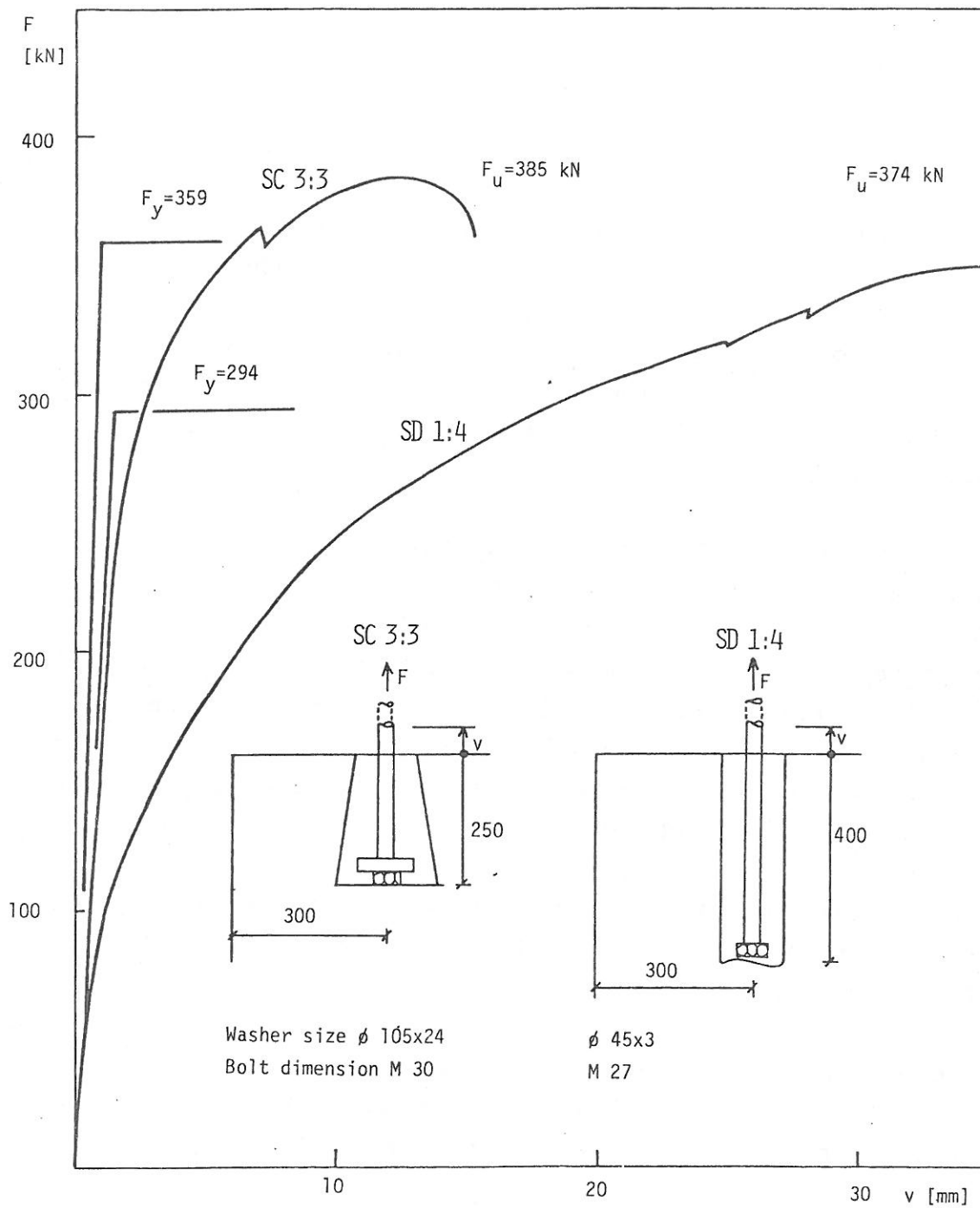


Fig 5.1 Load - displacement diagrams for two anchor bolts

Test series	SD1	SD2	SD3
(1)	(2)	(3)	(4)
Spacing of foundation reinforcement mesh (mm)	200	100	200
<u>Hole depth 200 mm</u>			
Bolt dimension (mm)	M27	M27	M30
Nominal yield force (kN)	294	294	359
Washer size (mm)	φ45x3	φ45x3	φ105x24
Edge distance 150 mm	162 (SD1:1)	185 (SD2:1)	147 (SD3:1)
"- 300 mm	180 (SD1:2)	190 (SD2:2)	206 (SD3:2)
<u>Hole depth 400 mm</u>			
Bolt dimension (mm)	M27	M30	M30
Nominal yield force (kN)	294	359	359
Washer size (mm)	φ45x3	φ52x6	φ105x24
Edge distance 150 mm	266 (SD1:3)	322 (SD2:3A)	344 (SD3:3A)
"- 300 mm	374 (SD1:4)	408 (SD2:4A)	> 400 (SD3:4)

Table 5.1 Ultimate loads (kN) for tests with drilled holes.

Test series	SW	SC1	SC2	SC3
(1)	(2)	(3)	(4)	(5)
Cone diameter (mm)	φ 120/170	φ 120/200	φ 120/200	φ 120/200
Recess depth (mm)	200	200	250	250
Edge distance (mm)	200	150	160	Variable
Bolt dimension (mm)	M 30	M 27	M 30	M 30
Nominal yield force (kN)	359	294	359	359
Washer size (mm)	Variable	φ 45 x 3	φ 52 x 6	φ 105 x 24
Anchorage holes	-	φ 10	φ 12	φ 12
Anchorage length	-	Variable	550	550
	Load Washer size	Load Edge length	Load	Load Edge distance
Bolt No 1	170 φ 52 x 6 (1:1)	235 0	424	418 150 (Failure in nut threads)
2	195 φ 72 x 12 (2:1)	236 200	291 (No spiral reinforcement)	425 300
3	218 φ 105 x 24 (3:1)	247 300	408	385 300
4	223 φ 105 x 24 (3:1)	254 500	307 (Metal cylinder)	345 150 (Plastic cylinder)

Table 5.2 Ultimate loads for tests with conical and cylindrical recesses.

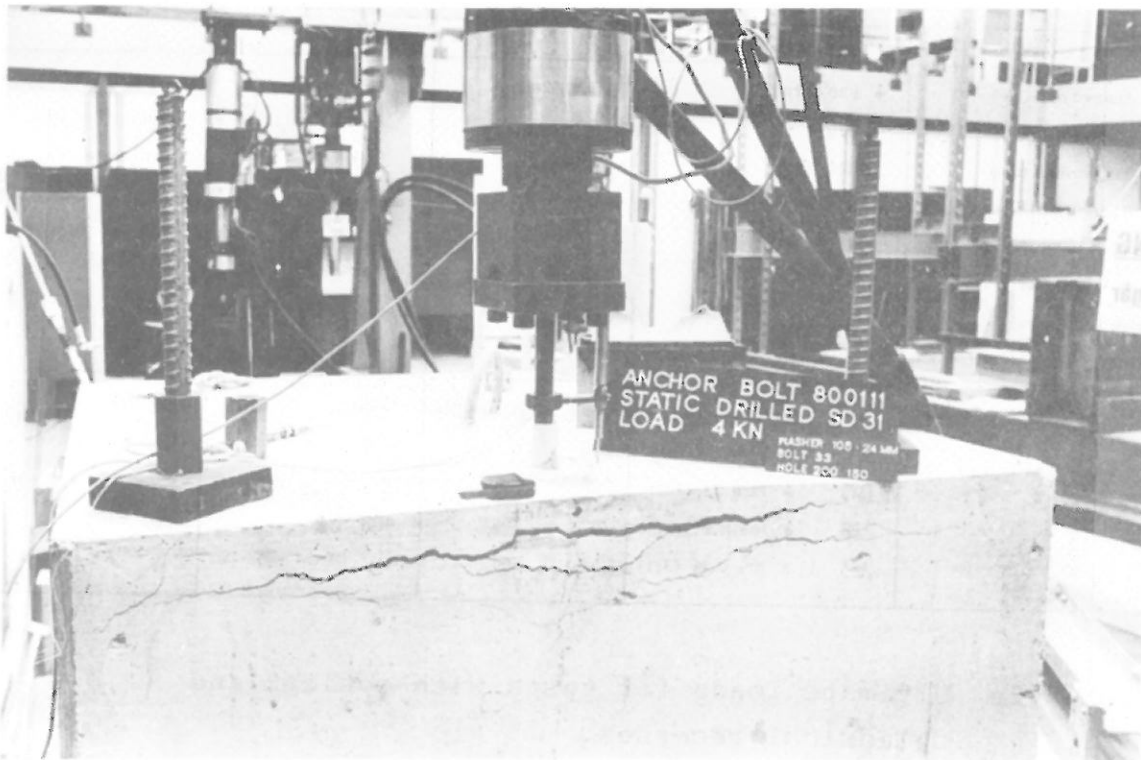
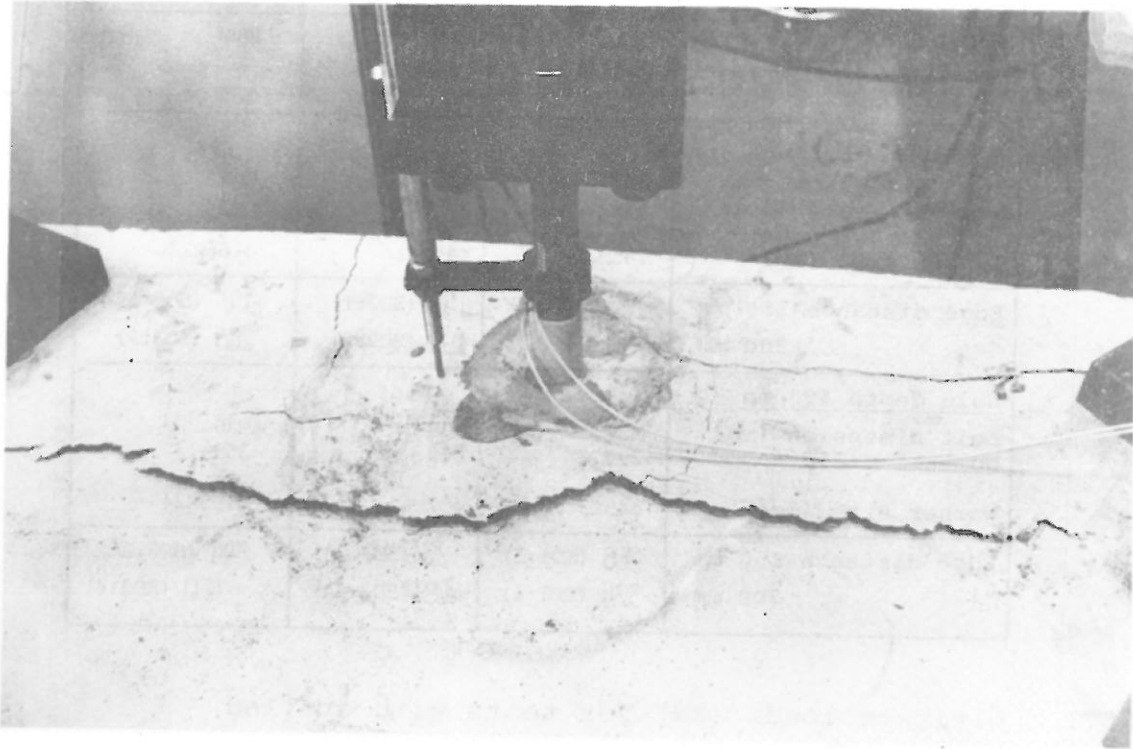


Fig 5.2 Anchor bolt SD 3:1 at failure. Drilled hole with 200 mm depth and 150 mm edge distance. Anchor bolt M30 with washer $\phi 105 \times 24$. Reinforcement $\phi 10$ Ks 400 # 200. Ultimate load 147 kN

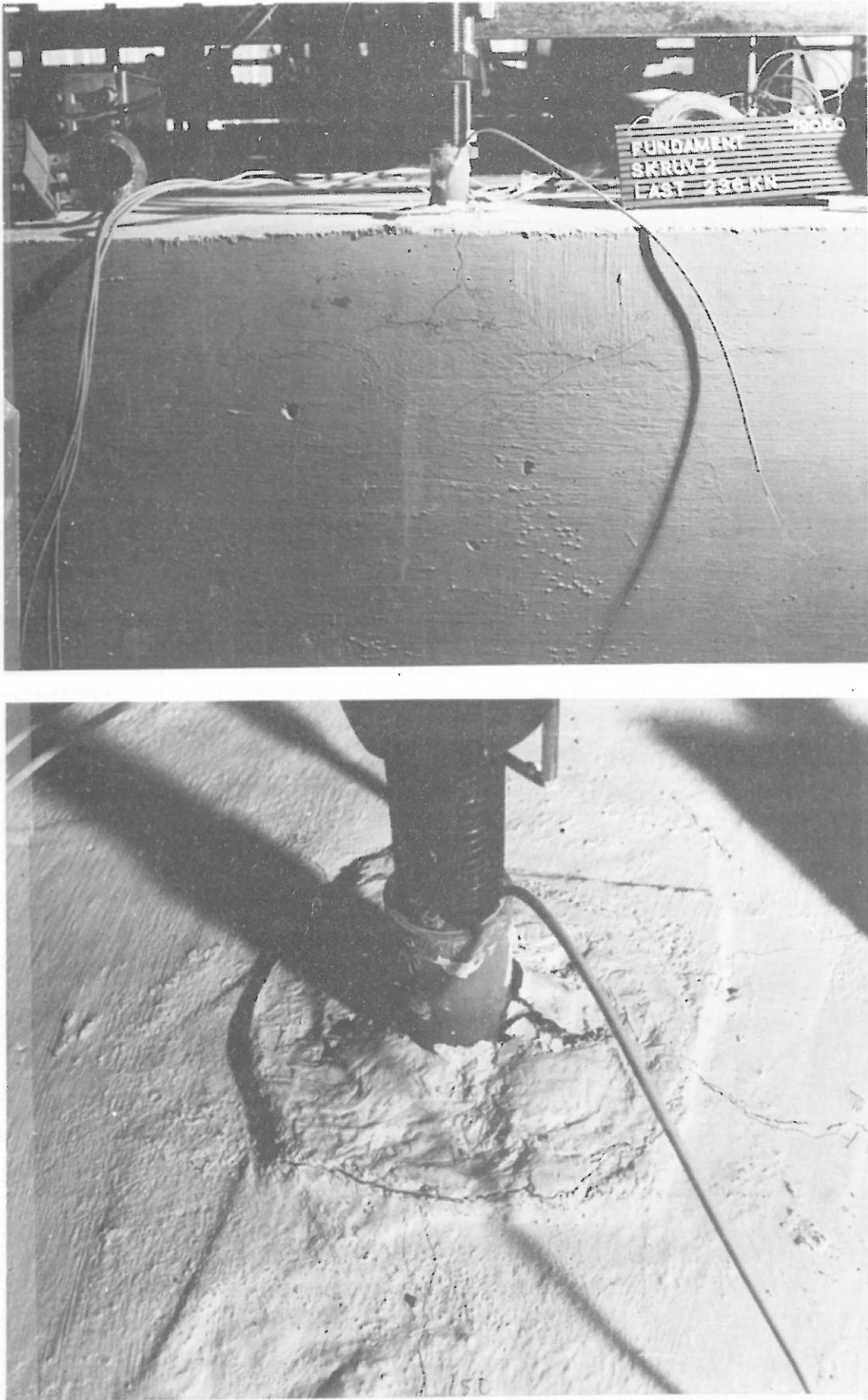


Fig 5.3 Anchor bolt SC 1:2 at failure. Conical recess with 200 mm depth and 150 mm edge distance. Anchor bolt M27 with washer $\phi 45 \times 3$. Reinforcement mesh $\phi 10$ Ks 400 # 200. Ultimate load 236 kN

5.2 Displacement

The displacement v of the anchor head relative to the concrete surface at the top of the foundation is shown in Figs 5.4 and 5.5 for some typical bolts. Detailed information of the deformation of all the tested bolts are given in Appendix B.

Characteristic results from the drilled holes are presented in Fig 5.4. The main variables of the tests were

- the dimension of the anchor bolt and the size of the washer (bolt M27 with washer $\phi 45 \times 3$ mm or bolt M30 with washer $\phi 52 \times 6$ mm or $\phi 105 \times 24$ mm).
- the depth of the drilled hole (200 or 400 mm)
- the distance of the anchor bolt to the edge of the foundation (150 or 300 mm)
- the amount of reinforcement in the foundation ($\phi 10 \# 200$ mm or $\phi 10 \# 100$ mm)

In the right part of the figure six bolts with a hole of small depth ($d = 200$ mm) are shown. It can be seen that the bolts with a large washer (SD 3:1 and 3:2) are stiffer than the bolts with a small washer (SD 1:1, 1:2, 2:1 and 2:2). In foundation SD 2 the reinforcement net had a smaller mesh size ($\#100$ mm) than in foundations SD 1 and SD 3 ($\#200$ mm). This has some influence on the ultimate load, compare SD 1:1 with SD 2:1 and SD 1:2 with SD 2:2. It can also be seen that the ultimate loads are somewhat higher for the edge distance $e = 300$ mm than for the edge distance $e = 150$ mm.

In the left part of Fig 5.4 six bolts with a hole of big depth ($d = 400$ mm) are shown. Here the effect of the washer size on the stiffness is very pronounced, compare SD 2:3A with SD 3:3 and SD 2:4A with SD 3:4. The effect of the

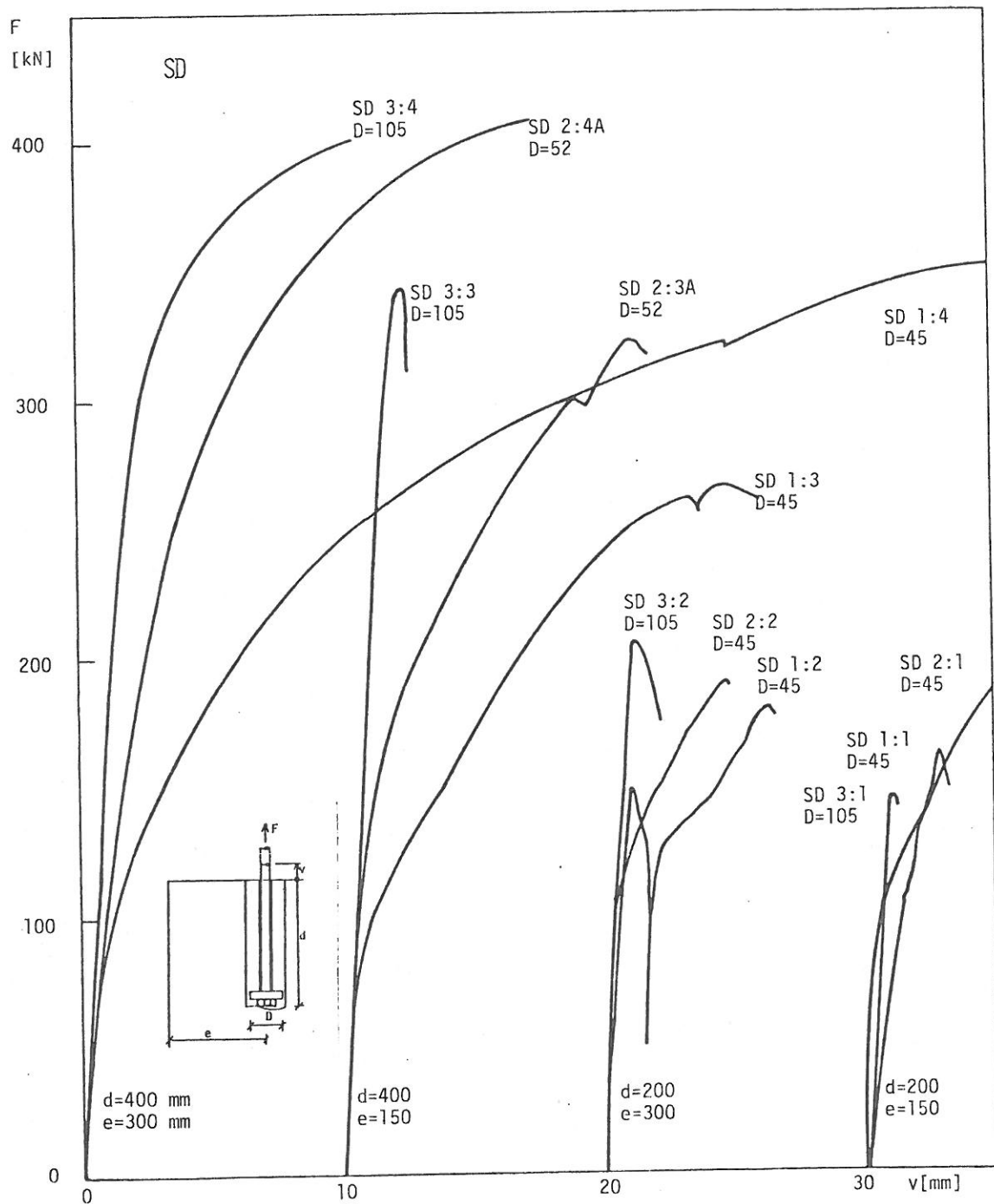


Fig 5.4 Displacement v of anchor head relative to the concrete surface for bolts in drilled holes. Main variables for the different bolts are given in Table 3.1

reinforcement mesh size is also seen although the difference between bolts SD 1:3 and SD 2:3A as well as the difference between SD 1:4 and SD 2:4A to a certain degree is due to larger bolts (M30) in foundation SD 1 than in foundation SD 1 (M27).

In Fig 5.5 some results from the conical and cylindrical recesses are presented. The main variables in the tests were:

- the dimension of the anchor bolt and the size of the washer (bolt M27 with washer $\phi 45 \times 3$ mm or bolt M30 with washer $\phi 52 \times 6$ mm or $\phi 105 \times 24$ mm).
- the diameter and the depth of the recess (cone $\phi 120/170$ mm with 200 mm depth, cone $\phi 120/200$ mm with 250 mm depth, or corrugated cylinder $\phi 150$ mm with 250 mm depth)
- the distance of the anchor bolt to the edge of the foundation (150, 160, or 300 mm).
- the amount of spiral reinforcement and the length of the anchorage hoops (with or without 4 turns of $\phi 10$ spiral reinforcement and with anchorage hoops of 0, 200, 300, 500, or 550 mm depth).

In the right part of the figure three bolts SW 1:1, 2:1, and 3:1 with a varying washer size are shown. It can be seen that both the stiffness and the ultimate load increase when the washer size increases.

In the middle part of the figure bolts SC 1:1 and SC 1:4 show the influence of hoop reinforcement. Bolt SC 1:1 had no hoops while bolt SC 1:4 had hoops of depth 550 mm. The hoops provide a slight increase in the strength of the bolt. The difference in stiffness between the two bolts is not caused by the hoops. Instead it is due to the fact that bolt SC 1:4 was prestressed.

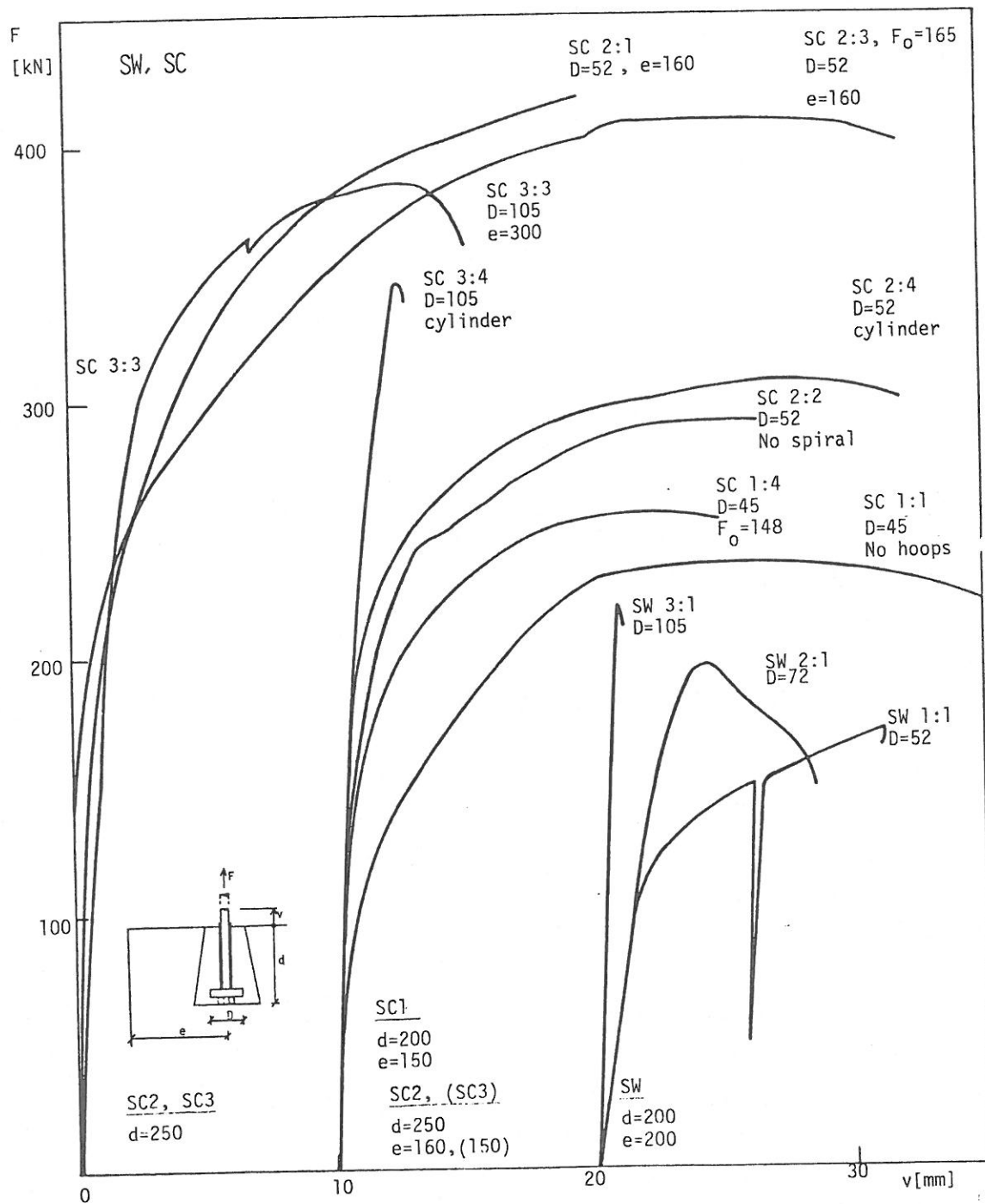


Fig 5.5 Displacement v of anchor head relative to the concrete surface for bolts in conical and cylindrical recesses. Main variables for the different bolts are given in Table 3.2

The bolts in foundation SC 1 had a small cone (depth $d = 200$ mm) and a small washer (diameter $D = 45$ mm). For the bolts in foundation SC 2 the cone depth was increased ($d = 250$ mm) and the bolts and washer were enlarged (from M27 to M30 and from $D = 45$ mm to $D = 52$ mm). The effect of this can be seen when the deformations of bolts SC 1:4 and SC 2:1 are compared. Bolt SC 2:1 is both stiffer and has a much higher ultimate load than bolt SC 1:4. The importance of the spiral reinforcement can be seen when bolt SC 2:1 (with spiral) is compared to bolt SC 2:2 (without spiral). The bolt without spiral has a much lower ultimate load.

In the middle part of Fig 5.5 are also shown two bolts in corrugated cylindrical recesses (SC 2:4 and SC 3:4). Here again the positive influence of the washer size on the stiffness and on the ultimate load can be seen. If the cylinders are compared to the cones it can be seen that the cylinders have smaller ultimate loads.

One of the bolts in foundation SC 3 with a big washer ($D = 104$ mm) in a conical recess is shown in Fig 5.5. This bolt (SC 3:3) is somewhat stiffer than other comparative bolts, at least at high loads, compare bolt SC 3:3 with SC 2:1 and SC 2:3.

Two of the bolts in Fig 5.5 were prestressed, SC 1:4 and SC 2:3. For bolt SC 1:4 a rubber pad (thickness 10 mm) was inserted between the machine footing and the foundation before prestressing. The load at testing was then applied directly to the bolt. Due to the low modulus of elasticity for rubber, notable deformations of the bolt took place even before the prestress force $F_0 = 148$ kN was achieved. For bolt SC 2:3 grout was placed under the footing and the load was applied to the footing. Accordingly only minor deformations were registered before the prestress load $F_0 = 165$ kN was achieved, compare with Appendix A.

In Table 5.3 some values are gathered summarizing the displacement v of the anchor head relative to the concrete surface at the loads $F = 100, 150$ and 200 kN as well as at the ultimate load F_u . In the table are also given the lengths L_e and L_a of the bolt. L_e is that part of the bolt which is embedded in concrete. The length is measured from the top of the nut to the top of the foundation. L_a is that part of the bolt which is located above the concrete surface. The length is measured from the top of the foundation to the location of the potentiometer used for measuring the deflections. The elastic deformation of the bolt is also given. It is calculated according to the formula

$$v = \frac{FL}{AE}$$

where F = applied load (100kN)

$$L = L_e + L_a$$

A = stress area of anchor bolt

E = modulus of elasticity (190 GPa)

Table 5.3 Anchor head displacements

Anchor Bolt No	Bolt length		Displacement v of anchor head						Ultimate load F_u kN	Notes
	L_e	L_a	Elast.	Measured						
			At load F [kN]							
			100		150	200	F_u			
	mm	mm	mm	mm	mm	mm	mm	mm		
SD 1:1	175	250	0.49	1.3	2.6	-	2.9	162	(a)	
1:2	173	260	0.50	0.6	4.5	-	6.4	180		
1:3	355	100	0.52	1.0	4.0	7.0	15.0	266		
1:4	362	75	0.50	1.1	3.1	6.2	>30.0	374		
SD 2:1	167	90	0.29	0.6	2.8	-	4.9	185	(b)	
2:2	175	90	0.30	0.5	2.3	-	4.9	190		
2:3	380	67	0.42	1.3	2.3	5.9	>36.0	252		
2:3A	360	145	0.47	0.6	1.5	3.0	11.3	322		
2:4	380	75	0.43	1.0	2.0	6.0	>30.0	252	(b)	
2:4A	357	160	0.49	1.0	1.8	2.6	17.5	408		
SD 3:1	166	110	0.26	0.7	-	-	1.0	147	(c)	
3:2	184	100	0.36	0.4	0.8	1.2	1.3	206		
3:3	369	100	0.44	1.0	1.6	2.2	6.1	>285		
3:3A	369	95	0.43	0.6	0.9	1.2	2.6	344		
3:4	374	85	0.44	0.6	0.9	1.2	>10.5	>400		
SW 1:1	177	80	0.24	1.5	6.2	-	11.3	170		
2:1	177	80	0.24	1.6	2.4	-	4.4	195		
3:1	177	90	0.25	0.4	0.6	1.0	1.1	218		
3:2	177	83	0.24	0.7	1.1	1.9	2.5	223		
SC 1:1	180	90	0.31	1.0	3.1	6.8	14.0	235	(d)	
1:2	180	90	0.31	1.0	3.1	6.1	12.0	236		
1:3	180	90	0.31	1.0	3.9	7.7	16.0	247		
1:4	180	90	0.31	0.4	0.9	2.8	11.5	254		
SC 2:1	227	90	0.30	0.3	0.7	1.3	>20.0	424	(e)	
2:2	227	90	0.30	0.5	1.0	1.8	16.5	291		
2:3	227	90	0.30	0.0	0.1	0.8	22.0	408		
2:4	227	90	0.30	0.3	0.7	1.1	18.0	307		
SC 3:1	227	101	0.31	1.3	2.0	2.7	7.2	418	(f)	
3:2	227	68	0.28	1.9	2.8	3.6	14.2	425	(f)	
3:3	227	60	0.27	0.6	1.0	1.3	12.7	385		
3:4	227	100	0.31	0.5	0.8	1.1	2.9	345		

Notes:

- (a) High deformation speed during first loading
- (b) Yielding of anchor bolt (inferior bolt quality)
- (c) Maximum load of actuator
- (d) Prestress force 148 kN
- (e) Prestress force 165 kN
- (f) Failure of threads in bolt

5.3 Strain

The strain in the anchor bolts have been recorded in most of the tests. Two strain gages have been placed 20 mm above the washer on opposite sides of the bolt, compare with Fig 3.11. Some results are presented in Fig 5.6. Average strains are given there for the bolts in foundation SC 3. In the figure are also shown theoretical nominal strains for a bolt M30 (stress area $A_s = 561 \text{ mm}^2$) with a modulus of elasticity $E = 190 \text{ GPa}$. As can be seen, the tested bolts have a slightly smaller stiffness than the theoretically predicted values. This is mostly due to the reduction of the stress area which took place when the bolt was grinded in order to prepare an even surface for the strain gage. From the figure it can also be seen that there is some scatter regarding the deformation at the nominal yield load.

Strain measurements on the concrete wall in a drilled hole are shown in Fig 5.7 for test SD 1:2. It can be seen that a crack has passed the wall for a load between 120 and 150 kN. The outer gage close to the foundation edge registered increased strains while the inner gage registered reduced strains.

Strains in some of the conical recesses are presented in Fig 5.8. In the left part of the figure horizontal and vertical strains for test SC 3:2 are shown. The horizontal strains (in tangential direction to the cone) are quite small $0,3 \text{ ‰}$. This corresponds to a tangential stress of about 60 MPa. In the vertical direction the strain is $2,3 \text{ ‰}$ which indicates yielding as

$$\epsilon_y = \frac{\sigma_y}{E} = \frac{350}{200000} = 1,75 \text{ ‰}$$

For tests SC 2:1 and SC 2:3 vertical strains of $0,8$ and $1,4 \text{ ‰}$ were recorded. This correspond to 160 MPa in test SC 2:1 and 280 MPa in test SC 2:3.

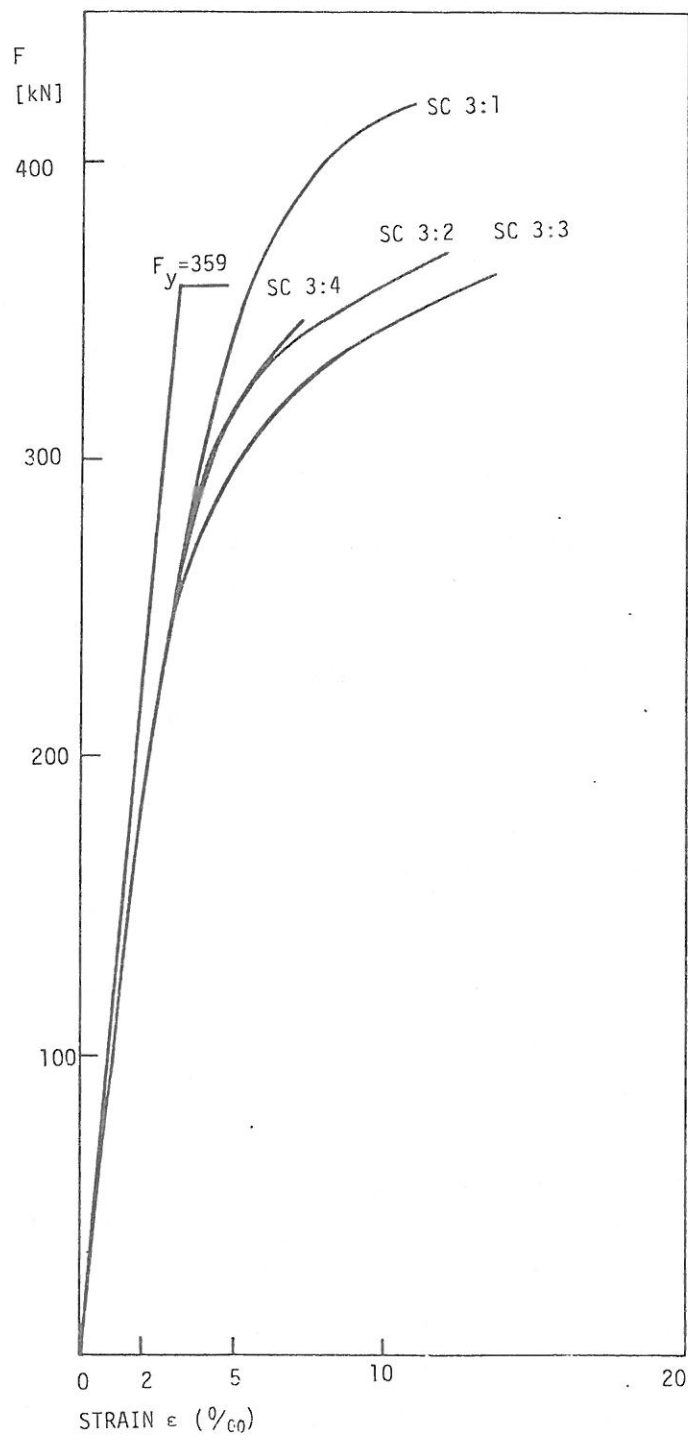


Fig 5.6 Strain in anchor bolts for foundation SC 3 with M30 bolts

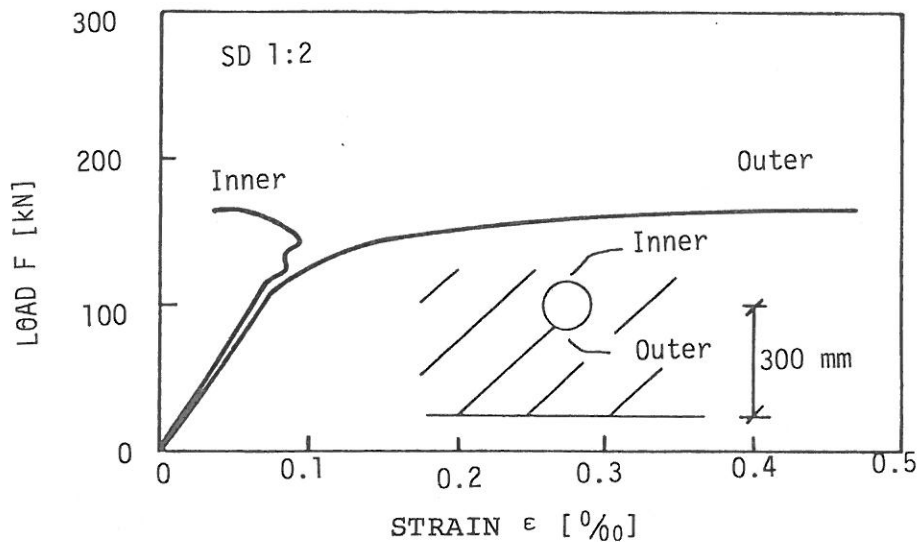


Fig 5.7 Strain in concrete wall in drilled hole for bolt SD 1:2. Hole depth is 200 mm and edge distance is 300 mm. The two gages are placed about 100 mm under the top of the foundation. One of them is placed close to the edge of the foundation (outer) and one is placed on the opposite side of the hole

In the middle part of the figure vertical strains are presented for test SC 2:2. This bolt had no spiral reinforcement. One of the gages recorded yielding in the cone at the ultimate load $F_u = 291$ kN. The maximum strain was then 2,8 ‰.

In the right part of the figure strains recorded from test SC 1:3 are presented. This conical recess only had a depth of 200 mm while the other ones in the figure had a depth of 250 mm. Low strains of 0,4 ‰ were registered corresponding to 80 MPa. However, for loads higher than 200 kN one of the gages indicates compressive strains of up to -1,4 ‰ corresponding to -280 MPa.

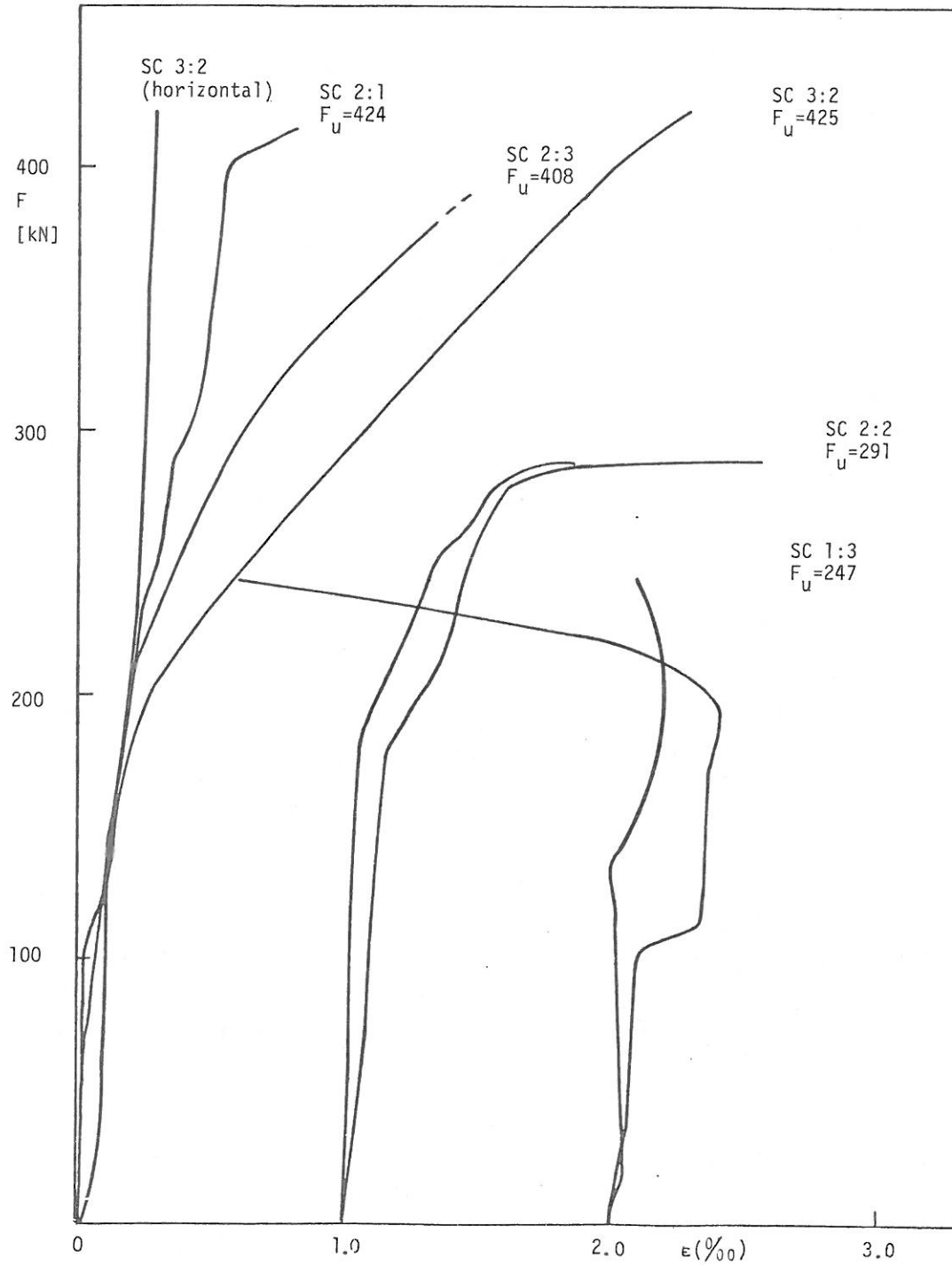


Fig 5.8 Strains in conical recesses. The gages are glued to the inside of the cone about 100 mm above the bottom of the recess. One gage is horizontal. The other ones are "vertical"

Strains in the spiral reinforcement are presented in Fig 5.9 for tests SC 1:2, :3, and :4. The difference between the three tests is the length of the hoops which was 200 mm for bolt SC 1:2, 300 mm for bolt SC 1:3, and 500 mm for bolt SC 1:4. Besides, bolt SC 1:4 was prestressed. In the top of the spirals, at a distance of 0,5 turn from their beginning, low tensile strains of 0,015 to 0,040 ‰ were registered before the ultimate load was reached. This corresponds to 3 to 8 MPa. In gages further down in the spirals compressive strains of -0,015 to -0,220 ‰ were obtained which correspond to -3 to -44 MPa. The strain was also measured half the way down after 2 turns on the spiral in test SC 2:3. Here the maximum tensile strain was 0,23 ‰ corresponding to about 46 MPa.

Strains in the hoop reinforcement are presented in Fig 5.10 for the same bolts as in Fig 5.9. Low tensile strains were registered in three of the gages on the hoops in tests SC 1:2 and :3. They varied between 0,03 and 0,17 ‰ corresponding to 6 to 34 MPa. In the fourth gage, the strain changed from tension to compression and to tension again. The tensile strain at ultimate load was 0,57 ‰ corresponding to about 115 MPa.

In test SC 1:4 (with a prestressed bolt) only compressive strains were observed during the test. They were of the order -0,01 to -0,12 ‰ corresponding to 2 to -24 MPa.

Generally it can be said that the stresses were low in the studied spirals and hoops. No yielding has been recorded. However, all the measurements but one have been carried out on the small recess (depth 200 mm). The measurement on the spiral of bolt SC 2:3 with bigger recess (depth 250 mm) showed a higher stress level (85 MPa). Bearing in mind that the strains and stresses in a reinforcement bar can vary considerably along the length of the bar, it is possible that higher stresses than have been recorded can occur locally in the spirals and in the hoops.

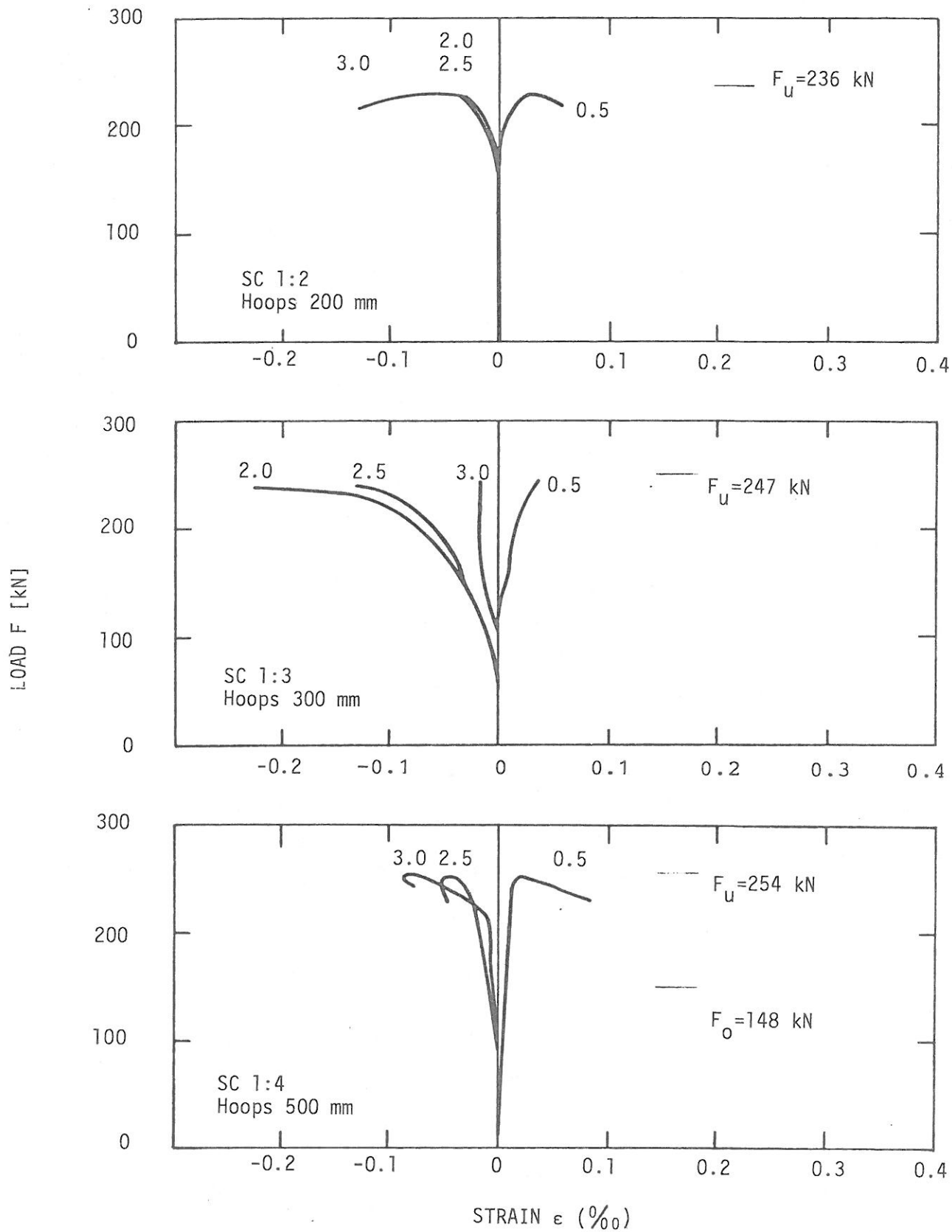


Fig 5.9 Strain in spiral reinforcement. The number at the curves indicates the location of a gage counted in number of turns of the spiral reinforcement from the top of the spiral

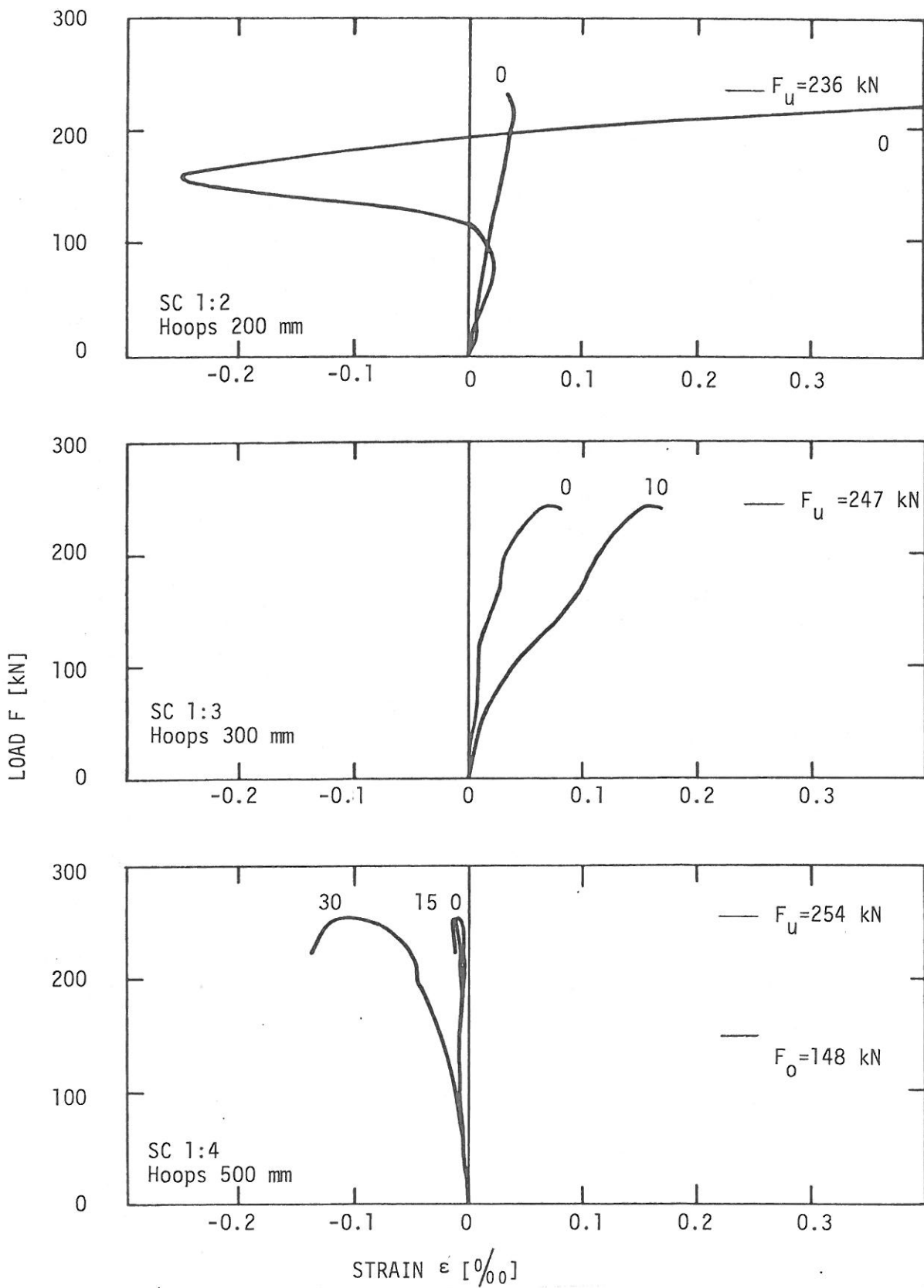


Fig 5.10 Strain in hoop reinforcement. The number at the curves indicates the location of a gage measured in mm from the bottom of the recess (compare with Fig 3.2)

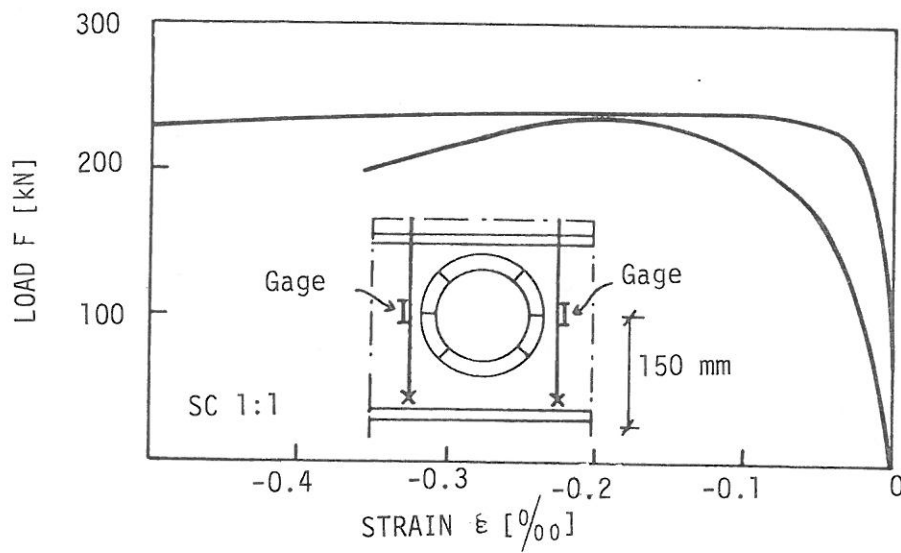


Fig 5.11 Strain in top reinforcement of bolt SC 1:1

Some strains in the reinforcement net surrounding bolt SC 1:1 are presented in Fig 5.11. The reinforcement bars had compressive strains of -0,1 to -0,2 ‰ at the ultimate load. This correspond to -20 to -40 MPa. The reinforcement bars are situated quite close to the bolt.

6 COMPARISON WITH THEORETICAL MODELS

6.1 General

In this chapter the test results are compared to values calculated with some of the theoretical models presented in chapter 2. For the sake of comparison some additional test results by Mogens Lorentsen [1-54] will also be presented and discussed.

6.2 Elastic model

According to the elastic model in Figs 2.4 - 2.6 the tensile strength f_{ct} of the concrete will reach its maximum value in the vicinity of the washer for loads smaller than $F = 100$ kN. For a value of $f_{ct} = 3,0$ MPa. Fig 2.5g implies that a crack of the length of about 40 mm already has developed when $F = 100$ kN. The model corresponds best to bolt SD 3:4 with a drilled hole of the depth 400 mm and a distance to the edge of the foundation of 300 mm. The deformation of bolt SD 3:4 is given in Figs 5.4 and A.3. For $F = 100$ kN the displacement of the anchor head is measured to $v = 0,6$ mm which can be compared to a calculated value for the elastic model of $v = 0.044$ mm (see Table 2.1, point A) + 0.440 mm (see Table 5.3, SD3:4) = 0.48 mm.

The ratio between the elastic prediction and the measured value is $0,48/0,6 = 0,73$. The difference between the values can be due to the fact that the washer has been modelled as a console reaching out from the bolt and not as a ring placed on top of the nut and free to rotate. In addition to this, there is the fact that the limits on the accuracy of the measured value can be some $\pm 0,15$ mm.

The elastic models of section 2.2 also implies that radial cracks will propagate out from the bolt at some distance above the washer, see Figs 2.3c and 2.5c, f, i. From Fig 2.5c, f, i it can be seen that the point with the maximum tensile θ -stress moves upwards as the inclined crack from the washer edge propagates. For bolt SD 3:4 no radial cracks appeared before the maximum load. However, for bolts with a smaller depth such cracks generally could be observed between $F = 100$ kN and $F = 200$ kN.

6.3 Punching

According to the CEB-FIP Model Code [2-13] the punching shear stress f_v^{CEB} can be written as

$$f_v^{CEB} = \kappa(1+50\rho)\tau_{Rd} \quad (6-1)$$

where $\kappa = 1,6 - d[m]$ but not less than 1,0

$\rho = \sqrt{\rho_x \rho_y}$ but not greater than 0,008

$$\rho_x = \frac{A_{sx}}{b_w d} \quad \rho_y = \frac{A_{sy}}{b_w d}$$

A_{sx}, A_{sy} = the area of the tensile reinforcement in the x- and y-directions anchored beyond the intersection of the steel and the line of a possible 45° crack starting at the washer head.

b_w = width of section

d = effective depth of section

τ_{Rd} = tabulated value given for different values of the characteristic concrete compressive strength f_{ck}

According to the Swedish Code BBK 79 [2-14] the punching shear stress in a similar way can be written as

$$f_v^{BBK} = \xi (1+50\rho) 0,4 f_{ct} \quad (6-2)$$

where $\xi = 1,4$ for $d \leq 0,2$ m

$\xi = 1,6 - d$ for $0,2 < d \leq 0,5$ m

$\rho = \sqrt{\rho_x \rho_y}$ but not greater than 0,01

f_{ct} = design value for the concrete tensile strength in safety class 2 (serious).

Values of f_v^{CEB} and f_v^{BBK} are calculated in Table 6-1 for all the bolts in drilled holes and for two characteristic bolts in conical recesses (SC 1:1 and SC 3:1)

The horizontal projection A_h of the mantle area for the different bolts are calculated in Table 6.2, see Fig 6.1.

Based on the values of f_v and A_h ultimate loads are calculated according to CEB-FIP (F^{CEB}) and BBK 79 (F^{BBK}). The results are presented in Table 6.3.

TABLE 6.1 Punching shear stresses.

Anchor Bolt No	d	H	ξ	100 ρ	τ_{Rd}	f_{ctk}	f_v^{CEB}	f_v^{BBK}
	m				MPa	MPa	MPa	MPa
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
SD 1:1	0.142	1.458	1.400	0.391	0.34	0.97	0.59	0.65
1:2	0.140	1.460	1.400	0.397	"	"	0.59	0.65
1:3	0.322	1.278	1.278	0.172	"	"	0.47	0.54
1:4	0.329	1.271	1.271	0.169	"	"	0.47	0.53
SD 2:1	0.134	1.466	1.400	0.586	0.34	0.97	0.64	0.70
2:2	0.142	1.458	1.400	0.553	"	"	0.63	0.69
2:3	0.344	1.256	1.256	0.228	"	"	0.48	0.54
2:4	0.344	1.256	1.256	0.288	"	"	0.48	0.54
SD 3:1	0.112	1.488	1.400	0.496	0.34	0.97	0.63	0.68
3:2	0.130	1.470	1.400	0.427	"	"	0.61	0.66
3:3	0.315	1.285	1.285	0.176	"	"	0.48	0.54
3:4	0.320	1.280	1.280	0.174	"	"	0.47	0.54
SC 1:1	0.147	1.453	1.400	0.378	0.38	1.09	0.66	0.73
3:1	0.173	1.427	1.400	0.321	"	"	0.63	0.71

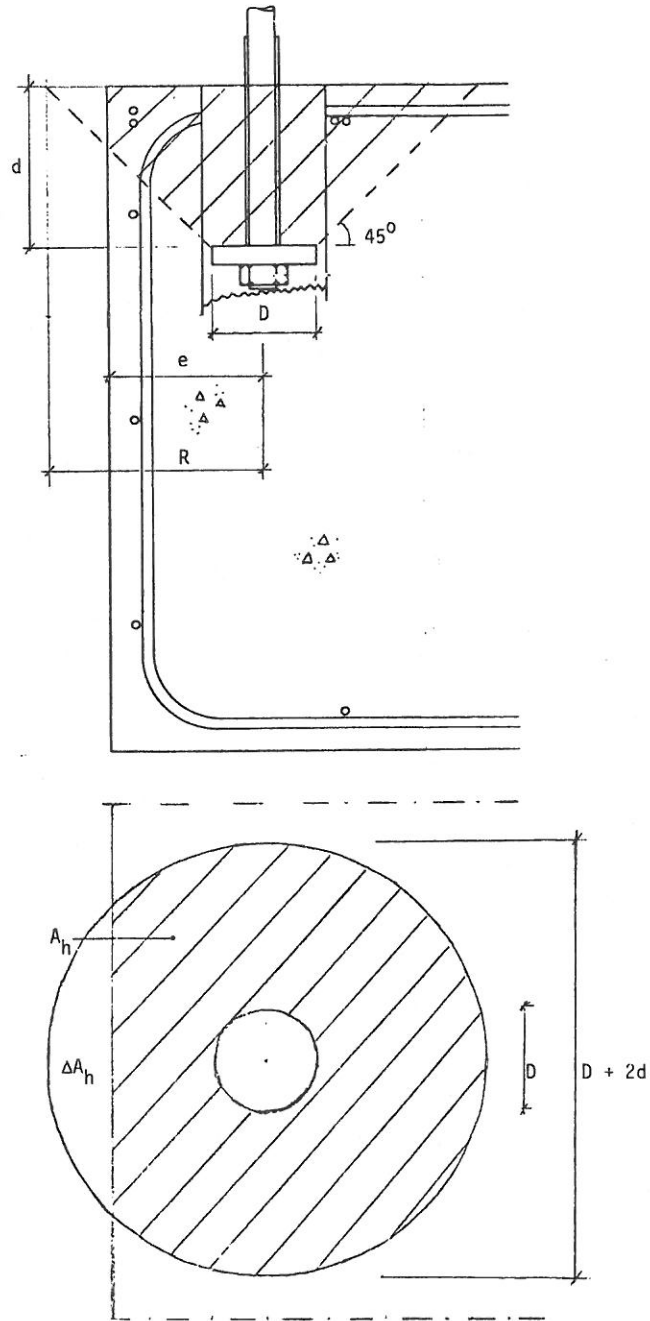


Fig 6.1 Failure cone in punching analysis

TABLE 6.2 Punching stress area

Anchor Bolt No	d	D	e	R	A_h^O	ΔA_h	A_h
	mm	mm	mm	mm	mm	mm	mm
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
SD 1:1	142	45	150	164.5	0.0834	0.0011	0.0823
1:2	140	"	300	162.5	0.0814	-	0.0814
1:3	322	"	150	344.5	0.3713	0.0858	0.2854
1:4	329	"	300	351.5	0.3866	0.0125	0.3741
SD 2:1	134	45	150	156.5	0.0754	0.0002	0.0752
2:2	142	"	300	164.5	0.0834	-	0.0834
2:3	344	52	150	370	0.4280	0.1064	0.3216
2:4	344	"	300	370	0.4280	0.0202	0.4078
SD 3:1	112	105	150	164.5	0.0764	0.0002	0.0762
3:2	130	"	300	182.5	0.0960	-	0.0960
3:3	315	"	150	367.5	0.4156	0.1019	0.3137
3:4	320	"	300	372.5	0.4273	0.0201	0.4072
SC 1:1	147	45	150	169.5	0.0887	0.0018	0.0869
3:1	173	105	150	225.5	0.1511	0.0153	0.1358

TABLE 6.3 Punching forces

Anchor Bolt No	F^{CEB}	F^{BBK}	F^u	$\frac{F^u}{F^{CEB}}$	$\frac{F^u}{F^{BBK}}$
	kN	kN	kN		
(1)	(2)	(3)	(4)	(5)	(6)
SD 1:1	48.6	53.5	162	3.33	3.03
1:2	48.0	52.9	180	3.75	3.40
1:3	134.1	154.1	266	1.98	1.73
1:4	175.8	198.3	374	2.13	1.89
SD 2:1	48.1	52.6	185	3.84	3.51
2:2	52.5	57.6	190	3.62	3.30
2:3A	154.1	173.7	322	2.09	1.85
2:4A	195.7	220.2	408	2.08	1.85
SD 3:1	48.0	51.8	147	3.06	2.84
3:2	58.6	63.4	206	3.52	3.25
3:3A	150.6	169.4	344	2.28	2.03
3:4	191.4	219.9	>400	>2.09	>1.82
SC 1:1	57.3	63.4	235	4.10	3.70
3:1	85.6	96.4	418	4.89	4.34
			m =	3.05	2.75
			$\sigma =$	0.94	0.87

6.4 Thick walled cylinder

The cracking stress p_{cr} and the cracking force F_{cr} according to Eqs (2-8) and (2-9) in Section 2.4 are calculated in Table 6.4 for the tested bolts. For comparison two series of test results obtained by Mogens Lorentsen are also included: bolts ML I-IV (published in [1-54]) and bolts ML 2:1-2 and 3:1-2 (not earlier published). Geometrical data for the tests by Mogens Lorentsen are given in Fig 6.2.

The coefficient of friction μ has been estimated to 0,5 for the drilled holes and to 0,35 for the conical and cylindrical recesses.

As a comparison in Table 6.4 is also listed the load F_{cr}^{exp} when the first visible crack was observed in a test. For seven of the bolts the value of F_{cr}^{exp} was not documented during the experiments. The comparison between F_{cr}^{exp} and the calculated value F_{cr} is for that reason only possible for 29 bolts.

It can be seen that the ratio in column (10) between F_{cr}^{exp} and the calculated value F_{cr} usually is greater than 1. The mean value of the ratio is $m = 1.52$ and the standard deviation is $\sigma = 0,55$.

Low values of the ratio are obtained in Series SC 3 for large washers and in Series ML for cylindrical recesses.

For the drilled holes the calculated value of F_{cr} seems to give a resonable prediction of the cracking load. For the recesses the calculated value of F_{cr} usually overestimates the cracking load especially for large washers.

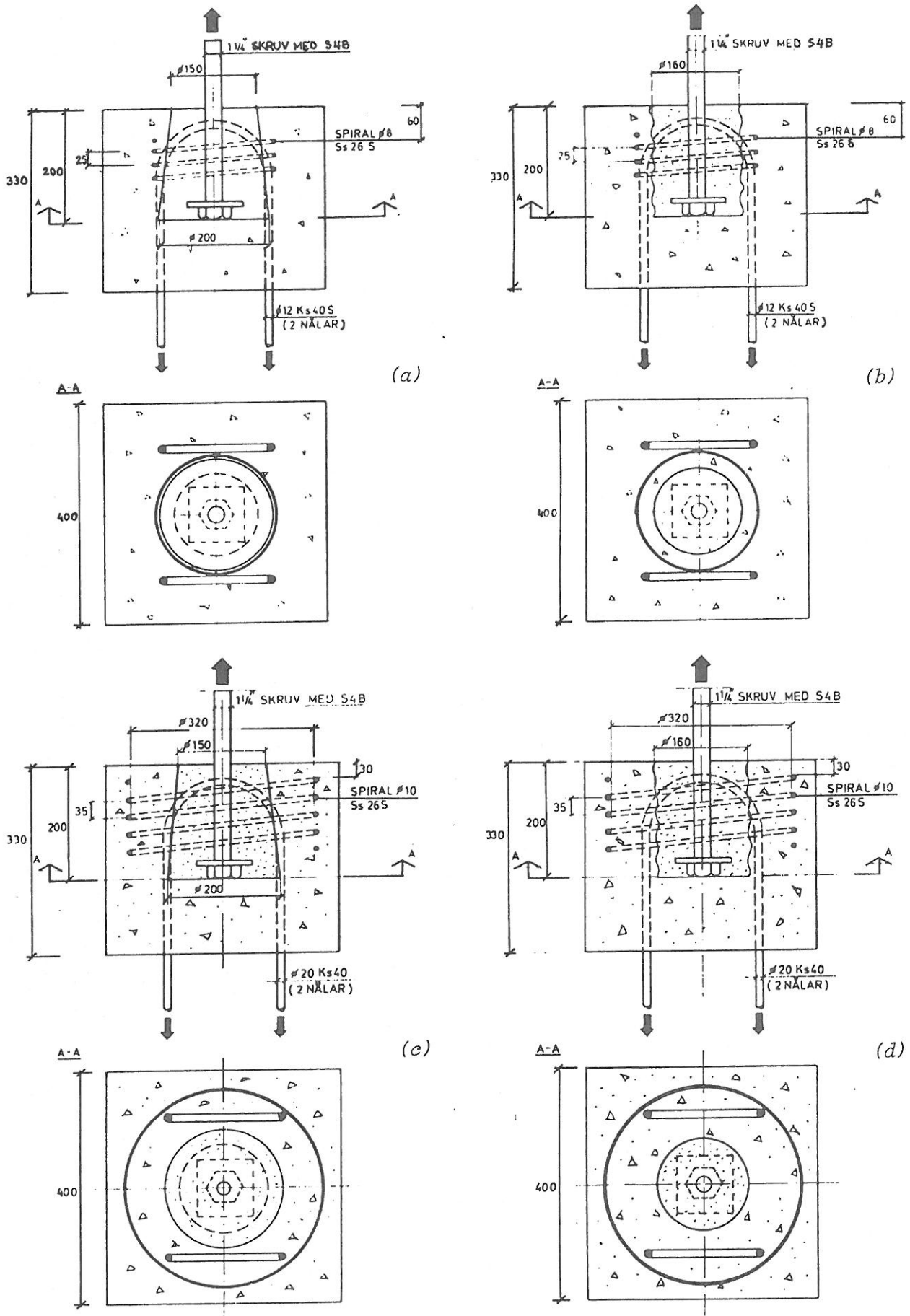


Fig 6.2 Test specimen used by Mogens Lorentsen in series ML [1-54]

(a) ML I, (b) ML II, (c) ML III, (d) ML IV

TABLE 6.4 Thick walled cylinder

Anchor Bolt No	Recess		Outer radius r_o	Concrete strength		P_{cr} Eq. (2-8)	F_{cr} Eq. (2-9)	F_{cr}^{exp}	$\frac{F_{cr}^{exp}}{F_{cr}}$	Notes
	Diameter top/bottom	Depth		f_c	f_t					
m	m	m	MPa	MPa	MPa	kN	kN			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
SD 1:1	0.12	0.175	0.15	31	2.6	1.88	62.1	105	1.69	
1:2	"	"	0.30	"	"	2.40	79.2	126	1.59	
1:3	"	0.360	0.15	"	"	1.88	127.8	230	1.80	
1:4	"	"	0.30	"	"	2.40	162.9	200	1.23	
SD 2:1	0.12	0.175	0.15	32	3.0	2.17	71.1	170	2.37	
2:2	"	"	0.30	"	"	2.77	91.4	190	2.08	
2:3	"	0.360	0.15	"	"	2.17	147.4	>252	>1.71	
2:4	"	"	0.30	"	"	2.77	187.9	>256	>1.36	
SD 3:1	0.12	0.175	0.15	37	2.9	2.10	69.3	100	1.44	
3:2	"	"	0.30	"	"	2.68	83.3	165	1.87	
3:3	"	0.360	0.15	"	"	2.10	142.5	162	1.14	
3:4	"	"	0.30	"	"	2.68	181.7	-	-	
SW 1:1	0.12/0.17	0.20	0.20	37	2.5	1.92	86.9	125	1.44	
2:1	"	"	"	"	"	"	"	80	0.92	
3:1	"	"	"	"	"	"	"	-	-	
3:2	"	"	"	"	"	"	"	-	-	
SC 1:1	0.12/0.17	0.20	0.15	37	4.0	1.55	70.3	146	2.08	
1:2	"	"	"	"	"	"	"	135	1.92	
1:3	"	"	"	"	"	"	"	100	1.42	
1:4	"	"	"	"	"	"	"	-	-	(a)
SC 2:1	0.12/0.20	0.25	0.16	30	2.5	1.50	101.8	-	-	
2:2	"	"	"	"	"	"	"	-	-	
2:3	"	"	"	"	"	"	"	258	2.53	(a)
2:4	0.15	"	"	"	"	1.60	94.7	239	2.52	(b)
SC 3:1	0.12/.20	0.25	0.15	35	3.0	1.67	113.5	105	0.93	
3:2	"	"	0.30	"	"	2.60	176.6	117	0.66	
3:3	"	"	0.15	"	"	"	"	-	-	
3:4	0.15	"	0.30	"	"	1.80	106.6	83	0.78	(b)
ML I	0.15/0.20	0.20	0.20	46	3.5	2.38	129.7	147	1.13	(c)
II	0.16	"	"	"	"	2.53	128.1	95	0.74	(b), (c)
III	0.15/0.20	"	"	56	"	2.38	129.7	210	1.62	(c)
IV	0.16	"	"	"	"	2.53	128.1	70	0.55	(b), (c)
ML 2:1	0.15/0.20	0.20	0.20	68	4.0	2.71	148.3	170	1.15	(c)
2:2	"	"	"	"	"	"	"	200	1.35	(c)
3:1	"	"	"	23	2.0	1.36	74.1	150	2.02	(c)
3:2	"	"	"	"	"	"	"	160	2.16	(c)
m = 1.52										
$\sigma = 0.55$										

(a) Prestressed bolt ($F_o = 148$ kN for SC 1:4; $F_o = 165$ kN for SC 2:3)(b) Corrugated cylinder with $\tan \alpha = 0.13$ (c) The value of f_t is an estimation based on f_c .

6.5 Ring reinforcement

The yielding stress p_y and the yielding force F_y according to Eqs (2-10) and (2-11) in Section 2.5 are listed in Table 6.5 together with the ultimate load F_u obtained during testing. Again the test results of Mogens Lorentsen are included. The coefficient of friction μ has been estimated to 0,35.

The ratio between the ultimate load F_u and the theoretical yield force F_y is listed in column (7) in the table. For Series SW and SC 1 the ratio is less than one. The recess is here too small (depth 200 mm) to be able to anchor the applied load.

In series ML the recess also has the same depth but here the test values are in better correspondance with the predicted values. This is probably due to the favourable way in which the loads were applied in Series ML, see Fig 6.2. The load is carried by two pairs of vertical reinforcement hoops. These hoops induce compressive stresses in the concrete around the anchor which helps the concrete to carry the anchor load.

In Series SC 2 and SC 3 the ratio is above or close to unity. However, the validity of the model must still be questioned also for these bolts as the measured strains on the spirals (see Section 5.3) never indicated yielding. Further, it is obvious that the metal cones used for forming the recess contribute to the load carrying capacity.

Although the spirals do not reach yielding during testing, they are most valuable to keep the anchorage zone together and they do have a large influence on the ultimate load, compare bolt SC 2.2 (with no spirals) with the other bolts in Series SC 2.

TABLE 6.5 Ring reinforcement

Anchor Bolt No	No. and diameter of spirals	Yield stress f_y	Eq. (2-10)	F_y Eq. (2-11)	F_u	$\frac{F_u}{F_y}$	Noks
	mm	MPa	MPa	kN	kN		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
SW 1:1	3 ϕ 10	440	7.15	323.6	170	0.53	
2:1	"	"	"	"	195	0.60	
3:1	"	"	"	"	218	0.67	
3:2	"	"	"	"	223	0.69	
SC 1:1	3 ϕ 10	440	7.15	323.6	235	0.73	
1:2	"	"	"	"	236	0.73	
1:3	"	"	"	"	247	0.76	
1:4	"	"	"	"	254	0.78	(a)
SC 2:1	3 ϕ 10	440	5.18	351.2	424	1.21	
2:2	-	-	-	-	291	-	
2:3	3 ϕ 10	440	5.18	351.2	408	1.16	(a)
2:4	"	"	5.53	327.6	307	0.94	(b)
SC 3:1	3 ϕ 10	440	5.18	351.9	418	1.19	
3:2	"	"	"	"	425	1.21	
3:3	"	"	"	"	385	1.09	
3:4	"	"	5.53	327.6	345	1.05	(b)
ML I	3 ϕ 8	341	2.94	160.5	150	0.93	
II	"	"	3.21	162.5	160	0.98	
III	4 ϕ 10	343	6.16	336.3	300	0.89	
IV	"	"	6.73	340.5	240	0.70	
ML 2:1	3 ϕ 10	310	4.17	228.0	240	1.05	
2:2	"	"	"	"	240	1.05	
3:1	"	"	"	"	190	0.83	
3:2	"	"	"	"	220	0.96	
m = 0.90							
$\sigma = 0.20$							

(a) Prestressed bolt ($F_o = 148$ kN for SC 1:4; $F_o = 165$ kN for SC 2:3)

(b) Corrugated cylinder with $\tan \alpha = 0.13$

7. SUMMARY AND CONCLUSIONS

This report treats anchor bolts placed in a recess or in a drilled hole in a concrete foundation. The anchors are fixed in position by grouting of concrete or mortar.

In Chapter 1 an introduction is given providing background material and a review of literature.

The anchor bolts are studied theoretically in Chapter 2. Elastic models using the finite element method are applied to study stresses and crack propagation. An analogy with punching of slabs is used to model the ultimate load and an analogy with a thick walled cylinder is used to model the cracking load.

In Chapters 3 and 4 the test program and the material properties are presented.

Twelve anchor bolts in drilled holes and sixteen anchor bolts in conical and cylindrical recesses have been tested. The washer size has varied from ϕ 45 x 3 mm to ϕ 105 x 24 mm. The depths of the holes and recesses have been 200, 250, and 400 mm and the distances to the edge of the foundation have been 150, 160, 200, and 300 mm.

Test results and a comparison with theoretical models are given in Chapters 5 and 6.

The washer size had a marked influence on the stiffness of the bolt. A large washer gave a stiffer bolt than a small washer (see e.g. bolts SW 1:1, 2:1, and 3:1 in the right part of Fig 5.5). A large washer also gave a slightly higher ultimate load. (In test series SW the ultimate load was 170 kN for a small washer ϕ 52 x 6 mm, 195 kN for a medium washer ϕ 72 x 12 mm, and 218-223 kN for a large washer ϕ 105 x 24 mm). A high stiffness is preferable, especially for a bolt which is going to be prestressed. For that reason, the main focus of this investigation has been on bolts with large washers.

Regarding the ultimate load F_u the values in Table 7.1 were obtained for the largest washers ϕ 105 x 24.

TABLE 7.1 Ultimate loads for tested anchor bolts with washer ϕ 105 x 24 mm

Edge distance	Conical recess Depth (mm)	Cylindrical recess Depth (mm)	Drilled hole Depth (mm)	
	250	250	200	400
mm	kN	kN	kN	kN
150	385-418	345	147	344
300	425	-	206	>400

As can be seen from the table, the edge distance was an important factor for the ultimate load for a bolt in a drilled hole with a small depth (200 mm). A large edge distance gave a higher ultimate load than a small edge distance. The edge distance was less important when the drilled hole was deeper (400 mm) or when a conical recess was used.

The depth of the holes was another important factor. For a drilled hole, the ultimate load was doubled when the depth was increased from 200 mm to 400 mm.

A conical recess of depth 250 mm had the same load carrying capacity as a drilled hole of depth 400 mm. A cylindrical recess had a somewhat smaller ultimate load than a similar conical recess.

The influence of the amount of reinforcement was studied in some of the test series. With a foundation reinforcement of ϕ 10 Ks 400 only slightly higher ultimate loads

were achieved for a mesh size of # 100 mm than for a mesh size of # 200 mm.

The influence of the length of the hoop reinforcement was also studied. The hoop reinforcement was used to anchor the conical recesses. Only small differences in the behaviour were found for various hoop lengths.

The spiral reinforcement used for the conical recesses gave a considerable contribution to the ultimate load. However, the recorded strains in the spirals were small and no yielding was observed.

In order to get an indication of the allowable loads for the tested anchor bolts, the ultimate loads can be divided by a safety factor. The value of such a safety factor can be discussed. Too few tests have been performed to enable a statistical evaluation [7-1], [7-2]. However, for expanding fittings, a safety factor of three is applied to the characteristic ultimate load (defined as the lower 5 %-fractile determined on a 75 % confidence level) according to Swedish rules [1-62]. An expanding fitting has usually a more brittle failure mechanism than the anchor bolts tested here. This is partly due to the influence of the foundation reinforcement. Accordingly, it should be justified to use the same high safety factor for bolts as for expanding fittings. If then, a safety factor of three is applied to the loads in Table 7.1, the values in Table 7.2 will be obtained for the allowable loads for the tested anchor bolts.

The deflection of the anchor head relative to the top of the concrete was for the largest washer linear to about 250 kN (if the ultimate load had not occurred at that load). The displacement at that point had a value of 1 - 3 mm.

TABLE 7.2 Allowable loads for M30 anchor bolts of quality 8.8 with ϕ 105 x 24 mm washers. Foundation made of concrete C 30 with a reinforcement net of ϕ 10 Ks 400 # 200 mm

Edge distance	Conical recess	Drilled hole	
	Depth (mm) 250	Depth (mm) 200 400	
mm	kN	kN	kN
150	125	50	115
300	140	68	133

For design purposes, a method was checked, which is used to calculate ultimate punching loads for slabs in the CEB-FIP model code [2-13] and in the new Swedish Concrete Code, BBK 79 [2-14]. The method gave results which had a ratio of tested value to design value of 2 to 4. The ratio was about 3 for drilled holes of the length 200 mm, about 2 for drilled holes of the length 400 mm, and about 4 for conical recesses of the length 250 mm. Accordingly, the values obtained with the punching method of the codes seem to be useful for design purposes for statically loaded anchor bolts in conical recesses and in drilled holes under short time loading.

For cracking, a method was used which is based on an analogy with a thick walled cylinder. The method gave values which had a ratio of tested values to calculated values of about 1.5.

Shrinkage and creep will be of major importance for the long time safety of drilled holes. Tests are now in progress to study these phenomena. Tests are also being carried out to check the fatigue capacity of bolts in conical recesses and of bolts in drilled holes. These tests will be reported separately.

APPENDIX A. INFLUENCE OF PRESTRESS

In section 1.1 the influence of prestress on the stress variation of a bolt was touched upon. In this Appendix is presented a closer examination of the influence of prestress.

In Fig A.1 a prestressed bolt is shown. A prestressing force P_0 gives rise to a strain ϵ_{so} in the steel bolt and a strain ϵ_{co} in the concrete grout under the machine footing. The bolt area is called A_s , the effective concrete area is called A_c , and the modulus of elasticity for steel and concrete grout are called E_s and E_c respectively. Equilibrium gives, see Fig A.2 (a)

$$P_0 = E_s \epsilon_{so} A_s = E_c \epsilon_{co} A_c \quad (A-1)$$

If now a force F (less than P_0) is applied to the machine footing, the strain will increase in the bolt and it will decrease in the concrete grout. We assume that the changes $\Delta\epsilon$ of the strain values are equal for the bolt and the concrete. (This implies that the length of the bolt is equal to the height of the effective concrete volume. This is approximately true). The applied force F can then be written as the difference between the tensile force F_s in the steel bolt and the compressive force F_c in the concrete grout, see Fig A.2 (b)

$$\begin{aligned} F &= F_s - F_c = E_s (\epsilon_{so} + \Delta\epsilon) A_s - E_c (\epsilon_{co} - \Delta\epsilon) A_c = \\ &= \Delta\epsilon (E_s A_s + E_c A_c) \quad \text{for } F < P_0 \end{aligned} \quad (A-2)$$

If the applied force F is greater than P_0 , the concrete compressive force will be reduced to zero. The applied load will then be carried by the steel bolt alone, see Fig A.2 (c)

$$F = F_s = E_s (\epsilon_{so} + \Delta\epsilon) A_s \quad \text{for } F > P_0 \quad (A-3)$$

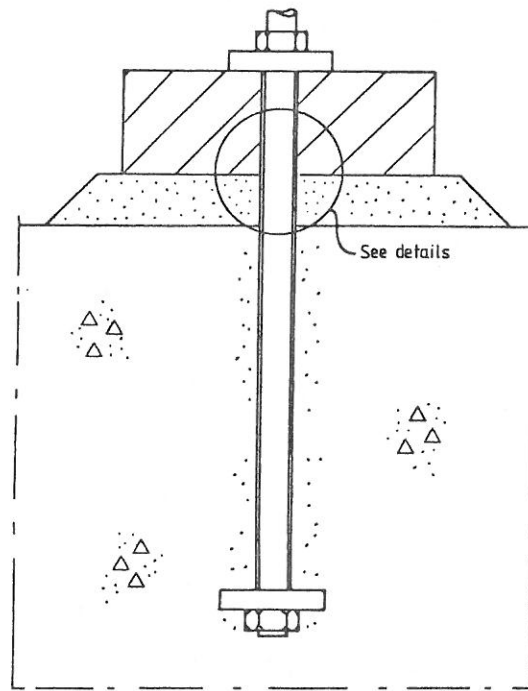


Fig A.1 Prestressed bolt

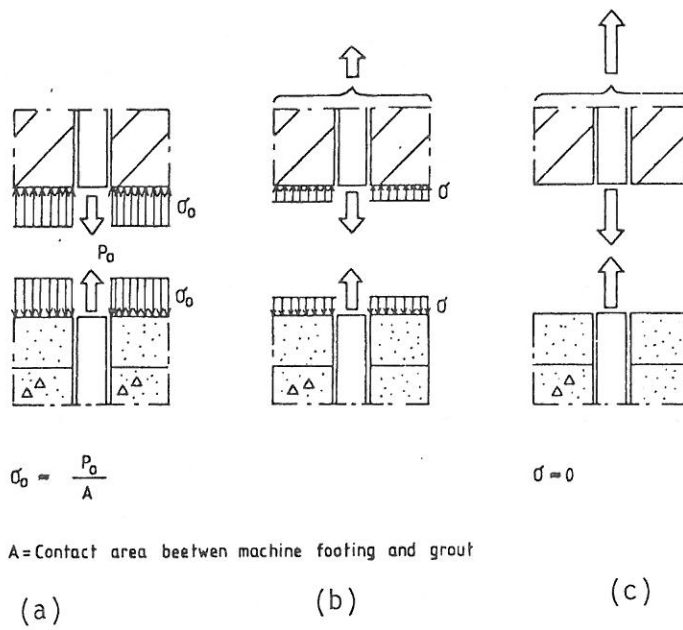


Fig A.2 Details of prestressed bolt

The applied force F , the tensile steel force F_s and the compressive concrete force F_c are shown in Fig A.3 as a function of $\Delta\epsilon$. The numerical values are chosen to be representative for a bolt with dimension M30. The applied force F is increasing steeply for low strains $\Delta\epsilon$ when $F < P_o$. When the concrete compressive stress disappears for $\Delta\epsilon = \epsilon_{co}$ and

$$F = F_p = E_s (\epsilon_{so} + \epsilon_{co}) A_s \quad (A-4)$$

the applied load must be carried by the steel bolt alone. Accordingly there is change of the slope of the F - $\Delta\epsilon$ -curve.

If the applied load F is varying with an amplitude $\pm\Delta F$ so that $F_o \pm \Delta F < F_p$ only small variations ΔF_s will occur in the steel stress, see Fig A.4

$$\Delta F_s = \Delta F \frac{E_s A_s}{E_s A_s + E_c A_c} \quad (A-5)$$

If, for example, $A_s = 569 \text{ mm}^2$ (M30), $A_c = 150^2 = 22500 \text{ mm}^2$, $E_s = 190 \text{ GPa}$ and $E_c = 25 \text{ GPa}$ we get for

$$F = F_o \pm \Delta F = 100 \pm 50 \text{ kN}$$

the following variations in $\Delta\epsilon$ and F_s , see Fig A.4

$$\Delta\epsilon = \frac{F}{E_s A_s + E_c A_c} = 0.149 \pm 0.075 \text{ ‰}$$

$$F_s = E_s (\epsilon_{so} + \Delta\epsilon) A_s = P_o + E_s \Delta\epsilon A_s = 150 + 15.9 \pm 8.0 \text{ kN} =$$

$$= F_{so} \pm \Delta F_s = 165.9 \pm 8.0 \text{ kN}$$

where $\Delta F_s / \Delta F = 8.0 / 50 = 0.16$

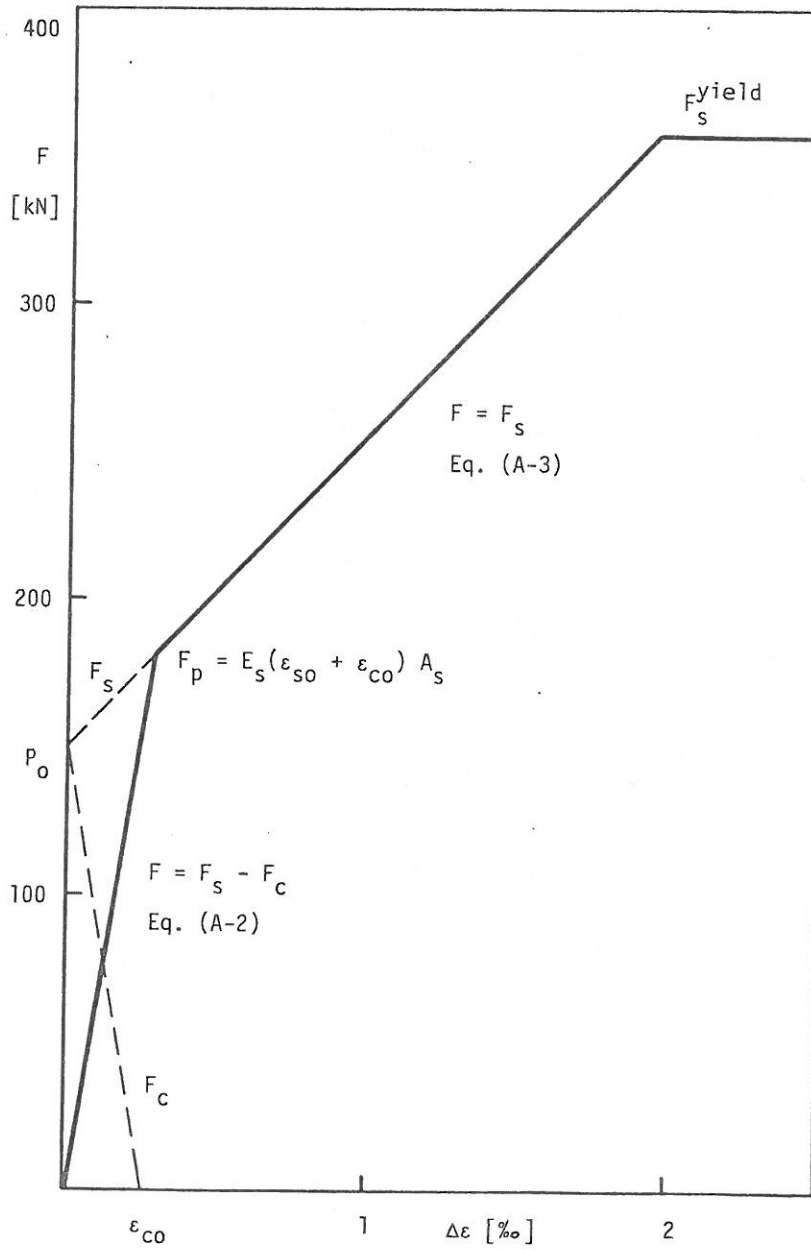


Fig A.3 Applied force F , tensile bolt force F_s and compressive concrete force F_c as functions of strain increase $\Delta\epsilon$. Numerical values:
 $A_s = 561 \text{ mm}^2$ (M30), $A_c = 150^2 = 22500 \text{ mm}^2$, $E_s = 190 \text{ GPa}$, $E_c = 25 \text{ GPa}$,
 $P_o = 150 \text{ kN}$, $\sigma_s^{yield} = 640 \text{ MPa}$

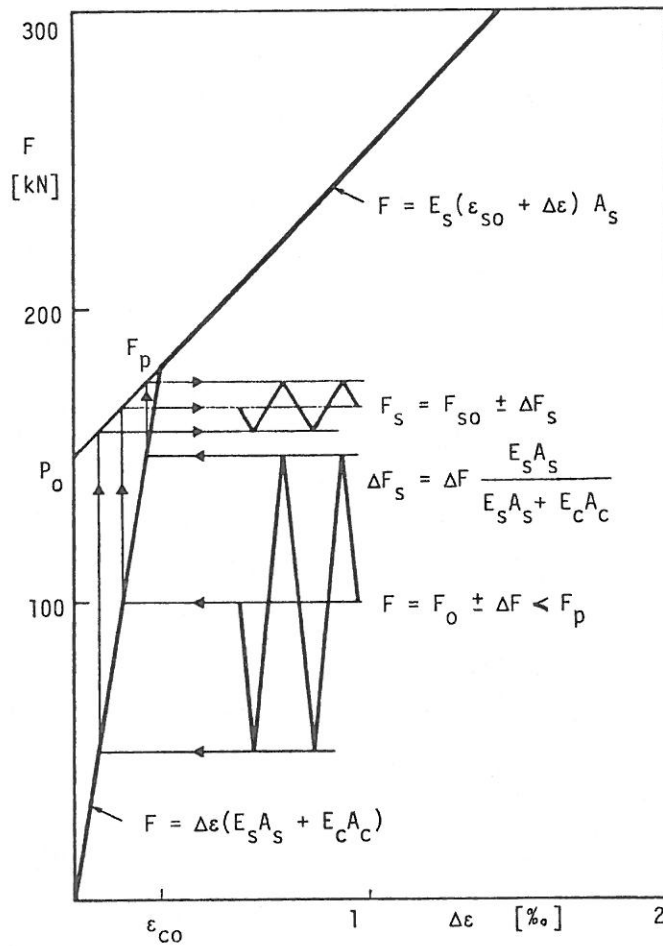


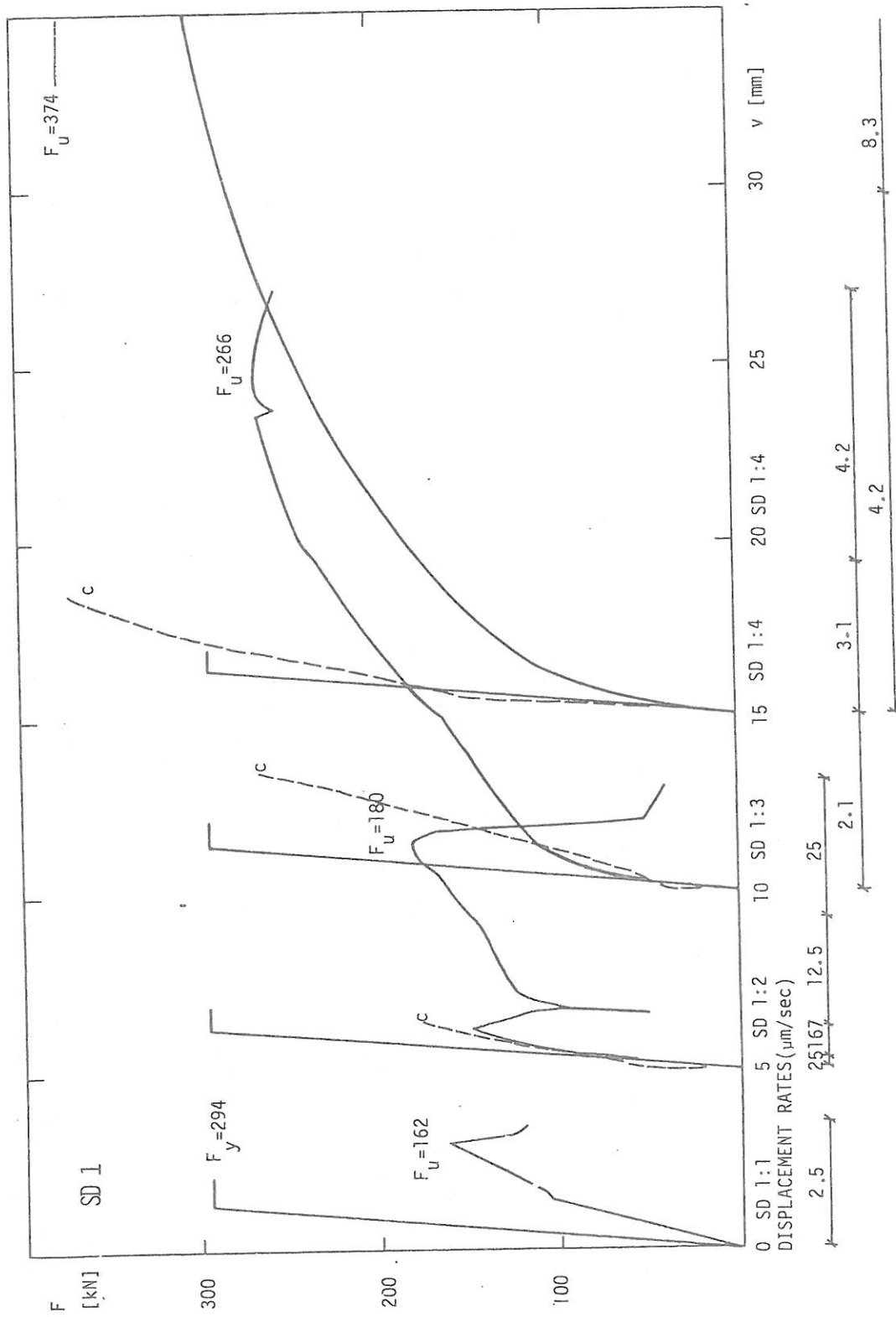
Fig A.4 Variation in bolt load $F_s = F_{so} \pm \Delta F_s$ when applied load $F = F_o \pm \Delta F$ is smaller than $F_p = E_s(\epsilon_{so} + \Delta\epsilon)A_s$

APPENDIX B. DISPLACEMENTS

The displacements registered for all the tested bolts are presented in Figs B1 - B7. The bolts in one foundation are grouped together and shown in the same figure.

In the figures are shown with full lines the displacement v of the anchor head relative to the concrete surface. With dotted lines are shown the displacement c of the concrete surface (compare with Fig 3.11). The total displacement of the anchor head is the sum of v and c . In the figures are also shown the theoretical deformation of the bolts if they were locked at the level of the washer nut. The theoretical values are based on a modulus of elasticity $E = 190 \text{ GPa}$ and a stress area $A_s = 459 \text{ mm}^2$ for bolt M 27 and $A_s = 561 \text{ mm}^2$ for bolt M 30.

The tests were run in position control and the velocities the hydraulic actuator piston are shown in the figures below the load-displacement diagrams. The velocity was typically $2.5 \text{ } \mu\text{m/sec} = 2.5 \cdot 10^{-6} \text{ m/sec} \approx 9 \text{ mm/hour}$ in the beginning of the tests. Later on the displacement rate was gradually speeded up and close to failure it usually was $25 \text{ } \mu\text{m/sec} \approx 90 \text{ mm/hour}$.



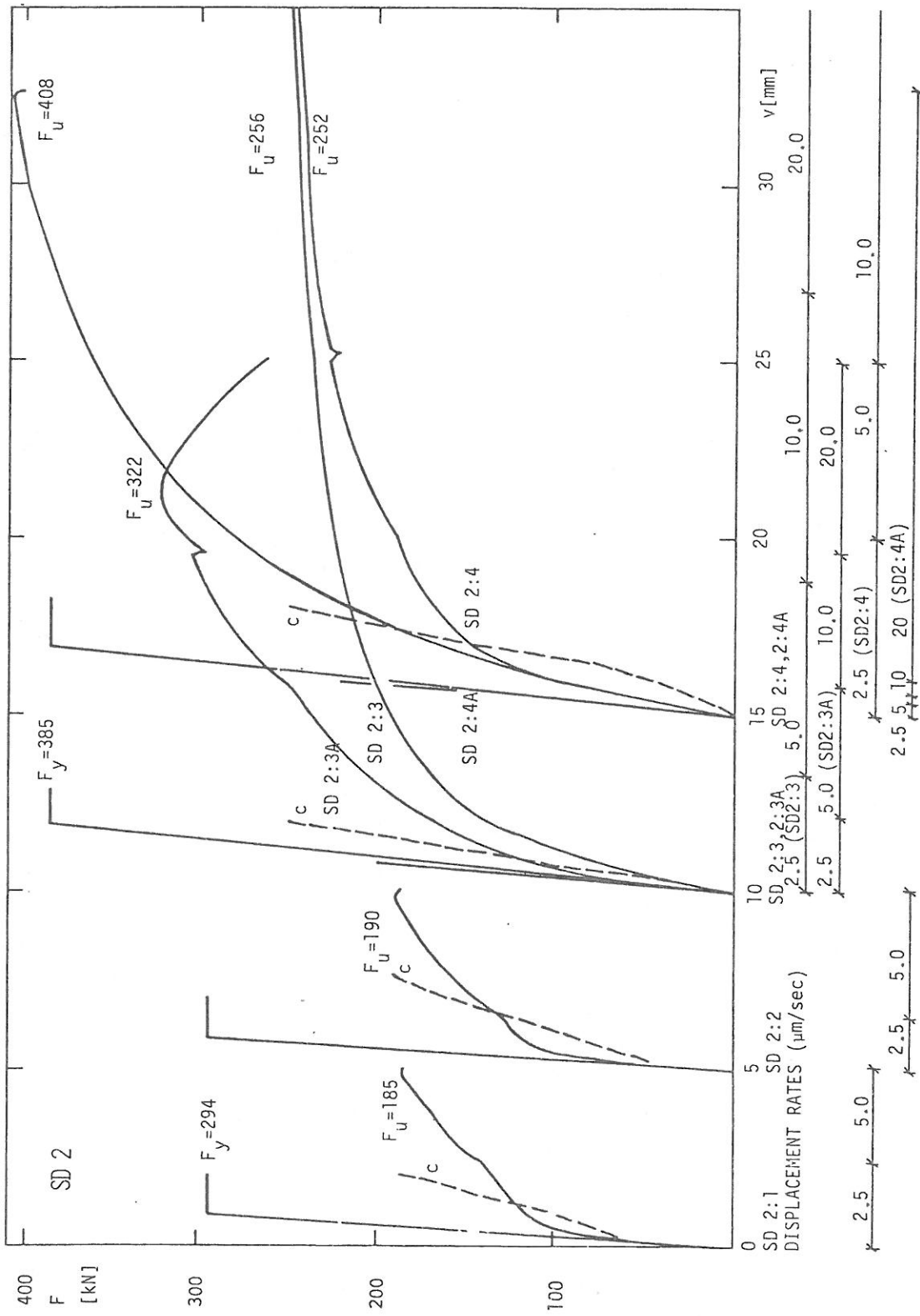


Fig B.2 Load displacement curves for foundation SD 2

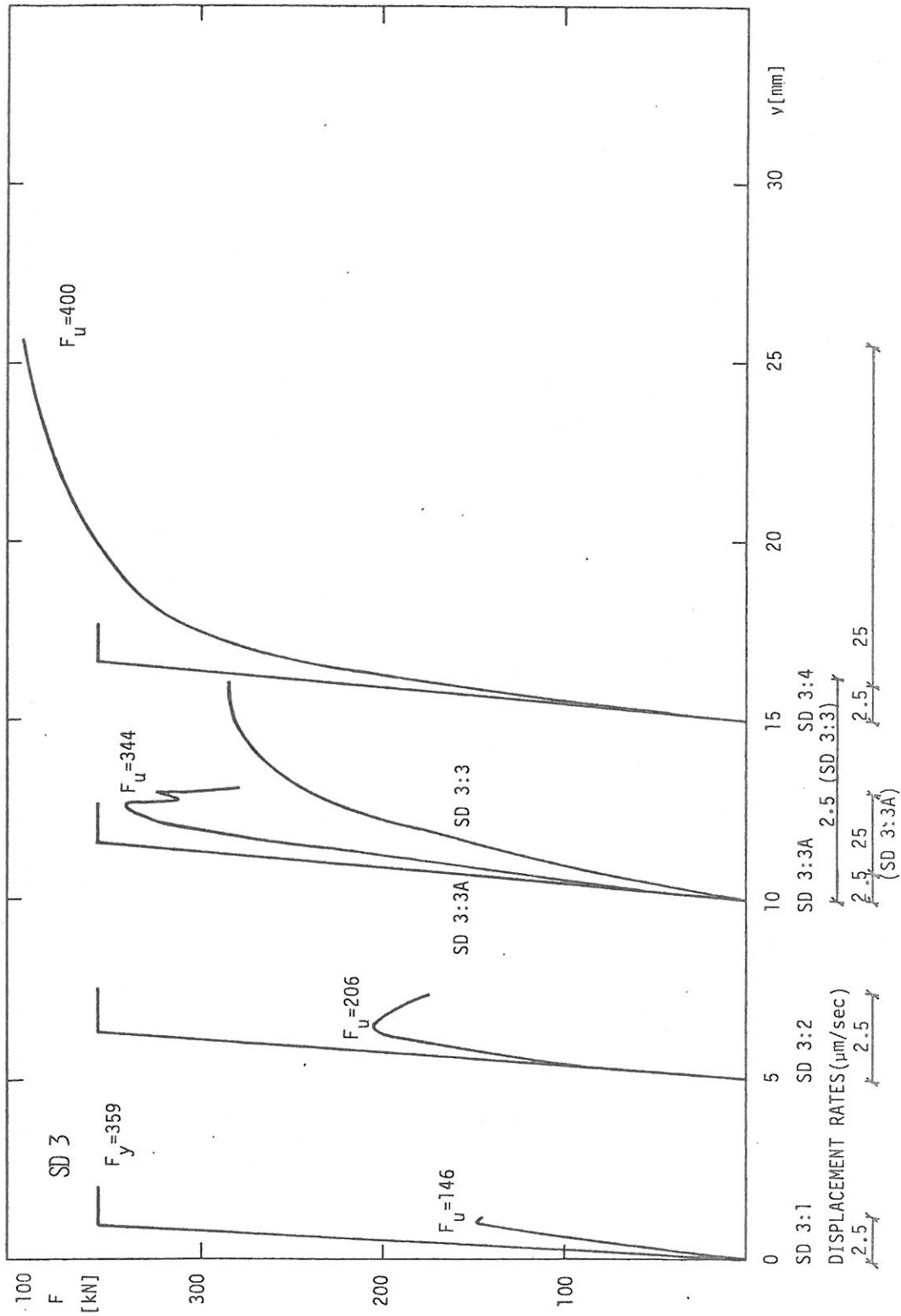


Fig E.3 Load displacement curves for foundation SD 3

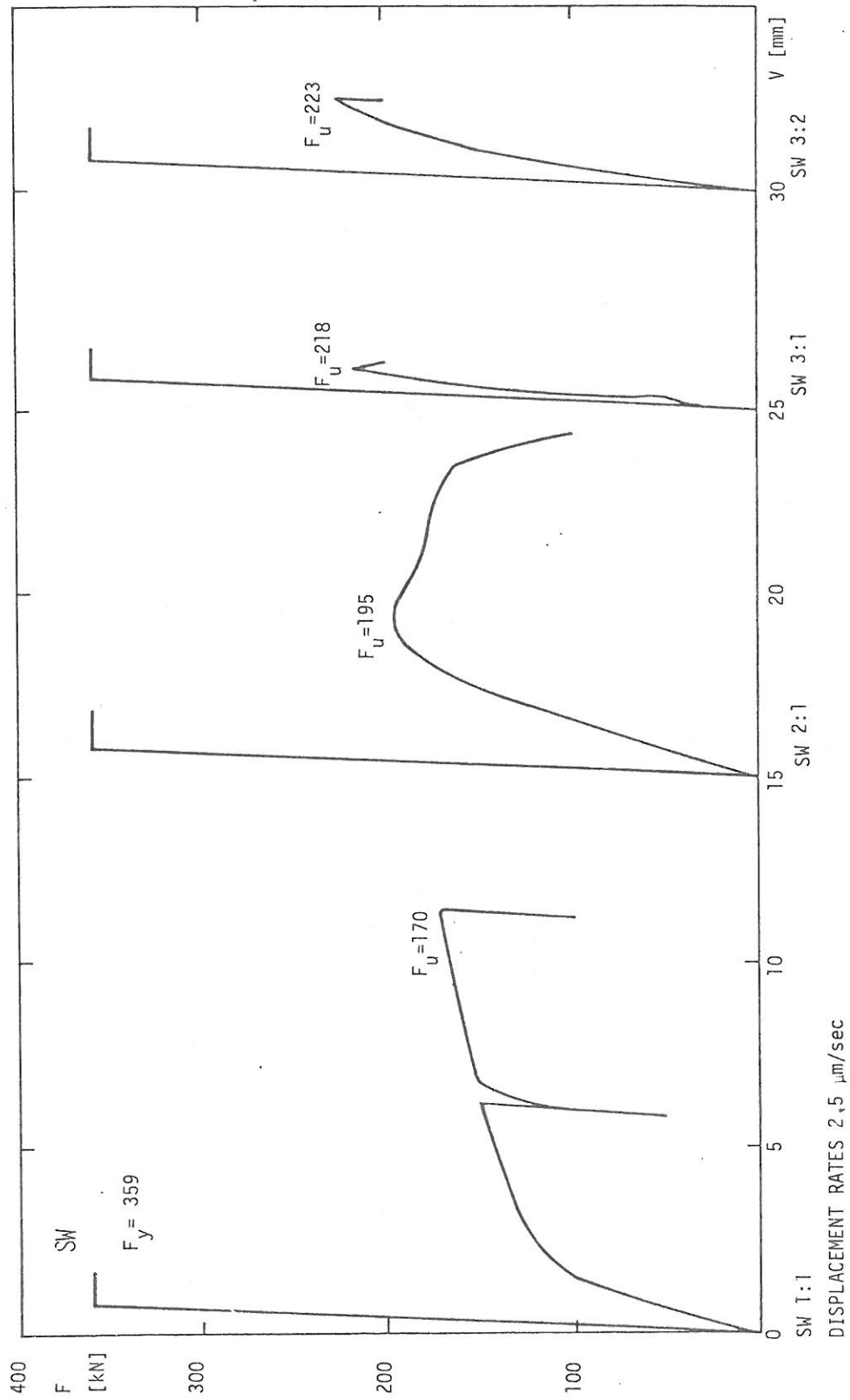


Fig B.4 Load displacement curves for foundations SW

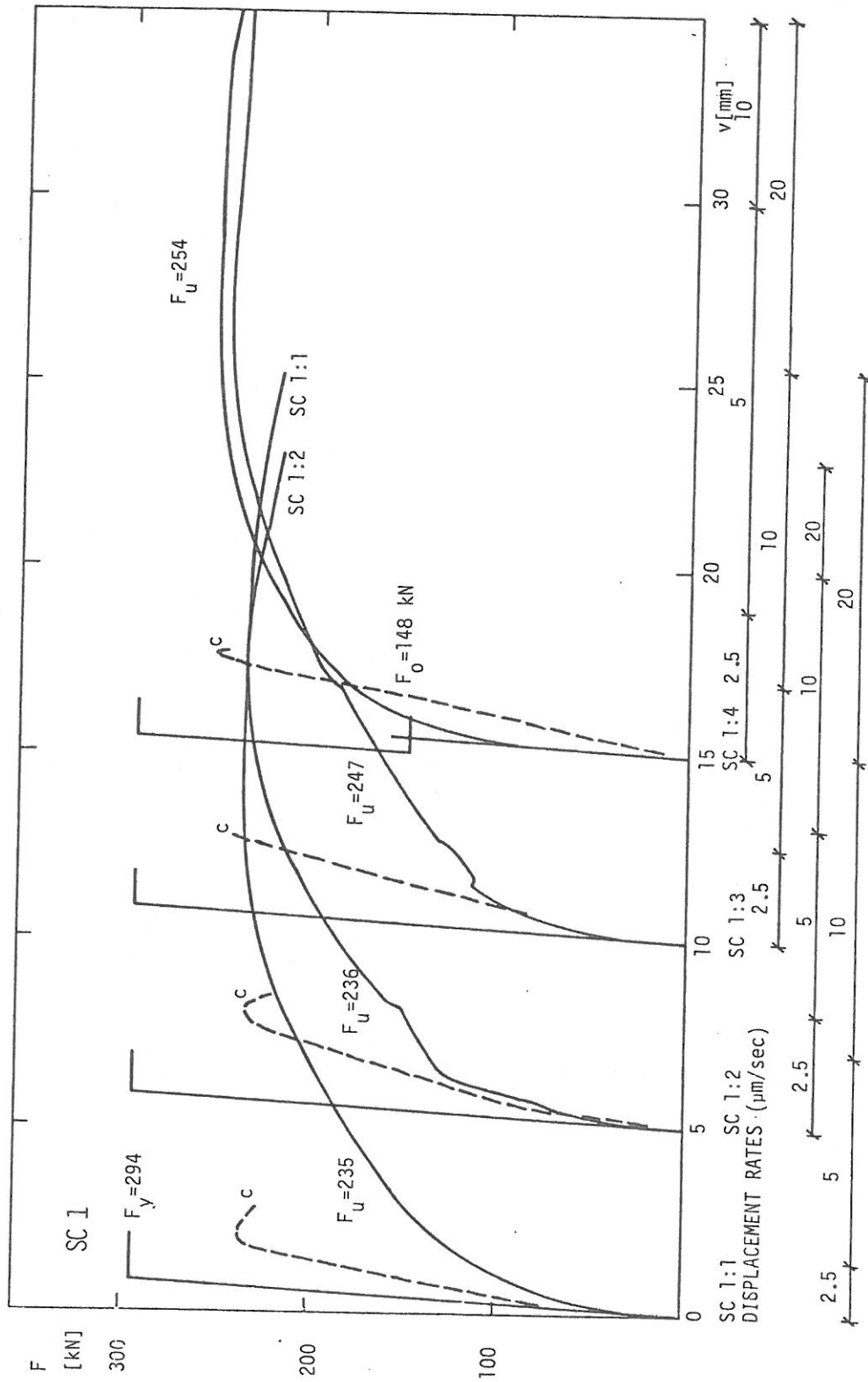


Fig B.5 Load displacement curves for foundation SC 1

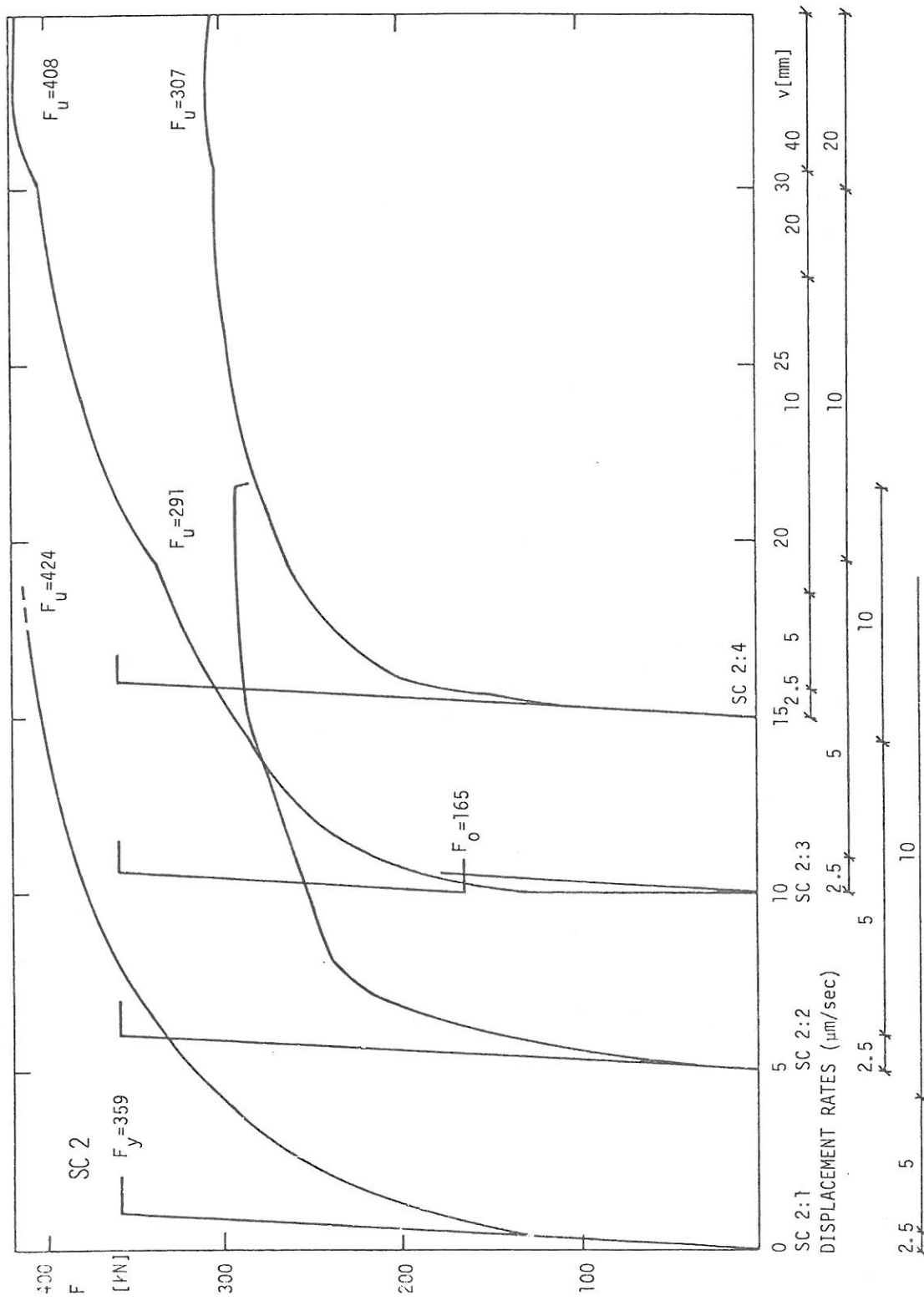


Fig B.6 Load displacement curves for foundation SC 2

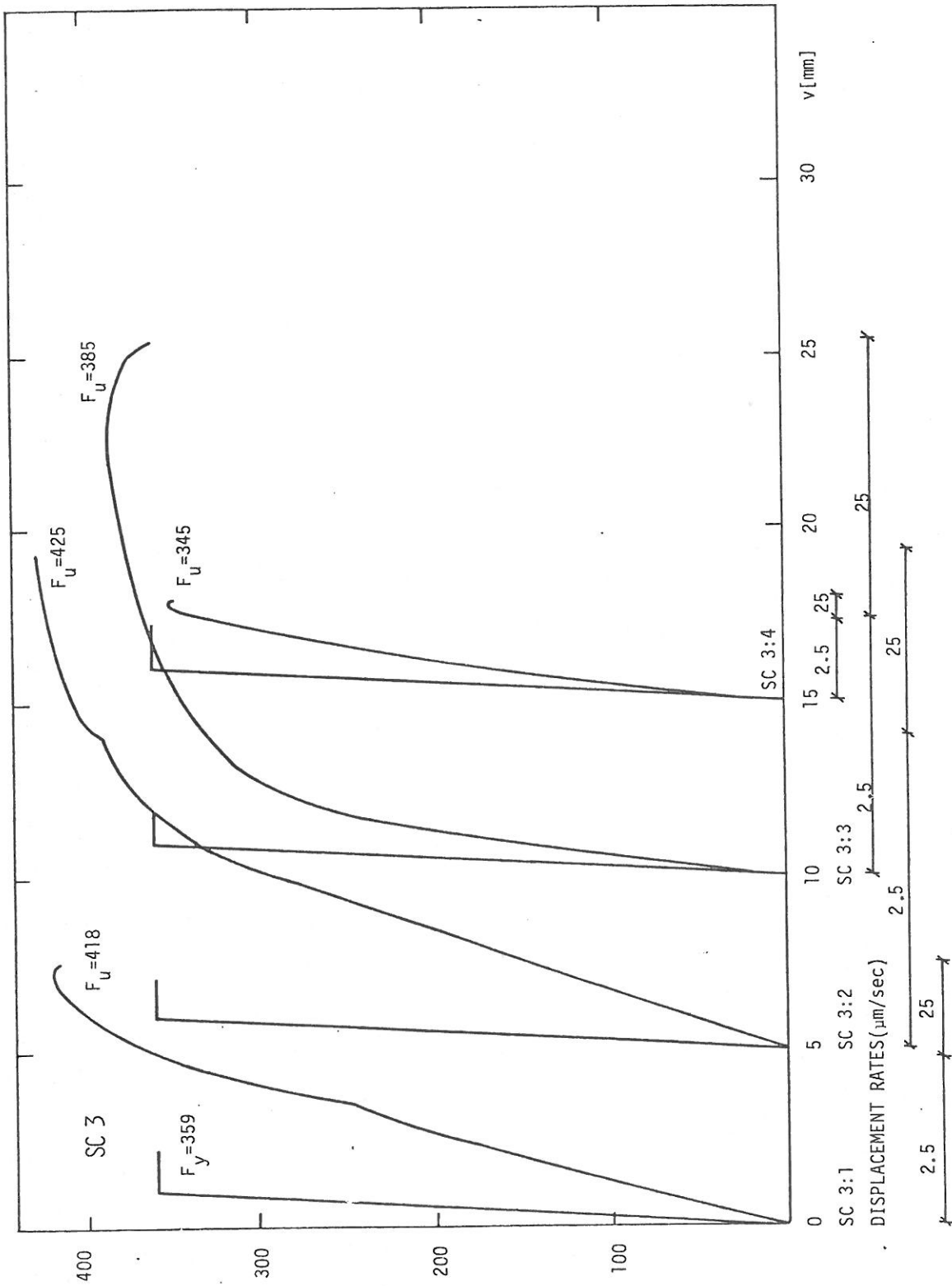


Fig B.7 Load displacement curves for foundation SC 3

APPENDIX C. PHOTOS

Photos of some of the bolts after failure are given in Figs C.1 - C.12.

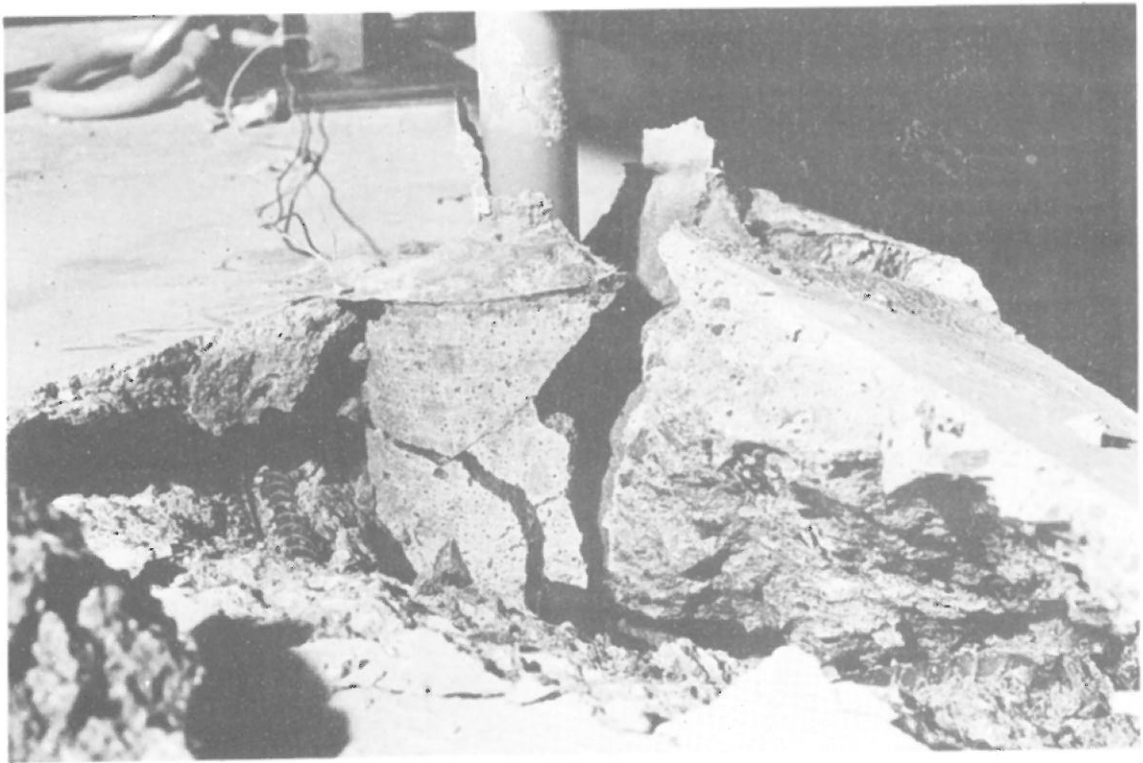
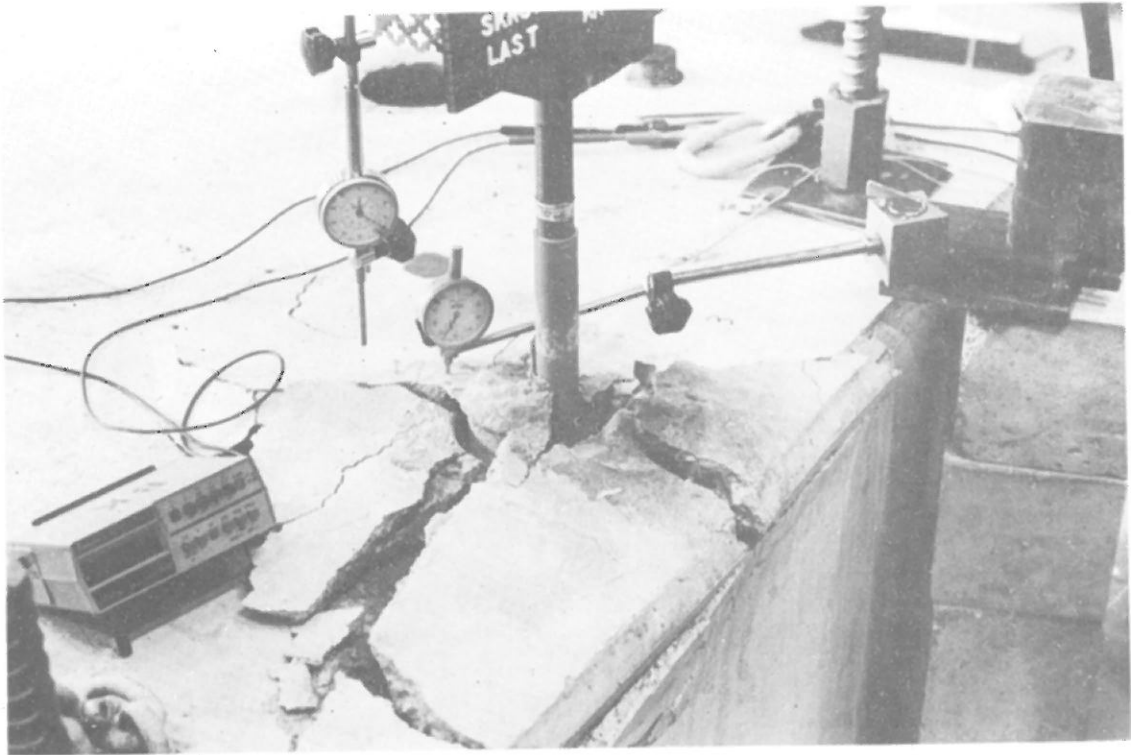


Fig C.1 Anchor bolt SD 1:1 at failure. Drilled hole with 200 mm depth and 150 mm edge distance. Anchor bolt M27 with washer $\phi 45 \times 3$. Reinforcement $\phi 10$ Ks 400 # 200. Ultimate load 162 kN

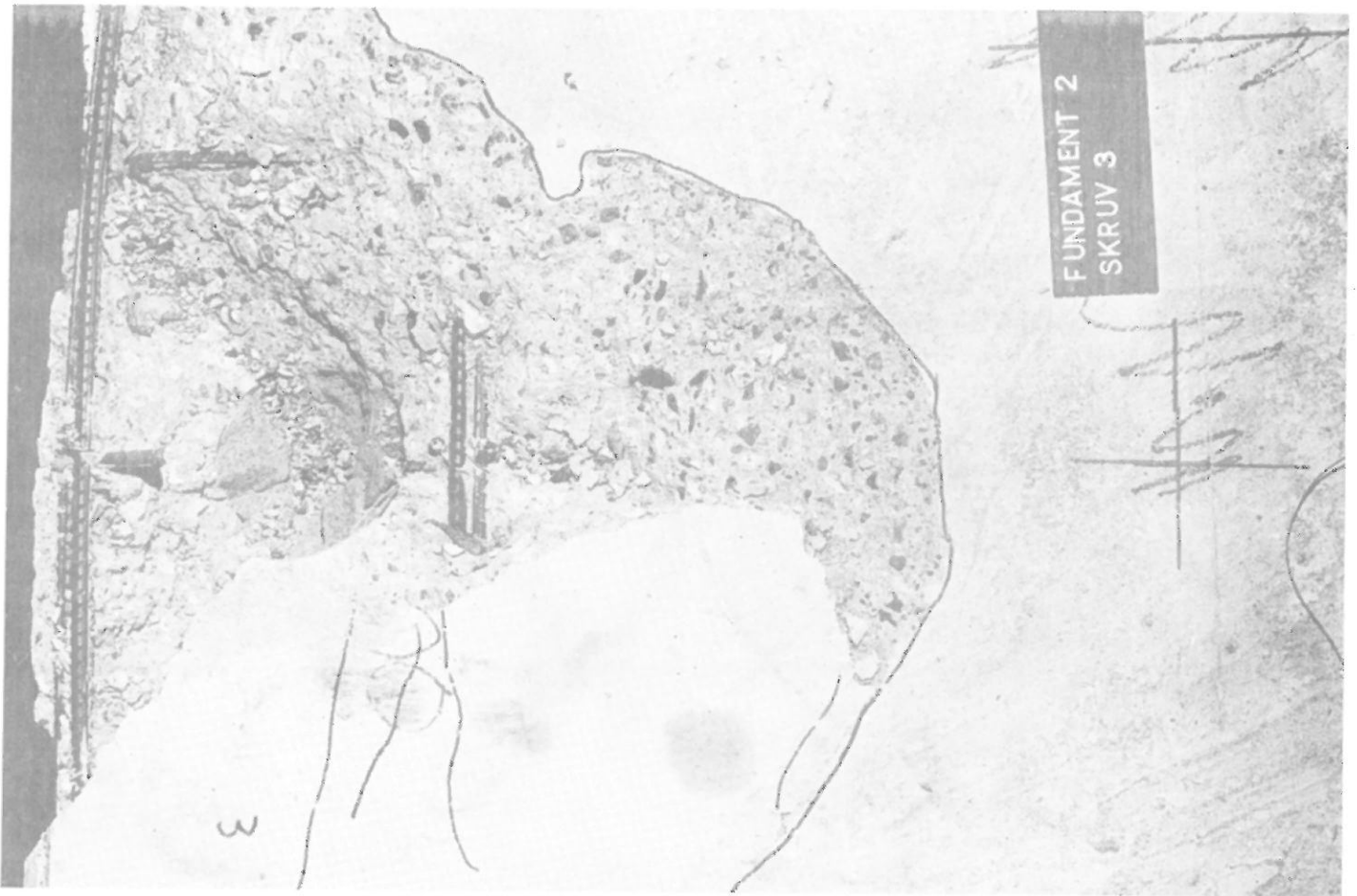


Fig C.2 Anchor bolt SD 1:1 at failure (continued)

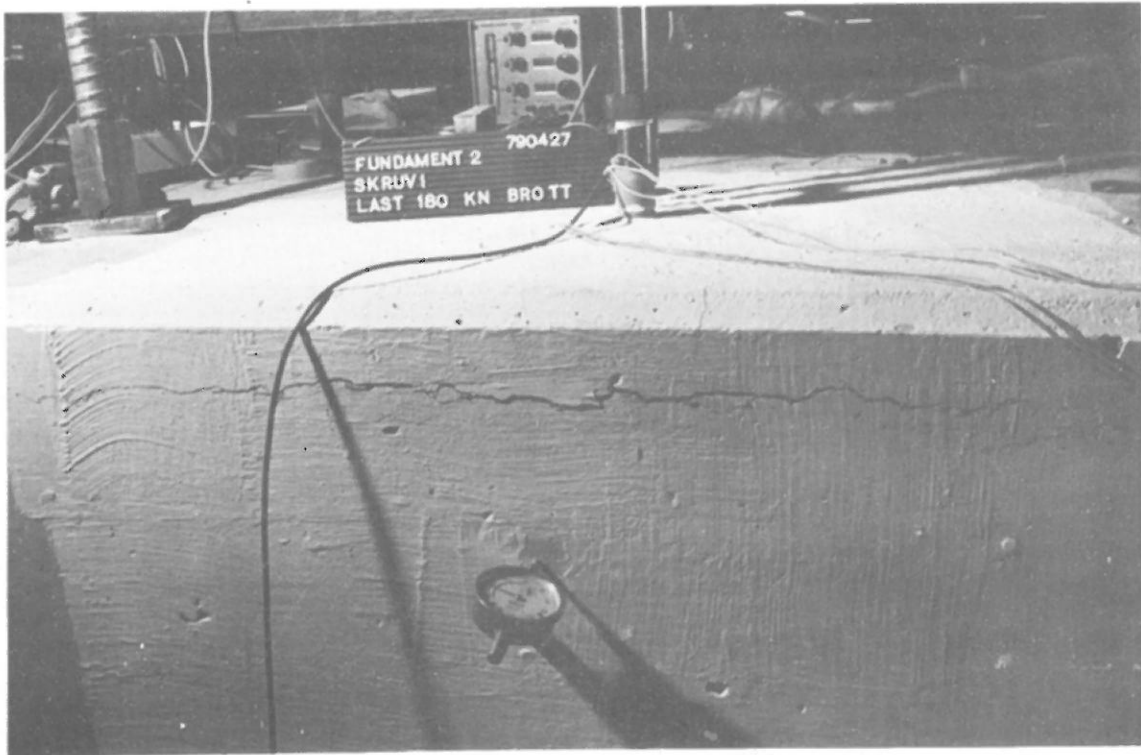
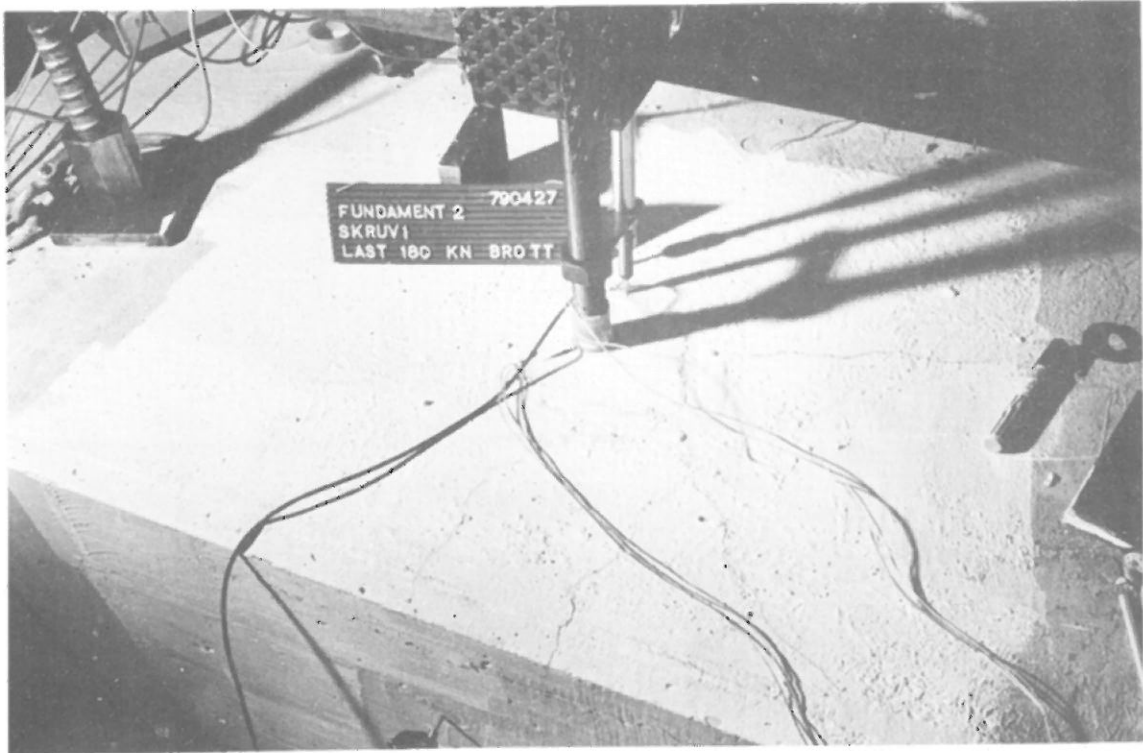


Fig C.3 Anchor bolt SD 1:2 at failure. Drilled hole with 200 mm depth and 300 mm edge distance. Anchor bolt M27 with washer $\phi 45 \times 3$. Reinforcement $\phi 10$ Ks 400 # 200. Ultimate load 180 kN

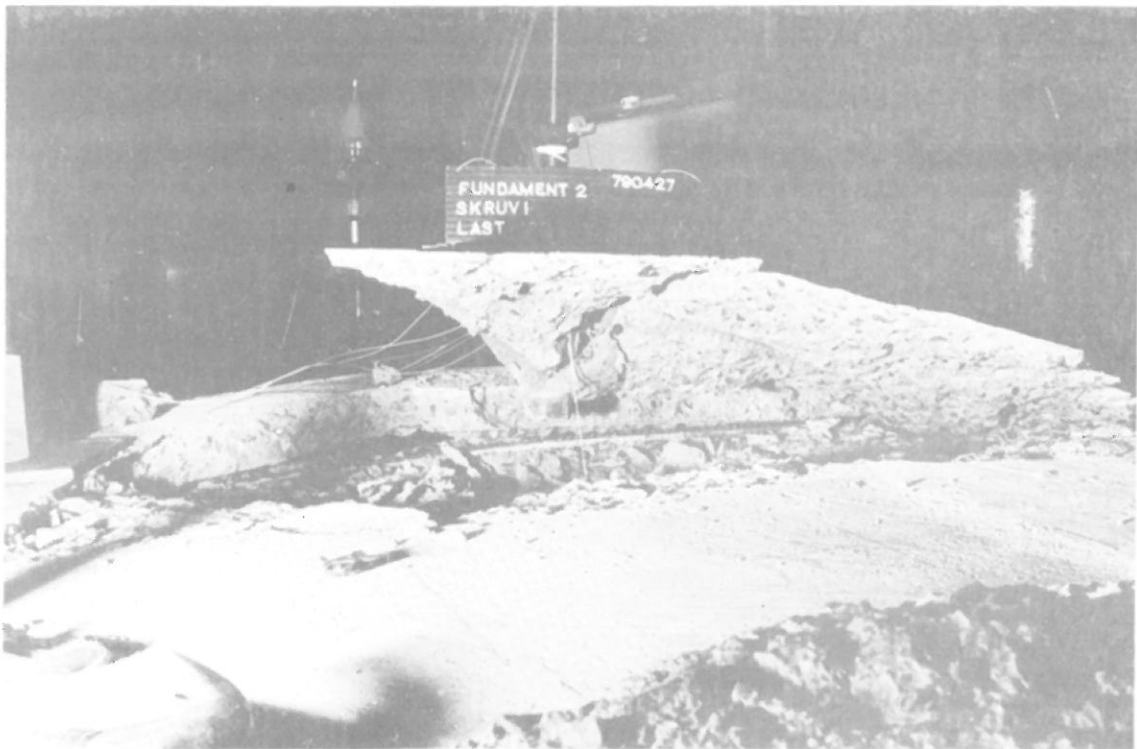
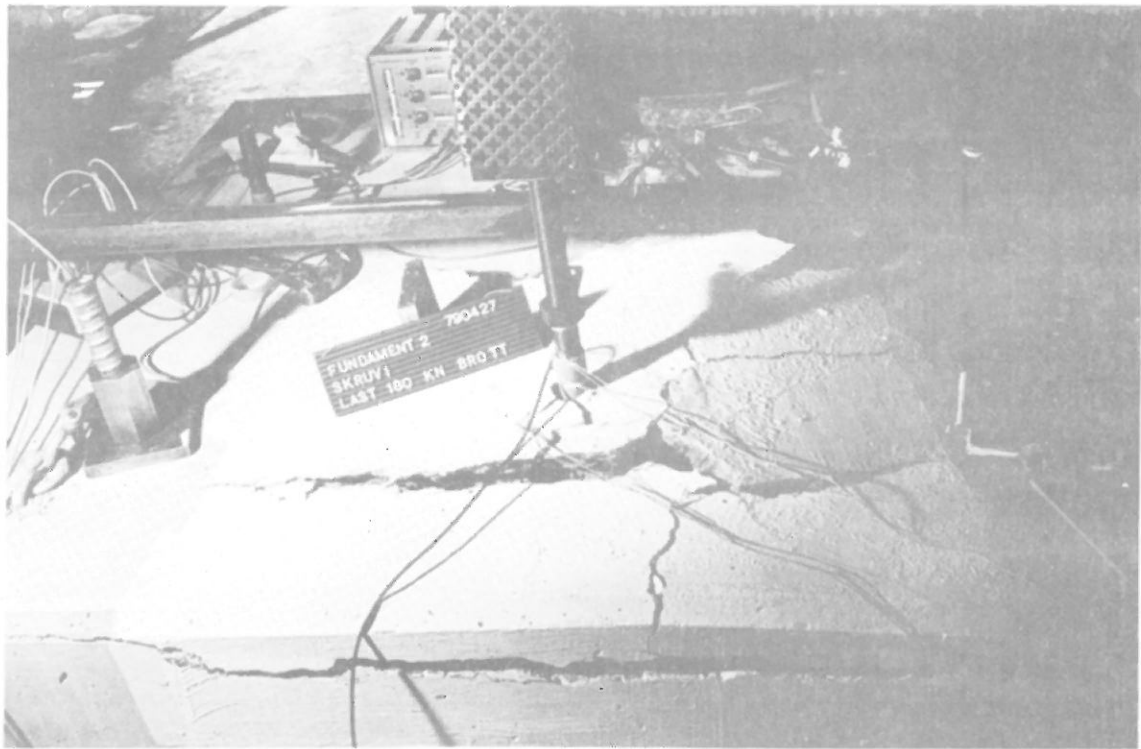


Fig C.4 Anchor bolt SD 1:2 at failure (continued)

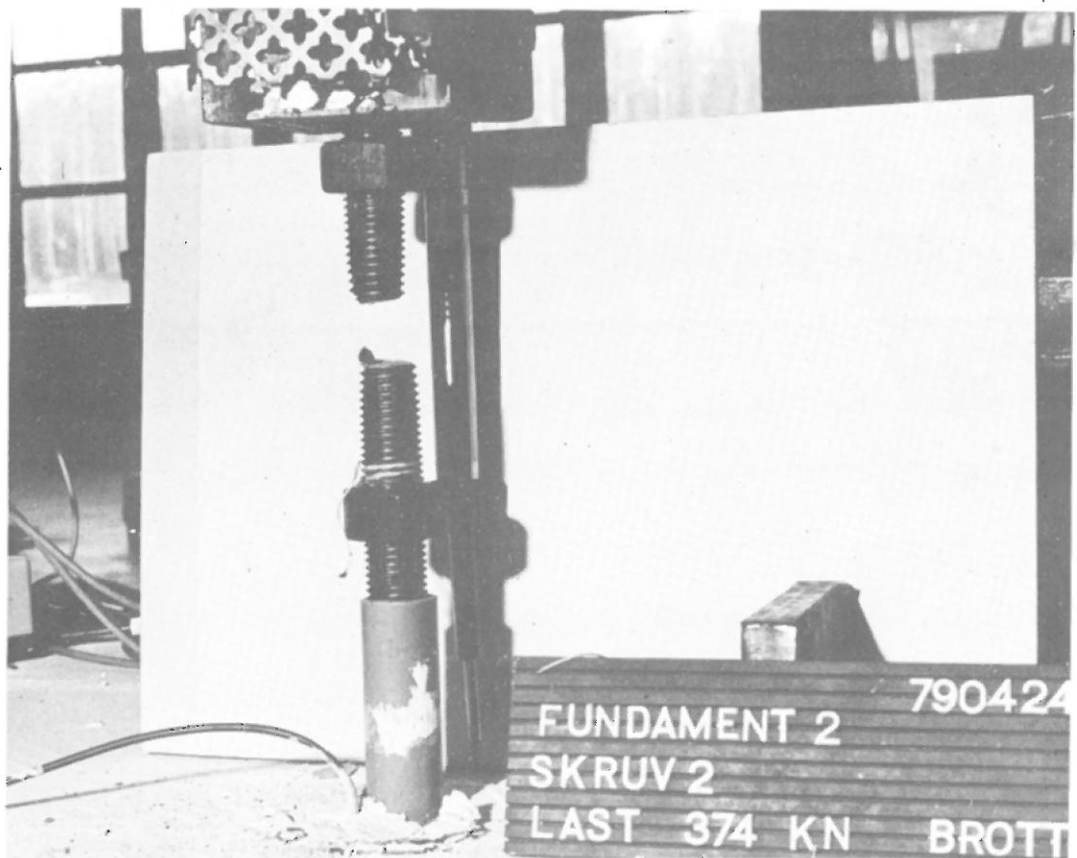
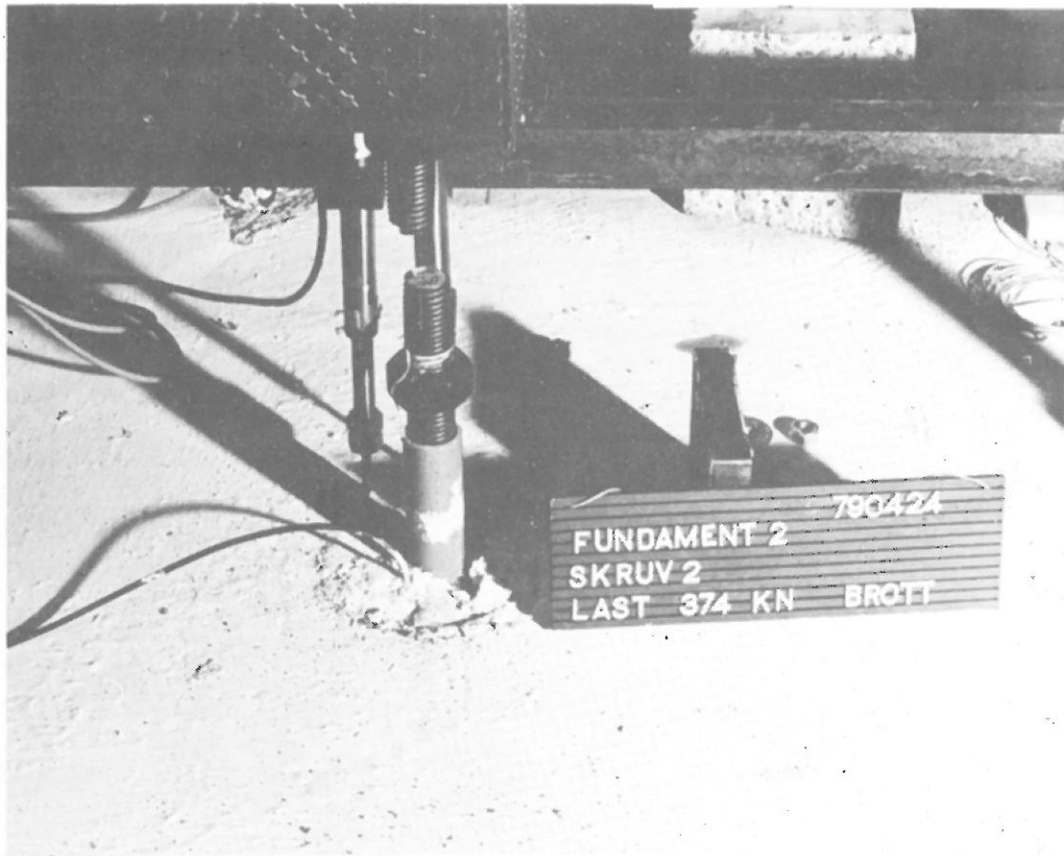


Fig C.5 Anchor bolt SD 1:4 at failure. Drilled hole with 400 mm depth and 150 mm edge distance. Anchor bolt M27 with washer $\phi 45 \times 3$. Reinforcement $\phi 10$ Ks 400 # 200. Ultimate load 374 kN (bolt failure)

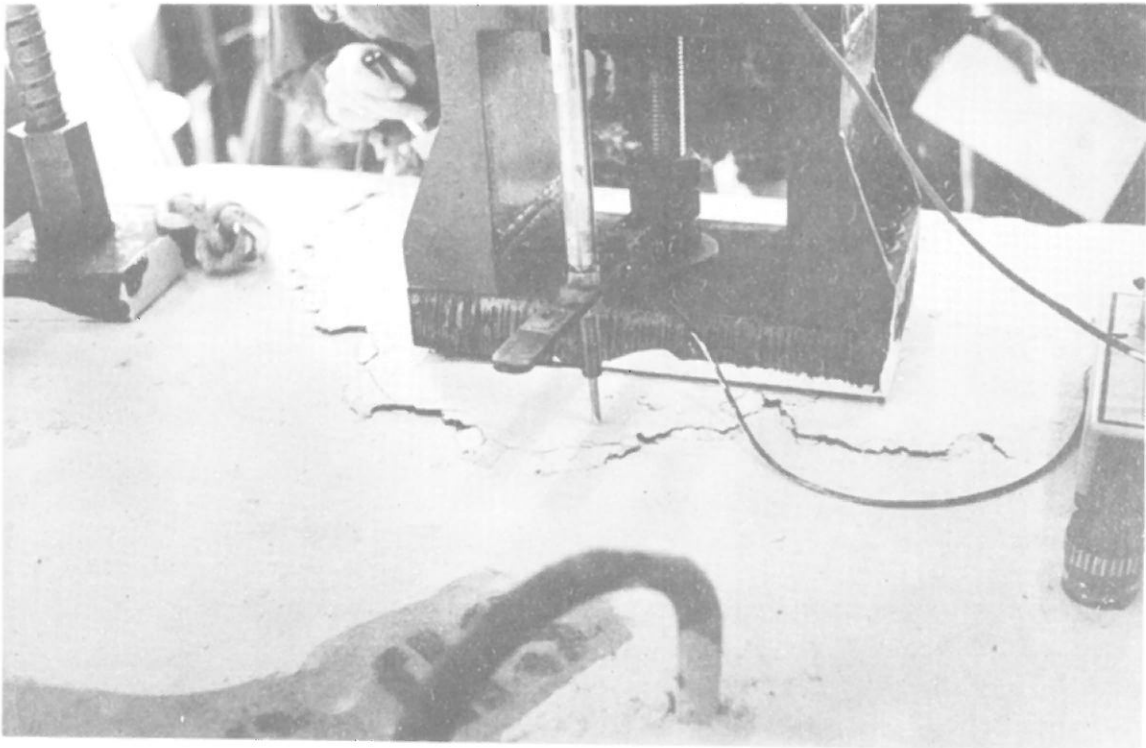
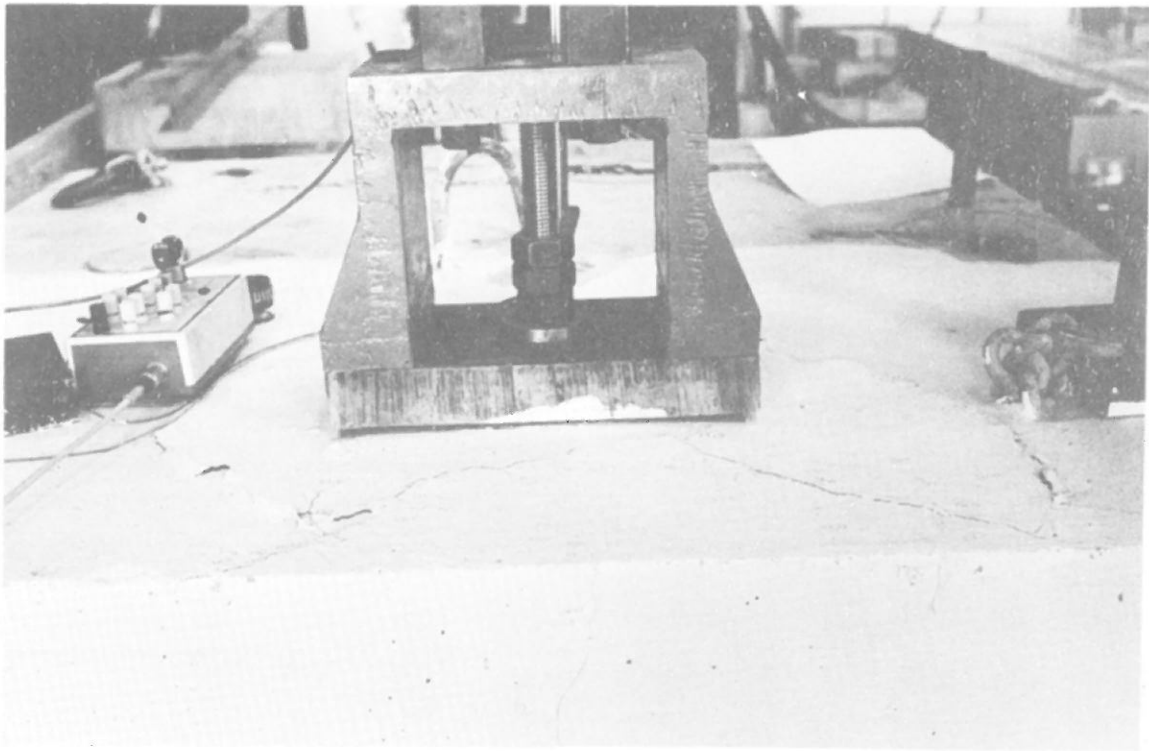


Fig C.6 Anchor bolt SD 3:2 at failure. Drilled hole with 200 mm depth and 300 mm edge distance. Anchor bolt M30 with washer $\phi 105 \times 24$. Reinforcement $\phi 10$ Ks 400 # 200. Ultimate load 206 kN. The load is applied with a fixing aimed for prestressed bolts. However, this bolt was not prestressed

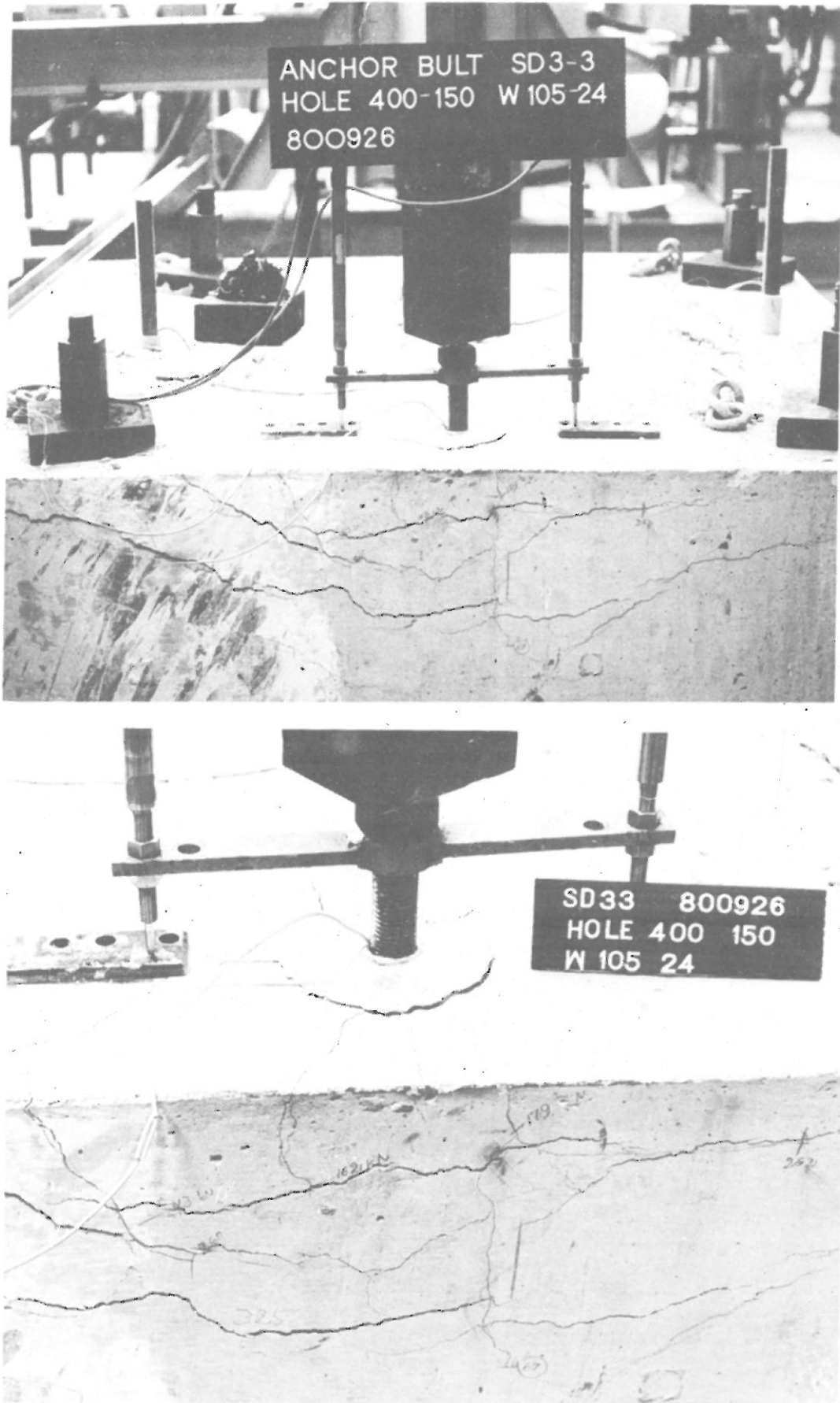


Fig C.7 Anchor bolt SD 3:3A at failure (second loading of bolt SD 3:3). Drilled hole with 400 mm depth and 150 mm edge distance. Anchor bolt M30 with washer $\phi 105 \times 24$. Reinforcement $\phi 10$ Ks 400 # 200. Ultimate load.

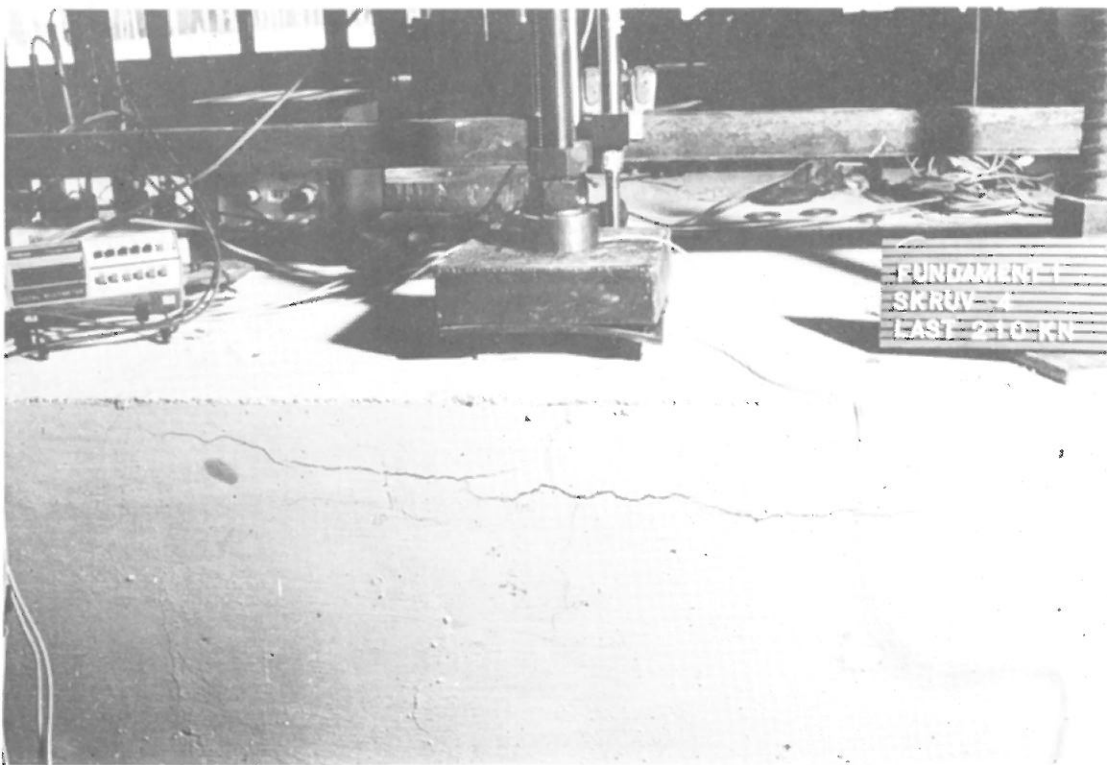
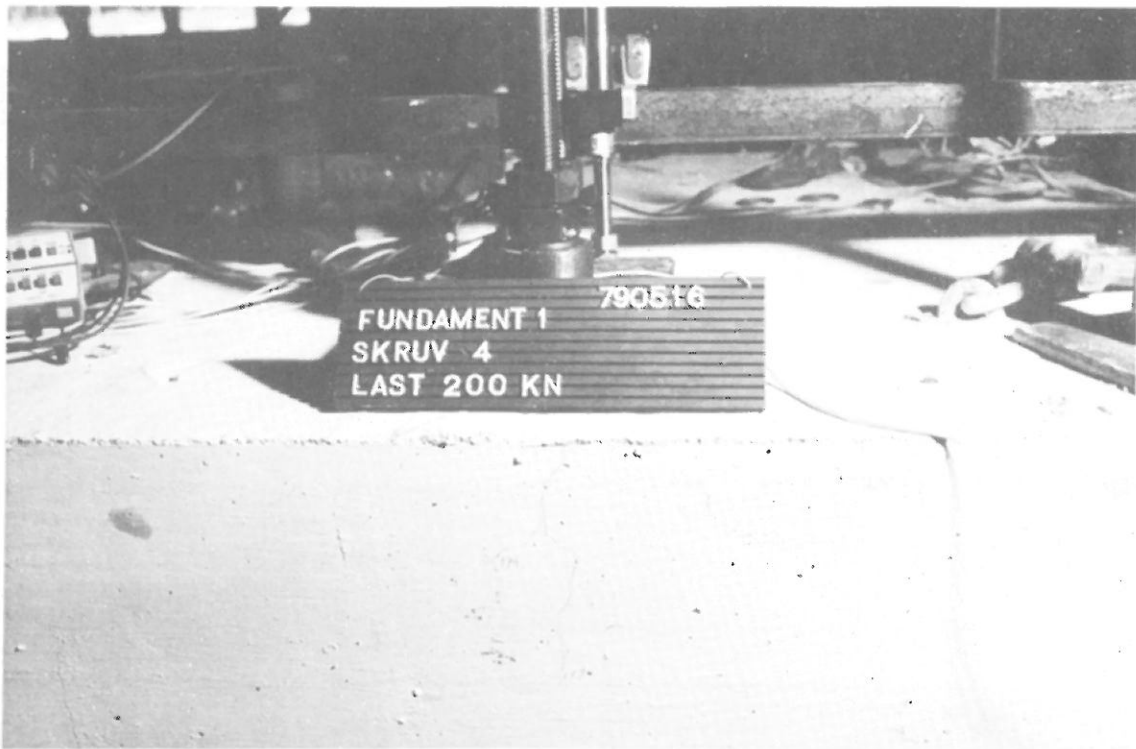


Fig C.8 Anchor bolt SC 1:4 at failure. Conical recess $\phi 120/170$ with 200 mm depth and 150 mm edge distance. Anchor bolt M27 with washer $\phi 45 \times 3$. Reinforcement $\phi 10$ Ks 400 # 200. Bolt prestressed to 163 kN. Ultimate load 254 kN.

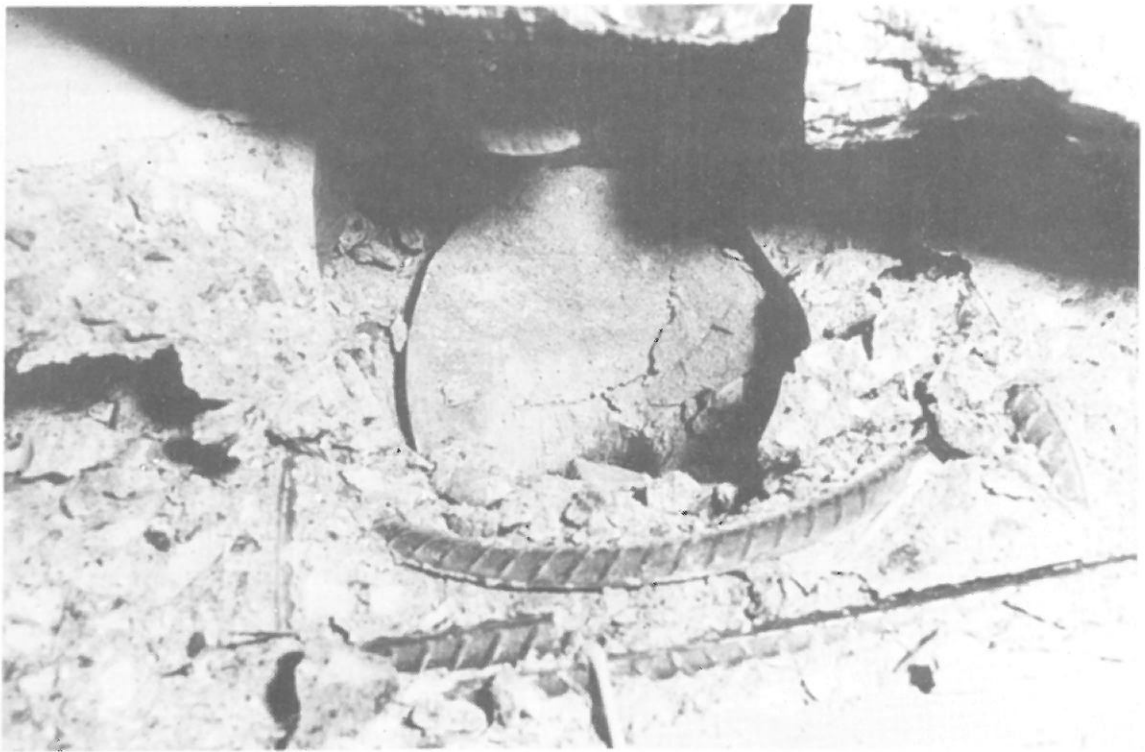
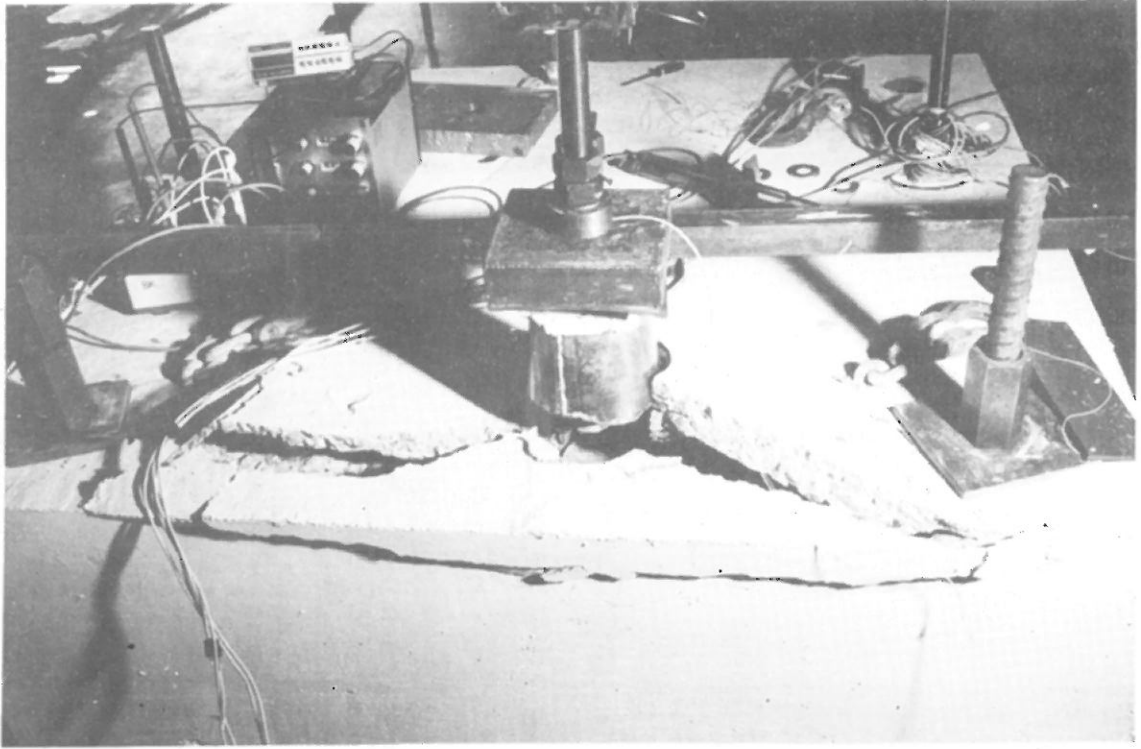


Fig C.9 Anchor bolt SC 1:4 after failure (continued)

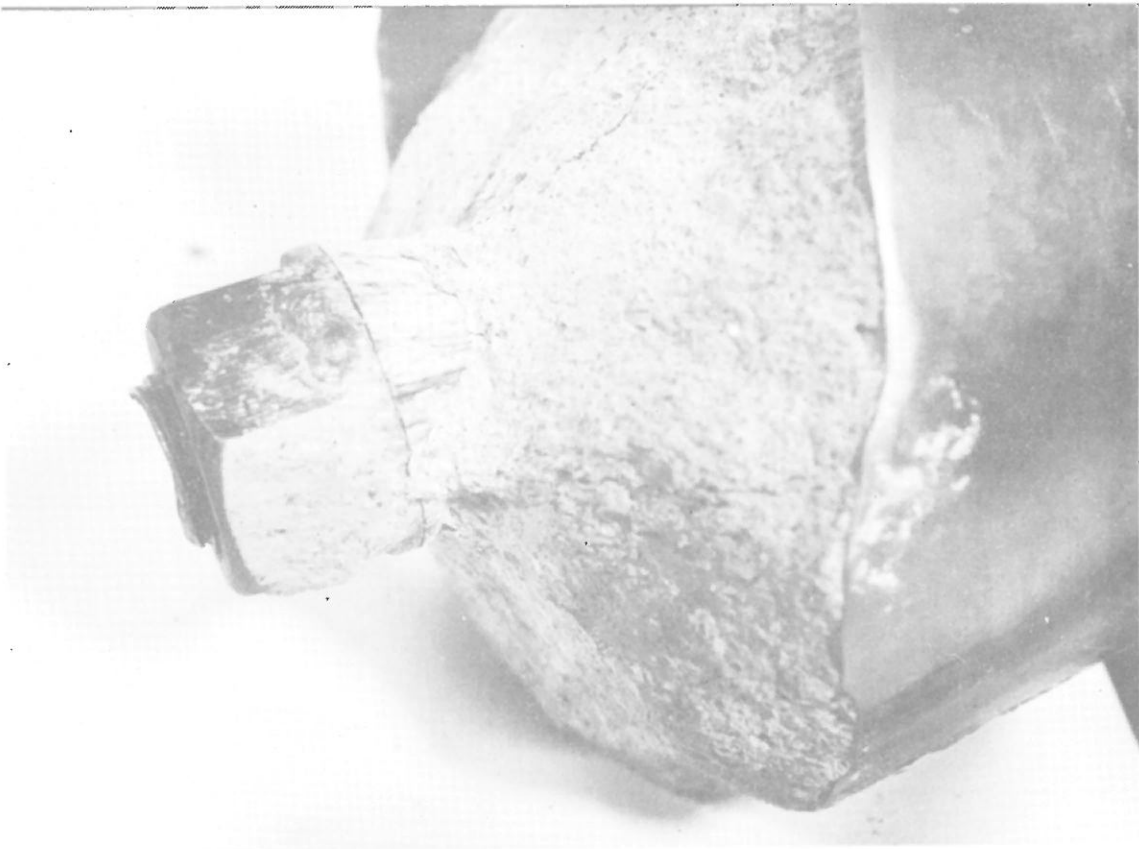
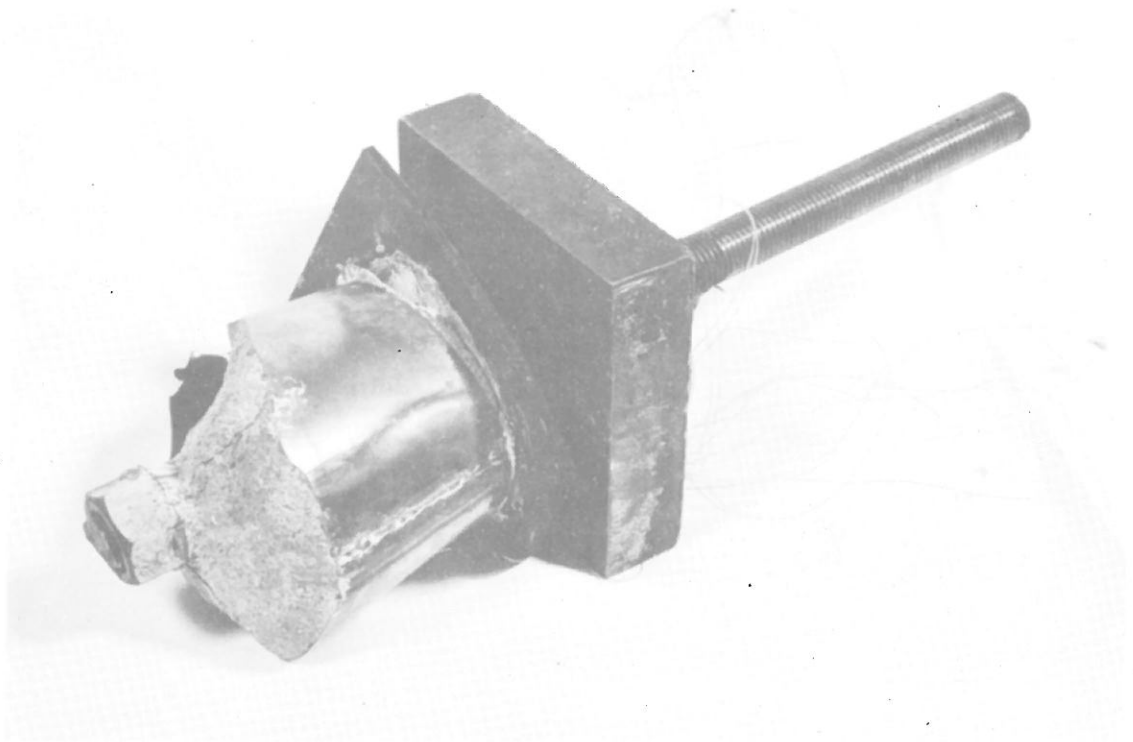


Fig C.10 *Anchor bolt SC 1:4 after failure. Detail of concrete above washer*

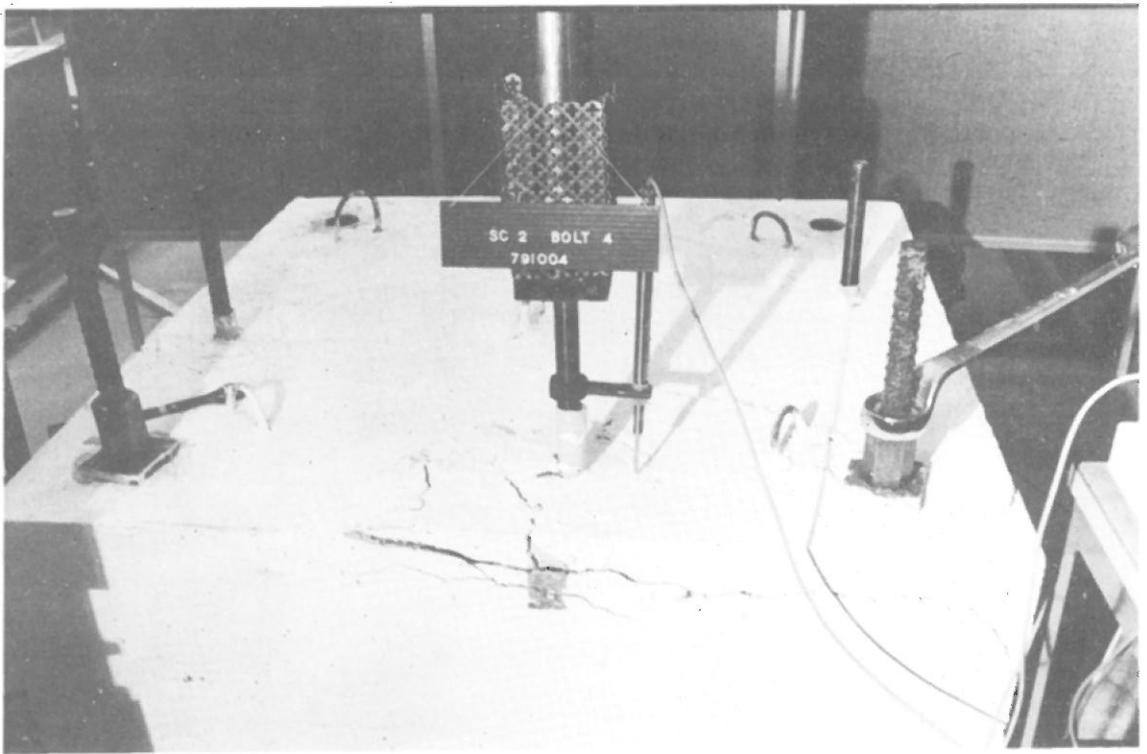
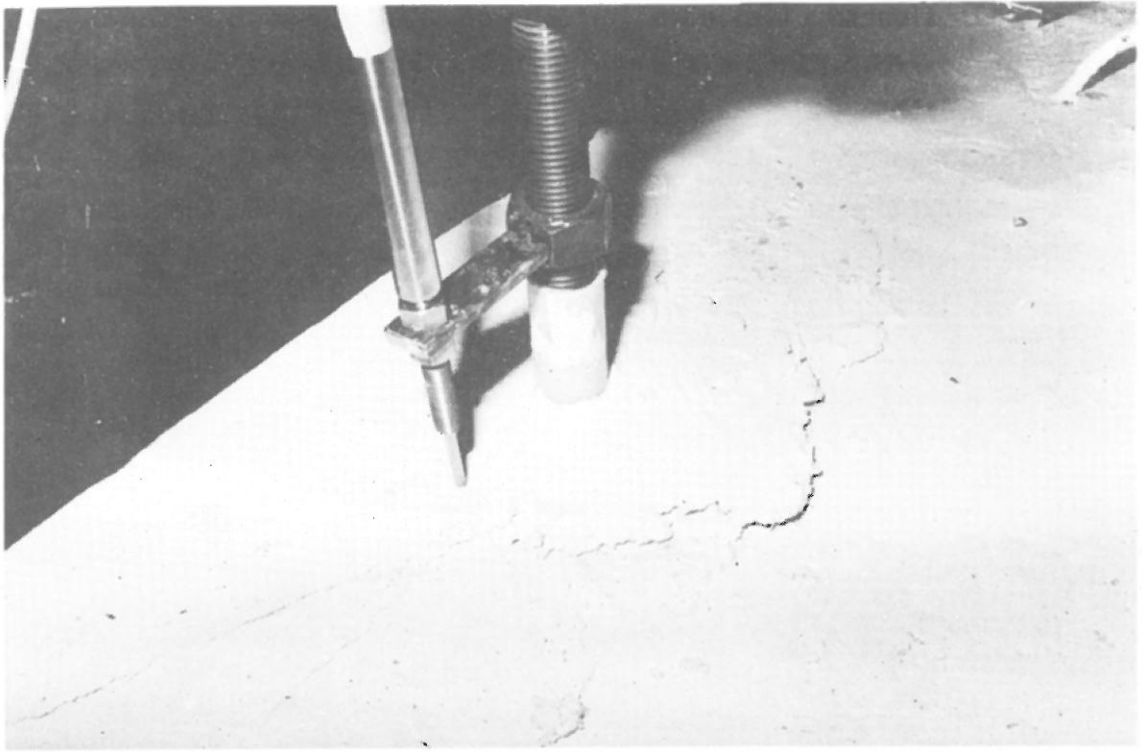


Fig C.11 Anchor bolt SC 2:4 at failure. Cylindrical recess $\phi 150$ mm made of steel with 250 mm depth and 160 mm edge distance. Anchor bolt M30 with washer $\phi 52 \times 6$. Reinforcement $\phi 10$ Ks 400 # 200. Ultimate load 307 kN

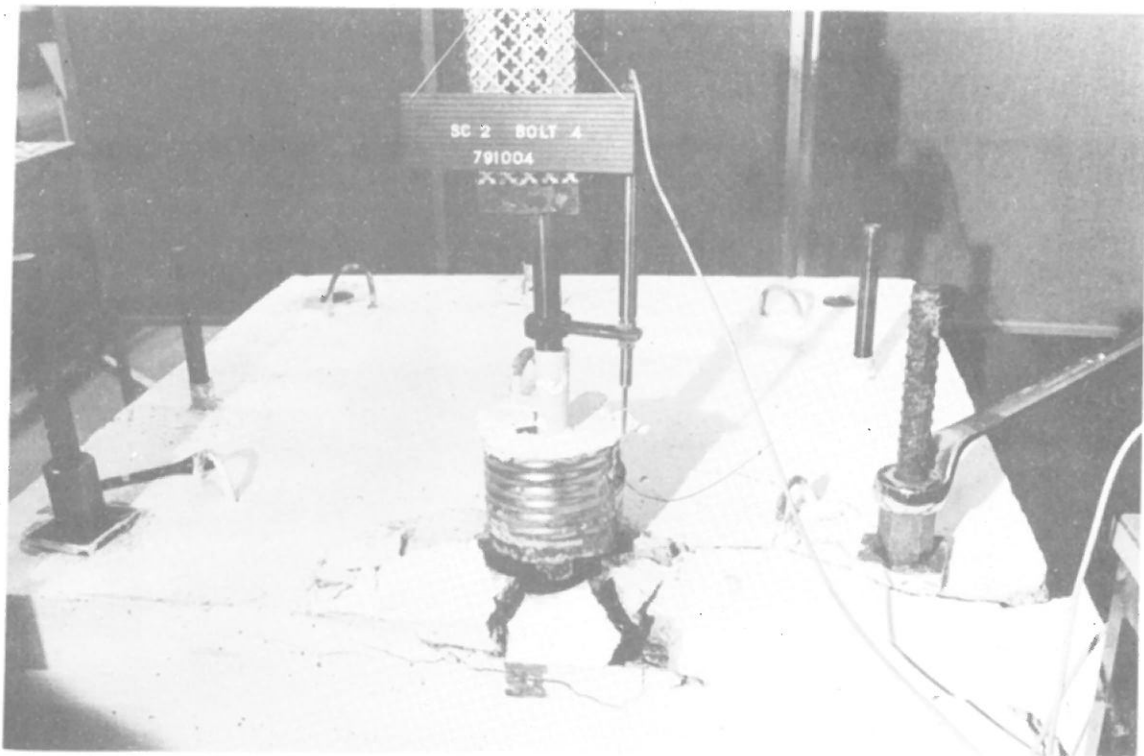
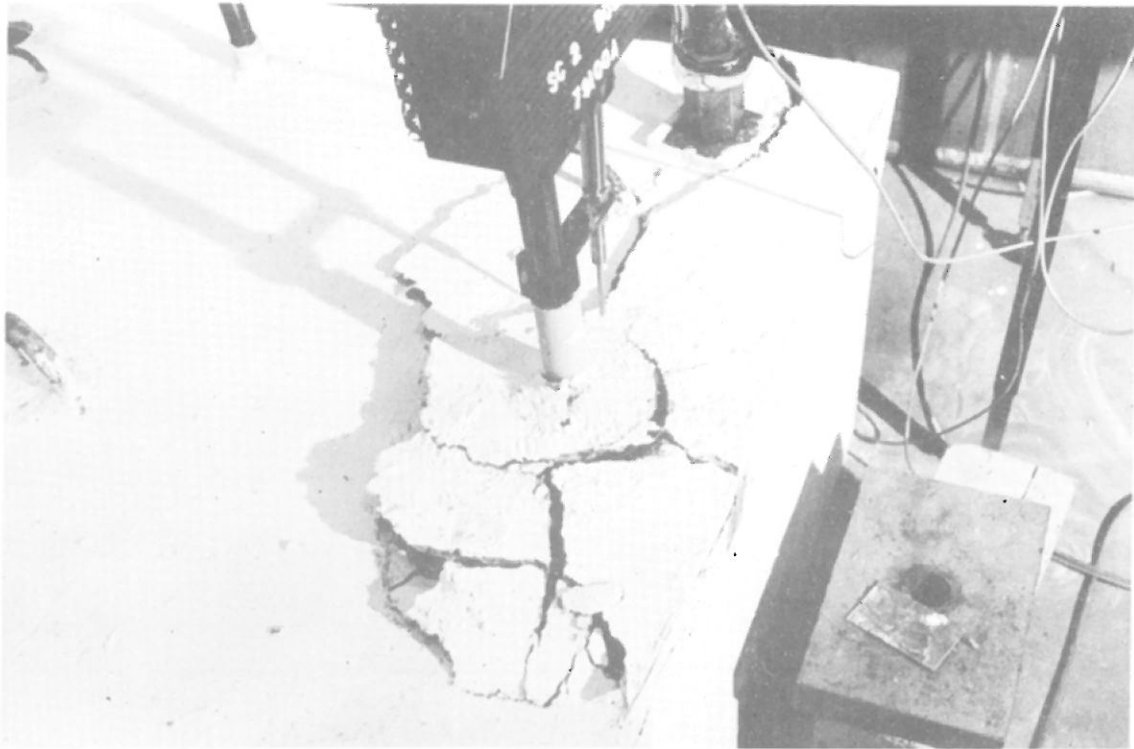


Fig C.12 Anchor bolt SC 2:4 at failure (continued)

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