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Fatigue of Anchor Bolts in Reinforced Concrete Foundations

Fatigue des boulons d'ancrage dans les fondations en béton armé

Ermüdung von Verankerungsbolzen in Stahlbetonfundamenten

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SUMMARY
Analytical methods to design anchor bolts are compared to test results from 16 tests with cyclic loading. The level of prestress is the most important factor for the life length of a bolt.

RESUME
Des méthodes analytiques pour le dimensionnement des boulons d'ancrage sont comparées aux résultats expérimentaux de seize essais soumis à des charges cycliques. Le degré de précontrainte est le facteur de plus important qui influence la durée de vie des boulons d'ancrage.

ZUSAMMENFASSUNG
Analytische Methoden für die Dimensionierung von Verankerungsbolzen werden mit Ergebnissen aus sechzehn Versuchen mit zyklischer Belastung verglichen. Der Vorspanngrad hat den grössten Einfluss auf die Lebensdauer des Verankerungsbolzens.

1. INTRODUCTION

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 foundation even long time after the foundation was cast.

These requirements have led to the development of various types of anchor bolts.

To be able to withstand cyclic loading, it is advisable to use prestressed bolts. In other cases very heavy bolts are required to withstand also relatively small cyclic loads. This is due to low fatigue capacity of bolts [1].

Two major types of anchor bolt arrangements are tested in this project [2]-[6]. In the first one, the recess for the bolt is provided by drilling a hole in the cast foundation, see Figure 1a. This type of recess has two main advantages. No special arrangements are needed 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 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 Figure 1b [2]. The cone is provided with a spiral reinforcement which helps to carry the splitting forces in the concrete. This type has a good ability to carry sustained and cyclic loading although some more effort is needed during construction.

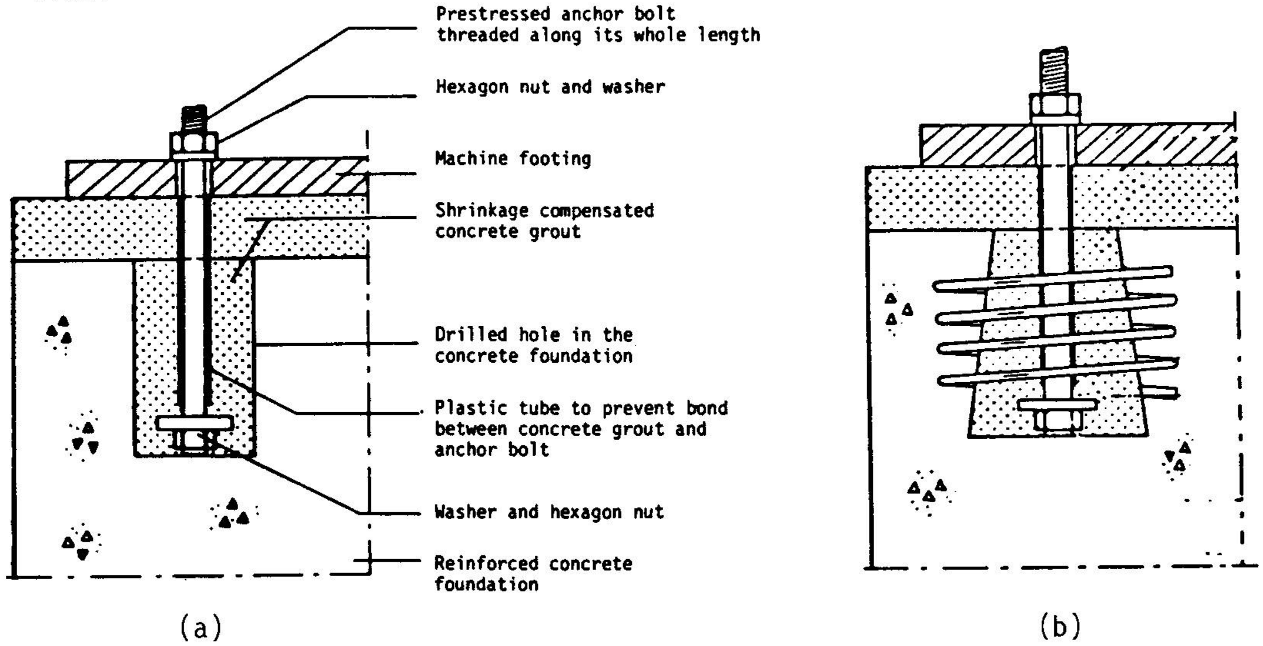

Fig 1 *Tested anchor bolts. (a) Bolt placed in a cylindrical hole drilled into a reinforced concrete foundation. (b) Bolt placed in a cylindrical recess. The recess is formed by a 0.5 mm thick metal sheet*

2. ANALYTICAL MODELS

2.1 Crack propagation

In order to study the propagation of a crack in the concrete, a fracture mechanics finite element model was used [6]-[8]. The model is illustrated in Figure 2 a, b and some results are given in Figure 2 c - f.

As can be seen from Figure 2, the fictitious (dashed line) and the real cracks (full line) grow as the load is increased. The cracks form a cone and the crack tip has to penetrate a larger area the more it grows. This implies that the crack is very stable also for fatigue loads. As soon as the crack tip penetrates a small distance, the stress in the zone around the crack tip will decrease and thus the crack propagation will be halted. For this reason there is usually no fatigue problems for the concrete [9], for a bolt which is loaded at a level reasonably below its static failure load.

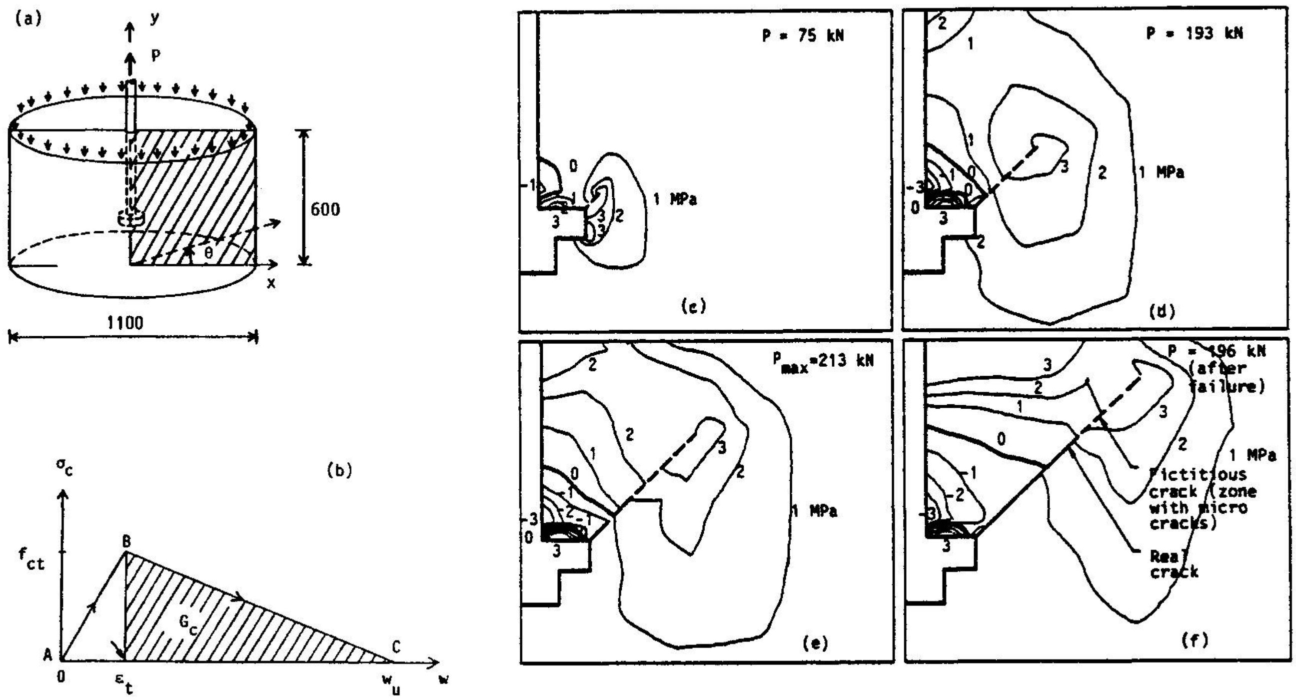

Fig 2 *Fracture mechanics model used for study of crack propagation* [4], [6]. *(a) Dimension of finite element model (96 axisymmetric elements + 10 linear crack elements). (b) Material model for loading (AB) and unloading of crack element (BC),* ε_t *= tensile strain,* w *= crack width. The following material properties were used for steel and concrete* E_s = 210 GPa, ν_s = 0.3, ρ_s = 7 800 kg/m^3, E_c = 30 GPa, f_{ct} = 3.0 MPa, ν_c = 0.2, ρ_c = 2400 kg/m^3, G_c = 60 N/m *(fracture energy) and* w_u = $= 40 \cdot 10^{-6}$ m *(maximum fictitious crack width). (c)-(f) Isostress lines for maximum tensile stress for different load levels. A micro crack (fictitious crack) is marked with a dashed line and a real crack is marked with a full line. (c) P = 75 kN, (d) P = 193 kN, (e) P =213 kN, maximum load, (f) P = 196 kN, after maximum load. The figure illustrates a test, where the anchor head deflection is the steering parameter.*

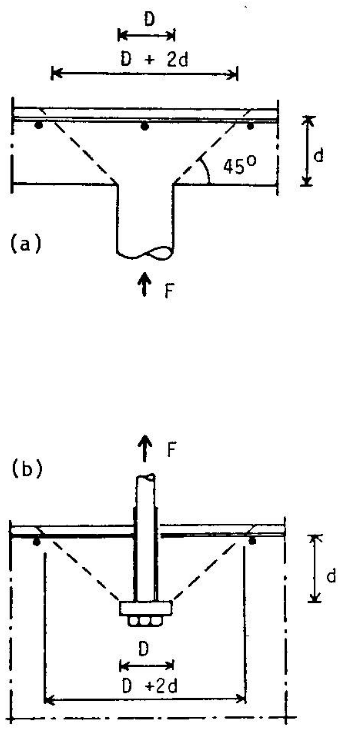

Fig 3 Comparison between punching (a) and anchor bolt failure (b)

2.2 Punching

The anchorage failure of a bolt is related to punching of slabs, see Figure 3. 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 Figure 3, $A = \pi 0.5(D+D+2d)\, d\sqrt{2} = \pi(D+d)\, d\sqrt{2}$, where D is the diameter of the column or the washer and d is the effective depth of the slab or the foundation.

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

$$F = Af_v/\sqrt{2} = \pi(D+d)d\, f_v \qquad (1)$$

In the 1978 CEB-FIP Model Code [10] the value of f_v depends on the concrete strength, the depth d, and the amount of the reinforcement in the top of the slab. In the United States a similar approach has been proposed [12].

2.3 Influence of prestress

A simplified model illustrating the influence of prestress is shown in Figure 4. A prestressing force P_o 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 A_s, the effective concrete area is A_c, the length of the bolt is L_s, the effective length of the concrete is L_c, and the modulus of elasticity for steel and concrete grout are E_s and E_c, respectively. Equilibrium gives, see Figure 4a, $P_o = E_sA_s\varepsilon_{so} = E_cA_c\varepsilon_{co}$. Here ε_{so} and ε_{co} can be written as $\varepsilon_{so} = v_{so}/L_s$ and $\varepsilon_{co} = v_{co}/L_s$, where v_s and v_c denote the elongation and the compression of the bolt and the concrete, respectively.

If now a force F (less than P_o) is applied to the machine footing, the bolt head will move a small distance v. The strain will increase in the bolt and it will decrease in the concrete grout. 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 Figure 4a and 4b, $F = F_s - F_b = E_sA_s\, v(r+1)/(L_s r)$, where $r = E_sA_sL_c/(E_cA_cL_s)$. This holds for $F \leq P_o$. If the applied force F is greater than P_o, the concrete compressive force will be reduced to zero. The applied load will then be carried by the steel bolt alone, $F = F_s = E_sA_s(v_{so}+v)/L_s$.

The applied force F, the tensile steel force F_s and the compressive concrete force F_c are shown in Figure 4b as functions of v. The numerical values are chosen to be representative for a bolt with dimension M 30. The applied force F is increasing steeply for small deformations v when $F < P_o$. When the concrete compressive stress disappears for $v = v_{co}$ and $F = F_p = E_sA_s(v_{so} + v_{co})/L_s$ the applied load must be carried by the steel bolt alone. Accordingly, there is a change of the slope of the F-v-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 Figure 4b,

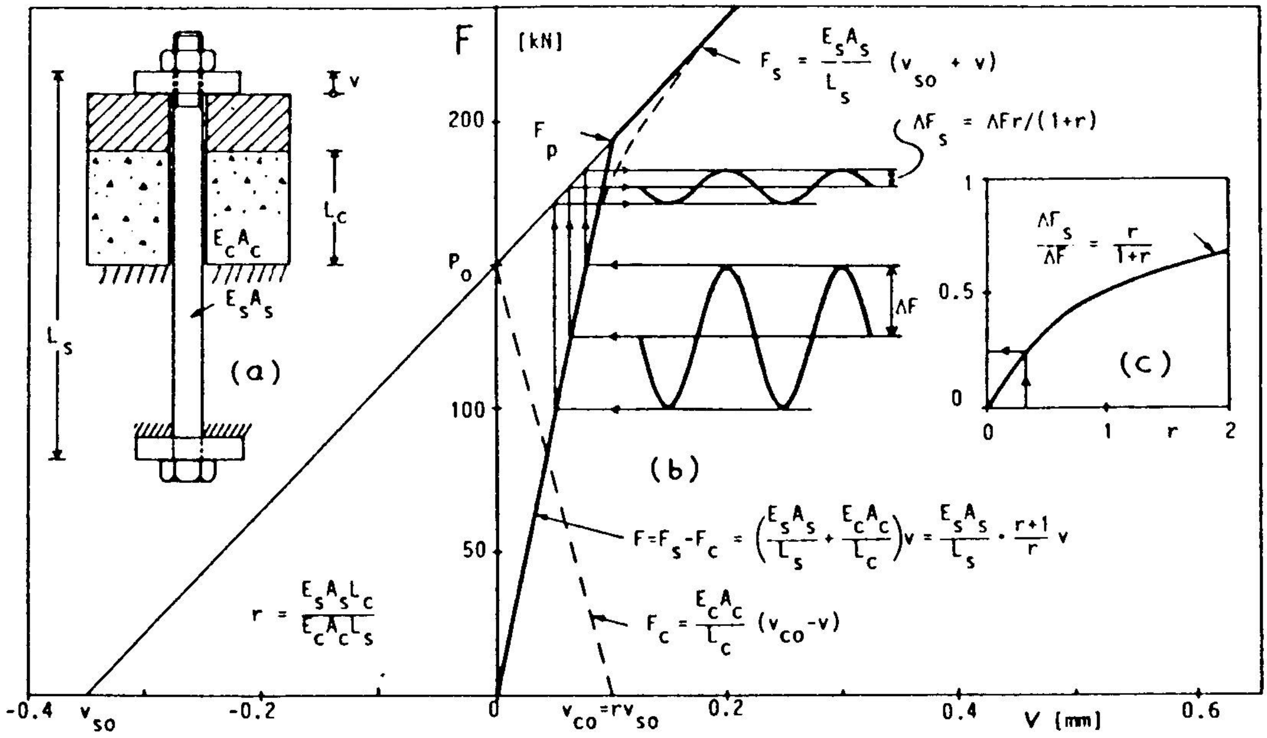

Fig 4 *Prestressed anchor bolt. (a) Simplified theoretical model. (b) Applied force F, tensile bolt force F_s and compressive concrete force F_c as function of bolt displacement v. Numerical values: E_s = 190 GPa, A_s = 561 mm^2 (M 30), L_s = 250 mm, E_c = 30 GPa, A_c = 2500 mm^2, L_c = 50 mm, P_o = 150 kN, $r = E_sA_sL_c/(E_cA_cL_s) = 0.284$, $v_{so} = P_oL_s/(E_sA_s) = 0.352$ mm. (c) Relation between bolt steel stress range and applied stress range, $\Delta F_s/\Delta F$, as function of r.*

$$\Delta F_s = \Delta F \frac{E_sA_s/L_s}{E_sA_s/L_s + E_cA_c/L_c} = \Delta F \frac{r}{r+1} \qquad (2)$$

The ratio of $\Delta F_s/\Delta F$ is illustrated in Figure 4c as a function of r.

The model is simplified. The effective concrete area is a fictive concept and is in reality influenced by the prestressing. For this reason there will be no sharp change in the slope of the F-w-curve as shown in Figure 4b. Instead, there will be a gradual change from the slope of the F-w-curve to the slope of the F_s-w-curve (indicated as a dashed line in Figure 4b).

3. TEST RESULTS

3.1 Test program

A general view of the test set up is shown in Figure 5. The dimensions of the tested foundations were 1450x1450x650 mm^3 with two to four bolts in each foundation in Tests Nos 1-6 and 400x400x400 mm^3 with one bolt in each foundation in Tests Nos 7-9.

The test program for the fatigue tests [4] are summarized in Table 1. Two bolt dimensions were used, M30 and 1 1/4". They were both made of a material with a nominal yield stress of 640 MPa. The nominal yield load was 359 kN for the M30 bolt and 400 kN for the 1 1/4" bolt. The M30 bolts were used in Tests Nos 1-6 and the 1 1/4" bolts were used in Tests Nos 7-9. The M30 bolts had washers ϕ104x24 and the 1 1/4" bolts had washers ø100x8 mm. The concrete strength in the foundations is given in Table 1. For grouting, a commercial grout was used in Tests Nos 1-6 (f_{cc} = 50-60 MPa, f_{ct} = 2.5-3.5 MPa) while a concrete made of Standard Portland cement was used in Tests 7-9 (f_{cc} = 13-20 MPa).

As a comparison, ultimate loads from equivalent static tests [3] are also given in Table 1 together with accompanying punching loads calculated according to Eq (1). The punching loads predict the ultimate loads with a reasonable degree of safety.

3.2 Stress range

Test results are summarized in Table 2. The ratio σ_r/σ_{ro} of the stress range with and without prestress varies between 0.04 (for a very low load level) to 0.63 (for higher load levels). The value of the ratio is linked to the value of the parameter r as discussed in section 2.3. For example, if the bolt length L_s is doubled, the parameter r will be half as big as before and the ratio σ_r/σ_{ro} will be reduced considerably. This phenomenon can be seen in Table 2 if tests Nos 2A and 2B with L_s = 250 mm are compared to Tests Nos 3 and 4 with L_s = = 450 mm. The ratio σ_r/σ_{ro} is here reduced from 0.53 and 0.43 to 0.29 and 0.26.

To be able to determine r one must know the parameter A_c/L_c of the effective concrete. Using the relationship $\sigma_r/\sigma_{ro} = r/(1+r)$ and the test values for σ_r/σ_{ro}, we calculated the value of A_c/L_c for the different tests. We got low values, A_c = 10 L_c to 75 L_c. Consequently, to be on the safe side a low value should be used for design purposes, e g A_c/L_c = 5 to 10 mm.

The test results are plotted in a Wöhler diagram in Figure 6. In the figure is also drawn a line which represents the Swedish Code for bolts [11]. There is a fair agreement between the test results and the code.

The level of prestress is reduced with time due to shrinkage and creep in the grout. Tests on four commercially manufactured so called non-shrinkage grouts show larger reductions in prestress force than normal concrete under equal conditions [5]. In most of the tested bolts the ratio of σ_r/σ_{ro} has increased with time. However, for some of the short bolts the opposite phenomenon appeared. The maximum stress level in a cycle here remained constant whereas the minimum stress level increased slightly. This was probably due to some interlocking effect which prevented the bolt to unload completely.

3.3 Conclusions

No concrete fatigue failures have appeared for prestressed anchor bolts (except for cyclic loads on a very high level close to the ultimate static load for the bolt). Consequently, there is no fatigue problem for the concrete.

Steel fatigue failures have appeared in several tests. The most important factor governing the life length of a prestressed bolt is the stress range in the bolt. The stress range can be reduced by prestressing the bolt. Reductions of 50 to 75% of the stress range can be achieved. The magnitude of the reduction depends on the length of the bolt and the level of prestressing.

It is important to use a grout with a small shrinkage and it is advisable to check the level of prestress periodically in order to ensure a low stress range.

Table 1 Test program

Test No	Depth of hole or recess	Diameter of hole or recess	Distance to edge of foundation	Spiral reinforcement	Concrete strength		Results from equivalent static tests		
					Compression f_{cc}	Tension f_{ct}	Punching load (Eq 1) F_{th}	Ultimate load F_u	Bolt No Ref [3]
	mm	mm	mm	mm	MPa	MPa	kN	kN	
1 A-B	200	ϕ120	150	-	35	3.0	48	147	SD 3:1
2 A-B	200	ϕ120	300	-	35	3.0	59	206	SD 3:2
3	400	ϕ120	150	-	35	3.0	151	344	SD 3:3
4	400	ϕ120	300	-	35	3.0	191	>400	SD 3:4
5	250	ϕ120/200	150	(a)	35	3.0	86	418	SC 3:1
6	250	ϕ120/200	300	(a)	35	3.0	95	425	SC 3:2
7 A-B	200	ϕ150/200	200	(b)	65	4.0 (d)	-	300	ML III
8 A-D	200	ϕ150/200	200	(c)	23	2.0 (d)	-	190	ML 3:1
9 A-B	200	ϕ150/200	200	-	28	2.5 (d)	-	-	-

Notes: (a) 4ϕ10 Ks400, f_y = 400 MPa; (b) 5ϕ10 Ss260, f_y = 260 MPa; (c) 4ϕ10 Ss 260, f_y = 260 MPa; (d) The value f_{ct} is an estimation based on f_{cc}

Table 2 Test results

Test No	Prestress force P_o	Applied load F	Stress range		σ_r / σ_{ro}	Number of cycles	Mode of failure Ultimate load F_u after fatigue loading [kN]	
			Without prestress σ_{ro}	With prestress (measured) σ_r				
	kN	kN	MPa	MPa	-	Megacycles		
1A	102	62.5 ±27.5 (a)	98.0	16.2	0.17	8.556	Run out	F_u = 153
1B	100	5.0 ± 5.0 (b)	(17.8)	(0.7)	(0.04)	<0.001	Concrete spalling	F_u = 138.5
2A	143	142.8 ±20.4	72.7	38.0	0.53	>13.000	Run out	F_u = 252
2B	150	125.0 ±25.0 (c)	89.1	38.0	0.43	2.040	Concrete spalling	F_u = 225
3	180	125.0 ±55.0	196.1	57.0	0.29	>4.000	Run out	F_u = 296
4	220	137.5 ±82.5	294.1	76.0	0.26	>0.937	Run out	
5	287	172.5 ±42.5	151.5	95.0	0.63	>3.780	Run out	F_u = 433
6	215	161.0 ±54.0	192.5	120.0	0.62	0.671	Bolt fatigue failure	
7A	-	112.5 ±37.5	120.0	-	-	1.700	Bolt fatigue failure	
7B	-	112.5 ±37.5	120.0	-	-	>2.000	Run out	F_u = 285
8A	-	112.5 ±37.5	120.0	-	-	0.600	Concrete spalling	
8B	-	112.5 ±37.5	120.0	-	-	0.250	Bolt fatigue failure	
8C	-	112.5 ±37.5	120.0	-	-	0.750	Bolt fatigue failure	
8D	-	112.5 ±37.5	120.0	-	-	0.820	Bolt fatigue failure	
9A	-	112.5 ±37.5	120.0	-	-	>1.000	Run out	F_u = 200
9B	-	112.5 ±37.5	120.0	-	-	0.525	Bolt fatigue failure	

Notes (a) After 3 megacycles increased to 82.5 ± 27.5 kN; (b) Gradually increased to 65.0 ± 65.0 kN with load steps of 5 kN after 10 cycles (c) After 2 megacycles increased with steps of 7.5 kN after every 10 000 cycles up to 162.5 ± 62.5 kN

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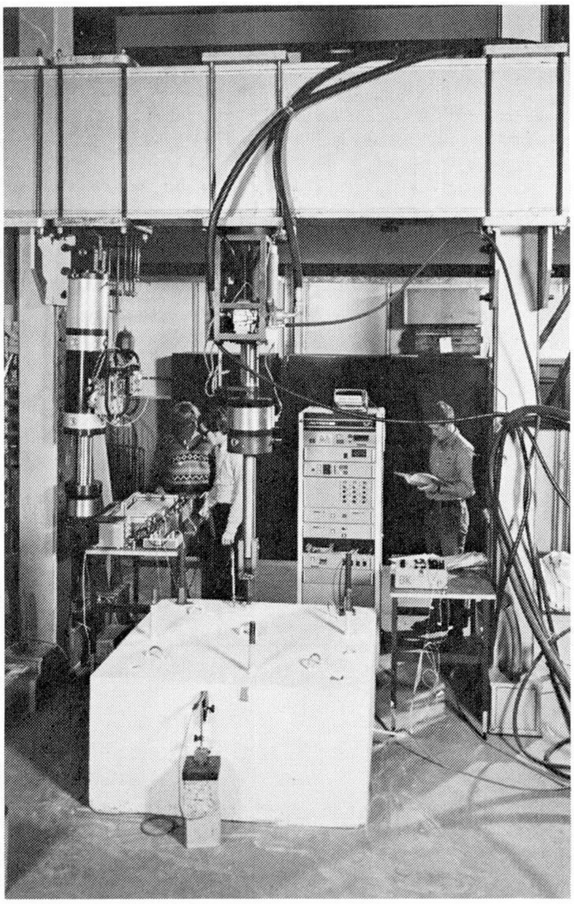

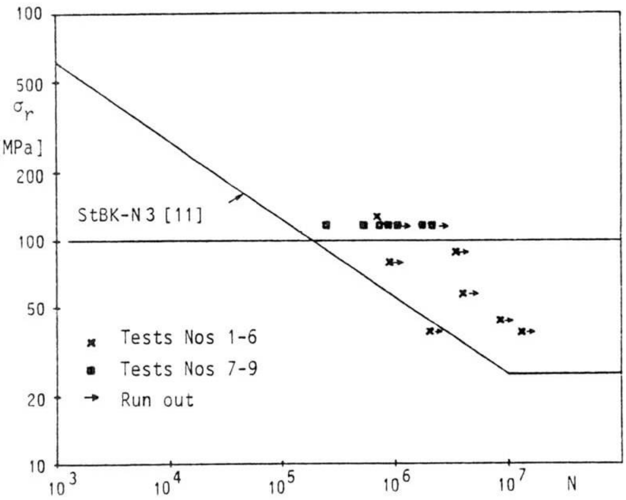

Fig 5 (left)

General view of test set-up

Fig 6 (above)

Wöhler curve for tested bolts. The stress range σ_r is based on measured strain rates

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