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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.



#### 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 <u>drilling a hole</u> 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 <u>conical shell</u>, 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.

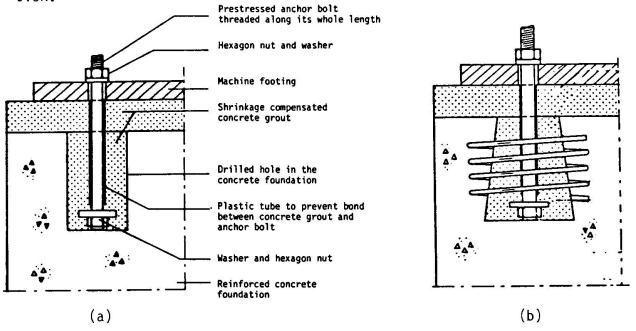


Fig 1 Tested anchor bolts. (a) Bolt placed in a cylindrical hole drilled into a reinforced concrete foundation. (b) Bolt placed in a cylindrical recess. The recess is formed by a 0.5 mm thick metal sheet



### 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.

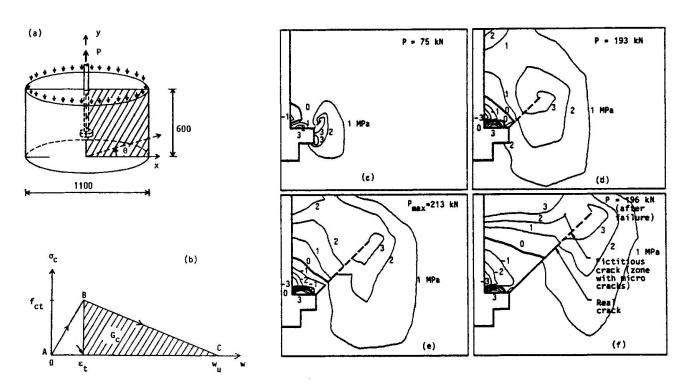
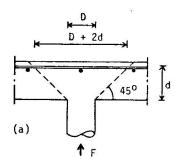


Fig 2 Fracture mechanics model used for study of crack propagation [4], [6]. (a) Dimension of finite element model (96 axisymmetric elements + 10 linear crack elements). (b) Material model for loading (AB) and unloading of crack element (BC),  $\epsilon_t$  = tensile strain,  $\omega$  = crack width. The following material properties were used for steel and concrete  $E_s$  = 210 GPa,  $\nu_s$  = 0.3,  $\rho_s$  = 7 800 kg/m³,  $E_c$  = 30 GPa,  $f_{ct}$  = 3.0 MPa,  $\nu_c$  = 0.2,  $\rho_c$  = 2400 kg/m³,  $G_c$  = 60 N/m (fracture energy) and  $\omega_u$  = 40·10<sup>-6</sup> 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.





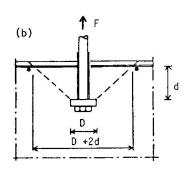


Fig 3 Comparison between punching (a) and anchor bolt failure (b)

## 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 450 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 at failure. A vertical projection equation then  $^{\rm V}$  gives

$$F = Af_{v}/\sqrt{2} = \pi(D+d)d f_{v}$$
 (1)

In the 1978 CEB-FIP Model Code [10] the value of  $f_{\nu}$  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  $P_0$  gives rise to a strain  $\varepsilon_{SO}$  in the steel

force  $P_0$  gives rise to a strain  $\varepsilon_{SO}$  in the steel bolt and a strain  $\varepsilon_{CO}$  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,  $P_0 = E_S A_S \varepsilon_{SO} = E_C A_C \varepsilon_{CO}$ . Here  $\varepsilon_{SO}$  and  $\varepsilon_{CO}$  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  $P_0$ ) 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,  $F = F_s - F_b = E_s A_s \ v(r+1)/(L_s r)$ , where  $r = E_s A_s L_c/(E_c A_c L_s)$ . This holds for  $F \leq P_0$ . 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,  $F = F_s = E_s A_s (v_{s0} + v)/L_s$ .

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 =  $F_D$  =  $E_SA_S(v_{SO} + v_{CO})/L_S$  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<sub>0</sub>  $\pm \Delta F < F_p$  only small variations  $\Delta F_s$  will occur in the steel stress, see Figure 4b,



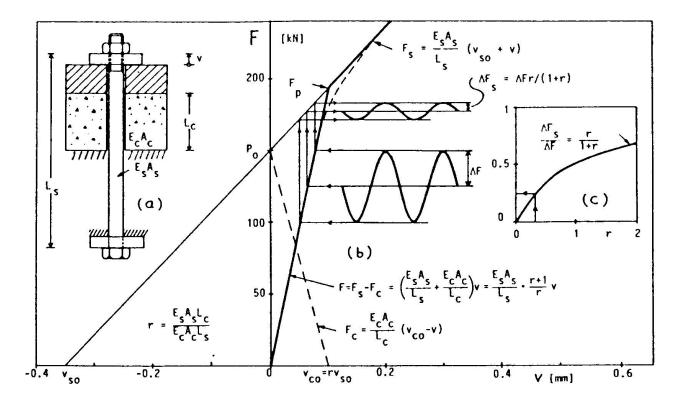


Fig 4 Prestressed anchor bolt. (a) Simplified theoretical model. (b) Applied force F, tensile bolt force Fs and compressive concrete force Fc as function of bolt displacement v. Numerical values:  $E_s = 190~\mathrm{GPa}, \ A_s = 561~\mathrm{mm}^2~\mathrm{(M~30)}, \ L_s = 250~\mathrm{mm}, \ E_c = 30~\mathrm{GPa},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

$$\Delta F_{s} = \Delta F \frac{E_{s}A_{s}/L_{s}}{E_{s}A_{s}/L_{s} + E_{s}A_{s}/L_{c}} = \Delta F \frac{r}{r+1}$$
(2)

The ratio of  $\Delta F_{\rm S}/\Delta F$  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  $F_c$ -w-curve (indicated as a dashed line in Figure 4b).

### 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  $1450 \times 1450 \times 650$  mm<sup>3</sup> with two to four bolts in each foundation in Tests Nos 1-6 and  $400 \times 400 \times 400$  mm<sup>3</sup> 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  $\phi104x24$  and the 1 1/4" bolts had washers  $\phi100x8$  mm. The concrete strength in the foundations is given in Table 1. For grouting, a commercial grout was used in Tests Nos 1-6 (fcc = 50-60 MPa, fct = 2.5-3.5 MPa) while a concrete made of Standard Portland cement was used in Tests 7-9 (fcc = 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  $\sigma_r/\sigma_{r0}$  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  $\sigma_r/\sigma_{r0}$  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  $\sigma_r/\sigma_{r0}$  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  $A_{\rm C}/L_{\rm C}$  of the effective concrete. Using the relationship  $\sigma_{\rm r}/\sigma_{\rm ro}$  = r/(1+r) and the test values for  $\sigma_{\rm r}/\sigma_{\rm ro}$ , we calculated the value of  $A_{\rm C}/L_{\rm C}$  for the different tests. We got low values,  $A_{\rm C}$  = 10  $L_{\rm C}$  to 75  $L_{\rm C}$ . Consequently, to be on the safe side a low value should be used for design purposes, e g  $A_{\rm C}/L_{\rm C}$  = 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  $\sigma_r/\sigma_{r0}$  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 <u>concrete fatigue failures</u> 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	Spiral reinforcement	Concrete strength		Results from equiv- alent static tests		
			foundation		Compression <sup>f</sup> cc	Tension f <sub>ct</sub>	Punching load (Eq 1) Fth	load	Bolt No Ref [3]
	rium	mm	וותוו	inim.	MPa	MPa	kN	kN	
1 A-B	200	ф120	150	) <del>-</del>	35	3.0	48	147	SD 3:1
2 A-B	200	φ120	300	=	35	3.0	59	206	SD 3:2
3	400	ф120	150	<u>+</u>	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	ф120/200	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)  $4\phi10$  Ks400,  $f_y=400$  MPa; (b)  $5\phi10$  Ss260,  $f_y=260$  MPa; (c)  $4\phi10$  Ss260,  $f_y=260$  MPa; (d) The value  $f_{ct}$  is an estimation based on  $f_{cc}$ 

Table 2 Test results

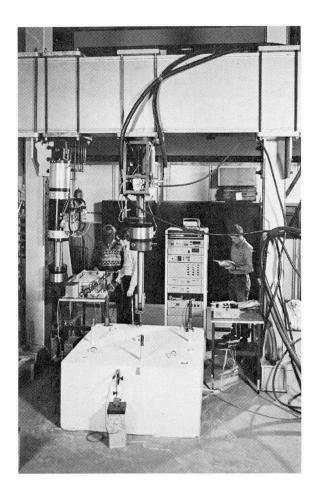
Test	Prestress force	Applied	Stress range		σ <sub>r</sub> σ <sub>ro</sub>	Number of	Mode of failure		
No	Po	load F	Without prestress	With prestress (measured)	σ <sub>ro</sub>	cycles	Ultimate load F <sub>u</sub> after fatigue loading [kN]		
			σ <sub>ro</sub>	σ <sub>r</sub>					
	kN	kN	MPa	MPa	-	Megacycles			
1A	102	62.5 <u>+</u> 27.5 (a)	98.0	16.2	0.17	8.556	Run out	F <sub>u</sub> = 153	
18	100	5.0 <u>+</u> 5.0 (b)	(17.8)	(0.7)	(0.04)	<0.001	Concrete spalling	$F_{u} = 138.5$	
2A	143	142.8 <u>+</u> 20.4	72.7	38.0	0.53	>13.000	Run out	F <sub>u</sub> = 252	
28	150	125.0 <u>+</u> 25.0 (c)	89.1	38.0	0.43	2.040	Concrete spalling	F <sub>u</sub> = 225	
3	180	125.0 ±55.0	196.1	57.0	0.29	>4.000	Run out	F <sub>11</sub> = 296	
4	220	137.5 <u>+</u> 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 <sub>u</sub> = 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 <u>+</u> 37.5	120.0	-	-	>2.000	Run out	$F_{u} = 285$	
8A	-	112.5 <u>+</u> 37.5	120.0	-	-	0.600	Concrete spalling	-	
88	-	112.5 ±37.5	120.0	-	-	0.250	Bolt fatigue failure		
8C	-	112.5 ±37.5	120.0	-	-	0.750	Bolt fatigue failure		
80	-	112.5 <u>+</u> 37.5	120.0	-	-	0.820	Bolt fatigue failure		
9A	-	112.5 ±37.5	120.0	-	-	>1.000	Run out	F <sub>u</sub> = 200	
9B	-	112.5 <u>+</u> 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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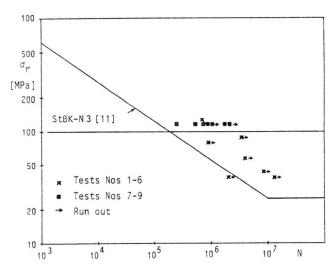


Fig 5 (left)
General view of test set-up

Fig 6 (above) Wöhler curve for tested bolts. The stress range  $\sigma_{\rm r}$  is based on measured strain rates

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