**Zeitschrift:** IABSE reports = Rapports AIPC = IVBH Berichte

**Band:** 37 (1982)

**Artikel:** Fatigue strength of weldable high strength reinforcing steel

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**DOI:** https://doi.org/10.5169/seals-28914

# Fatigue Strength of Weldable High Strength Reinforcing Steel

Résistance à la fatigue de l'acier d'armature soudable à haute résistance

Dauerschwingfestigkeit von schweissbarem hochfestem Betonstahl

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## SUMMARY
The paper presents the mechanical, metallurgical and fatigue properties of micro-alloy, cold-worked and heat-treated steels produced to Swiss standards. Correlations between the fatigue strength and method of steel manufacture are explained by fractography at the crack initiation zone.

## RESUME
L'article présente les propriétés mécaniques, métallurgiques et de fatigue d'aciers micro-alliés, déformés à froid et trempés, produits selon les normes suisses. Des rapports entre la résistance à la fatigue et les méthodes d'élaboration des aciers sont exposées au moyen d'analyse fractographique des zones d'amorce de fissure.

## ZUSAMMENFASSUNG
Die Dauerschwingfestigkeitsdaten der nach Schweizer Norm hergestellten, mikrolegierten, kaltverformten und thermisch behandelten Betonstähle werden mit ihren mechanischen und metallurgischen Eigenschaften dargestellt. Zusammenhänge zwischen Dauerfestigkeit und Stahlherstellung werden mit fraktografischen Untersuchungen an den Risseinleitungsstellen erläutert.

# 1. HIGH STRENGTH CONCRETE REINFORCING STEEL ACCORDING TO SWISS STANDARD SIA 162 (similar to Fe B 500/EURO Norm 80)

## 1.1 General Description

Today's electric-furnace-steels for concrete structures in Switzerland have been developed during 15 years to an optimum for practice. At a mostly given quality of scrap-metal (exportation is limited) the electro-steel-manufacturers have reached a fatigue strength on the ribbed steel bars under the following limiting conditions: nominal yield strength (5 % fractile at 490 N/mm$^2$), elongation at rupture (at least 13 % resp. 16 %), and acceptable bonding resistance and weldability as well. Most types of steel bars reach endurance-limits of $\sigma_w$ = 200 N/mm$^2$ (R = 0), some of them $\sigma_w$ = 250 N/mm$^2$ or more (see 3.3 Diagramme).

## 1.2 State of the art [1]

The two common steel grades, the low-alloy ribbed steel bars type III a, the cold-worked (twisted) ribbed bars type III b, and additional new quenched and "autotempered" ribbed bars type III c are presented. The table Fig. 1 summarizes the essential metallurgical and mechanical properties of accepted steels.

Fig. 1

| property<br>steel grade | Re<br>5% fractile<br>min/max<br>N/mm$^2$ | Rm<br>min/max<br>N/mm$^2$ | $A_5$<br>5 diam.<br>min/max<br>p. cent | $a_k$<br>ISO-V<br>notch<br>J | HV<br>centre<br>edge | $\sigma_w$<br>R=0<br>min<br>max | common analysis max contents in p.cent divisor 100<br>C | Mn | Si | Va | Cr | S+P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| III a | 510<br>520 | 680<br>790 | 16<br>26 | 30<br>40 | 240<br>250 | 240<br>260 | 35 | 110 | 45 | 10 | 20 | 6 |
| III b | 490<br>500 | 540<br>670 | 13<br>18 | 20<br>25 | 150<br>230 | 180<br>260 | 25 | 95 | 20 | -- | 20 | 7 |
| III c | 510 | 600<br>690 | 18<br>26 | 150<br>170 | 140<br>270 | ca.<br>200 | 20 | 110 | 16 | -- | -- | 7 |

## 1.3 Discussion of the data of the three steels

The raw materials and the steel-producing-techniques (scrap, electric furnace, string casting), the cost of micro-alloys, the rolling and cold-twisting methods, and the finish for preparing the diagonal ribs with a mild notch radius and the high yield strength of these steels are determinant for the endurance limit of the ribbed steels according to the SIA 162 Standard [2]. The requirements for a good weldability (low contents of impurities) are favourable for good fatigue properties, the pull-out-test in [2] leads to mild notch effects and high fatigue strength as well (in this point the German Standards with prescribed "relative rib area" are unfavourable). The data shown before (Fig. 1) represent the actual technological limits, they will be reached only if the steel properties are optimized within the requirements of the standard.

## 1.4 Comparison between international standards with respect to fatigue

In European Standards the comparable grades of Fe B 500 are specified differently: The DIN 488 and the ÖNORM B 4200 require medium to high endurance-limits and strong ribs as well; standards of middle and southern Europe do not specify any basic fatigue properties. For comparison the European Standard for prestressing-bars, EURO 138-79, specifies a high endurance-limit of $\sigma_W$ = 195 N/mm$^2$ for ribbed and $\sigma_W$ = 245 N/mm$^2$ for smooth bars. One reason for this differentiation is that grade Fe B 500 is usually applied for fabricated bar mats for building purposes.

# 2. METALLURGY AND CRACK INITIATION IN TERMS OF FRACTURE TOUGHNESS

## 2.1 Influence of steel-producing on the mechanism of crack initiation

In the zone of fatigue crack initiation when the variation in stress intensity is smaller than the threshold limit of fatigue crack propagation the load cycles produce local damage by accumulating dislocations at metallurgical defects e.g. concentrations of slag, segregations (manganese sulfides), defects at the grain boundary caused by detrimental elements in the automobile-scrap as copper, chromium, tin. These defects (soft spots) cause accelerated damage if they are concentrated at the mill-surface, this may happen more frequently with continuous casting than with vertical ingot-casting where impurities concentrate in the centre. Fatigue tests with cold-worked III b steel showed an increase of fatigue strength from $\sigma_W$ = 200 N/mm$^2$ to 250 N/mm$^2$ by reducing the contents of detrimental elements (P + S) = 0,07 %, (Cu) = 0,4 %, (Sn) = 0,05 % down to half of these values. In this first case longitudinal cracks appeared, see Fig. 2. This may explain the higher toughness against cracking in the transversal direction of the bar.

## 2.2 Subcritical cracks in the fatigue-crack-propagation period

Sharp-edged flaws, delaminations, discontinuities in mill scale, notches working as crack-starters lead to fatigue-crack-propagation as soon as the variation of stress intensity ($\Delta K$) passes the threshold-limit which is supposed to be at least 250 N mm$^{-3/2}$ [8] . Such a type of defect is shown in Fig. 3, in that specific case the defect caused a premature failure in the fatigue test. In general, the crack growth rate is higher in material quenched or embrittled by abrupt cooling, this is an effect of toughness of material. Other critical defects are shown in Figs. 4 and 5, they caused premature failures which started at high stress levels only.

## 2.3 Fatigue life as a function of flaw size

Especially at welded splices of steels but also on steels with superficial defects flaw sizes of 2 mm in tangential sense and 1 mm in depth are realistic (as in Fig. 3). Flaws of this size are usually delaminating in fabrication of cold-worked steels type III b so they can be rejected during production. The following crack growth analysis shows that this defect will propagate ($\Delta K > \Delta K_{th}$): For the above sharp-edged defect the amplitude of stress intensity can be written as follows using notations of Lit. [8]: $\Delta K = \sqrt{\pi} \cdot \Delta\sigma \cdot \sqrt{a/Q}$ = 362 Nmm$^{-3/2}$ for the flaw of Fig. 3 with crack depth of a=1,6 mm and 2c=3,2 mm (means Q = 2.3 [8]. After initiation the crack-speed is: $da/dN \cong 10^9 (\Delta K/E)^{3,4} = 3,2 \cdot 10^{-6}$ mm/cycle.

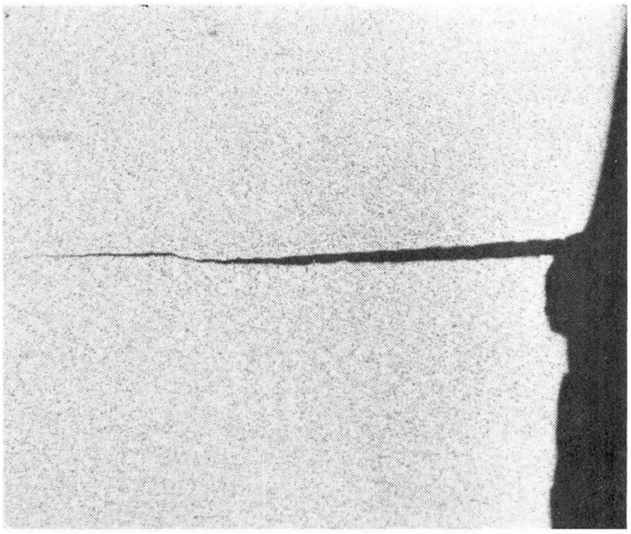


Fig. 2 steel III b, cold-worked
Longitudinal crack in connection with slag in the fatigue-crack-surface.
$\sigma_W$ = 200 N/mm$^2$ at 1 million cycles

macrography enlarg. 8 x

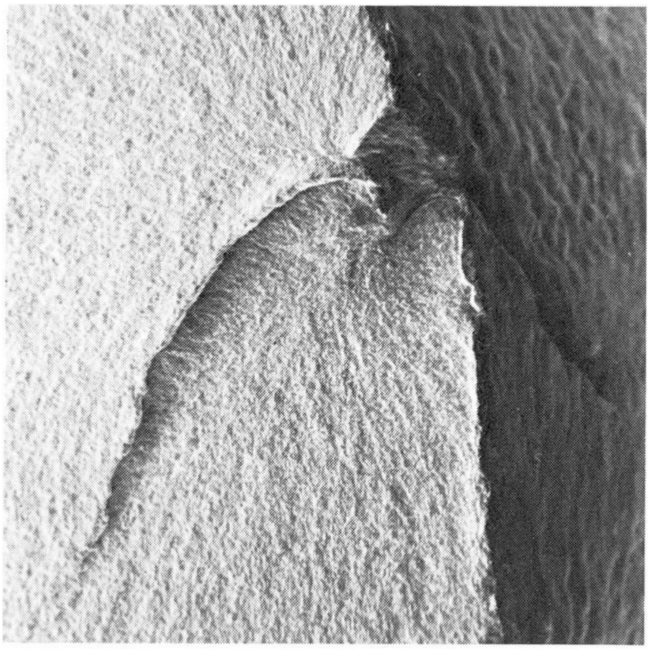


Fig. 3 steel III a (mill test without ribs)
Delamination at fatigue crack-initiation, typical hot-roll-defect.
$\sigma_W$ = 245 N/mm$^2$ at 1 million cycles

SEM enlarg. 24 x

Fig. 4 steel III a, "micro-alloy"
Local superficial defect in mill scale, initiation at medium stress:
$\sigma_W$ = 260 N/mm$^2$ at 0,6 million cycles

SEM enlarg. 20 x

Fig. 5 steel III b, cold-worked
Small delamination defect, initiation at high stress level:
$\sigma_W$ = 280 N/mm$^2$ at 1 million cycles

SEM enlarg. 20 x

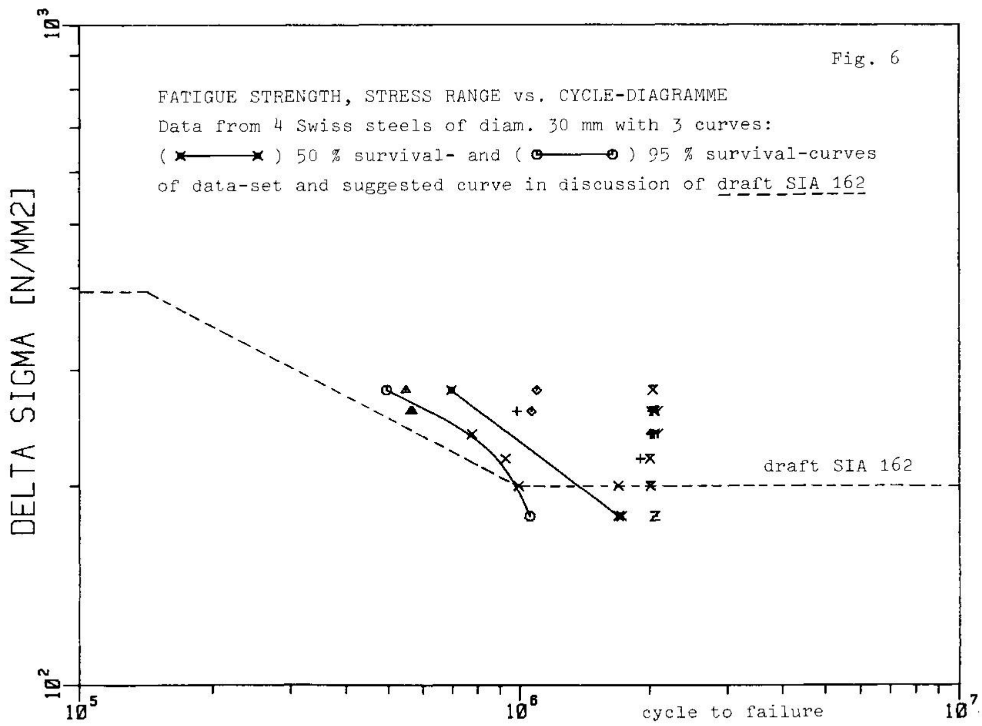
## 3. FATIGUE PROPERTIES, TESTING TECHNIQUES

### 3.1 General significance of fatigue properties

The fatigue strength of a structure is to be considered if the service load is mostly variable as in transversal girders of bridges, cranes, machine foundations and wind exposed towers. Possible crack initiation depends mainly on the influence (see 3.3) of the structure (connections and bends in reinforcements) and the load history; the fatigue strength of the straight bar is rarely determinant. Reinforced concrete structures are likely to be insensitive to fatigue failures because of the great number of bars in one structural element. Due to the good fracture toughness of the steels presented (compare table Fig. 1 to structural steel Fe 360-B $\cong$ A 36, where 28 J at 20° C is required), the structural redundancy might be able to support fatigue-crack-induced brittle failure of single bars at low temperatures.

### 3.2 Testing methods

Im comparable standards fatigue strength is proved differently: pulsating tensile-fatigue tests with or without bond, beam tests with straight and with bent bars. The first type of tests is a simple steel test without detrimental effect of fretting corrosion in concrete. Cast concrete beam specimens are closer to structural behaviour, expensive and dependant upon the concrete quality which produces scatter; therefore with this method the individual fatigue properties of steel cannot be determined. Publications by Wascheidt [6] show that fatigue strength of straight bars does not show any effect of composite action. Fatigue tests with representative samples of perfectly straight bars - length 20 times diametre - are useful if the cracks happen outside the anchorage [3].



### 3.3 Fatigue tests on bars and beams

Pulsating tension-tests with free bars (agreement tests):
For adequate testing of the fatigue strength of the straight bar, the endurance-limit after 2 million cycles ($\sigma_w$) is of interest. Either 6 samples tested up to rupture and representing a lognormal-distribution or 16 samples tested according to the "staircase-method" allow to determine the 95 %-survival value of $\sigma_w$ with 50 % confidence. These samples should be taken at random and cover a certain period of production [3]. The plotted example Fig. 6 above shows the lower bound of data of Swiss-steels of the 30 mm diameter bars in a log-log-stress - vs. cycle diagramme. For comparison, the requirement of the actual draft [3] for the SIA 162-standard is plotted. The suggested stress amplitude of $\sigma_w$ = 200 N/mm$^2$ compared to the endurance-limit in the design curves for structural steel (SIA-standard 161, AASTHO in USA e.g.) of $\sigma_w$ = 170 N/mm$^2$ appears relatively high.

Other structural parameters and full-scale tests:
For prediction of fatigue life of structural elements, test results of other parameters have been presented in Lit. [4] [6] [7]; these results of several tests are likely to show the full-scale behaviour:
- Increasing of the bar-diameter from 20 to 38 mm yields a reduction of the endurance-limit of about 25 % of $\sigma_w$.
- Cold formed bends of bars in the permissible range down to a radius of 7,5 diameters yield a reduction of 15 % of $\sigma_w$.
- But-welded splices were presented in Lit. [5] [7]: standard joints and welded joints with tubular connectors commonly used in Switzerland have shown max. endurance-limits of $\sigma_w$ = 100 N/mm$^2$ to 180 N/mm$^2$.

Several research works in the past years have shown that the scatter of test data of beam-tests is influenced by the scatter and quality of the manufacturing of the reinforced concrete. Therefore, full-scale fatigue-tests are only worth-while if conditions as random loading, low-cycling, impact loading are present in the structure.

## 4. CONCLUSIONS

Based on actual technology, fatigue- and welding-properties of reinforcing steels in Europe can be characterized as follows:

The micro-alloy grade is mainly determined by its balanced contents of alloy elements as carbon, manganese, silicium and costly grain-refining elements as vanadium or niobium. The cooling process in the mill is very important, therefore the crack sensitivity and weldability may be limited at low temperatures.

The other two grades may be less sensitive in terms of weldability-problems but they require also low contents of impurities as phosphorus, sulphur, copper, tin and other unintended scrap-elements. In terms of production costs, the cold deforming and twisting procedures may be the limiting conditions. The new "auto-tempered" grade seems to be promising. To achieve good fatigue strength, both the chemical and the metallurgical properties require advanced technology and a well developed quality-supervising in the steel-work and the mill.

## NOTATIONS

| | |
|---|---|
| $R_e$ | nominal yield point, 5 %-fractile (N/mm$^2$) |
| $R_m$ | tensile strength (N/mm$^2$) |
| $A_5$ | elongation at rupture, 5 diam. sample (%) |
| $a_k$ | fracture toughness, ISO-V-notch sample (J) |
| HV | vickers hardness (HV) |
| $\sigma_w$ | endurance-limit (Wöhler), $R = \sigma_{min}/\sigma_{max} = 0$ (N/mm$^2$) |
| K | stress intensity (Nmm$^{-3/2}$) |
| $\Delta K$ | variation of stress intensity (Nmm$^{-3/2}$) |
| $\Delta K_{th}$ | threshold-limit of $\Delta K$ for starting crack growth |
| Q = fct (a/2c) | crack-shape parameter for elliptical surface crack<br>a: crack depth, 2c: crack length |
| E | modulus of elasticity (N/mm$^2$) |

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