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REPORT

Nr. BI-79-55/62.1.3210
September 18, 1979
Gan

Re: THE MECHANICAL PROPERTIES OF REINFORCING AND PRESTRESSING STEEL DURING AND AFTER A FIRE

by: Ir. G.J. Gantvoort

TESTRESULTS

yield stress and tensile strength

of reinforcement steel

at high temperatures

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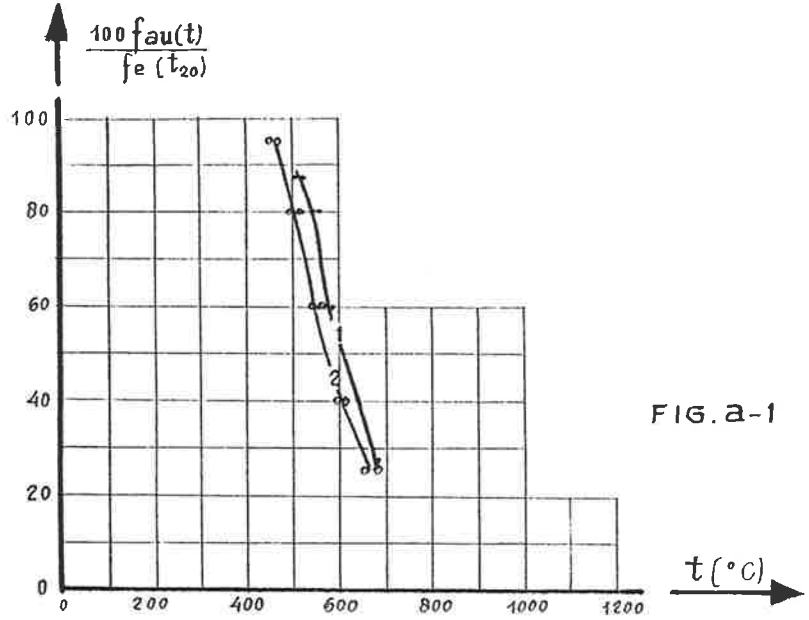

FIG. a-1

The ultimate stress (tensile strength) of hot rolled and cold deformed reinforcement steel (indicated as BE 40 a and BE 40 b) in the heated state (critical temperatures at constant stress levels).

The graphs show the relation between temperature and tensile strength as found by tests. During the tests the stress level was kept constant while the temperature was increased by a constant heating rate.
The (Belgian) test results are published in [1] (1976).

1 = hot rolled steel

2 = cold deformed steel

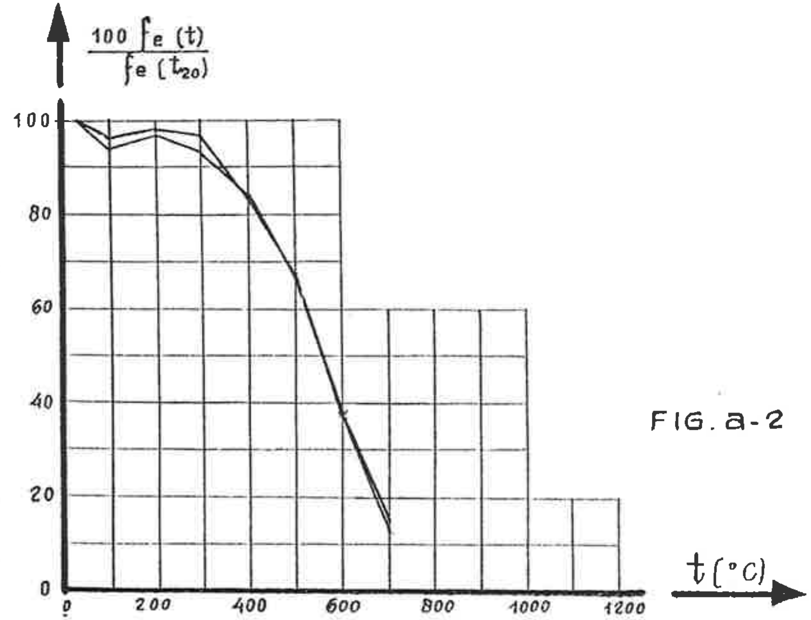

FIG. a-2

The yield stress (0.2% stress) of cold deformed reinforcement steel (indicated as BE 40 b) in the heated state (constant temperature).

The initial yield stresses (0.2% stresses) of the test pieces at 20 $^{\circ}$C were av. 450 N/mm^2.
The graphs are derived from Belgian test results, published in [1] (1976).
The tests were performed in the CRM-laboratories.

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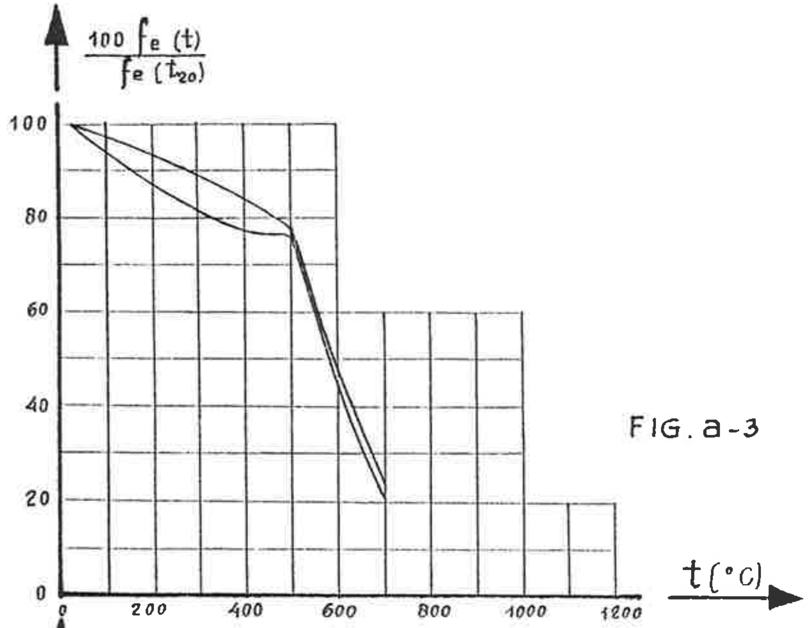

FIG. a-3

The yield stress (0.2% stress) of hot rolled reinforcement steel (indicated as BE 40 a) in the heated state (constant temperature).

The initial yield stresses of the testpieces at 20°C were 500 and 510 N/mm^2.
The graphs are derived from Belgian test-results, published in [1] (1976). (The tests were performed in the CRM-laboratories.)

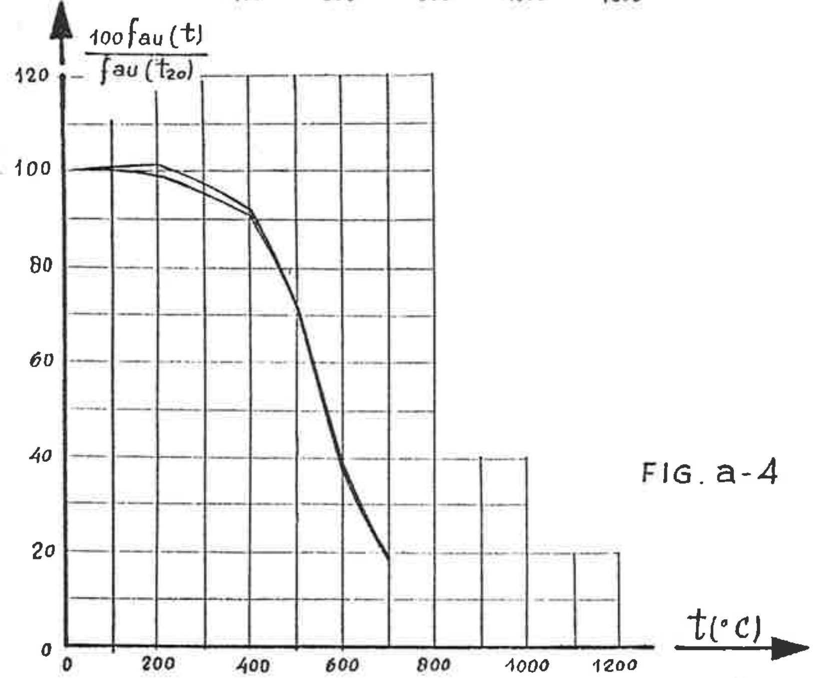

FIG. a-4

The ultimate stress (Tensile sttength) of hot rolled reinforcement steel (indicated as BE 40 a) in the heated state (constant temperature).

The initial ultimate stresses at 20°C were 810 and 850 N/mm^2.
The graphs are derived from Belgian test-results, published in [1] (1976).
The tests were performed in de CRM-laboratories.

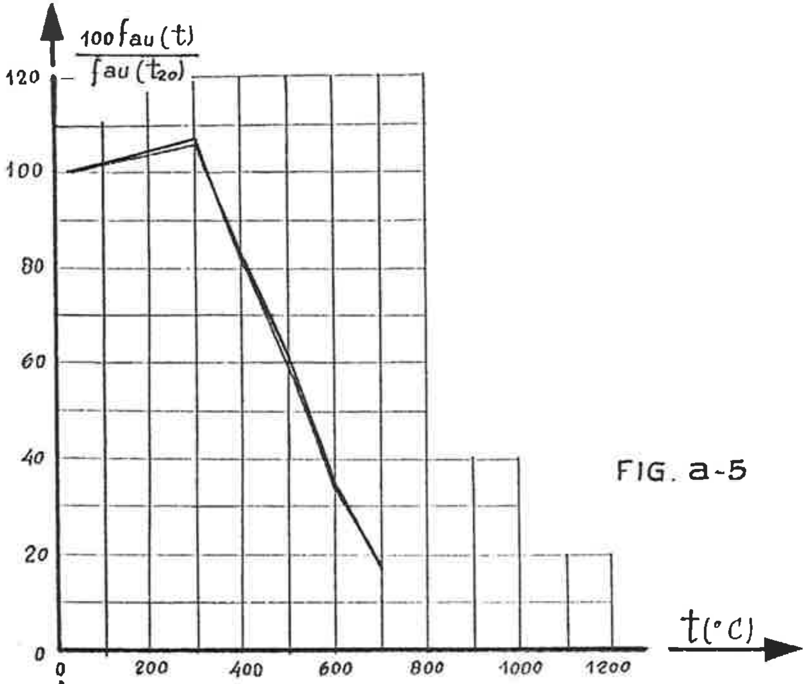

FIG. a-5

The ultimate stress (tensile strength) of cold deformed reinforcement steel (indicated as BE 40 b) in the heated state (constant temperature).

The initial ultimate stresses at 20°C were av. 580 N/mm².
The graphs are derived from Belgian test results, published in [1] (1976).
The tests were performed in the CRM-laboratories.

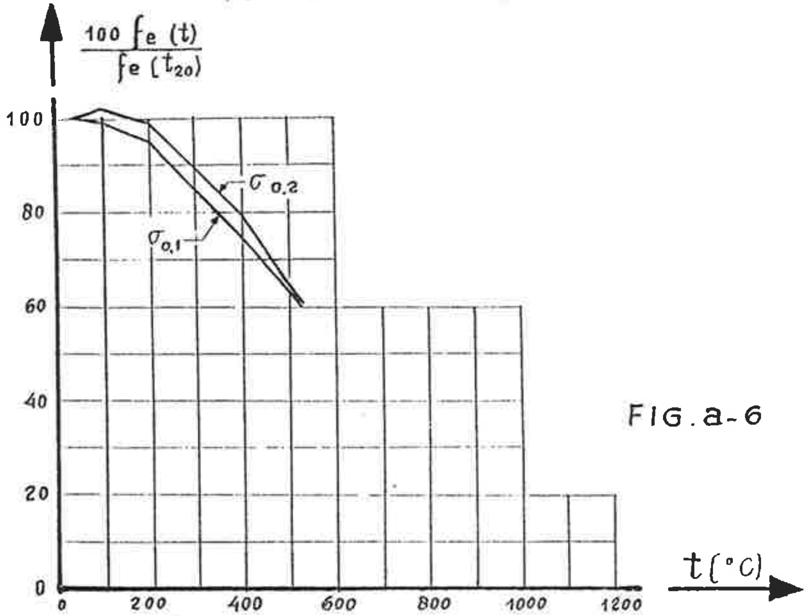

FIG. a-6

The yield stress (0.2% stress) of cold deformed reinforcement steel (Tor-steel) in the heated state (constant temperature).

The initial 0.2% stresses of the test pieces were between 450 and 500 N/mm².
The tests were performed on bars with a nominal diameter Ø 18 mm which were heated internally electricity.
($\sigma_{0.1}$ refers to the stress at 0.1% plastic strain,
$\sigma_{0.2}$ refers to the stress at 0.2% plastic strain)
The tests and test results are described in the French report, published by the A.S.P. in 1971 [2].

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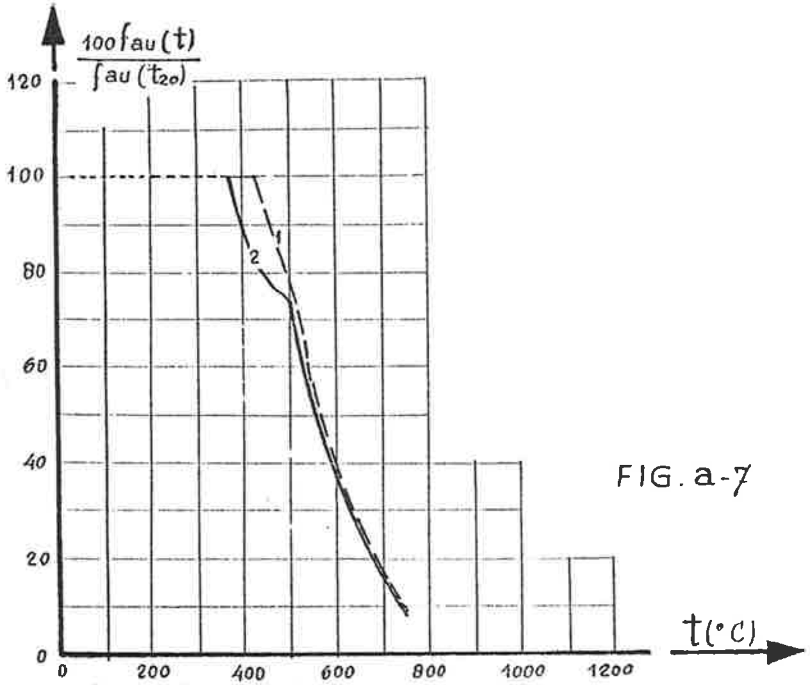

FIG. a-7

The ultimate stress (tensile strength) of cold deformed reinforcement steel (Tor-steel) and hot rolled steel in the heated state (increasing temperature and constant stress level).

---

1 = hot rolled steel (Ø 20 mm; f_{au} at 20°C = 700 N/mm²)

2 = Torsteel (Ø 18 mm; f_{au} at 20°C = 525 N/mm²)

The information is taken from a French report, published by the A.S.P. in 1971 [2].

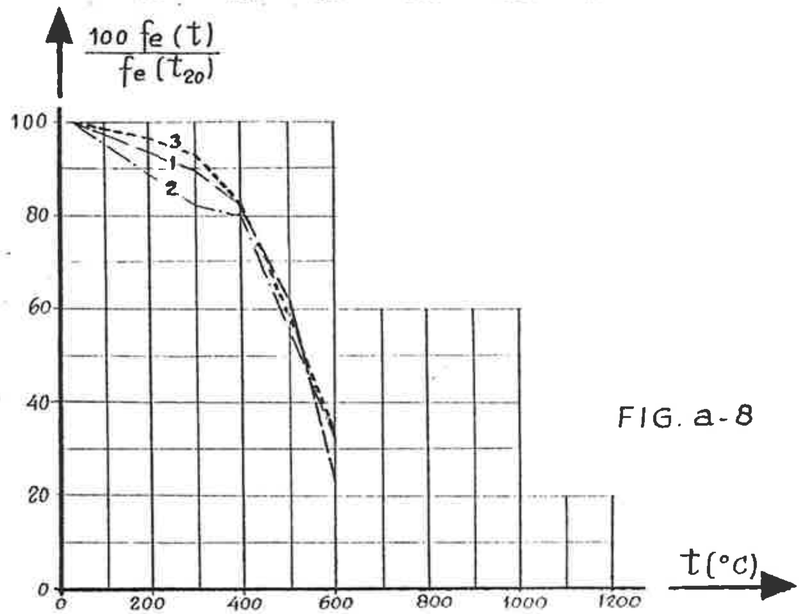

FIG. a-8

The yield stress (o.2% stress) in the heated state of cold deformed reinforcement steel (Tor-steel) (constant temperature).

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1. Ø 24 mm: initial 0.2% stress at 20°C: 484 N/mm² [5]
2. Ø 20 mm: " " " " " : 477 N/mm² [5]
3. Ø 8 mm: " " " " " : 500 N/mm² [4]

The tests are described in the German reports [4], [5] (1957) and [6] (1959).

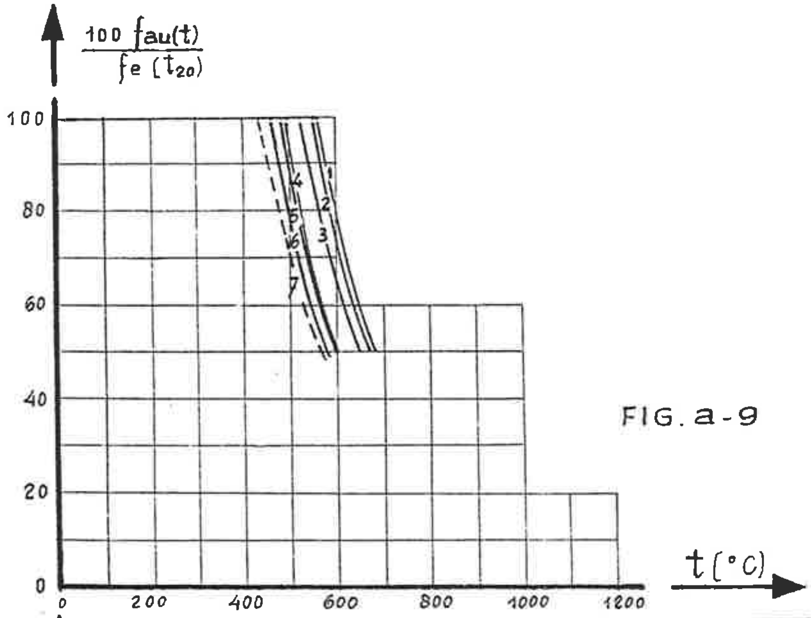

FIG. a-9

The ultimate stress (tensile strength) of cold deformed reinforcement steel (Tor-steel) and hot rolled steel in the heated state (critical temperatures at constant stress-levels).

1,2 and 3: hot rolled steel, Ø 28 mm (BSt $^{42}/_{50}$ RU) $\sigma_{0.2}$ at 20°C = 400 N/mm^2

4, 5 and 6: cold deformed steel Ø 28 mm (Tor-steel: BSt $^{42}/_{50}$ RK) $\sigma_{0.2}$ at 20°C = 470 N/mm^2

7 : cold deformed steel Ø 18 mm, Tor-steel: BSt $^{42}/_{50}$ RK) $\sigma_{0.2}$ at 20°C = 430 N/mm^2

1 and 4 : heating rate 16.5°C/min

2 and 5 : " " 9.4°C/min

3, 6 and 7: " " 3.6°C/min

The graphs are derived from data, published by the Techn. University of Braunschweig (Germany) in 1977 [3].

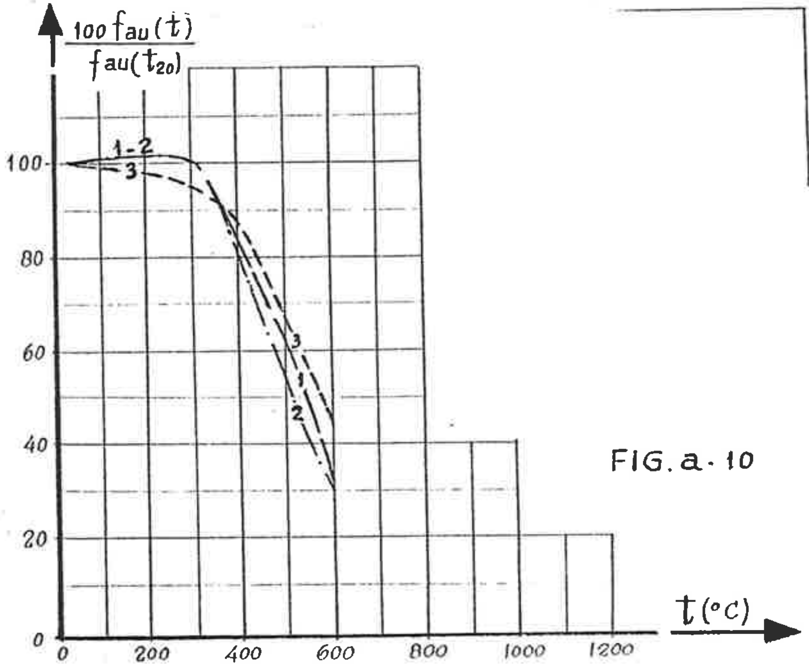

FIG. a-10

The ultimate stress (tensile strength) in the heated state of cold deformed reinforcement steel (Tor-steel) (constant temperature).

1= Ø 24 mm: initial ultimate stress at 20°C: 606 N/mm^2

2= Ø 20 mm: " " " " " : 593 N/mm^2

3= Ø 8 mm: " " " " " : 630 N/mm^2

The tests are described in the German reports [4], [5] and [6]. (1957-1959)

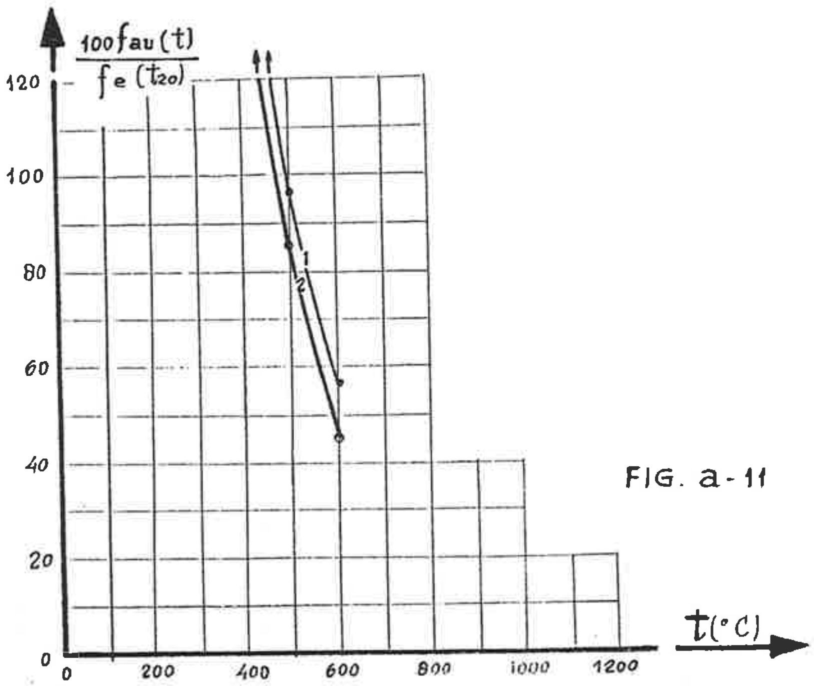

FIG. a-11

The ultimate stress (tensile strength) of mild steel reinforcement in relation to the yield stress (0.2% stress) in the heated state.

The test-results which were used for the graphs are taken from the German report [20], 1959.

1 = bar Ø 24 mm

2 = bar Ø 20 mm

yield stress (0.2% stress): 290 N/mm^2

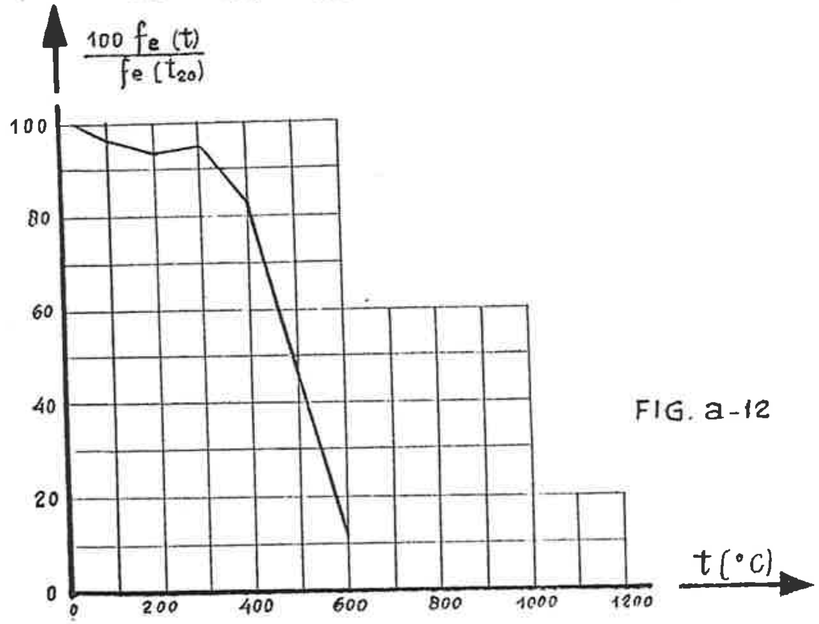

FIG. a-12

The yield stress (0,2%-stress) of welded fabric in the heated state.

The information is taken from the German report [5] (1957).

The yield stress at 20°C ≈ 560 N/mm^2.

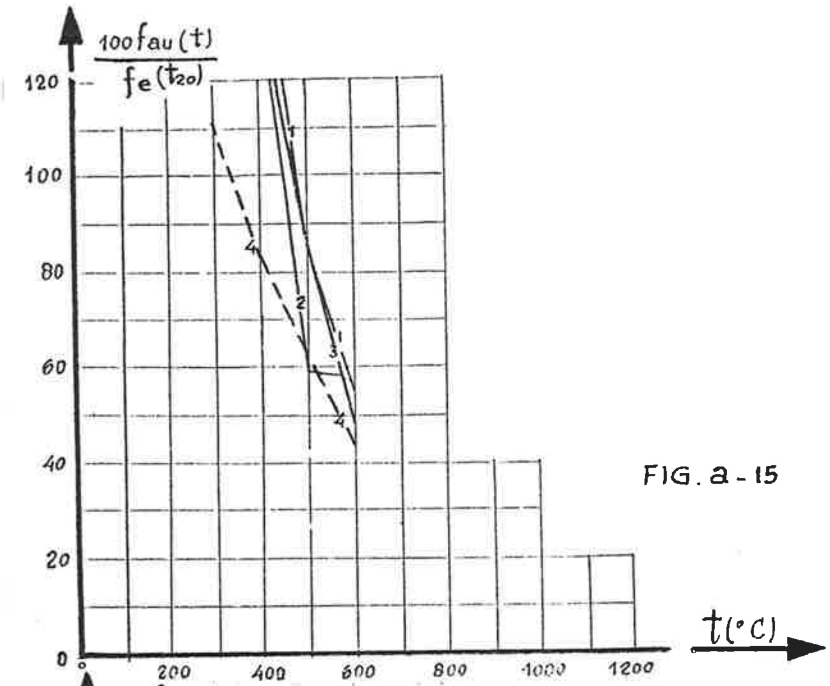

FIG. a-15

The ultimate stress (tensile strength) of hot rolled reinforcement steel and of welded steel fabric in the heated state.

The tensile strength at T°C is given in relation to the yield-stress (0,2% stress) at 20°C.
The information is taken from the German report [5] (1957).

1 hot rolled bar (St 37) Ø 8 mm
2 " " " (St 52) Ø 10 mm
3 " " " (St 52) Ø 8 mm
4 welded steel fabric (f_{au} = 680 N/mm^2)

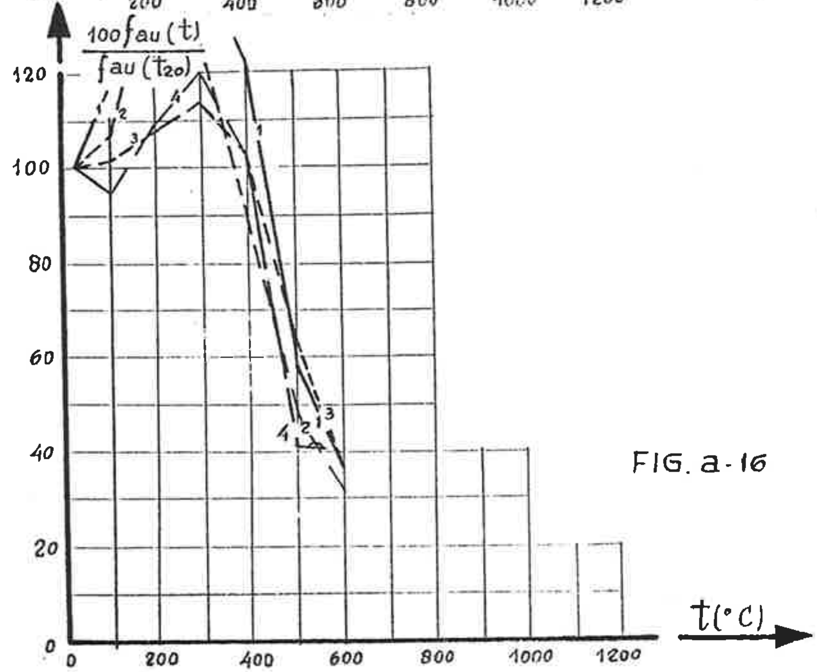

FIG. a-16

The ultimate stress (tensile strength) of hot rolled reinforcement steel in the heated state.

The information is taken from the German report [5] (1957).

1 = hot rolled bar (St 37) Ø 8 mm (f_{au} ≈ 415 N/mm^2)
2 = " " " (St 37) Ø 10 mm (f_{au} ≈ 370 N/mm^2)
3 = " " " (St 52) Ø 8 mm (f_{au} ≈ 620 N/mm^2)
4 = " " " (St 52) Ø 10 mm (f_{au} ≈ 600 N/mm^2)

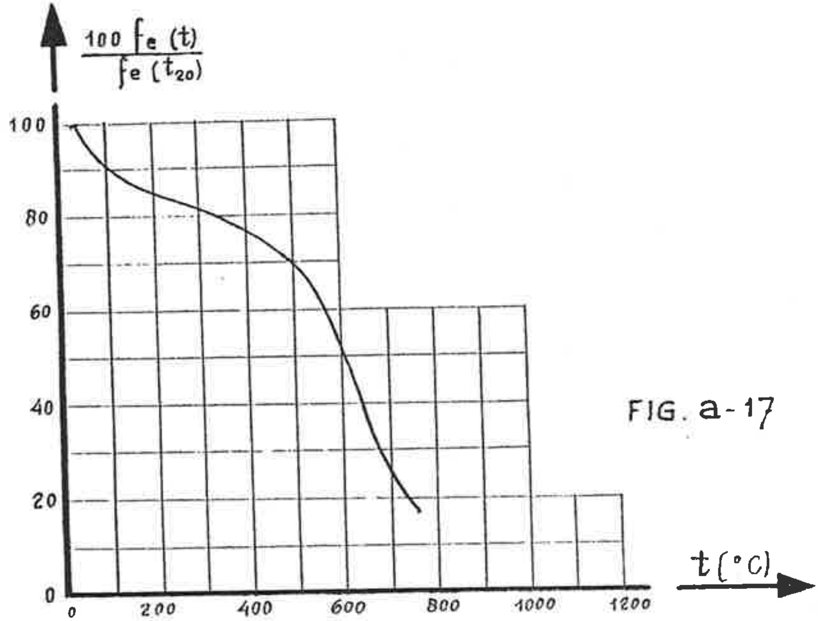

FIG. a-17

The yield stress of hot rolled reinforcement steel in the heated state.

The graph is published in the American PCI Manual: Design for fire resistance of precast prestressed concrete [8] (1977) which for the backgrounds refers to [9] (1968).

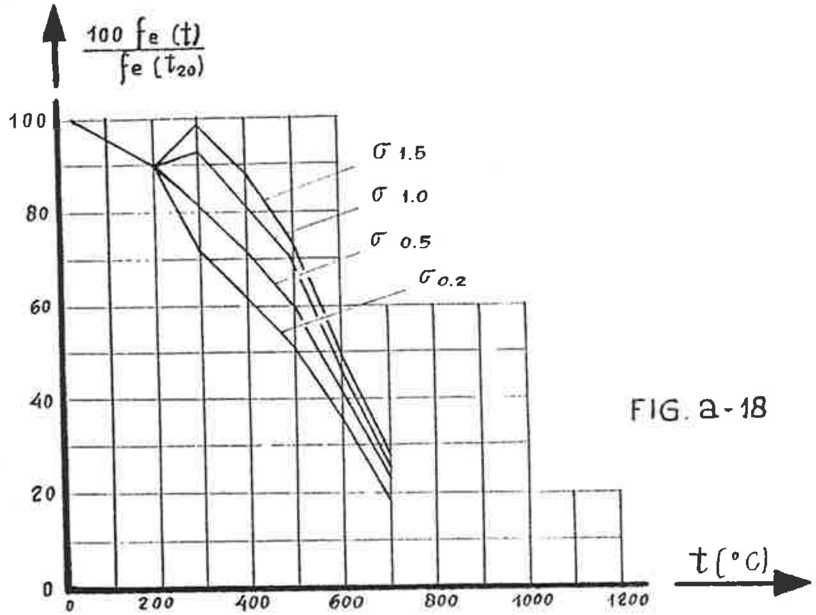

FIG. a-18

The critical stress in the heated state of hot rolled reinforcing steel.

The graphs give information about Swedish hot-rolled reinforcing steels of which the quality is indicated as Ks 40, Ks 40 SE and Ks 60 x)
To show the importance of a clear definition of "critical stress", graphs are given for the stress at a certain temperature-level at which the 0.2%, 0.5%, 1.0% and 1.5% non-elastic strain is reached.
The information is given in [7] (1978)

x) The testing procedure and the definition of "critical stress" on which the figure is based are not exactly known.

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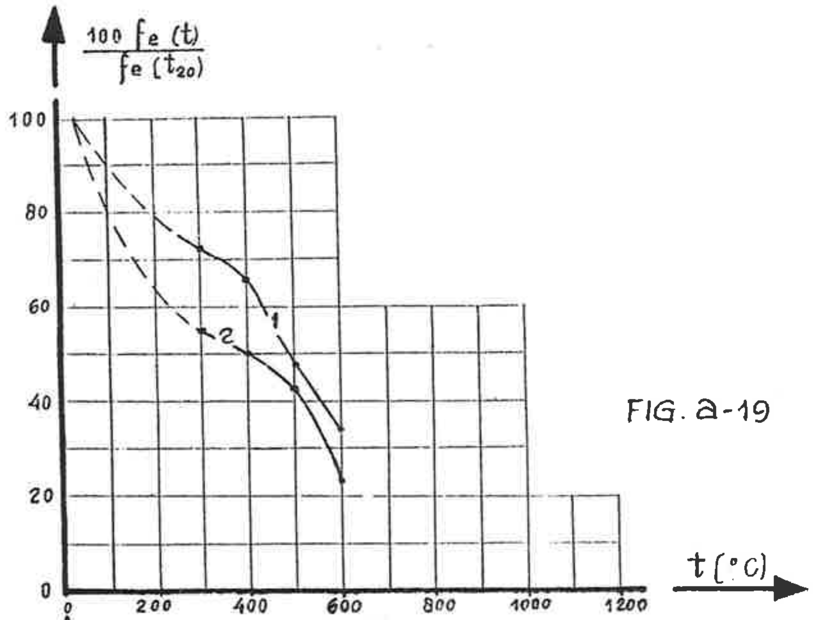


FIG. a-19

The yield stress (0,2%-stress) of mild steel reinforcement bars in the heated state.

The information is taken from the German report [20] (1959).

1 = Ø 24 mm: f_e = 290 N/mm^2
2 = Ø 20 mm: f_e = 290 N/mm^2

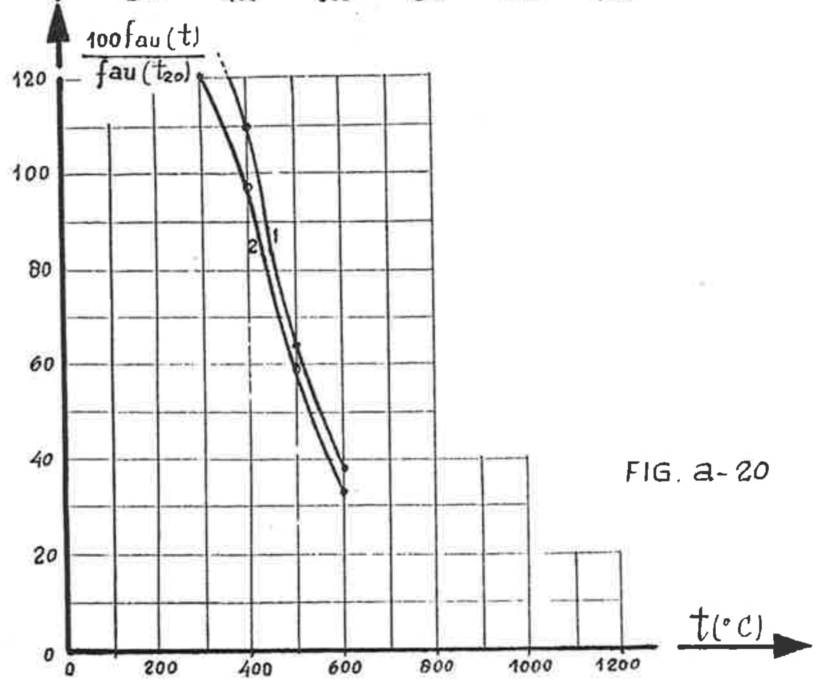
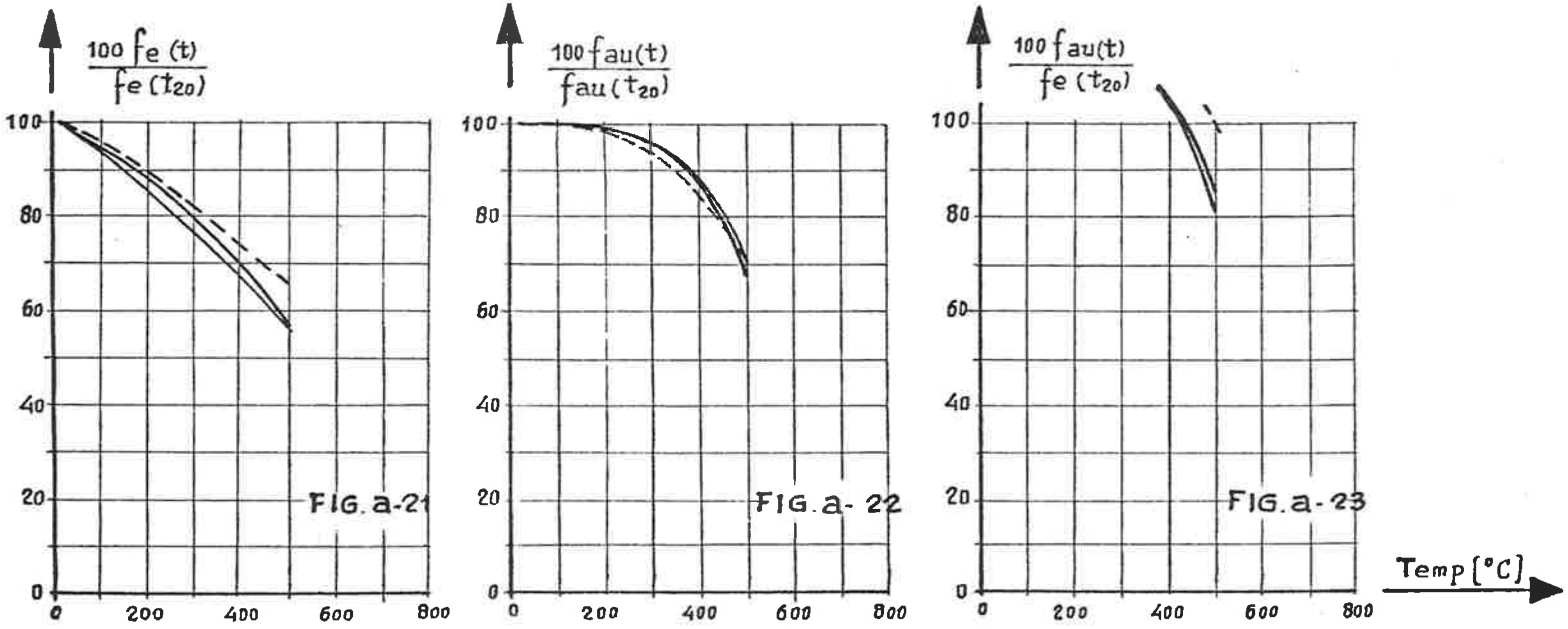


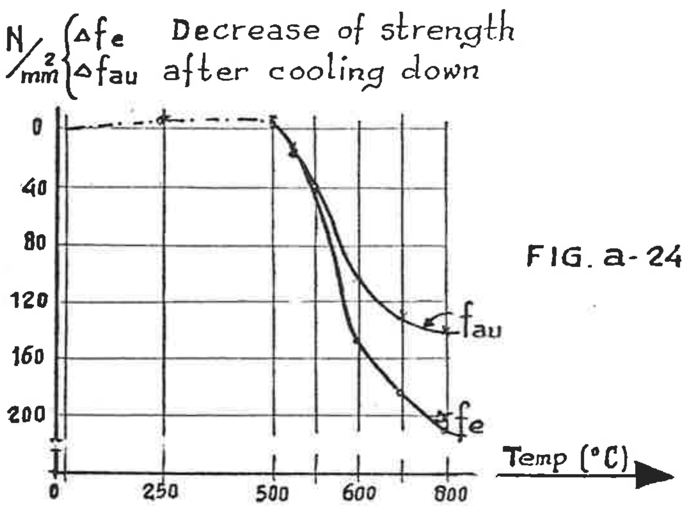
FIG. a-20

The ultimate stress (tensile strength) of mild steel reinforcement bars in the heated state.

The information is taken from the German report [20] (1959).

1 = Ø 24 mm: f_{au} = 440 N/mm^2
2 = Ø 20 mm: f_{au} = 410 N/mm^2





The decrease of strength by heating of Tempcore steel (—) and hot rolled steel (---)

Fig. a-21 : yield-stress (0.2%-stress) in the heated state

Fig. a-22, 23: tensile strength in the heated state

Fig. a-24 : Remaining decrease of yield-stress and tensile strength after cooling down to 20°C

Properties at 20°C before heating:

Tempcore steel: 0.2% stress = 456 and 512 N/mm²

Tensile strength = 545 and 616 N/mm²

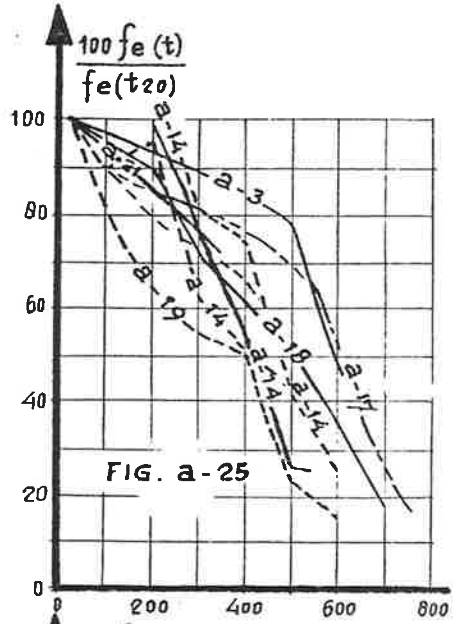
Hot rolled steel: 0.2% stress = 455 N/mm²

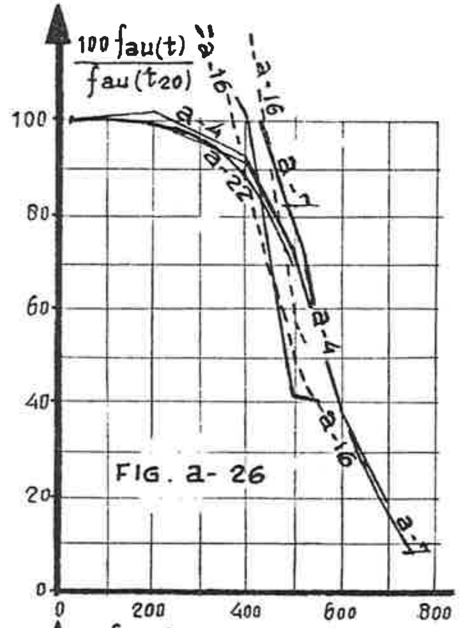
Tensile strength = 666 N/mm²

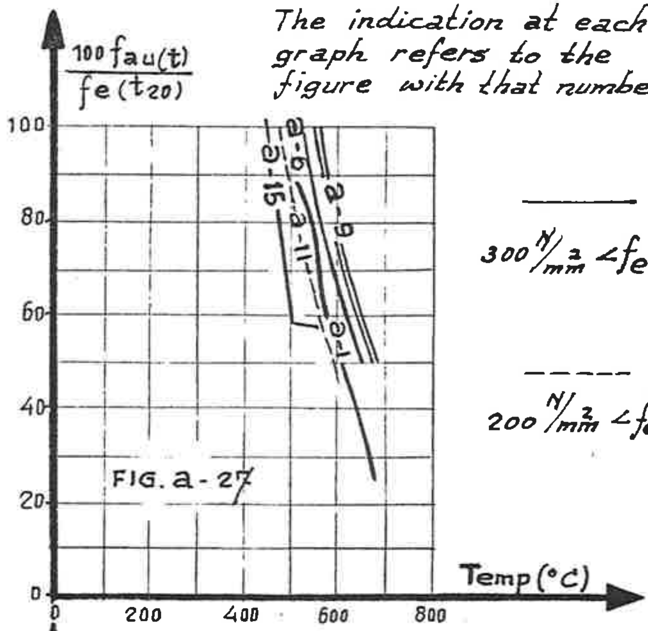
More information is given in [22].

The indication at each graph refers to the figure with that number.

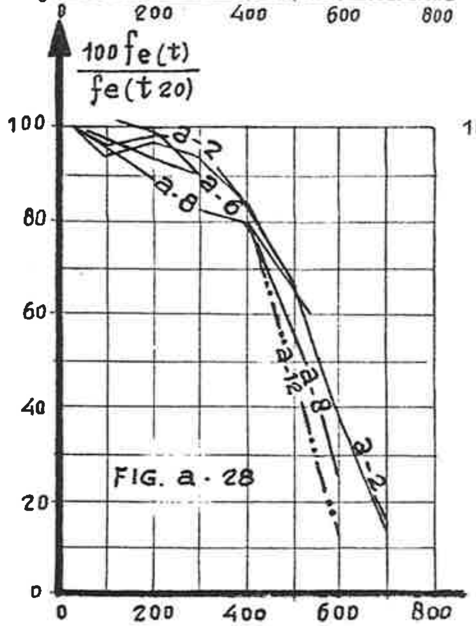
HOT ROLLED STEEL

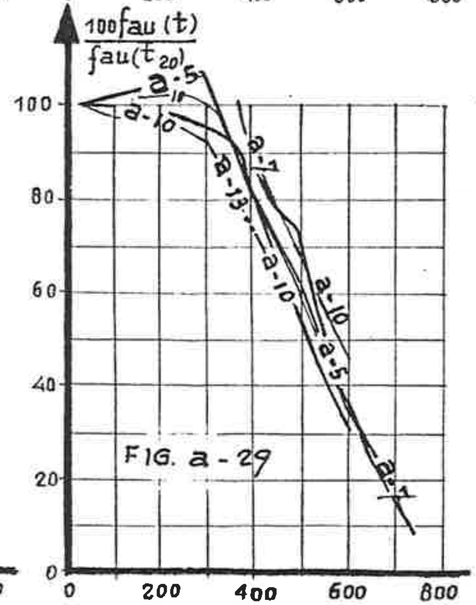


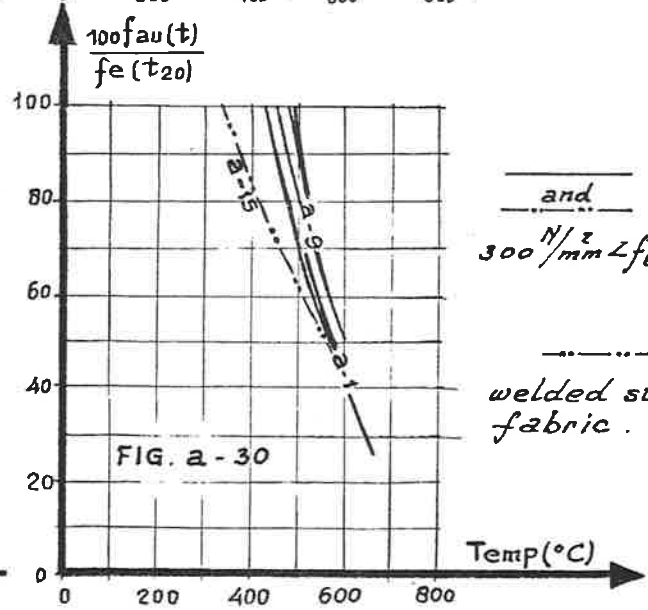




COLD DEFORMED STEEL







——— : $300\ N/mm^2 < f_e < 600\ N/mm^2$

– – – – : $200\ N/mm^2 < f_e < 300\ N/mm^2$

——— and ——— : $300\ N/mm^2 < f_e < 600\ N/mm^2$

–·–··– : welded steel fabric.

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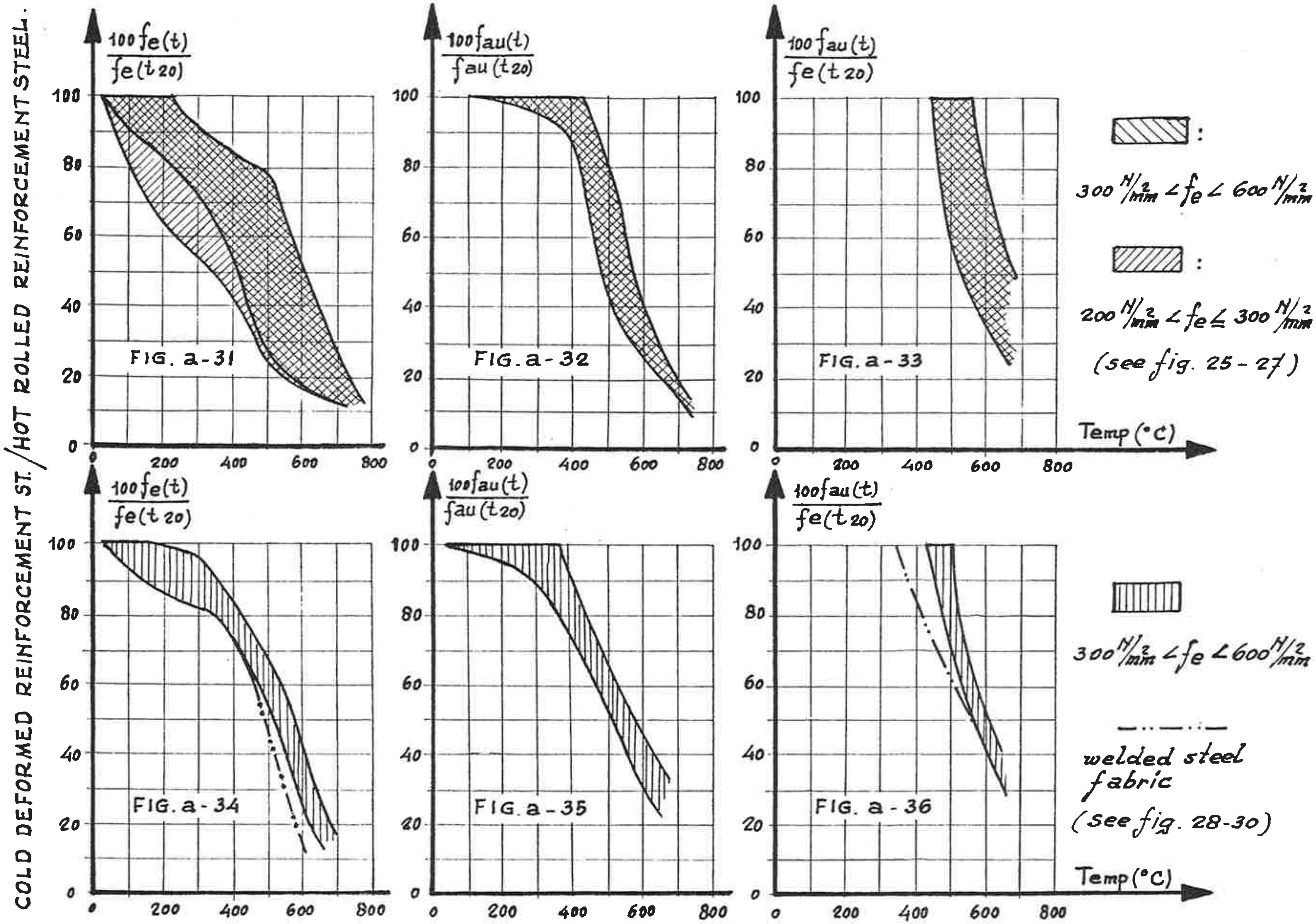

COLD DEFORMED REINFORCEMENT ST. / HOT ROLLED REINFORCEMENT STEEL.
100 fe(t) / fe(t 20)
FIG. a-31
100 fau(t) / fau(t 20)
FIG. a-32
100 fau(t) / fe(t 20)
FIG. a-33
Temp (°C)
300 N/mm² < fe < 600 N/mm²
200 N/mm² < fe ≤ 300 N/mm²
(see fig. 25 - 27)
100 fe(t) / fe(t 20)
FIG. a-34
100 fau(t) / fau(t 20)
FIG. a-35
100 fau(t) / fe(t 20)
FIG. a-36
300 N/mm² < fe < 600 N/mm²
welded steel fabric
(see fig. 28-30)
Temp (°C)

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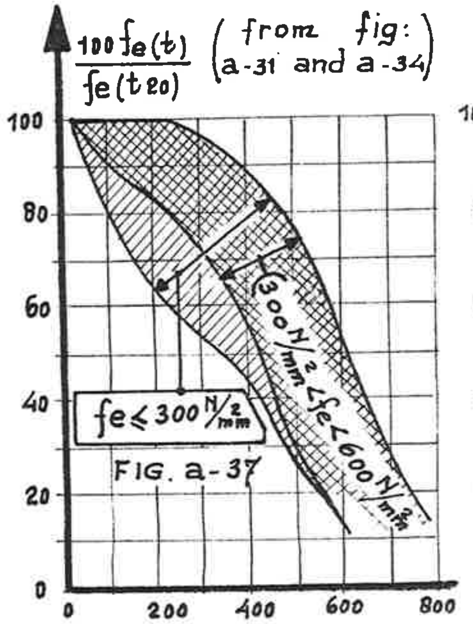
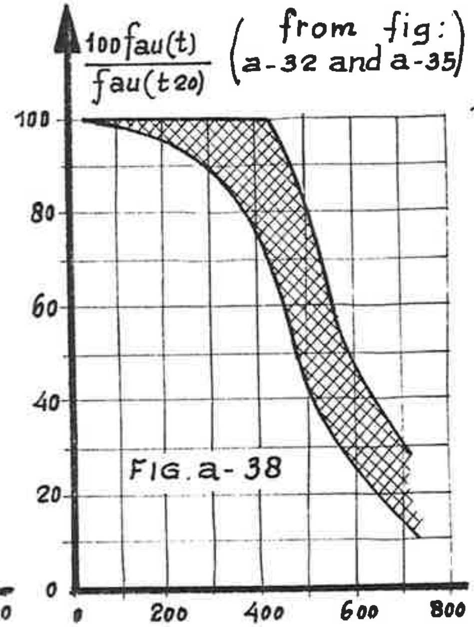
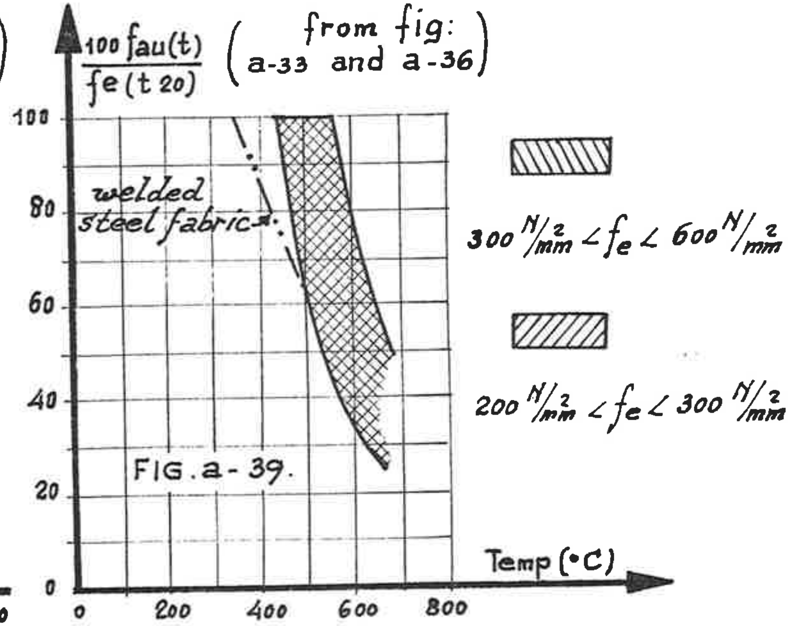
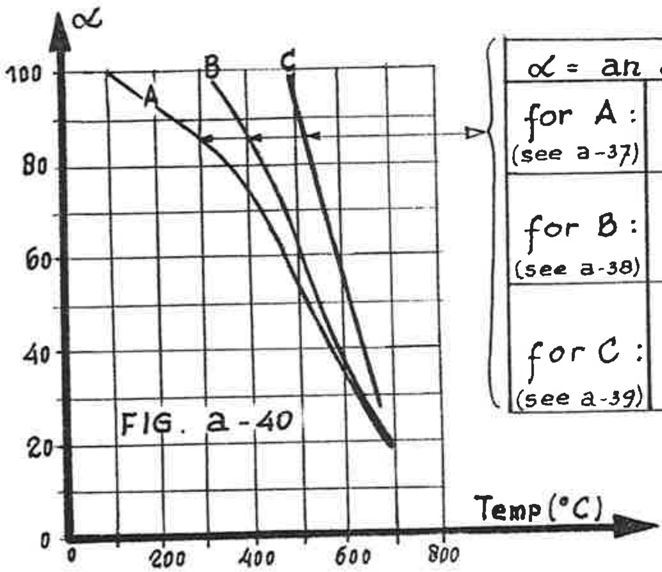








α = an average value		
for A: (see a-37)	$\alpha = \frac{100\, fe(t)}{fe(t_{20})}$	$fe < 600\ N/mm^2$
for B: (see a-38)	$\alpha = \frac{100\, fau(t)}{fau(t_{20})}$	$fe > 300\ N/mm^2$
for C: (see a-39)	$\alpha = \frac{100\, fau(t)}{fe(t_{20})}$	(at 20° C)

About equal values are given in fig:

a-8 (A); a-4,5,20 (B);
a-1 (C)

Substantial lower values are given in fig:

a-12,14,19 (A);
a-13 (B);
a-15 (C)

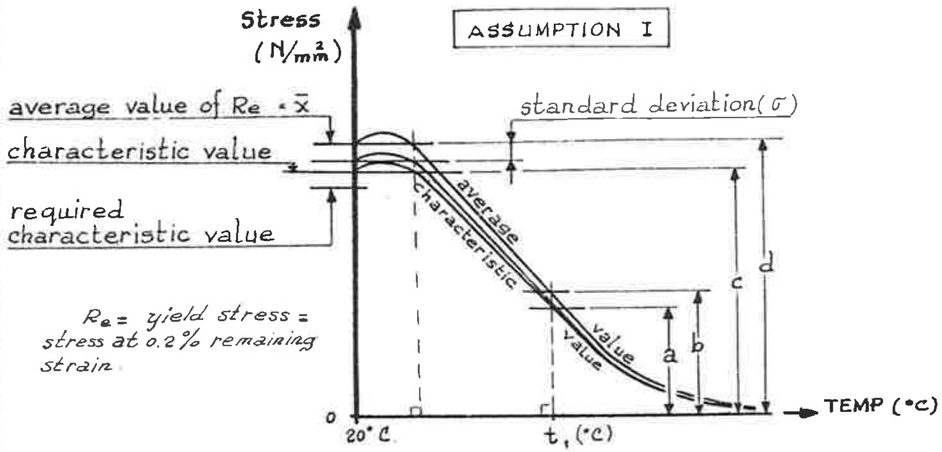


FIG. a-41

Assumption I :

It is assumed, that by an increase of temperature, the standard deviation decreases proportional to the decrease of the average value. Then the same applies to the characteristic value.

Example :
$d = 470\ N/mm^2$; $\sigma_{20} = 30{,}5\ N/mm^2$
$c = 470 - 1{,}64 * 30{,}5 = 420\ N/mm^2$

$b = 0{,}5 * d = 235\ N/mm^2$; $\sigma_{t_1} = 0{,}5 \cdot 30{,}5 = 15{,}25\ N/mm^2$
$a = 235 - 1{,}64 * 15{,}25 = 210\ N/mm^2$ $(= 0{,}5 * 420\ N/mm^2)$

So: $a/b = c/d$ and $a/c = b/d$

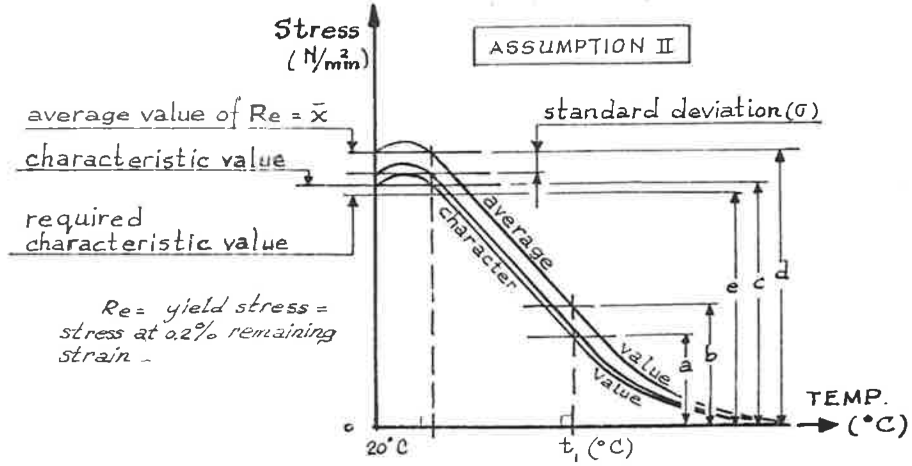


FIG. a-42

Assumption II :

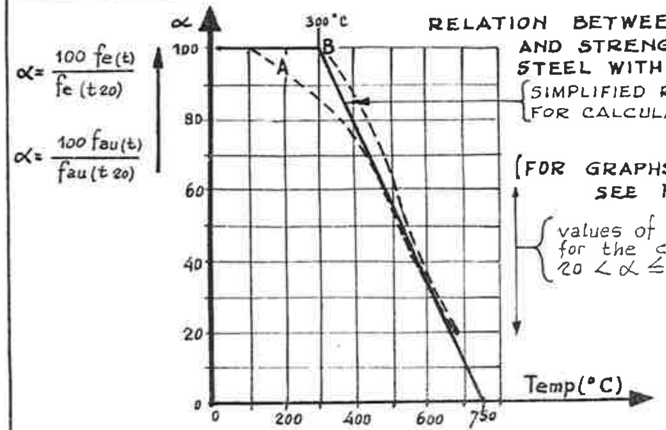
It is assumed, that the decrease of the average value and of the characteristic value of the tensile strength, caused by an increase in temperature, are equal. (at least for $0{,}5 \leq b/d \leq 1$)

Example :
$d = 470\ N/mm^2$; $\sigma_{20} = 30{,}5\ N/mm^2$
$c = 470 - 1{,}64 * 30{,}5 = 420\ N/mm^2$

$b = 0{,}5 * d = 235\ N/mm^2$; $\sigma_{t_1} = 30{,}5\ N/mm^2$
$a = 235 - 1{,}64 * 30{,}5 = 185\ N/mm^2$ $(= 0{,}44 * 420\ N/mm^2)$

So: $a/b \neq c/d$ and $a/c \neq b/d$

(In this example $a/c = 0.9\ b/d$)



RELATION BETWEEN TEMPERATURE AND STRENGTH OF REINFORCEMENT-STEEL WITH YIELD-STRESS AT 20°C ≈ 400 N/mm²

{SIMPLIFIED RELATIONSHIP FOR CALCULATIONS} PROPOSAL

(FOR GRAPHS A AND B : SEE FIG. a-40)

values of α, which are most important for the calculations $20 < \alpha \leq 60$

FIG. a-43.

TESTRESULTS

yield stress and tensile strength

of prestressing steel

at high temperatures

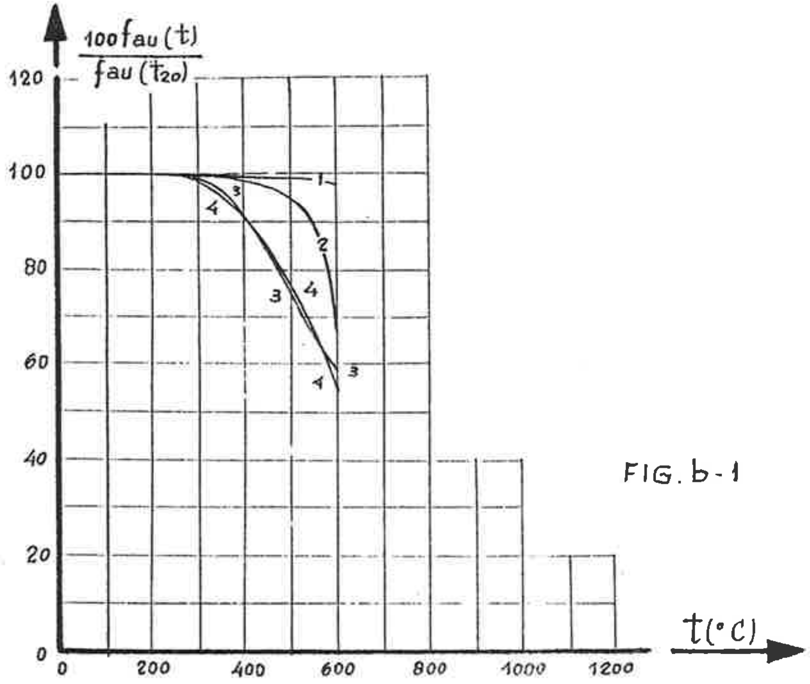


FIG. b-1

The residual tensile strength at 20°C (after cooling down) of prestressing steel.

The graphs are made, using test results, published in the German report [5] (1957).

1 = hot rolled bars (St 60/90) Ø 26 mm (f_{au} = 1050 N/mm^2)

2 = quenched and tempered wire St 145/160 Ø 5,2 mm (f_{au} = 1650 N/mm^2)

3 = cold drawn wire (St 160 .... St 180) Ø 5 mm (f_{au} = 1750 N/mm^2)

4 = cold drawn wire (St 180 - St 200) Ø 5 mm (f_{au} = 1830 N/mm^2).

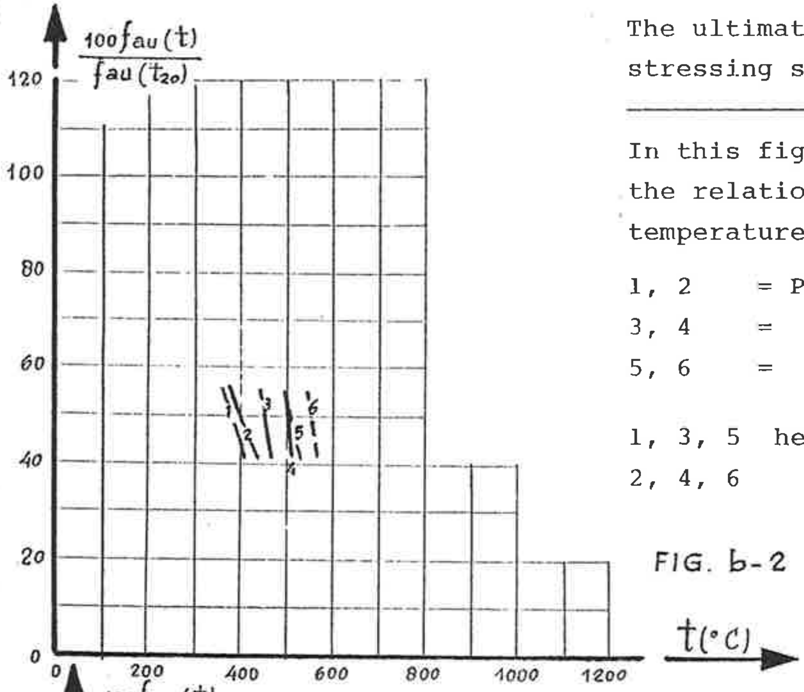


FIG. b-2

The ultimate stress (Tensile strength) of prestressing steel in the heated state.

In this figure for some kinds of prestressing steel the relation is given between ultimate stress, the temperature and the rate of heating.

1, 2 = Prestr. steel 1600/1800 - Ø 4 mm
3, 4 = " 1450/1600 - oval 30 mm
5, 6 = " 800/1050 - Ø 14 mm

1, 3, 5 heating rate = $8^{\circ}C$/min.
2, 4, 6 " " = $16^{\circ}C$/min.

The graphs are derived from German testresults, given in [14], (1965).

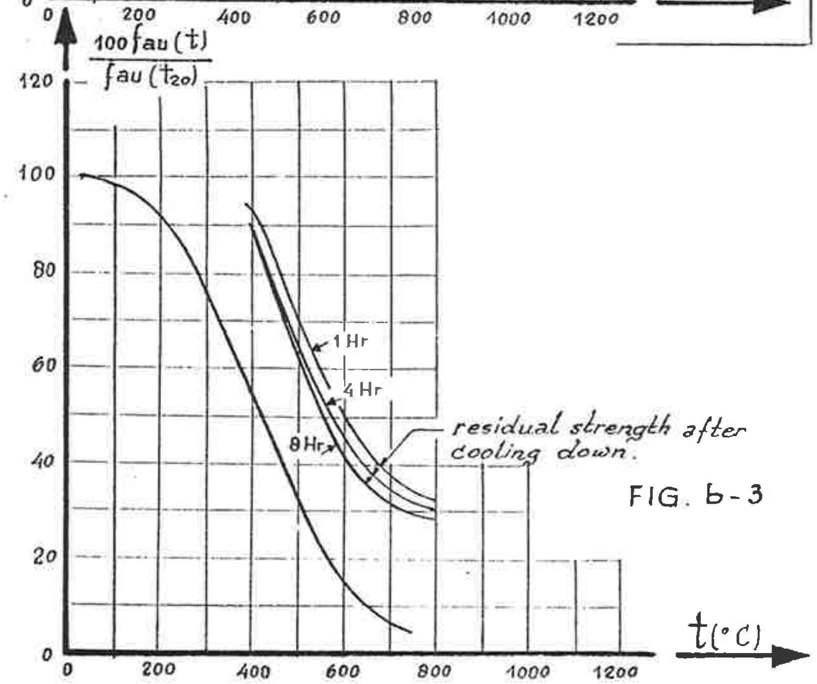


FIG. b-3

The ultimate stress (tensile strength) of prestressing steel in the heated state and after cooling down.

The graphs are made according results of American tests, performed with strands Ø 6,4 mm and Ø 11,1 mm. No influence of any significance was found by differences in the rate of heating between 3 and $8^{\circ}C$/min.

The time during which the temperature in the steel was sustained at a certain level apparently did not have an influence on the hot strength of any importance.

The strength after cooling down was also not significantly affected by the rate of cooling [16], 1961.

The time during which the high temperature was maintained had some effect on the residual strength, as is shown in the figure [17], 1967.

(The times indicated, refer to the length of the heating period.)

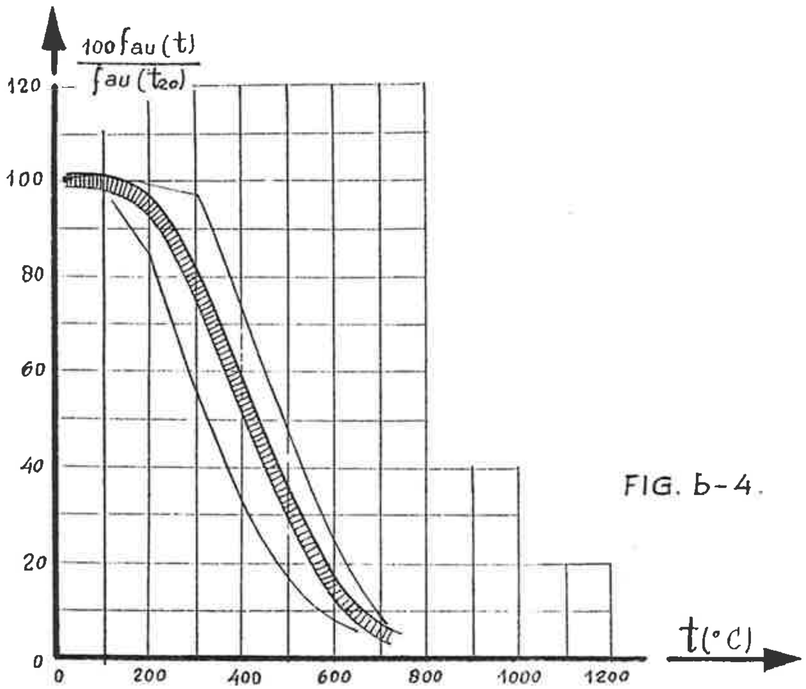


FIG. 6-4.

The ultimate stress (Tensile strength) of prestressing steel in the heated state.

The figure is based on test results with wire Ø 5 mm and Ø 7 mm and strands Ø 5,2 mm and Ø 12,7 mm.
It has been shown by comparison of test results, that the relation between the ultimate stress and the temperature is the same, whether the temperature is kept constant at an increasing load or the load is kept constant at an increasing temperature (if the heating-rate is moderate).
The increase of heating rate from 2,5°C/min to 10°C/min. causes a slight increase ($\approx$ 5%) in the critical temperature.
About 30 types of prestressing steel (wires and strands) with a strength between 1500 and 2200 N/mm^2 were tested.
All kinds of material gave high as well as low test results for the critical values. About 70% was found to be situated in the hatched area and almost all test results were between the two extreme boundaries.
The information was given in a Belgian paper, distributed at the FIP Congres 1978 in London [15].

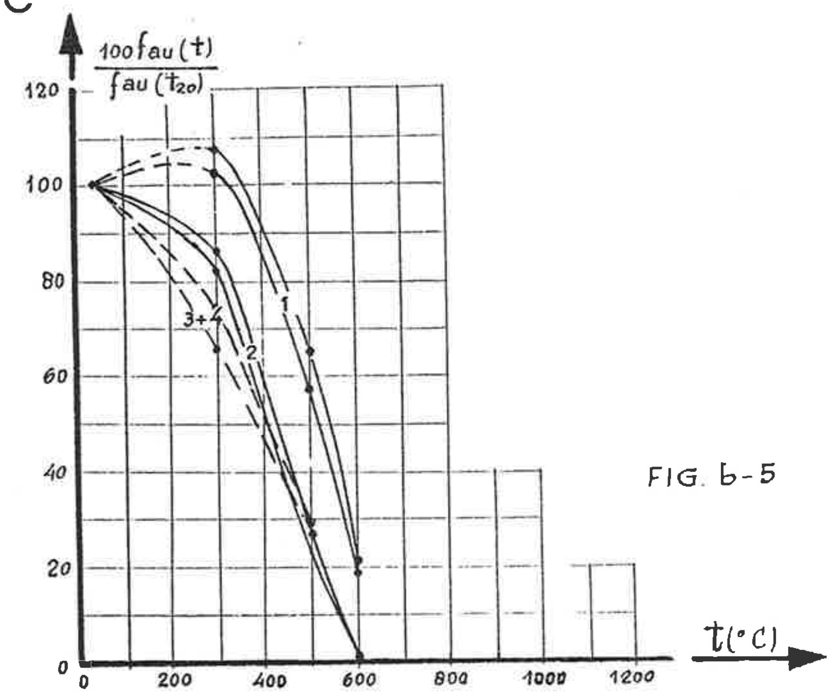


FIG. b-5

The ultimate stress (tensile strength) of prestressing steel in the heated state.

The graphs are made, using test results, published in the German report [5] (1957).

1 = hot rolled bars (St 60/90) Ø 26 mm
(f_{au} = 1050 N/mm^2)

2 = quenched and tempered wire St 145/160 Ø 5,2 mm
(f_{au} = 1650 N/mm^2)

3 = cold drawn wire (St 160 .... St 180) Ø 5 mm
(f_{au} = 1750 N/mm^2)

4 = cold drawn wire (St 180 - St 200) Ø 5 mm
(f_{au} = 1830 N/mm^2)

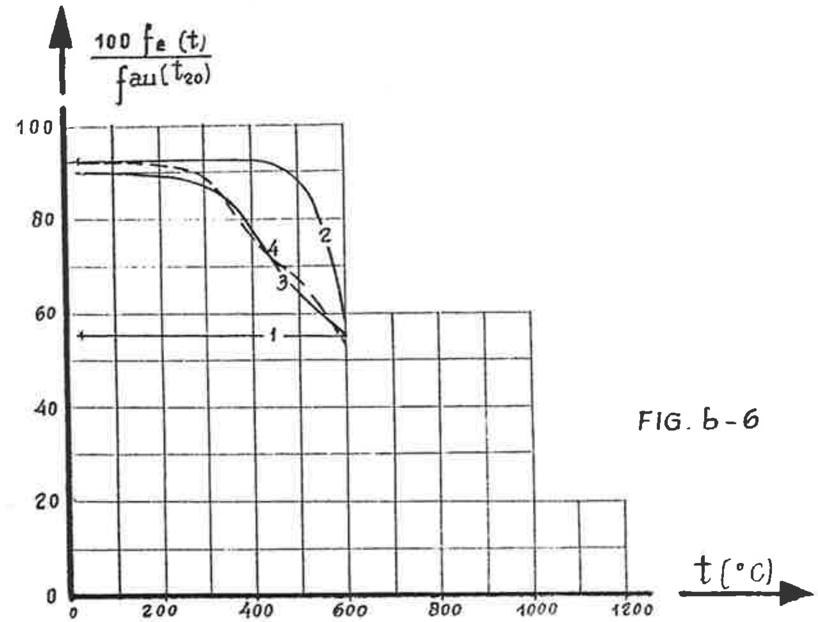


FIG. b-6

The residual 0,2% stress at 20°C (after cooling down) of prestressing steel.

The graphs are made, using test results, published in the German report [5] (1957).

1 = hot rolled bars (St 60/90) Ø 26 mm,
f_{au} = 1050 N/mm^2)

2 = quenched and tempered wire St 145/160 Ø 5,2 mm
f_{au} = 1650 N/mm^2)

3 = cold drawn wire (St 160 .... St 180) Ø 5 mm
(f_{au} = 1750 N/mm^2)

4 = cold drawn wire (St 180 - St 200) Ø 5 mm
(f_{au} = 1830 N/mm^2)

DIAGRAMS – RECOMMENDATIONS

strength – temperature relation
for reinforcement and prestressing steel

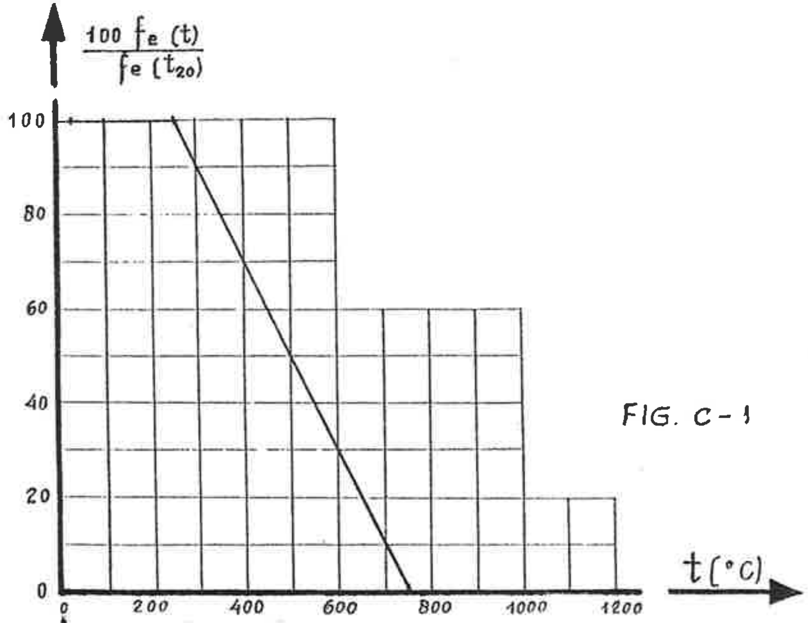


FIG. C-1

The yield stress (0.2% stress) of reinforcement steel in the heated state.

The graph shows the relation between the yield stress and the temperature of reinforcing steel, given in the French recommendations for the calculation of the behaviour of concrete structures under fire-conditions [13] (1974). (In 1978 a proposal is made for new recommendations in which the yield stress is supposed to decrease in about the same way as the ultimate stress.)

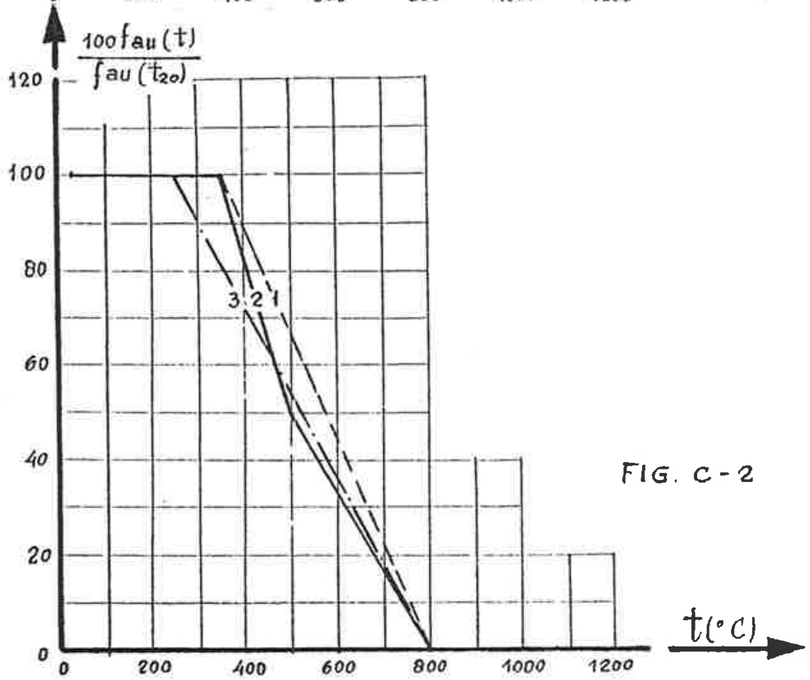


FIG. C-2

The ultimate stress (Tensile strength) of reinforcement steel in the heated state.

The relation are given in the French recommendations for the calculation of the behaviour of concrete structures under fire conditions.

1 = steelquality FeB 400

2 = the steelqualities FeB 220 and 240

3 = welded steel fabric

From: [13], (1974)

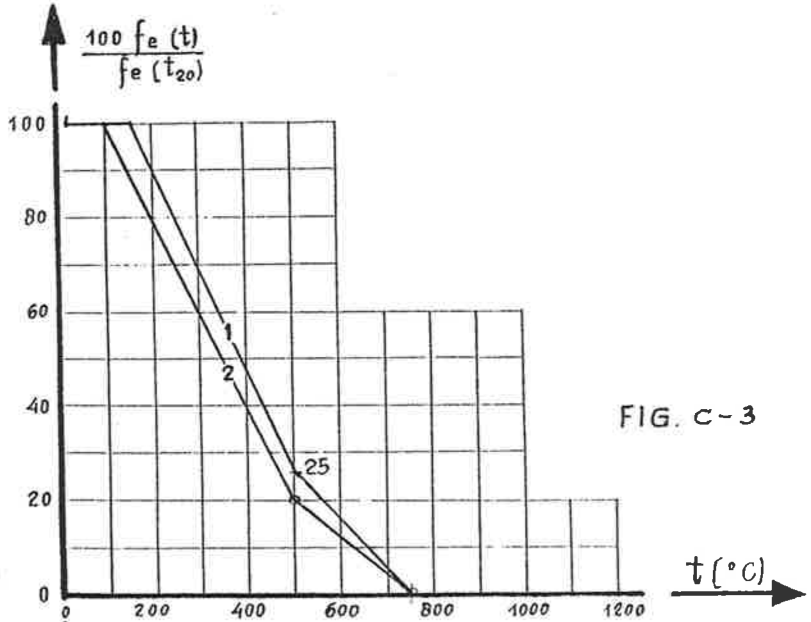


FIG. C-3

The yield stress of prestressing steel in the heated state.

The graphs show the relation between the yield stress of prestressing steel and the temperature according the French recommendations for the calculation of the behaviour of concrete structures under fire conditions [13], 1974.

1 = rolled steel and strands

2 = stabilized cold drawn wires

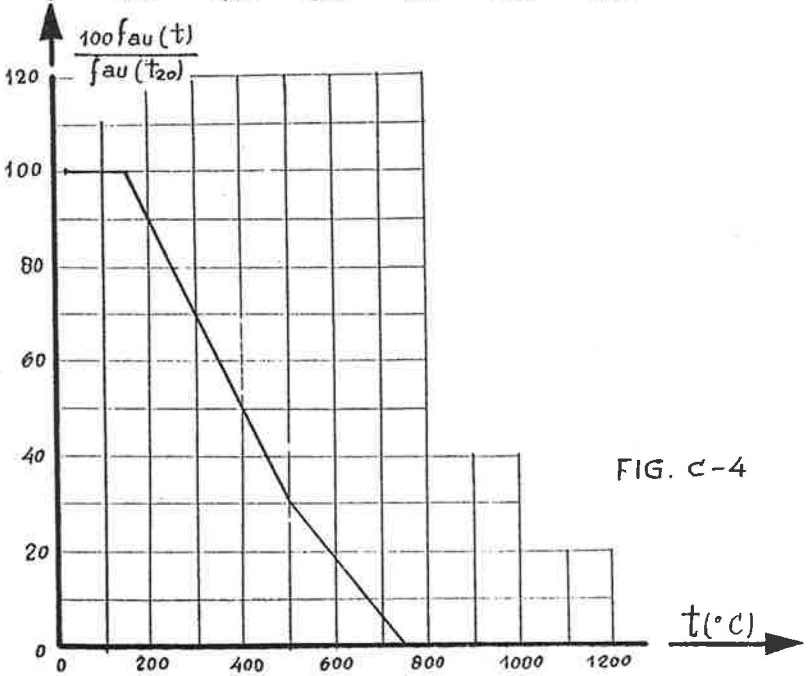


FIG. C-4

The ultimate stress (tensile strength) of prestressing steel in the heated state.

The graph shows the relation between tensile strength and temperature for rolled prestressing steel and strands according the French recommendations for the calculation of the behaviour of concrete structures under fire conditions [13], 1974.

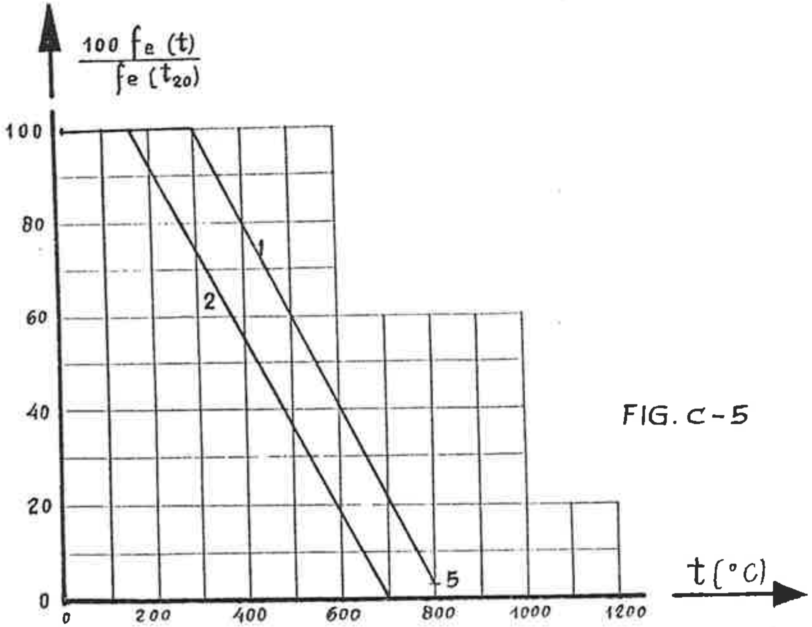


FIG. C-5

The variation of the yield stress (0.2% stress) or tensile strength of reinforcement and prestressing steel in the heated state.

---

1. - high yield reinforcement bars
   - mild steel reinforcement bars
   - high strength alloy steel bars
2. - prestressing wires and strands

The figure is taken from the English publication: "Design and detailing of concrete structures for fire resistance" [19], 1978.

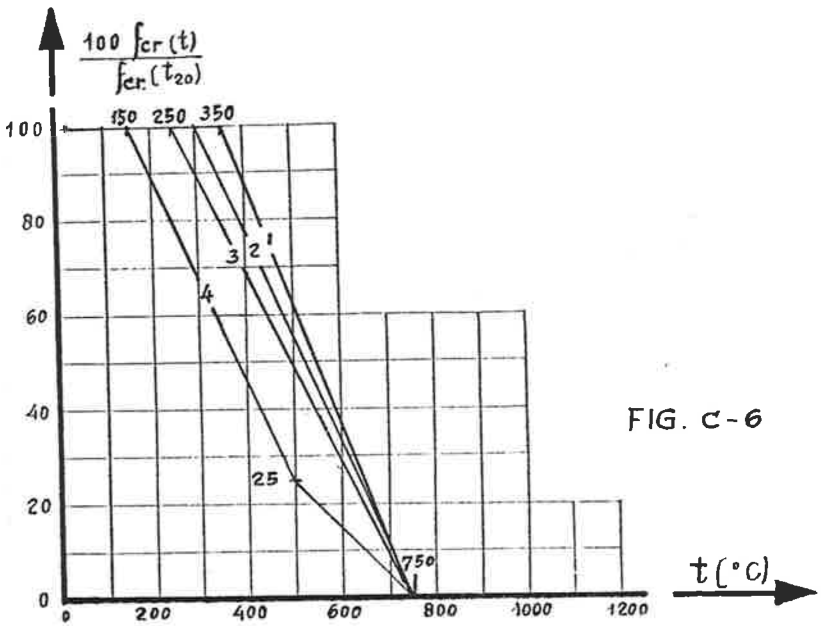


FIG. C-6

The critical combination of stress and temperature for reinforcement steel and prestressing steel.

---

1 = reinforcement steel FeB 240

2 = " " FeB 400

3 = { welded steel fabric FeB 500
hot rolled prestressing steel FP 1050

4 = cold drawn prestressing steel (strands included)

The graphs are taken from the Dutch report [21], 1972.

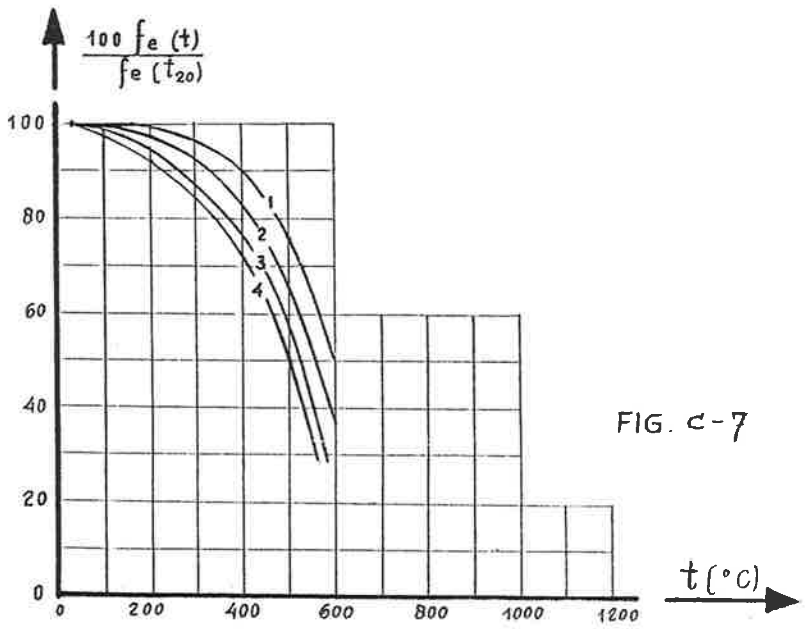


FIG. C-7

The yield stress of reinforcement steel in the heated state.

---

1 hot rolled steel, 220/340 (= yield stress / tensile strength) at 20°C

2 hot rolled steel, 420/500 (") at 20°C

3 cold twisted steel, 420/500 (") at 20°C

4 cold drawn steel, 500/500 (") at 20°C

The information is given in the FIP/CEB publications: [10] , (1975) and [11] (1978). In the latter it is said, that the information given here, necessarily must be general, because comprehensive investigations leading to statements of general validity are not yet available. Since there can be differences in types of steel from country to country, a close agreement in test results should not be expected.

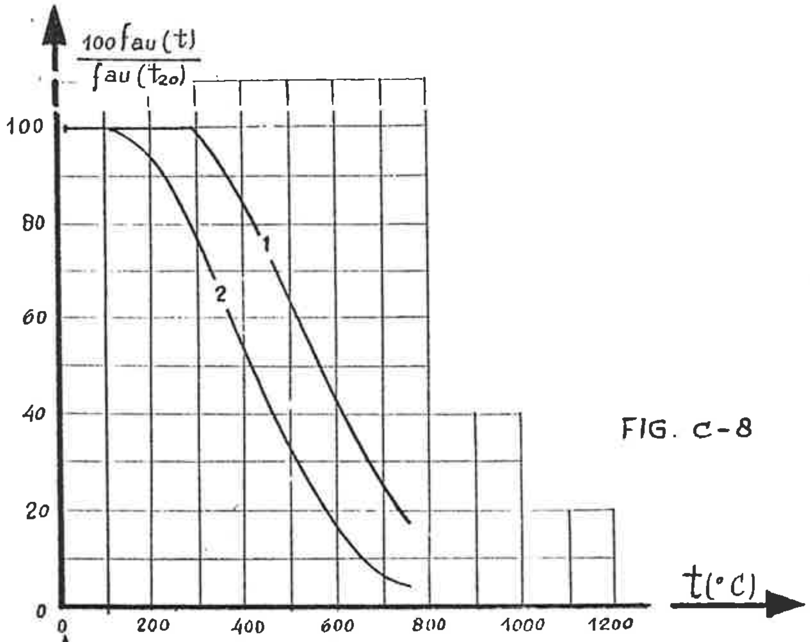


FIG. C-8

The ultimate stress (tensile strength) of prestressing steel in the heated state.

The graphs are published in the American P.C.I.-Manual: "Design for fire resistance of precast prestressed concrete" [8], 1977, which for the backgrounds refers to [16], 1961 and [18], 1971.

1 = high strength alloy steel bars

2 = cold drawn prestressing steel (tensile strength: 1750 or 1890 N/mm^2

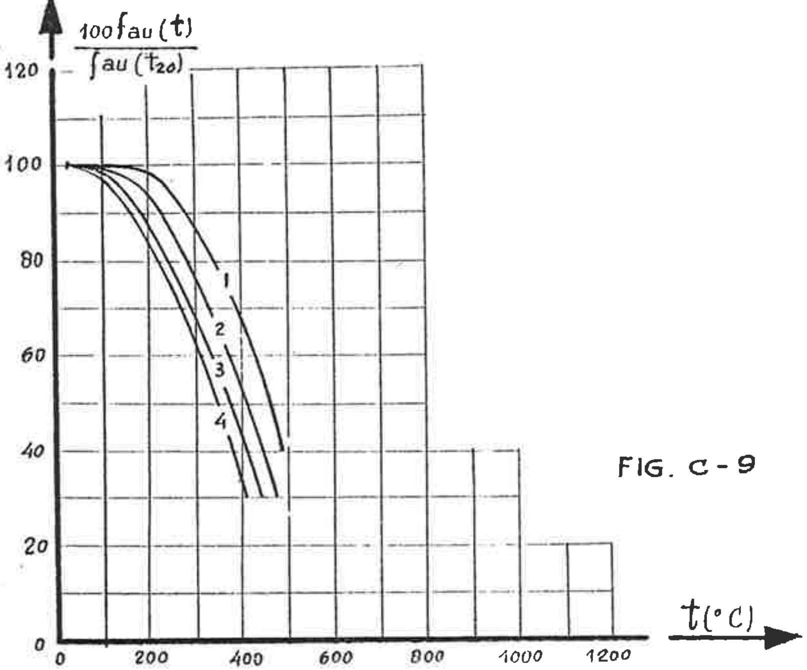


FIG. C-9

The ultimate stress (tensile strength) of prestressing steel in the heated state.

---

1 = quenched and tempered steel

2, 3, 4 =stabilized, cold drawn steel

Tensile strength at 20^{o}C:

1, 2:	f_{au}	=	1600 N/mm^2
3 :	"	=	1800 "
4 :	"	=	1850 "

The information is given in the FIP/CEB publications [10], (1975) and [11] , (1978).

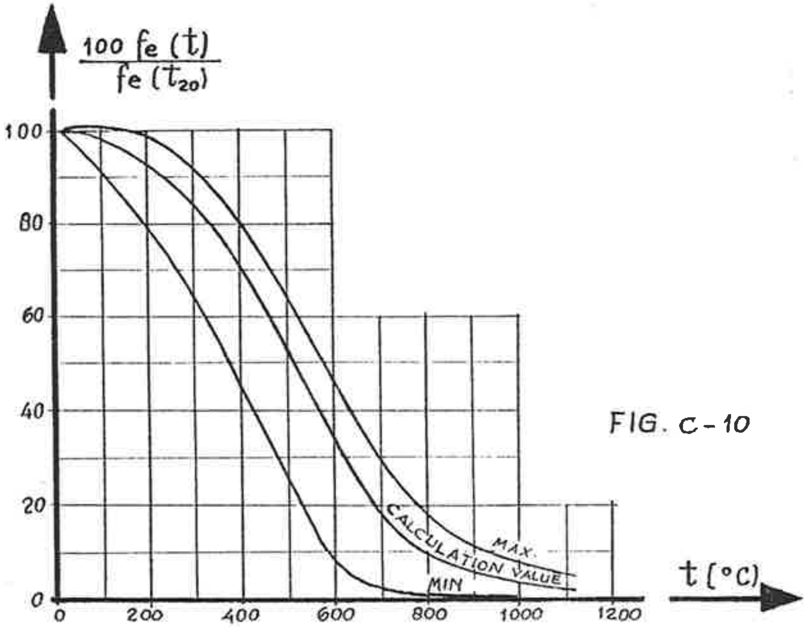


FIG. C-10

The yield stress (0.2% stress) of reinforcement-steel in the heated state.

Many test results were collected after which the boundaries could be given between which the majority of the test-results are situated. The calculation value $f_{e(t)}$ has been defined for cold deformed steel and is assumed to give the lowest values found in tests. The values are given by the equation:

$$f_{e(t)} = \begin{cases} f_{e(20)} \sum_{n=0}^{2} a_n (t - t_2)^n & \text{for } t_o \leqq t \leqq t_1 \\ f_{e(20)} \left(\sum_{n=0}^{2} b_n t^n \right)^{-1} & \text{for } t > t_1 \end{cases}$$

The values for a, b, t (Temperature) and for n = 0, 1 or 2 are given in the table below.

n =		0	1	2
calculation value	a	1,0	$-0,91 \cdot 10^{-5}$	$-1,988 \cdot 10^{-6}$
	b	24,1	$-0,881 \cdot 10^{-1}$	$0,881 \cdot 10^{-4}$
	t	20,0	550,0	20,0
min.	a	1,0	$-0,98 \cdot 10^{-3}$	$-1,176 \cdot 10^{-5}$
	b	754,66	$-2,827$	$0,267 \cdot 10^{-2}$
	t	20,0	550,0	20,0
max.	a	1,0	$0,339 \cdot 10^{-3}$	$-0,224 \cdot 10^{-5}$
	b	12,389	$-0,427 \cdot 10^{-1}$	$0,427 \cdot 10^{-4}$
	t	20,0	550,0	20,0

The information is given in [12], to be used for the calculation of the fire resistance of reinforced concrete structures (T.U. Braunschweig, 1976)

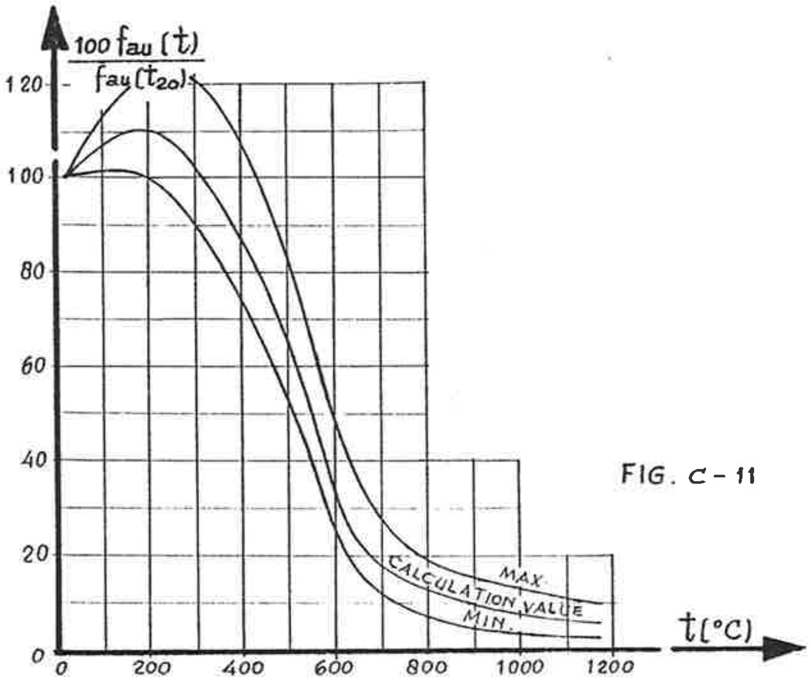


FIG. C-11

The ultimate stress (tensile strength) of reinforcement steel in the heated state.

In this figure the boundaries are given between which most of the test-results are supposed to be situated. The calculation value is defined by the equation:

$$f_{au}(t) \begin{cases} = f_{au_{20}} \sum_{n=0}^{2} a_n \, (t - t_2)^n & \text{for } t_o \leq t \leq t_1 \\ = f_{au_{20}} \, b_o \, (t - t_3)^{-1} & \text{for } t > t_1 \end{cases}$$

The values for a, b and t (Temperature) are given in the table below.

n =		0	1	2	3
calculation - value	a	1,1	$- 0{,}2 \cdot 10^{-3}$	$- 0{,}421 \cdot 10^{-5}$	-
	b	41,6	-	-	-
	t	20,0	600,0	200,0	480,0
min.	a	1,0	$0{,}585 \cdot 10^{-3}$	$- 0{,}324 \cdot 10^{-5}$	-
	b	21,5	-	-	-
	t	20,0	600,0	20,0	514,0
max.	a	1,25	$0{,}337 \cdot 10^{-3}$	$- 0{,}584 \cdot 10^{-5}$	-
	b	65,8	-	-	-
	t	20,0	600,0	200,0	454,0

The information is taken from [12] (T.U. Braunschweig, 1976).

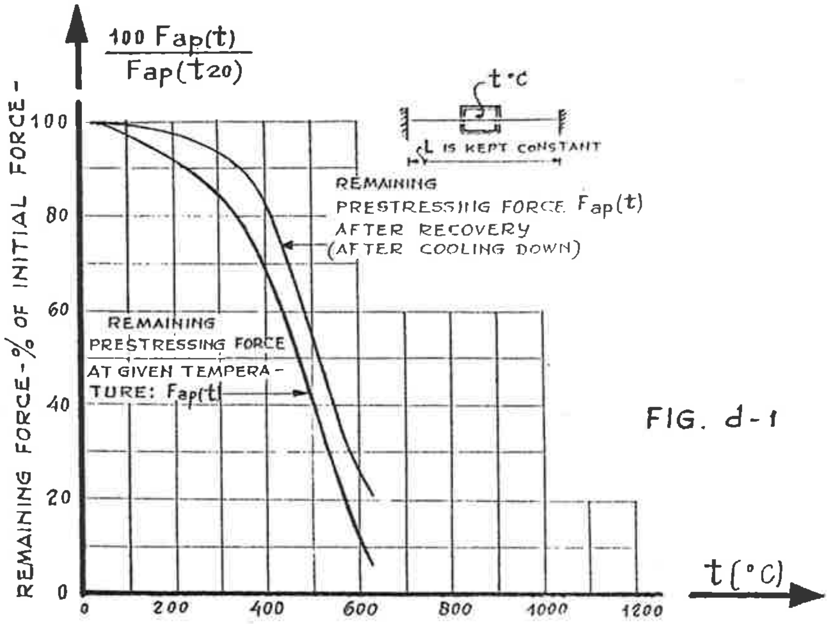


FIG. d-1

The prestressing force as a function of the temperature in the prestressing steel.

The relation is based on American test results. In the tests $\frac{3}{8}$ in diameter (Ø 9.5 mm) strands were initially loaded to 40, 56 and 71% of the ultimate strength at room temperature, after which the temperature over some length was raised in an electrically heated furnace as is shown in the figure. The length of each strand specimen between the grips was six feet (1.83 m).
The length of the strand in the furnace was 8 inches (203 mm).
The tests and the results are described in [16], 1961.

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