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## Properties of Materials at High Temperatures Steel

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# PROPERTIES OF MATERIALS AT

# HIGH TEMPERATURES

# STEEL

Edited by

Y Anderberg

# B E H A V I O U R   O F   S T E E L   A T   H I G H

# T E M P E R A T U R E S

by

Yngve Anderberg

February   1983

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FOREWORD

During mid-seventies international discussions indicated
that research into fire and fire behaviour of structures
was being pursued by a number of international organiza-
tions; a Commission of CIB (W14) was studying basic fire
phenomena and had been asked by the liaison committee of
the international engineering associations to provide a
common approach for the design of structures against fire.
Various materials committees were starting work on design
codes and CIB/W14 set up a Code Advisory Panel to provide
some general principles. A directorate of the EEC Commis-
sion started activity on the harmonization of fire test
standards and fire safety codes. The fire test standards
were prepared by the ISO Technical Committe TC 92. One ob-
vious ommission in this system was the absence of agreed
data on material properties which could be used in the
structural design codes. An approach was made to the RILEM
Permanent Committee, as the General Council was known at
that time, to initiate a technical committee to deal with
this topic. Approval was given in 1977 for the formation
of Committee 44 - PHT and it met for the first time in
April 1978. The active membership of the committee came
from many countries as the list on the inside front page
shows. Over a period of 5 years the committee held 10
meetings, including a special seminar in the middle of
1982 in the Hague.

When examining the range of materials to be studied, maxi-
mum emphasis was placed on the major materials of construc-
tion, i.e. concrete, masonry, steel and wood but others
having an important role in the building construction were
also included. However it was necessary to keep the work
within manageable proportions and the maximum effort was
devoted to the study of concrete and steel. The list of
materials examined is as follows:

Concrete; dense and lightweight,
Steel; structural, reinforcing and prestressing,
Wood; soft and hardwoods,
Masonry; brick and concrete blocks,
Plactics; constructional,
Gypsum; plaster and board.

The amount of data available on concrete and steel was
large and it required much effort on the part of the spe-
cialist panels to consolidate the information. For steel
this task was undertaken by Dr. Y. Anderberg who also edi-
ted the final document. The amount of data was so exten-
sive that it became difficult for the RILEM secretariat
with its limited resources to publish it. Lund Institute
of Technology has kindly come to our assistance and agreed
to publish the information so that it may become available
to individuals and associations who are interested in this
field. I wish to express my personal thanks and those of
the RILEM Secretariat to Dr. Anderberg and the Division of
Building Fire Safety and Technology for this most valuable
help.

The document is unique in presenting information for the
first time in this collective form and in a way that direct
comparisons can be made. It has also highlighted areas
where further research may be successfully carried out.
Determination of the physical properties under transient
heating conditions and their expression as a mathematical
model will assist fire engineers in the design and analysis
of structures exposed to fire conditions.

I appreciate the valuable help given by all committe mem-
bers of 44 - PHT during our meeting in various host insti-
tutes and my only regret is that we were not able to comp-
lete the work on some of the other materials. Data on con-
crete is being published simultaneously. No doubt another
RILEM technical committee will be able to take in on board.

H.L. Malhotra
Chairman 44 - PHT

# C o n t e n t

Preface

## Part I: Introduction

## Part II: Steel properties

## Part III: Steel literature

Preface

The objectives of the technical committee are to iden-
tigy those properties and characteristics, which are
of inportance, survey the existing knowledge, evaluate
the data and the relevant literature, suggest activity
in areas not already covered and provide facilities for
the dissemination of information in papers and by dis-
cussion.

In this report the main features of the behaviour of
steel at high temperature are summarized and discussed.
The report is divided into three parts:

Part I      - INTRODUCTION

Part II     - STEEL PROPERTIES

Part III    - STEEL LITERATURE


        Part I: INTRODUCTION

1 Background

Many investigations on mechanical properties of steels at high
temperatures have been reported during the last 30 years. How-
ever, the results are sometimes hard to interpret and to com-
pare with other investigations due to the fact that

· test specimens are different (variation in chemical compo-
  sition, shape and size)

· descriptions are incomplete

· test procedures differ

· test conditions are not comparable

· unsatisfactory accuracy and reliability of testing equipment.

Therefore, it is useful to try to clarify and elucidate the
main characteristics and features of steel behaviour and the
different test methods used.

A careful distinction is made between stabilized temperature tests and transient tests, and also between hot-rolled and cold-worked reinforcing steel and structural and prestressing steel. These steels behave in many ways differently. The most important properties are discussed and a comparative study is made of test results from different sources. The paper also briefly discusses analytical models of steel. In many papers one agrees to the fact that in a deformation process of steel the total strain can be separated into three components, i.e. thermal strain, instantaneous stress-related strain and creep strain. These strains are also discussed separately.

In the list of references the properties of steel are divided into a number of main headings following the same sequence as in chapter 3. Further, each property includes subheadings, which separate the three categories of steel, i.e. structural steel, reinforcing steel and prestressing steel. A few references to other materials such as cast iron are included. The reference list also contains sections on structural behaviour and analytical models of steel and steel structures.

## 2  Different methods of testing

There exist two main groups of tests, steady state tests and transient tests. Material properties measured are closely related to the test method used. It is therefore of great importance that the test conditions are well defined.

During a fire situation the material is normally subjected to transient processes with varying temperature and stress, and to understand this, transient tests are needed. Steady state tests cannot be used solely to explain the stress-strain characteristics of steel in all cases.

Mechanical properties of steel can be established by follo-
wing a number of different test procedures. The three main
test parameters are the heating process, application and
control of load, and control of strain. These can have cons-
tant values or be varied during testing, giving steady state
or transient conditions depending on the heating procedure.

Six practical regimes which can be used for determining
mechanical properties are illustrated in Fig. 1. Properties
in these regimes are as follows:

steady state tests

- stress-strain relationship  (stress rate controlled)

- stress-strain relationship  (strain rate controlled)

- creep

- relaxation

transient tests

- total deformation, failure temperature  (stress control)

- total forces, restraint forces  (strain control).

## 2.1  Steady state tests

Steady state tests are characterized by a heating period, $t_H$,
and a period of time, $t_s$, during which the temperature of the
specimen is stabilized before any load is applied, as shown
in Fig. 2. The time $t_s$ depends on the size of the specimen,
but is usually not more than 0.5 h. The strain measured be-
fore the load is applied corresponds to the thermal expansion.

After time $t_H + t_s$ the temperature is kept constant and four
types of steady state tests are usually carried out as indi-
cated above. Properties related to these tests are described
below.

- 4 -

### 2.1.1 σ-ε relationship, stress rate controlled

After the stabilized period of heating, the specimen is sub-
jected to a constant rate of loading until failure occurs
(see Fig. 3a). The data obtained provide σ-ε relationships
at different temperatures of the type shown in Fig. 3b and
can be used to establish compressive or tensile strength,
modulus of elasticity and ultimate strain at collapse. For
prestressing steels, however, there exists no yielding plateau
as indicated in Fig. 3b. The stress-strain relationship is
often obtained at a high rate of loading, $\dot{\sigma}$, (loading time
1-2 minutes) in order to avoid the influence of creep, which
is of importance above about 400°C for ordinary steel (for
cold-worked steel above about 250°C). The influence of creep
results in a displaced σ-ε curve and a lower ultimate (rup-
ture) strength, which will be illustrated in chapter 4.

### 2.1.2 σ-ε relationship, strain rate controlled

σ-ε relationships measured under strain rate control are close-
ly related to the test described above. After the stabilized
period of heating the specimen is loaded at a specified strain
rate, $\dot{\varepsilon}$, as indicated in Fig. 4a. This test yields σ-ε curves
as illustrated in Fig. 4b. Depending on the strain rate, the
influence of creep above a certain temperature level yields
differing σ-ε curves. This will be illustrated in chapter 4.

In these kinds of tests the maximum stress is reached for a
given strain and at higher strains the stress decreases
somewhat with failure occurring at much greater strains than
in the corresponding stress controlled σ-ε tests. The σ-ε
curves obtained not only provide properties mentioned in
2.1.1, but also mechanical dissipation energy. The ultimate
strain, however, is related to the maximum stress level and
not to the failure state.

### 2.1.3 Creep

When the desired temperature is attained in a creep test, the specimen is loaded and the load is then kept constant during the whole test period as shown in Fig. 5a. At the time $t_H + t_S$, when the load is applied, the immediate response results in an instantaneous elastic strain and thereafter a deformation as function of time, i.e. creep, takes place, which is illustrated at different temperatures in Fig. 5b. The test period of inte-rest during a fire is usually from 2-4 hours. A typical creep curve is shown in Fig. 6 indicating that the creep process con-tains three phases, i.e. primary, secondary and a tertiary phase. Normally, only the initial creep, i.e. the primary and the secondary phase, are studied.

### 2.1.4 Relaxation

A relaxation test is closely related to a creep test, but when the specimen has been loaded the initial strain is kept con-stant and the decrease in stress is measured during the whole test period. Fig. 7a illustrates the whole strain history. The reduction of stress or relaxation as function of time, which is due to the creep, is shown in Fig. 7b. Normally, a period of 2-4 hours is of interest during fire situations.

## 2.2 Transient tests

Transient temperature tests or non-steady state tests are characterized by a varying temperature (often increasing linearly, see Fig. 8) and a simultaneous load. The load can be applied before heating or developed during heating by restraint against thermal expansion. These two types of transient tests are carried out with load and strain cont-rol, respectively. The second alternative appears only in compression. Properties related to these tests are described below.

2.2.1  Failure temperature, total deformation

A load is applied to the specimen before heating; heating pro-
ceeds at a specified rate ($\dot{T}$ = 5-50$^{O}$C/min) until failure occurs.
Usually, the load is constant as shown in Fig. 9a. Total de-
formation as a function of time is recorded until the failure
point, i.e. when the strain rate or total strain is approaching
infinity. The temperature measured at that critical point is
called the failure (critical) temperature. Typical results are
illustrated in Fig. 9b for different load levels. The result
is very much influenced by the rate of heating as creep cannot
be avoided. The curves enable failure temperatures which pro-
vide strength/temperature relationships to be found in Fig. 9c.
Similar relationships can be obtained from steady state σ-ε
curves.

If one plots the total deformation minus the thermal strain,
against the temperature, one obtains curves as illustrated in
Fig. 9d. From these curves, σ-ε relationships can be constructed
in which the creep strain corresponding to a specified heating
rate is included, Fig. 9e. The heating rate has a great influ-
ence on these σ-ε curves, just as the strain rate has in steady
state σ-ε tests. This is illustrated in chapter 3.5.2 and 4.

2.2.2  Restraint forces

If the deformation is kept constant during a transient heating
process, restraint forces arise. The deformation can be zero
or correspond to the initial strain response of load applica-
tion before heating as indicated in Fig. 10a. In such a strain
controlled transient test at temperatures above about 550-600$^{O}$C,
the total force (initial load + restraint force) is indepen-
dent of the initial load, which can also be zero, see Fig. 10b.
If the total load minus the initial load is considered, one
will obtain differing curves depending on the varying influ-
ence of creep. Measurements of restraint forces can only be
carried out on steel structures with no buckling influence,
i.e. very short columns.

Fig 1    Different testing regimes for determining
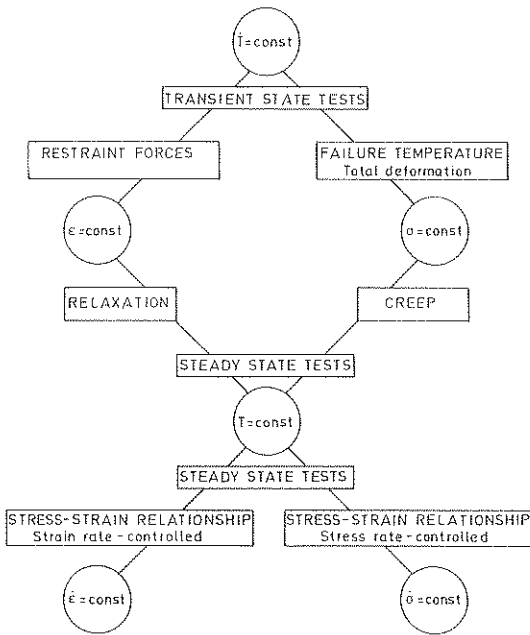          mechanical properties
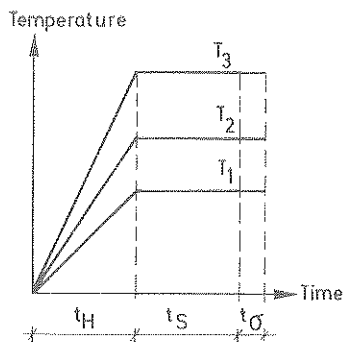
Fig 2   Typical steady state temperature curve
$t_H$ = heating period
$t_S$ = stabilizing period
$t_\sigma$ = loading period (1-3 minutes)

a)



b)
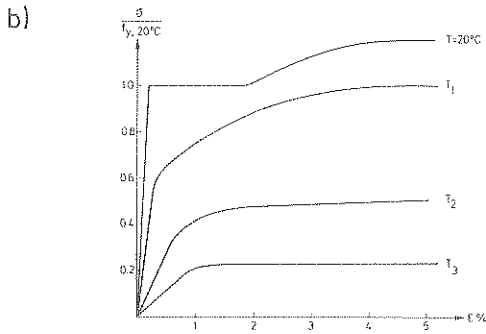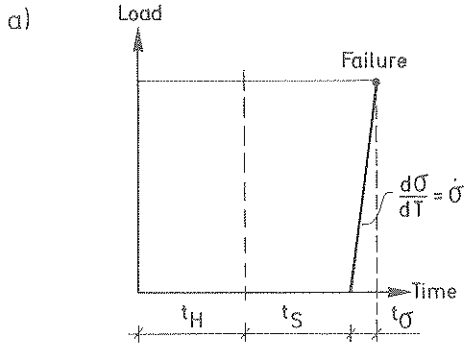


Fig 3   Stress rate controlled $\sigma-\varepsilon$ tests

a) Loading procedure
b) Typical results

a)



b)
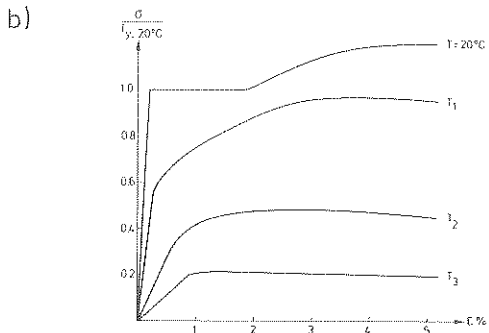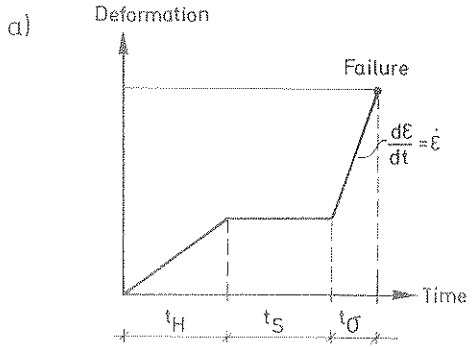


Fig 4  Strain rate controlled σ-ε tests
a) Deformation procedure
b) Typical results

a)

Load · · · · · Load

$\sigma_3$

$\sigma_2$

$\sigma_1$

$t_H + t_S$

0　1　2　3　Time, h

b)

Strain

$\sigma_3 , T_1$

$\sigma_2 , T_1$

$\sigma_1 , T_1$

1　2　3　Time, h

$\varepsilon_{\sigma_3}$　$\varepsilon_{\sigma_2}$　$\varepsilon_{\sigma_1}$
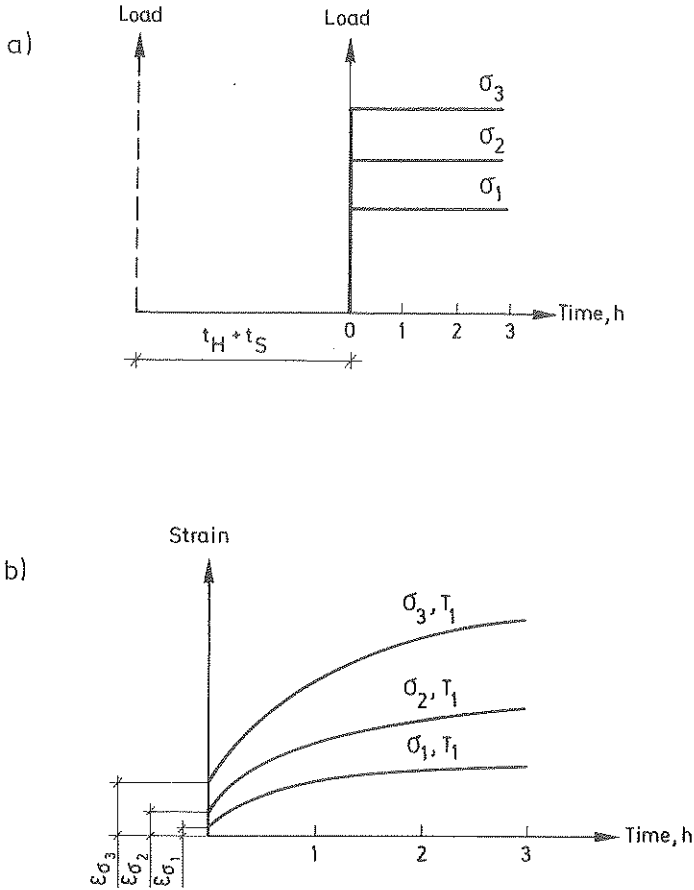
Fig 5　Creep tests

　　　a) Loading procedure
　　　b) Typical results
　　　　　$\varepsilon_\sigma$ - instantaneous stress-related strain
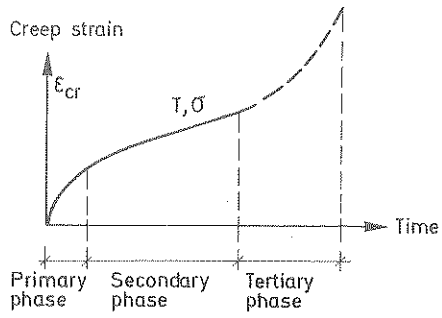
Fig 6  Typical creep curve
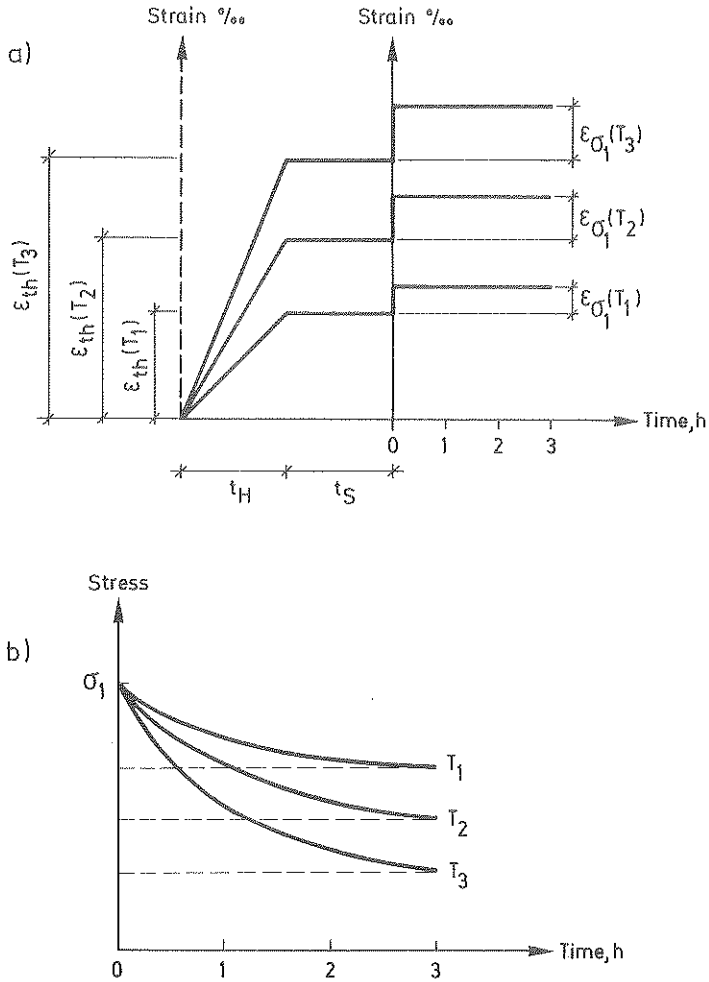
Fig 7   Relaxation tests
   a) Strain history
   b) Typical results
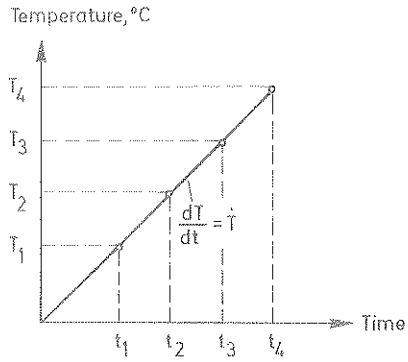
Fig 8 Typical transient state temperature curve
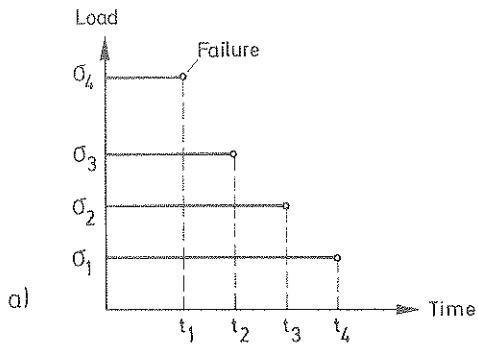


Fig 9 Transient tests with load control
a) Load history

b)



c)
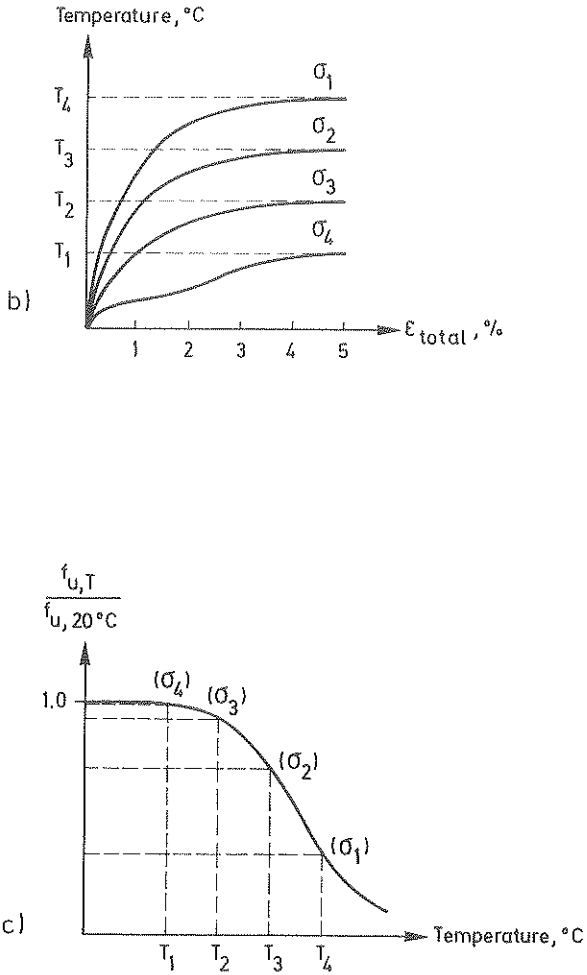
Fig 9   Transient tests with load control
        b) Typical deformation curves
        c) Typical strength-temperature relationships
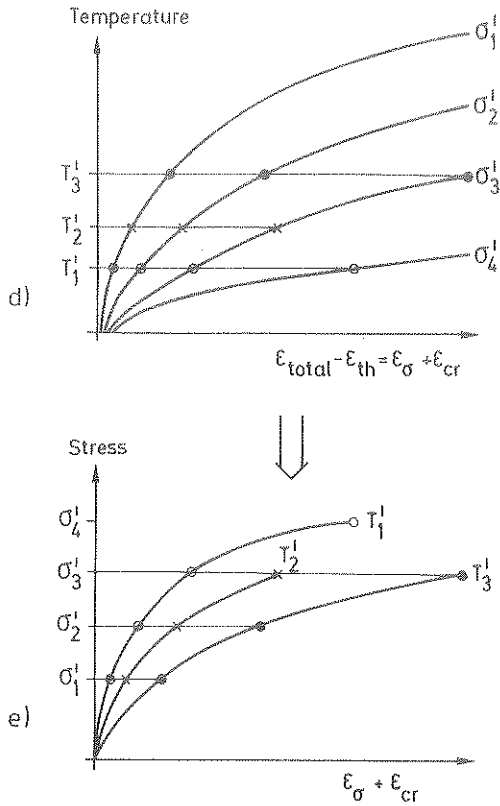
Fig 9    Transient tests with load control

d) Typical $\varepsilon$-T curves at four different stress levels.
$\varepsilon = \varepsilon_{tot} - \varepsilon_{th}$

e) Calculated $\sigma$-$\varepsilon$ curves (including creep) at different temperatures
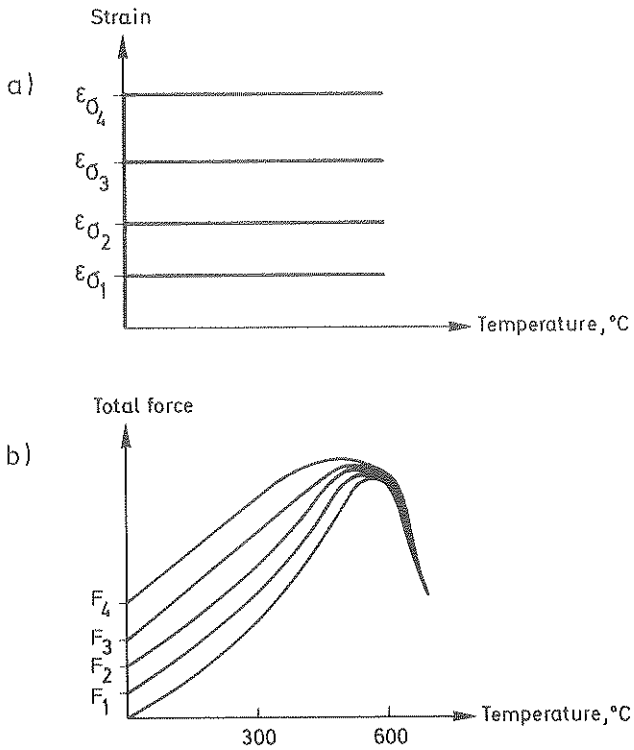
Fig 10   Transient tests with strain control
         a) Strain history
         b) Typical curves of restraint forces

Part II: STEEL PROPERTIES

## 3 Particular properties

Properties of steel obtained or derived from different tests described above are collected in this chapter. The data are based on a literature survey and the source can always be found in the reference list in part III, chapter 6.

The presentation is based on relevant data as far as possible and the basic test conditions and the strength characteristics, the chemical composition (when available) and the reference are always given. This is a screening of individual reports on reinforcing, structural and prestressing steel, and further data may continuously appear in future.

### 3.1 Tensile strength

It is not only important to define the precise meaning of tensile strength, but also to define the type of test whether steady state or transient state. It can be the ultimate tensile strength, $f_u$ (rupture strength), or the tensile strength related to a specified residual stress induced strain in the $\sigma$-$\varepsilon$ curve as principally illustrated in Fig 11. The stress which produces for instance a residual strain of 0.2% is called the 0.2% proof stress or the yield stress, $\sigma_{0.2}$, although the yielding plateau for hot-rolled steels disappears at temperatures above $300^{\circ}C$. When the strength is defined by the proof stress for a given residual, non-recoverable strain, for instance 0.2% and 0.5%, it will be denoted $f_{0.2}$ and $f_{0.5}$.

When the ultimate strength is measured in a transient test with constant load control it can either be related to the critical temperature when the strains reach infinite values or to a strain rate criteria, for instance $\dot{\varepsilon} = 1.0 \cdot 10^{-4} \cdot s^{-1}$. If it is connected to a strain rate criteria this will be specially indicated when presenting data. The ultimate strength and proof stress are obtained from $\sigma$-$\varepsilon$ curves at different temperature levels or from load controlled transient tests as described in chapter 2.2.1

Depending on the test procedure the creep may influence the strength-temperature curve and, therefore, it must be considered when comparing such curves from different laboratories. The creep results in a decreased value of the tensile strength above about $250^\circ$C and $400^\circ$C for cold-worked and hot-rolled steel, respectively.

Parameters of importance in an analysis of the tensile strength are

in steady state $\sigma-\epsilon$ tests

- rate of stress, $\overset{\bullet}{\sigma}$, at stress rate control
- rate of strain, $\overset{\bullet}{\epsilon}$, at strain rate control

and in load controlled transient tests

- rate of temperature increase, $\overset{\bullet}{T}$
- strain rate criteria.

Depending on the test characteristics the influence of creep is different.

A general conclusion is that the relative decrease in tensile strength of all hot-rolled and prestressing steels is almost the same, which means that the original strength has little influence on the strength-temperature curve. The 0.2% proof stress and the ultimate strength of such steels obtained in steady state and transient state tests have at 500-550$^\circ$C 50% of its original value left, and at 700$^\circ$C about 20%. For prestressing steel the 50 and 20% limits are reached at 350-400$^\circ$C and 500$^\circ$C, respectively. Fig. 11 indicates that cold-worked steel has a higher strength-temperature curve. Too little data are available to make a certain conclusion.

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The influence of strain rate, $\dot{\varepsilon} = 0.1\text{-}100\cdot10^{-3}\cdot\text{min}^{-1}$, is
illustrated in Fig 8 and at $600^{\circ}$C the strength value varies
from 0.65 to $0.3\cdot f_{0.2,20^{\circ}C}$. In Fig 9 different rates of load-
ing, 0.03-1.63 MPa/s, result in strength values 0.35-0.25·
$f_{0.2,20^{\circ}C}$ at $600^{\circ}$C.
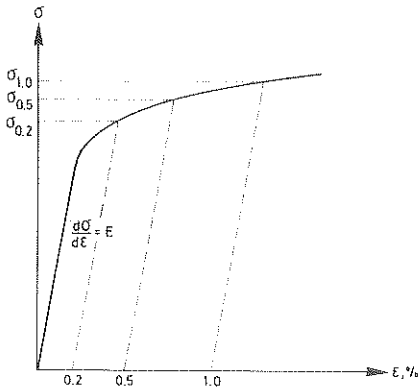


Fig 11   The principal for determining the proof stress,
which is based on the residual stressinduced strain

## 3.1  TENSILE STRENGTH

a) Structural steel    : ASTM A36, $f_{0.2,20^\circ C}$ = 300 MPa

$f_{u,20^\circ C}$ = 440 MPa

Test conditions    :
Steady state
Strain rate control
$\dot{\varepsilon}$ = 72-102·$10^{-3}$·min$^{-1}$

Specimen    : $\emptyset$ = 5.2 mm, $\ell$ = 23 mm

Chem. composition  :
| C | P | S | Mn | Si |
|------|-------|------|------|------|
| 0.19 | 0.007 | 0.03 | 0.71 | 0.09 |

Remarks    : Ultimate strength and 0.2% proof
stress as function of temperature

Reference    : Harmathy & Stanzak (1970)

Fig 1
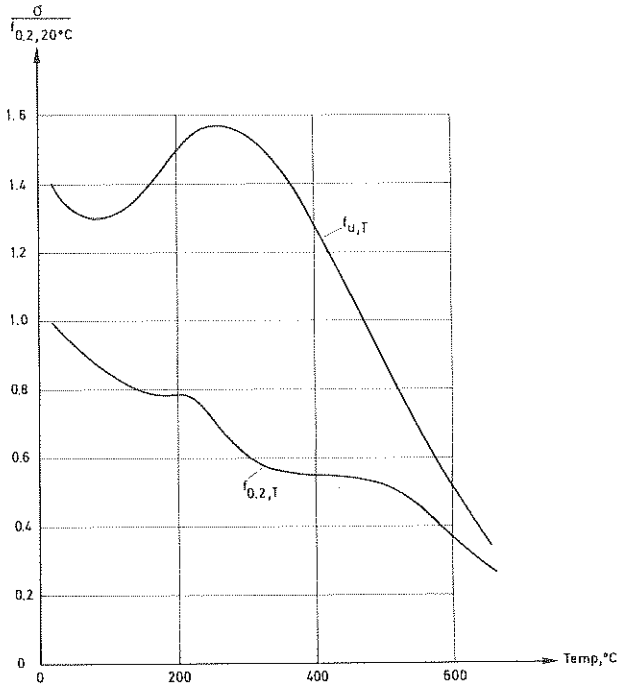
## 3.1  TENSILE STRENGTH

a) Structural steel  : CSA G40.12, $f_{0.2,20^\circ C}$ = 340 MPa

$f_{u,20^\circ C}$ = 520 MPa

Test conditions  : Steady state
Strain rate control
$\dot{\varepsilon}$ = 51-76·$10^{-3}$·$min^{-1}$

Specimen  : $\emptyset$ = 5.2 mm, $\ell$ = 23 mm

Chem. composition :

| C | P | S | Mn | Si | Cu |
|---|---|---|----|----|----|
| 0.195 | 0.015 | 0.019 | 1.40 | 0.022 | 0.08 |

| Ni | Cr |
|----|----|
| 0.03 | 0.01 |

Remarks  : Ultimate strength and 0.2% proof stress
as function of temperature

Reference  : Harmathy & Stanzak (1970)

Fig 2
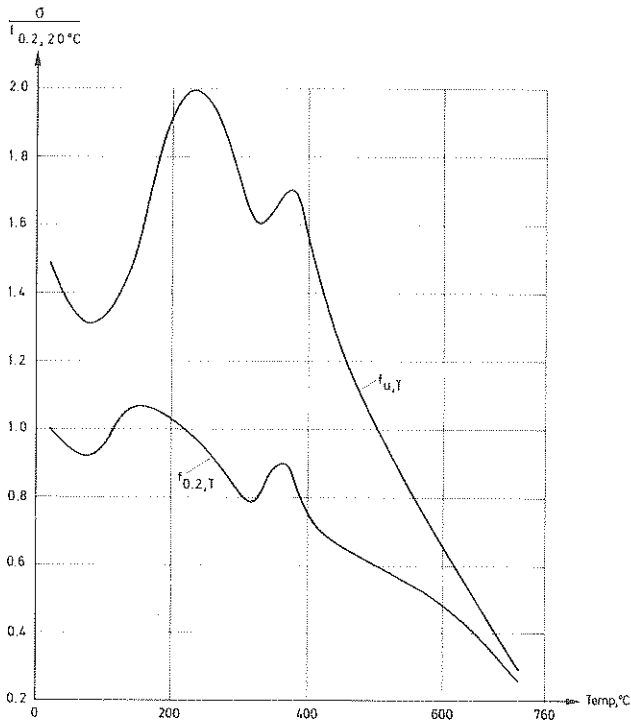
## 3.1 TENSILE STRENGTH

a) Structural steel     : Different kinds

    Test conditions     : Steady state
                          Strain rate control, $\dot{\varepsilon} = 16.7 \cdot 10^{-3} \cdot min^{-1}$

    Specimen            : $\emptyset = 6.3$ mm, $\ell = 57$ mm

    Chem. composition   :

    Remarks             : 0.2% proof stress for
                          different kinds of steel as function
                          of temperature

    Reference           : Teesside Laboratories (1980)

Fig 3



$\dfrac{f_{0.2,T}}{f_{0.2, 20°C}}$
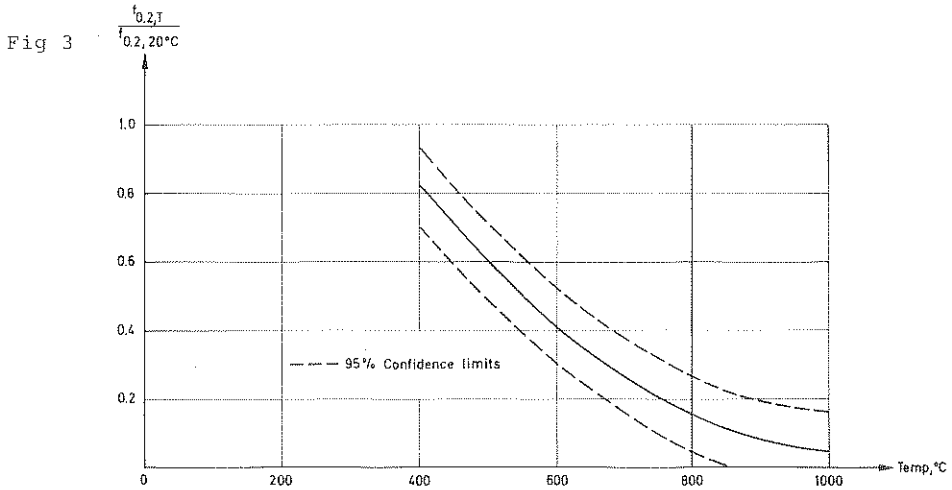
## 3.1 TENSILE STRENGTH

a) Structural steel : Steel 37, $f_{0.2,20^{\circ}C}$ = 250 MPa

Test conditions : Steady state
Strain rate control, $\overset{\circ}{\varepsilon} = 2 \cdot 10^{-3} \cdot \min^{-1}$

Specimen : $\emptyset$ = 7.2 mm, $\ell$ = 71 mm

Chem. composition :

| C | P | S | Mn | Si | Cr |
|------|-------|-------|------|-------|------|
| 0.27 | 0.033 | 0.041 | 0.65 | 0.128 | 0.16 |

Ni
0.086

Remarks : Proof stress related to
different stress induced strains

Reference : Skinner, D.H. (May 1972)

Fig 4
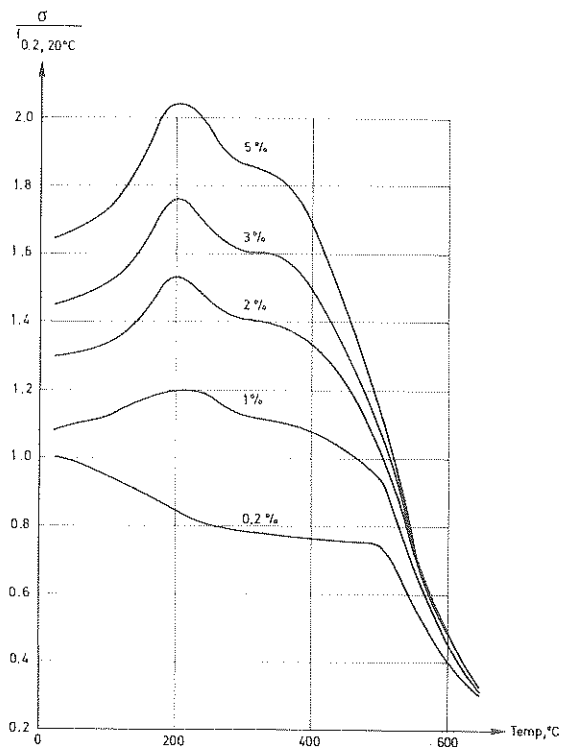
## 3.1  TENSILE STRENGTH

a) Structural steel     : ① St 60/90, $f_{0.2,20^oC}$ = 590 MPa
c) Prestressing steel   : ② St 145/165, $f_{0.2,20^oC}$ = 1520 MPa
                          ③ St 160...180, $f_{0.2,20^oC}$ = 1570 MPa

Test conditions    : Steady state
                     Stress rate control, $\overset{\circ}{\text{o}}$ is unknown

Specimen           : ① Hot-rolled, $\emptyset$ = 26 mm
                     ② Cold-drawn, $\emptyset$ = 5.2 mm
                     ③ Cold-drawn, $\emptyset$ = 5 mm

Chem. composition  :

Remarks            : 0.2% proof stress as func-
                     tion of temperature

Reference          : Dannenberg et al (1959)

Fig 5

## 3.1   TENSILE STRENGTH

a) Structural steel    : ① St 60/90, $f_{u,20^{o}C}$ = 1050 MPa
c) Prestressing steel  : ② St 145/165, $f_{u,20^{o}C}$ = 1650 MPa
                         ③ St 160...180, $f_{u,20^{o}C}$ = 1740 MPa

Test conditions    : Steady state
                     Stress rate control, $\dot\sigma$ is unknown

Specimen           : ① Hot-rolled, Ø = 26 mm
                     ② Cold-drawn, Ø = 5.2 mm
                     ③ Cold-drawn, Ø = 5 mm

Chem. composition  :

Remarks            : Ultimate strength (rupture strength)
                     as function of temperature

Reference          : Dannenberg et al (1959)

Fig 6
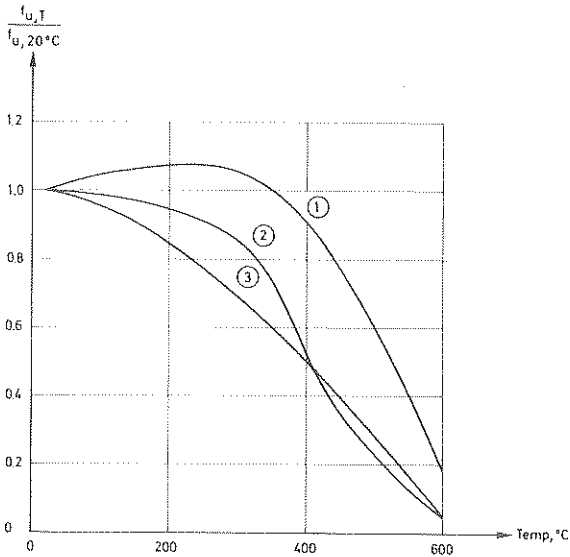
## 3.1  TENSILE STRENGTH

a) Structural steel        : Plate steel A36, $f_{0.2,20^{\circ}C}$ = 300 MPa

Low carbon            $f_{u,20^{\circ}C}$ = 440 MPa

Test conditions        : Steady state

Specimen               :

Chem. composition      :

Remarks                : Ultimate strength and 0.2% proof stress
as function of temperature

Reference              : Klippstein (1979)

Fig 7

## 3.1  TENSILE STRENGTH

a) Structural steel  : Steel 37, $f_{0.2,20^{o}C}$ = 250 MPa
$f_{u,20^{o}C}$ = 496 MPa

Test conditions  : Steady state
Strain rate control,
$\dot{\epsilon}$ = 0.1-100·$10^{-3}$·$min^{-1}$

Specimen  : $\emptyset$ = 7.2 mm, $\ell$ = 71 mm

Chem. composition :

| C | P | S | Mn | Si | Cr |
|------|-------|-------|------|-------|------|
| 0.27 | 0.033 | 0.041 | 0.65 | 0.128 | 0.16 |

Ni
0.086

Remarks  : The influence of strain rate $\dot{\epsilon}$ on 0.2%
proof stress

Reference  : Skinner (1972)
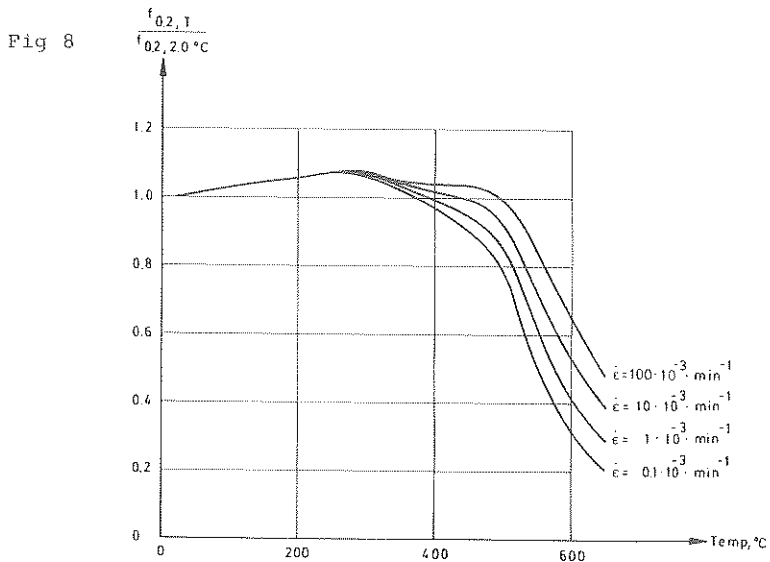
Fig 8  $\dfrac{f_{0.2,T}}{f_{0.2,20\,°C}}$

## 3.1 TENSILE STRENGTH

a) Structural steel     : SIS 14 1411, $f_{0.2,20^{\circ}C}$ = 340 MPa


Test conditions     : Steady state
                        Stress rate control
                        ① $\dot{\sigma}$ = 1.63 MPa/s
                        ② $\dot{\sigma}$ = 0.03 MPa/s

Specimen            : $\ell$ = 95 mm, b = 15 mm, t = 3 mm


Chem. composition   : 
|   | C | P | S | Mn | Si | Cr |
|---|---|---|---|----|----|----|
|   | 0.27 | 0.033 | 0.041 | 0.65 | 0.128 | 0.16 |
| Ni |  |  |  |  |  |  |
| 0.086 |  |  |  |  |  |  |

Remarks             : The influence of rate of loading on
                      0.2% proof stress

Reference           : Thor, J. (1972)
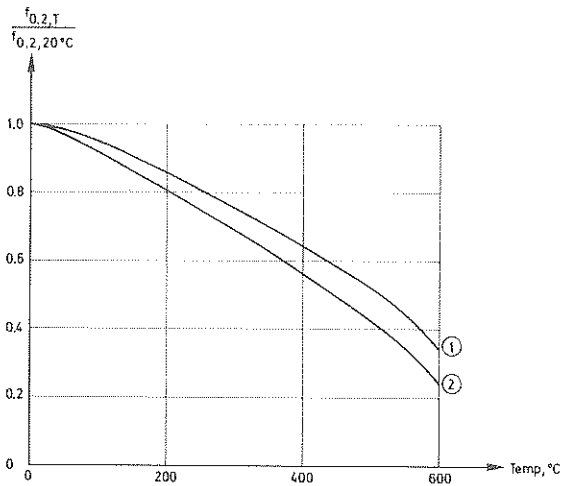
Fig 9

3.1  TENSILE STRENGTH

b) Reinforcing steel    : Different kinds


   Test conditions      : Steady state
                          Stress rate control,
                          $\overset{\bullet}{\sigma}$ = 3.5 MPa/s

   Specimen             : $\emptyset$ = 8-10 mm, $\ell$ = 100 mm
                          Hot-rolled


   Chem. composition    :


   Remarks              : Proof stress related to different
                          stress induced strains

   Reference            : Anderberg (1978)
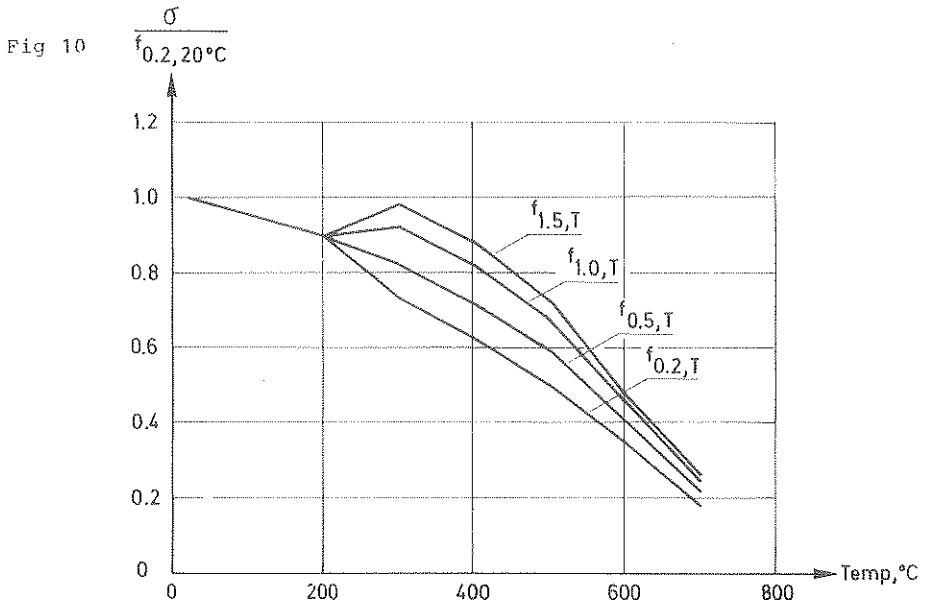
Fig 10

3.1  TENSILE STRENGTH

b) Reinforcing steel   :  ① BSt 42/50 RU, $f_{0.2, 20^{\circ}C}$ = 430 MPa
                          ② BSt 42/50 RK, $f_{0.2, 20^{\circ}C}$ = 430 MPa

   Test conditions     :  Transient state with load control
                          Rate of heating, $\dot{T}$ = 3.8 - 24$^{\circ}$C/min

   Specimen            :  ① Hot-rolled, $\emptyset$ = 16 mm, $\ell$ = 10 x $\emptyset$
                          ② Cold-worked, $\emptyset$ = 18 mm, $\ell$ = 10 x $\emptyset$

   Chem. composition   :

   Remarks             :  Ultimate strength (rupture strength)
                          as function of temperature

   Reference           :  Ruge & Winkelmann (1978-80)

Fig 11   $\dfrac{f_{u,T}}{f_{0.2, 20^{\circ}C}}$
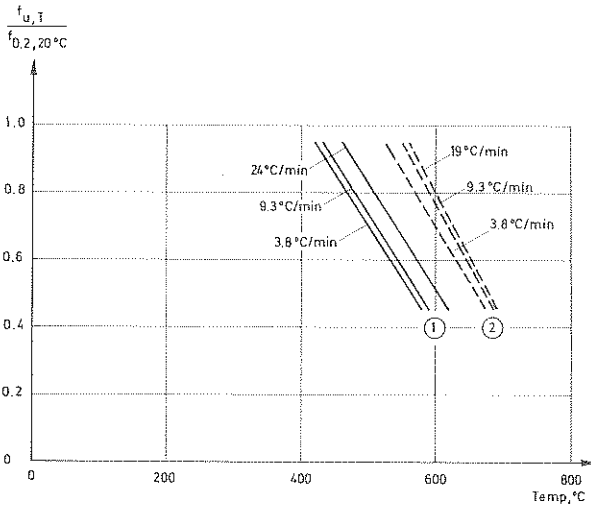
## 3.1  TENSILE STRENGTH

b) Reinforcing steel : ① BSt 42/50 RU, $f_{0.2,20^{\circ}C}$ = 430 MPa
  ② BSt 42/50 RK, $f_{0.2,20^{\circ}C}$ = 430 MPa

Test conditions : Transient state with load control
  Rate of heating, $\dot{T}$ = 3.8 – 19$^{\circ}$C/min
  Failure temperature criteria, $\dot{\varepsilon}$ =
  = $1.0 \cdot 10^{-4} \cdot s^{-1}$

Specimen : ① Hot-rolled, $\emptyset$ = 16 mm, $\ell$ = 10 x $\emptyset$
  ② Cold-worked, $\emptyset$ = 18 mm, $\ell$ = 10 x $\emptyset$

Chem. composition :

Remarks : Ultimate strength as function of tempera-
  ture, related to the strain rate
  $\dot{\varepsilon}$ = $1.0 \cdot 10^{-4} \cdot s^{-1}$

Reference : Ruge & Winkelmann (1978-80)
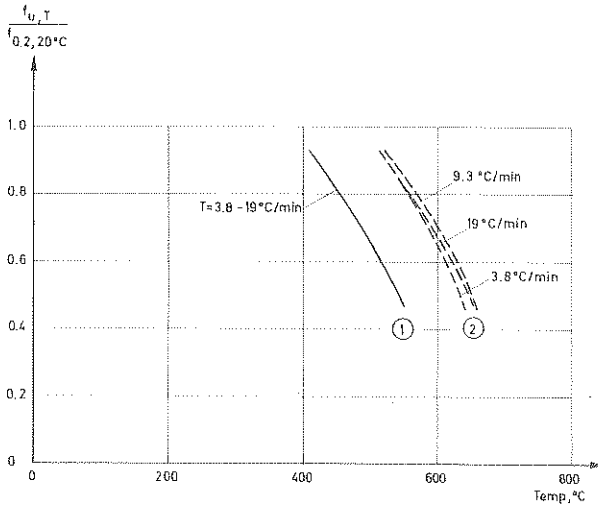
Fig 12

## 3.1 TENSILE STRENGTH

c) Prestressing steel :

$$f_{0.2,20^{\circ}C} = 1559 \text{ MPa}$$
$$f_{u,20^{\circ}C} = 1848 \text{ MPa}$$

Test conditions : Steady state
Strain rate control, $\dot{\varepsilon}$ is unknown
$t_s$ = 10 min

Specimen : $\emptyset$ = 4.5 mm

Chem. composition :

Remarks : Ultimate strength and 0.2% proof stress
as function of temperature

Reference : Voves, B. (1978)

Fig 13
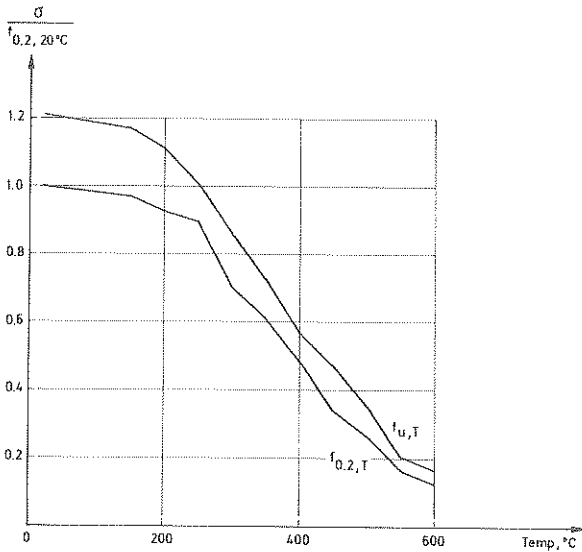
## 3.1  TENSILE STRENGTH

c) Prestressing steel : 87 E 35, $f_{u,20^{O}C}$ = 1700 MPa
Fagersta steel, $f_{u,20^{O}C}$ = 1900 MPa

Test conditions    : Steady state
Strain rate control,
$\dot{\varepsilon}$ = 75·10$^{-3}$·min$^{-1}$

Specimen           : $\emptyset$ = 4.3 mm, $\ell$ = 200 mm

Chem. composition  :

Remarks            : Ultimate strength as function of tem-
perature

Reference          : Anderberg (1983)
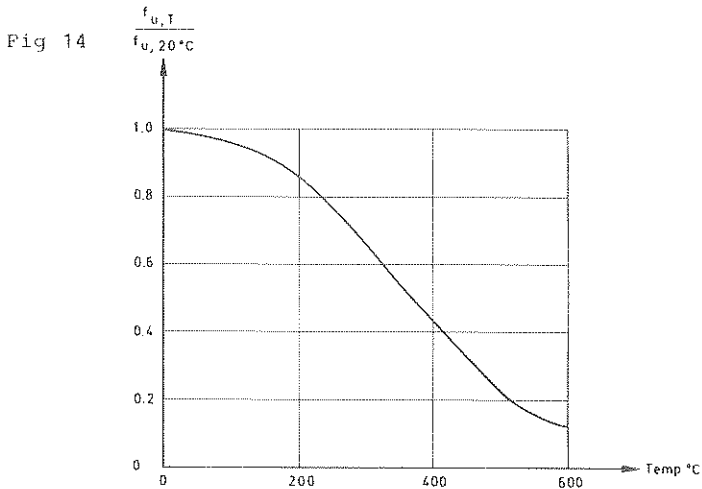
Fig 14   $\dfrac{f_{u,T}}{f_{u,20°C}}$

## 3.1  TENSILE STRENGTH

c) Prestressing steel : ASTM A 421, $f_{0.2,20^{\circ}C}$ = 1470 MPa

$f_{u,20^{\circ}C}$ = 1720 MPa

Test conditions : Steady state
Strain rate control
$\dot{\varepsilon}$ = 19-29·10$^{-3}$·min$^{-1}$

Specimen : $\emptyset$ = 4.4 mm, $\ell$ = 23 mm

Chem. composition :
| C | P | S | Mn | Si |
|---|---|---|----|----|
| 0.749 | 0.012 | 0.031 | 0.78 | 0.187 |

Remarks : Ultimate strength and 0.2% proof stress
as function of temperature

Reference : Harmathy & Stanzak (1970)

Fig 15
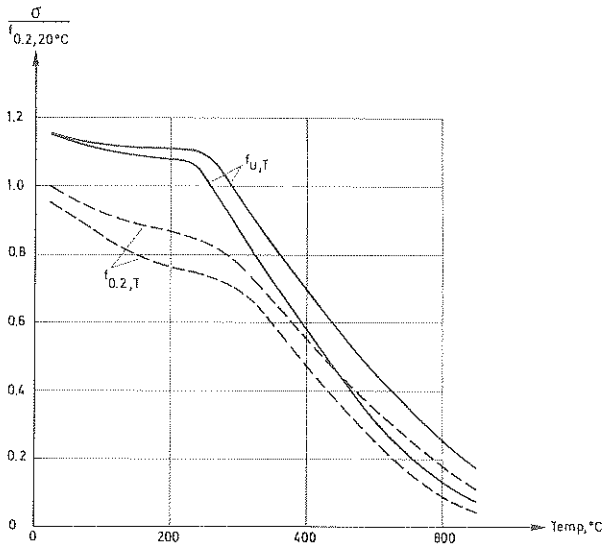
## 3.1  TENSILE STRENGTH

c) Prestressing steel  :                                    $f_{0.2,20^{O}C}$ = 1070 MPa

$f_{u,20^{O}C}$ = 1630 MPa

Test conditions      : Steady state

Specimen             :

|  | C | P | S | Mn | Si |
|---|---|---|---|---|---|
| Chem. composition : | 0.78 | 0.024 | 0.022 | 0.63 | 0.21 |

Remarks              : Ultimate strength and 0.2% proof stress
as function of temperature

Reference            : Cahill (1965)

Fig 16    $\dfrac{\sigma}{f_{0.2,20°C}}$
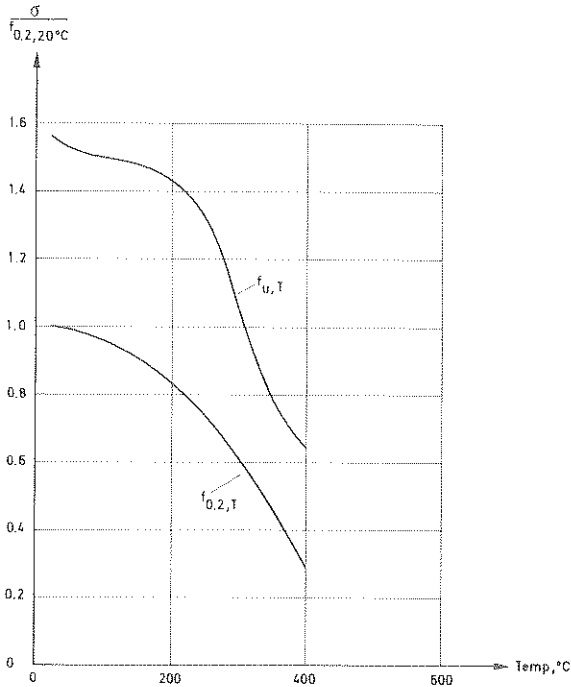
## 3.1   TENSILE STRENGTH

c) Prestressing steel  :

$$f_{0.2,20^\circ C} = 1559 \text{ MPa}$$
$$f_{u,20^\circ C} = 1848 \text{ MPa}$$

Test conditions        : Transient state with load control
                         Rate of heating, $\dot{T} = 12^\circ C/min$

Specimen               : $\emptyset = 4.5$ mm

Chem. composition      :

Remarks                : Ultimate strength (rupture strength)
                         as function of temperature

Reference              : Voves, B. (1978)

Fig 17     $\dfrac{f_{u,T}}{f_{u,20^\circ C}}$
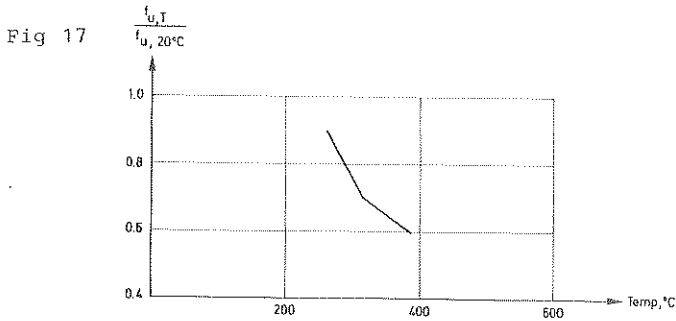
## 3.1  TENSILE STRENGTH

c) Prestressing steel  : St 1570/1770, 1 $f_{0.2,20^{\circ}C}$ = 1570 MPa

$$2\ f_{u,20^{\circ}C} = 1660\ \text{MPa}$$

Test conditions : Transient state with load control
Rate of heating, $\dot{T} = 4^{\circ}C/min$
Failure temperature criteria,
$\dot{\varepsilon} = 1.0 \cdot 10^{-4} \cdot s^{-1}$

Specimen : ① Cold-worked, $\emptyset = 7.5$ mm
② "     "    , $\emptyset = 5.0$ mm
$\ell$ 10 x $\emptyset$

Chem. composition : Ultimate strength as function of tempe-
rature, related to the strain rate
$\dot{\varepsilon} = 1.0 \cdot 10^{-4} \cdot s^{-1}$

Remarks :

Reference : Ruge & Winkelmann (1978-80)

Fig 18
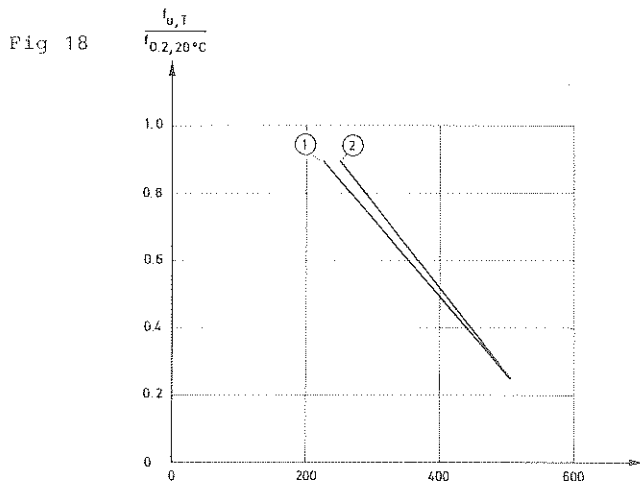
## 3.1 TENSILE STRENGTH

a) Prestressing steel : PTV $f_{u,20^{\circ}C}$ = 1750 MPa
   LTP   "        = 1550 MPa
   LTR   "        = 1550 MPa
   PTS   "        = 1700 MPa

    Test conditions : Transient state with load control
   Rate of heating, $\overset{\circ}{T}$ is unknown

    Specimen : 

    Chem. composition : 

    Remarks : Ultimate strength (rupture strength)
   as function of temperature

    Reference : Baus, Brenneisen & Langueville (1968)

Fig 19
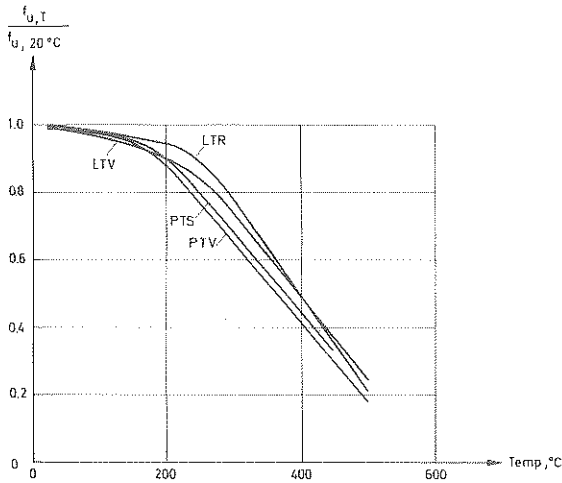
## 3.2 Modulus of elasticity

The variation of the modulus of elasticity with time, $E_T$, can be directly obtained from $\sigma$-$\varepsilon$ relationships as the initial inclination of the curve. If the $\sigma$-$\varepsilon$ relationships include creep strains the value of $E_T$ will be somewhat decreased. The test conditions are therefore of importance, when comparing results from different sources. If $E_T$ is determined in a dynamic test the result can also differ. If $E_T$ is obtained from constructed $\sigma$-$\varepsilon$ curves which are related to transient tests (see chapter 3.5.2) the influence of creep cannot be avoided.

The modulus of elasticity decreases with temperature and at 500-550$^O$C the value is about $0.5 \cdot E_{20^OC}$. The original strength characteristics seems to have little influence on $E_T$. Essential results are summarized in Fig 1-7.

## 3.2   MODULUS OF ELASTICITY

a) Structural steel    : Plate steel A36, $f_{0.2,20^{\circ}C}$ = 300 MPa

Low carbon          $f_{u,20^{\circ}C}$ = 440 MPa

   Test conditions     : Steady state

   Specimen            :

   Chem. composition   :

   Remarks             : Modulus of elasticity

   Reference           : Klippstein (1979)

Fig 1
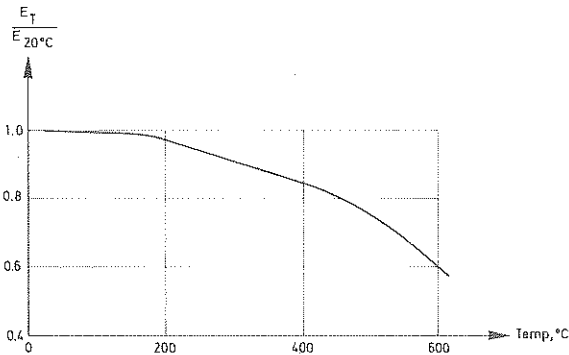
## 3.2  MODULUS OF ELASTICITY

a) Structural steel     : Various steels


Test conditions      :


Specimen             :


Chem. composition    :


Remarks              : Modulus of elasticity


Reference            : Stirland (1980)
                       Teesside Laboratories

Fig 2   $\frac{E_T}{E_{20°C}}$
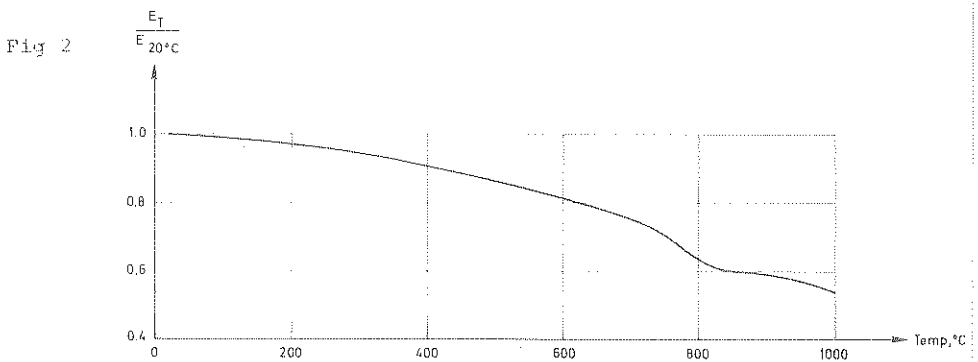
## 3.2   MODULUS OF ELASTICITY

a)  Structural steel      : Carbon steels


   Test conditions        : Steady state


   Specimen               :


   Chem. composition      :


   Remarks                : Modulus of elasticity (mean curve from
                            three sources: Garofalo (1950), Lea et
                            al (1914), Versé (1935)

   Reference              : Harmathy (1967)

Fig 3
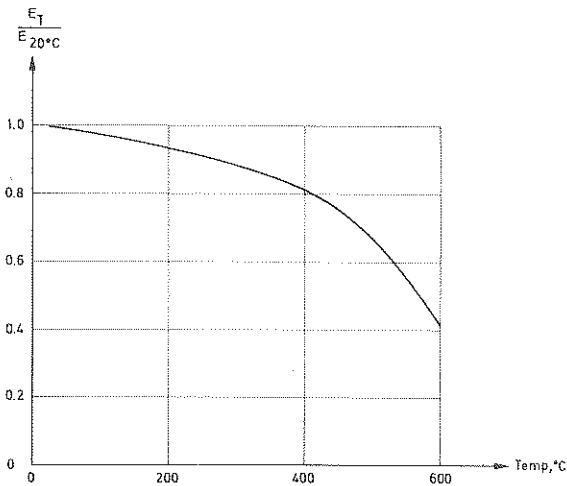
## 3.2 MODULUS OF ELASTICITY

a) Structural steel    :


   Test conditions      : Steady state
                          Stress rate control, $\dot{\sigma}$ = 1.63 MPa/s


   Specimen             :


   Chem. composition    :


   Remarks              : Modulus of elasticity


   Reference            : Thor, J. (1972)


Fig 4
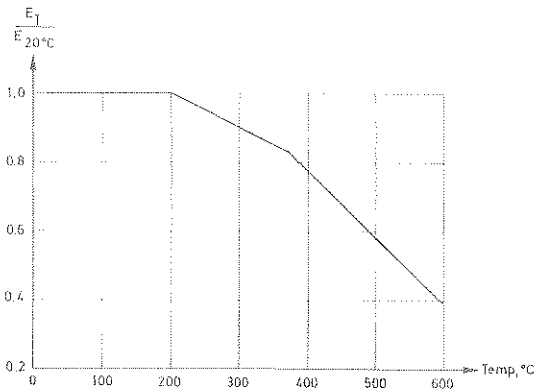
## 3.2  MODULUS OF ELASTICITY

a) Structural steel      : Fe E 24, $f_{0.2,20^{\circ}C}$ = 270 MPa

   Test conditions       : Transient state
                           Constant load control
                           Rate of heating, $\dot{T}$ = $10^{\circ}$C/min

   Specimen              :

   Chem. composition     :

   Remarks               : Modulus of elasticity

   Reference             : Copier, W.J. (1972)

Fig 5
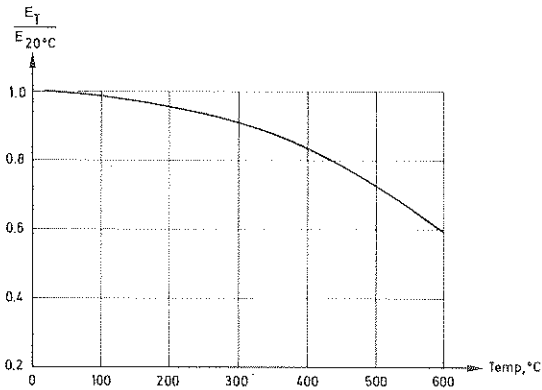
3.2  MODULUS OF ELASTICITY
_____

b) Reinforcing steel     : Different kinds, Ks 40, Ks 60


   Test conditions       : Steady state
                           Stress rate control, $\overset{\circ}{\sigma}$ = 3.5 MPa/s


   Specimen              : Hot-rolled, $\emptyset$ 8-10, $\ell$ = 100 mm


   Chem. composition     :


   Remarks               : Modulus of elasticity (mean curve)


   Reference             : Anderberg (1978)


Fig 6
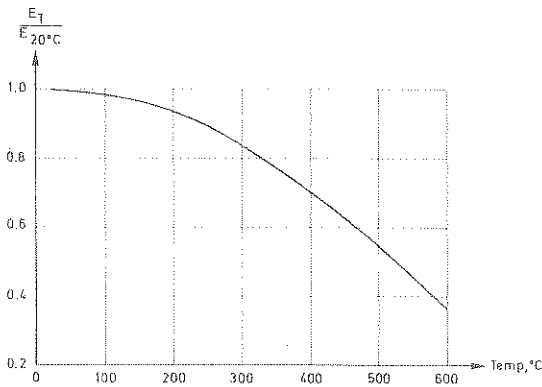
## 3.2  MODULUS OF ELASTICITY

c) Prestressing steel  : St 1570/1770, $E_{20^oC} = 2.14 \cdot 10^5$ MPa


Test conditions      : Steady state
                       Rate of stress, $\dot{\sigma}$ is unknown

Specimen             : Cold-worked, $\varnothing$ = 7.5 mm

Chem. composition    :

Remarks              : Modulus of elasticity

Reference            : Ruge & Winkelmann (1978-80)

Fig 7
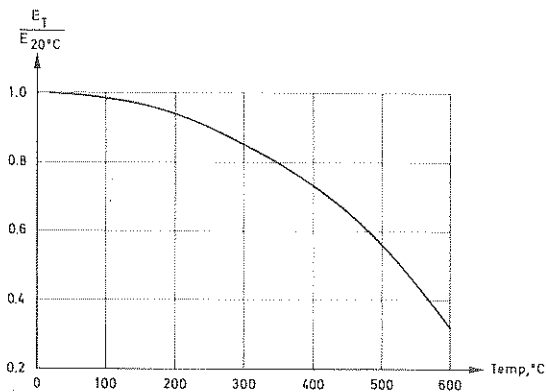
## 3.3 Thermal strain

The thermal strain or thermal expansion is measured on un-
loaded specimens in a transient test. Investigations pub-
lished in literature indicate small deviations for structu-
ral and prestressing steels. Type of steel and strength cha-
racteristics seem to have no significant influence. In Fig 1
the thermal strain for structural steel is taken from four
different sources. The curves are relatively close together.
For reinforcing steels there is only one source of informa-
tion available which indicates lower thermal strain than
other steels as shown in Fig 2. In this figure the results
from a prestressing steel are also indicated.

## 3.3   THERMAL STRAIN

Fig 1 Thermal strain (expansion) for structural steel as func-
       tion of temperature

   ① St 37-2, Ruge & Winkelmann (1978-80)
   ② Steel 37, Skinner (1972)
   ③ A 36, Harmathy (1967)
   ④         Stirland (1980)

Fig 1
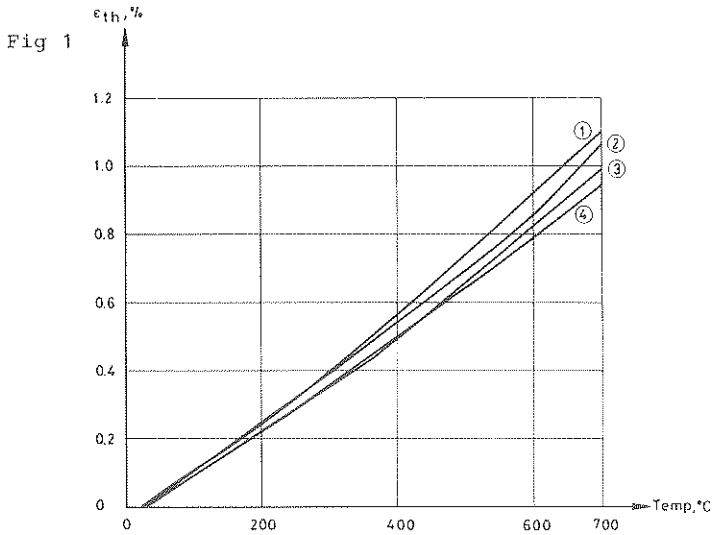
3.3   THERMAL STRAIN

Fig 2 Thermal strain (expansion) for ① reinforcing and
        ② prestressing steel as function of temperature

        ① Anderberg (1978)
        ② Ruge & Winkelmann (1978-80)



Fig 2
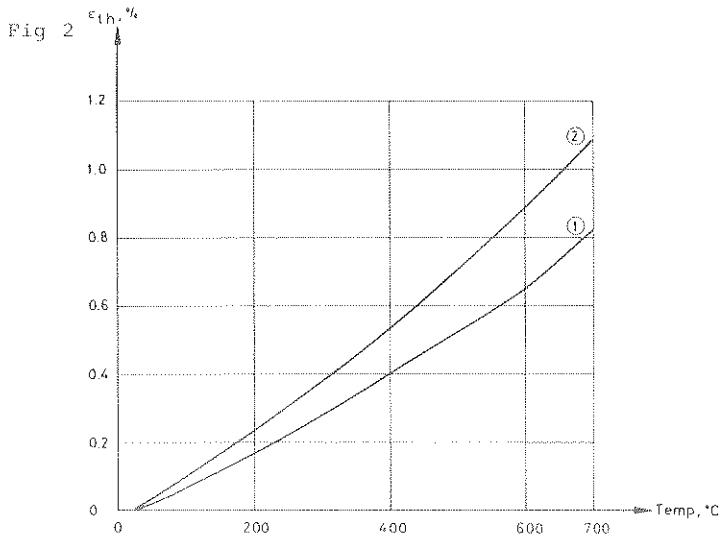
3.4  Creep strain

Creep behaviour is unique for every type of steel and a common description is hard to find. This is due to the fact that the chemical composition and the degree of processing strongly influences this. The creep tendency seems not to be related to the 0.2% proof stress or other strength characteristics at room temperature. Therefore the absolute value of stress is used when describing creep analytically. Analytical creep models will be presented in chapter 5. The creep starts to be of importance at about $250^{\circ}C$ for cold-worked steel and at about $400^{\circ}C$ for hot-rolled steel.

The creep strain can only be directly measured in steady state tests and if the stress is kept constant it can be separated into two phases as illustrated in Fig 6. However, the creep from steady state tests can be used in order to predict the creep process in transient tests, which is illustrated in chapter 5.

Measurements on creep at high temperatures are very complicated and the accuracy and reliability of the testing equipment are of decisive importance for the results. In Fig 5 creep results are shown from two identical tests on specimens from the same heat. The creep strain after 1.5 h indicates a difference of about 20%. If the specimens are not from the same heat deviation may rise to 40%. The scatter in the results are not only due to the testing equipment but also to the difference in shape and processing of the specimen.

Some results on creep published in literature are illustrated in Fig 1-5. More results for analytical studies are given in chapter 5.

3.4 CREEP STRAIN

a) Structural steel     : Al 149, $f_{0.2,20^O C}$ = 250 MPa

                          X-60, $f_{0.2,20^O C}$ = 450 MPa

   Test conditions      : Steady state
                          Constant load control

   Specimen             :

   Chem. composition    :

   Remarks              : Creep at $500^O C$ for different load
                          levels

   Reference            : Knight et al (1971)

Fig 1
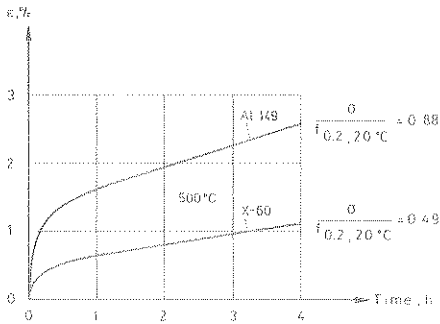
## 3.4  CREEP STRAIN

a) Structural steel : Steel 37, $f_{0.2,20^{O}C}$ = 250 MPa

$f_{u,20^{O}C} \approx 496$ MPa

Test conditions : Steady state
Constant load control

Specimen : $\emptyset$ = 7.2 mm, $\ell$ = 71 mm

Chem. composition :

| C | P | S | Mn | Si | Cr |
|------|-------|-------|------|-------|------|
| 0.27 | 0.033 | 0.041 | 0.65 | 0.128 | 0.16 |

Ni
0.086

Remarks : Creep at 550$^{O}$C for different load
levels

Reference : Skinner (1972)

Fig 2
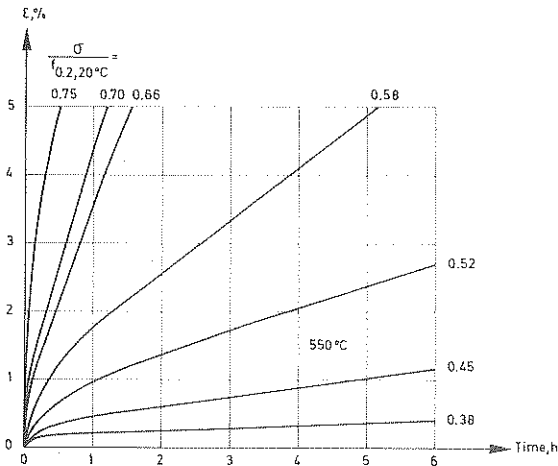
## 3.4  CREEP STRAIN

b) Reinforcing steel  : Ks 40, $f_{0.2,20^{o}C}$ = 456 MPa

Ks 60, $f_{0.2,20^{o}C}$ = 710 MPa

Test conditions  : Steady state
Constant load control

Specimen  : $\emptyset$ = 8 mm, $\ell$ = 100 mm
Hot-rolled

Chem. composition  :
| C | P | S | Mn | Si |
|------|-------|-------|------|------|
| 0.41 | 0.029 | 0.039 | 0.66 | 0.27 |

Remarks  : Creep at about $600^{o}$C for different
load levels

Reference  : Anderberg (1978)

Fig 3
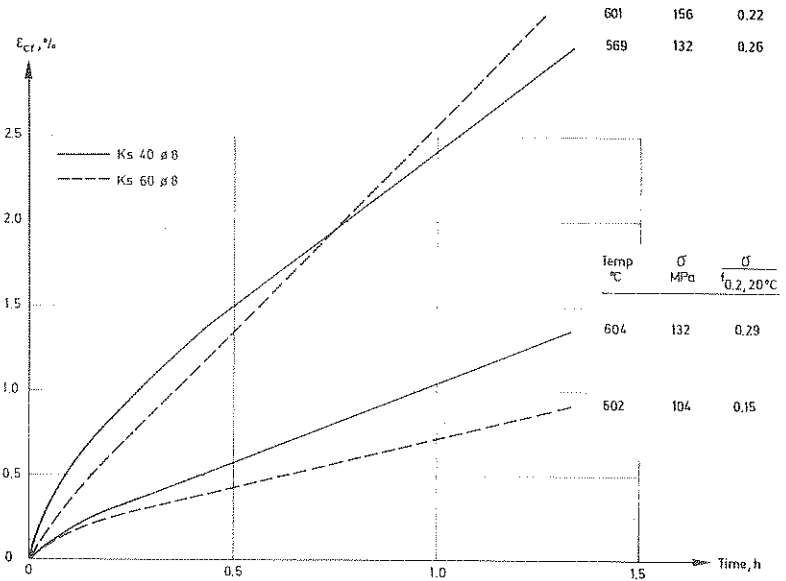
## 3.4  CREEP STRAIN

b) Reinforcing steel    : Ks 40, different kinds


Test conditions        : Steady state
                         Constant load control


Specimen               : $\emptyset$ = 8mm, $\ell$ = 100 mm
                         Hot-rolled


Chem. composition      :


Remarks                : Creep at about 650$^o$C for
                         different hot-rolled steels


Reference              : Anderberg (1978)

Fig 4



| Temp °C | σ MPa | σ / $f_{0.2, 20°C}$ |
|---------|-------|---------------------|
| 642 | 83 | 0.16 |
| 653 | 80 | 0.18 |
| 644 | 63 | 0.12 |
| 651 | 66 | 0.12 |
| 654 | 65 | 0.14 |
| 650 | 65 | 0.14 |

Ks 40 Ø8
Ks 40 Ø8 (2 B)
Ks 40 SE Ø8
Ks 40 Ø10
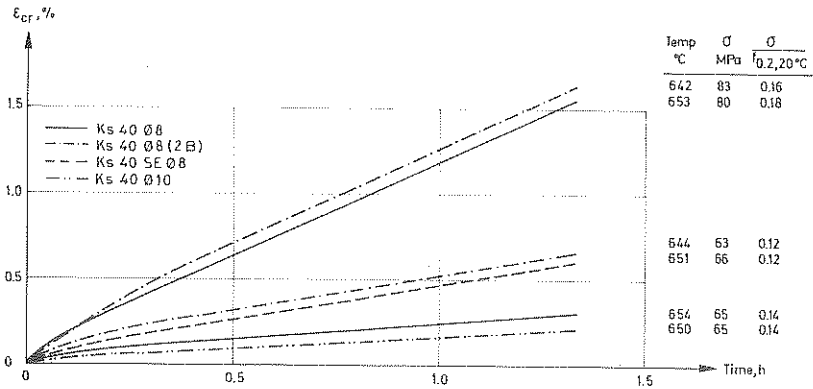
## 3.4 CREEP STRAIN

b) Reinforcing steel : Ks 40, $f_{0.2, 20^{\circ}C}$ = 483 MPa

Test conditions : Steady state
Constant load control

Specimen : $\emptyset$ = 10 mm, $\ell$ = 100 mm
Hot-rolled

|  | C | P | S | Mn | Si |
|---|---|---|---|---|---|
| Chem. composition : | 0.31 | 0.024 | 0.021 | 0.75 | 0.27 |

Remarks : Deviation in results in two
creep tests with specimens from
the same heat

Fig 5
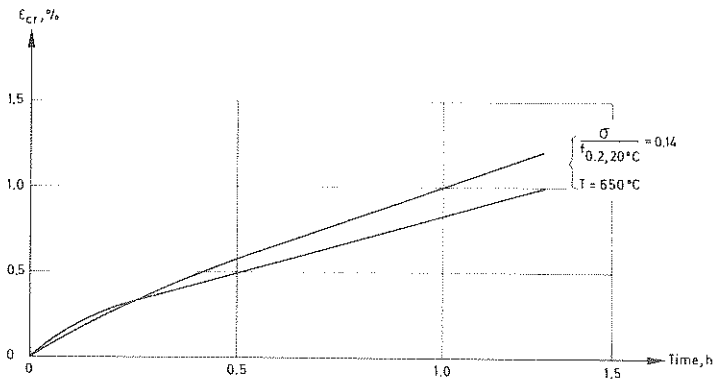
## 3.5 Stress-strain characteristics

The data presented are divided into two categories, namely steady state and transient state properties. A survey of the most important properties related to the test procedure is given.

### 3.5.1 Steady state data

$\sigma-\varepsilon$ relationships obtained under strain rate or stress rate control are illustrated in eighteen (18) diagrams for the three types of steel: structural, reinforcing and prestressing steel. All curves are drawn dimensionless and are related to $f_{0.2,20^{\circ}C}$.

The stress-strain relationship is often obtained at a high rate of stress or a high rate of strain (test duration period less than 1-2 min for structural and reinforcing steel and less than 1/2 min for prestressing steel) in order to avoid the influence of creep which is of importance above about 250 and $400^{\circ}C$ for hot-rolled and cold-worked steels, respectively. At these higher temperatures a slow stress rate or strain rate (test duration period is more than about 1 h for structural and reinforcing steel and more than about 5 min for prestressing steel) considerably influence the amount of creep observed. This results in a displaced $\sigma-\varepsilon$ curve and a lower ultimate strength.

It can be generally stated for hot-rolled steel that the ultimate strength (maximum point in the $\sigma-\varepsilon$ curve) at 500 and $600^{\circ}C$ decreases to about 0.8 and 0.5 of $f_{0.2,20^{\circ}C}$, respectively, if the test duration period is short (high rate of stress or strain). For prestressing steel the comparative values are about 0.45 and 0.25 of $f_{0.2,20^{\circ}C}$.

Some comparisons have also shown that steels that are not cold-worked have very similar dimensionless $\sigma-\varepsilon$ relationships at elevated temperatures.

In the presented test results the strain rate, $\dot{\varepsilon}$, has been varied from 2 to $200 \cdot 10^{-3} \cdot \text{min}^{-1}$ for structural steel and from 25 to $700 \cdot 10^{-3} \cdot \text{min}^{-1}$ for prestressing steel. This means a variation of the test duration period from about 1 h to 1 min and from about 6 min to 20 s, respectively. The influence of $\dot{\varepsilon}$ can be separately studied in Figs 7 and 17.

The stress rate, $\dot{\sigma}$, has been varied from 0.03 to 3.5 MPa/s, which means a variation of the test duration period from about 2.5 h to 15 s. The influence of $\dot{\sigma}$ is illustrated in Figs 10, 11 and 13.

It can be generally noticed that the maximum decrease of ultimate strength due to creep effects amounts to about 15% of $f_{0.2,20^\circ\text{C}}$ at 550-600$^\circ$C except for prestressing steel.

## 3.5.1 STEADY STATE DATA

a) Structural steel : CSA G40.12, $f_{0.2,20^{\circ}C} = 340$ MPa

Test conditions : Strain rate control
$\dot{\varepsilon} = 51-76 \cdot 10^{-3} \cdot min^{-1}$

Specimen : $\emptyset = 5.2$ mm, $\ell = 23$ mm

Chem. composition :

| C | P | S | Mn | Si | Cu |
|---|---|---|----|----|----|
| 0.195 | 0.015 | 0.019 | 1.40 | 0.022 | 0.08 |
| N | Cr | | | | |
| 0.03 | 0.01 | | | | |

Remarks : $\sigma$-$\varepsilon$ relationships

Reference : Harmathy & Stanzak (1970)

Fig 1
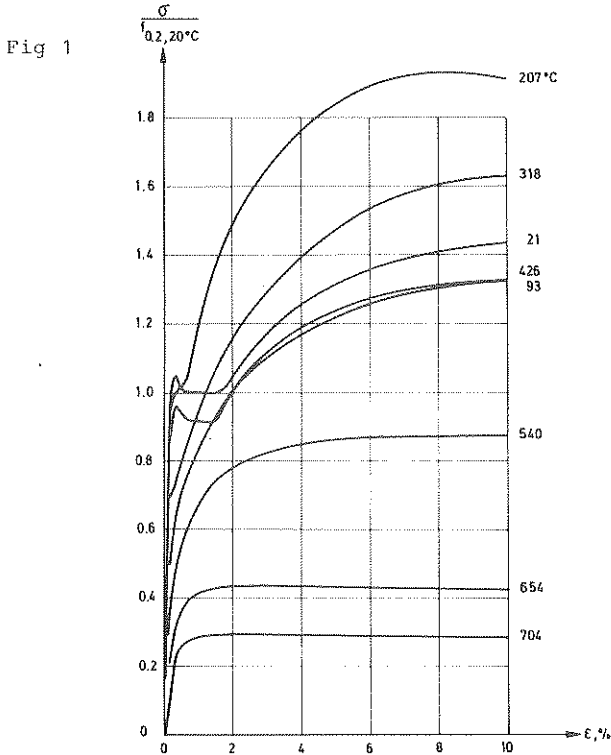
## 3.5.1  STEADY STATE DATA

a) Structural steel        : ASTM A36, $f_{0.2,20^{\circ}C}$ = 300 MPa


Test conditions        : Strain rate control
$\dot{\varepsilon}$ = 72-102·10$^{-3}$·min$^{-1}$

Specimen            : $\emptyset$ = 5.2 mm, $\ell$ = 23 mm


Chem. composition    :  C      P      S      Mn     Si
                        0.19   0.007  0.03   0.71   0.09

Remarks              : $\sigma$-$\varepsilon$ relationships

Reference            : Harmathy & Stanzak (1970)

Fig 2
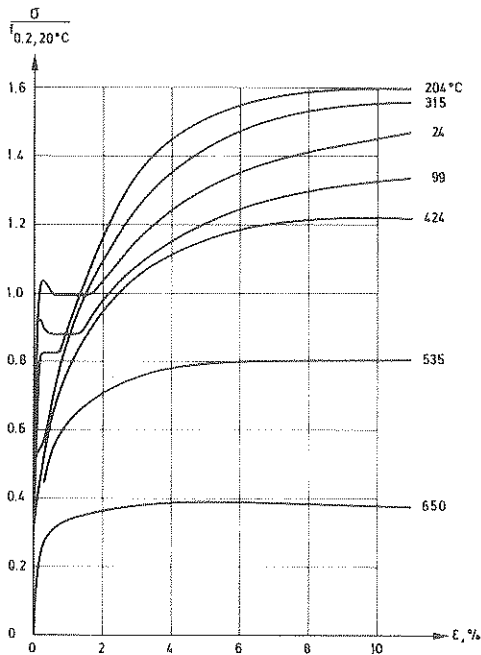
## 3.5.1  STEADY STATE DATA

a) Structural steel        : Grade  43A, $f_{0.2,20^{o}C}$ = 260 MPa

   Test Conditions         : Strain rate control, $\dot{\varepsilon}$ = $17 \cdot 10^{-3} \cdot min^{-1}$

   Specimen                : $\varnothing$ = 6.3 mm, $\ell$ = 57 mm

   Chem. composition       :

   Remarks                 : $\sigma-\varepsilon$ relationships

   Reference               : Teesside Laboratories (1980)

Fig 3
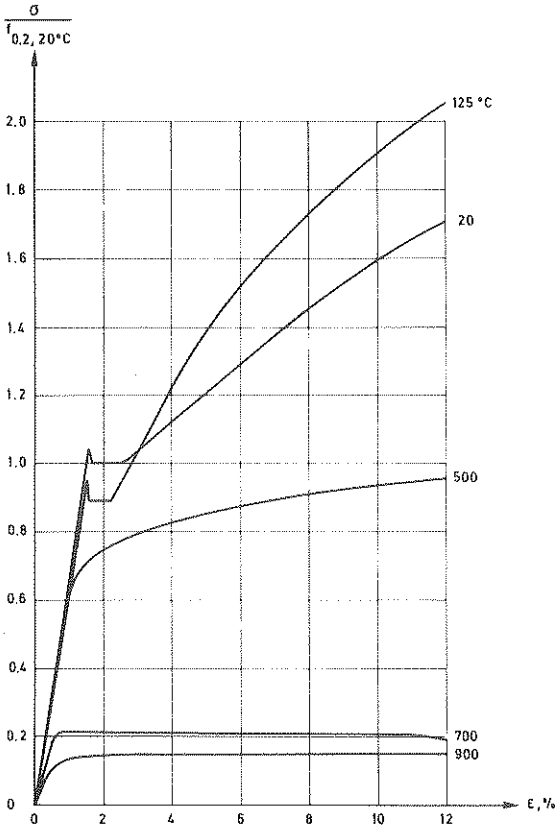
### 3.5.1   STEADY STATE DATA

a) Structural steel      : Steel 37, $f_{0.2,20^{o}C}$ = 253 MPa


   Test conditions       : Strain rate control
                           $\overset{\circ}{\varepsilon}$ = $2 \cdot 10^{-3} \cdot min^{-1}$


   Specimen              : $\emptyset$ = 7.2 mm, $\ell$ = 71 mm


   Chem. composition     : C       P      S      Mn    Si    Cr
                           0.27  0.033  0.041  0.65  0.128 0.16
                           Ni
                           0.086

   Remarks               : $\sigma$-$\varepsilon$ relationships


   Reference             : Skinner (1972)
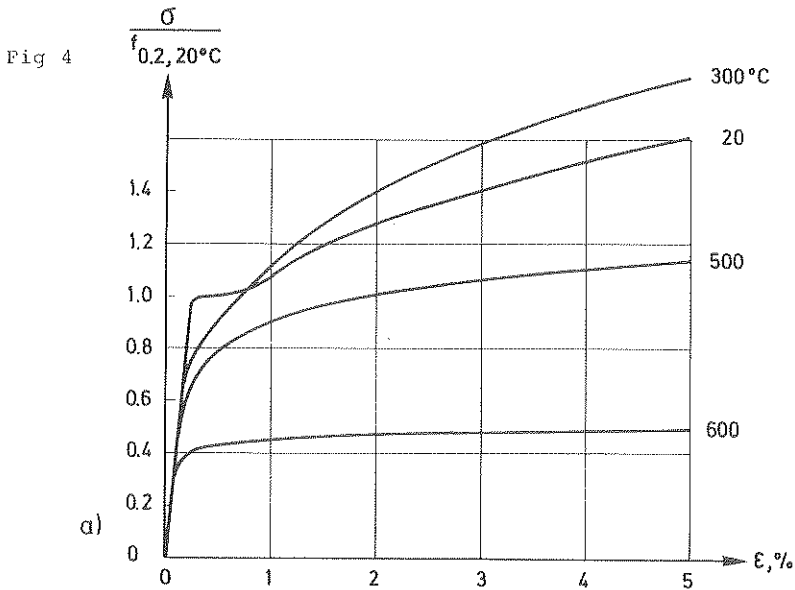
Fig 4



a)

3.5.1  STEADY STATE DATA

a) Structural steel    :              , $f_{0.2,20^{O}C}$ = 265 MPa

Test conditions    : Strain rate control
                     $\dot{\varepsilon}$ = $5 \cdot 10^{-3} \cdot min^{-1}$

Specimen           : $\emptyset$ = 8 mm, $\ell$ = 100 mm

Chem. composition  :

Remarks            : $\sigma$-$\varepsilon$ relationships

Reference          : Jörgensen et al (1980)

Fig 5
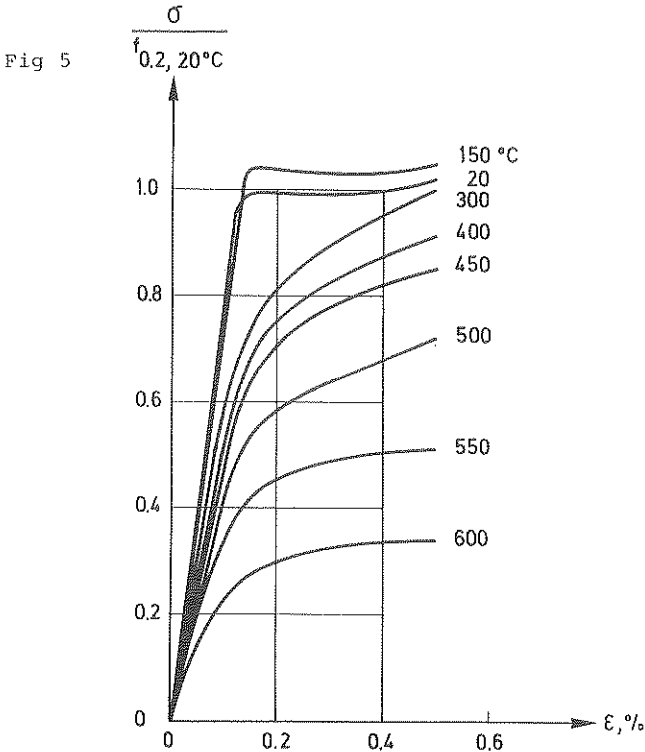
3.5.1  STEADY STATE DATA

a) Structural steel      :          , $f_{0.2,20^{\circ}C}$ = 265 MPa

    Test conditions     : Strain rate control
                       $\dot{\varepsilon}$ = 200·10$^{-3}$·min$^{-1}$

    Specimen            : $\emptyset$ = 8 mm, $\ell$ = 100 mm

    Chem. composition   :

    Remarks             : $\sigma$-$\varepsilon$ relationships

    Reference           : Jörgensen et al (1980)

Fig 6  $\dfrac{\sigma}{f_{0.2,20^{\circ}C}}$
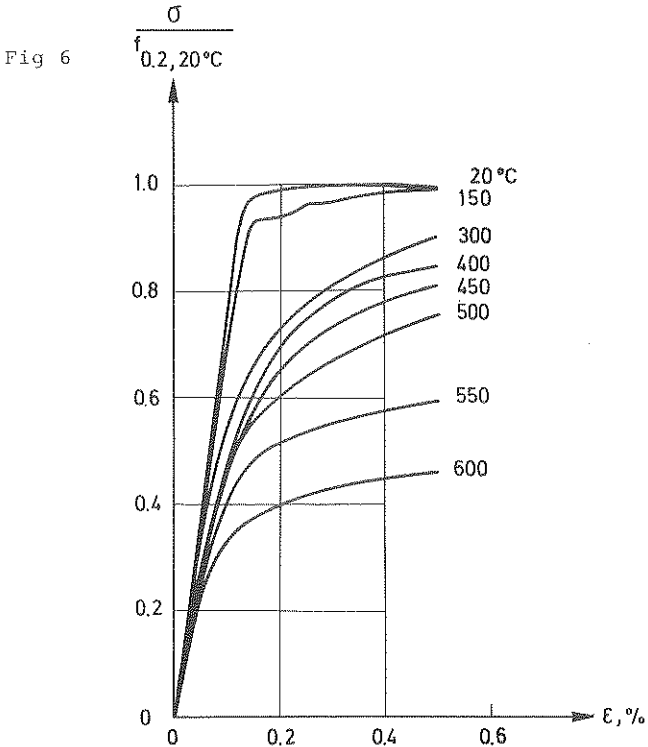
### 3.5.1  STEADY STATE DATA

a) Structural steel        :                    $f_{0.2,20^{\circ}C}$ = 265 MPa


Test conditions      : Strain rate control
                       ① $\dot{\varepsilon}$ = 200·10⁻³·min⁻¹
                       ② $\dot{\varepsilon}$ =   5·10⁻³·min⁻¹

Specimen             : $\emptyset$ = 8 mm, $\ell$ = 100 mm


Chem. composition    :


Remarks              : Influence of strain rate on σ-ε rela-
                       tionship att 550 and 600°C

Reference            : Jörgensen et al (1980)
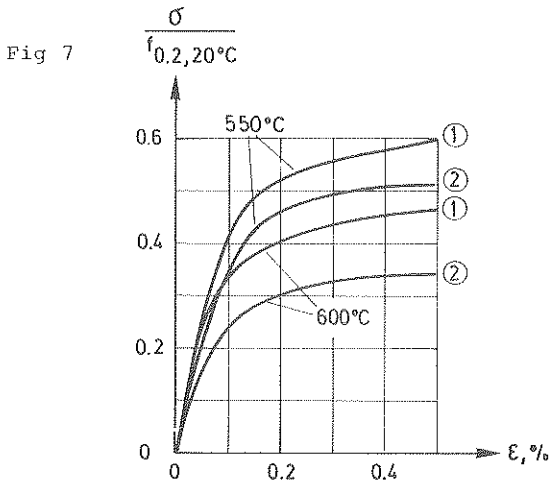

Fig 7

## 3.5.1  STEADY STATE DATA

a) Structural steel     : SIS 141411, $f_{0.2,20^{\circ}C}$ = 340 MPa

   Test conditions      : Stress rate control, $\dot{\sigma}$ = 1.63 MPa/s

   Specimen             : $\ell$ = 95 mm, b = 15 mm and t = 3 mm

   Chem. composition    :

   Remarks              : $\sigma$-$\varepsilon$ relationships

   Reference            : Thor, J. (1972)

Fig 8
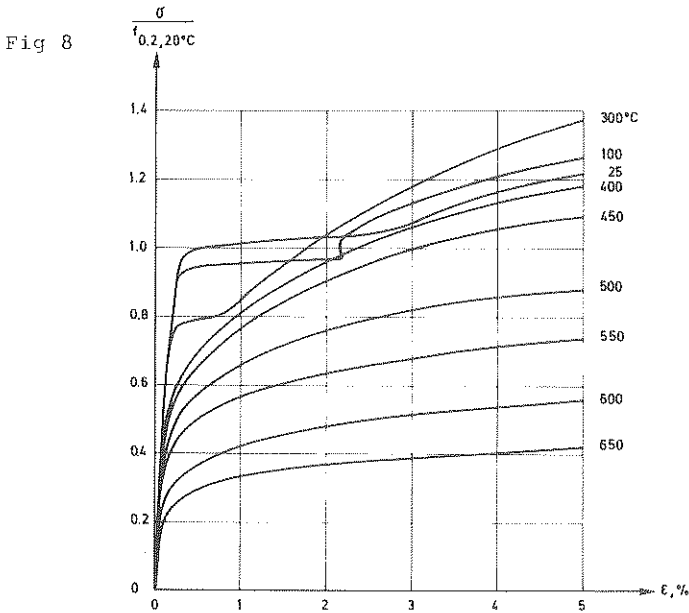
## 3.5.1   STEADY STATE DATA

a) Structural steel    : SIS 141411, $f_{0.2, 20^{\circ}C} = 340$ MPa

Test conditions    : Stress rate control, $\dot{\sigma} = 0.03$ MPa/s

Specimen    : $\ell = 95$ mm, $b = 15$ mm and $t = 3$ mm

Chem. composition    :

Remarks    : $\sigma - \varepsilon$ relationships

Reference    : Thor, J. (1972)

Fig 9    $\dfrac{\sigma}{f_{0.2, 20^{\circ}C}}$
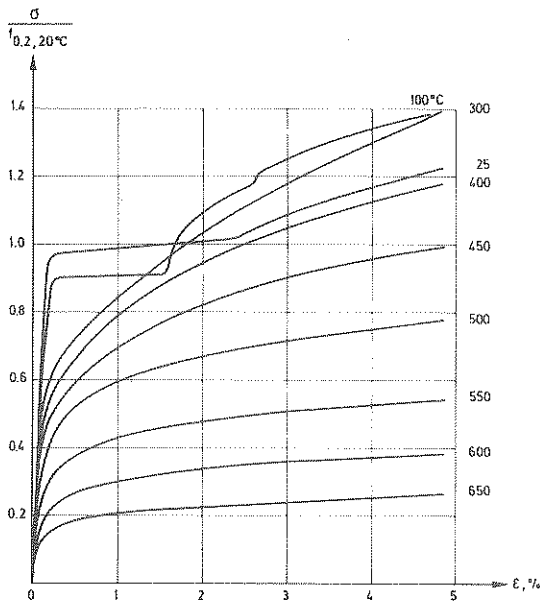
## 3.5.1  STEADY STATE DATA

a) Structural steel   : SIS 141411, $f_{0.2,20^{\circ}C}$ = 340 MPa

   Test conditions   : Stress rate control ① $\mathring{\sigma}$ = 1.61 MPa/s
                                  ② $\mathring{\sigma}$ = 0.32 MPa/s
                                  ③ $\mathring{\sigma}$ = 0.03 MPa/s

   Specimen   : $\ell$ = 95 mm, b = 15 mm and t = 3 mm

   Chem. composition:

   Remarks   : Influence of stress rate on $\sigma$-$\varepsilon$ relationship at $550^{\circ}$C

   Reference   : Thor, J. (1972)
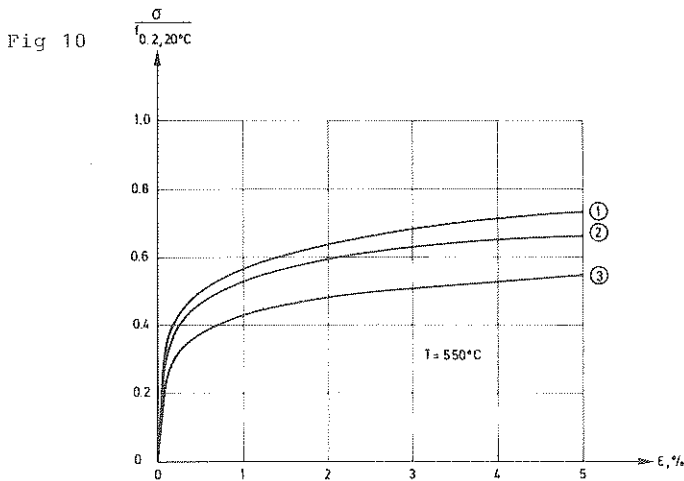
Fig 10

## 3.5.1  STEADY STATE DATA

a) Structural steel    : SIS 141411, $f_{0.2,20^\circ C}$ = 340 MPa

   Test conditions     : Stress rate control ① $\dot{\sigma}$ = 1.62 MPa/s
                                              ② $\dot{\sigma}$ = 0.32 MPa/s
                                              ③ $\dot{\sigma}$ = 0.03 MPa/s

   Specimen            : $\ell$ = 95 mm, b = 15 mm and t = 3 mm

   Chem. composition   :

   Remarks             : Influence of stress rate on $\sigma$-$\varepsilon$ rela-
                         tionship at 600$^\circ$C

   Reference           : Thor, J. (1972)

Fig 11
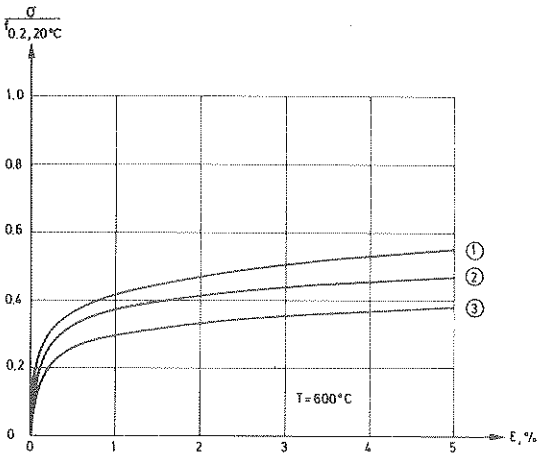
## 3.5.1  STEADY STATE DATA

b)  Reinforcing steel    : Different kinds

    Test conditions      : Stress rate control, $\overset{\circ}{\sigma}$=3.5 MPa/s

    Specimen             : $\emptyset$ = 8-10 mm,  $\ell$ = 100 mm
                           Hot-rolled

    Chem. composition    :

    Remarks              : $\sigma$-$\varepsilon$ relationships

    Reference            : Anderberg (1978)
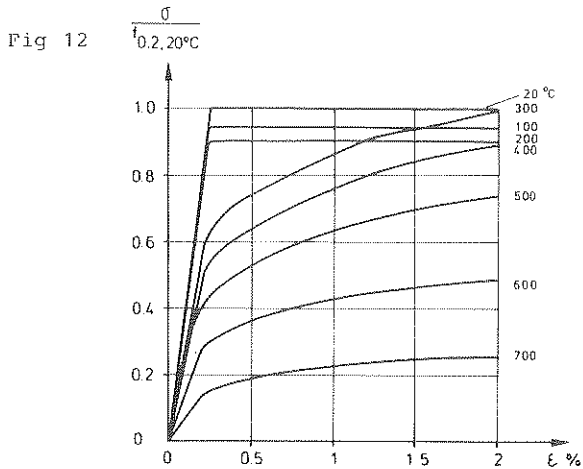
Fig 12    $\dfrac{\sigma}{f_{0.2,20°C}}$

## 3.5.1  STEADY STATE DATA

b) Reinforcing steel   : Different kinds


Test conditions     : Stress rate control
$\dot{\sigma}$ = 3.5 and 0.07 MPa/s


Specimen           : $\emptyset$ = 8-10 mm, $\ell$ = 100 mm
Hot-rolled


Chem. composition    :


Remarks           : Influence of stress rate on $\sigma$-$\varepsilon$ rela-
tionship at different temperatures

Reference          : Anderberg (1978)


Fig 13
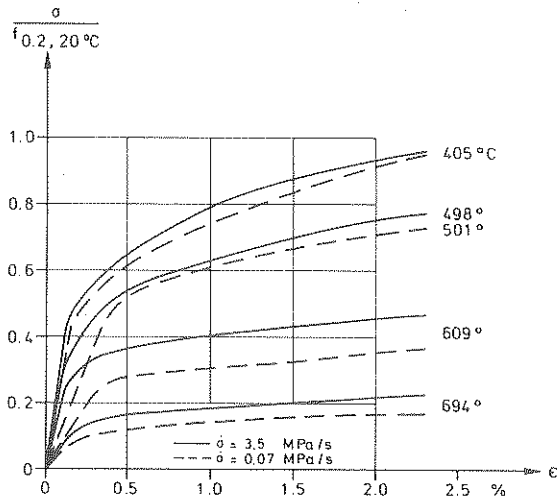
## 3.5.1  STEADY STATE DATA

c) Prestressing steel : ASTM A421, $f_{0.2,20^{\circ}C}$ = 1470 MPa

$f_{u,20^{\circ}C}$ = 1720 MPa

Test conditions : Strain rate control

$\dot{\epsilon}$ = 19-29·10$^{-3}$·min$^{-1}$

Specimen : $\emptyset$ = 4.4 mm, $\ell$ = 23 mm

Chem. composition :

| C | P | S | Mn | Si |
|-------|-------|-------|------|-------|
| 0.749 | 0.012 | 0.031 | 0.78 | 0.187 |

Remarks : $\sigma$-$\epsilon$ relationships

Reference : Harmathy & Stanzak (1970)

Fig 14
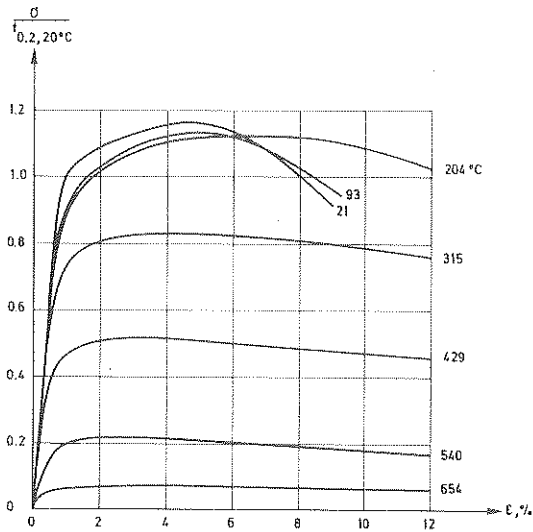
3.5.1   STEADY STATE DATA

c) Prestressing steel : ASTM A421, $f_{0.2,20^{\circ}C}$ = 1470 MPa

$f_{u,20^{\circ}C}$ = 1720 MPa

Test conditions    : Strain rate control
$\dot{\varepsilon}$ = 56-98$\cdot 10^{-3}\cdot$min$^{-1}$

Specimen         : $\emptyset$ = 4.4 mm, $\ell$ = 23 mm

Chem. composition  :   C      P      S     Mn    Si
0.794  0.012  0.031  0.78  0.187

Remarks          : $\sigma$-$\varepsilon$ relationships

Reference         : Harmathy & Stanzak (1970)

Fig 15
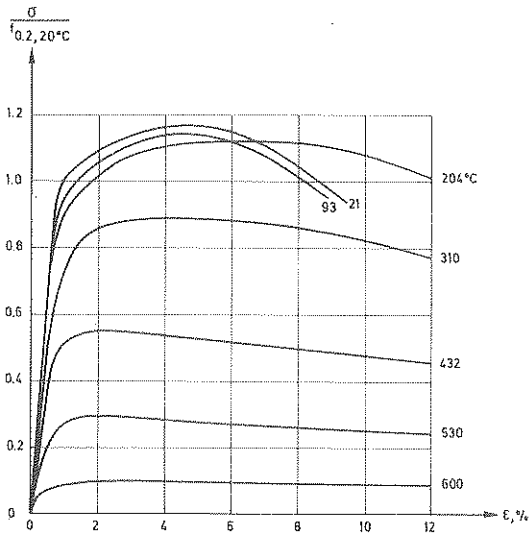
## 3.5.1   STEADY STATE DATA

c) Prestressing steel   : ASTM A421, $f_{0.2,20^{\circ}C} = 1470$ MPa

$\qquad\qquad\qquad\qquad\qquad\qquad\qquad f_{u,20^{\circ}C} = 1720$ MPa

Test conditions   : Strain rate control

$\qquad\qquad\qquad\qquad\quad \dot{\varepsilon} = 370-700\cdot10^{-3}\cdot min^{-1}$

Specimen   : $\varnothing = 4.4$ mm, $\ell = 23$ mm

Chem. composition   : 
| C | P | S | Mn | Si |
|---|---|---|---|---|
| 0.794 | 0.012 | 0.031 | 0.78 | 0.187 |

Remarks   : $\sigma-\varepsilon$ relationships

Reference   : Harmathy & Stanzak (1970)

Fig 16
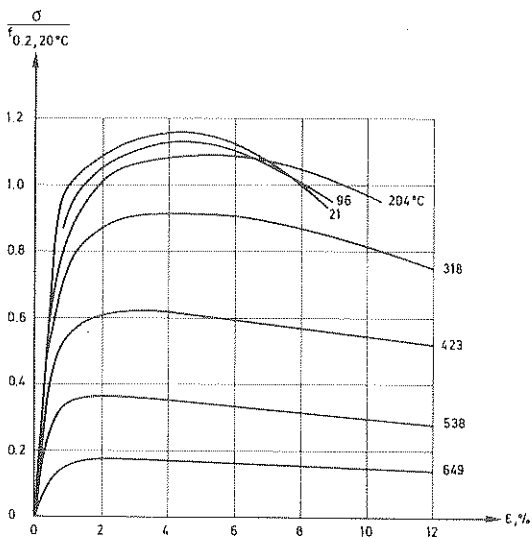
## 3.5.1   STEADY STATE DATA

c) Prestressing steel   : ASTM A421, $f_{0.2,20^{\circ}C}$ = 1470 MPa

$$f_{u,20^{\circ}C} \approx 1720 \text{ MPa}$$

Test conditions   : Strain rate control
①  $\dot{\varepsilon}$ = 550·$10^{-3}$·min$^{-1}$
②  $\dot{\varepsilon}$ =  80·$10^{-3}$·min$^{-1}$
③  $\dot{\varepsilon}$ =  25·$10^{-3}$·min$^{-1}$

Specimen   : $\emptyset$ = 4.4 mm, $\ell$ = 23 mm

|  | C | P | S | Mn | Si |
|---|---|---|---|---|---|
| Chem. composition : | 0.749 | 0.012 | 0.031 | 0.78 | 0.187 |

Remarks   : Influence of strain rate on $\sigma$-$\varepsilon$ relationship at 430 and 540$^{\circ}$C

Reference   : Harmathy & Stanzak (1970)
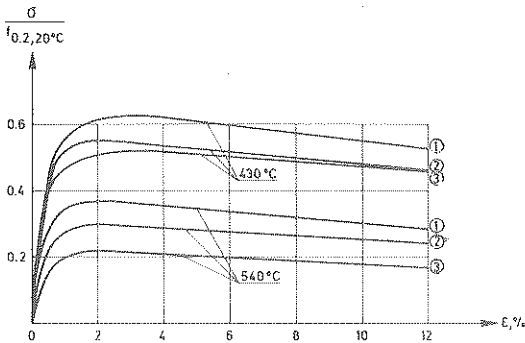
Fig 17

## 3.5.1  STEADY STATE DATA

c) Prestressing steel    :          , $f_{0.2,20^{\circ}C}$ = 1559 MPa

$f_{u,20^{\circ}C}$ = 1848 MPa

Test conditions    : Steady state
Strain rate control, $\dot{\varepsilon}$ is unknown
$t_s$ = 10 min

Specimen    : $\emptyset$ = 4.5 mm

Chem. composition    :

Remarks    : $\sigma$-$\varepsilon$ relationships

Reference    : Voves, B. (1978)

Fig 18
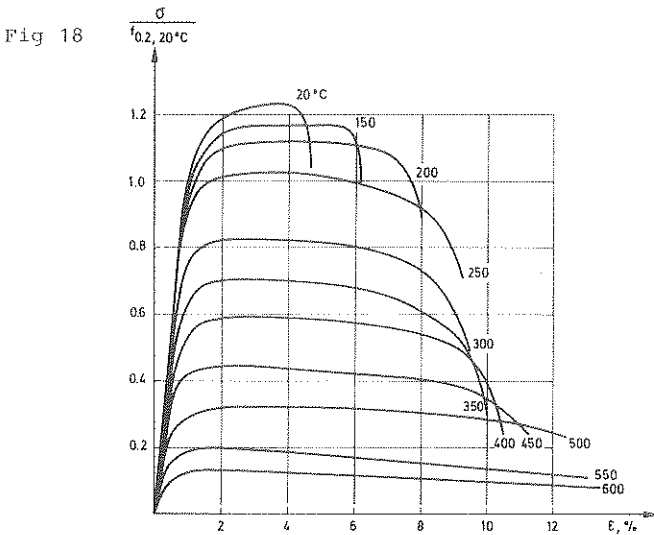
3.5.2  Transient state data

In this chapter two kinds of data will be presented namely
deformation as function of temperature and constructed $\sigma-\varepsilon$
relationships as described in section 2.2.1. The deformation
can be total or total deformation minus initial elastic strain
and/or thermal strain. Results are presented in fifteen (15)
diagrams with constructed $\sigma-\varepsilon$ curves in Figs 6, 7, 8 and 15.

The deformation-temperature curves are very much influenced by
the rate of heating, $\dot{T}$, and in the presented results it has
been varied from 1.7 to $50^{\circ}$C/min. For protected steel the rate
of heating is in most cases between 5 and $10^{\circ}$C/min.

Some of the results indicate an instability phase of the steel
which suddenly results in increased deformation and give a
more or less marked plateau in the diagram, see Figs 1, 3, 9,
12, 13 and 14. This deformation instability occurs at the load
level $0.6-0.9 \cdot f_{0.2,20^{\circ}C}$. How the rate of heating influences
this behaviour is not clear.

Due to the rate of heating, the time for the creep to develop
is different and this influences the total deformation. As a
consequence this also makes the critical temperature dependent
on the value of $\dot{T}$. By studying the results presented in the
diagrams, the following decrease in failure temperature is
obtained:

| Source | T, $^{\circ}$C/min | Decrease, $^{\circ}$C |
|---|---|---|
| Skinner (1972) | 10-1.7 | 35 |
| Copier (1972) | 50-5 | 40 |
| Ruge & Winkelmann (1978-80) | 10-4 | 20 |

It may be noted that there are great differences in the deforma-
tion curves taken from different sources.

Finally, it can be noticed that in $\sigma-\varepsilon$ curves constructed from
transient data a great deal of creep is included. The results
for structural steel given in Figs 6 and 7 are in a relatively
good agreement.

## 3.5.2  TRANSIENT STATE DATA

a) Structural steel     : FeE 24, $f_{0.2,20^{\circ}C}$ = 270 MPa

    Test conditions     : Constant load control
                               Rate of heating, $\dot{T}$ = $10^{\circ}$C/min

    Specimen             :

    Chem. composition    :

    Remarks              : Total deformation minus thermal strain
                               as function of temperature at different
                               load levels

    Reference            : Copier, W.J. (1972)

Fig 1
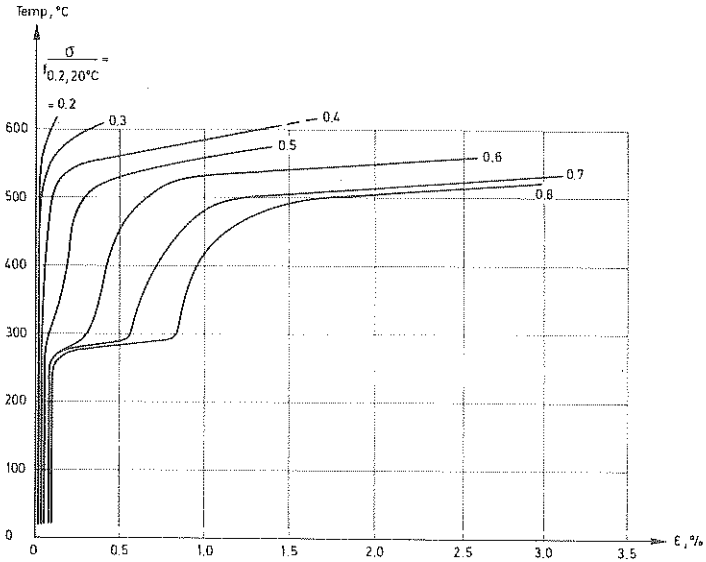
## 3.5.2   TRANSIENT STATE DATA

a) Structural steel    : Fe E24, $f_{0.2,20^{O}C}$ = 270 MPa

      Test conditions    : Constant load control
                                 Rate of heating, $\dot{T}$ = 5,10,50$^{O}$C/min

      Specimen               :

      Chem. composition    :

      Remarks               : Influence of rate of heating on total
                                 deformation minus thermal and initial
                                 elastic strain as function of tempera-
                                 ture at different load levels
      Reference            : Copier, W.J. (1972)

Fig 2
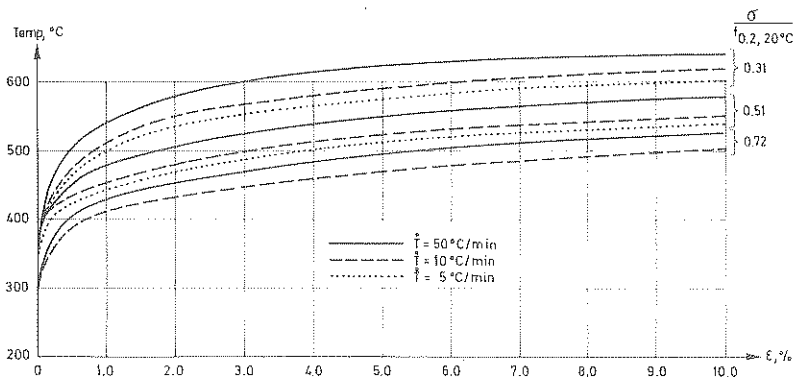
## 3.5.2  TRANSIENT STATE DATA

a) Structural steel : St 52, $f_{0.2,20^{\circ}C}$ = 480 MPa


   Test conditions : Constant load control
                      Rate of heating, $\mathring{T}$ = 4 and $10^{\circ}C/min$

   Specimen : b = 10 mm, ℓ = 100 mm


   Chem. composition :

   Remarks : Total deformation minus thermal strain
             and initial elastic strain as function
             of temperature at different load levels

   Reference : Ruge & Winkelmann (1978-80)

Fig 3

## 3.5.2  TRANSIENT STATE DATA

a) Structural steel    : Steel 37, $f_{0.2,20^oC}$ = 250 MPa

$$f_{u,20^oC} = 496 \text{ MPa}$$
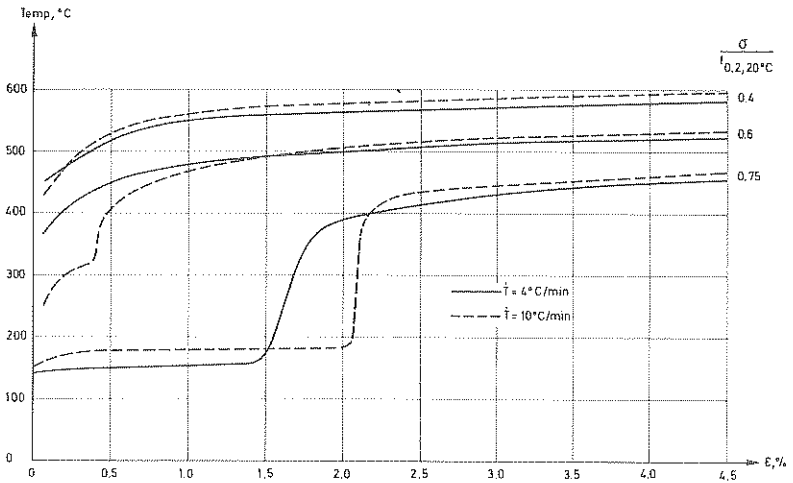
Test conditions    : Constant load control
Rate of heating, $\dot{T}$ = 1.7 and $10^oC$/min

Specimen    : $\phi$ = 7.2 mm, $\ell$ = 71 mm

Chem. composition    :

| C | P | S | Mn | Si | Cr |
|------|-------|-------|------|-------|------|
| 0.27 | 0.033 | 0.041 | 0.65 | 0.128 | 0.16 |

Ni
0.86

Remarks    : Total deformation minus thermal and initial elastic strain as function of temperature at different load levels

Reference    : Skinner (1972)

Fig 4

## 3.5.2 TRANSIENT STATE DATA

a) Structural steel : Steel 37, $f_{0.2,20^{O}C}$ = 250 MPa

$f_{u,20^{O}C}$ = 496 MPa

Test conditions : Constant load control
Rate of heating, $\dot{T}$ = 1.7 and $10^{O}C$/min

Specimen : $\emptyset$ = 7.2 mm, $\ell$ = 71 mm

|  | C | P | S | Mn | Si | Cr |
|---|---|---|---|---|---|---|
| Chem. composition : | 0.27 | 0.033 | 0.041 | 0.65 | 0.128 | 0.16 |
|  | Ni |  |  |  |  |  |
|  | 0.086 |  |  |  |  |  |

Remarks : Influence of rate of heating on total
deformation minus thermal strain as
function of temperature at different
load levels

Reference : Skinner (1972)

Fig 5
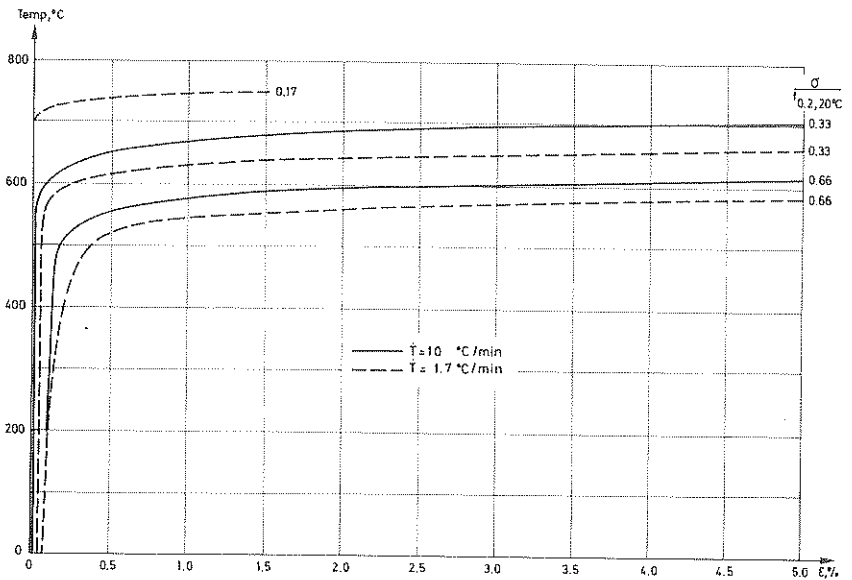
## 3.5.2 TRANSIENT STATE DATA

a) Structural steel : St 37-2, $f_{0.2,20^{o}C}$ = 255 MPa

Test conditions : Constant load control
Rate of heating, $\dot{T}$ = $10^{o}C/min$

Specimen : b = 10 mm, $\ell$ = 100 mm

Chem. composition :

Remarks : Constructed $\sigma$-$\varepsilon$ relationships

Reference : Ruge & Winkelmann (1978-80)

Fig 6
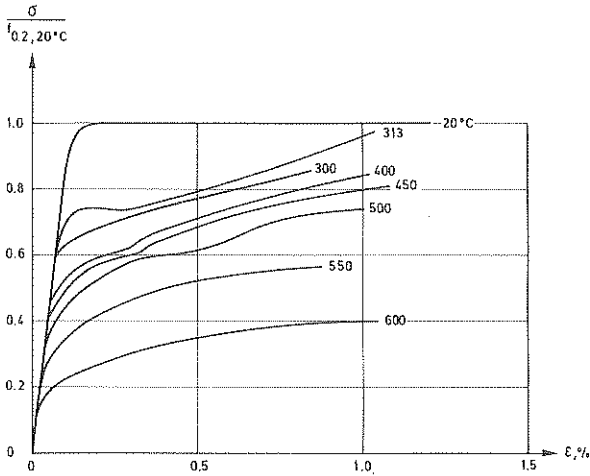
3.5.2  TRANSIENT STATE DATA

a) Structural steel    : FeE 24, $f_{0.2,20^{O}C}$ = 270 MPa


   Test conditions     : Constant load control
                         Rate of heating, $\dot{T} = 10^{O}C/min$


   Specimen            :


   Chem. composition   :


   Remarks             : Constructed σ-ε relationships


   Reference           : Copier, W.J. (1972)

Fig 7
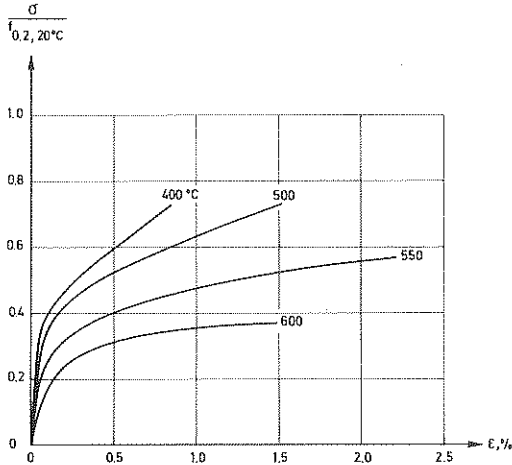
## 3.5.2 TRANSIENT STATE DATA

a) Structural steel        : Fe E24, $f_{0.2,20^\circ C}$ = 270 MPa

    Test conditions        : Constant load control
                                       Rate of heating, $\dot{T}$ = $10^\circ C$/min

    Specimen                :

    Chem. composition        :

    Remarks                : Constructed σ-ε relationships for ECCS

    Reference                : Witteveen, J. et al (1977)

Fig 8
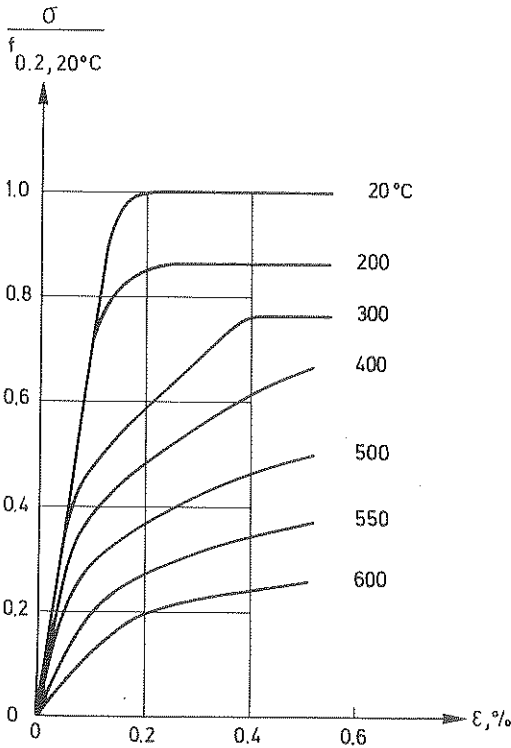
3.5.2 TRANSIENT STATE DATA

b) Reinforcing steel : Ks 60, $f_{0.2,20^{\circ}C}$ = 710 MPa

Test conditions : Constant load control
Rate of heating, $\dot{T}$ = $10^{\circ}$C/min

Specimen : $\emptyset$ = 8 mm, $\ell$ = 100 mm

Chem. composition : 
| C | P | S | Mn | Si |
|------|-------|-------|------|-------|
| 0.31 | 0.040 | 0.041 | 1.11 | 0.033 |

Remarks : Total deformation minus initial elastic
strain as function of temperature at
different load levels

Reference : Anderberg (1982)

Fig 9

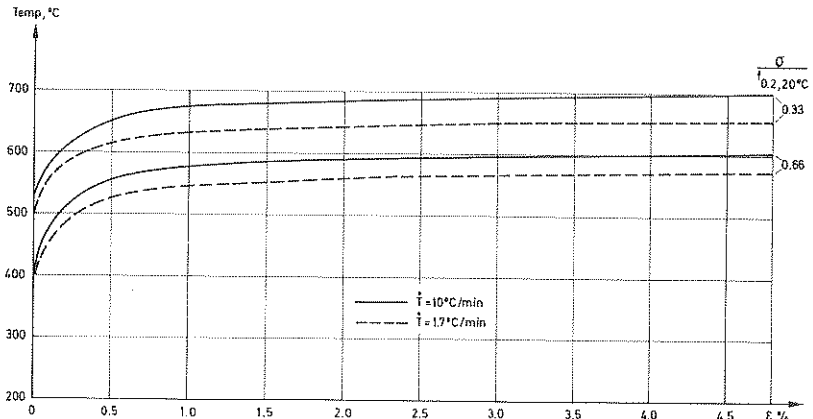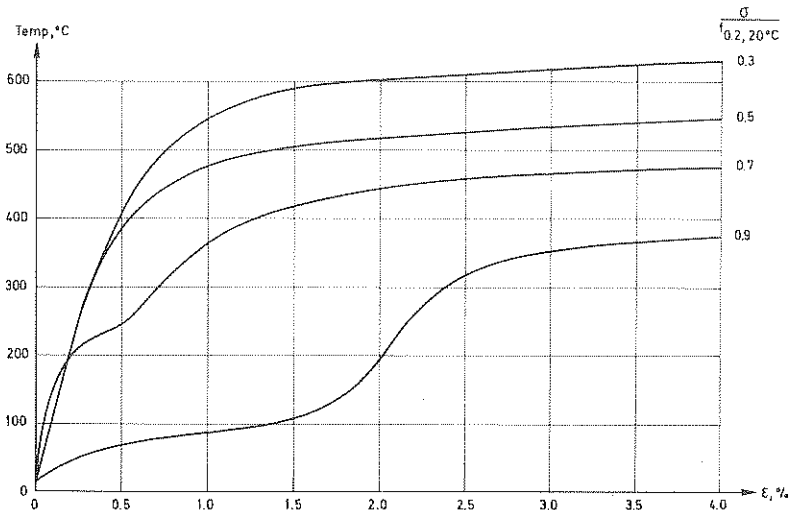## 3.5.2   TRANSIENT STATE DATA

a) Reinforcing steel : (1) Hot-rolled, $f_{0.2,20^{\circ}C}$ = 210-670 MPa
   (2) Torsteel, $f_{0.2,20^{\circ}C}$ = 430-460 MPa

   Test conditions   : Constant load control
                       Rate of heating, $\dot{T}$ = 10$^{\circ}$C/min

   Specimen          : $\emptyset$ = 10 mm, $\ell$ = 400 mm
                       (1) Hot-rolled
                       (2) Cold-worked

   Chem. composition :

   Remarks           : Total deformation minus initial elastic
                       strain at different load levels as func-
                       tion of temperature

   Reference         : Soretz (1967)

Fig 10

## 3.5.2 TRANSIENT STATE DATA

c) Prestressing steel : $f_{0.2,20^{O}C} = 1559$ MPa
$f_{u,20^{O}C} = 1848$ MPa

Test conditions : Constant load control
Rate of heating, $\dot{T} = 12^{O}C/min$

Specimen : $\emptyset = 4.5$ mm

Chem. composition :

Remarks : Total deformation as function of tem-
perature at different load levels

Reference : Voves, B. (1978)

Fig 11
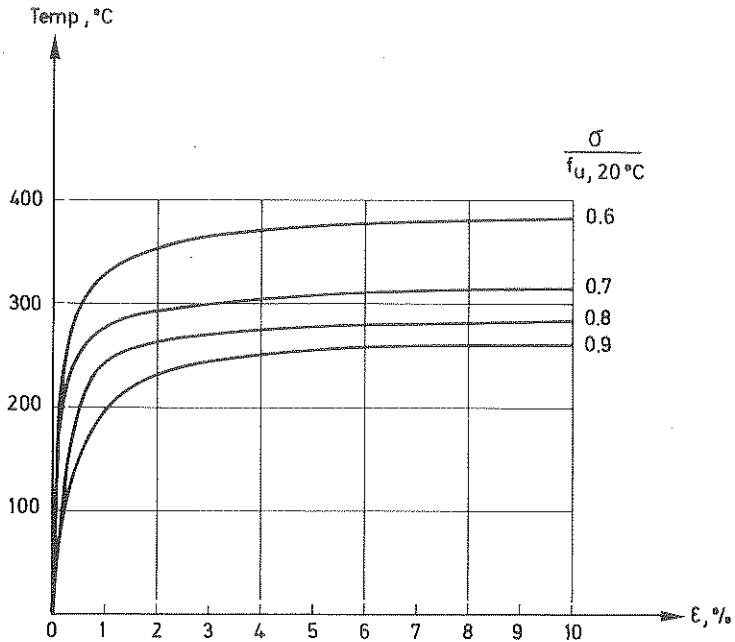
## 3.5.2  TRANSIENT STATE DATA

c) Prestressing steel  : St 1570/1770, $f_{0.2,20^\circ C}$ = 1570 MPa

    Test conditions  : Constant load control
                            Rate of heating, $\dot{T}$ = $4^\circ$C/min

    Specimen  : Cold-drawn, $\emptyset$ = 7.5 mm, $\ell$ = 10 x $\emptyset$

    Chem. composition  :

    Remarks  : Total deformation minus initial elastic
                            strain as function of temperature at
                            different load levels

    Reference  : Ruge & Winkelmann (1978-80)
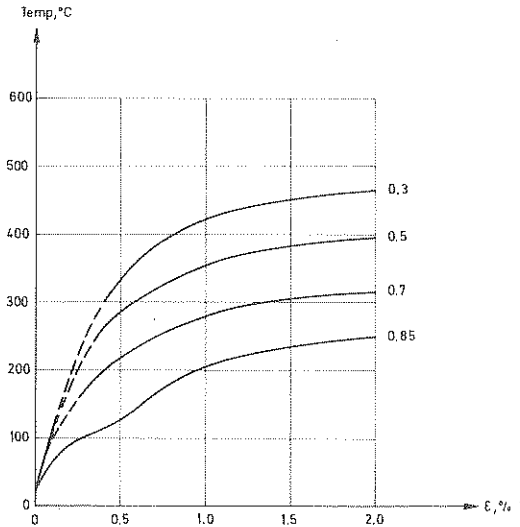
Fig 12

## 3.5.2   TRANSIENT STATE DATA

c) Prestressing steel   : St 1570/1770, $f_{0.2,20^{\circ}C}$ = 1570 MPa


   Test conditions       : Constant load control
                           Rate of heating, $\dot{T}$ = $4^{\circ}$C/min


   Specimen              : Cold-worked, $\emptyset$ = 7.5 mm, $\ell$ = 10 x $\emptyset$


   Chem. composition     :


   Remarks               : Total deformation minus thermal strain
                           and initial elastic strain as function
                           of temperature at different load levels


   Reference             : Ruge & Winkelmann (1978-80)

Fig 13
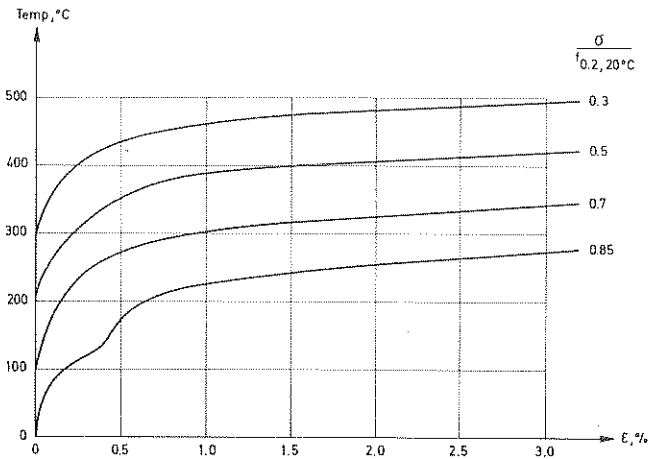
## 3.5.2  TRANSIENT STATE DATA

c) Prestressing steel  : St 1570/1770, $f_{0.2,20^{\circ}C}$ = 1660 MPa

    Test conditions  : Constant load control
                                 Rate of heating, $\dot{T}$ = 4$^{\circ}$C/min

    Specimen  : Cold-worked, $\emptyset$ = 5 mm, $\ell$ = 10 x $\emptyset$

    Chem. composition  :

    Remarks  : Total deformation minus initial elastic
                                 strain as function of temperature at
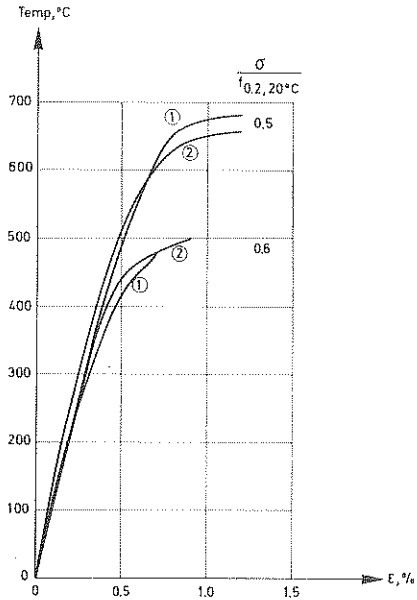                                 different load levels

    Reference  : Ruge & Winkelmann (1978-80)

Fig 14
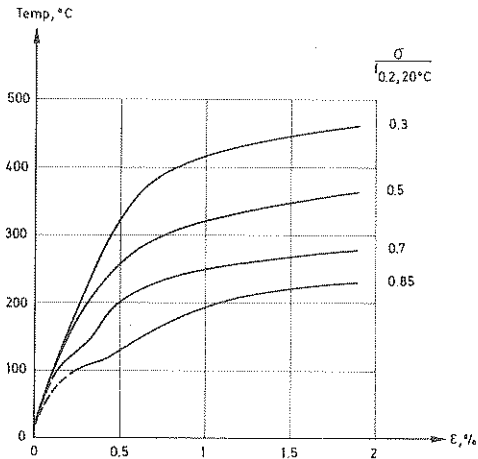
### 3.5.2  TRANSIENT STATE DATA

c) Prestressing steel  : St 1570/1770, $f_{0.2, 20^{o}C}$ = 1570 MPa

  Test conditions       : Constant load control
                          Rate of heating, $\dot{T}$ = 4$^{o}$C/min

  Specimen              : Cold-drawn, $\emptyset$ = 7.5 mm

  Chem. composition     :

  Remarks               : Constructed $\sigma$-$\varepsilon$ relationships

  Reference             : Ruge & Winkelmann (1978-80)

Fig 15
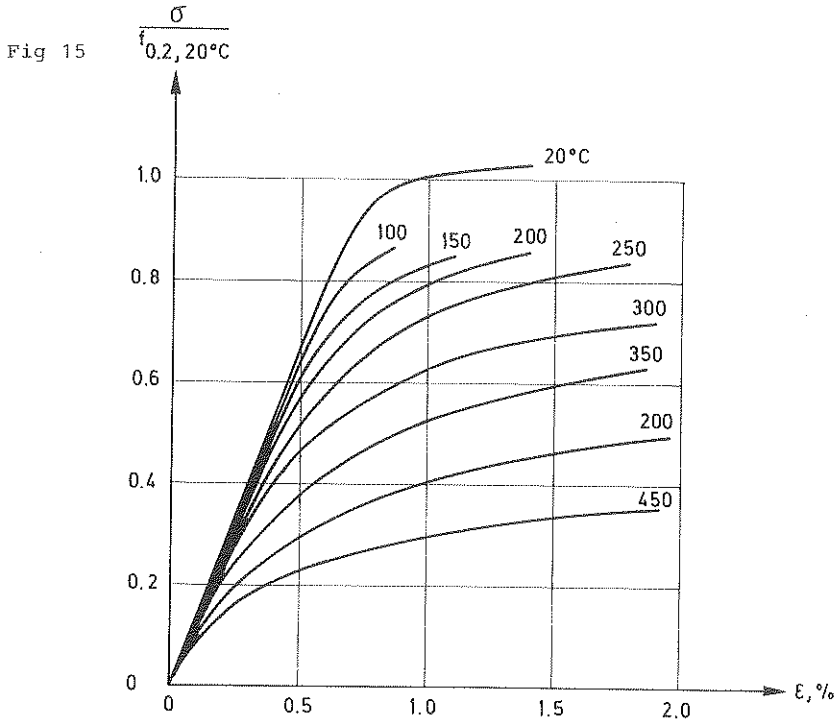
3.6 Relaxation

A relaxation test is in most cases carried out at constant
strain and temperature and the stress decrease is studied as
a function of time. However, in a fire-exposed prestressed
concrete structure the temperature is varying and the loss in
prestress is due to substantial relaxation. As the temperature
increases the relaxation process develops more rapidly, which
makes the situation more complicated. The relaxation in pre-
stressed concrete structures can only be studied analytically,
which is only done fragmentarily so far.

Dimensionless relaxation curves for reinforcing and prestress-
ing steel are illustrated in Figs. 1-3 from Anderberg (1983),
Cahill (1965) and Voves (1978). The results deviate very much
from each other, the reason of which is hard to find when only
three sources are to be found.

3.6   RELAXATION

c) Prestressing steel   :               $f_{0.2,20^{O}C}$ = 1070 MPa

                                        $f_{u,20^{O}C}$ = 1630 MPa

   Test conditions     : Steady state
                         An initial strain related to 0.2% proof
                         stress at each test temperature was
                         kept constant during the test

   Specimen            :


                         C      P       S      Mn    Si
   Chem. composition  : 0.78   0.024  0.022   0.63  0.21


   Remarks             : Relaxation at different temperatures


   Reference           : Cahill (1965)

Fig 2
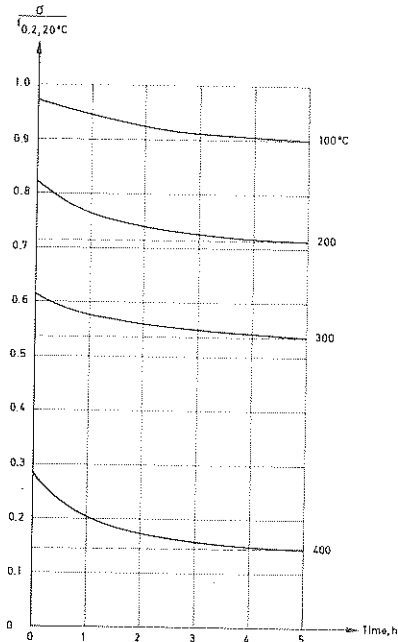
## 3.6   RELAXATION

b) Reinforcing steel   :                $f_{0.2,20^oC}$ = 710 MPa

                                        $f_{u,20^oC}$ = 880 MPa

    Test conditions   : An initial strain related to diffe-
rent load levels was kept constant
at different temperatures

    Specimen           : $\emptyset$ = 8 mm

                            C     P    S   Mn   Si
    Chem. composition  : 0.31  0.040  0.33  1.11  0.041

    Remarks            : Relaxation at different temperatures
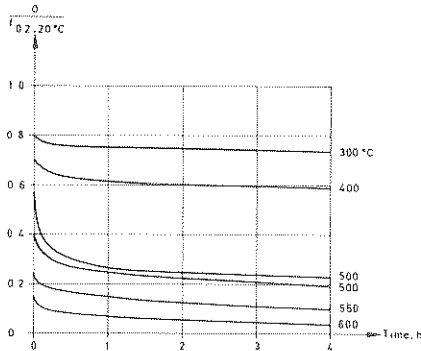
    Reference          : Anderberg (1983)

Fig 1

## 3.6   RELAXATION

c) Prestressing steel   :                     $f_{0.2,20^\circ C} = 1559$ MPa

$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad f_{u,20^\circ C} = 1848$ MPa

Test conditions      : Steady state
An initial strain related to different
load levels was kept constant at dif-
ferent temperatures

Specimen             : $\emptyset = 4.5$ mm

Chem. composition    :

Remarks              : Relaxation at different temperatures

Reference            ' : Voves, B. (1978)

Fig 3
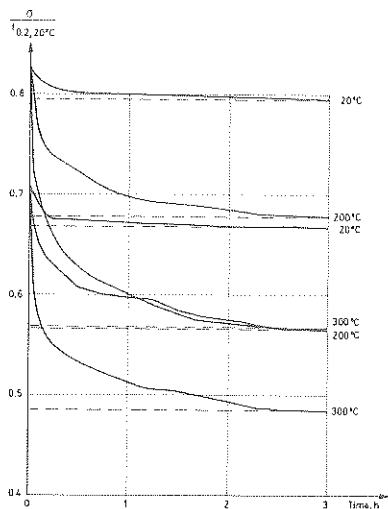
## 3.7  Thermal properties

Information about thermal properties of steel is in litera-
ture very limited. Four  references are sorted out represent-
ing the thermal conductivity, specific heat and specific volu-
metric enthalpy as function of temperature for structural steel,
see Figs 1-4. The thermal conductivity curves taken from three
different investigations seem to be in good agreement with
each other.

## 3.7  THERMAL PROPERTIES

a) Structural steel        : ① Fe 52
                             ② Fe 33, Fe 37, Fe 44

   Remarks                 : Thermal conductivity as
                             function of temperature

   Reference               : ① and ② Stirland (1980)
                             ③ Alpsten (1967), Wickström (1979)

Fig 1

Thermal conductivity, W/m °C
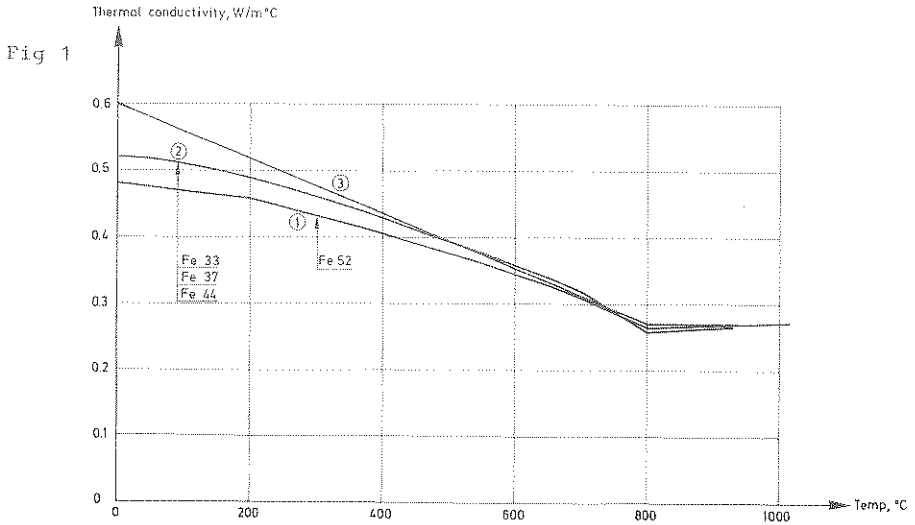
## 3.7 THERMAL PROPERTIES

a) Structural steel :

    Remarks : Specific heat as function of
                             temperature

    Reference : Stirland (1980)

Fig 2
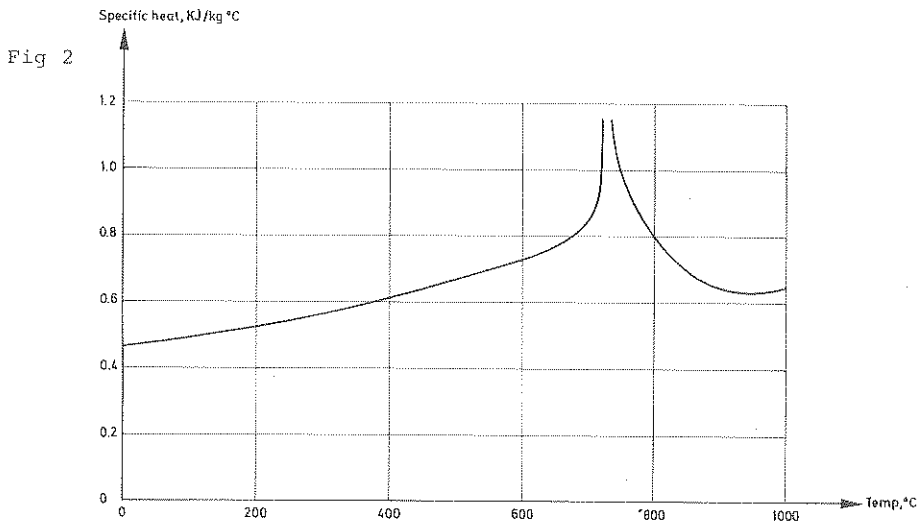
3.7  THERMAL PROPERTIES

a) Structural steel      :

    Remarks               : Specific volumetric enthalpy
                              as function of temperature

    Reference            : Alpsten (1967), Wickström (1979)

Fig 3



Specific volumetric enthalpy MJ / m$^3$ as function of Temp, °C
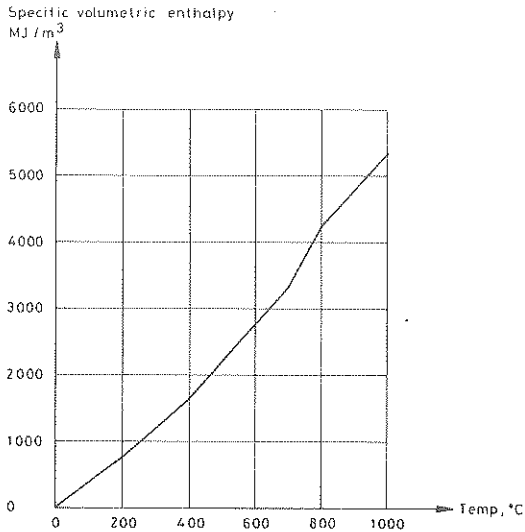
## 3.7  THERMAL PROPERTIES

a,b,c) Different steels  :

Remarks                  : Thermal conductivity as function
                           of temperature

Reference                : Schneider & Diederichs (1981)

Fig 4



Thermal conductivity, W/m°C
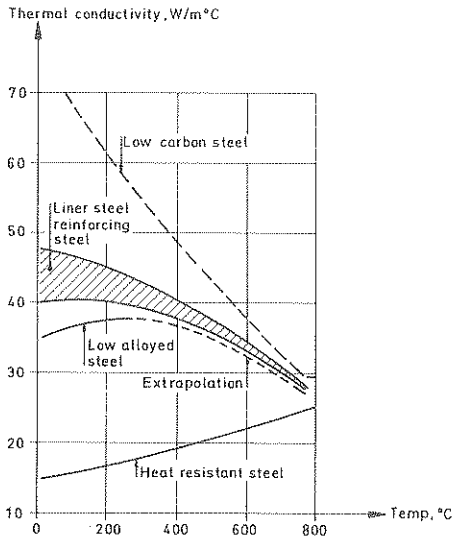
## 3.8  Residual properties

Residual properties as 0.2% proof tensile stress and ultimate tensile strength are illustrated in Figs 1-5. The residual 0.2% proof stress is only meaningful to be measured when the specimen is unloaded during heating and cooling. Hot-rolled steel is not influenced by temperature as concerns neither 0.2% proof stress nor tensile strength. Cold-drawn steel may have some decrease in strength above $500^{\circ}C$ (see Fig 4, specimen is loaded during heating), which, however, only amounts to 10% of the original strength. Prestressing steel does not recover from temperatures above about $250^{\circ}C$ and exposed to $600^{\circ}C$ the residual strength reaches about $0.6\ f_{0.2,20^{\circ}C}$.

## 3.8  RESIDUAL PROPERTIES

a) Structural steel    : ① St 60/90, $f_{0.2,20^oC}$ = 590 MPa

c) Prestressing steel   : ② St 145/165, $f_{0.2,20^oC}$ = 1520 MPa

                                ③ St 160...180, $f_{0.2,20^oC}$ = 1570 MPa

    Test conditions      : No loading during heating or cooling

    Specimen           : ① Hot-rolled, $\emptyset$ = 26 mm

                                 ② Cold-drawn, $\emptyset$ = 5.2 mm

                                 ③ Cold-drawn, $\emptyset$ = 5mm

    Chem. composition    :

    Remarks            : Residual 0.2% proof tensile stress

    Reference           : Dannenberg et al (1959)

Fig 1
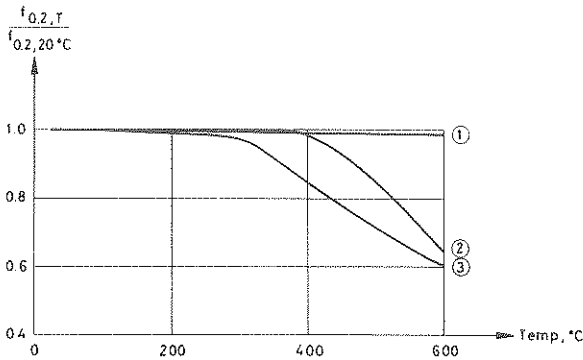
## 3.8  RESIDUAL PROPERTIES

a) Structural steel      : ① St 60/90, $f_{u,20^{o}C}$ = 590 MPa

c) Prestressing steel    ② St 145/165, $f_{u,20^{o}C}$ = 1650 MPa

③ St 160...180, $f_{u,20^{o}C}$ = 1740 MPa

Test conditions      : No loading during heating or  cooling

Specimen            : ① Hot-rolled, $\emptyset$ = 26 mm

② Cold-drawn, $\emptyset$ = 5.2 mm

③ Cold-drawn, $\emptyset$ = 5 mm

Chem. composition    :

Remarks             : Residual ultimate tensile strength

Reference           : Dannenberg et al (1959)

Fig 2
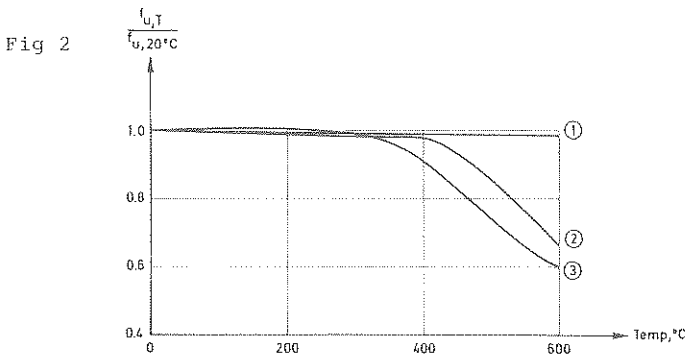
## 3.8  RESIDUAL PROPERTIES

a) Structural steel      : BSt  37-2, $f_{0.2,20^{\circ}C}$ = 255 MPa

Test conditions      : Rate of heating, $\dot{T}$ = $10^{\circ}$C/min

Specimen           : b = 10 mm, $\ell$ = 100 mm

Chem. composition    :

Remarks           : Residual ultimate tensile strength

Reference          : Ruge & Winkelmann (1978-80)

Fig 3
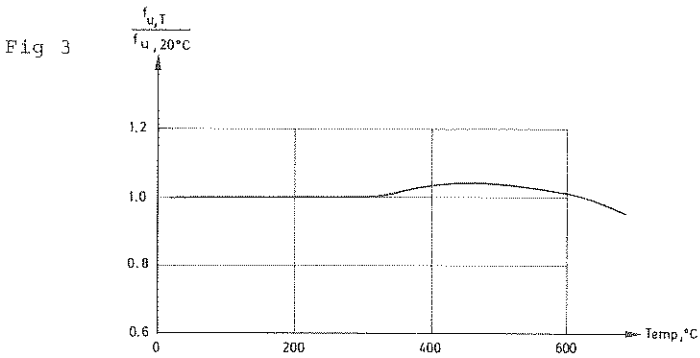
## 3.8  RESIDUAL PROPERTIES

b) Reinforcing steel   : BSt  42/50 RK ① $f_{0.2,20^{O}C}$ = 430 MPa

② $f_{0.2,20^{O}C}$ = 470 MPa

Test conditions    : Rate of heating, $\dot{T}$ = $10^{O}$C/min

Specimen       : $\emptyset$ = 18 mm, $\ell$ = 10 x $\emptyset$
$\emptyset$ = 28 mm, $\ell$ = 10 x $\emptyset$
Cold-drawn

Chem. composition   :

Remarks        : Residual ultimate tensile strength

Reference       : Ruge & Winkelmann (1978−80)

Fig 4
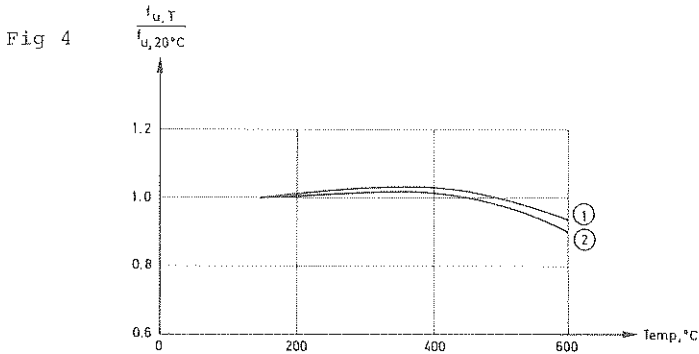
3.8   RESIDUAL PROPERTIES

c) Prestressing steel   :

$f_{0.2,20^{\circ}C} = 1559$ MPa

$f_{u,20^{\circ}C} = 1848$ MPa

Test conditions  : Heated to a specified temperature level with a stabilizing period of 10 minutes before a cooling down to room temperature

Specimen     : $\emptyset = 4.5$ mm

Chem. composition  :

Remarks     : Residual ultimate tensile strength and 0.2% proof stress

Reference    : Voves, B. (1978)

Fig 5
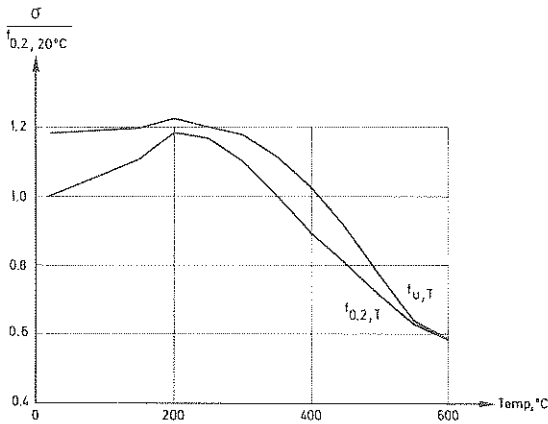
## 4 A review and comparative study of different properties

When the results are comparable (i.e. test procedure is simi-
lar), it can be shown that the relative decrease in ultimate
tensile strength with increasing temperature in most cases is
almost the same for all steels, prestressing steels and others
separated. Som deviations may occur for cold-worked steel. For
hot-rolled steel the decrease in 0.2% proof stress has the same
tendency.

When comparing the ultimate strength curves obtained from a
steady state test with stress rate control and from a tran-
sient state test, a difference can be observed as illustrated
for hot-rolled steels in Fig 12. The transient test results
are here about 10% lower at temperatures above $450^{\circ}$C. If,
however, the stress rate had been chosen much lower, the
curves should be much closer to each other.

$\sigma-\epsilon$ relationships on stress rate controlled steady state con-
ditions for Swedish hot-rolled steel and different structural
steels are compared in Figs 13-15. The $\sigma-\epsilon$ curves shown in
Fig 13 are in good agreement due to very similar test condi-
tions. The agreement is not that good in Figs 14 and 15, which
may be explained by the fact that the exact test conditions
are not known for Reichel's results.

A similar comparison is illustrated for two kinds of structu-
ral steel under strain rate controlled steady state conditions.
The $\sigma-\epsilon$ curves are in good concordance with each other.

In transient tests the rate of heating influences the deforma-
tion-temperature curve. Comparing results when $\dot{T} = 10^{\circ}$C/min for
reinforcing and structural steels, curves as illustrated in Fig
17 are obtained. The curves are quite close to each other. The
instability phase at about $275^{\circ}$C, however, are more marked in
Copier's results.

From transient test results σ-ε curves can be evaluated. Such
curves on structural steel from two different sources are com-
pared in Fig 18. The curves from Ruge & Winkelmann are all
above those from Copier.

In Fig 19 σ-ε curves from steady state and transient state
tests on prestressing steel are compared. The curves on steady
state conditions are lying above the corresponding constructed
curves. If, however, the stress rate or strain rate in the
steady state test is chosen lower, the curves are approaching
each other.

Theoretically, it is possible to evaluate what stress rate or
strain rate in a steady state test that shall be coupled with
a certain rate of temperature increase in a transient test in
order to get the same σ-ε curve or ultimate strength. Analy-
tical modelling will be discussed and illustrated in chapter 5.
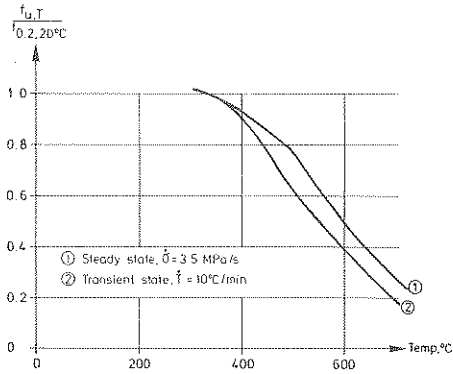
Fig 12    Ultimate strength as function of temperature for hot-
          rolled steels in (1) a steady state test and in (2) a
          transient state test. Anderberg (1982)
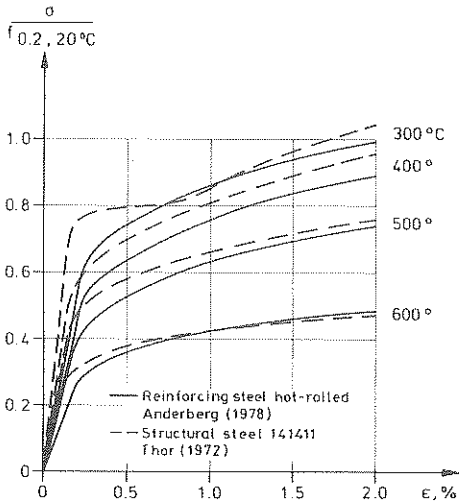


Fig 13    σ-ε curves from steady state tests under stress rate
          control for reinforcing and structural steel.
          σ̇ = 3.5 and 1.6 MPa/s, respectively
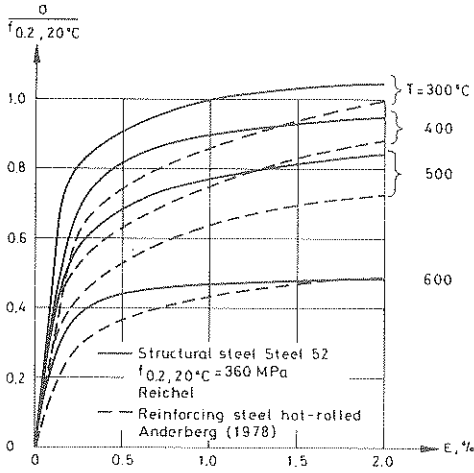
Fig 14  σ-ε curves from steady state tests under stress rate
control for structural and reinforcing steel
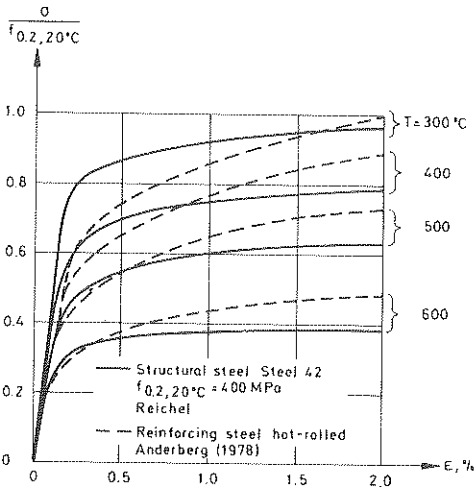


Fig 15  σ-ε curves from steady state tests under stress rate
control for structural and reinforcing steel
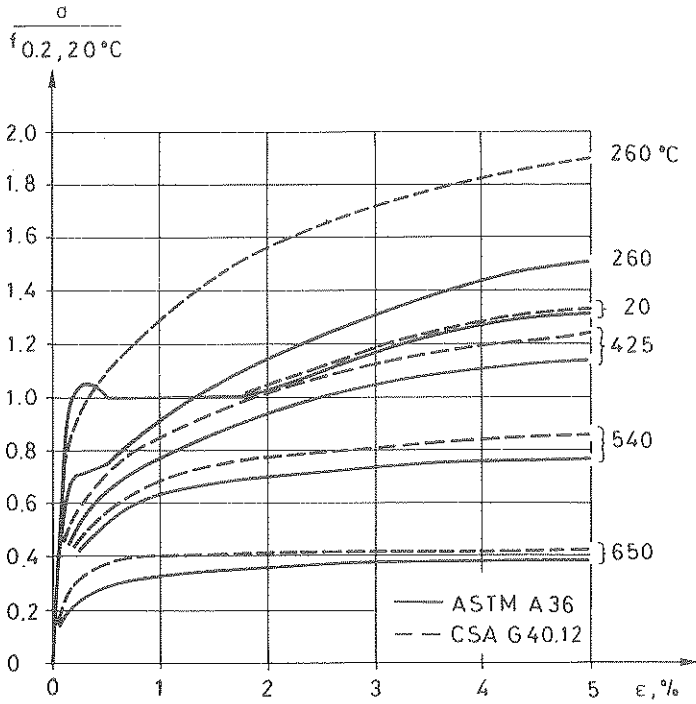
Fig 16   σ-ε curves from steady state tests under strain rate
control for different structural steels.
$\dot{\varepsilon}$ = 50-100·$10^{-3}$·$min^{-1}$. Harmathy & Stanzak (1970)
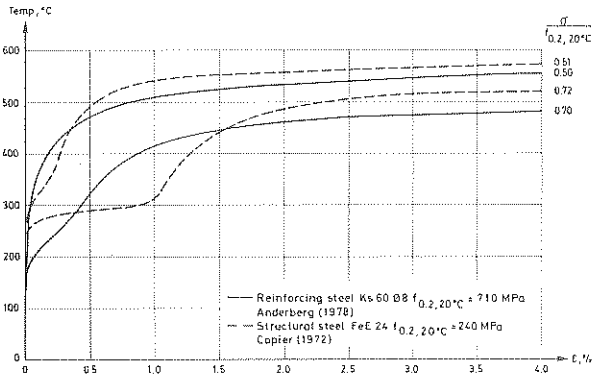


Fig 17   Total deformation minus initial elastic and thermal
strain as function of temperature for reinforcing and
structural steel.
$\dot{T}$ = $10^{O}$C/min
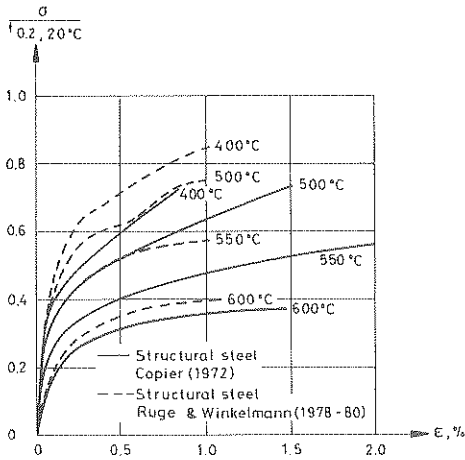
Fig 18　Calculated σ-ε curves from transient tests for structural steel.
$\dot{T} = 10^{O}C/min.$
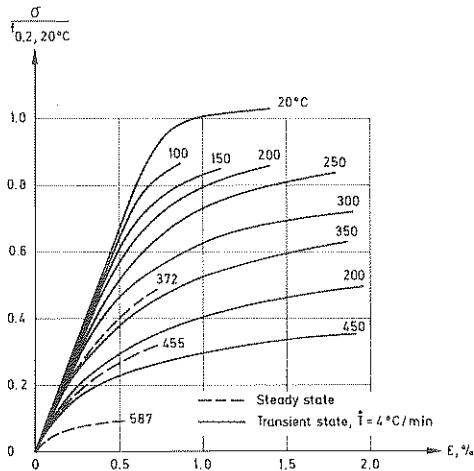


Fig 19　A comparison of σ-ε curves for prestressing steel
St 1570/1770 obtained from steady state and transient
state tests

## 5  Analytical modelling

### 5.1  Models

It is generally agreed that the deformation process of steel
at elevated temperatures can be described by the three strain
components defined below, namely thermal strain, instantaneous,
stress-related strain and creep strain. Thus

$$\varepsilon_{total} = \varepsilon_t = \varepsilon_{th}(T) + \varepsilon_\sigma(T,\sigma) + \varepsilon_{cr}(t,T,\sigma) \qquad (1)$$

where

$\varepsilon_{th}(T)$          = thermal strain

$\varepsilon_\sigma(T,\sigma)$          = instantaneous, stress-related strain based on
                    $\sigma$-$\varepsilon$ relationship

$\varepsilon_{cr}(t,T,\sigma)$  = creep strain or time dependent strain

The strains are found separately in steady state tests and
several analytical expressions are presented in literature.
Behaviour models based on steady state data only partially
predict the transient behaviour of any given fire process,
load and strain history.

An analytical description of the $\sigma$-$\varepsilon$ curve as a function of
temperature can be made in different ways as illustrated in
Figs 20 and 21. In the first case the curve is approximated
by two straight lines and in the second case by an elliptic
branch placed between straight lines. The curve can also be
approximated by other analytical expressions.

Models of creep are in most cases based on a concept put for-
ward by Dorn (1954), in which the effect of variable tempera-
tures is considered. The extension of the model to be applic-
able to variable stress can, for instance, be based on the
strain hardening rule.

The creep strain is assumed to be dependent on the magnitude
of stress and on the temperature-compensated time evaluated

from the expression

$$\theta = \int_{0}^{t} e^{-\frac{\Delta H}{RT}} dt \quad (h)$$ (2)

where

$\Delta H$ = activation energy of creep, J/mol
$R$ = gas constant, J/mol·K
$t$ = time

The relation between creep strain, $\varepsilon_{cr}$, and temperature-compensated time, $\theta$, at different stress levels is shown principally in Fig 22. The change from the curved branch to the straight line (primary and secondary phase) is denoted by $\theta_o$ and the intersection between the straight line and the creep axis is called $\varepsilon_{cr,o}$. The slope of the straight line is called Z. Harmathy (1967) has derived an analytical expression between $\varepsilon_{cr}$ and the parameters $\theta$, Z and $\varepsilon_{cr,o}$ as follows:

$$\varepsilon_{cr} = (\varepsilon_{cr,o}/\ln 2) \text{ arcosh } (2^{Z\theta/\varepsilon_{cr,o}})$$ (3)

A modified expression is also made by Plem (1975) where the primary phase is defined by a parabolic equation and the secondary phase by a linear slope. The transfer occurs at time $\theta_o$. The mathematical formula is

$$\left. \begin{array}{ll} \varepsilon_{cr} = \varepsilon_{cr,o}(2 \cdot \sqrt{\dfrac{Z \cdot \theta}{\varepsilon_{cr,o}}}) & \text{when} \quad 0 \leq \theta \leq \theta_o \\[3mm] \varepsilon_{cr} = \varepsilon_{cr,o}(1+\dfrac{Z \cdot \theta}{\varepsilon_{cr,o}}) & \text{when} \quad \theta \geq \theta_o \end{array} \right\}$$ (4)

where

$$\theta_o = \frac{\varepsilon_{cr,o}}{Z}$$ (5)

A simplified way is to approximate the creep curve by two straight branches with slopes $Z_p$ and $Z_s$ (Anderberg 1978)

as illustrated in Fig 23. The creep strain is an explicit
function of time, temperature and stress, where

$$\varepsilon_{cr}(t,T,\sigma) = t \cdot Z(T,\sigma) \tag{6}$$

$$\left.\begin{array}{ll} \dot{\varepsilon}_{cr} = Z_p(T,\sigma) & \text{if } 0 \leq t \leq t_t \\[2mm] \dot{\varepsilon}_{cr} = Z_s(T,\sigma) & \text{if } t > t_t \end{array}\right\} \tag{7}$$

Nomograms for the rate of creep in primary and secondary phase
for reinforcing steel Ks 40 Ø8 were published by Anderberg (1978).
These nomograms including the determination of the transition
time, $t_t$, are given in Fig 24. These diagrams facilitate an
estimation of the magnitude of creep.

The Dorn-Harmathy creep theory has not only been used by
Harmathy but also by Thor (1972). In Figs 25-27 the validity
of the creep model can be studied. The agreement is satisfac-
tory. In Anderberg (1978) the modified version of the Dorn-
Harmathy theory has been used and the concordance between test
and calculation is shown in Figs 28-30.

Creep parameters for different kind of steels and used in cal-
culations are collected in Table 5.1. The following equations
are governing Z and $\varepsilon_{cr,o}$:

$$\varepsilon_{cr,o} = A \cdot \sigma^B \tag{8}$$

$$Z = \begin{cases} C \cdot \sigma^D & \text{if } \sigma \leq \text{SIG 1} \\ H \cdot e^{F \cdot \sigma} & \text{if } \sigma > \text{SIG 1} \end{cases} \tag{9}$$

The coefficients in these equations are given in Table 5.1 for
steels accounted for in three sources, 1. Thor (1972), 2. Har-
mathy & Stanzak (1970) and 3. Anderberg (1978).

## 5.2   Comparison test and calculation

Using the complete behaviour model as expressed in Eq (1), any
test can be simulated. The total deformation as a function of

temperature measured in a transient test, $\dot{T} = 10^{o}C/min$, is
calculated in Anderberg (1983) and the comparison is illustra-
ted in Fig 31. The calculation is very close to the measured
curves. σ-ε curves from steady state and transient state tests
at different temperatures are compared to each other in Fig 32.
Agreement between calculations and measurements is also close
in this case. The curve of the steady state conditions con-
tains no creep due to the high stress rate. In the curve of
the transient state conditions the influence of creep, however,
is of importance. The difference between the curves at ε > 2%
and the decrease in ultimate strength at 500 and 600$^{o}$C amount
to about 15% of $f_{0.2,20^{o}C}$.

σ-ε curves from steady state tests (strain controlled) on pre-
stressing steel are compared to calculated data in Fig 33. The
agreement is very good up to the maximum stress. However, the
negative slope is not obtained in the calculation which may be
due to a contraction of the steel area during the experiment.
The reduced cross-section causes a decrease in total load but
the stress may be constant?

It is also possible to simulate a relaxation test. A compari-
son is made between measured curves (Cahill 1965) and curves
predicted on the basis of creep data according to A421-65
(Harmathy 1967). The result is illustrated in Fig 34. The
American prestressing steel seems to be a little more sensi-
tive to relaxation above 300$^{o}$C, but at 400$^{o}$C the curves are
close to each other.

The predictions illustrated above indicate that any test pro-
cess can be calculated satisfactorily, when the model is based
on steady state data.

Table 5.1

Creep parameters for different kind of steels (1) Thor (1972), (2) Harmathy-Stanzak (1970) and (3) Anderberg (1978)

| Stål | $f_{0.2,20°C}$ MPa | A | B | C min$^{-1}$ | D | H min$^{-1}$ | F | $\frac{\Delta H}{R}$ K | SIG 1 MPa |
|------|------|------|------|------|------|------|------|------|------|
| 1312 (test 1) | 254 | $5.56 \cdot 10^{-6}$ | 1.722 | $6.083 \cdot 10^{+9}$ | 7.808 | $1.383 \cdot 10^{+23}$ | 0.0578 | 55 800 | 108 |
| 1312 (test 2) | 263 | $2.66 \cdot 10^{-7}$ | 2.248 | $8.95 \cdot 10^{+8}$ | 7.644 | $5 \cdot 10^{+21}$ | 0.0601 | 53 900 | 108 |
| 1411 (Thor) | 340 | $3.52 \cdot 10^{-7}$ | 2.08 | $6.767 \cdot 10^{+12}$ | 8.402 | $4.417 \cdot 10^{+27}$ | 0.0603 | 66 000 | 118 |
| A36-66 | 304 | $4.07 \cdot 10^{-6}$ | 1.75 | $6.217 \cdot 10^{+6}$ | 4.70 | $2 \cdot 10^{+14}$ | 0.0434 | 38 900 | 103 |
| 2172 | 331 | $2.085 \cdot 10^{-8}$ | 2.30 | $1.33 \cdot 10^{+10}$ | 5.38 | $1.083 \cdot 10^{+19}$ | 0.0446 | 50 000 | 108 |
| G40-12 | 333 | $1.766 \cdot 10^{-7}$ | 1.00 | $4.733 \cdot 10^{+7}$ | 3.25 | $6.17 \cdot 10^{+12}$ | 0.0319 | 36 100 | 103 |
| A421-65 | 1470 | $9.262 \cdot 10^{-5}$ | 0.67 | $3.253 \cdot 10^{+6}$ | 3.0 | $1.368 \cdot 10^{+12}$ | 0.0145 | 30 600 | 172 |
| Ks 40 Ø 10 | 483 | $28.5 \cdot 10^{-9}$ | 1.037 | $1.16 \cdot 10^{+9}$ | 4.7 | $4.3 \cdot 10^{+16}$ | 0.0443 | 45 000 | 84 |
| Ks 40 Ø 8 | 456 | $3.39 \cdot 10^{-7}$ | 0.531 | $7.6 \cdot 10^{+5}$ | 4.72 | $1.25 \cdot 10^{+13}$ | 0.0512 | 40 000 | 90 |
| Ks 40 Ø 8 | 504 | $19.9 \cdot 10^{-6}$ | 1.28 | $4.05 \cdot 10^{+4}$ | 7.26 | $5.0 \cdot 10^{+17}$ | 0.0384 | 47 000 | 120 |
| Ks 40 SE Ø 8 | 558 | $38.6 \cdot 10^{-9}$ | 1.117 | $5.8 \cdot 10^{+7}$ | 3.83 | $4.133 \cdot 10^{+13}$ | 0.0414 | 40 000 | 96 |
| Ks 60 Ø 8 | 710 | $2.06 \cdot 10^{-6}$ | 0.439 | $5.111 \cdot 10^{+7}$ | 2.93 | $2.65 \cdot 10^{+14}$ | 0.0313 | 40 000 | 90 |
| Ps 50 Ø 5 | 500 | $1.10 \cdot 10^{-6}$ | 0.557 | $9.738 \cdot 10^{+6}$ | 4.47 | $2.133 \cdot 10^{+15}$ | 0.0368 | 40 000 | 100 |
| Ps 50 Ø 8 | 749 | $1.28 \cdot 10^{-7}$ | 0.844 | $1.367 \cdot 10^{+8}$ | 3.94 | $1.02 \cdot 10^{+15}$ | | 41 000 | 133 |

(1) — rows 1312 (test 1) through G40-12
(2) — A421-65
(3) — Ks 40 Ø 10 through Ps 50 Ø 8
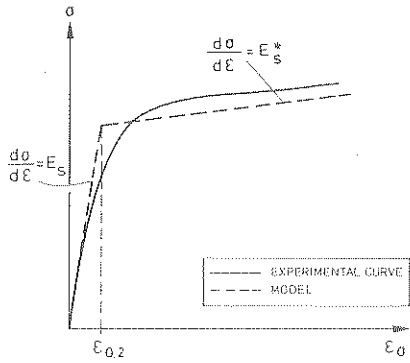
Fig 20    Simplified model of the stress-strain curve for steel
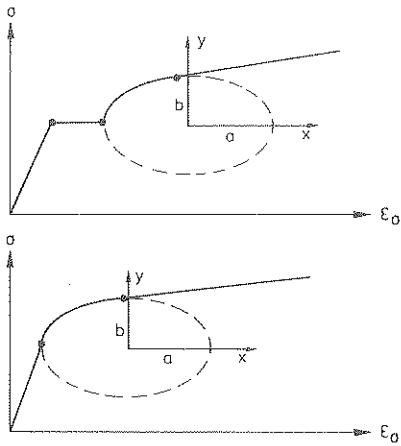


Fig 21    Refined model of the stress-strain curve for steel
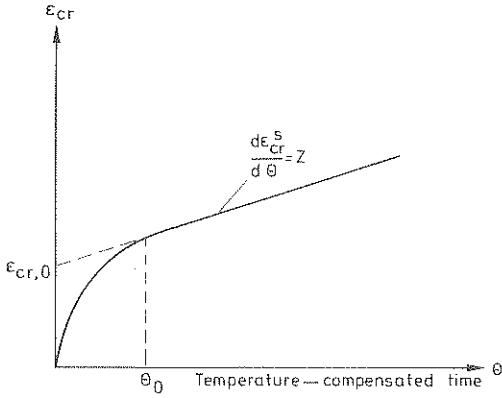
Fig 22   Principal creep curve for steel according to Dorn's theory
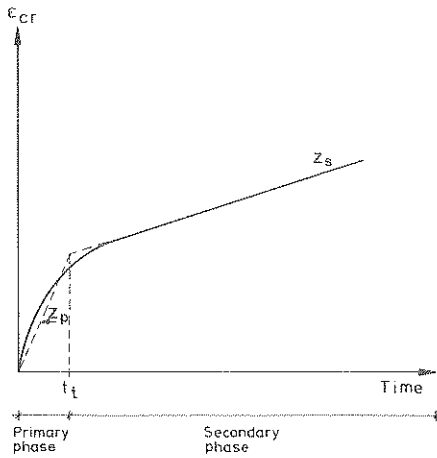


Fig 23   Measured creep curve approximated by two straight branches with slopes $Z_p$ and $Z_s$

Fig 24   Nomogram for rate of creep

a) Primary phase
b) Secondary phase
c) Transition between primary and secondary phase
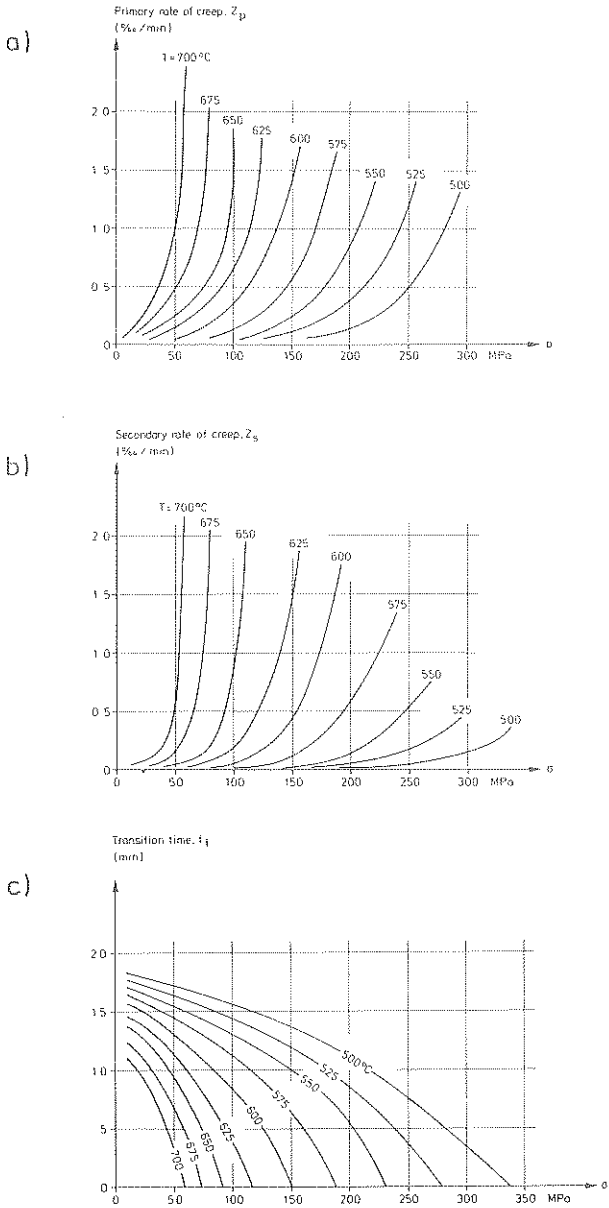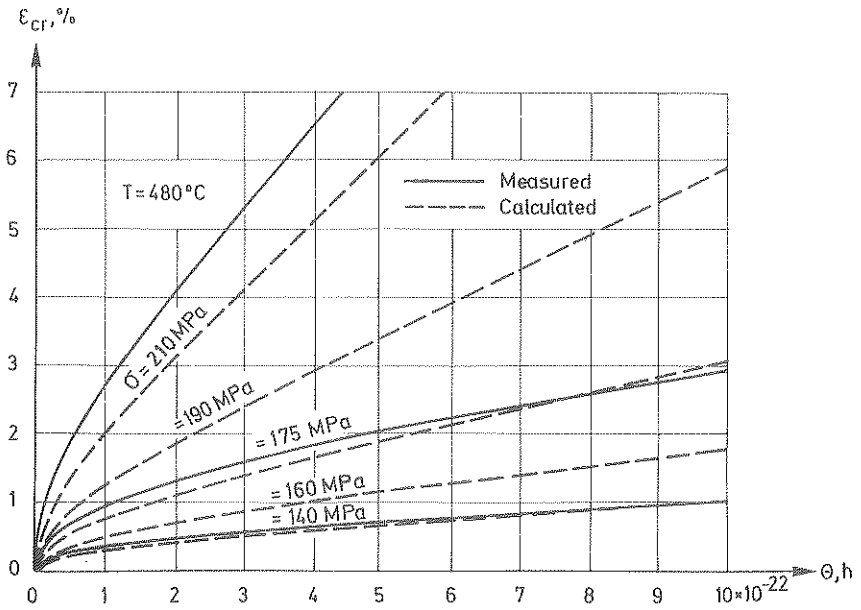
Fig 25  Measured and predicted creep (Dorn-Harmathy theory) at different stress levels. Structural steel ASTM A36, $f_{0.2,20°C}$ = 300 MPa, Harmathy (1967)
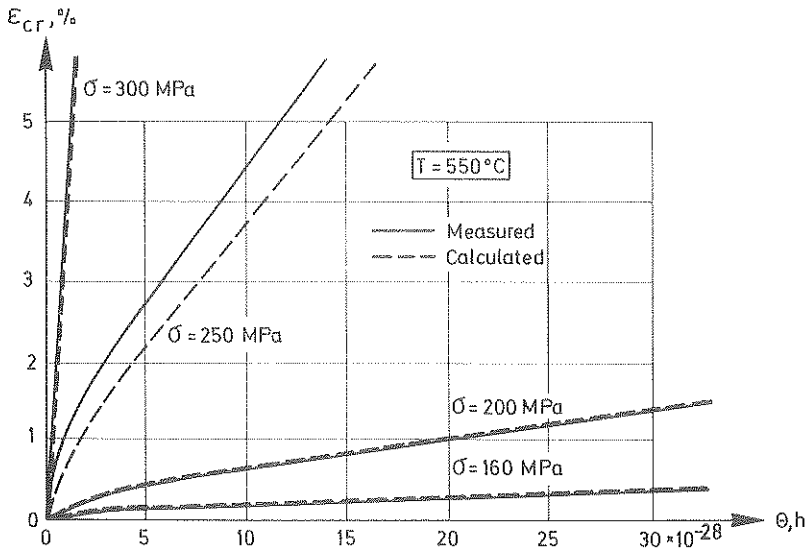


Fig 26  Measured and predicted creep (Dorn-Harmathy theory) at different stress levels. Structural steel SIS 142172, $f_{0.2,20°C}$ = 340 MPa, Thor (1972)
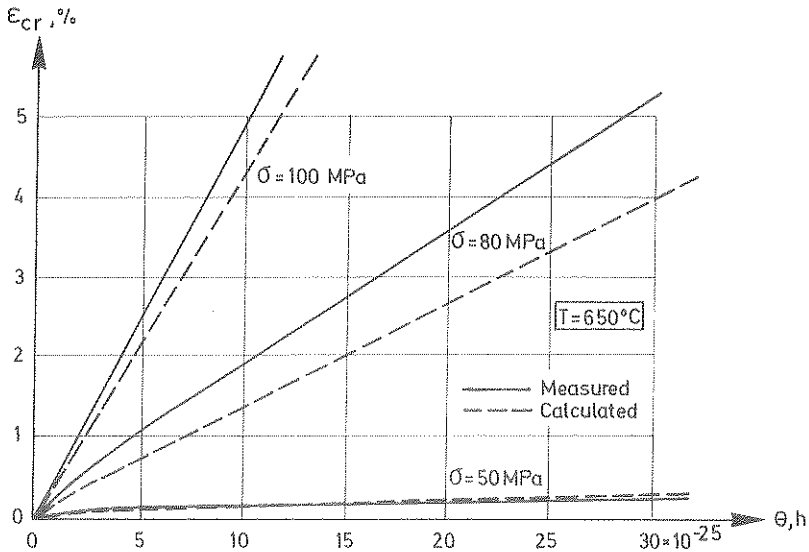
Fig 27  Measured and predicted creep (Dorn-Harmathy theory)
at different stress levels. Structural steel SIS
142172, $f_{0.2,20^{\circ}C}$ = 340 MPa, Thor (1972)
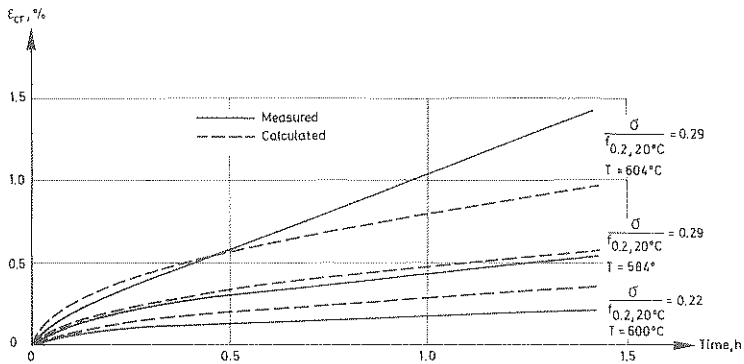


Fig 28  Measured and predicted creep (modified Dorn-Harmathy
theory) at different stress levels. Reinforcing steel
Ks 40 Ø8, $f_{0.2,20^{\circ}C}$ = 456 MPa, Anderberg (1978)
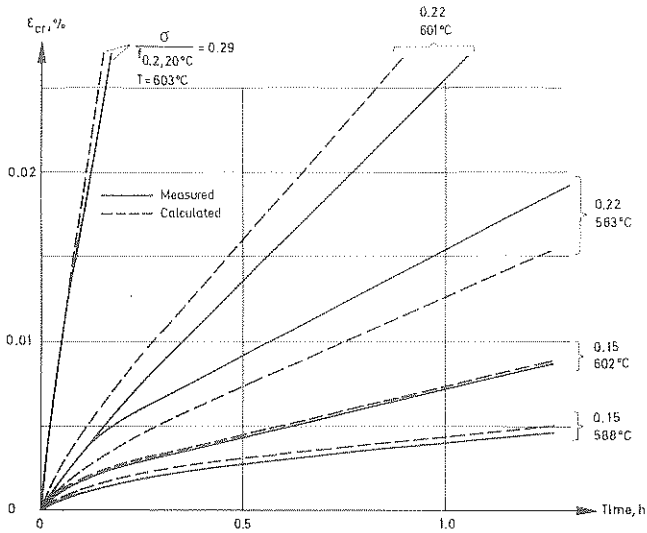
Fig 29   Measured and predicted creep (modified Dorn-Harmathy
         theory) at different stress levels. Reinforcing steel
         Ks 60 Ø8, $f_{0.2,20^\circ C}$ = 710 MPa, Anderberg (1978)
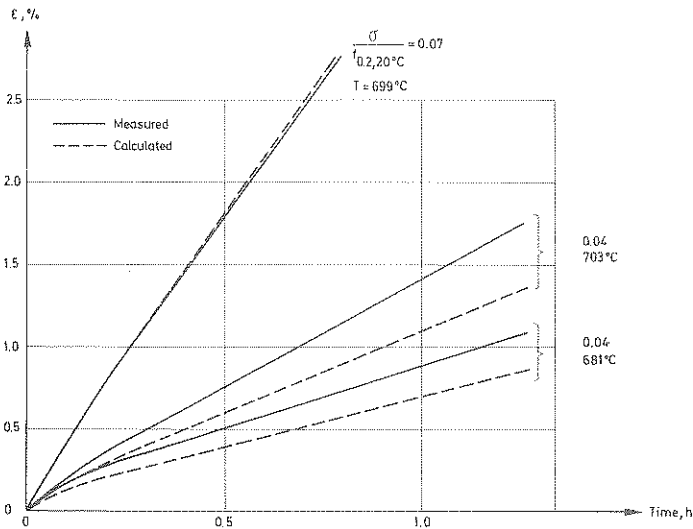


Fig 30   Measured and predicted creep (modified Dorn-Harmathy
         theory) at different stress levels. Reinforcing steel
         Ks 60 Ø8, $f_{0.2,20^\circ C}$ = 710 MPa, Anderberg (1978)
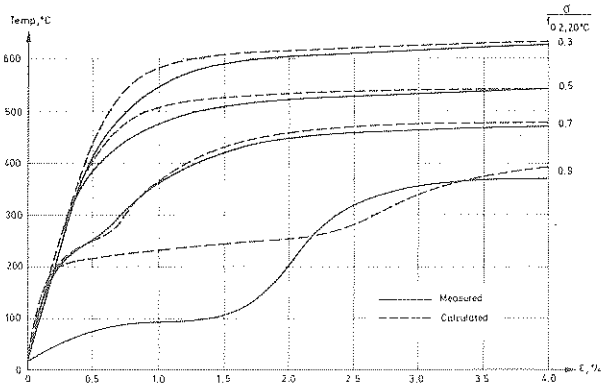
Fig 31   Measured and predicted total deformation as a func-
         tion of temperature at different load levels in a
         transient process, $\dot{T} = 10^{O}$C/min. Reinforcing steel
         Ks 60 Ø8, $f_{0.2,20^{O}C}$ = 710 MPa, Anderberg (1978)
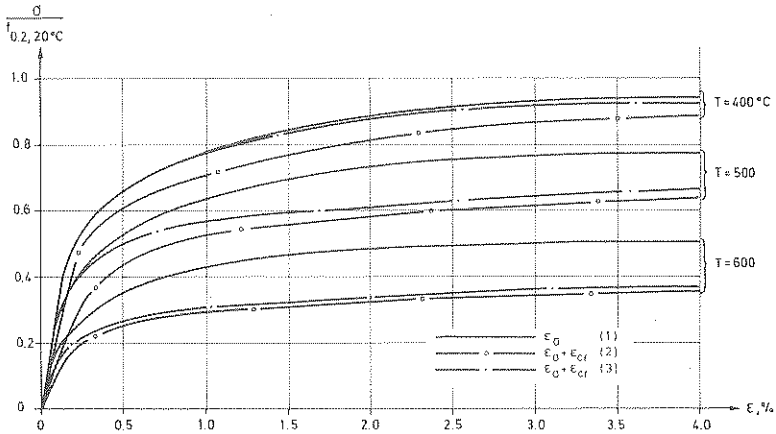


Fig 32   Measured and predicted $\sigma$-$\varepsilon$ curves from steady state
         and transient state tests.

         1. Steady state test, stress-controlled, $\dot{\sigma}$=3.5 MPa/s

         2. Transient state test, constructed curve, $\dot{T}$=10$^{O}$C/min

         3. Transient process, curve derived analytically,
            $\dot{T}$=10$^{O}$C/min
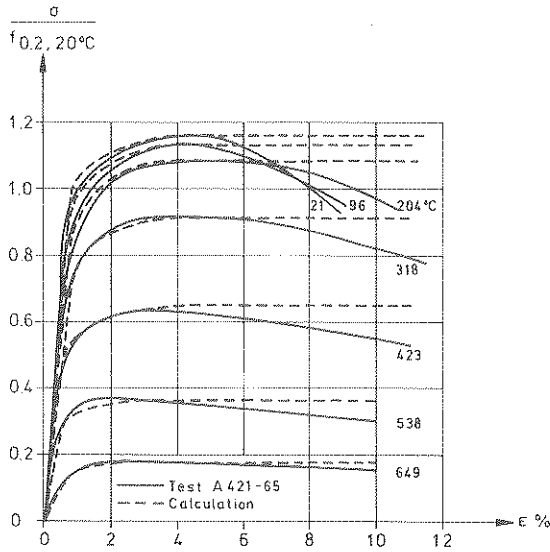
Fig 33    Measured and predicted σ-ε curves from strain
          controlled steady state tests on prestressing
          steel ($\dot{\varepsilon} = 700 \cdot 10^{-3} \cdot min^{-1}$).
          Anderberg (1983)
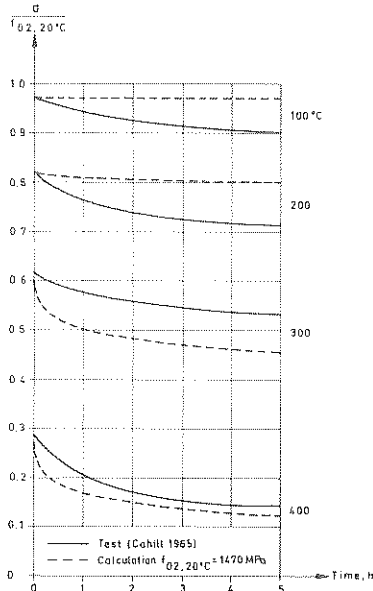


Fig 34    Measured and predicted relaxation curves for pre-
          stressing steel.
          Calculation is based on creep data of A421-65, pub-
          lished in Harmathy 1967.
          Anderberg (1983)

5.3 How to compare results obtained at different test proce-
dures

Analytical modelling opens up the possiblity of relating steady
state and transient state tests. For instance, the strain or
stress rate can be determined in steady state tests to give
the same ultimate strength as occurs in a transient test for
a given rate of heating.

The predicted influence of stress and strain rates on the stress-
strain relationship under steady state conditions can be studied
in Figs 35-37. From such curves the ultimate strength as a func-
tion of temperature can be evaluated (Figs 38-41). In Fig 40 a-
b, the influence of stress and strain rates on the ultimate
strength under steady state conditions is illustrated. The in-
fluence of rate of temperature under transient state conditions
is given in Fig 40 c. The ultimate strength is defined by the
stress at which the strain is 4%, the thermal strain excluded.

In the analytical modelling (Anderberg 1983) the strain and
stress rate in a steady state procedure to give the same ulti-
mate strength as under transient state conditions is found,
if the rate of heating is chosen to $10^{\circ}$C/min. The result is
shown in Fig 40 d  for a specific reinforcing steel (Ks 60,
$f_{0.2,20^{\circ}C}$ = 710 MPa). The strain and stress rates obtained by
computation are thus

$$\dot{\varepsilon} = 20\%/min$$
and
$$\dot{\sigma} = 0.20 \text{ MPa/s} = 12 \text{ MPa/min}$$

These values presented here vary somewhat depending on the
type of steel, which is shown in Table 5.3.1 for

a) structural steel 1411, $f_{0.2,20^{\circ}C}$ = 340 MPa
b) hot-rolled reinforcing steel Ks 40, $f_{0.2,20^{\circ}C}$ = 456 MPa
c) hot-rolled reinforcing steel Ks 60, $f_{0.2,20^{\circ}C}$ = 710 MPa
d) prestressing steel ASTM A 421-65, $f_{0.2,20^{\circ}C}$ = 1470 Mpa

Table 5.3.1   (Anderberg 1983)

| Type of steel | $\dot{T}$ °C/min | $\dot{\sigma}$ MPa/s | $\dot{\varepsilon}$ ‰/min |
|---|---|---|---|
| Steel 1411 | 10 | 0.20 | 10 |
| Ks 40 | 10 | 0.20 | 10 |
| Ks 60 | 10 | 0.20 | 20 |
| ASTM A 421-65 | 10 | 0.50 | 10 |

For the additional steels in Table 5.3.1 the results of compu-
tation are given in Figs 38-39, 41.

If the strength-temperature curve, based on the transient state
condition where for instance $\dot{T} = 10$°C/min is accepted as a re-
ference curve, test results can be directly interpreted and,
thus, comparable. If the rates $\dot{\varepsilon}$ and $\dot{\sigma}$ are below the values
mentioned above, the measured ultimate strength should be cor-
rected upwards. If one has the opposite situation the strength
values are corrected downwards.

The rate of stress or strain in a steady state test and the
rate of temperature in a transient test are governing the de-
velopment of creep which causes the change in the ultimate
strength. The influence of creep for three different procedures
is also fully illustrated in Figs 35-41. It is also important
to observe that there is a great difference between the time
history of creep development in a stress and strain controlled
steady state test. This is principally illustrated in Fig 42,
where curve 1 represents a stress-strain curve at a very high
stress or strain rate and curve 2 and 2' represent a curve at
a slow stress and strain rate, respectively. The points A and
A' indicate the time at which creep starts to be significant
and point B is the assumed failure point ($\varepsilon = 4$%). In the stress
controlled test the time to reach point A is about 50% of the
total testing period but in the strain controlled test the cor-
responding time is only about 15%. If a test is carried out at
600°C at the stress rate $\dot{\sigma} = 12$ MPa/min and at the strain rate
$\dot{\varepsilon} = 20$‰/min the testing period amounts to 22 and 2 min, respec-
tively. Although these differences exist, the creep influence
on the ultimate strength is the same. In the corresponding
transient test this period is about 58 min. This means that
the testing period is not a critical parameter in the analyti-
cal study by rather the time period of the test when creep de-
velops.
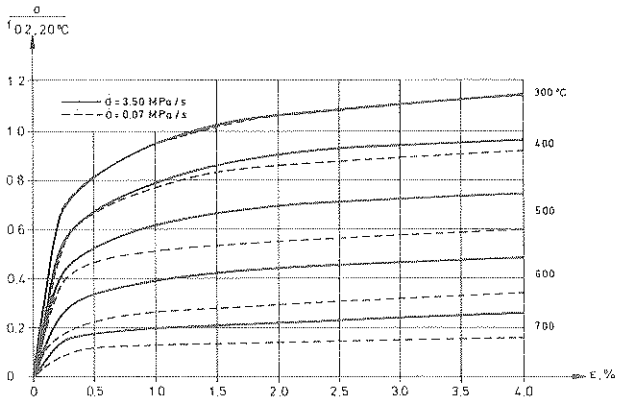
Fig 35 Predicted σ-ε curves at different stress rates for reinforcing steel (Ks 60, $f_{0.2,20^{\circ}C}$ = 710 MPa). Anderberg (1983)
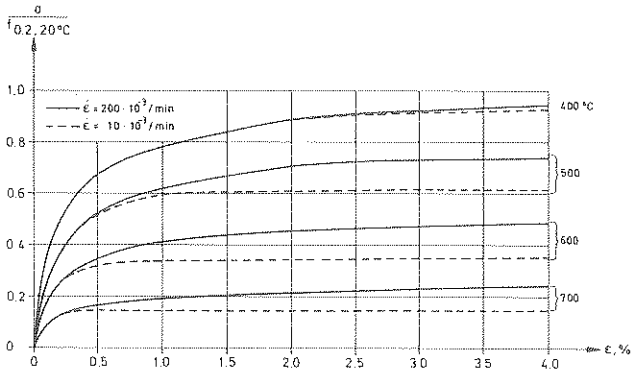


Fig 36 Predicted σ-ε curves att different strain rates for reinforcing steel (Ks 60, $f_{0.2,20^{\circ}C}$ = 710 MPa). Anderberg (1983)
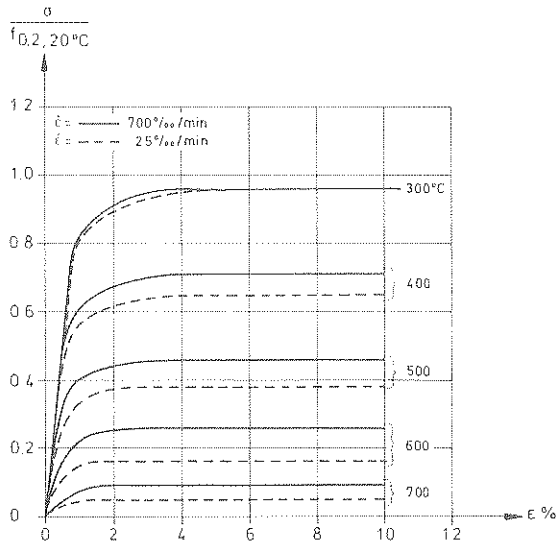
Fig 37    Predicted σ-ε curves at  different strain rates for
          prestressing steel (A 421-65, $f_{0.2,20^{\circ}C}$ = 1470 MPa).
          Anderberg (1983)
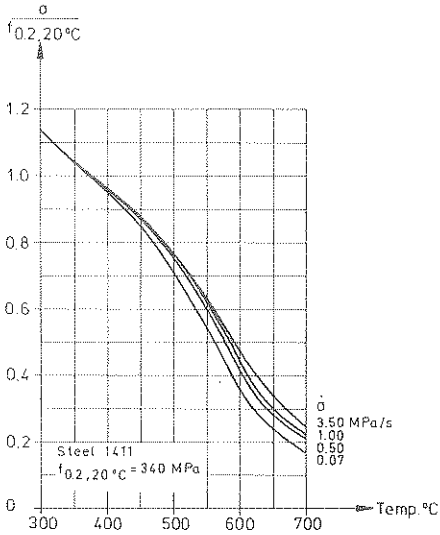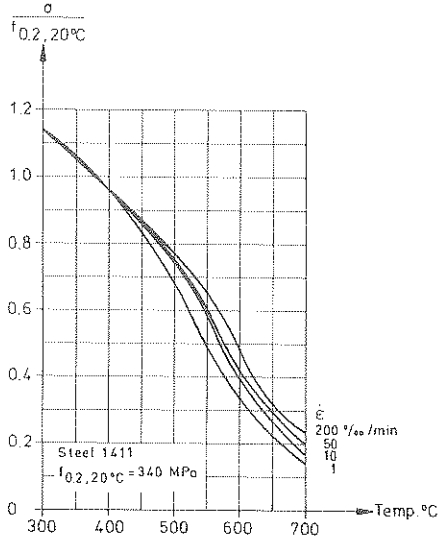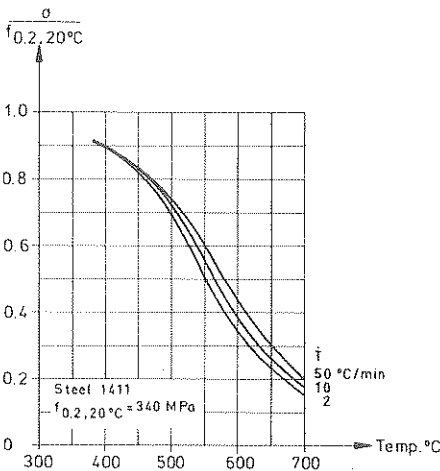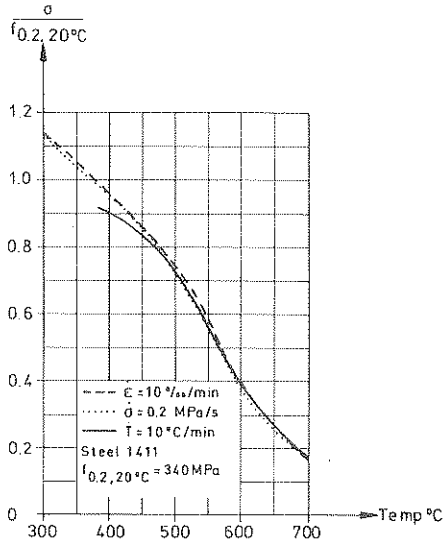
Fig 38   Predicted ultimate strength versus temperature for
         structural steel.

         a) Steady state, stress rate controlled
         b) Steady state, strain rate controlled
         c) Transient state
         d) Comparison between steady state and transient state
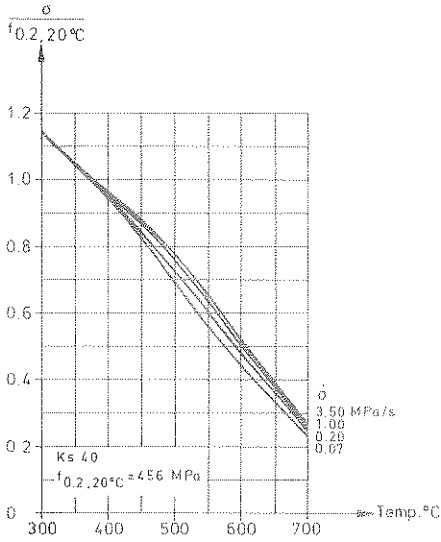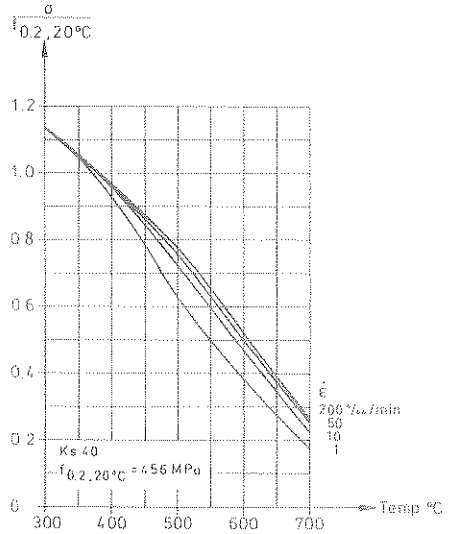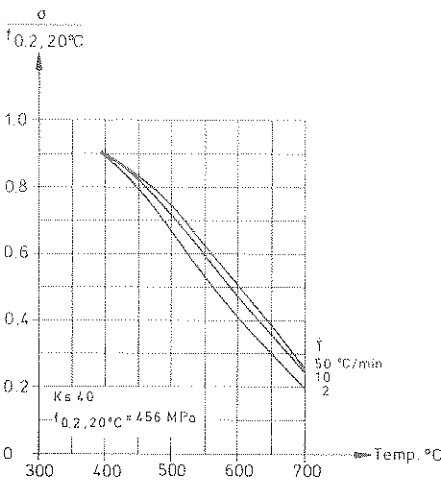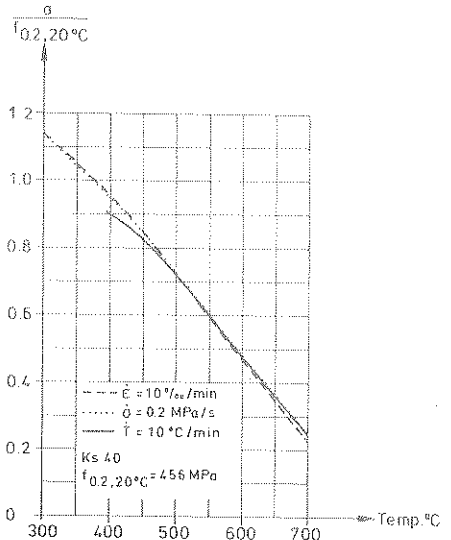
Fig 39    Predicted ultimate strength versus temperature for
          reinforcing steel.

          a) Steady state, stress rate controlled
          b) Steady state, strain rate controlled
          c) Transient state
          d) Comparison between steady state and transient state
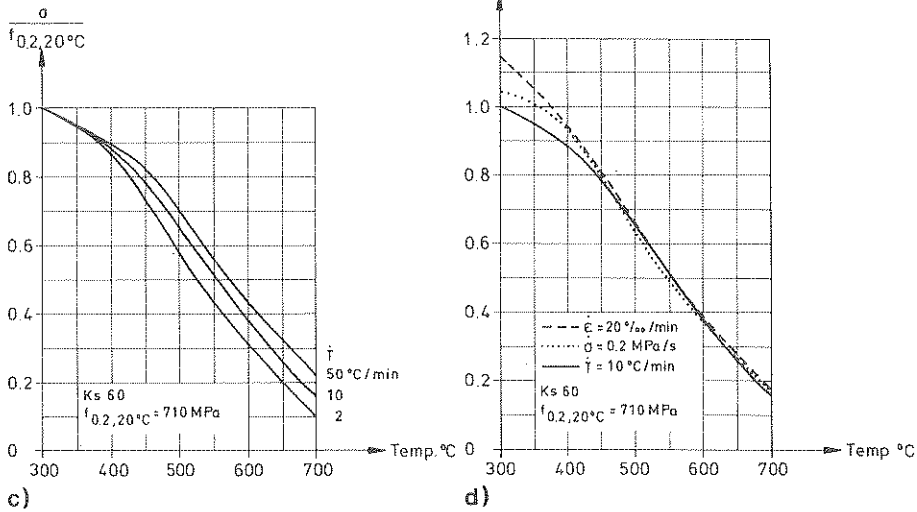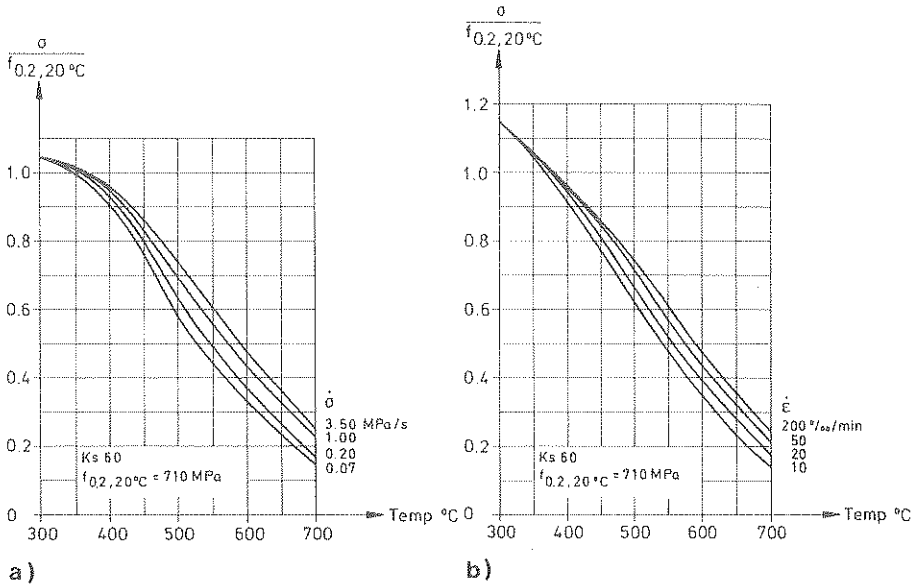
Fig 40    Predicted ultimate strength versus temperature for
          reinforcing steel.

          a) Steady state, stress controlled

          b) Steady state, strain controlled

          c) Transient state

          d) Comparison between steady state and transient state
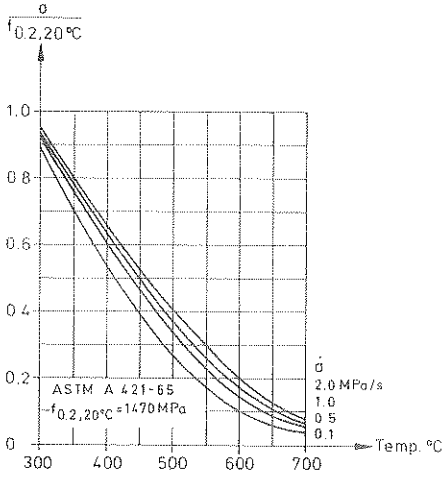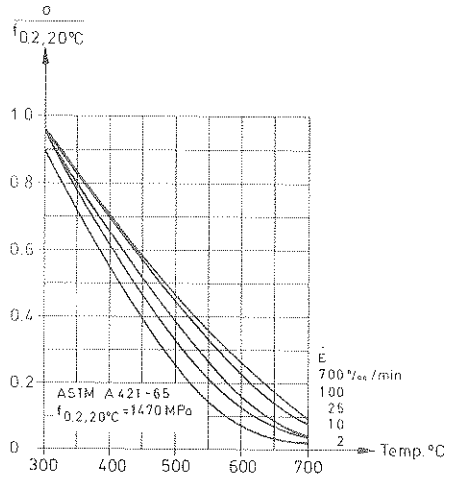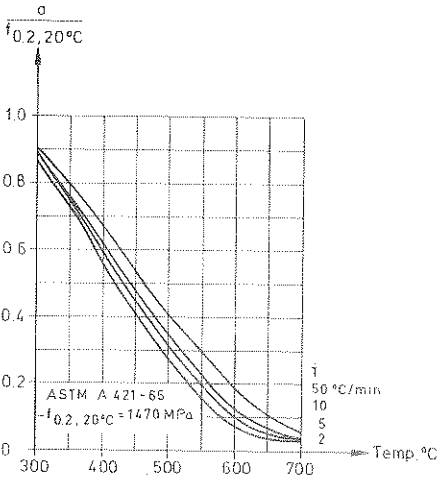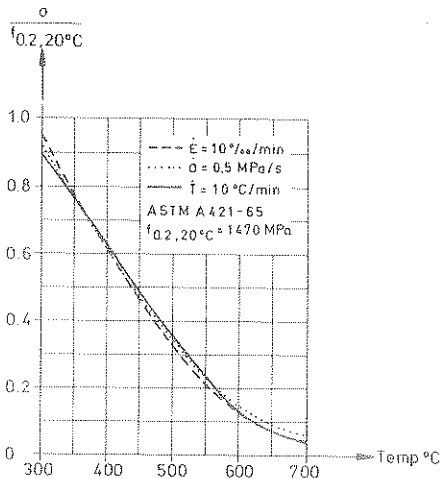
Fig 41  Predicted ultimate strength versus temperature for
        prestressing steel.

        a) Steady state, stress rate controlled
        b) Steady state, strain rate controlled
        c) Transient state
        d) Comparison between steady state and transient state
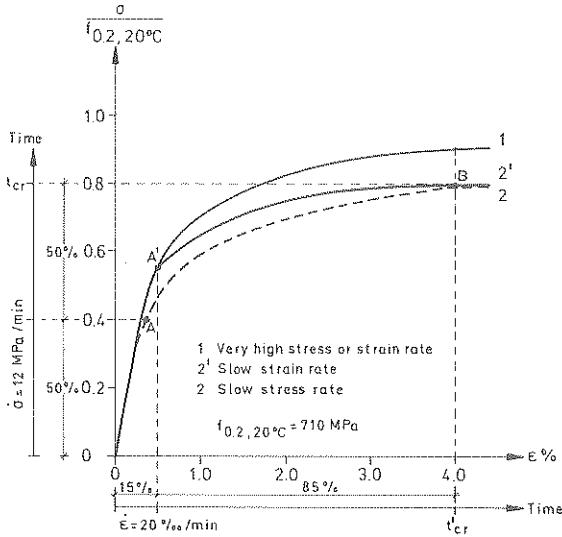
Fig 42   Principal σ-ε curves in stress and strain rate
         controlled steady state tests with time
         scales indicated (t'$_{cr}$ and t$_{cr}$ represent the
         testing period).

Part III: STEEL LITERATURE

6  References

6.1  Particular properties

6.1.1  General properties
6.1.2  Tensile strength
6.1.3  Modulus of elasticity
6.1.4  Thermal strain
6.1.5  Creep strain
6.1.6  Stress-strain characteristics
       6.1 Steady state tests
       6.2 Transient tests
6.1.7  Compressive strength
6.1.8  Relaxation
6.1.9  Thermal properties
6.1.10 Residual properties after cooling


6.2  Structural behaviour


6.3  Analytical models

6.3.1  Material
6.3.2  Structures


Subheadings

a) Structural steel
b) Reinforcing steel
c) Prestressing steel
d) Cast iron
e) Insulation material for steel protection

6.1    PARTICULAR PROPERTIES

6.1.1. General properties                              Additional
    a) Structural steel                                headings


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6.1.    PARTICULAR PROPERTIES

6.1.2. Tensile strength

a) Structural steel

Additional
headings

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6.1.2. Tensile strength

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6.1.2. Tensile strength

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6.1.    PARTICULAR PROPERTIES

6.1.3. Modulus of elasticity

    b) Reinforcing steel

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    c) Prestressing steel

       Reichel, V. - see 6.1.1c.

       Ruge, J., Winkelmann, O. - see 6.1.1a.

6.1.    PARTICULAR PROPERTIES

6.1.4. Thermal strain

    a) Structural steel

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        Skinner, D.H. - see 6.1.1a.

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    b) Reinforcing steel

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6.1.   PARTICULAR PROPERTIES

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6.1.    PARTICULAR PROPERTIES

6.1.6. Stress-strain characteristics

6.1.6.1 Steady state tests

   a) Structural steel

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6.1.    PARTICULAR PROPERTIES

6.1.6. Stress-strain characteristics

6.1.6.1 Steady state tests

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6.1.    PARTICULAR PROPERTIES

6.1.6. Stress-strain characteristics

6.1.6.2 Transient tests

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6.1.    PARTICULAR PROPERTIES

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6.1.    PARTICULAR PROPERTIES

6.1.10. Residual strength

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6.1.    PARTICULAR PROPERTIES

6.1.10. Residual strength

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6.3.    ANALYTICAL MODELS

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## 7    Symbols and abbreviations

$c_p$    specific heat    $kJ/kg\,^{\circ}C$

$I$    specific volumetric enthalpy    $MJ/m^3$

$\lambda$    thermal conductivity    $W/m\,^{\circ}C$

$E_{20\,^{\circ}C}$    modulus of elasticity at room temperature

$E_T$                          $-"-$          temperature T

$f_{0.2,20\,^{\circ}C}$    0.2 % proof stress at room temperature

$f_{0.2,T}$                          $-"-$          temperature T

$f_{u,20\,^{\circ}C}$    ultimate strength at room temperature

$f_{u,T}$                          $-"-$          temperature T

$t$    time    (h, s)

$T$    temperature    $^{\circ}C$

$\dot{T}$    rate of heating    $^{\circ}C/min$

$\varepsilon$    strain

$\dot{\varepsilon}$    rate of strain    $s^{-1}$

$\varepsilon_{th}$    thermal strain

$\varepsilon_{\sigma}$    stress-related strain

$\varepsilon_{ct}$    creep strain

$\sigma$    stress    MPa

$\dot{\sigma}$    rate of stress    MPa/s