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Creep Buckling of Steel Column at Elevated Temperatures

Flambage par fluage d'un poteau en acier aux températures élevées

Kriechknicken von Stahlstützen bei hohen Temperaturen

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1. INTRODUCTION

The buckling strength of a steel column may be considerably reduced due to exposure to elevated temperatures during a fire. This reduction is now taken into account by use of a chart where the buckling stress for the steel material is plotted versus the slenderness ratio for each temperature considered [1]. Such curves have been obtained by introducing in conventional room-temperature buckling formulas the mechanical properties determined from standard material tests at the various temperatures. There is a large variation between curves for temperatures exceeding 500°C published by different authors. The reason is probably that the creep rate of ordinary structural carbon steels increases rapidly at this temperature. The material tests rather arbitrarily include creep during the time taken to increase the load to ultimate failure. During a fire the column is usually subjected to constant load during the whole heating period implying a larger creep deformation. Furthermore, creep buckling has a non-linear course, rendering the present design procedure an unconservative approximation.

In order to establish the basis of a more reliable method, including the time parameter, for determining the collapse load of a column in a fire, a study has been made of a hinged steel column of I-section with an initial deflection, subjected to elevated temperatures, mainly 600°C but also 550 and 650°C. Material creep tests were carried out at 600°C, the results being extrapolated to other temperatures by use of the Dorn-theory. Creep constants were determined and introduced into a computer programme providing the creep life at given constant stress and temperature. By performing a large number of such calculations at different stress levels a diagram was obtained giving the buckling stress versus the slenderness ratio for various times of exposure to the temperature considered. The computer programme was also modified to allow a realistic variation of temperature history and computations were run to determine the critical stresses corresponding to maximum temperatures of 600 and 650°C.

2. CREEP LAW AND CREEP TESTS

Standard creep tests are performed on material coupons at constant load and temperature, giving a relationship between strain ε and time t.

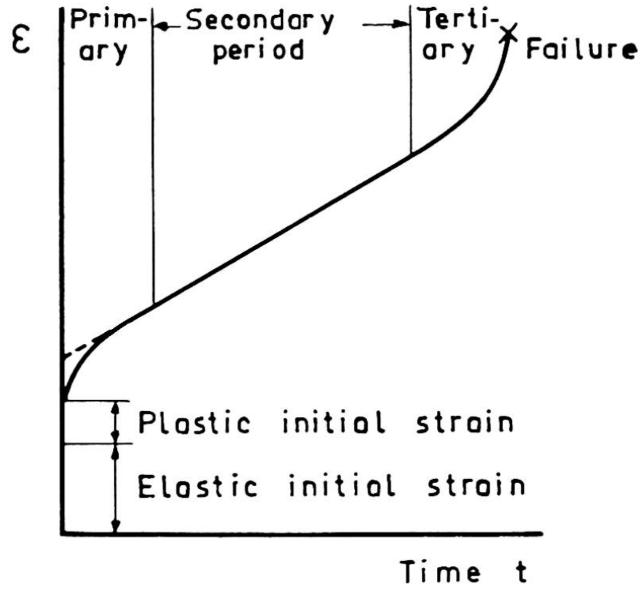

Fig 1

Creep curve for metal at constant load and constant temperature

A creep curve typical for metals at elevated temperatures, Fig 1, includes three phases of which the secondary creep is dominating. In modern metal creep research the creep law of Norton-Odqvist is normally used

$$d\varepsilon/dt = \dot{\varepsilon} = k\sigma^n \tag{1}$$

where σ is the constant stress and k and n are creep constants belonging to the temperature applied. It was found by Dorn that the creep rate $\dot{\varepsilon}$ may be determined for other elevated temperatures by introducing a temperature compensated time parameter

$$\theta = \int_0^t \exp(-\Delta H/RT)dt \tag{2}$$

where ΔH and R are constants and T the temperature in $^{\circ}$K. Harmathy [2] carried out several creep tests and established a generalized creep curve, based on Dorn's theory, for ASTM A36 steel valid for temperatures of 400-700°C. Results of creep tests within the same temperature range have also been published by Thor[3].

To obtain creep data for calculations of critical times to buckling, creep tests were run in tension at 600°C with four constant stress levels σ = 30, 40, 50 and 60 MPa. The material coupons were made of a carbon steel with yield strength 300 MPa and ultimate strength 460 MPa, i.e. rather similar to A36. The creep rates determined gave the creep constants

$k = 1.88 \times 10^{-11}$ $\quad n = 4.9$

For other temperatures the Dorn theory was used to obtain creep rates, introducing $(\Delta H/R) = 39000$ $^{\circ}$K as found by Harmathy for A36. This gives a constant value of n for all temperatures, while

$$k = 1.88 \times 10^{-11} \exp(44.7 - 39000/T) \tag{3}$$

3. THEORY OF CREEP BUCKLING

In a column having an initial maximum deviation w_o from a straight line and subjected to an axial load P with an excentricity a, Fig 2,

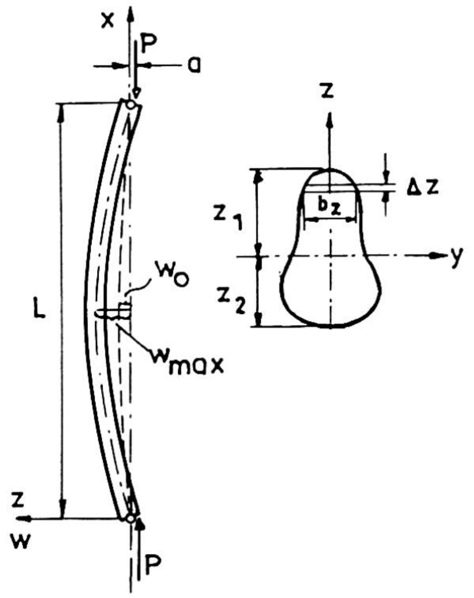

Fig 2 Initially curved column hinged in both ends, with cross-section of single symmetry and eccentric axial load P

a bending moment will occur increasing the deflection to w_{max}. If the load is much smaller than the short-time buckling load, and no bending out of the xz-plane can take place, the increase is rather small but if the load is kept constant and creep sets in, the deflection increases with time. The creep strain rate at a distance z from the CG-axis of a section, Fig 2, may be written

$$\dot{\epsilon}_x = \dot{\sigma}_x/E_o + k\sigma_x^{\,n} \qquad (4)$$

where σ_x is the compression stress which is continuously growing with increasing deflection. E_o is a modulus taking elastic and plastic deformation, and possibly also primary creep, into account. The second term represents the secondary creep. A constant n considerably larger than one will obviously cause a fast acceleration of the deflection w_{max} with growing stress.

Creep buckling theories and approximate solutions of the creep buckling life t_k for metal struts were first published by Hoff and Hult. Closed solutions for more general cases present considerable mathematical difficulties. Samuelson [4] developed a computer programme for a hinged column of singly symmetrical constant section subjected to constant load and temperature. The cross section was divided into thin layers of thickness Δz and width b_z, while the length L was split up into elements Δx and time into intervals Δt. This programme was used for evaluating the critical time for different loads on a column with varying slenderness ratios, and also modified to allow a variation of the temperature between time intervals.

4. DISCUSSION OF COMPUTED CREEP LIVES

The numerical analysis was carried out for a column section HE240B, Fig 3, assuming no excentricity, but an initial deviation according to Dutheil

$$w_o = 4.8 \times 10^{-5}\, L^2/d = 4.8 \times 10^{-5} L^2/0.12 = 4 \times 10^{-4}\, L^2$$

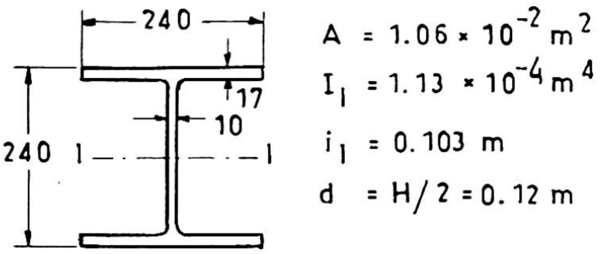

Fig 3

Column section HE 240B used in computations

The modulus of elasticity E_o of Eq(4) was determinad from a formula proposed by Thor [3].

$$E_o = 325000 - 404\ \vartheta_s \text{ MPa} \tag{5}$$

The creep buckling was defined as the moment when w_{max} exceeded twice the height of the section in the buckling direction giving a very high creep rate. Critical creep times at 600°C were determined for columns of four different lengths L = 3, 4.5, 6 and 9 m, yielding slenderness ratios $\lambda = L/i_1 = 30, 45, 60$ and 90. A number of different mean stresses were treated for each column length. The results of the computations are presented in Fig 4, where the creep buckling time is plotted versus the compression stress of the column for each slenderness ratio. Creep lives were also obtained for the steel temperatures ϑ_s = 550 and 650°C, assuming in both cases $\lambda = 45$, while σ was 70 and 35 MPa respectively. These results are entered into Fig 4 as isolated

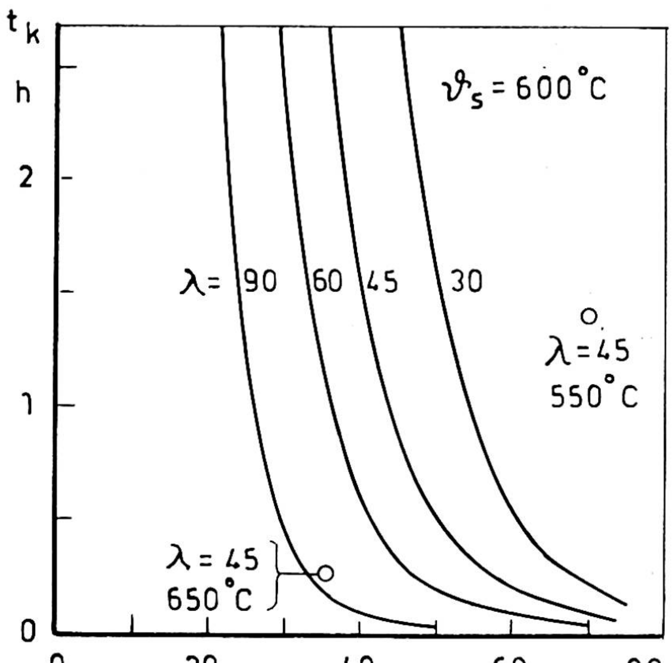

Fig 4

Creep buckling time versus compression stress for various slenderness ratios at 600°C

points which indicate that a rise in temperature of 50°C corresponds to a shortening of life by a factor of 10, or a decrease in stress by about 40 per cent.

The curves of Fig 4 are replotted in Fig 5, giving the buckling stress versus the slenderness ratio for exposures to 600°C from 0.2 to 2 h. The buckling curves presented by Kawagoe-Saito [1a] and Sfintesco [1b] are introduced for comparison. While the former is extremely conservative, corresponding to several hours of heat exposure, the latter seems to be

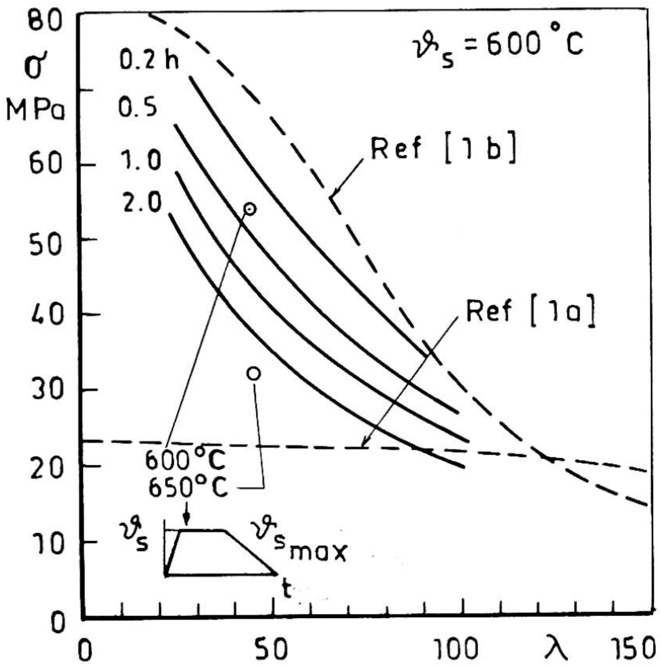

Fig 5

Buckling stress versus slenderness ratio for various times of exposure to 600°C

unsafe even for a few minutes of 600°C.

In a fire the temperature of the steel structure is normally gradually rised from room temperature to a maximum determined e.g. by the fire load, after which the cooling starts. A temperature-time history according to Fig 6 was introduced in the computer programme assuming $\vartheta_{s\ max} = 600$

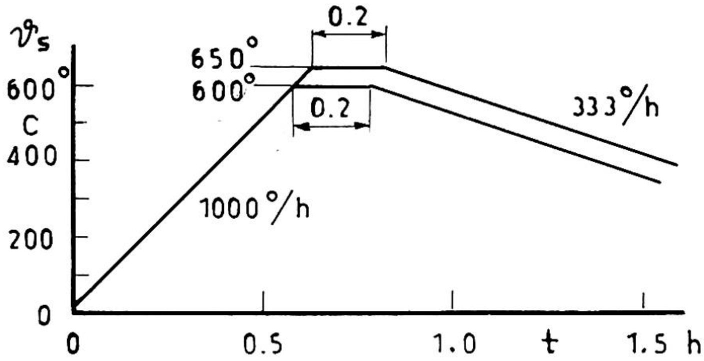

Fig 6

Temperature-time history introduced into computer programme

and 650°C. Using the same column section as before, the slenderness ratio $\lambda = 45$, the stress was varied to allow interpolation of the value just causing collapse during a temperature cycle. These stresses are also plotted in the diagram, Fig 5.

Although it may be objected that still a number of factors remain to be considered in a realistic analysis of the behaviour of a steel column during fire, the results of the calculations clearly show that an analysis of creep buckling is worth-while.

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SUMMARY

The creep buckling life of a steel column is determined by feeding data from standard creep tests into a computer programme. It is shown that the effect of creep on the buckling strength is very important at temperatures around 600 °C.

RESUME

L'évolution du flambage par fluage d'un poteau en acier est déterminé au moyen d'un calcul numérique, dans lequel on introduit les résultats des essais de fluage standard. Il est montré que l'influence du fluage est très important aux températures de 600 °C environ.

ZUSAMMENFASSUNG

Die Belastungsdauer einer Stahlsäule bis zum Kriechknicken wird durch ein numerisches Programm bestimmt, wobei man Dehnungsmessungen von Standardkriechversuchen benutzt. Es wird gezeigt, dass dem Kriechen bei Temperaturen um 600 °C grosse Bedeutung zukommt.