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Objekttyp: **Article**

Zeitschrift: **IABSE reports of the working commissions = Rapports des commissions de travail AIPC = IVBH Berichte der Arbeitskommissionen**

Band (Jahr): **21 (1975)**

PDF erstellt am: **09.08.2024**

Persistenter Link: https://doi.org/10.5169/seals-18796

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IV

Predicting the Performance of Steel Members during Fire Conditions

Résistance au feu des éléments métalliques

Verhalten von Stahlträgern unter Brandeinwirkung

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1. INTRODUCTION

In 1968 the Melbourne Research Laboratories of the Australian steel company, The Broken Hill Proprietary Co. Ltd became interested in the performance of steel buildings in fire. It came as a shock to discover that little was known of how plain steel will behave in a fire.

Within this paper, only structural performance under fire conditions will be discussed. The reader is referred to other publications (Refs 1, 2, 3, 5, 6, 11 and 12) for a consistent treatment of other important aspects of fire technology which must be known in order to analyse a structure in a fire. Some of the important aspects are (Ref. 1):

(1) Fire conditions within a building (Refs 1, 10, 11).
(2) Thermal history of the complete building components (Refs 3, 5).
(3) Thermal properties of the elements in the building (Refs 6, 7, 8, 9).

2. NOTATION

D = depth of beam
E = Young's modulus
L = length of beam
ΔL = change in length of beam
n = stress ratio (stress divided by room temperature yield stress)
$R_1 - R_8$ = equation constants
T_o = initial ambient temperature
t = time
Δt = increment of time
t_K = time defining end of thermally stable range
ε = strain
$\dot{\varepsilon}$ = strain rate

ε_{TE} = strain due to thermal expansion
σ_{YT} or F_{YT} = yield stress values at temperature T
F_{YTO} = room temperature F_{YT}

3. MECHANICAL PROPERTIES

As the temperature of a member is changed, a number of material factors become important. Firstly, additional strains arise due to thermal expansion. Secondly, Young's modulus varies causing changes in the stress-induced strain. Thirdly, the material yield stress drops and so further strains may be introduced due to new yielding. Typical values of these three effects are shown in Figures 1 and 2 (Refs 6, 7 and 8). Above 200°C creep effects may become significant and will over-ride the stress-induced strain due to yielding. Research carried out in this area has been described in References 7, 8, 9, 10 and 11. Creep effects under varying temperature conditions are known as anisothermal creep and are of considerable importance in determining structural behaviour in fires.

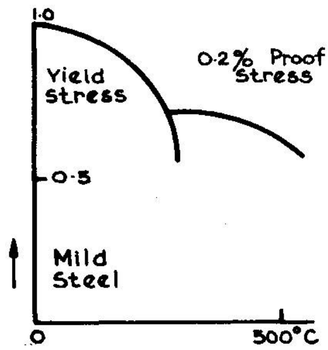


FIG. 1.

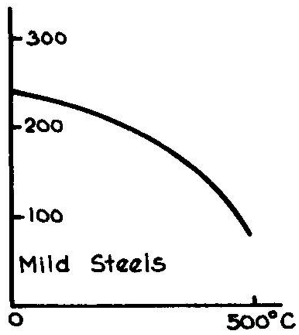


FIG. 2.

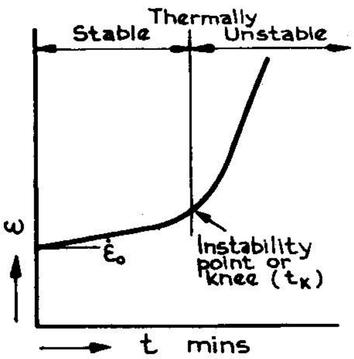


FIG. 3.

When a tensile specimen under some steady load is subjected to a fire environment the anisothermal creep effect is as shown in Figure 3. It can be seen that there is a pronounced linear strain-time part of the curve before an acceleration of creep takes place. The linear portion is part of the so-called "thermally stable" range (Ref. 11) whereas the acceleration of the creep range is defined as the "thermally unstable" range. There is a strong analogy here between the definition and the concepts of plastic design.

Many techniques were tried to quantitatively define the change-over point, t_K, (knee) between these thermal stages. The most successful was that of taking t_K as the time when the strain rate was five times the initial strain rate.

The relationship between the stress level and initial strain rate and the stress level against time to knee, t_K, for varying heating rates were empirically derived from the results of a large series of experimental results obtained by Skinner (Ref. 7). The results can be expressed as (Ref. 9):

$$\frac{dT}{dt} = (R_1 + R_2 n)\dot{\varepsilon}_o \quad (1)$$

$$\frac{dT}{dt} = (R_3\, n^{R_4}\, t_k^{R_5}) \quad (2)$$

The empirical equations form the basis of the subsequent beam theory as they embody a stress-strain relation for material under various thermal conditions. They effectively define the length of the linear response portion, t_K, and the strain rate, $\dot{\varepsilon}_O$, in this time period for a tension element subjected to a defined heating rate. Values of the constants R_n are given in Reference 9.

4. BEAM THEORY

Elastic Analysis

Conventional bending theory can be used to analyse the elastic behaviour of a beam within a temperature range of 0°C - 200°C or until the strain effects of creep are significant within this temperature range. The 200°C temperature level is arbitrary but related to the fact that the yield stress dropped away drastically from the 0.2% proof stress (Fig. 2) at this level.

The main parameters influencing the changes in stress, strain and strain rate distribution across a beam section elastically are the elastic modulus and thermal expansion. The limit to validity is provided by the yield stress or by creep. An iterative process for analysing the elastic thermal response was adopted and also formed the nucleus of the creep theory computer program.

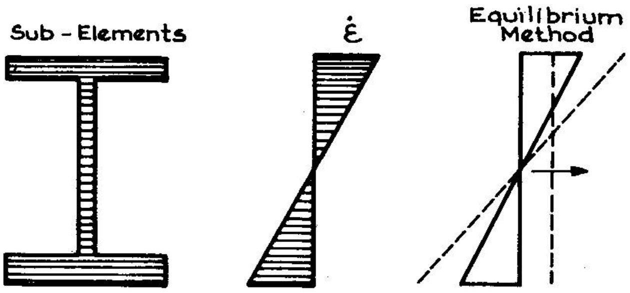


FIG. 4.

The beam is sectioned as shown in Figure 4 and each section is assumed to be a tension or compression element which has constant stress, strain, strain rate and temperature over its sub-area at any given time. These elements have their behaviour governed by equations (1) and (2). For this presentation only selected conditions will be examined, but the theory has been applied (Ref. 10) to other beam conditions.

The thermal history of the beam, and of each individual tension or compression element, must be known. This is obtained from the heat flow analyses assumed. The strain across the section is always assumed to be linear (Fig. 4) and the corresponding stress levels for each element are calculated from the strain and Young's modulus at the element's temperature. Equilibrium conditions are applied to the moment and forces and if equilibrium is not achieved, the initial strain distribution is changed by iteratively rotating and translating the strain distribution until equilibrium is satisfied.

For the next time increment, the temperature of each element changes, thus increasing the strain of each tension element by thermal expansion and the variation in E, thus:

$$\varepsilon_{t+\Delta t} = \varepsilon_t + \Delta\varepsilon_{TE} + \frac{\sigma}{E}\left(-\frac{E}{E}\right) \qquad (3)$$

where ε_{TE} is the strain due to thermal expansion.

If the stress level in an element exceeds the yield stress at that temperature, then the stress applied to the element is taken as its yield stress, σ_{YT} (Fig. 1).

For a non-uniform bending moment diagram, a number of positions along the beam are studied and at each point the beam's curvature is calculated (ε_t/D), where D is the depth of the beam and ε_t is as defined in Figure 4. The curvature equation for the total beam is estimated from these discrete points and the second integral of this equation gives the deflection equation for the beam.

The change in length, ΔL, of the beam due to expansion and deflection can be critical under thermal conditions and is included in the analysis. The strain due to change in length along the beam will be $\Delta L/L$ and will be in addition to the strain effects covered by equation (3).

This relatively simple elastic approach is continued by incrementing the time till an average beam temperature of 200°C is reached.

Creep Analysis

The creep solution uses the last strains determined elastically as a starting point and continues to assume a linear strain rate distribution. Errors at the transition from elastic behaviour to the use of equations (1) and (2) have not exceeded 2%.

From the strain rate distribution, the stress acting on each element is determined from equations (1) and (2). Whereas in the elastic region the stress of each element is compared to σ_{YT}, in the creep range equation (2) is used to determine whether or not the element is "thermally stable". If it is thermally unstable, the equation is used in reverse by applying the same heating rate as before but substituting the instantaneous time as the knee time and hence obtaining the maximum permissible stress that the element can carry whilst "thermally stable" at that temperature in the block. That is, the remainder of the section is assumed to "constrain" the critical block. Once again, there is a strong analogy with constrained flow in plastic design.

The force and moment equilibrium conditions are checked. If the forces are unbalanced, then the strain rate distribution is increased or decreased linearly. If the moment equilibrium is not achieved, the strain rate distribution is rotated about the zero strain rate point (Ref. 9). This procedure is repeated, until both equilibrium conditions are satisfied. These two effects interact and require further iteration for dual satisfaction of equilibrium to be attained.

5. DISCUSSION

Figure 5 shows the stresses in a longitudinally restrained beam when heated at a typical fire rate of 4°C/min. and loaded to a maximum design stress of 165 MPa. Note the very large stress increases produced by the longitudinal force developed when longitudinal expansion is prevented. The actual axial force produced

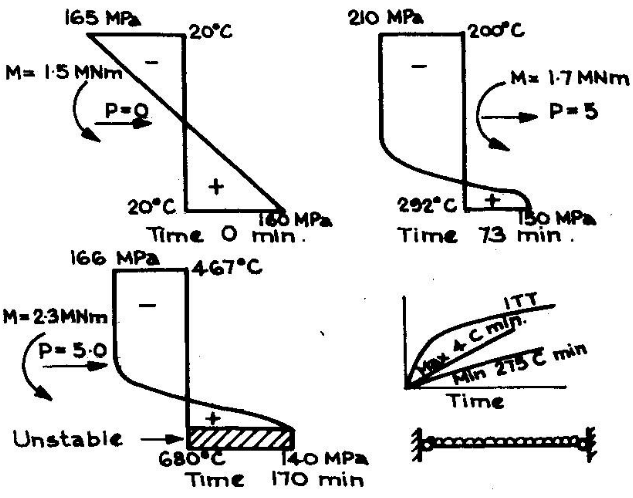


FIG. 5.

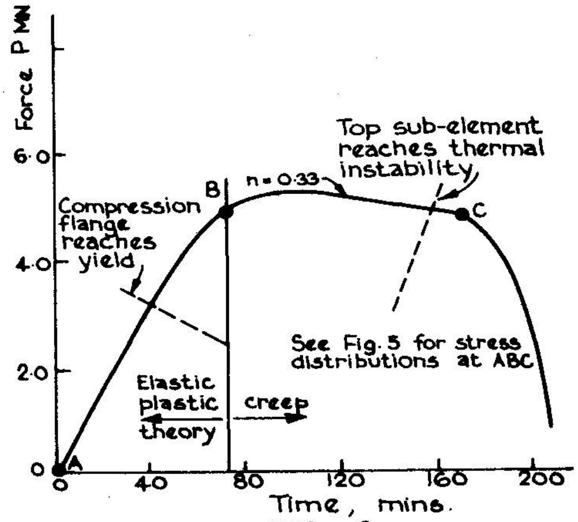


FIG. 6.

is illustrated in Figure 6. The forces reach an early peak and then begin to drop away after yielding begins (see the 70 minute stage in Figure 6).

Deflections at failure have been calculated for some 300 different beams and some 10 different heating conditions covering the range to be expected in building fires. It has been found that the temperature history has little bearing on the deflection value at failure. Deflection is dependent on the length, depth and design stress level of the hottest element.

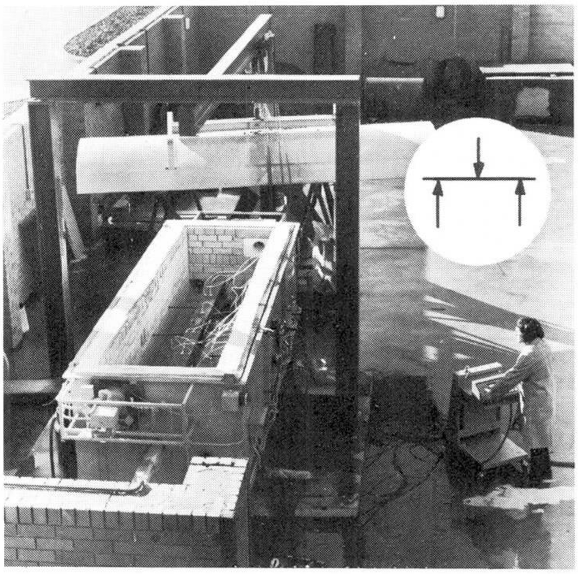
Figure 6 shows the results of the deflection values calculated at failure for both the simply supported and longitudinally fixed case plotted against $L^2D^{-1}n^{1/3}$. The slopes of the curves were found to be close to 1/500 and 1/800 respectively.

Ryan and Robertson (Ref. 12) have carried out experimental tests to determine a deflection criterion at failure. Their findings agree with those shown for simply supported conditions and stress levels of 0.66 F_{YTO}. The current results show the important fact that to consider other stress levels, the deflection criterion must include stress. Other workers (Refs 13, 14, 15) show various deflection-time curves and all deflection values at failure agree with those calculated from equation (4).

From the calculated results, the design stress level has a great bearing on the failure temperature, and this illustrates that fire ratings can be increased or decreased by changes in stress levels.

6. EXPERIMENTAL VERIFICATION

A number of experiments (Ref. 16) were conducted to verify the iterative approach described above. These experiments were carried out in a beam fire test furnace designed and built at the Broken Hill Proprietary Co. Ltd. Melbourne Research Laboratories (Fig. 7).



The internal dimensions of the furnace are 1.2 m x 4.2 m with reaction supports at 3 m centres. The loading procedure is as shown in the overlay on Figure 15.

Two gas fired burners are placed in opposing corners, as shown in Figure 7. Each burner has been designed to develop 0.1 million watts output with only a 75 mm flame length. Insulation bricks were the Newbold RI 28 type giving a furnace wall thickness of 220 mm.

Furnace controls to international test specifications can be carried out manually or with the use of a Hewlett-Packard data acquisition system (Ref. 17). The thermocouples used in the test pass through a 70°C reference junction prior to being connected to the data logger. This allows ambient temperature variation to be corrected. The speed of the data logging instruments is 15 a second with a monitoring capacity of 600.

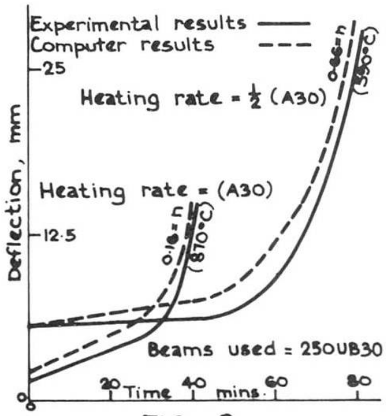


FIG. 8.

Test results and the associated theoretical prediction are plotted in Figure 8. It can be seen that there is good correlation between theory and experiment in this case. It was found that the applied stress level has a great bearing on the failure temperature and time (Fig. 8) and, as said previously, the fire rating of the component can be greatly changed by changing applied stress levels.

In Figure 8 it can be seen that for a stress level of n = 0.16 the failure temperature of the beam was 870°C whereas for a stress level of n = 0.66 the value was 590°C. Although, in the two examples, the heating rates were different, the failure temperature would not be altered if other heating rates were applied (Ref. 10).

7. CONCLUSIONS

Within this paper it has been shown that, from simple laboratory tests for thermal properties and the application of the principles of applied mechanics, it is possible to realistically predict the thermal structural behaviour of a building component subjected to fire situations.

Also, the applied stress level is a governing factor on the failure temperature and the fire endurance rating of a component.

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SUMMARY

This report shows how the performance of a steel member can be determined from the knowledge of thermal properties, mechanical properties and fundamental structural analysis under fire conditions.

RESUME

Cette contribution montre comment la résistance au feu d'un élément de construction métallique peut être déterminée à partir des propriétés thermiques et mécaniques. Le comportement fondamental de la structure en cas d'incendie est étudié également.

ZUSAMMENFASSUNG

Dieser Beitrag zeigt wie der Brandwiderstand eines Stahlelementes, aufgrund der Kenntnisse von thermischen und mechanischen Eigenschaften festgelegt werden kann. Eine grundsätzliche Tragwerkanalyse unter Brandverhältnissen wird ebenfalls untersucht