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BEHAVIOUR OF STEEL COLUMNS UNDER FIRE ACTION

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ABSTRACT

In modern deterministic conceptions of structural safety and design fire protection of constructions is no longer an afterthought, but is integrated in the normal statical calculations. A further step can be made by considering fire as a risk together with other risks like overloading and extreme wind loads, treating the problem with a probabilistic approach as is suggested in more advanced theories of structural safety. In view of the above, analytical and experimental studies are undertaken to evaluate the strength of structural members at elevated temperatures.

Probably the largest project in the field of steel construction is the programme of the European Convention for Constructional Steelwork (ECCS). Part of this project is a study on stability at elevated temperatures. In order to stay within the scope of the colloquium the discussion will be limited to the behaviour of individual compressed members.

After an introduction, first the influence of the rate of heating of the member on the bearing capacity is discussed. From small scale model tests it appears that this factor can be neglected for practical cases. This reduces the phenomena to a time independent problem. This implies that columns at elevated temperature can be treated with the theories developed for columns at normal temperatures, provided that the stress-strain relationships for elevated temperatures are known.

1. INTRODUCTION

In order to determine the bearing capacity of columns subjected to fire, the temperature distribution throughout the member as a function of the time must be known first. The ambient temperature in case of a fully developed fire obviously depends on the amount of combustible material (fire load) and some other factors, like the ventilation openings and the shape of the combustible material. All of these are in some way dependent on incidental fluctuations, so that the ambient temperature during a fire is a stochastic quantity. For practical reasons, however, up till now idealized time-temperature relationships are used. Taking into account the heat flow properties of the fire and the heat flow properties of the protected structure, the steel temperature in the relevant parts of the structure can be predicted.

In this paper we will consider the steel temperature as a function of time as known and devote our attention to the load-bearing capacity. Elevated temperatures affect the bearing capacity of the structure in several ways. The most important factors are:

1. The material properties like yield strength or $\sigma_{0.2}$ strength and modulus of elasticity decrease with the temperature.
2. Due to restraint of the thermal expansion stresses are induced, acting in addition to those produced by the applied load.
3. The thermal expansion causes deformations which may produce additional P-Δ effects.
4. When a structure or member is unequally heated, local thermal expansion causes redistribution of forces and moments affecting the load bearing capacity of individual members.

All these factors are included in the ECCS programme. The problem considered in this paper is the buckling behaviour of an individual column subjected to an uniform temperature increase along its length and cross section. Although this represents an idealized case it is the first necessary step to provide insight into more complicated cases.

2. EVALUATION OF THE INFLUENCE OF THE RATE OF HEATING ON THE LOAD-BEARING CAPACITY

In buckling problems at normal temperatures the stress-strain relationship of the material is considered as time independent. Due to creep this may be no longer valid at elevated temperatures more than 250 to 300^{o}C. Creep is the phenomenon of continuous deformation under constant load, and constant temperature (fig. 1). It is clear that creep affects particularly the bearing capacity of compressed members, as the deflections and consequently the bending moments increase as time goes on.

Due to creep a theoretical evaluation of the behaviour of columns at elevated temperatures will become very complicated because time has to be considered as a parameter. In case of fire in general the column will be under constant load while the temperature rises as a function of time. Depending on the isolation of the member the rate of heating can vary. Therefore first experiments were performed to investigate the influence of the rate of heating on the load-bearing capacity, resp. the critical temperature of steelcolumns at elevated temperatures under fire conditions.

It was decided to study this effect by small scale model tests on beams and columns. Two different approaches were used:

a. Testpieces with a constant load were heated at different heating rates (fig. 2). Heating rates were chosen of 50°C per minute (approximately corresponding to an unprotected steel member); 10°C per minute (normally protected steel member) and 5°C per minute (highly protected steel member). If the rate of heating would have any influence on the critical temperature*, one would expect this temperature to be systematically higher if the testpiece is heated faster.

b. Testpieces with a constant load were heated up to a certain temperature level. If no creep appeared at this level (i.e. no time-dependent deformation), temperature was raised to another, higher level and so on (fig. 3). The temperature at which the testpiece starts to creep (what in the end leads to collapse) was defined as the critical (creep) temperature.

It will be clear that both methods are supplementary to each other.

3. EXPERIMENTS ON THE INFLUENCE OF THE RATE OF HEATING

a. Experiments on model beams (Fe E 24, σ_y = 240 N/mm^2)

Rectangular beams (cross-section 6 x 6 mm; span 400 mm) were loaded in a way shown in fig. 4. The applied load P was respectivily: $P = 0.19\ P_{b20^o}$, $P = 0.37\ P_{b20^o}$, $P = 0.57\ P_{b20^o}$ and $P = 0.74\ P_{b20^o}$ (P_{b20^o} is the collapse-load at room temperature, which was determined experimentally).

The influence of the rate of heating was studied in a way described in 3.a. It followed from the tests that the

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* The critical temperature is the temperature at which the steel member collapses or a certain deformation criterion is reached.

heating rate does not influence the deformation behaviour in a significant way. This is illustrated in fig. 4 in which, as an example, the temperature is given at which a maximum deflection is reached of 1/30th of the span. Similar figures are obtained for other deformation criteria.

b. Experiments on model-columns (Fe E 24, σ_y = 240 N/mm^2)

Columns with rectangular cross-sections (6 x 12 mm and 9 x 15 mm) were centrically loaded by constant load. The slenderness-ratio was varied (λ = 40, 80, 118, 160 and 200). For the applied load was chosen: $P = 0.2\ P_{b20^o}$, $P = 0.4\ P_{b20^o}$, $P = 0.6\ P_{b20^o}$ and $P = 0.8\ P_{b20^o}$ (P_{b20^o} is the collapse load at room temperature, which was determined experimentally and appeared to be in good agreement with the CECM-curve).

The influence of the rate of heating was studied in both ways described in 3.a. and 3.b. As an example, in fig. 5 the behaviour of a column under the conditions according to 3.b. is given. Results of all the tests are given in fig. 6. It appears that the rate of heating does not influence the critical temperature in a significant way. In agreement with this, the critical (creep) temperatures obtained by the experiments according to 3.b. are close too those obtained by experiments according to 3.a. It is noted that the scatter in the observed critical temperatures is rather high, which is also the case with buckling tests at normal temperatures.

4. CONCLUSIONS AND IMPLICATIONS ON THE SIGNIFICANCE OF THE INFLUENCE OF THE RATE OF HEATING

It follows from the test results, that although creep will occur (see fig. 5) the critical temperature of steel members in practical cases will not be affected in a significant way by the heating rate. This implies that the critical temperature of steel columns under fire conditions can be considered as time independent and consequently not influenced by the "heating history". This conclusion will make possible a theoretical approach of stability-problems which is identical to well-known methods at room temperature.

Condition is that reliable stress-strain relationships at elevated temperatures are available. To find this relationships warm-creep tests were carried out. In fig. 7 is shown in what way the stress-strain relationships can be obtained. The adventage of this method is that the rate of loading, which is an uncertain factor in warm-tensile tests, is eliminated. It is noted that the transformation shown in fig. 7 is only justified for "practical" heating-rates (i.e. between 5 to 50^{o}C per minute and temperatures not over, say 600^{o}C), where the creep behaviour can be considered as incorporated in the stress-strain relationships. In addition also stress-strain relationships were obtained by analyzing the small-scale bending tests. It appeared that the σ-ε curves found in this way were in reassonable agreement with those obtained by warm creep tests.

5 . PRESENTATION OF EXPERIMENTAL RESULTS

Anticipating on the theoretical approach and full scale tests at the ECCS-Station at Metz, France, experiments on small-scale columns at elevated temperatures were performed. In fig. 8 the results are presented.

Note that it appears that the critical temperature T_{crit} depends on the slenderness-ratio. There is a minimum for T_{crit} at $\lambda = 80$. This phenomenon can be explained as a result of the fact that the stress-strain relationship at normal temperature differs significantly from those at elevated temperatures, whereas the

the stress level in the column is based on the first relationship.

6. STABILITY WORK CURRENTLY UNDERWAY

As already has been stated an analytical approach of columns under fire conditions can be simplified to a time independent problem, and consequently normal stability procedures can be used.

The first step which has already been undertaken is the analytical verification of the experimental results from the model buckling tests (fig. 8). Stress-strain relationships obtained from warm creep tests and bending tests are used as basic data (see chapter 5). In fig. 9 the so derived stress-strain relationships for Fe E 24 (σ_y = 240 N/mm^2) are given. In fig. 10 computated buckling curves are presented together with experimental results. Also the buckling curve based on the Dutch-design code is given. It appears that the present-criterion for the critical temperature of about 300-400°C is a fairly good estimate. A full presentation of the method used in obtaining stress-strain relationship and buckling curves will be published shortly. The result will lead to buckling curves for elevated temperatures to be used in practice.

Full scale tests at Metz will give additional verification. Thus far the investigations have been limited to the behaviour of individual members. The interaction which occurs between the various members in structures leads to problems which were summarized in chapter 2. In the ECCS programme these problems are studied by theoretical analysis, small scale model tests and full scale tests. Results obtained from this work should lead to the possibility of analyzing the behaviour of building frames in fire.

7. ACKNOWLEDGMENT

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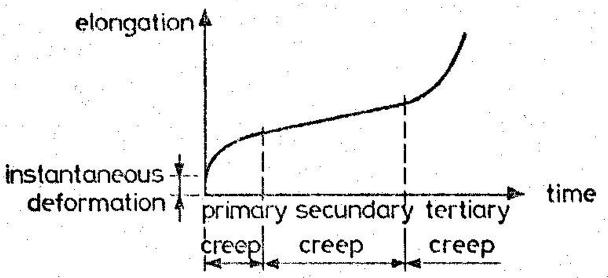


fig. 1: creep behaviour of steel at elevated temp. (schematical)

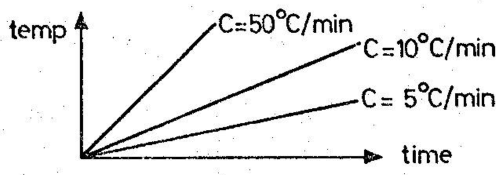


fig. 2: time-temp. relationships during the buckling tests

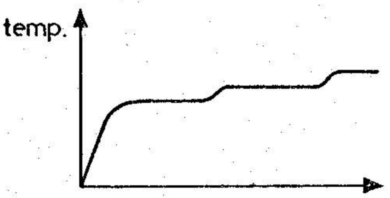
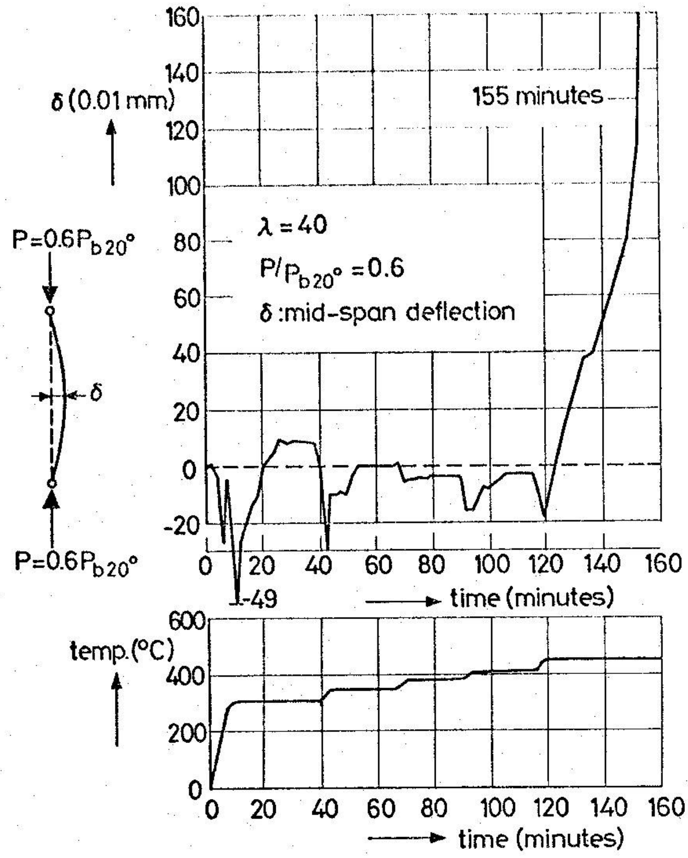
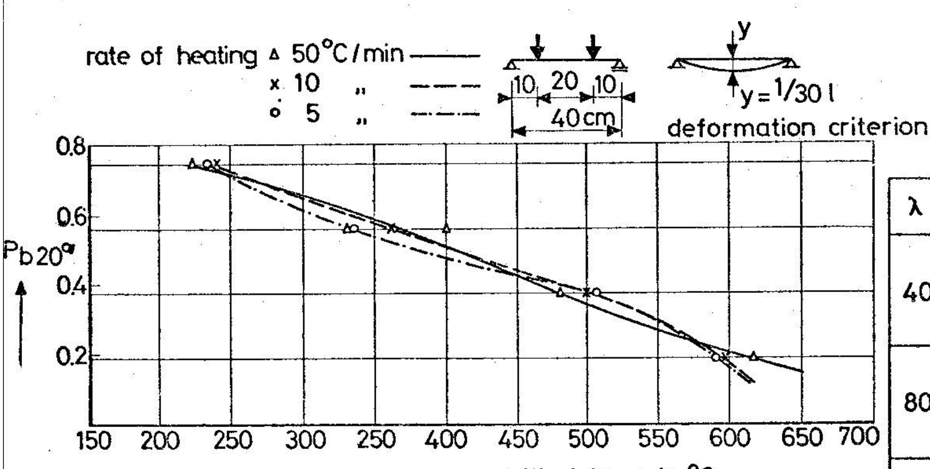


fig. 3: time-temp. relationship during a creep-test



working-method of the creep-buckling-test

fig. 5



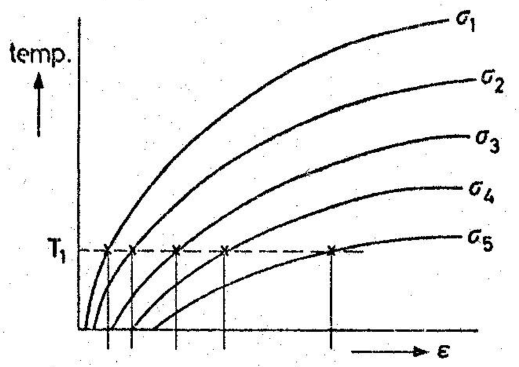
temperature at which a critical midspan deflection is reached as function of the load and the rate of heating (FeE 24)

fig. 4

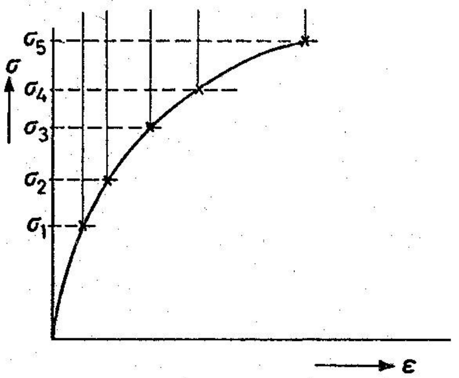
λ	$P/P_{b20°}$	creep test		buckling-test at different heating-rates C [°C min] C = 5	C = 10		C = 50
40	0.4	460°			510°	520°	
	0.6	450°			360°	400°	375°
80	0.6	230°		260°	220° 270°	250°	
	0.8	210°		205°	230° 180°	220° 175°	
118	0.4	490°	520°	510° 525°	480° 430°	495°	
	0.6	210°	235°	320°	255° 285°	295° 320°	
160	0.6	260°			305° 295°	280°	
200	0.4			570°	590° 590°	585°	590° 570°

comparison of T_{cr} [°C] resulting from the creep buckling-tests and from buckling-tests at different heating-rates (FeE 24)

fig. 6

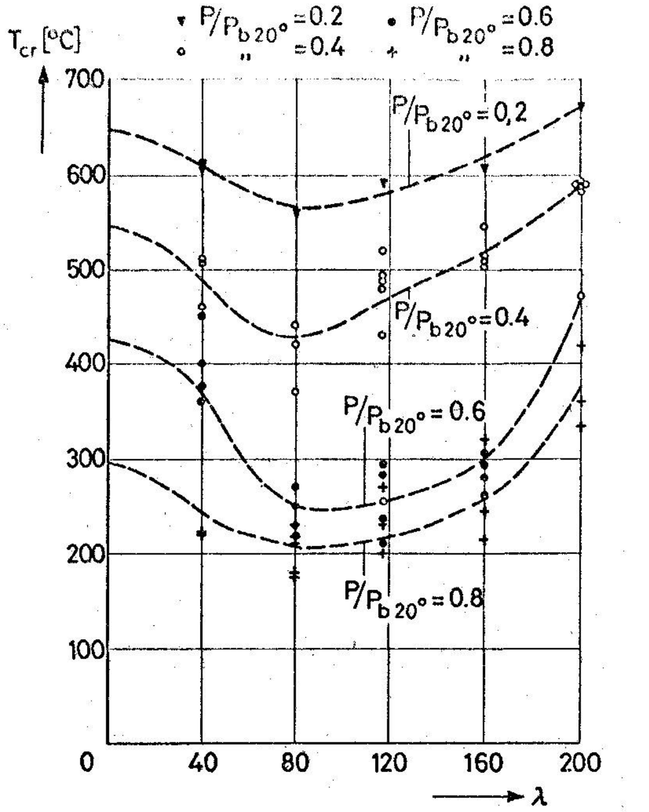


ε-T diagrams at different stresses $\sigma_1 < \cdots < \sigma_5$ (schematic)



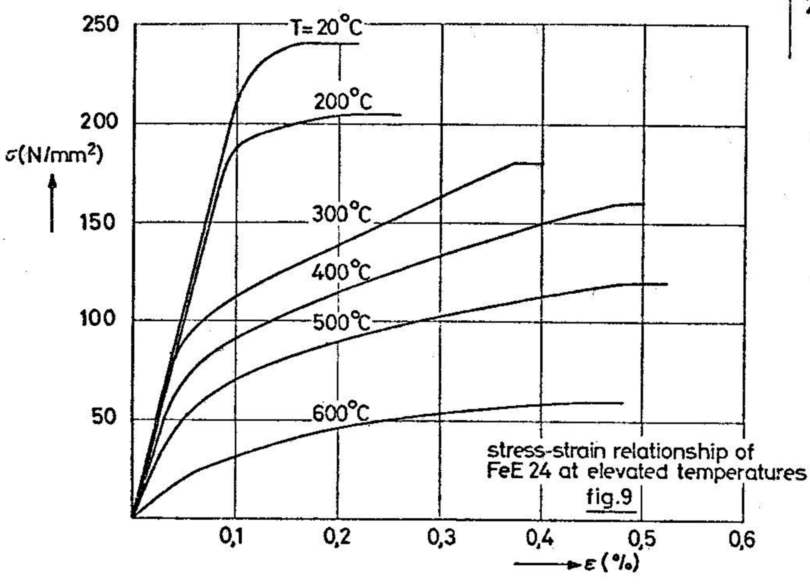
artificial σ-ε diagram at temperature $T=T_1$ (schematic)

fig.7



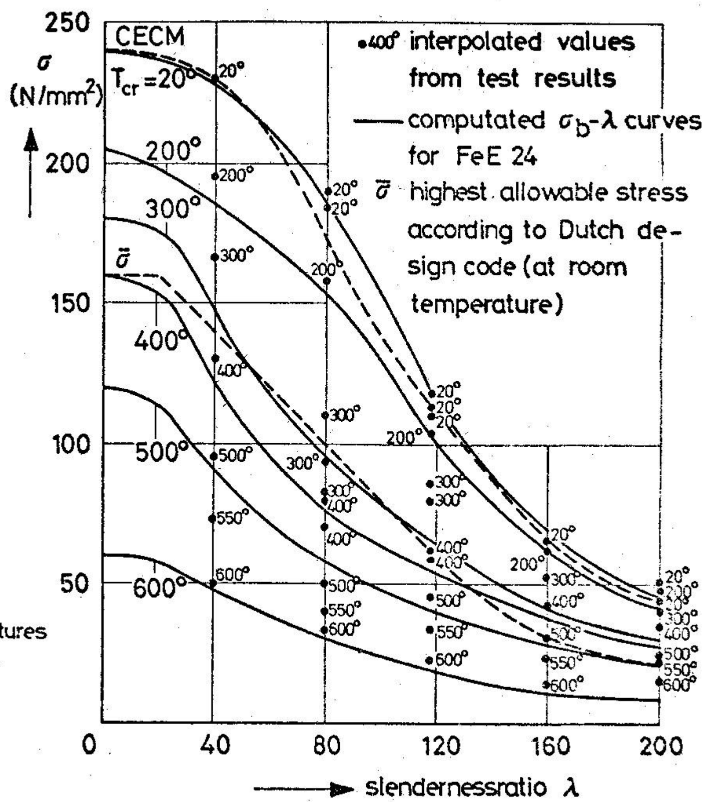
Relation between critical temperature and slend nessratio at different values of $P/P_{b\,20^\circ}$ (FeE 2

fig.8



stress-strain relationship of FeE 24 at elevated temperatures

fig.9



relationship between critical stress and slendernessratio at different temperatures

fig.10