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"STABA-F; A Computer Program for the Determination of Load-Bearing and Deformation Behaviour of Uni-Axial Structural Elements under Fire Action"

Braunschweig, March 1984

1. Introduction

In recent years extensive experimental research has been carried out on the load-bearing and deformation behaviour of steel, reinforced concrete and composite columns under fire action by the "Institut für Baustoffe, Massivbau und Brandschutz der Technischen Universität Braunschweig" *) [1], [2], [3], [4].

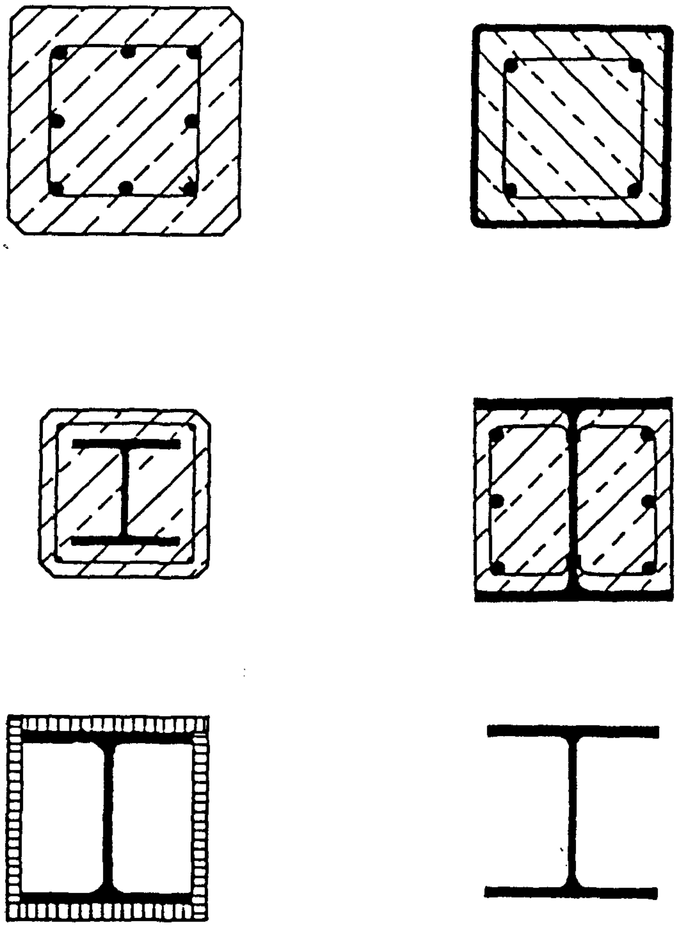

Fig. 1: Typical sections of investigated columns

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*) Institute for building materials, concrete structures and fire protection, Technical University of Braunschweig.

The computer program "STABA-F" was developed, to support the investigations theoretically and numerically. This calculation method allows to evaluate the load-bearing and deformation behaviour of uni-axial structures under fire actions. Deformations, 2^{nd} order effects, are taken into account.

2. Design of the Computer Program

The computer program "STABA-F" consists of three parts independent of each other.

1. Determination of the temperature distribution in arbitrary cross-sections by any given external temperature-time curve.

2. Determination of the nonlinear interaction between bending moment M_y and curvature 1/r dependent on normal force N_x for any cross-section with given temperature distribution.

3. Determination of bending moment M_y, shear force Q_z, slope of the bar φ, deflection in accordance with 2^{nd} order theory w and dilitation u for structural elements with any boundary conditions and no matter how loaded for any given relationship between bending moment M_y and curvature 1/r.

2.1 Determination of Temperature Distribution

Heat conduction is described by the well-known equation from Fourier, valid for homogeneous and isotropic materials. Applied to reinforced concrete or composite structures, some simplifications are necessary:

- water vaporises as soon as reaching the boiling-point,
- movement of the steam is put together with other effects,
- consumption of energy for vaporizing the water and other similar peculiarities are taken into account in a simplified way by suitable design values for the specific heat capacity of concrete up to 200 °C.
- Concrete is taken into account in a simplified way as a homogeneous material, the heterogeneous structure, as well as capillary pores and internal cracks, are lumped together.

A finite element method in connection with a time-step integration is used to calculate the temperature distribution in the section [5]. The time steps have to be chosen quite small, $\Delta t = 2{,}5 - 5$ min, because the characteristic values of thermal conductivity λ, specific density ρ and specific heat capacity c_p are very much dependent on temperature.

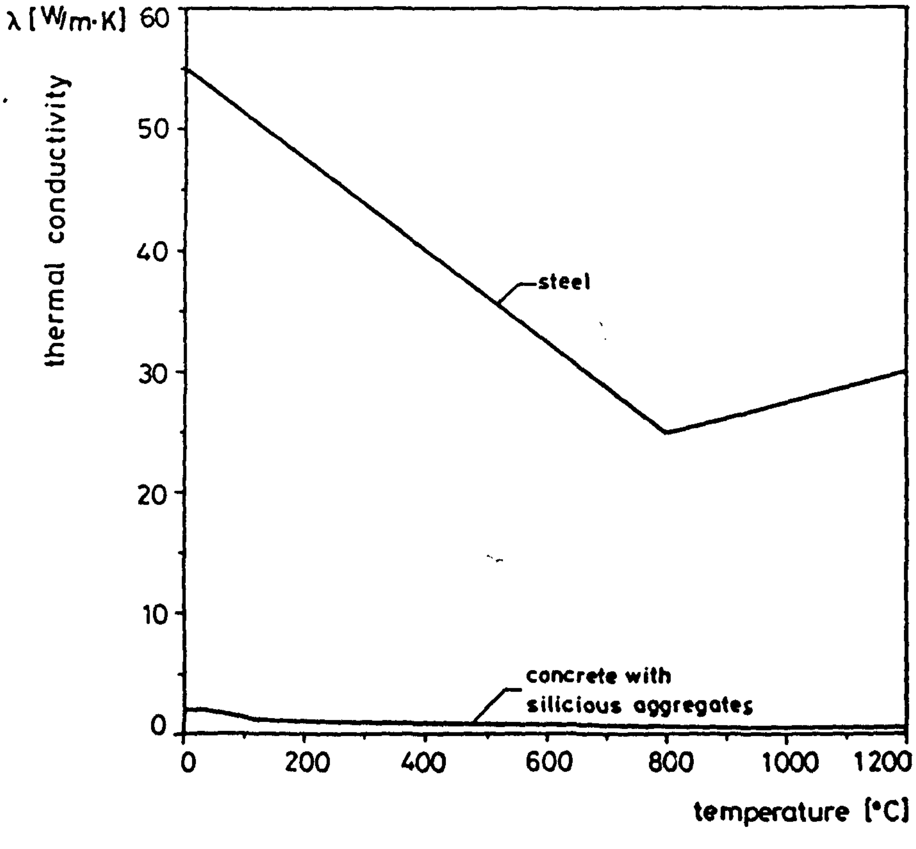

Fig. 2: Thermal conductivity of steel and concrete with siliceous aggregates

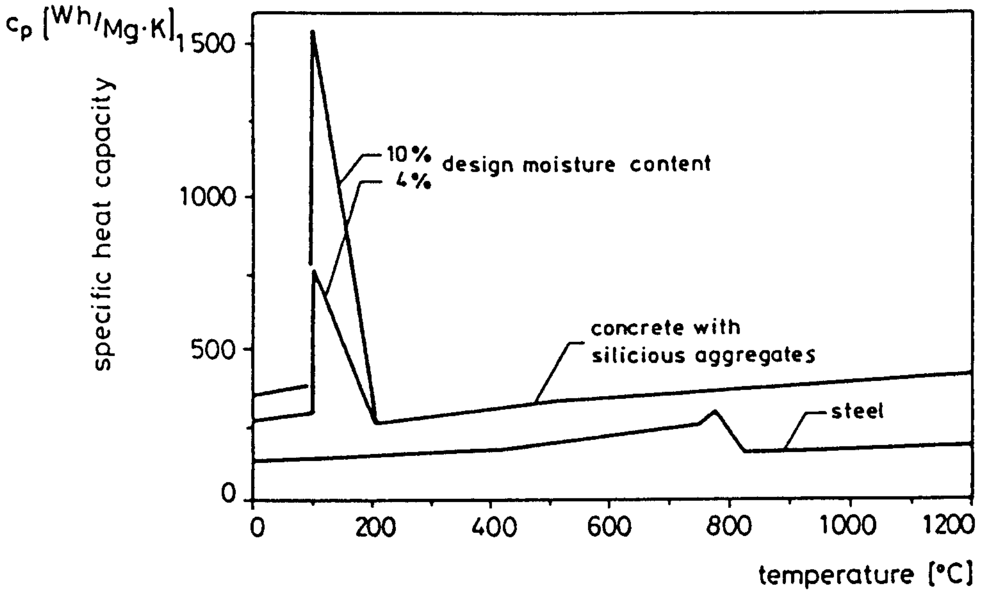

Fig. 3: Specific heat capacity of steel and concrete with siliceous aggregates

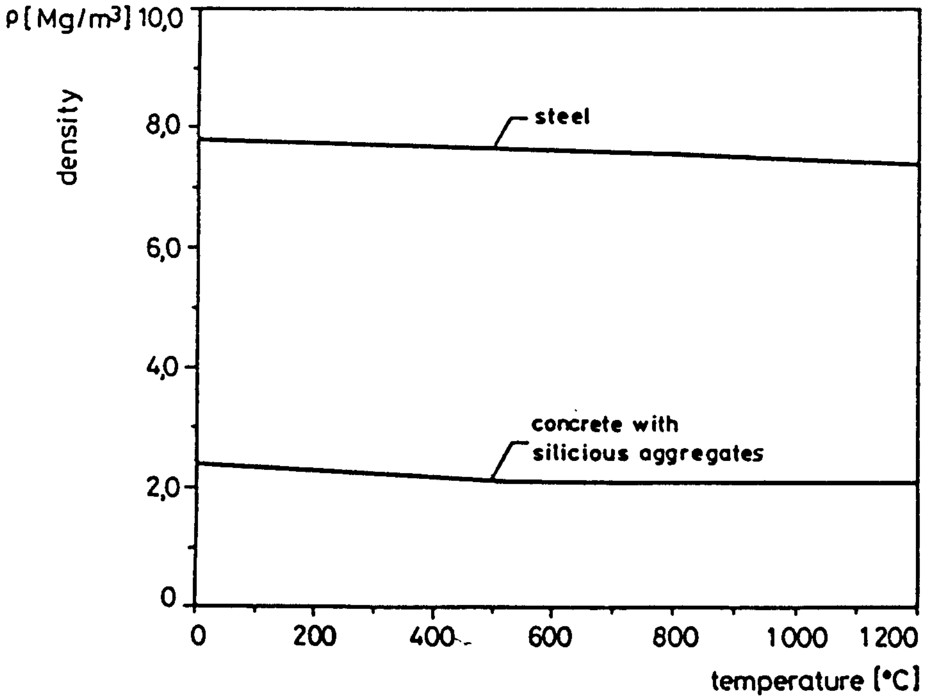

Fig. 4: Density of steel and concrete with siliceous aggregates

To determine the temperature distribution a rectangular network is preferred. The elements have either corresponding thermal materials of steel or concrete or weighted properties.

The heat transfer from the fire to the structural element depends on

- material at the surface of the member,
- colour of the flames,
- geometry of the furnace,
- material properties of the furnace walls,
- ventilation conditions.

Extensive investigations in the furnace for columns of the "Institut für Baustoffe, Massivbau und Brandschutz" showed, that there is sufficient correspondence between measured and calculated temperature distribution in a section, assuming

α = 25 W/m²K for the coefficient of convection heat transfer,
ε = 0,3 - 0,6 for concrete and
ε = 0,5 - 0,7 for steel for the resultant emissivity.

2.2 Determination of the relationship between bending moment and curvature

The relationship between curvature 1/r and the bending moment M_y of a cross section includes also the load dependent stiffness. The determination of the mentioned relationship assumes the following simplifications:

- the Bernoulli-Navier hypothesis: plane sections remain plane,
- only uniaxial stresses are taken into account , shear stresses are neglected ,
- there is no slip between concrete and steel,
- the stress-strain relationships are nonlinear elastic.

To determine the load dependent moment/curvature relationship the same network as in the calculation of the temperature distribution is used. It is possible to derive the thermal strain $\varepsilon_{th}(y,z,T)$ for the cross-section elements from the already existing element temperatures $T(y,z) = f(t)$, using the temperature dependent thermal strain for concrete and steel shown in figure 5.

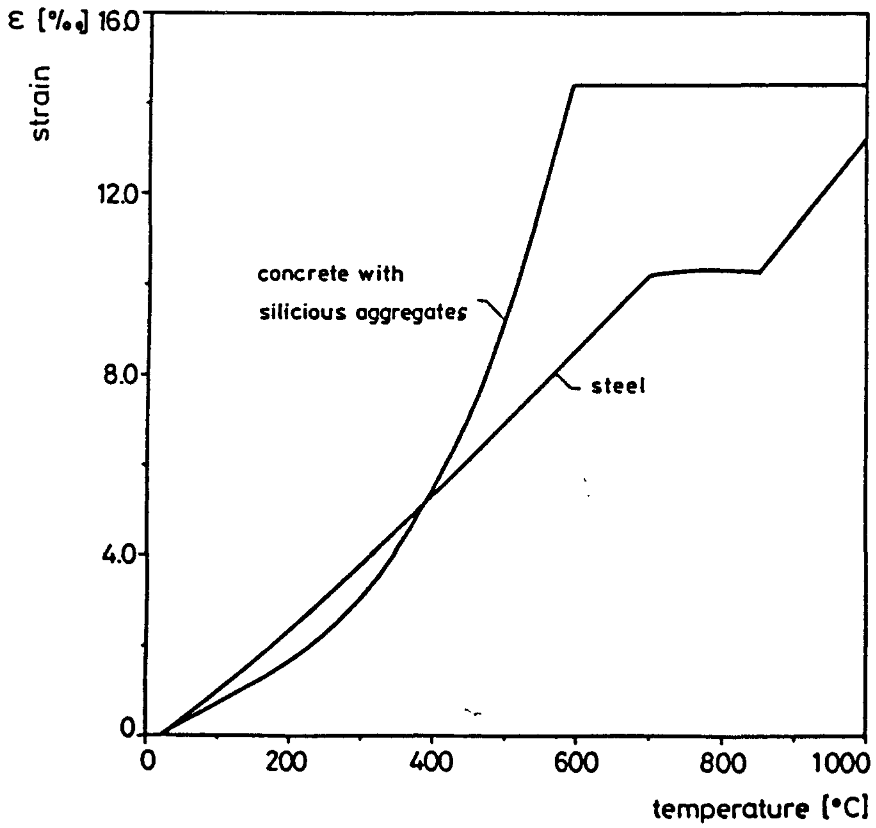

Fig. 5: Thermal strain of steel and concrete with siliceous aggregates

Equation (1) is a compatibility condition assuming a certain curvature 1/r and the initially unknown strain ε_{lo} referred to z = 0, y = 0

$$\varepsilon_{\sigma}(y,z,T) = \varepsilon_{lo} + z/r - \varepsilon_{th}(y,z,T) \qquad (1)$$

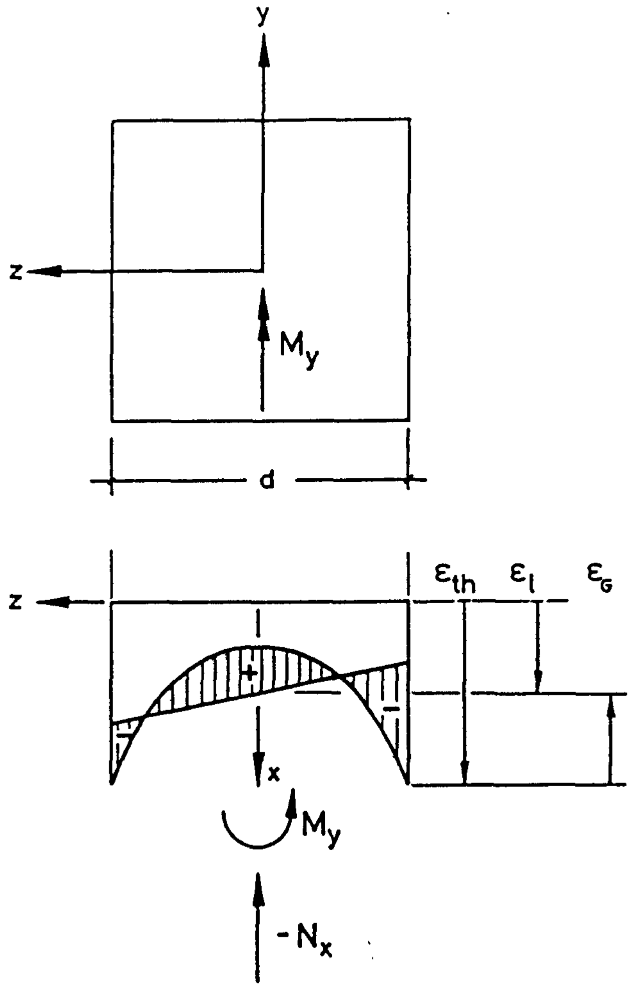

Fig. 6: Evaluation of the stress causing strains

The strain ε_{lo} is determined iteratively in that way, that the equilibrium condition (2) between the force in all n elements and the load N_x is fulfilled.

$$\sum^{n} A \cdot \sigma_x(y,z,T) = N_x \qquad (2)$$

The stress causing strain $\varepsilon_\sigma(y,z,T)$ and the strain dependent stresses are linked by the temperature dependent stress-strain relationships.

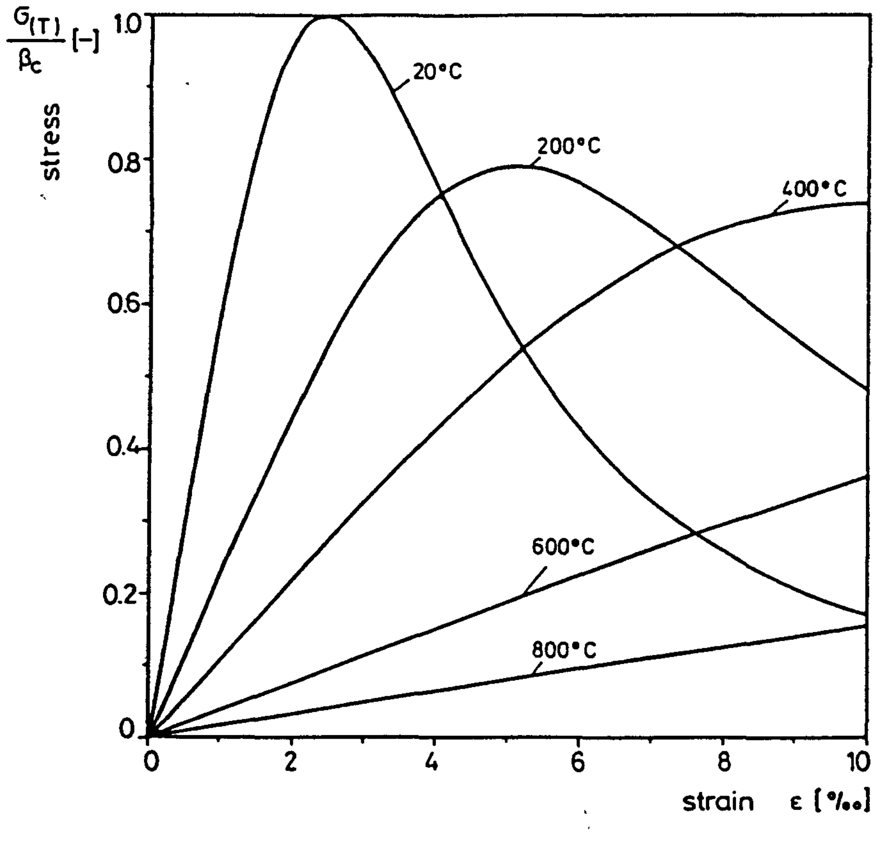

Fig. 7: Relations between stress and strain dependent on temperature, concrete with siliceous aggregates [6]

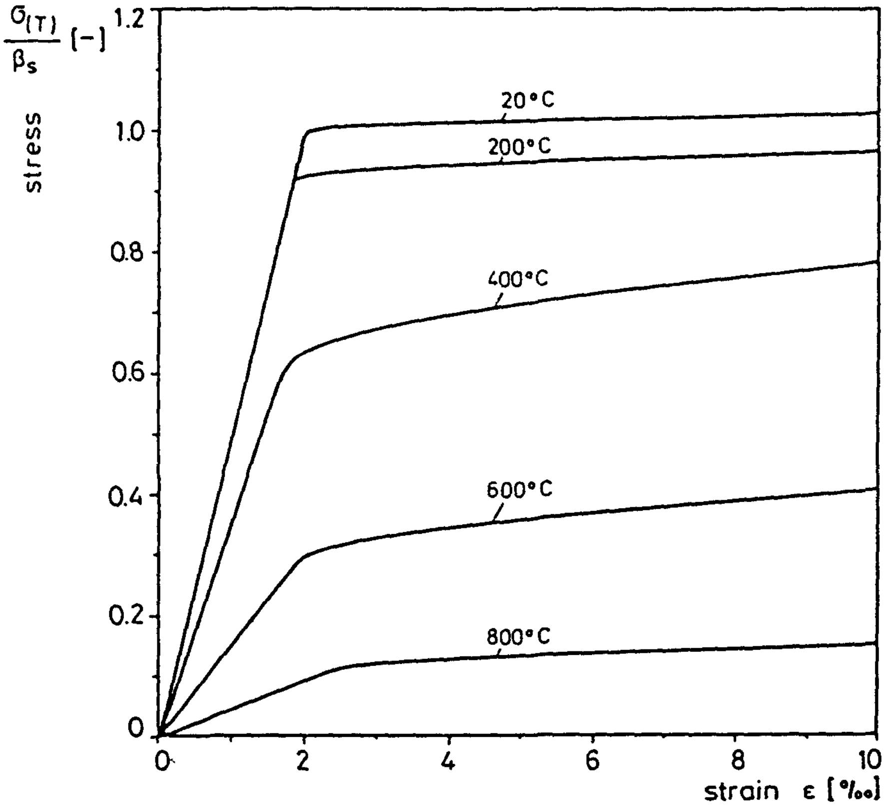

Fig. 8: Relations between stress and strain dependent on temperature, reinforcing steel bars, hot rolled [7]

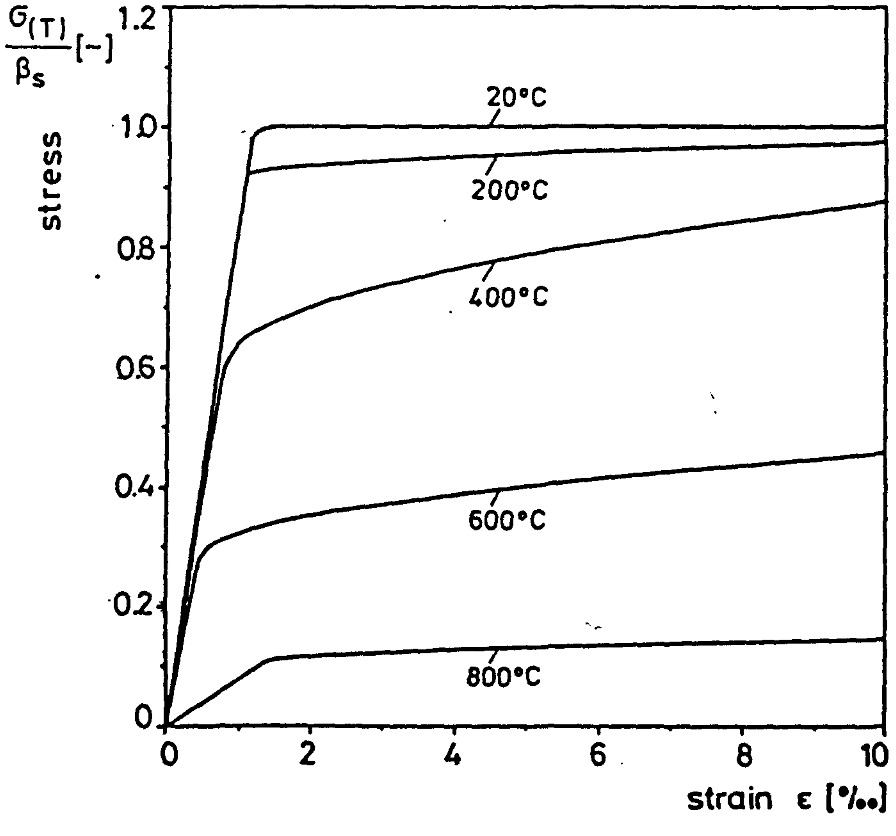

Fig. 9: Relations between stress and strain dependent on temperature, structural steel St 37-2 [3]

The effect of creep is included in these stress-strain relationships.

Equilibrium condition

$$\sum^{n} A \cdot \sigma_x(y,z,T) \cdot z = M_y \qquad (3)$$

results in the corresponding bending moment M_y belonging to the given curvature 1/r [8]. The complete moment/curvature relationship consists of a certain number of values for 1/r and M_y.

2.3 Determination of load-bearing and deformation behaviour

An accurate evaluation of the load-bearing behaviour has to take into account the influence of mechanical (nonlinear moment/curvature relationships) and geometrical (2^{nd} order theory) nonlinear interaction between load and deformation. To determine bending moment M_y, shear force Q_z, slope of the bar φ and deflection w the method of transferring these values from one division to the next is used [9]. The initially unknown forces or deformations at the beginning of the structural element have to be determined iteratively in that way, that the compatibility condition at the end of the structural element is fulfilled. The definition of the stiffness as the gradient of the partially linear moment/curvature relationship results in a quick converging calculation algorithm. For instance it is not necessary to increase the normal load N_x in small increments for ultimate state design, even if some sections along the axis of the structural element have large rotations, similar to plastic hinges. It is possible to determine the load-bearing and deformation behaviour with different moment/curvature relationships for the division points. This may be necessary for instance, if there are

- different cross sections along the axis x,
- different kind of heating of the cross section along the axis x,
- variable normal force in different sections.

Loads can be applied as concentrated loads to the division points. Imperfections can as an alternative either be taken into account as additional eccentricities at the ends of the structural element or as an initially unstressed state of deformation of the bar. Any isostatic or hyperstatic support of the elements is possible, even elastic or nonlinear elastic springs.

3. Synopsis

The computer program "STABA-F" is presented detailed. The general validity of the theoretical approach is demonstrated by analysis of tests on columns. It is also possible to determinate the load-bearing and deformation behaviour of beams. The tests were carried out under standard fire action according to ISO 834. It is not only possible to predict the failure time, but also the load-bearing and deformation behaviour of the specimen during the tests.

Another use is to calculate permissible loading of components at certain required times of fire duration. This may be used to build up a kind of catalogue, which gives permissible loads for components dependent on:

- shape of the section
- material properties
- length of the element
- boundary conditions
- load eccentricities
- fire action

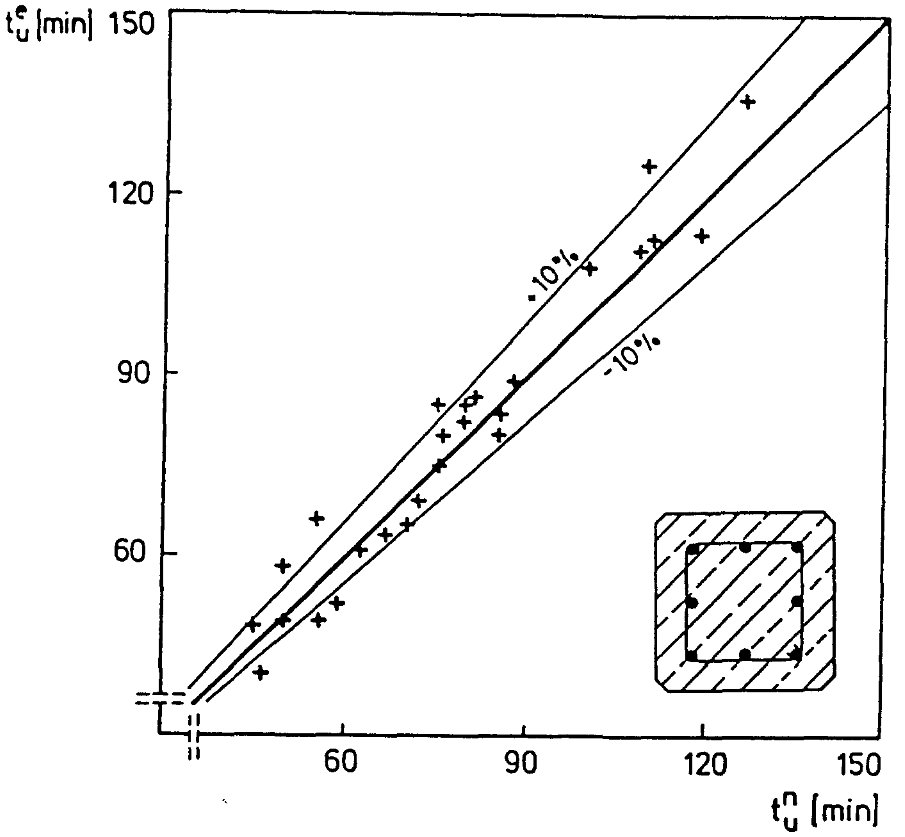

Fig. 10: Comparison between calculated t_u^n and measured t_u^e failure times (reinforced concrete columns)

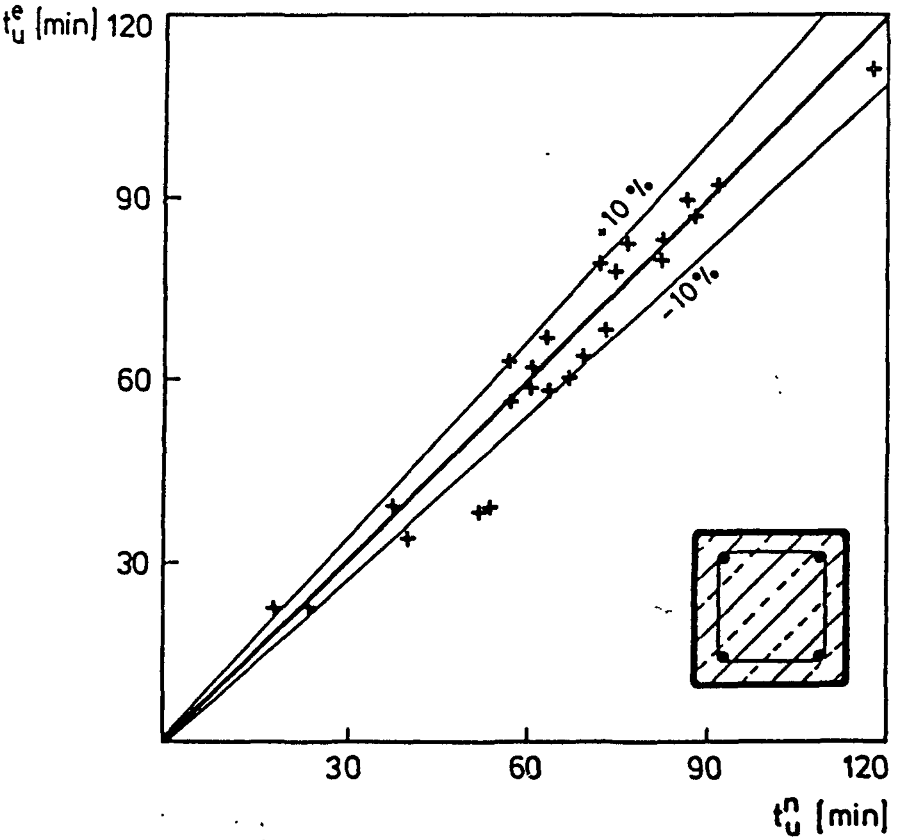

Fig. 11: Comparison between calculated t_u^n and measured t_u^e failure times

(concrete filled hollow sections)

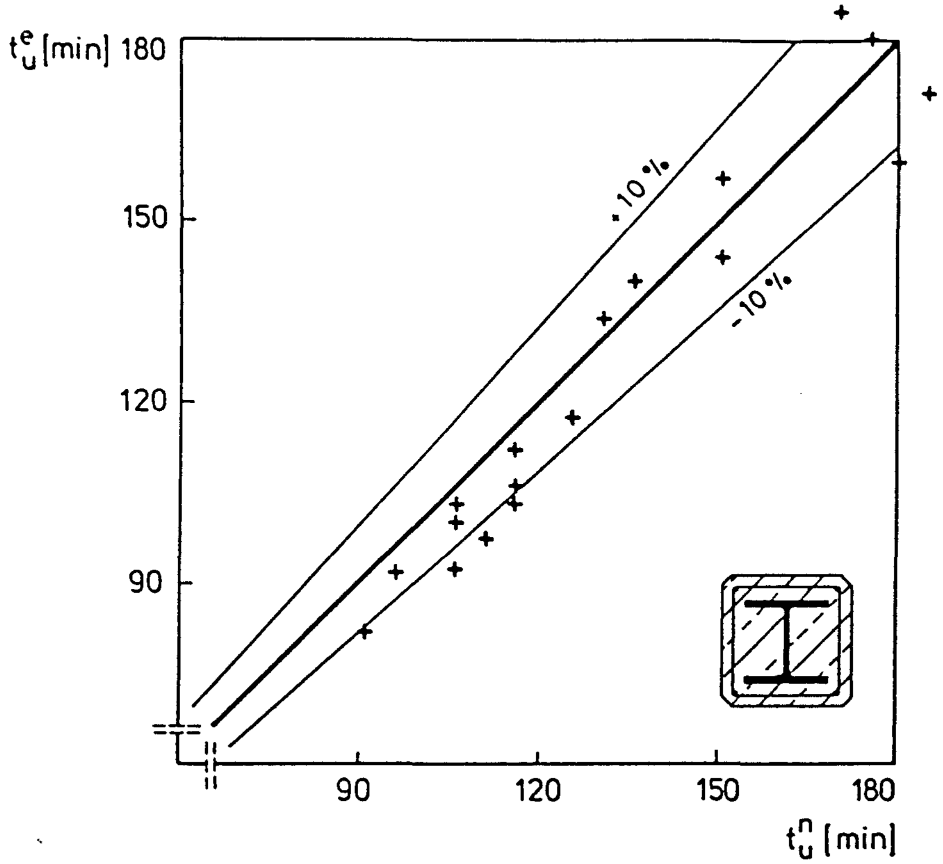

Fig. 12: Comparison between calculated t_u^n and measured t_u^e failure times
(hot rolled sections completely embedded in concrete)

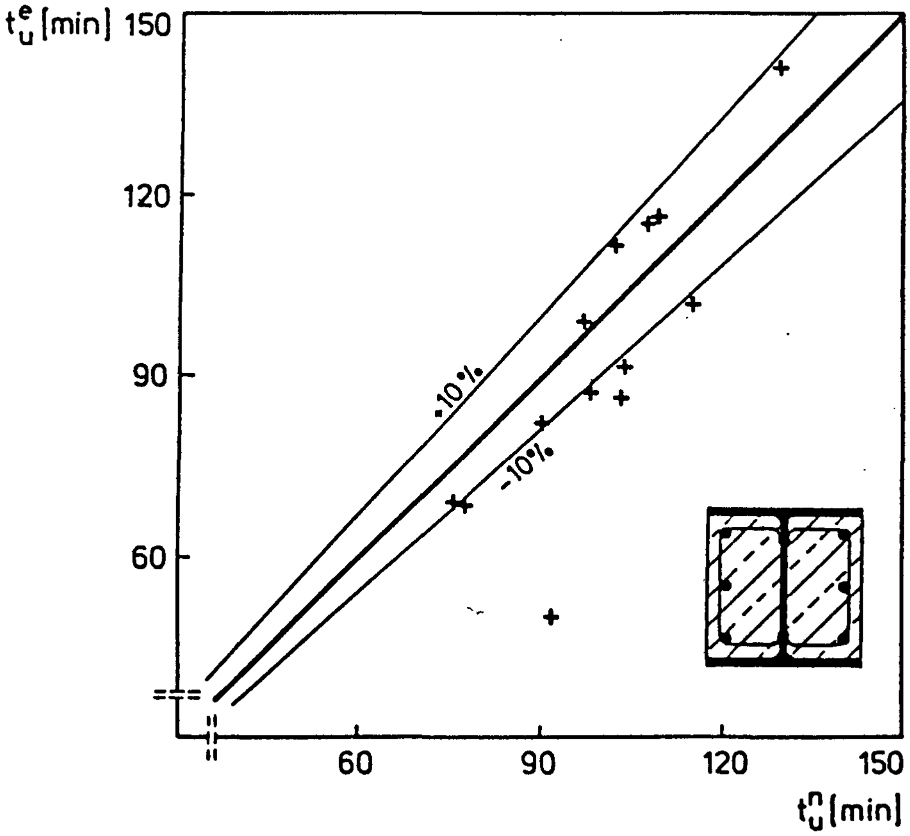

Fig. 13: Comparison between calculated t_u^n and measured t_u^e failure times
(hot rolled sections concrete filled between the flanges)

4. References

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