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Practical Need of Scientific Material Models for Structural Fire Design — General Review

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SUMMARY

More and more countries are now permitting a classification of structural elements with respect to fire exposure to be formulated analytically as an alternative to the internationally prevalent method of classification, based on results of standard fire resistance tests. In some countries, the authorities also have taken the next step to approve a general practical application of a direct analytical design procedure, based on the natural compartment fire concept.

The process of an analytical structural fire design comprises three main components — the determination of the fire exposure, the thermal analysis and the mechanical behaviour analysis. The components require access to well-defined input information on: (a) material properties for describing the characteristics of the fire load and the compartment fire; (b) material properties for determining the transient temperature state of the fire-exposed structure; and (c) material properties for determining the related mechanical behaviour and load-bearing capacity.

With a summary presentation of the development and characteristics of the analytical structural fire design as a background, the paper is focusing on the mechanical material properties at elevated temperatures. A systematic scheme of classification of available tests is referred to and the importance is stressed of using such functionally well-defined tests which give material properties, stringently connected to material behaviour models being independent of the type of load-bearing structure.

1. INTRODUCTION

In a general sense, the fire engineering design problem is non-deterministic. Some

level of risk is virtually unavoidable and we have to recognize the impossibility of absolute compliance with a preset goal. Performance has to be described and measured in probabilistic terms.

This is one perspective from which we have to judge or appraise the building fire-safety code systems now in force. Historically, they were written without actually stating their objective safety level and, still less, without any analytical measurement of the objectives involved. For this reason, there is an urgent need to evaluate the levels of safety inherent in present local and national fire protection regulations. Lack of knowledge concerning the structure of the analytical models describing the physical processes has, for a long time, prevented all efforts to assess risk levels quantitatively.

2. DEVELOPMENT AND MAIN CHARACTERISTICS OF STRUCTURAL FIRE DESIGN

The situation described applies to the whole field of fire engineering design. As far as load-bearing and separating structures are concerned, important and rapid progress has been noted during the last twenty years in the development of analytical and computational methods for the determination of the behaviour and limit state at fire. Today, an analytical fire design can be carried out for most cases where steel structures are involved. Validated material models for the mechanical behaviour of concrete under transient high-temperature conditions and thermal material models for the calculation of the charring rate in wood exposed to fire, derived during recent years, have significantly increased the area of application of analytical design.

Consequently, more and more countries are now permitting a classification of structural

elements with respect to fire to be formulated analytically, as an alternative to the internationally prevalent method of classification based on results of standard fire resistance tests. In a long-term perspective, the development goes towards an analytical design, directly based on a natural fire exposure, specified with regard to the combustion characteristics of the fire load and the geometrical, ventilation and thermal properties of the fire compartment. In the individual application, the heat exposure on the structure or structural element then can either be calculated from the energy and mass balance equations for the compartment fire or be derived from curves or tables in manuals, giving the time variation of either the gas temperature within the compartment or the corresponding heat flux to the structure — a summary state of the art is given in ref. 1 together with a comprehensive list of references.

Figure 1 exemplifies such a design basis as given in an appendix to the Swedish Building Code [2]. The Figure shows a set of curves for the gas temperature of the compartment fire — for a thermally specified type of compartment — as a function of the fire-load density q and the opening factor of the fire compartment $A\sqrt{h}/A_t$. A is the total area of door and window openings, h the mean value of the heights of the openings, weighted with respect to each individual opening area, and A_t the total interior area of the surfaces bounding the compartment, opening areas

included. The fire load density q is defined per unit area of bounding surfaces A_t.

Parallel to the described progress of analytical and computational methods for the determination of the structural fire behaviour, a development is going on towards a reliability based structural fire engineering design, based on either a system of partial safety factors (practical design format) or the safety index concept. For an everyday design, a direct application of the safety index concept then is too cumbersome and the more simplified practical design formats have to be used.

Internationally, the importance of deriving national codes and design guides on a probability based structural fire design has been stressed by the CIB W14 Workshop "Structural Fire Safety", chaired by Dr Kersken-Bradley. In order to stimulate such a development, the Workshop has produced two background documents — one state-of-the-art report [1] and one model code or design guide [3].

The fundamental components of a probability based structural fire design are:
- the limit state conditions;
- the physical model;
- the practical design format;
- deriving the safety elements.

Depending on the type of practical application, one, two or all of the following *limit state conditions* apply:
- limit state with respect to load-bearing capacity;
- limit state with respect to insulation;
- limit state with respect to integrity.

For a load-bearing structure, the design criterion implies that the minimum value of the load-bearing capacity $R(t)$ during the fire exposure shall meet the load effect on the structure S, i.e.,

$$\min\{R(t)\} - S \geqslant 0 \qquad (1)$$

The criterion must be fulfilled for all relevant types of failure. The requirements with respect to insulation and integrity apply to separating structures. The design criterion regarding insulation implies that the highest temperature on the unexposed side of the structure — max $\{T_s(t)\}$ — shall meet the temperature T_{cr}, acceptable with regard to the requirement to prevent a fire spread from the fire compartment to an adjacent compartment, i.e.,
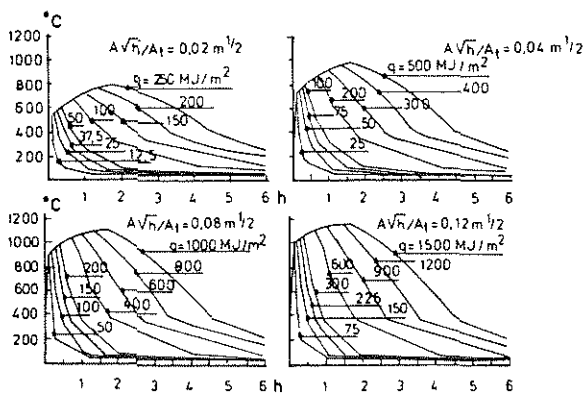

Fig. 1. Example of gas temperature–time curves for fully developed compartment fires as a function of fire-load density q and opening factor $A\sqrt{h}/A_t$. The curves apply to a fire compartment with certain specified bounding structure characteristics. Via effective values for fire-load density and opening factor, other types of bounding structure can be considered [2].

$$T_{\mathrm{cr}} - \max\{T_{\mathrm{s}}(t)\} \geqslant 0 \qquad (2)$$

For the integrity requirement, there is no analytically expressed design criterion available. Consequently, this limit state condition has to be proved experimentally, when required, in either a fire resistance test or a simplified small-scale test.

The *physical model* comprises the deterministic model, describing the relevant physical processes of the thermal and mechanical behaviour of the structure at specified fire and loading conditions. Supplemented with relevant partial safety factors, the physical model is transferred to the *practical design format*.

Figure 2 [1, 3, 4] presents the practical design format for an analytical fire design of load-bearing structures, based on the natural compartment fire concept. The process starts by a determination of the design fire exposure using the design values of the fire-load density and the fire-compartment characteristics as input data. Together with design values of the constructional data of the structure and the thermal and mechanical properties of the structural materials, the design fire exposure provides the design temperature

state and the related stress–strain state and design load-bearing capacity R_d for the lowest value of the load-bearing capacity during the relevant fire process.

The design format condition to be proved is

$$R_{\mathrm{d}} - S_{\mathrm{d}} \geqslant 0 \qquad (3)$$

where S_{d} is the design load effect at fire. Depending on the type of practical application the condition has to be verified for either the complete fire process or a limited part of it, determined by, for instance, the design evacuation time for the building.

The probabilistic influences are considered by specifying characteristic values and related partial safety factors for the fire-load density, such structural design data as imperfections, the thermal properties, the mechanical strength and the loading. The *partial safety factors* then are *to be derived* by a probabilistic analysis, based on a first-order reliability method, with the following probabilistic effects taken into account:

● the uncertainty in specifying the loads and of the model, describing the load effect on the structure;

● the uncertainty in specifying the fire load and the characteristics of the fire compartment;

● the uncertainty in specifying the design data of the structure and the thermal and mechanical properties of the structural materials;

● the uncertainty of the analytical models for the calculation of the compartment fire, the heat transfer to and within the structure and its ultimate load-bearing capacity;

● the probability of occurrence of a fully developed compartment fire;

● the efficiency of the fire brigade actions;

● the effect of an installed extinction system;

● the consequences of a structural failure.

The latter four influences, then can be accounted for by partial safety factors or differentiation factors γ_n allocated to either the design mechanical strength or the design fire load and design fire exposure.
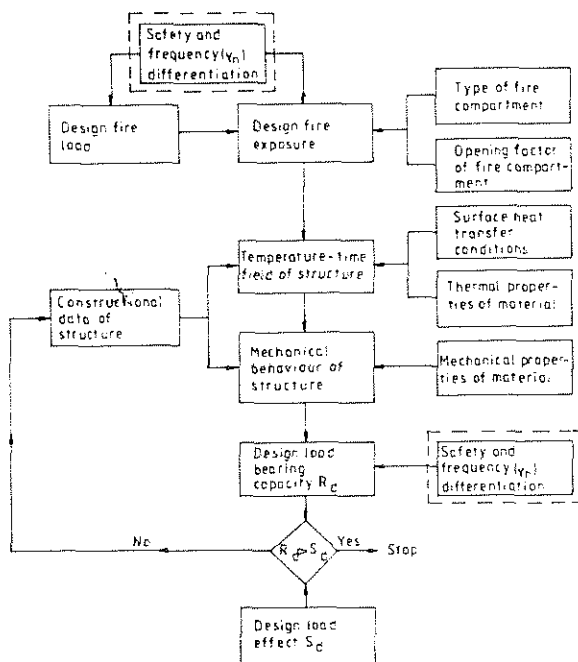

Fig. 2. Flow chart for a reliability based, analytical fire design of load-bearing structures, exposed to a compartment fire. The flow chart shows two alternative allocations of the differentiation factor γ_n [1, 3, 4].

3. MATERIAL PROPERTIES AT ELEVATED TEMPERATURES

Summing up, the process of an analytical structural fire design comprises three main

components — the determination of the design fire exposure, the thermal analysis and the structural analysis. The three components require access to well-defined input information on:

• material properties for describing the characteristics of the fire load and fire process;

• material properties for determining the transient temperature state of the fire-exposed structure;

• material properties for determining the related mechanical behaviour and load-bearing capacity.

In conformity with the subject of the Workshop, the following presentation focuses on the mechanical material properties at elevated temperatures. However, before dealing with these properties, some comments will be given on the thermal material properties required for the thermal analysis.

3.1. Thermal material properties

The transient heat flow within a fire-exposed structure is governed by the heat balance equilibrium equation, based on the Fourier law

$$\nabla^T(\lambda \nabla T) - \dot{e} + Q = 0 \tag{4}$$

$$e = \int_{T_0}^{T} \rho c_p \, dT + \sum_i l_i \tag{5}$$

$$\nabla = \begin{bmatrix} \dfrac{\delta}{\delta x} \\ \dfrac{\delta}{\delta y} \\ \dfrac{\delta}{\delta z} \end{bmatrix} \tag{6}$$

where

∇ = the gradient operator

∇^T = transpose of ∇

T = temperature

λ = symmetric positive definite thermal conductivity matrix

$\dot{e} = \delta e / \delta t$ = rate of specific volumetric enthalpy change

Q = rate of internally generated heat per volume

ρ = density

c_p = specific heat

l_i = latent volumetric heat due to phase changes at various temperature levels

x, y, z = Cartesian coordinates

t = time.

Thus, the thermal material properties required for the transient thermal analysis are identified.

The solution of the heat-balance equilibrium equation, eqn. (4), is complicated by the fact that the thermal conductivity matrix λ and the rate of specific volumetric enthalpy change $\dot{e}$ depend on the temperature T to an extent that cannot be disregarded. Further complications arise when the material undergoes phase changes during the heating and when the material has an initial moisture content.

Well-defined measurements of the thermal conductivity λ for moist materials are difficult to undertake within the temperature range relevant at fire exposure, due to the complicated interaction between moisture and heat flow. As concerns the enthalpy e, the way evaporable water reacts to pressure has not been experimentally clarified and consequently, this influence has to be included in a simplified manner in calculating the transient temperature state of a fire-exposed structure. Usually, all moisture is assumed to evaporate, without any moisture transfer, at the temperature 100 °C or within a narrow temperature range with the heat of evaporation giving a corresponding discontinuous step in the enthalpy curve. This simplification has proved to give acceptable results for most practical situations.

In reality, the evaporation of moisture in a fire-exposed material is not comparable to that of a free-water surface. Capillary forces, adhesive forces, and interior steam pressure will allow the temperature to increase during evaporation. In a fire-exposed structure, the moisture distribution changes continuously during heating. Hence, in principle, it is not correct to include the effect of moisture content in the thermal properties. For a moist material the heat transfer is combined with moisture transport and, from a strict thermo-dynamical point of view, these two transport mechanisms should be analysed simultaneously by a system of related partial differential equations. Consequently, the heat-balance equilibrium equation, eqn. (4), constitutes an approximation when solely applied to fire-exposed structures made of materials that contain moisture.

For materials used, for instance, for *fire protection* of steel structures, there are test methods developed for a determination of derived values characterizing the thermal material behaviour of a product at fire exposure in an integrated way, including the influence of initial moisture content, crack formations, disintegration of materials, and partial failure of the product and its fastening devices, if any. The derived values then are normally obtained from test results by the use of some simplified analytical simulation model. Consequently, such values do not represent any well-defined material or product properties but are influenced also by the characteristics of the analytical model, adopted for the evaluation. This leads to limitations with respect to a generalized application of the derived values.

3.2. Mechanical material properties

A reliable calculation of the mechanical behaviour of a *fire-exposed* structure or structural element on the basis of the transient temperature state requires access to validated models for the mechanical behaviour of the materials involved within the temperature range associated with fires.

In computer programmes for a structural fire analysis, it is not unusual that the material model for the mechanical behaviour is specified by temperature-dependent stress–strain curves which indirectly include the creep strains and transient strains. Figure 3 exemplifies such a model for normal concrete with siliceous aggregates [5]. The stress–strain curves then are determined either from small-scale material tests or from full-scale tests on that type of load-bearing structure, for which the computational procedure is developed.

Such a technique may be acceptable as an intermediate solution. In a long-term perspective, it is important that the material behaviour models are so formulated that they are independent of type of load-bearing structure and based on input information received from functionally well-defined material tests.

Available tests for a determination of the mechanical material properties at elevated temperatures can mainly be divided into steady-state tests and transient-state tests, see Fig. 4 [6]. Fundamental parameters are the heating process, application and control
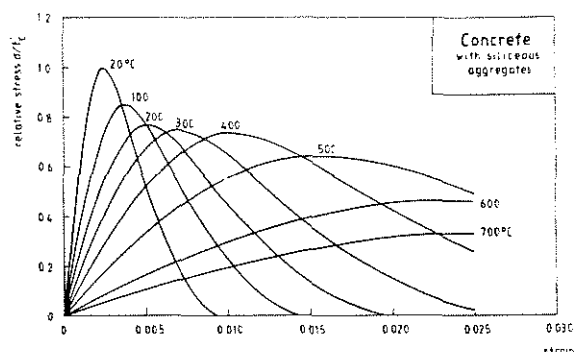

Fig. 3. Stress–strain curves at elevated temperatures for concrete with siliceous aggregates. f'_c = compressive strength at 20 °C [5].
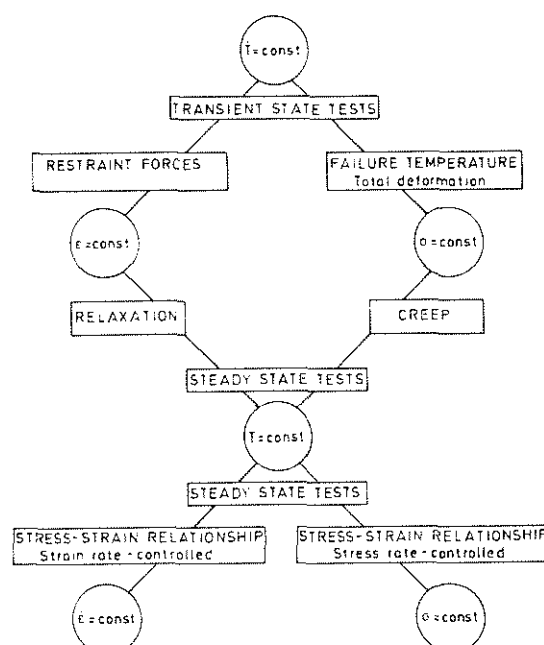

Fig. 4. Different testing regimes for determining mechanical properties of materials at elevated temperatures [6].

of load, and control of strain. These can have constant values or be varied during the test. The following six practical regimes are defined:

● *Steady-state tests*, giving
— stress–strain relationship under stress-rate control ($\dot{\sigma}$ = const);
— stress–strain relationship under strain-rate control ($\dot{\epsilon}$ = const);
— creep under stress control (σ = const.);
— relaxation under strain control (ϵ = const);
● *Transient state tests*, giving
— failure temperature and total deformation under stress control (σ = const);
— restraint forces and total forces under strain control (ϵ = const).

The material properties measured are closely related to the test method used. Consequently, it is extremely important that the test results always are accompanied by an accurate specification of the test conditions applied. For steel, there is an analytical modelling technique available enabling a transfer of results from steady-state to transient-state tests, and vice versa [6].

For *steel*, validated mechanical behaviour models for transient, high-temperature conditions have been available for many years: cf., for instance refs. 6 - 11. The models divide the total strain into thermal strain, instantaneous stress-related strain and creep strain. Some of the models operate with temperature-compensated time according to Dorn [7].

For *concrete* the deformation behaviour at elevated temperatures is much more complicated than for steel. Stressed concrete involves special difficulties since considerable deformations develop during the first heating which do not occur at steady-state temperature conditions.

For practical applications, the total strain ϵ can adequately be given as the sum of four strain components, defined with reference to accurately specified tests and depending on the temperature T, the stress σ, the stress history $\tilde{\sigma}$, and the time t. For concrete, stressed in compression, the following constitutive equation applies [12]

$$\epsilon = \epsilon_{th}(T) + \epsilon_\sigma(\tilde{\sigma},\sigma,T) + \epsilon_{cr}(\sigma,T,t)$$

$$+ \epsilon_{tr}(\sigma,T) \tag{7}$$

where

ϵ_{th} = thermal strain, including shrinkage, measured on unstressed specimens under variable temperature

ϵ_σ = instantaneous, stress-related strain, based on stress–strain relations, obtained at a rapid rate of loading under constant, stabilized temperature

ϵ_{cr} = creep strain or time-dependent strain, measured under a constant stress at constant, stabilized temperature

ϵ_{tr} = transient strain accounting for the effect of temperature increase under stress, derived from tests under constant stress and variable temperature.

For stressed concrete in a transient high-temperature state, the transient strain component ϵ_{tr} normally plays a predominant role,
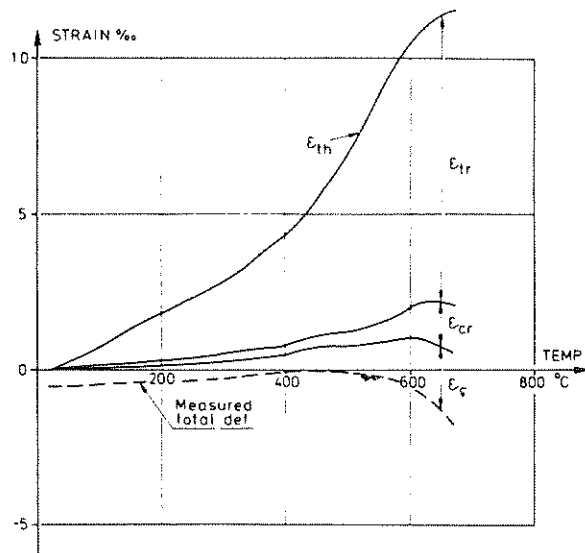

Fig. 5. Total deformation and relation between different strain components for a heat-exposed concrete specimen, axially loaded in compression to a stress level equal to 35% of the ambient temperature strength. Rate of heating 5 °C min^{-1} [12].

see Fig. 5 [12]. Parameter formulations are available for each of the strain components as well as a practical guidance on the application of the material behaviour model at a time-varying stress and temperature state [12]. An alternative model formulation of the mechanical behaviour of concrete at transient elevated temperatures is derived in ref. 13. A comprehensive state-of-the-art report on the mechanical properties of concrete under high temperature exposure is given in ref. 14.

In ref. 15, an attempt is made to formulate a multi-axial constitutive model for concrete in the temperature range up to 800 °C. The model can be characterized as isotropic, elastic–viscoplastic–plastic in the compression region. Brittle failure is assumed in the tensile region.

Access to a structure-independent, functionally well-defined material behaviour model of the kind exemplified, enables a general application to different types of structures. An example is shown in Fig. 6 [16, 17] which presents the time curves of the axial restraint force, calculated by the use of the computer programme CONFIRE by Forsén, for a simply supported concrete slab at different permissible axial expansions ΔL = 0, 2, 4 and 6 mm, followed by a complete restraint against further expansion. The slab is thermally exposed from below according to the standard
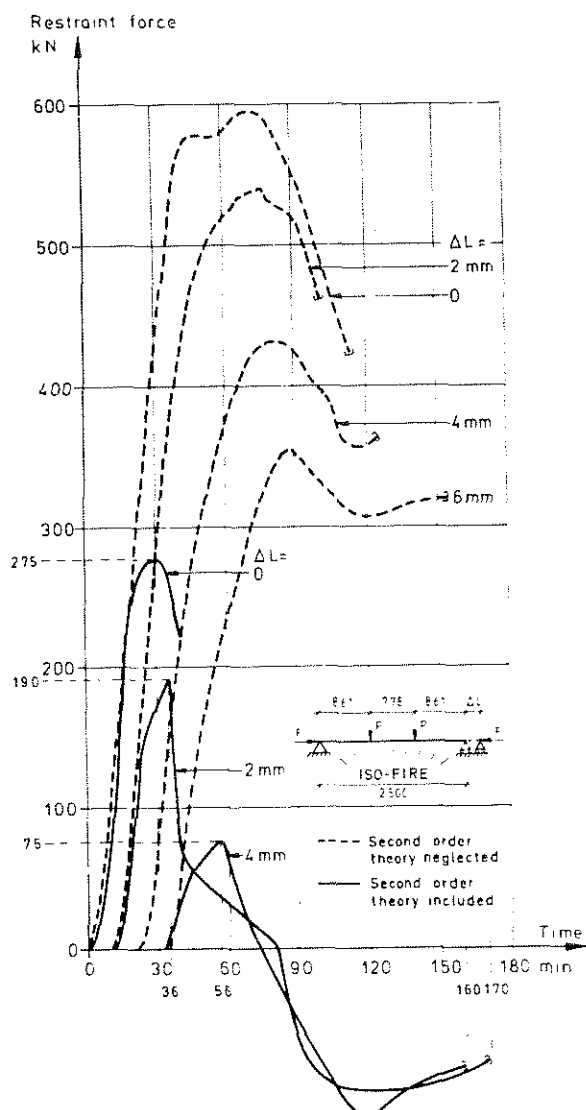
of fire-exposed load-bearing structures has now been developed so far that it comprises most types of frequent structures and structural elements. Combined with test results, this development has considerably improved our understanding of the physical processes of the structural fire behaviour. The development has given the basis from which we now can move from the present schematic fire design towards a probability based, analytical design, directly related to the natural compartment fire exposure [18]. The qualitative success of this change of design approach depends on the reliability of the input data and of the models, simulating the fire exposure, the loading conditions, and the thermal and mechanical behaviour of the structure. Well-defined and structure-independent material data and material behaviour models constitute an important prerequisite for this success. High priority should also be given to sensitivity studies of the contribution of the various design components to the total structural fire safety and a related improvement of the probabilistic basis of the design.

Fig. 6. Calculated restraint force F for s simply supported, concrete plate strip at different permissible, axial expansion ΔL, followed by a complete restraint. Thermal exposure from below according to the standard fire resistance test [16, 17].

fire resistance test. The second-order effects are included in the full-line curves but neglected in the dash-line curves. The great difference between the two sets of curves emphasizes the necessity of including these effects in analysing a structural fire behaviour of this kind.

4. CONCLUDING REMARKS

The analytical and computational modelling of the thermal and mechanical behaviour

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