Structural Fire Safety - As exemplified by a Swedish Manual for Analytical Design

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STRUCTURAL FIRE SAFETY - AS EXEMPLIFIED BY A SWEDISH MANUAL FOR ANALYTICAL DESIGN

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INTRODUCTION

For a fire engineering design of load bearing structures and partitions, an analytical procedure is permitted to be applied in Sweden, as one alternative, since about ten years. The procedure is a direct design method based on temperature characteristics of the fully developed compartment fire as a function of the fire load density, ventilation of the fire compartment and thermal properties of the structures enclosing the fire compartment. The method is approved for a general use by the National Swedish Board of Physical Planning and Building (1). For facilitating the application, design diagrams and tables are systematically produced, giving directly, on one hand, the design temperature state of the fire exposed structure, on the other, a transfer of this information to the corresponding design load bearing capacity of the structure; cf., for instance (2), (3), (4).

The analytical design procedure is now further developed towards a reliability based method in connection with a Swedish handbook project in progress on fire exposed concrete structures (5).

The method is related to a semi-probabilistic approach based on a system of partial safety coefficients. The functional requirement then implies that the design value of the minimum load bearing capacity of the structure during the fire exposure R_d shall meet the design load effect on the structure S_d, i.e.

$$R_d - S_d \geq 0 \tag{1}$$

The functional requirements apply to all relevant types of failure - bending failure, shear failure, instability failure, etc.

In the design, the following probabilistic influences should be taken into consideration:

* the uncertainty in specifying the statical loading,
* the uncertainty in specifying the fire load and the characteristics of the fire compartment,
* the uncertainty in specifying the thermal and mechanical properties of the structural materials,
* the uncertainty of the models for calculation of the compartment fire, the heat transfer to and within the structure and the ultimate load bearing capacity of the structure, and
* the consequences of a structural failure.

DESIGN PROCEDURE

In a summary way, the Swedish design procedure under development can be described as follows - Fig. 1.

The design fire load density, the fire compartment characteristics, and the fire extinguishment systems constitute the basis for the determination of the design fire exposure, given as the gas temperature-time curve T-t of the fully developed compartment fire. Depending on the type of practical application, the load bearing function of the structure will be required to comply with either the complete fire process or a limited part of the fire process t_d, determined from the time necessary for the fire to be extinguished under the most severe conditions, or from the design evacuation time for the building.

Together with the structural design data, the design thermal properties and the design mechanical strength of the structural material, the design fire exposure provides the design temperature state and the related design load bearing capacity R_d for the lowest value of the load bearing capacity during the relevant fire process.

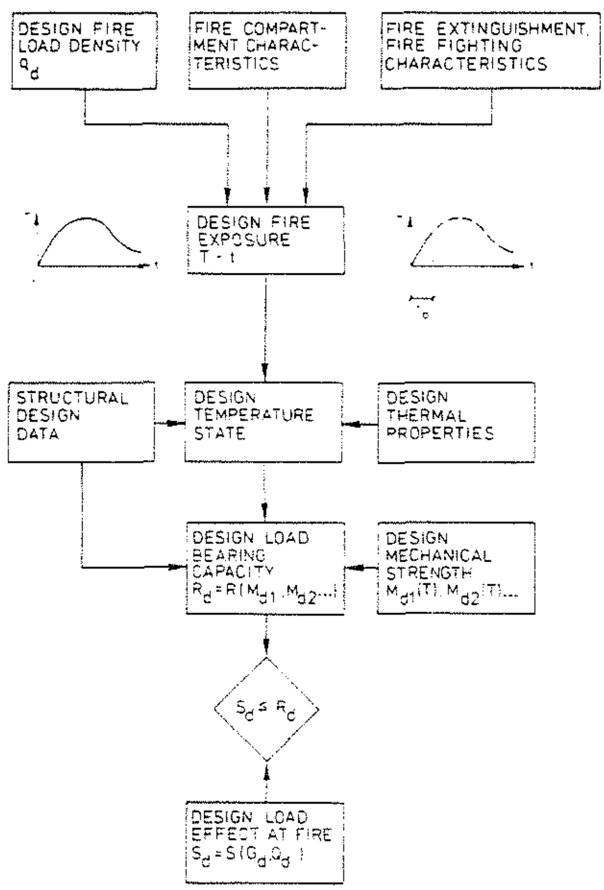

Fig. 1. Reliability based, structural fire engineering design procedure

A direct comparison between the design load bearing capacity R_d and the design load effect at fire S_d finally decides whether or not the structure or structural member can fulfil its required function on exposure to fire - Eq. (1).

Design Fire Exposure, Categories of Structures

The functional requirements to be laid down for a fire engineering design should be differentiated with respect to such effects as the occupancy, the height and volume of the building, and the importance of the structure or structural member to the overall stability of the building. In the Swedish method this is done by dividing the structures or structural members into four categories with a related differentiation of the design fire load density and the length of the fire exposure to be considered in the design according to table 1. The design fire load density q_d is specified in relation to the characteristic fire load density q_k defined as that value corresponding to a probability in excess of 20%. The related gas temperature-time curves of the fire exposure are specified in accordance to Fig. 2 as a function of the fire load density q and the opening factor of the fire compartment $A\sqrt{h}/A_t$, where A = total area of window and door openings, h = mean value of the opening heights, weighted with respect to each individual opening area, and A_t = total interior area of the surfaces, bounding the compartment, opening areas included.

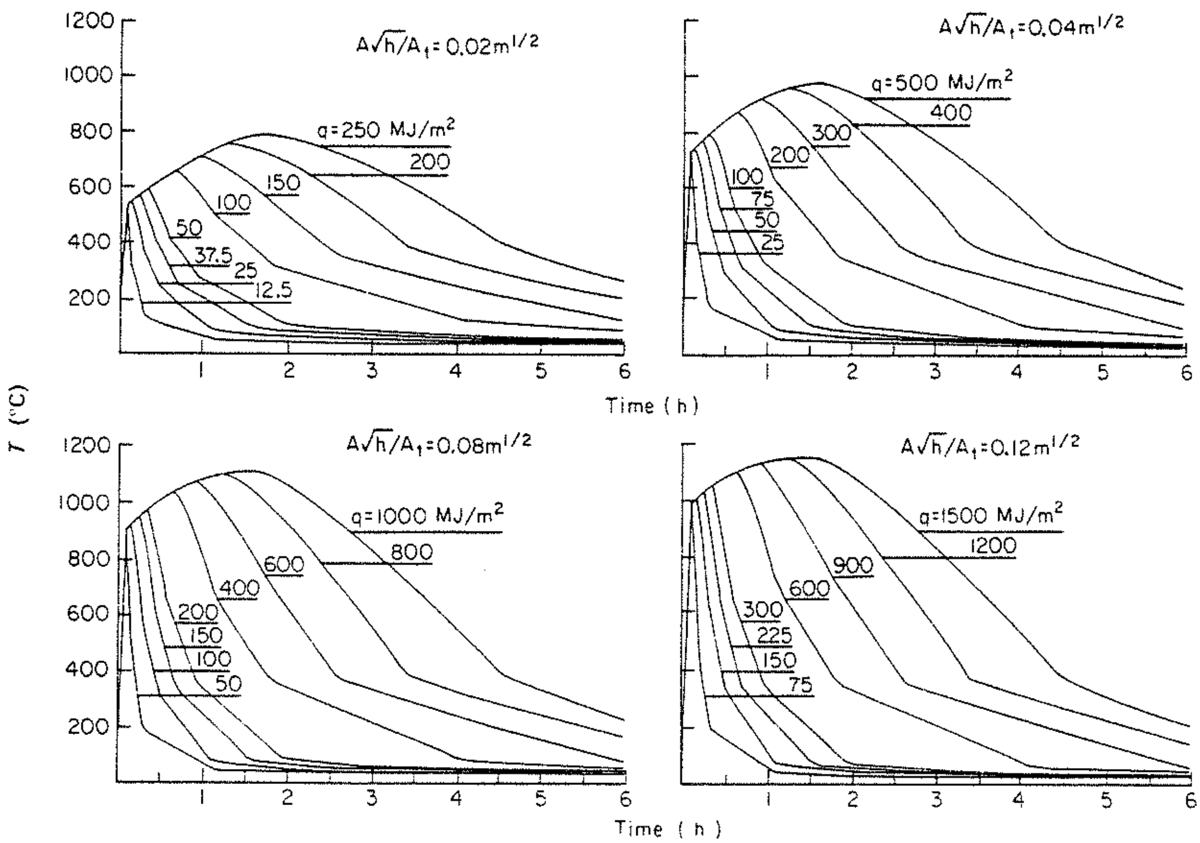

Fig. 2. Gas temperature-time curves of complete process of fire development as function of fire load density q and opening factor $A\sqrt{h}/A_t$. Fire compartment, type A

The gas temperature-time curves in Fig. 2 apply to a certain fire compartment, type A, defined with respect to the thermal properties of the bounding structures. Fire compartments with bounding structures of deviating thermal properties can be transferred to fire compartment, type A, via effective values of the fire load density and the opening factor, (1)-(5).

Category of structural member	Design fire load density q_d	Duration of fire exposure
K 0	-	-
K 1	1.0 q_k	≤ 30 min
K 2	1.0 q_k	complete fire process
K 3	1.5 q_k	" " "

Table 1. Design fire exposure, expressed by design fire load density q_d and duration of fire exposure

The probability and consequences of a fire outbreak are strongly influenced by various types of active fire protection measures. The present version of the method does not allow for such influences to be included in any detailed way. Discussions are in progress concerning whether the presence of an approved sprinkler system could be taken into account in a rough way by a transfer of a structure or structural member to the next lower category.

Design Load Effect and Design Load Bearing Capacity

The design consists of an analysis of simultaneous exposure to static loading and fire, dealt with as an accidental case. The determination of the design load effect S_d then follows the procedure according to Fig. 3. The characteristic value of the permanent load G_k is chosen as the average, and the characteristic value of a variable load F_k as that corresponding to a

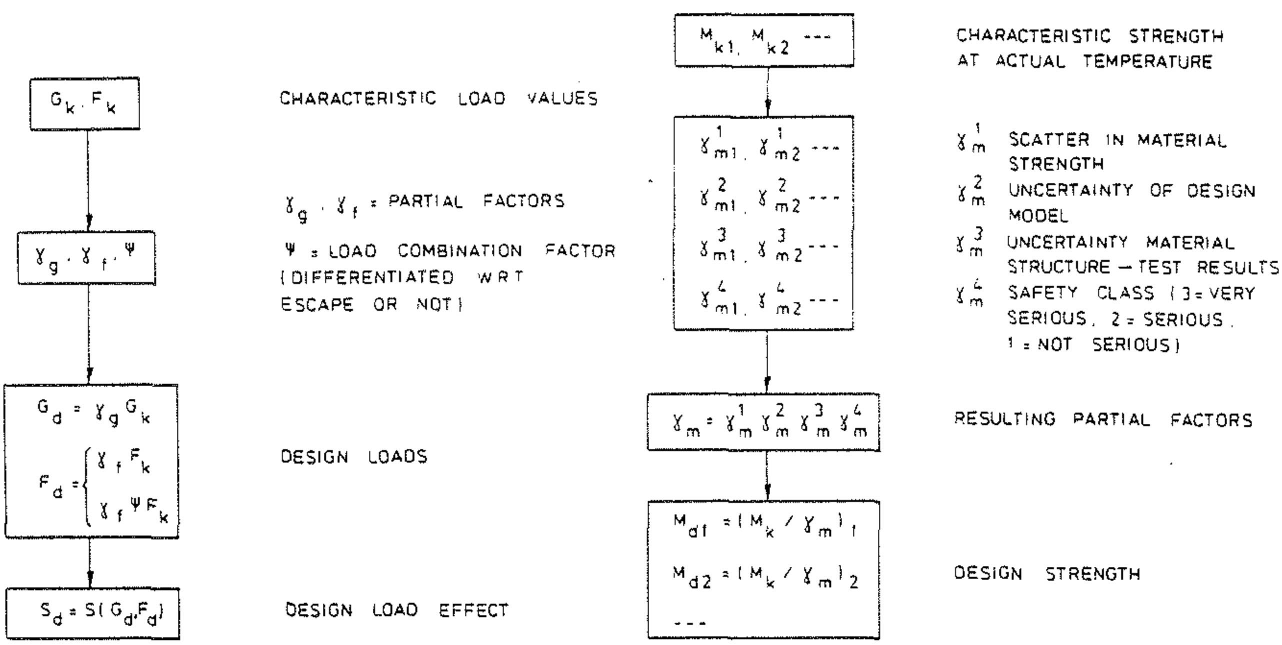

Fig. 3. Determination of design load effect S_d and design strength M_d

probability of excess at least once a year. The characteristic F_k values may be differentiated with respect to whether a complete evacuation of people can be assumed or not in the event of fire.

In a design for the ultimate limit state, the determination of the design strength M_d follows the procedure shown in Fig. 3, defining four partial factors γ_m^1, γ_m^2, γ_m^3, and γ_m^4.

By introducing various categories of structure and structural member when specifying the design fire load density and the design fire exposure, the influence of different safety classes is already covered. Consequently, the partial factor γ_m^4 is to be made equal to 1 in the fire design.

Values of M_k and γ_m, to be applied in a fire design of reinforced concrete structures, are given in the Swedish regulations (6).

THERMAL AND STRUCTURAL RESPONSE

During the last decade, considerable progress has taken place on the development of validated material models for the thermal and mechanical behaviour of concrete at transient high-temperature conditions and verified computer programs for the behaviour and load bearing capacity of different types of fire exposed, reinforced and prestressed concrete structures have been published (7)-(13). Consequently, an analytical basis now exists for dealing with most types of common concrete structures under fire exposure. For the ultimate load bearing capacity, this is primarily so with respect to failure in bending. For other kinds of failure - shear, bond, anchorage and spalling - the present state of knowledge is still unsatisfactory and in a practical fire engineering design, it is therefore important to detail the structure in such a way that these types of failure will have a lower probability of occurrance than the bending failure.

As the structural behaviour of most types of fire exposed concrete structures is very complicated, it is important for the practical application that simplified design rules and methods are developed. Such a method is presented in (5) for an analytical determination of the ultimate bending moment capacity of a reinforced concrete member under fire exposure. The method is based on the hypothesis that concrete exposed to more than 500°C can be neglected in a calculation of the load bearing capacity of a reinforced concrete section with respect to axial load, bending moment and their combinations, while concrete with lower temperature can be assumed to retain the ordinary room temperature strength. The hypothesis has been verified by a comprehensive analytical study of the behaviour and load bearing capacity of different types of cross-sections, loaded by a bending moment or a compressive force or combinations of both and exposed to fire symmetrically or unsymmetrically.

On the basis of this approach, the fire design procedure for a reinforced concrete structure or structural member will generally be as follows:

(1) determine the isotherm of 500°C for the specified fire exposure - facilitated by the availability of design tables and diagrams, presented in (3)-(5),

(2) determine a new width b' and a new effective height d' of the cross-section by excluding the concrete outside the 500°C isotherm,

(3) determine the temperature of reinforcing bars in the tension and compression zones,

(4) determine the critical stress due to the temperature for the tension and compression reinforcement - for the tension reinforcement design diagrams as exemplified in Fig. 4 are available (5),(14), for the compression reinforcement, it is recommended to use the 0.5% proof stress, $\sigma_{0.5}(T)$,

(5) use conventional calculation methods for the reduced cross-section for the determination of the ultimate bending moment capacity with stresses of the reinforcing bars, as obtained in (4),

(6) apply the bending moment capacities, determined according to (5), to the decisive cross-sections for a determination of the ultimate load bearing capacity of the structure or structural member, and

(7) compare the ultimate load bearing capacity with the design load effect.

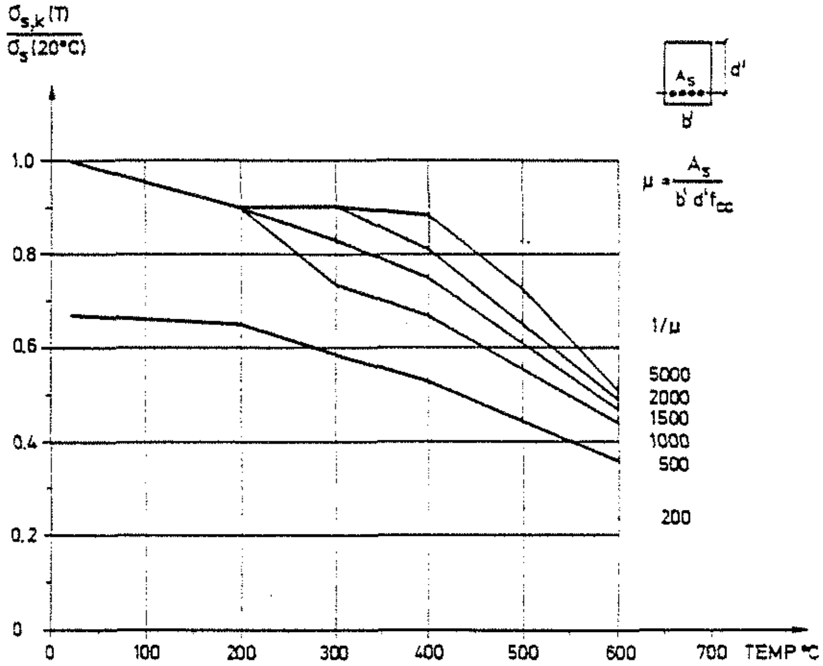

Fig. 4. Critical stress $\sigma_{s,k}(T)$ for tensile reinforcement of hot-rolled steel as a function of temperature of the reinforcement and $1/\mu$. $\sigma_s(20^oC)$= design value of yield stress at ordinary room temperature. In formula for μ, A_s is in m^2, b' and d' in m, and f_{cd} (design compressive strength of concrete) in MPa (5), (14)

The application of an ultimate limit state approach to a fire exposed, continuous, reinforced concrete beam or slab requires that the thermally induced restraint stresses and moments are reduced to zero at the failure of the structure, or, alternatively, that the cross-sectional rotations caused by the thermal gradient must be less than the rotational capacity of the fire exposed structure. Comprehensive experimental and analytical studies confirm that the rotational capacity ordinarily is sufficient. An ultimate limit state approach, however, must be applied with great care if high quality steels with a good bond but low ductility is used for the negative reinforcement over the supports (14).

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STRUCTURAL FIRE SAFETY - AS EXEMPLIFIED BY A SWEDISH MANUAL FOR ANALYTICAL DESIGN

by Ove Pettersson

SUMMARY

During the last decade, a rapid progress has been made in the development of validated analytical models for the thermal and mechanical behaviour of fire exposed structures and structural members. In a long-term perspective, the development now goes towards an analytical design, directly based on a natural fire exposure and specified with respect to the combustion characteristics of the fire load and the geometrical, ventilation, and thermal properties of the fire compartment. Internationally, the development then includes a probabilistic approach, based either on a system of partial safety coefficients or the safety index concept.

The paper describes the basic characteristics of an analytical method for a structural fire engineering design starting from the natural fire exposure and related to the semi-probabilistic approach via partial safety coefficients. The consequences of a structural failure are considered by dividing the structures or structural members into categories with a differentiation with regard to the design fire load density and length of fire exposure. The application is briefly exemplified on the basis of a Swedish manual, in preparation, for fire exposed reinforced concrete structures.

SÉCURITÉ DE LA CONSTRUCTION FACE À L'INCENDIE - ILLUSTRÉ PAR UN MANUEL SUÉDOIS DU CALCUL THÉORIQUE

par Ove Pettersson

SOMMAIRE

Pendant la dernière dizaine d'années, un progrès rapide a été fait concernant le développement des modèles analytiques validés pour le comportement thermique et méchanique des structures et des éléments de structures exposés au feu. A long terme le développement est dirigé vers le calcul théorique, fondé directement sur l'incendie naturelle et specifié par les charactéristiques de la combustion de la charge-incendie, les charactéristiques de ventilation et les propriétés thermiques du compartiment au feu. Internationalement le développement alors comprend un rapprochement probabilistique, fondé sur un système des coefficients partiels de sécurité ou de l'index de sécurité.

La dissertation traite les charactéristiques fondamentales d'une méthode analytique au feu pour les structures porteuses, partante de l'incendie naturelle et relatée au rapprochement semi-probabilistique via des coefficients partiels de sécurité. Les conséquences d'une rupture de structures sont considérées en classifiant les structures et les éléments de structures en catégories differenciées d'après la densité de charge-incendie et la durée de l'incendie. L'application est brèvement illustrée dans le domaine des structures en béton armé exposées au feu, se fondant sur un manuel Suédois en préparation.

ANALYTISCHE SICHERHEITSNACHWEISE VON BAUKONSTRUKTIONEN - EXEMPLIFIZIERT DURCH EIN SCHWEDISCHES HANDBUCH

von Ove Pettersson

ZUSAMMENFASSUNG

Während des letzten Jahrzehntes sind die verifizierten, analytischen Methoden für die Berechnung der thermischen und mechanischen Wirkung feuerbeanspruchter Baukonstruktionen schnell entwickelt worden. Auf lange Sicht geht nun die Entwicklung in die Richtung gegen analytische Methoden, die von den Eigenschaften des Naturbrandes unter Berücksichtigung der Brandbelastung, der Ventilationsverhältnisse des Brandabschnittes und der Wärmedämmung der Umfassungsbauteile ausgehen. Die Methoden sind entweder deterministisch oder auf Wahrscheinlichkeitstheorie gegründet.

In der vorliegenden Arbeit wird ein analytisches Nachweisverfahren für die brandschutztechnische Bemessung von Baukonstruktionen kürzlich beschreibt. Das Verfahren ist semi-probabilistisch und auf den zeitlichen Verlauf der Raumtemperaturen während eines natürlichen Schadenfeuers basiert. Die Konsequenzen von einem Versagen des Bauteiles werden durch ein System von Kategorien der Bauteile berücksichtigt, wobei die Brandbeanspruchung in Hinsicht auf die dimensionierende Brandbelastung und Branddauer differentiiert worden ist. Die praktische Anwendung ist kürzlich von einem Schwedischen Handbuch bezüglich brandbeanspruchter Betonkonstruktionen erläutert.