Some Factors and Aspects of a New Structural Design System of Fire Exposed Building Components. A Combined Deterministic and Probabilistic Study

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SOME FACTORS AND ASPECTS OF A NEW STRUCTURAL DESIGN SYSTEM OF FIRE-EXPOSED BUILDING COMPONENTS. A COMBINED DETERMINISTIC AND PROBABILISTIC STUDY

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Lund Institute of Technology, Sweden, 1974

Acknowledgements

As regards the papers /A/, /B/ and /C/, Magnusson is responsible for the computer program and the numerical problems connected with the programming. In /A/, chapter 3, some aspects on the rate of gas flow originate from a graduate thesis by Ahlquist & Thelandersson. Otherwise the work accounted for in /A/, /B/ and /C/ has been carried out in close cooperation between the authors and it is virtually impossible to specify individual contributions.

Some Factors and Aspects of a New Structural Design System of Fire-Exposed Building Components. A Combined Deterministic and Probabilistic Study.

This thesis comprises the following publications

/A/	Sven Erik Magnusson Sven Thelandersson	Temperature-Time Curves of Complete Process of Fire Development. Theoretical Study of Wood Fuel Fires in Enclosed Spaces. Acta Polytechnica Scandinavica, Ci 65, Stockholm 1970
/B/	Sven Erik Magnusson Sven Thelandersson	Comments on Rate of Gás Flow and Rate of Burning for Fires in Enclosures, Division of Structural Mechanics and Concrete Construction, Lund Institute of Technology, Bulletin 19, Lund 1971
/C/	Sven Erik Magnusson Sven Thelandersson	A Discussion of Compartment Fires. Fire Technology, Vol. 10, No. 3, August 1974
/D/	Sven Erik Magnusson	Probabilistic Analysis of Fire Exposed Steel Structures, Division of Structural Mechanics and Concrete Construction, Lund Institute of Technology, Bulletin 27, Lund 1974

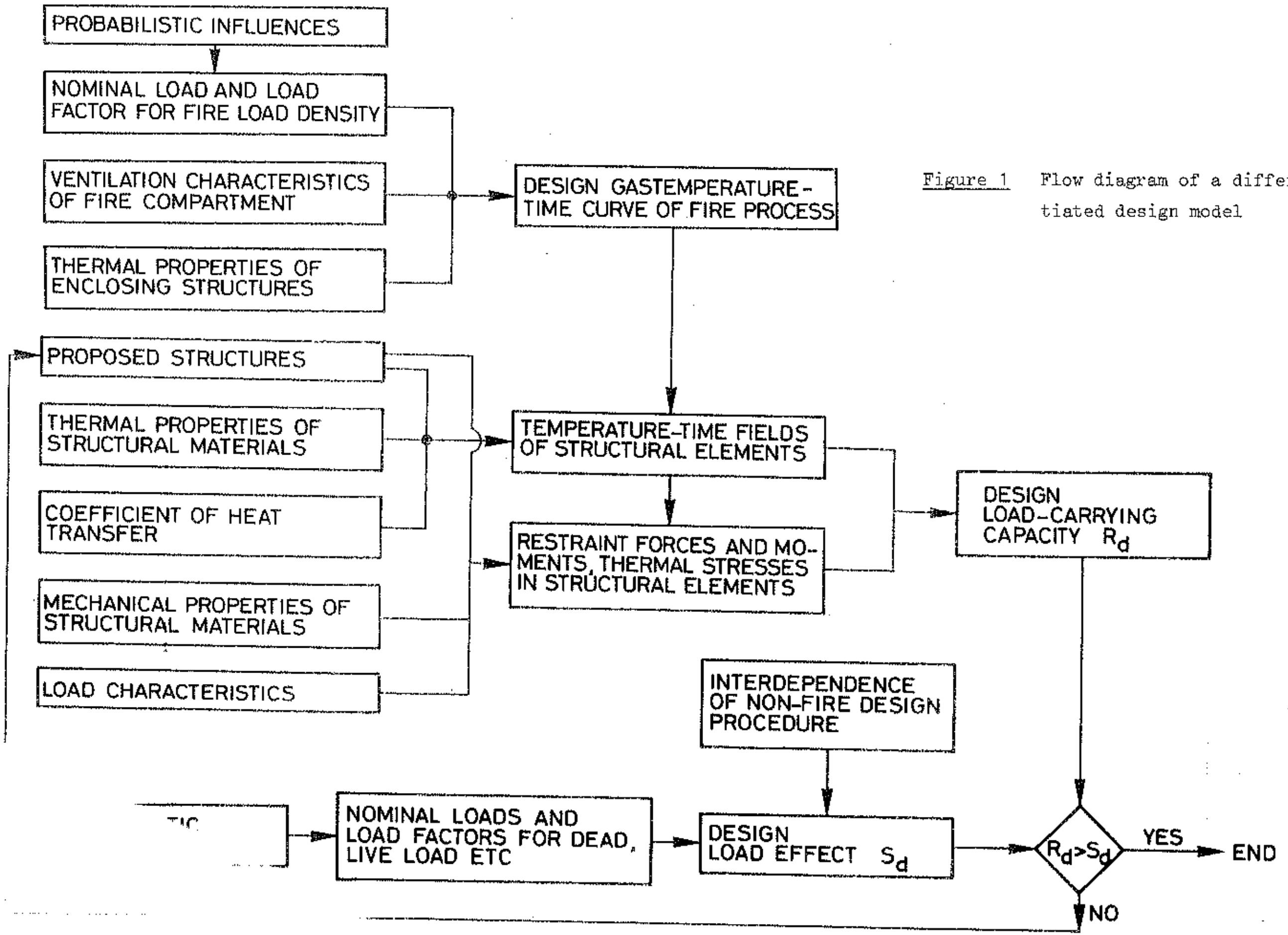
Introduction

The cost of fire-protective measures of an ordinary Swedish office steel building constitutes a substantial percentage of the total cost of the load-carrying system.

The percentage allocated to secure a fire safe building must be related to the degree of sophistication inherent on one hand in the normal temperature design, on the other hand in the standard fire resistance design. The discrepancy is obvious. The basic rules determining the standard fire design procedure are derived by Ingberg /1/ in his pioneer burn-out experiments during the 1920's. Evaluation of these tests led to the still universal standard design method of measuring the fire resistance as endurance time in a furnace test with fixed temperature-time curve. The endurance time required by the code specifications is in general related to only one of the parameters governing the fire behaviour, the fire load density. Ingberg in his experiments observed the influence coming from the ventilation conditions of the fire compartment but made no effort to evaluate the actual effect.

After these early National Bureau of Standard experiments, the next major developments in this area were to come from Japan. Fujita started his work in 1940, and his studies were continued by Kawagoe, Yokoi, Sekine and others (see e.g. /2/, /3/). The Japanese were the first to make an investigation of the gas flow and energy balance conditions of a compartment fire. The first report written in English was issued in 1958 /2/ and not widely distributed. The first explicit statements of a heat balance model of the compartment fire process were made in 1963 /3/, /5/. These two independent studies by Kawagoe - Sekine and Ödeen presented similar computational models of the natural, fully-developed fire behaviour. The 1960's meant a heavy increase of the research activities in this area with major studies e.g. performed at Fire Research Station, London by Thomas, Law, Heselden and co-workers /7/.

Regarding the over-all structural design problem, Pettersson in 1965 presented a comprehensive state-of-art review /6/. As a result of



<u>Figure 1</u> Flow diagram of a differentiated design model

this study a design model was proposed, based on the natural fire behaviour and on the actual response of structural materials and structural components to fire exposure /6/. See Figure 1. In consequence, the Swedish Building Code from 1967 (SBN 67) explicitly permits the more advanced designed procedure sketched in Figure 1. So far Sweden is the only country allowing a general application of such a design system, but there are manifest signs indicating an international development according to the outlined principles.

It is evident that a change form one design model (standard fire endurance test) to another (the differentiated model in Figure 1) is only motivated if the latter procedure results in final reliability levels that are improved with respect to uniformity or consistency. Of the different components of the design model given by Figure 1, the theoretical analysis of the compartment fire process has internationally been given special interest and discussion in detail. The first three papers /A/, /B/, /C/ are devoted to the problem of establishing a deterministic model of the complete wood fuel fire process. The last paper /D/ presents a systematized procedure for a probabilistic analysis of the structural safety of fire exposed load-carrying steel components. An important part of this paper will demonstrate how the final system uncertainty may be decomposed into a sum of component uncertainties, making it possible to discuss the reliability of the proposed fire process model within the frame of the over-all reliability.

A Theoretical Model of Compartment Fire Behaviour

The heat- and mass-balance model of the compartment fire process derived by Kawagoe - Sekine and Ödeen is shown in Figure 2, where

I_C = rate of heat release by combustion,

I_L = rate of heat loss by convection in the openings,

I_W = rate of heat loss through bounding walls, floor and ceiling,

I_R = rate of heat loss by radiation through the opening.

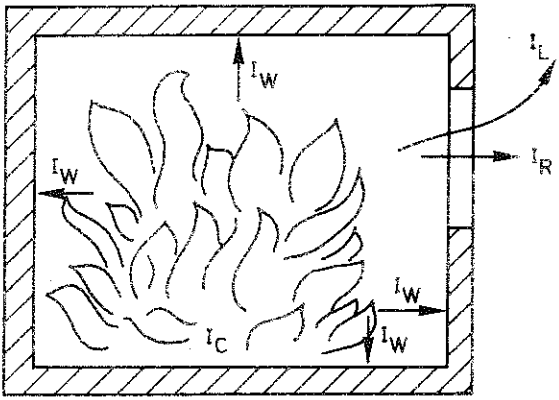


Figure 2 Illustration of heat- and mass-balance equation

The gastemperature-time curve of the fire process is given in a step by step solution in time of the equation

$$I_C = I_L + I_W + I_R \qquad (1)$$

When Thelandersson's and the author's study started in 1968, no valid connection had been obtained between the complete natural fire process (the decay or cooling down period included) and the constructed heat balance models. Of the four terms in Eq. (1), I_W and I_R are of minor importance and are described with sufficient accuracy by classical heat transfer formulas. More difficult to analyze are I_C and I_L. Kawagoe - Sekine /3/ computed I_L by assuming fire compartment openings with a neutral pressure level and a constant pressure gradient. With these assumptions, the gas flow was shown to be proportional to the ventilation factor $A\sqrt{h}$, where

A = area of openings (doors, windows)

h = an averaged height of these openings.

Assuming the combustion to be controlled by the ventilation, the maximum rate of burning R_{max} could be evaluated

$$R_{max}/A\sqrt{h} \approx 5 - 6 \text{ kg} / (\text{min}\cdot\text{m}^{5/2}) \qquad (2)$$

The actual gastemperature-time curve comprising an ignition, flame and cooling down phase was replaced by a time curve computed on the basis of a constant rate of burning = R_{max} for a duration M/R_{max}, where

M = the original amount of combustibles in kg

The decay period was simulated by prescribing fixed linear rates of temperature decrease. In a later publication from 1967 /4/, the conservatism of this approximation was acknowledged and an effort made to compute the decay part of the process. There was no attempt to correlate experiment and theory and as a conclusion, it was stated that "if the safety duration is necessary, it should be added on the fire duration .... instead of inclusion of unreasonable and uncertain decay line into the estimation of temperature time curve". In a design procedure, these curves were to be used by equating areas above a certain threshold value of the gastemperature, i.e. principally the approach used by Ingberg. The Ödeen studies were also based on constant rates of burning R, with no coupling between R and size of ventilation factor $A\sqrt{h}$.

The natural way of improving our knowledge of the temperature-time curve of the fire process is to take a closer look at the basic physical and chemical laws governing the process. A depressing array of basic unsolved combustion and heat transfer problems immediately materializes. Some of these lacking relations are listed in a recent survey paper by Emmons /8/.

- general equations for the flow of multicomponent gas mixtures with heat conduction, diffusion, viscous friction, and radiation exchange
- general equation system for the movement of reacting pyrolysis products through a piece of partially decomposed wood

As a consequence, it will soon be abundantly clear to the ambitious researcher that "when we observe that all these phenomena occur intimately intermixed in a complex geometry, an expert in any field immediately abandons fire to the hapless and returns to his specialty for a "reasonable" problem".

This remark refers to the over-all environmental analysis of fire initiation and spread. Looking at fire from a structural engineering point of view (see Figure 1) many detail problems are of negligible importance due to the fact that our attention will be limited to the steady burning of a fully developed compartment fire and its impact on structural components. But even with this restriction, we are forced to recognize that our knowledge of the heat transfer and combustion phenomena taking place admits only a simplified analysis. To the author's knowledge, there is only one paper taking a more advanced equilibrium combustion theory into account /10/. The paper does not include any correlations between theory and experiment. At the same time, a systematic approach based on experiments is met with difficulties. The number of variables, some of which interact in an unknown way, implies that the necessary quantity of tests will be prohibitive. All these factors led to the conclusion that a simplified theoretical approach was justified and, as a matter of fact, the only possible alternative.

The greatest uncertainties in Eq. 1 were related to the term I_C and, to a smaller extent, to the term I_L. Regarding I_C, both its instantaneous value and the time integral $\int_0^\infty I_C dt$ are unknown. The latter quantity determines the average degree of complete combustion or the average effective heat value of the fuel. The time curve of I_C varies in a complex way with a number of factors. There are three main parameters governing the behaviour of the natural compartment fire: size and form of ventilation openings, amount of combustible material and the fire exposure geometry, mainly porosity and specific surface area, of this material. For sufficiently small values of the ventilation factor $A\sqrt{h}$ combined with high values of the fire load, or rather fire exposed surface area A_f, very extensive test series have shown that the maximum rate of burning R_{max} is approximately given by Eq. 2, which was derived by theoretical combustion analysis. The process is called "ventilation-controlled". For larger values of the ratio $A\sqrt{h}/A_f$ where the available air supply is no longer the limiting factor, the rate of burning will be determined by the specific interrelated fuel bed properties such as average thickness, particle size and porosity. In this "fuel bed controlled" regime, the maximum rate of burning during a fire process can vary from almost zero up to the value given by Eq. (2). The value of $A_f/A\sqrt{h}$ denoting the transition point is fluctuating even if the type of fire load is restricted to cribs of wooden sticks /11/. If fire loads with a more authentic exposure geometry, such as furniture, are included, the difficulty in predicting the actual maximum rate of burning will increase. Even with known maximum rate of burning R_{max}, our incomplete knowledge of the pyrolysis and combustion processes governing the effective heat release would still make the corresponding value of I_C, $I_{C,MAX}$, to some degree unknown.

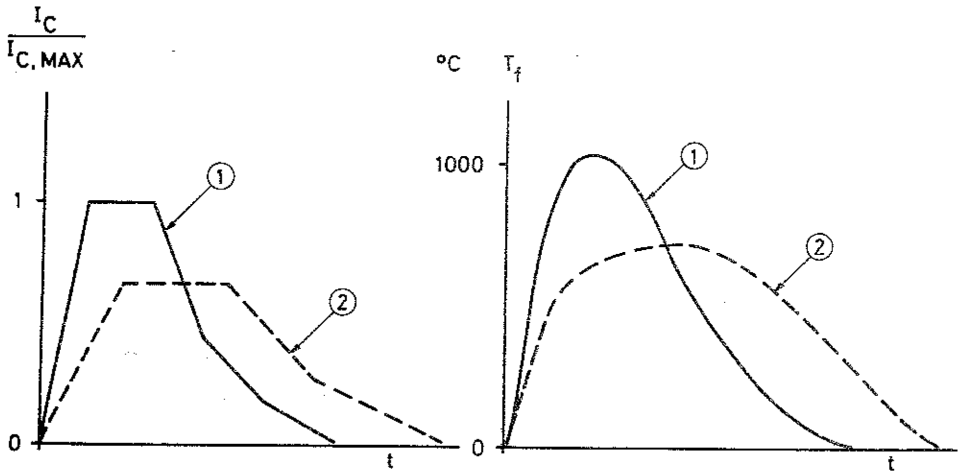


Figure 3 The time variation of rate of energy release I_C and gas-temperature T_f for the ventilation controlled ① fire process and one of the possible processes in the fuel bed controlled regime ②. $I_{C,\ MAX}$ = the maximum rate of energy release for the ventilation-controlled process

The consequences of different fire behaviour are sketched in Figure 3, where two possible $t - I_C$ curves are shown for a given combination of fire load M in kg and ventilation opening. Assuming that the maximum level of curve 1 is determined by the rate of air supply, it follows that this curve corresponds to a ventilation controlled fire process. If the geometric properties of the fire load display are changed in such a way that the process becomes fuel bed controlled, see curve

2, the maximum level of I_C will be lower but the duration longer. As a first approximation it may be assumed that the transformation does not change the average degree of complete combustion, implying that the time integral $\int_0^\infty I_C dt$ is regarded as a constant. The change from curve 1 to curve 2 could be produced e.g. by an increase in the average thickness of the fuel. Obviously, one of the main purposee with an analysis of compartment fires must be to investigate which I_C-curve is valid for the individual combination of ventilation opening, fire load density and fuel bed display.

Turning our attention to the ventilation term I_L, earlier investigations of the gas flow conditions in the compartment openings were valid for the flame phase of the ventilation-controlled burning /2/. In an examination paper by <u>Ahlquist</u> and <u>Thelandersson</u> /9/, the dependence of the gas flow on the rate of burning was examined in detail. The assumption of a constant pressure gradient was kept unchanged. Coupled with a computer program of considerably increased general validity, the problem could now be tackled in the following way:

For tests with sufficient data for a calculation with the equation of heat balance to be possible, a time graph of I_C was chosen on trial. On the basis of this a time-temperature curve was calculated and compared to the measured temperatures. If needed, the time graph of I_C was changed and used for a new calculation. This was repeated until the calculated and measured time-temperature curves were in agreement. Such comparative calculations were in /1/ performed for some 30 full scale tests. For all trials of a certain test, the time integral of I_C was to be equal to a constant value $M \cdot W_{eff}$,

$$\int_0^\infty I_C \, dt = M \cdot W_{eff} \qquad (3)$$

where

M = contents of combustibles in kg

W_{eff} = effective average heat value

By neglecting the possible combustion taking place outside the compartment and taking the value of W_{eff} = the nominal heat value, corrected with respect to the humidity contents, it was for all 30 tests possible to determine a $t - I_C$ curve, leading to a close coincidence between theoretical values and the curve representing the maximum experimental fire compartment temperature. A typical simulation result is shown in Figure 4.

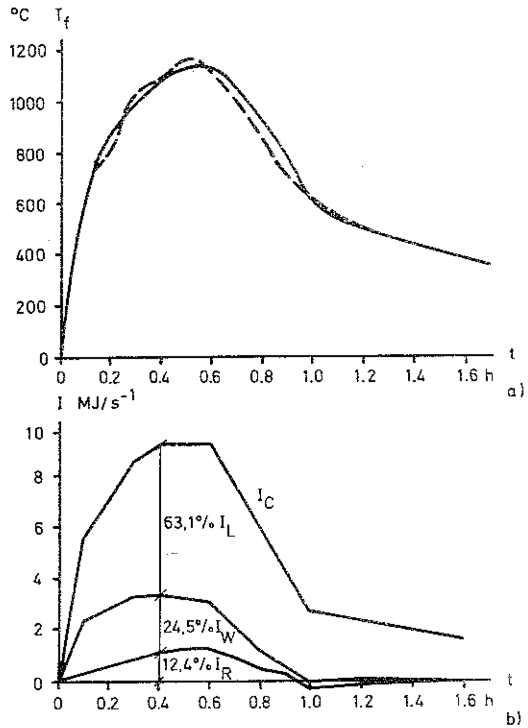


Figure 4 a) Measured (dash-line curve) and computed (full-line curve) gastemperature-time curves for a full-scale test, carried out at Fire Research Station, Boreham Wood, and characterized by a fire load q = 60 kg/m² floor area and an opening factor $A\sqrt{h}/A_t = 0.061 m^{1/2}$
b) Computed corresponding time curves for I_C, I_L, I_W and I_R in Eq. (1) /B/

Considering the range of test specification and testing laboratories, which excludes any possible bias due to specific testing circumstances, the agreement must be seen as a confirmation of the validity of the approach.

In /A/ some discussions are performed regarding the translation factor rate of burning - rate of energy release, the dependence of the gastemperature-time curve on thickness and porosity of fuel, the dependence of the same curve on varying thermal properties of materials in walls, floor and ceiling, the influence of horizontal openings, etc.

The agreement between theory and experiment must be connected to the uncertainties inherent in the analysis. There are two basic uncertainties:

- the variability in accepting or rejecting a trial simulation by means of eye inspection only
- indeterminacy in the physical model deriving from the insensitivity of the computational procedure to a simultaneous proportional change in I_L and $M \cdot W_{eff}$

The problem of finding the optimum time distribution of the rate of energy release may be transformed from the area of subjective estimation to a objective assessment by use of some of the minimum-seeking algorithms of mathematical programming. Regarding the second type of inaccuracy, existing physical measurements of I_L and $M \cdot W_{eff}$ are all subject to relatively large errors. The value of the term $M \cdot W_{eff}$ varies with the degree of complete combustion. Equating W_{eff} with the nominal heat value implies an assumption of perfect combustion. The gas analyses performed (see e.g. /2/) indicate that the overestimation of $M \cdot W_{eff}$ may be in the range 0 - 20 per cent. The gas flow term I_L depends on a contraction coefficient, which is known with approximately the same degree of accuracy as $M \cdot W_{eff}$. It follows that acceptable agreement between experimental and theoretical gastemperature-time curves may be obtained simultaneously as Eq. (3) is satisfied for different combinations of $M \cdot W_{eff}$ - time curves of I_C and I_L. The absolute values of I_C, I_L, I_R and I_W given by Figure 4 must be seen against this background.

Using the results from the comparative calculations, generalized rate of heat release-time curves were constructed for the complete ventilation controlled fire process with fire load of wood-fuel type. With these curves as a basis, gastemperature-time curves were computed for a systematic variation of fire load density, opening factor $A\sqrt{h}/A_t$ and type of structure. A_t = total surface of surrounding structures (walls, floor and ceiling) bounding the fire compartment. The computed curves, exemplified in Figure 5, are accepted by the Swedish National Board of Urban Planning as a base for a differentiated design of fire-exposed structural elements.

Publication /B/ and /C/ may be seen as a sequence to /A/ and discuss in some detail the general validity of the ventilation controlled design curves. In particular, it is investigated how the transformation from the ventilation controlled to the fuel bed controlled regime influences the different terms in the heat balance equation. The problems associated with a determination of the rate of energy release I_C have been touched upon earlier. Regarding the rate of gas flow, Thomas et al. /7/ pointed out that the assumption of constant horizontal pressure gradient will no longer satisfactorily describe the situation as the opening area grows larger. For openings larger than a certain size, the vertical acceleration of the gases will have to be considered, which means that the horizontal pressure differences and velocities decrease. In this area, the mathematical models of the physical opening size and gas flow has to be determined empirically.

Fifteen full-scale tests form testing laboratories in England and France are theoretically analyzed together with some small scale tests performed at LTH by Nilsson /11/. This analysis generally confirmed the value of a numerical simulation as a tool in discussing the natural fire behaviour. In particular, it was demonstrated how the simulation method permitted an empirical investigation of to what extent different parameters influence the rate of burning and rate of gas flow and consequently the gastemperature-time curve. The following is a summary of the general conclusions.

- For fires where the fire load consists of wood sticks piled in

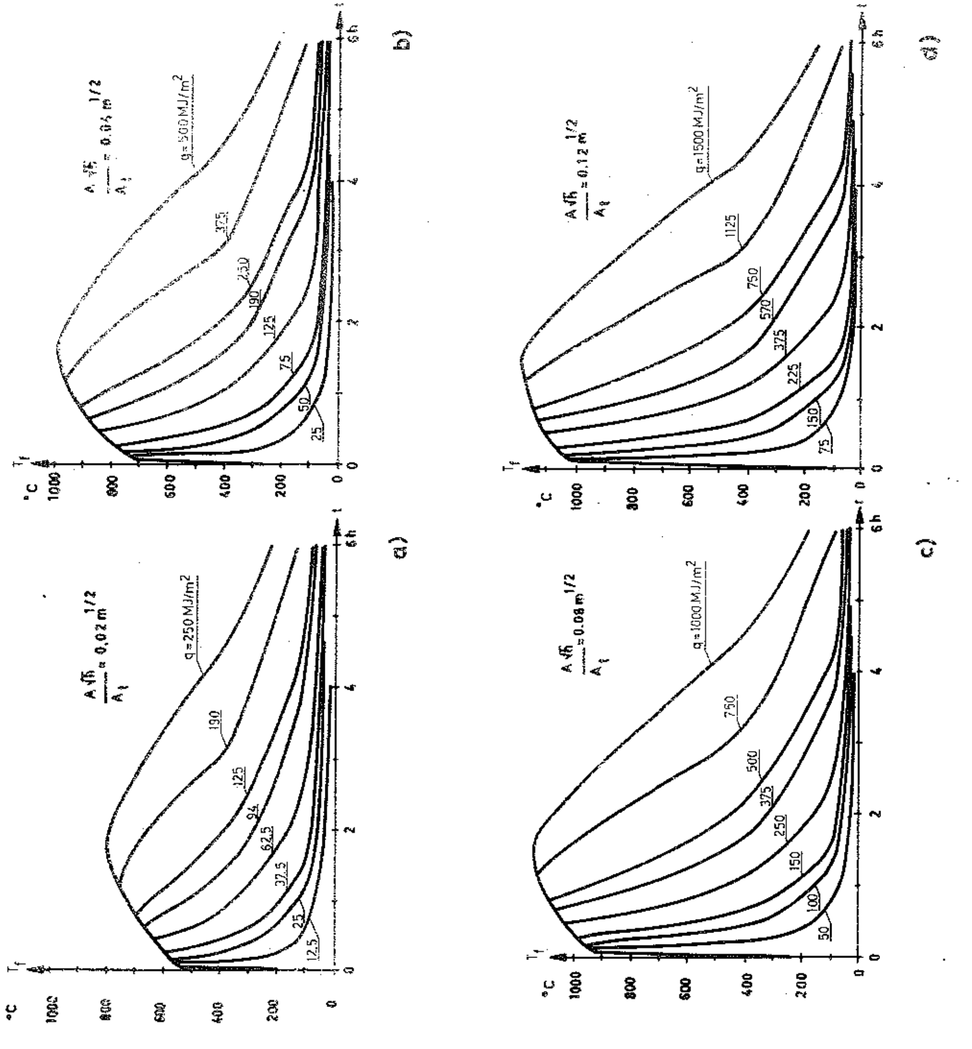


Figure 5 Design gastemperature-time curves (ventilation controlled) for different values of opening factor $A\sqrt{h}/A_t$ and design values of fire load density q

cribs the comparative theoretical analysis has given results that can be formulated in this way: As a rough estimate, the process of fire development ceases to be ventilation controlled when

$M/A\sqrt{h} \leq 175 \ kg \cdot m^{-5/2}$ or

$M/(rA\sqrt{h}) \leq 17000 \ kg \cdot m^{-7/2}$

where r = the average hydraulic radius of the fuel

- In this area, the fuel bed controlled regime, the mean rate of burning for all the full scale tests is approximately proportional to M and M/r. The rate of burning for the individual test, however, can considerably diverge from the mean value.
- Swedish tests with the fire load consisting of furniture and with $M/A\sqrt{h} < 175 \ kg \cdot m^{-5/2}$ have in a number of cases resulted in a ventilation controlled process of fire development.
- The rate of gas flow out of openings is proportional to $A\sqrt{h}$ as deduced by Kawagoe. For compartments with large openings and a rather small fire load, there is a reduction of this proportionality but only to a factor 0.7 - 0.8 for openings up to $A\sqrt{h}/A_t = 0.12 \ m^{1/2}$.

We are primarily interested in the natural fire behaviour from the standpoint of structural engineering. The important thing must be to analyze how, for a given design parameter combination of opening factor $A\sqrt{h}/A_t$ and fire load density, the structural impact of the fire exposure changes with possible fire developments deviating from the ventilation-controlled design curves. The problem was penetrated in /C/ and it was demonstrated that for fire-exposed insulated structural steel members, the maximum steel temperature was to a high degree insensitive to changes in combustion characteristics. The maximum steel temperature is obtained from the two possible fire exposures shown in Figure 3 by an integration procedure, where differences in gastemperature level and duration as a rule largely compensate each other. The size of the counterbalancing effect depends on choice of reference structure. For an uninsulated steel structure, the use of the ventilation-controlled design curves will in some cases give result markedly on the conservative side.

A possible way to decrease the degree of conservatism is shown by Nilsson /11/. He used the described simulation approach to analyze a large number of small scale burn out tests with wood-cribs as fuel and was able to describe and differentiate the complete $t - I_C$ curve with respect to size of ventilation opening, amount of fuel, piling density and wood stick thickness. If full scale calibration burn-out tests with authentic types of fire load are carried out and it appears that realistic fire loads in offices, schools, etc. may unambiguously be represented by equivalent values of piling density and wood stick thickness, then the results in /11/ can be used to theoretically calculate the gastemperature-time curve for the actual fuel-bed controlled fire process.

Summing up, a simplified theoretical model of the complete fire process has been developed. The relevance of the model to the natural fire behaviour has been demonstrated in about 150 simulations of small- and full-scale burn-out tests. The model has advanced our empirical knowledge of a very complex process and made possible a rational structural fire design model, based on the natural fire process.

Probabilistic Analysis of Fire Exposed Steel Structures

A large amount of work is presently in progress regarding the optimum level, in an economic sense, of the over-all fire protection of buildings. Structural damages can be prevented or limited by many measures, such as compartmentation, installation of detectors and sprinklers, reducing the attendance time of the fire brigade etc. Among those steps taken to reduce the fire damage, the oldest and most evident one is to increase the fire endurance of the individual structural member. For a high-rise building, the fire endurance must reach the level where the structural integrity of the building is maintained even during the most severe fire possible. For economic reasons, though, the fire endurance cannot be unlimitedly high. Some element of risk, however small, has to be accepted. Evidently, there is a need for a reliability analysis that makes it possible to identify this risk of structural collapse by fire and compare with the risks due to other kinds of catastrophic events.

This need has been accentuated by the different design rationales or systems put forward during the last few years. Particularly interesting in this connection is the differentiated Swedish method of Figure 1. The special attention derives partly from the fact that for the first time the new developments have been transformed into a ready-to-use design manual /12/. The manual is to be published during November 1974 and will, with the aid of charts, diagrams and tables, permit the practising engineer to make a rational design of fire-exposed steel structures. The method is based on the load factor concept, and as in any other design procedure, the choice of nominal loads (fire load density, live and dead load) and load factors will determine the final safety level.

The paper starts by describing and exemplifying the new design method. An elementary survey of probabilistic methods (first-order, second moment theories) used in normal structural design is given. (An explanation and derivation of basic probabilistic concepts are given in /13/).

The safety analysis of fire-exposed structures begins with the procedure critical in every reliability evaluation; the assessment of underlying uncertainties. The paper presents a general systematized scheme for the identification and evaluation of the various sources and kinds of uncertainty possible for a fire-exposed building component. With the basic data variables selected (type of structural element, type of occupancy), the different uncertainty sources in the design procedure are identified and dissembled in such a way that available information from laboratory tests can be utilized in a manner as profitable as possible. The derivation of the total or system variance Var(R) in the load-carrying capacity R is divided into two main stages:

- variability $Var(T_{max})$ in maximal steel temperature T_{max} for a given design fire compartment
- variability in strength theory and material properties for known value of T_{max}.

Consecutively $Var(T_{max})$ is decomposed into three parts:

- equation error in the theory of compartment fires and heat transfer from fire process to structural component,
- variability in insulation material characteristics,
- possible difference between T_{max} obtained in laboratory tests and in a real service condition.

In step number two, uncertainty in R for a given maximum steel temperature is, in the same way, broken down into three parts:

- variability in material strength,
- prediction error in strength theory,
- difference between laboratory test and a real life fire exposure.

These uncertainty terms must be superimposed upon the basic variability due to the stochastic character of fire load density. Mean and variance of load effect S are evaluated using results from publications covering the non-fire loading case.

To get appliable and efficient final safety measures, the reliability calculations are illustrated for the structural component, where the strength and deformation theories predicting the member performance under fire exposure seem most complete: an insulated simply supported steel beam of I-cross section as a part of a floor or roof assembly. The chosen statistics of dead and live load and fire load density are representative for office buildings.

The component variances are quantified, whenever possibel by comparing the design theory with experiments. System variance is evaluated in two ways: by Monte Carlo simulation and by use of a truncated Taylor series expansion. Employing the Monte Carlo procedure, the mean and variance of R and S have been computed for different values of ventilation factor of fire compartment, insulation parameter κ and ratio D_n/L_n, where D_n = nominal dead and L_n = nominal live load used in the normal temperature design. The second moment reliability as a function of these design parameters is evaluated by the Cornell and Esteva-Rosenblueth safety index formulations /13/.

The accuracy of the distribution-free second moment theories to uniquely define the reliability is touched upon, and the variation in safety-index value with varying uncertainty measures characterizing the insulation and the degree of complete combustion is examplified.

The Taylor series expansion method is compared with the Monte Carlo method and demonstrated to give surprisingly good agreement. The mathematical structure of the partial derivatives method makes it natural to use it as a basis for a closer investigation of how the total uncertainty in e.g. load-carrying capacity R varies with the uncertainties arising from different sources. Such information is necessary in a systematic study of how to economically optimize the avoidance of a structural failure.

Table 1 gives an example of such a decomposition. Of special interest is the variability inherent in the largely empirical design gastemperature-time curves of Figure 5. The variance of these curves was measured by comparing design maximum steel temperatures with the corresponding experimental values for 97 natural fire-exposed insulated steel columns. The comparison was made for well-known thermal characteristics of the insulation material, but includes scatter due to the approximate heat transfer theory used in computing steel temperature values. From Table 1 it may be deduced that the uncertainties deriving from ventilation-controlled gas-temperature-time curves is of minor importance for the final safety index value.

The following section turns to the problem of comparing the reliability levels of the traditional and the new, differentiated design method. It is demonstrated how the flexibility of the new method results in drastically improved consistency for the failure probability P_f.

At the same time it is shown that the temporary nominal loads and load factors given by the manual /12/ do not result in reliability levels that are independent of the ratio D_n/L_n. Using the linearization factor defined by Lind, see /13/, it is examplified how statistically more consistent load factors easily may be derived. Finally it is pointed out how mathematical programming algorithms may be employed to obtain load factors or partial safety factors that for a broader range of design parameters minimizes the difference between the demanded, preselected and the actual reliability level.

These load factor evaluation studies underline a fundamental fact. In sharp contrast to the standard design procedure, the design model of Figure 1 has the capability of being systematically and rationally improved as knowledge increases.

Summing up, this pilot study has demonstrated that a safety analysis, using probabilistic methods, of fire exposed structural steel components is today well within the bounds of possibility. The implication is that one of the main components in the over-all fire-safety problem for the first time has been rationally assessed, thus opening the way for an integrated system approach with a reliability optimization as final objective.

Variability in load-carrying capacity R due to	per cent of total variance
stochastic character of fire load density	36
uncertainty in insulation material properties	10
uncertainty in theory transforming fire load density into maximum steel temperature (theory of compartment fires and theory of heat transfer burning environment - structural steel component)	10
difference between laboratory test and an actual complete process of fire	2
uncertainty in yield strength of steel at room temperature	12
uncertainty in the deformation analysis giving the design capacity	11
difference between the impact of fire on R in laboratory test and under service conditions	19

Table 1 Decomposition of the total variance of load-carrying capacity into a sum of component variances for an insulated steel beam designed according to the differentiated Swedish model

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