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FUNCTIONAL APPROACHES - AN OUTLINE

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1. INTRODUCTION

In a general sense, the fire engineering design problem is nondeterministic. Some level of risk - the probability of an adverse event - 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 firesafety code systems now in force. Historically, they had to be written without actually stating their objective level of safety and, still far less, without any analytical measurement of the objectives involved. For this reason, there is an urgent need for future attempts to evaluate the levels of safety inherent in present local and national fire protection regulations. Lack of knowledge with respect to the structure of the analytical models describing the physical process has up till now effectively prevented all efforts to quantitatively assess risk levels. Gradually, with expanding modelling capabilities, the potential for a rational, reliability-based design will increase in proportion.

2. SCOPE

Very generally, a functional approach in a fire engineering design may be defined as a systematized scheme to

* collect and coordinate available information of a specific fire situation, and

* with this information as a basis, select values of appropriate design parameters, specifically taking into account the uncertainty induced by the behaviour of nature and by our incomplete state of knowledge about that behaviour.

Functional approaches may be defined by different classes of engineering design methodologies. The systems concept models, developed by GSA [1] and NFPA [2] to evaluate the hazards associated with fire situations of large complexity - in the NFPA analysis comprising explicit human response models interacting with the fire development model - constitute one such class. Recent extensive and vigorous efforts to mathematically model fire growth within compartments - exemplified by the NBS corridor studies [3] and the Harvard-FMRC Home Fire Project [4] - have successfully demonstrated our rapidly expanding modelling capabilities regarding the mechanisms of fire spread and fire product generation.

For the purpose of this paper, a more limited definition of the concept of functional fire design procedures will be applied. From the large and heterogeneous area of fire-related design problems, a number of subsystems have been selected. The selection has been done in order to demonstrate that, for specific problems, methods exist to quantify fire hazard assessments and to derive design parameters (safety factors), based on an explicit reliability analysis. Examples of design problems, at least potentially amenable to this kind of firesafety analysis, are

* structural integrity (criteria of requirements with respect to load-bearing capacity, insulation and integrity, connected to different safety classes on the basis of injury to people and extent of probable property loss),
* fire spread in small house areas (criteria of requirements with respect to time curve of radiation or accumulated radiative energy, giving rise to ignition of exposed combustible, exterior or interior materials),
* fire growth in a compartment (criteria of requirements with respect to occurance of flashover, time to flashover, levels of automatic release of detectors, integrated reaction to fire of materials and products), and
* smoke movement in escape routes (criteria of requirements with respect to the physiological reaction of people to heat, smoke and toxic products, taking into account also the psychological reaction of people, individually or in group, in a fire situation at the determination of the necessary time of evacuation).

Essential components of a rational design methodology include - in the ideal case

* analytical modelling of relevant processes; verification of model validation and accuracy; determination of critical design parameters,
* formulation of functional requirements independent of choice of design process and expressed either in deterministic or probabilistic terms,
* determination of design parameter values, and
* verification by the means of a reliability analysis that the choice of safety factors leads to safety levels, which are consistent with the expressed functional requirements.

As the enumerated sub-systems certainly differ from the ideal case, a discussion is necessary on the level of consistency and sophistication obtainable in each individual application.

3. TERMINOLOGY. DEFINITION OF UNCERTAINTY

Firesafety system variables, determined by the environment and beyond the control of the designer, are described as state variables. System variables, subjected to design specifications will be called design parameters. The proportion of the total risk P_f deriving from state and design variables will vary from case to case. A general outline of the situation is given in Fig. 1 which points to a few important facts. Firstly, due to the uncertainty created by variables beyond the designers control, the risk can be reduced only to a certain level. Secondly, the efforts to reach this level as closely as possible will require successively higher costs. Very extensive efforts will lead to solutions within an uneconomic region. Insufficient efforts can give a system which is unsafe. Acceptable solutions are falling within a design region between the unsafe and uneconomic regions.

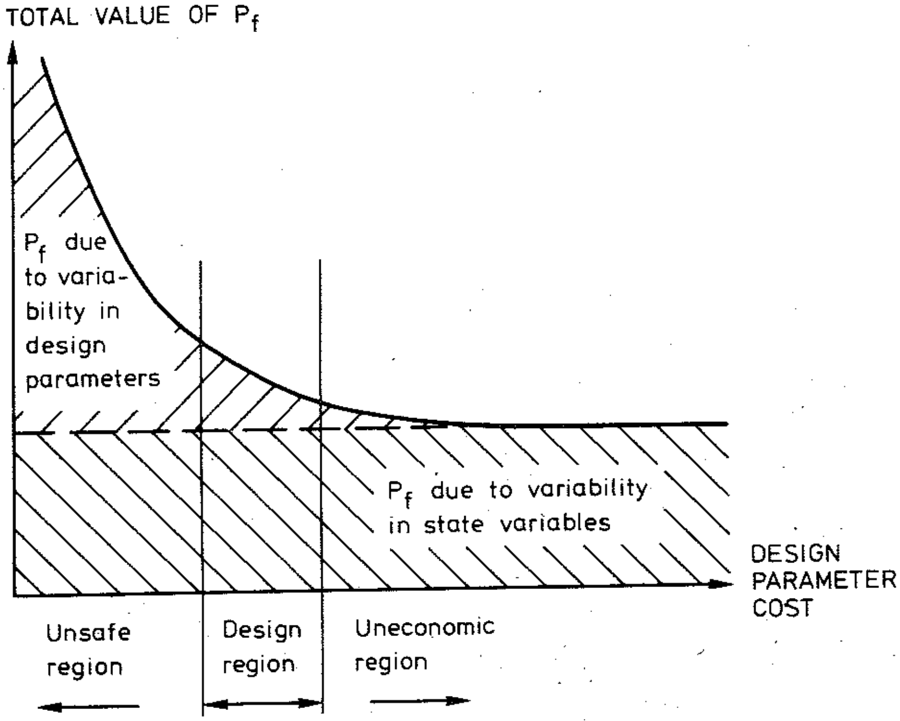


Fig.1. Total risk P_f due to variability in state variables and design parameters

The fire safety engineer faces at least three distinct types of uncertainty. The first is the intrinsic or fundamental uncertainty inherent in physical phenomena and human behaviour; examples could be weather conditions, a conflagration fire, location and behaviour of people at outbreak of fire. The second type of uncertainty can be called statistical. It is associated with failure to estimate parameters of statistical distributions representing for example the scatter of material properties. This uncertainty can be reduced by increasing the sample size. The third kind of uncertainty is caused by the incompleteness of the mathematical model, describing the physical reality. The prediction error has to be measured by comparison between theoretical model and experiments.

It must be recognized that lack of statistical data to provide perfectly accurate estimates of parameters (means, coefficients of variation, etc) describing stochastic components is not an argument against quantification of uncertainty. The imcompleteness is only another error factor which must be accounted for and is subject to quantification in terms of classical or Bayesian statistics.

Failure or the occurrence of an adverse event must be specified with respect to a defined reference state. For the four subsystems enumerated in the scope section, examples of these limit states may be respectively an excessive deformation for a load-bearing structure, an ignition of a neighbouring house in a small house area, the time to flash-over, a combustion product exceeding human tolerance levels. In each case, we may define one part of the analytical model as the system capacity R and the other part as the demand S on the system. Failure occurs when the demand S exceeds the capacity R and the probability of failure P_f

$$P_f = P(R \leq S) \tag{1}$$

The situation is outlined in Fig. 2. Stochastic variables defining component data, environmental characteristics and the prediction error are input data to the submodels giving the system demand S and the system capacity R as output variables. Input parameters may be either state or design variables.

In a fire engineering design of a load-bearing structure, different types of nominal loads constitute the component data or the environmental characteristics of the demand part of the design system to be transferred analytically into a design load effect by applying, for instance, partial factors and factors of load combination. Within the capacity part of the system, the component data are given by the structural design and the thermal and mechanical properties of the structural materials and the environmental characteristics by the gastemperature-time curve of the fire process, having the fire load combustion characteristics, the size and geometry of the fire compartment, the ventilation of the fire compartment and the thermal properties of its enclosing structures as entrance parameters.

In a design with respect to the risk of fire spread from one house to another within a small-house area, the demand S can be expressed as a radiation exposure level for an adjacent house with the fire load characteristics, the characteristics of the house in fire with regard to size, geometry, opening data, ventilation and thermal properties as component data. The exterior wind constitutes an environmental characteristic. The capacity can be specified by a radiation intensity and a connected time of exposure, giving ignition of the adjacent house. Component data then are relevant characteristics of the combustible materials involved and environmental characteristics, for instance, the relative humidity of the air, influencing the moisture content of the materials.

In a design of a building with respect to the smoke movement in escape routes, the exposure or demand is to be expressed as maximum values of smoke density and concentrations of toxic products during the necessary evacuation time. Connected component data refer to the conditions in the fire compartment, the design of the building and to the human response. The environmental characteristics are ambient condition and smoke control methods. The capacity is determined by the human tolerance levels, specified as allowable values in respect to the smoke density and the contamination of toxic gases.

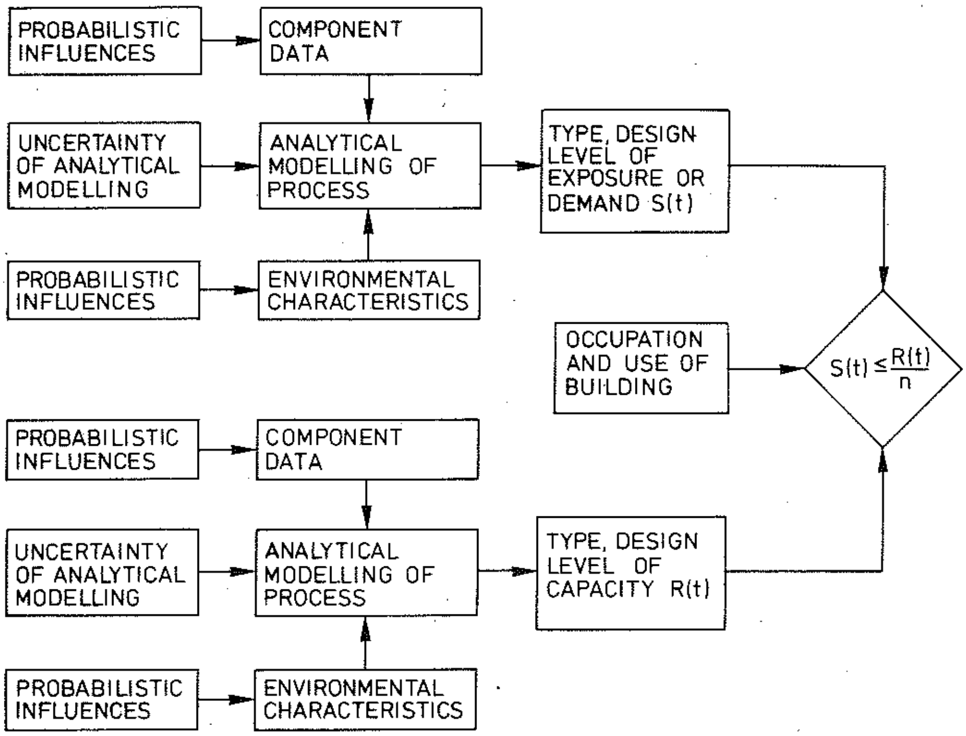


Fig. 2. Component data, environmental characteristics and analytical modelling of process, giving demand $S(t)$ and capacity $R(t)$ in a fire engineering design system

For the case that R and S can be expressed analytically, are statistically uncorrelated and have known probability density functions f_R and f_S, the probability of failure is given by the formula

$$P_f = \int_0^{\infty} \int_0^{S} f_S(s)\, f_R(r)\, d s\, d r \qquad (2)$$

cf. Fig. 3.

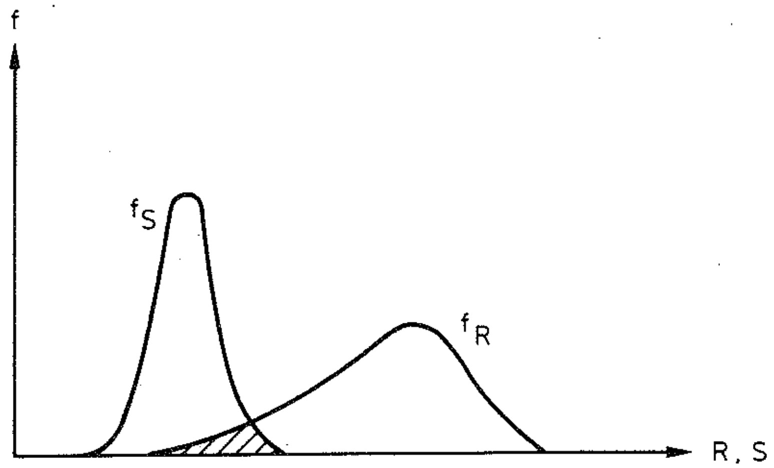


Fig. 3. Probability density functions f_R and f_S of system capacity R and system demand S

The computation of the probability of failure P_f can be re-formulated in the following way - Fig. 4. The difference between the capacity R and demand S defines the safety margin. In the probability density function of the safety margin f_{R-S}, positive values mean survival, negative values failure. The dashed area gives the failure probability P_f.

Ideally, P_f should form the basis for deriving design criteria. However, P_f can be evaluated accurately only if the probability density function of $R - S$ is known in detail. In practice, this is very seldom the case. Two main alternatives then are open [5], [6]

- to base a design code format on prescribed distributions of R and S, and
- to acknowledge the incompleteness of statistical information and disregard the form of the distribution involved.

In the latter case, a design scheme can be based simply on requiring that some minimum safety margin be maintained. In place of requiring that a calculated risk of failure must fall below a specified probability, it may be required that the average safety margin $\overline{R - S}$ must lie a specified number β standard deviation above zero, giving the formulas

$$\overline{R - S} \geq \beta\, \sigma_{R-S} \quad \text{or} \quad \overline{R} \geq \overline{S} + \beta \sqrt{\sigma_R^2 + \sigma_S^2} \qquad (3)$$

σ_{R-S} is the standard deviation of the safety margin $R - S$, σ_R and σ_S are the standard deviation of R and S, respectively.

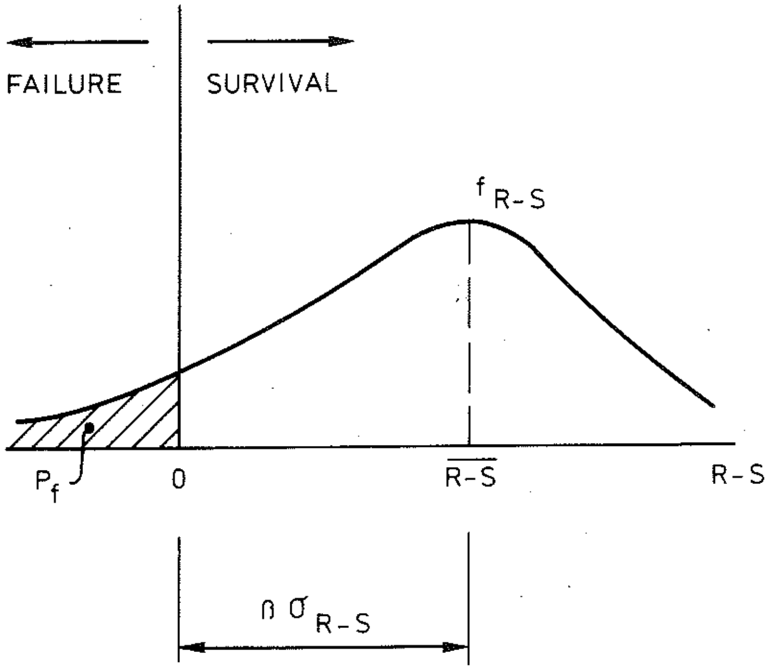


Fig. 4. Probability density function f_{R-S} of safety margin $R-S$ and definition of safety index β

The method is distribution-free and employs only the first and second central moments of relevant stochastic variables, hence the name "second moment code formats".

The safety index β defines the reliability of, for instance, a design system and offers a quantitative basis for comparing the relative safety of two or more design alternatives. A greater value of β then corresponds to a higher safety level. With this safety measure we can improve our design methods to be more consistent and assess the implications of assumptions and guesses.

Several other formulations of safety index exist. For further details of these, of different models for systematic evaluation of uncertainty and of formulation of practical design criteria, reference is made to [5], [6], [7].

4. STRUCTURAL INTEGRITY

For various firesafety subsystems, the level of a reliability analysis is determined by the knowledge and the modelling capabilities accumulated in the deterministic case. Thus, it is natural that structural integrity is the area where a probabilistic analysis could be initiated.

Since about ten years, a differentiated theoretical procedure can be applied in Sweden, as one alternative, for a structural fire engineering design of load-bearing structures and partitions. The procedure constitutes a direct design method based on gastemperature-time characteristics of the fully developed compartment fire as a function of the fire load density, the ventilation of the fire compartment and the thermal properties of the structures enclosing the fire compartment. The design method is approved for a general practical use by the National Board of Physical Planning and Building. For facilitating the practical 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 [8], [9], [10].

In a generalized summary way, the design method can be described as follows - Fig. 5.

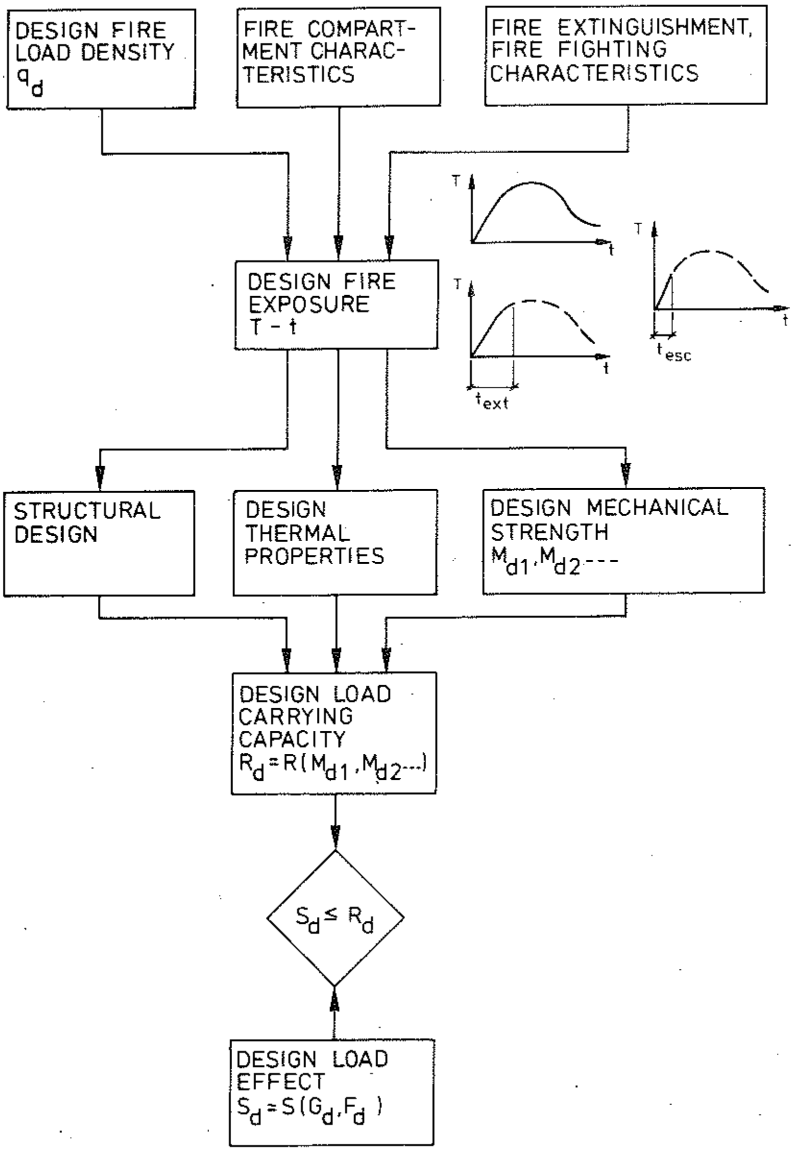


Fig. 5. Procedure of a differentiated, theoretical design of fire exposed load-bearing structures

The design fire load density, the fire compartment characteristics and the fire extinguishment and fire fighting characteristics constitute the basis for a determination of the design fire exposure, given as the gastemperature-time curve T-t of the fully developed compartment fire. Depending on the type of practical application, the load-bearing function of the structure can be required to be fulfilled for

* the complete fire process,
* a shortened fire process, limited by the time t_{ext}, necessary for the fire to be extinguished under the most severe conditions, or
* a shortened fire process, limited by the design evacuation time t_{esc} for the building.

Together with the structural design data, the design thermal properties and the design mechanical strength of the structural materials, the design fire exposure gives the design load-carrying capacity R_d as the lowest value during the relevant fire process.

A direct comparison between the design load-carrying capacity R_d and the design load effect at fire S_d decides whether the structure can fulfil its required function or not at the fire exposure.

Following a recent draft of safety regulations [11], the determination of the design load effect S_d starts from characteristic values of permanent and variable loads G_k and F_k, connected to a defined probability of excess during a specified time period (Fig. 6). A multiplication by partial factors γ and load combination factors ψ transfers the characteristic load values to design loads G_d and F_d. The load combination factors ψ then may be differentiated with respect to whether a complete evacuation of people can be assumed or not in the event of fire. Finally, the design loads are combined and transformed to the design load effect at fire S_d.

Analogously, the design material strength M_d is to be calculated via characteristic strength values M_k at actual temperature, divided by resulting partial factors γ_m (Fig. 7). The characteristic strength values are defined as corresponding to specified fractiles of the probability density distribution. The different partial factors γ_m^1, γ_m^2, γ_m^3, and γ_m^4, are expressing the influence of the scatter in material strength, the uncertainty of the design model, the uncertainty in relation between material property in the structure and material property determined in test, and the safety class, respectively. The predicted extent of personal and property damage at failure - very serious, serious, not serious - decides the safety class.

A methodology for a probabilistic analysis of fire exposed steel structures, connected to the described design method, has been developed in [12]. The methodology comprises a general systematized scheme for the

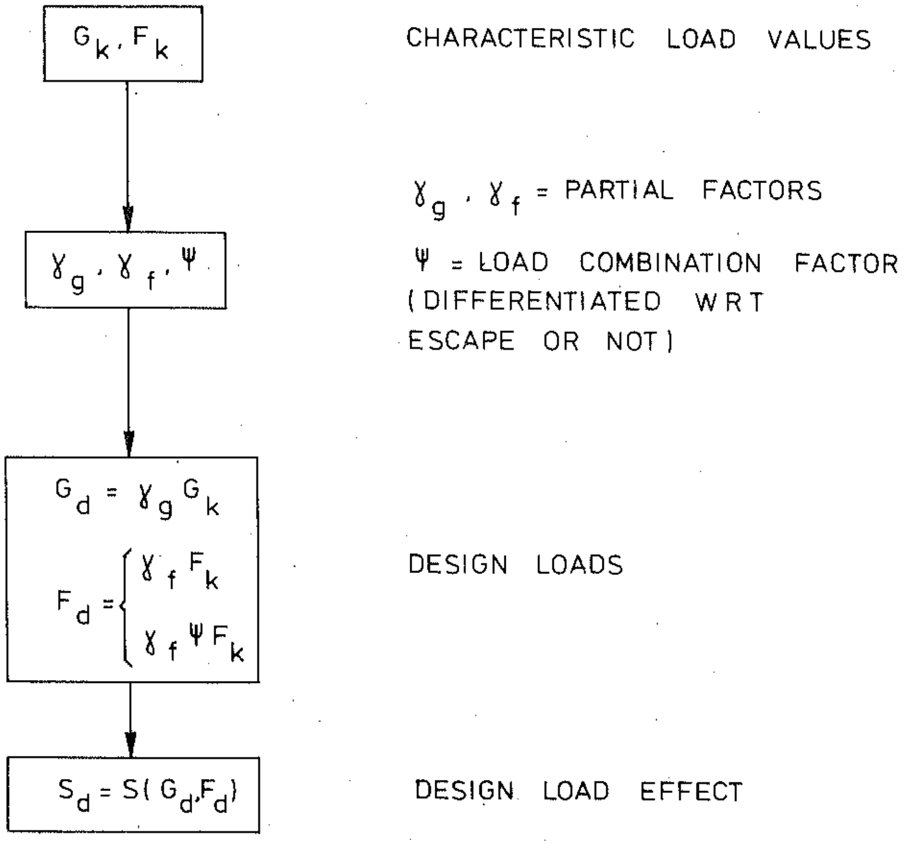


Fig. 6. Procedure of determination of design load effect S_d

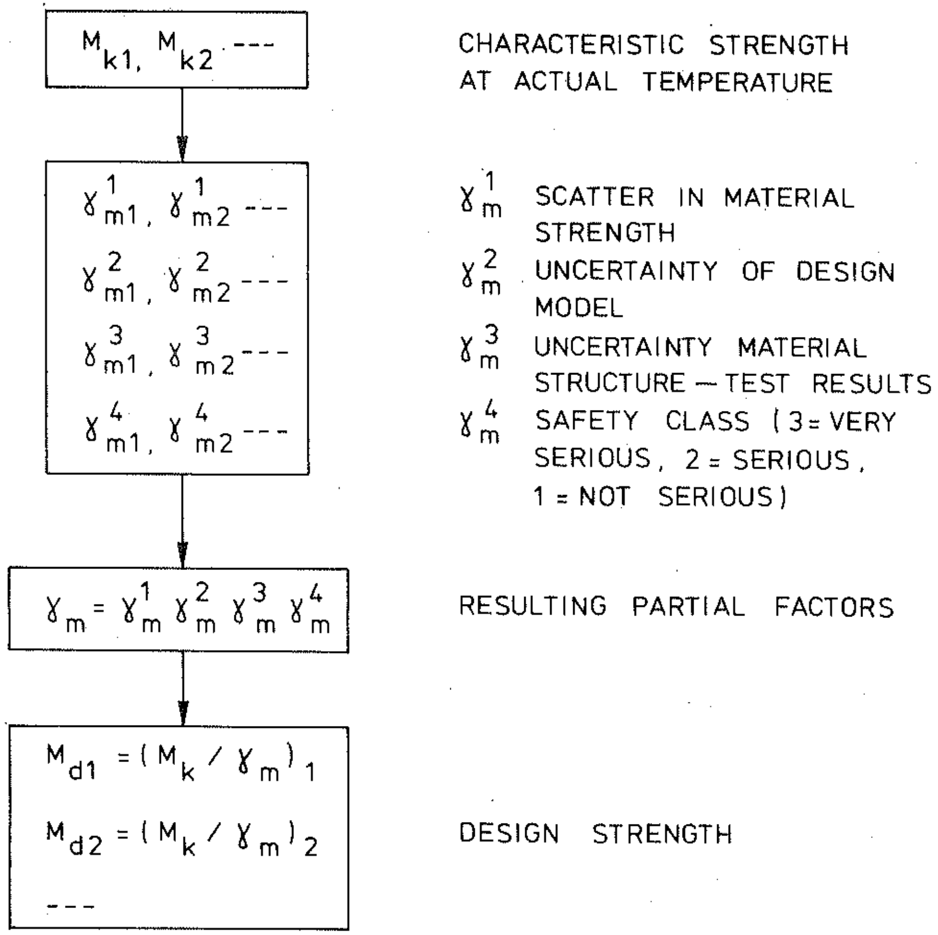


Fig. 7. Procedure of determination of design strength M_d

identification and evaluation of the various sources and kinds of uncertainty in the differentiated structural fire engineering design.

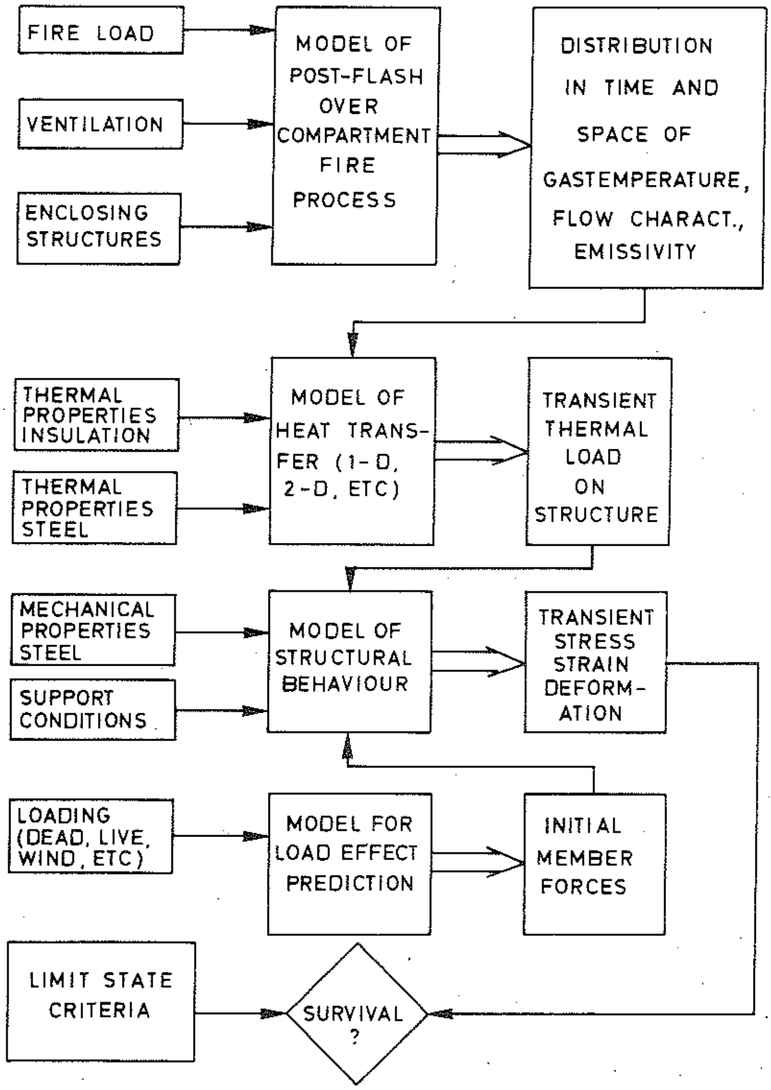


Fig. 8. Total system modelling of a differentiated theoretical design of fire exposed steel structures

Fig. 8 describes in greater detail the total system modelling, characterizing the design. The structure of the methodology is quite general and applicable to a wide class of structures and structural elements. To get appliable and efficient final safety measures, the investigation is numerically exemplified for one specified structural element - 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.

With the basic data variables selected, 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 type of structure and a given design fire compartment, and variability in strength theory and material properties for known value of T_{max}.

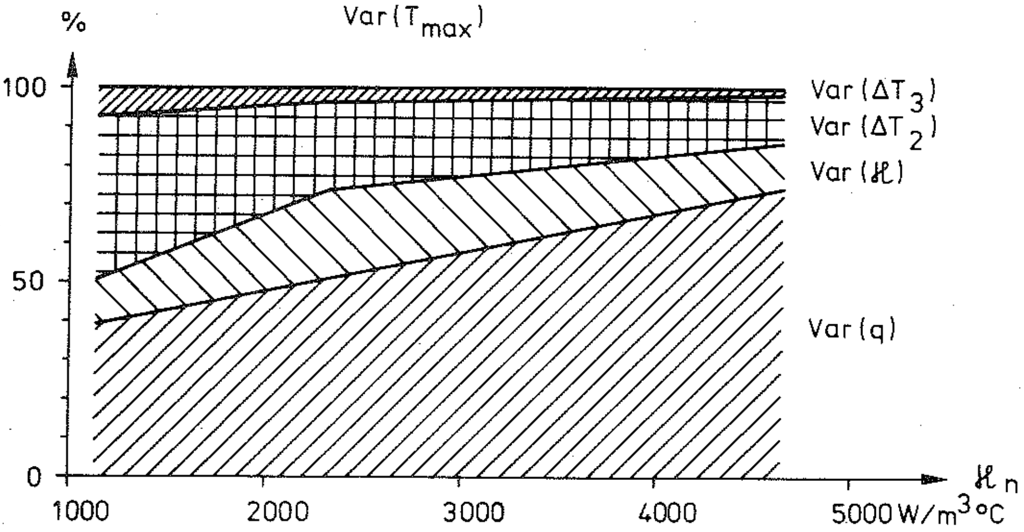


Fig. 9. Decomposition of total variance in T_{max} into component variances as a function of insulation parameter κ_n [12]

The results obtained are exemplified in Fig. 9, giving the decomposition of the total variance in maximum steel temperature T_{max} into the component variances as a function of the insulation parameter $\kappa_n = A_i\lambda_i/(V_s d_i)$. A_i is the interior jacket surface area of the insulation per unit length, d_i the thickness of the insulation, λ_i the thermal conductivity of the insulating material, corresponding to an average value for the whole process of fire exposure, and V_s the volume of the steel structure per unit length. Increasing κ_n expresses a decreased insulation capacity. The component variances refer to the stochastic character of the fire load density q, the uncertainty in the insulation properties κ, the uncertainty reflecting the prediction error in the theory of compartment fires and heat transfer from the fire process to the structural member ΔT_2, and a correction term reflecting the difference between a natural fire in a laboratory and under real life service conditions ΔT_3.

Analogously, Fig. 10 exemplifies the decomposition of the total variance in the load-carrying capacity R into component variances as a function of the insulation parameter κ_n. The component variances refer to the variability in the maximum steel temperature T_{max}, variability in material strength M, the uncertainty reflecting the prediction error in the strength theory $\Delta\phi_1$, and the uncertainty due to the difference between laboratory tests and in situ fire exposure $\Delta\phi_2$.

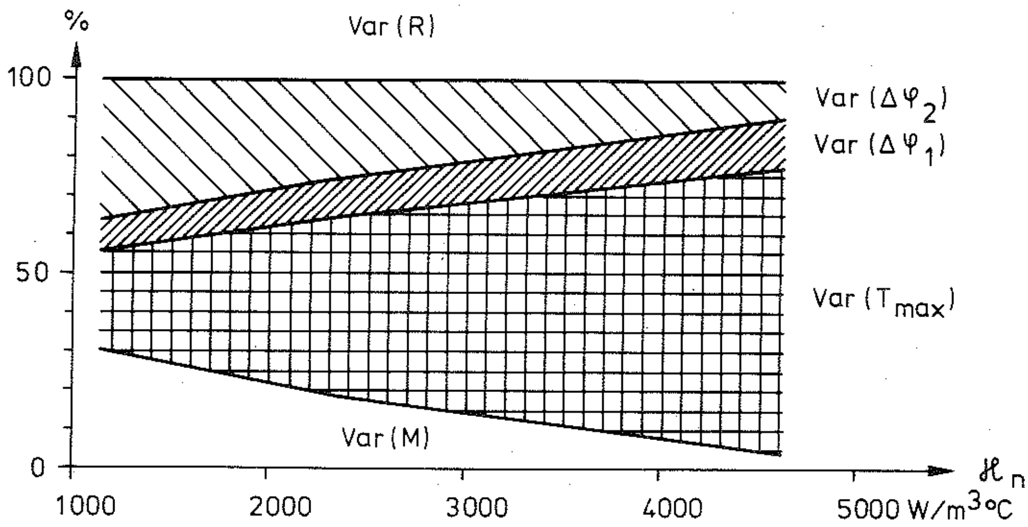


Fig. 10. Decomposition of total variance in load-carrying capacity R into component variances as a function of insulation parameter κ_n [12]

The component variances are quantified, whenever possible 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 the ventilation factor of the fire compartment, the insulation parameter κ and the ratio D_n/L_n, where D_n is nominal dead load 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. The dependence of the final safety index value on variables such as

- uncertainty in knowledge of the thermal properties of fire-protective materials, and
- uncertainty in the relation fire load statistics to effective calorific contents

is shortly discussed. Especially, the fundamental importance of differentiated and dependable fire load statistics is demonstrated.

A fragmentary illustration of the results received is given in Table 1, showing the range of variation for the safety index β, as determined for the present Swedish differentiated design model (case II). Varying the opening factor of the fire compartment $A\sqrt{H}/A_t$ from 0.04 to 0.12 $m^{1/2}$ and the ratio between the nominal value of dead load D_n and live load L_n from 1/3 to 3, then leads to a range of β from 1.66 to 2.84. A is the total area of the window openings, H the mean value of the heights of window and door openings, weighed with respect to each individual opening area, and A_t the total interior area of the surfaces bounding the compartment, opening areas included. For the structural member designed in accordance to the standard fire endurance test (case I), the corresponding range of β will be from 1.77 to 3.69. Completing the present differentiated design model with statistically derived load factors (case III) will improve the consistency of β considerably by giving a very narrow range from 2.35 to 2.45.

Table 1. Safety index β and probability of failure P_f for different design procedures, applied to an insulated, simply supported steel beam as a part of a floor or roof assembly in office buildings

Design procedure	Range of β	Range of P_f	$(P_f)_{max}/(P_f)_{min}$
I. Classification, standard endurance test	1.77 - 3.69	$(1\text{-}400)10^{-4}$	~ 400
II. Present Swedish design model	1.66 - 2.84	$(23\text{-}500)10^{-4}$	~ 20
III = II, improved by statistically derived load factors	2.35 - 2.45	$(72\text{-}95)10^{-4}$	~ 1.5

The corresponding range of the probability of failure P_f is shown in the table, too. Related to this quantity, the difference between the three design procedures is extremely striking with the respective ratios $(P_f)_{max}/(P_f)_{min}$ ~ 400, 20 and 1.5. The P_f values presented are connected to a probability = 1 for a fire outbreak leading to flashover within the fire compartment.

5. FIRE SPREAD IN LOW RISE RESIDENTIAL BUILDING AREAS

The spread of fire in high-density, small house building areas has always been regarded as a major threat to life safety ever since people started to live in communities. A design methodology, based on analytical models of the process of fire spread simply by thermal radiation or by thermal radiation in combination with flame, has been developed in Sweden and approved for general use by the National Board of Physical Planning and Building [13], [14]. As of now, the design method is limited in application to low rise, high density areas of small houses of stone material, primarily concrete or aerated concrete. The method further presupposes that the indoor wall and ceiling surfaces of the houses are made of materials and structures which are not easily ignitable and to no considerable extent contributing to the spread of fire.

The principles of an analytical design of a small house area with regard to the risk of fire spread from one house to another can be described according to Fig. 11.

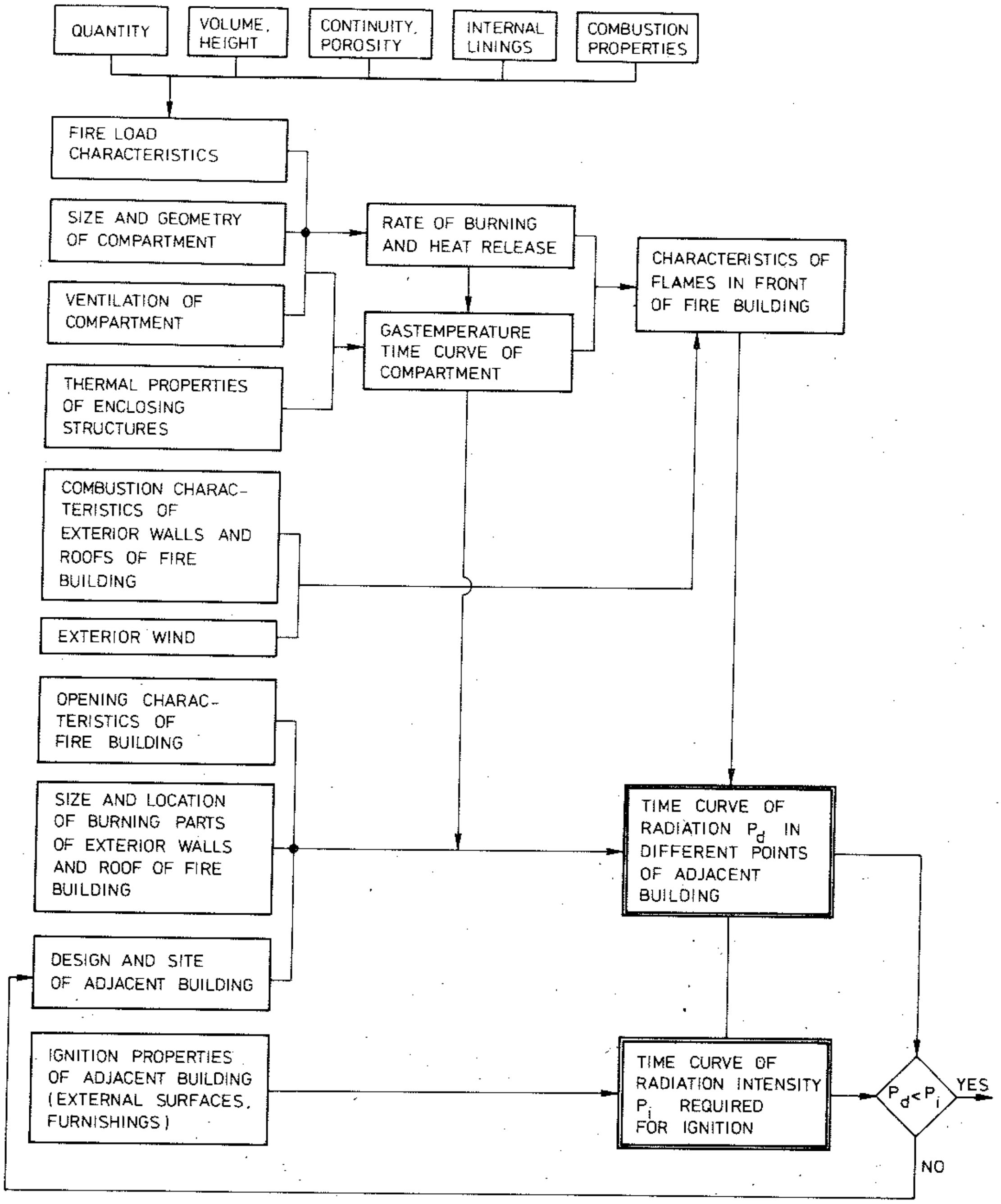


Fig. 11. Procedure of a differentiated theoretical design of a small house area with respect to fire spread from one house to another

The first part of the design comprises the determination of the characteristics of a fully developed fire in a single building of the small house area. The characteristics comprise the gastemperature-time curve and the convection and radiation of the flames and combustion gases in front of the building in fire.

In the second part of the design, a determination has to be carried out of the thermal input on the adjacent building of the small house area from the building in fire.

The output information is the time curve of the radiation intensity P_d in decisive points of the adjacent house. A comparison of this time curve with the corresponding radiation exposure P_i, giving ignition, decides whether the design of the individual house and the complete small house area is safe or not in regard to prevented fire spread from one house to another.

The design method presented in [14] and having a structure according to Fig. 11 comprises

(1) an analytical model for the heat and mass balance of the complete process of fire development, giving the gastemperature-time curve of a compartment fire as a function of the fire load density and the ventilation characteristics of the compartment,

(2) an analytical model, describing the radiation characteristics within a small house area at a fire in a single house - the radiation composed of one part, given by the radiation through the window openings of the house in fire from the fire within the fire compartment, and of one part, given by the radiation from the flames emerging from the fire compartment, and

(3) an analytical model, evaluating the time curve of the radiation intensity P_d with respect to ignition of decisive combustible materials in the neighbouring house.

The practical application of the design procedure enables a determination of the minimum distance between adjacent houses which, under different conditions, can be judged safe with regard to prevention of the risk of fire spread from house to house simply by thermal radiation or by thermal radiation in combination with flame.

In an assessment of the safety index β, the following kinds of uncertainties are to be taken into account:

(1) Uncertainty due to the stochastic character of input data, viz.
  - fire load (quantity of combustible material, degree of combustion),
  - thermal properties of structures enclosing the fire compartment,
  - combustion properties of exterior walls and roof,
  - exterior wind characteristics, and
  - ignition properties of radiation exposed materials.

(2) Uncertainty due to imperfection in the prediction models, wiz.
  - analytical model for heat and mass balance of fully developed compartment fire (gastemperature, flame characteristics),
  - analytical model for radiation from fire within fire compartment and from flames emerging from openings, and

- analytical model for ignition of materials exposed to radiation.

6. FIRE GROWTH

To the fire growth in a compartment belong criteria of safety requirements with respect to occurance of flashover, time to flashover, levels of automatic release of detectors, integrated reaction to fire of materials and products.

The fire hazard of a situation may be considered in terms of a series of probabilities which depend on

* presence of ignition sources,
* presence of products,
* product fire performance properties,
* environmental factors,
* presence of people,
* presence/operation of detection and suppression devices, and
* availability of escape.

Options for a fire hazard assessment related to a specified product include at least three different approaches.

As an interim first generation goal, ASTM subcommittee E-39.10.01 suggests a simplified classification and labeling scheme for products in terms of their several fire performance properties, similar to that used in NFPA Standard 704 M for hazardous chemicals.

A preliminary adaptation of such a concept for the description of performance properties is shown in Fig. 12. It is pointed out by the subcommittee that developing a method for numerically describing the severity of each criteria will require considerable discussion. Guidelines will also have to be prepared for the use of the system, including the weigthing to be assigned each criteria for determining the acceptability of a product in a given use situation.

In a second, more complex approach, also put forward by the ASTM E-39 committee, the fire performance of products is evaluated by a four step procedure as follows:

(1) Use loss statistics and in-depth case history investigation on fire accidents to identify particularly hazardous and likely fire scenarios involving the product,

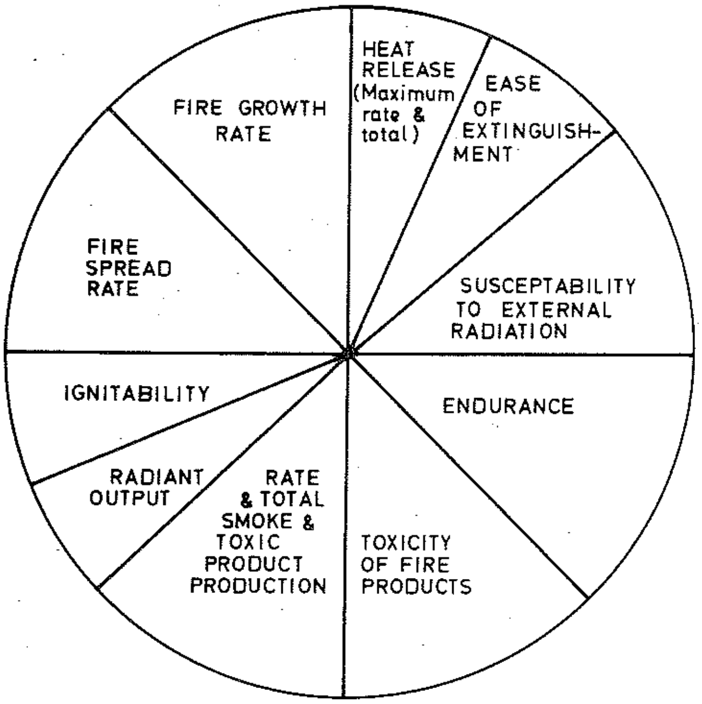
(2) with the main hazard patterns identified, run carefully instrumental full scale tests to define the environmental conditions which have to be reproduced by standardized laboratory test,

(3) develop standardized performance tests and generate fire performance data by use of such tests, and

(4) integrate the product test data into a general risk assessment scheme and investigate the sensitivity of the final hazard to fire performance data.

An example of this approach is given by the investigations leading to the

NBS Flooring Radiant Panel Test [3].



<u>SEVERITY OF FIRE PERFORMANCE PROPERTY</u>

0 = NO SPECIAL POTENTIAL FOR HARM
1 =
2 =
3 =
4 = SEVERE POTENTIAL FOR HARM

Fig. 12. Simplified classification and labeling scheme for fire performance of products and systems, proposed by ASTM committee E-39

In a long time view, a more fundamental and scientific approach may become gradually of practical importance. A combination of basic property tests and mathematical models of the fire development process should provide the basis for assessing the contribution of a tested product to the overall fire safety. The general structure of such an approach appears from Fig. 13.

If no analytical model of a small scale laboratory test is available, the test results have to be directly statistically correlated to full scale test data. If a validated analytical model of a small scale test is available, the test results can be used in a more general way for a determination of well-defined material properties. Subsequently, the information of this type can serve as input data in analytical models of the full scale fire development for specified scenarios. By such models available, supported and validated by full scale tests, it should be possible to predict the time variation of the extent and physical location of a compartment fire at different environmental conditions.

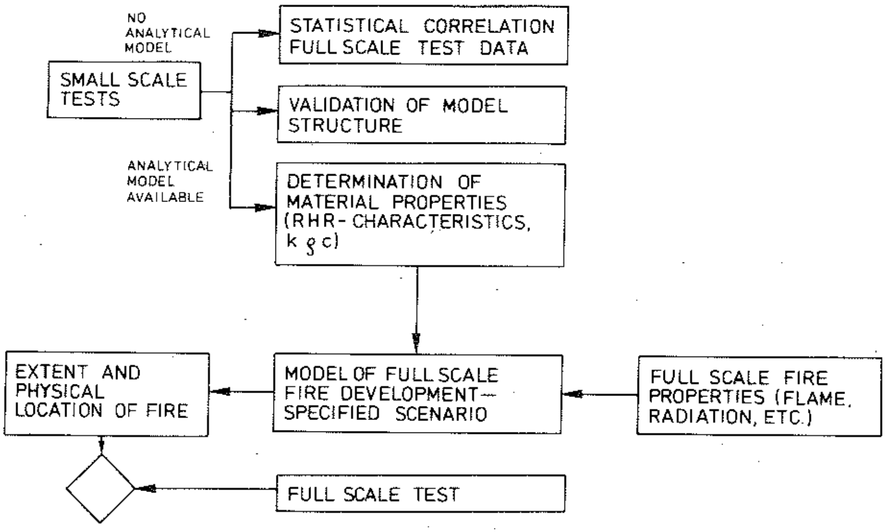


Fig. 13. Combination of basic property tests and mathematical models for assessing the contribution of a tested product to the overall fire safety

At present, the state of the art is thoroughly reviewed, as concerns available computer programs for mathematical fire modelling, within a US Ad Hoc Working Group. The survey comprises field models on turbulent flow in enclosures as well as different zone or control volume models (fire growth, fire plume theories, flame radiation, preflashover enclosure convection, postflashover-burning and convection, convective heat transfer in enclosure, radiative heat transfer, wall thermal response, remote ignition, next room problem).

The applicability of hazard assessment tests versus basic property tests is dealt with for the time being within ISO/TC92/WG 4. From this work the following statement - drafted by P.H. Thomas and S.E. Magnusson - may be quoted [15].

"A rational use of standard tests output in a functional design requires an understanding of the physical realities expressed by the test outcome. To this end, an analytical model of the test process dynamics is necessary. As a corollary to this we can say if a test is measuring something which can be quantitatively defined in physical or chemical terms it ought to be possible to predict test results for certain simple, idealised situations, eg a homogeneous flat material. Such exercises are commonly done in research and success allows one better to understand what the test really does and the extent to which the results are apparatus dependent.

Concurrently with the evolution of the theoretical analysis of testing methods, the last few years have meant rapid progress in our capacity to describe mathematically radiant and convective energy transport from large scale turbulent flames and the influence of this energy transport on burning and fire spread.

With the main features of the analytical model thus assumed and with material characteristics determined from the standard tests, comparison between theory and a specified full scale test should make possible the model structure validation as well as identification of undetermined parameters. Techniques to be used for this purpose have been developed within the field of automatic control to identify a variety of industrial chemical and physical processes.

When, for a given simplified geometrical full-scale situation, the process dynamics have been identified, deterministic sensitivity studies may be performed to ascertain the influence of test material properties on the fire spread and fire product generation process. Finally, going from the deterministic phase to a recognition of the stochastic nature of many state variables, reliability studies may be made, taking into account uncertainties in ignition processes, material properties, analytical modelling and environmental conditions. The output could have the form of time- and space-dependent probability density curves of fire products. More realistically, a distribution-free, first order linear analysis would provide the first and second moments of the maximum values of the corresponding quantities. Coupled with definitions of the limits of human tolerance and escape availability, the fire hazard may be evaluated. This may in turn lead to a consistent definition of the integrated concept of a 'reaction to fire' index for the given situation.

To reach this stage of development will take a considerable number of years. Research is required on

(1) the applicability, to the standard tests under development, of available analytical thermophysical mathematical models regarding fire product generation,

(2) systematic identification studies of model structures and parameters (such as basic and derived material properties),

(3) studies to identify those full-scale fire situations where at least the gross features of the process dynamics are known, and by use of model validation and parameter determination techniques to evaluate quantitatively the fire performance of the tested material, and

(4) procedures to translate fire perfomance quantities into a fire hazard assessment."

7. CONTROL OF SMOKE MOVEMENT IN ESCAPE ROUTES

Smoke is here used to describe the mixture of heated gases, liquid droplets and solid particles evolved from combustion. A stricter definition omits gases and terms smoke a mixture of particles and droplets of combustion products. Smoke flow models may vary in scale from the "bedroom" scenario and the corresponding calculation of the local gas concentration in single enclosures to the determination of smoke flow in large, multi-story buildings. We are here concerned with design of rational smoke control systems in escape routes. For the size of buildings considered here, measures to control horizontal and vertical smoke movements include smoke stop doors, forced extraction systems, pressurization systems.

Validation of designs to limit smoke flow requires predictive capability. Extensive efforts in a number of countries in recent years have produced numerical models describing smoke flow in naturally ventilated and/or air conditioned buildings. A comprehensive summary of the state of art is provided by papers in a 1975 CIB symposium on the control of smoke movements in buildings [16], [17], [18]. The flow chart in Fig. 14, taken from [19] outlines the basic approach. Smoke is distributed about the building by being carried with the building air flows between rooms and ventilation systems. The building is considered as a series of spaces or nodes, each at a specific pressure with air flow between them from areas of high to areas of low pressure. The pressure in each of the spaces and air flow through each opening is calculated by solving the air flow network equations for the complete building. The network is composed of the flow resistance of openings and ventilation systems and mass driving forces such as wind pressure and air gravity. The equations are obtained by the application of the law of mass constancy at each node and Bernoulli's law.

From Fig. 14, the more complete analysis of transient smoke flow requires the development of three major, interconnected subsystems

- fire process model, describing rate of smoke production
- building air pressure and air flow model
- human behaviour model and the impact of psychological factors on evacuation times.

For many practical applications, a less comprehensive analysis may be sufficient. For example, when an analysis is made for smoke control design the primary goal is to check pressure conditions and the explicit calculation of smoke concentrations and room temperatures may be omitted. When this approach is combined with the simplifying assumption of steady state conditions, even complicated systems may be checked fairly rapidly.

The improved computational efficiency is a prerequisite for sensitivity studies. With reference to the three subsystems enumerated, the stocastic nature of a large number of environmental factors is apparent. These factors include

fire process model: geometrical, ventilation and thermal properties of fire compartment, fire load characteristics such as quantity, porosity and category (cellulosic, synthetic polymer),

air flow model: wind speed and wind direction, location of fire room, number of open doors, windows and communication paths, performance of a mechanical ventilation system, human behaviour model: time for recognition/interpretation of danger, mode of action, number of people in building, performance of lighting and guide marking.

Final risk levels will depend on the accumulated effect of the variability inherent in the parameters mentioned. So far, no quantitative results are available. The large number of stochastic parameters, many of whom will be found to have a considerable variance in practice, makes it likely that the final outcomes will be characterized by a very large distribution scatter. Two examples of the uncertainty in input data will be given here, both relating to the difference between natural and synthetic fuel. The first example is shown in Table 2 giving mass burning rates of selected materials in simulated full scale fire environment. There is a variation in burning and thus smoke production with a factor 5.4.

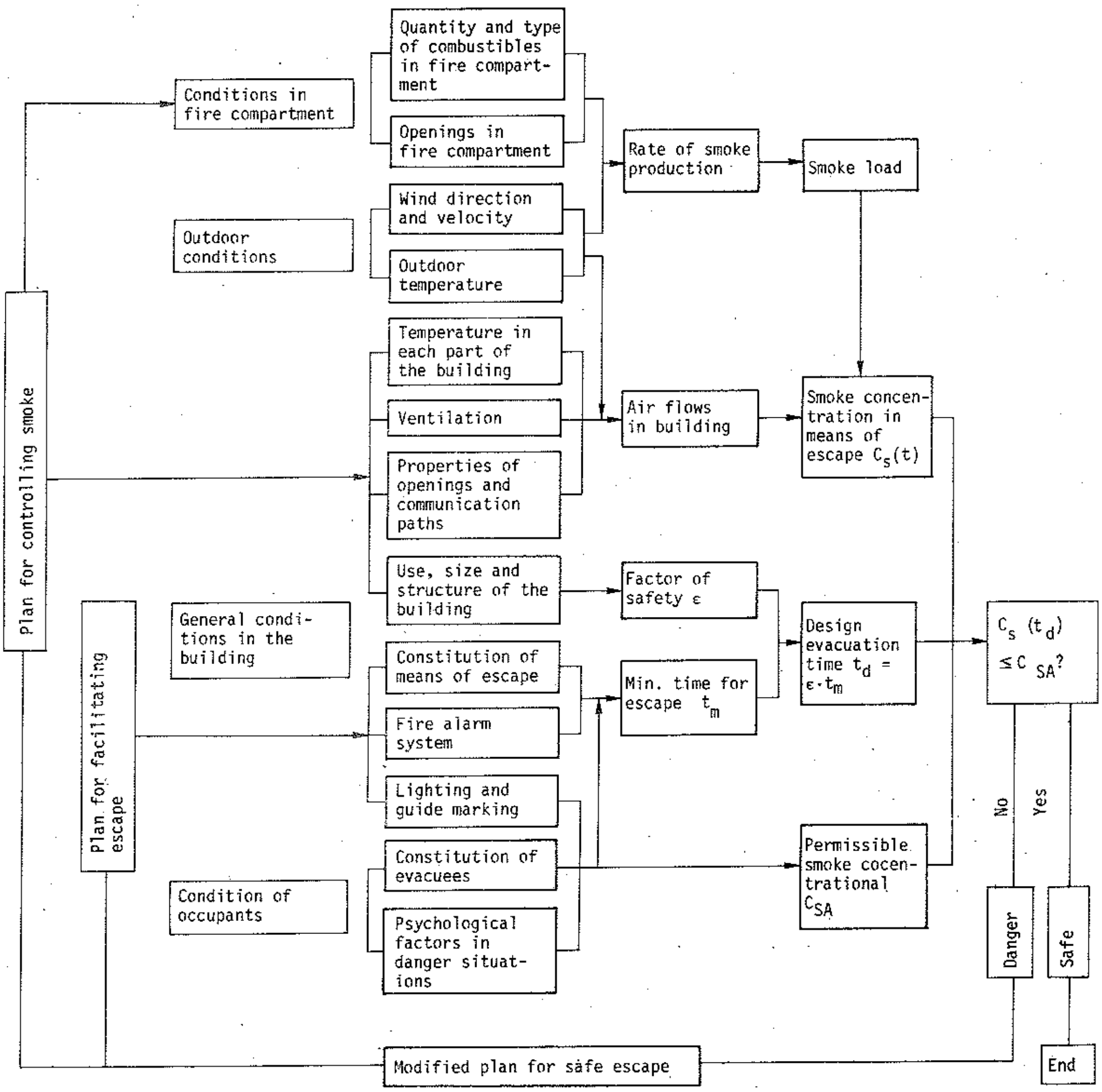


Fig. 14. Flow chart of smoke control design system [19]

Material	Burning rate g/m^2 s	Material	Burning rate g/m^2 s
Flexible polyurethane foam	54		
Rigid polyurethane foam	50	Polyoxmethylene	18
Ethyl alcohol	44	Polyethylene	16
Polystyrene	39	Polypropylene	16
FR rigid polyisocyanurate foam	37	Phenolic	14
Methyl alcohol	36	Wood (Douglas fir)	14
FR rigid polyurethane foam	29	FR rigid phenolic foam	12
FR rigid polystyrene. foam	28	FR plywood	11
Polycarbonate	27	FR glass fiber rigid polyisocyanurate foam	10
Glass fiber reinforce polyester	20		
FR glass fiber reinforced polyester	19		

Table 2. Mass burning rates for specific materials in simulated full scale fire tests [20]

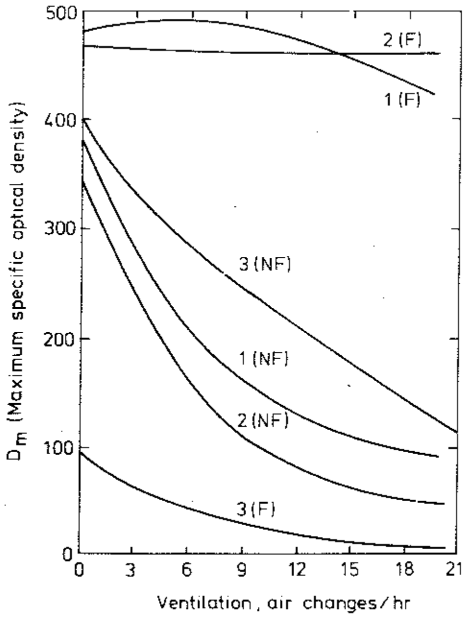


Fig. 15. Effect of ventilation and mode of burning on maximum smoke density. F = flaming combustion, NF = non-flaming (pyrolysis). Material 1 = acrylics, 2 = polystyrene, 3 = red oak [21]

Example number two concerns the light obscuration properties of specific materials burning in a thermal environment with specified ventilation conditions and thermal decomposition in flaming or non-flaming [21]. Materials were studied in a smoke density chamber similar to the NBS apparatus. Acrylics, polystyrene and red oak were subjected to radiant heat (non-flaming) or to radiant heat in presence of a pilot flame (flaming combustion). Of special interest is the fact that the smoke chamber, which in standard use functions as a closed box, in this version had been added a ventilating capability. Tests were run with a specified, constant number of air changes per hour. As can be seen in Fig. 15 changes in burning mode and room ventilation causes large and diametrically opposite changes in light obscuration properties.

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9. SUMMARY

For various firesafety systems, the level of a reliability analysis is determined by the knowledge and the modelling capabilities accumulated in the deterministic case. In the paper, four sub-systems - structural integrity, fire spread in small house areas, fire growth in a compartment, smoke movement in escape routes - are discussed as potentially amenable to explicit reliability analyses for quantifying fire hazard assessments and deriving design parameters (safety factors).

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