Reliability based design of fire exposed timber structures : state of art and summary design guide

Pettersson, Ove; Jönsson, Robert

1988

LUND UNIVERSITY · SWEDEN
INSTITUTE OF SCIENCE AND TECHNOLOGY
DEPARTMENT OF FIRE SAFETY ENGINEERING
REPORT LUTVDG/(TVBB - 3040)
ISSN 0282 - 3756

OVE PETTERSSON - ROBERT JÖNSSON

RELIABILITY BASED DESIGN OF FIRE EXPOSED TIMBER STRUCTURES - STATE OF ART AND SUMMARY DESIGN GUIDE

LUND 1988

PREFACE

The following presentation is primarily intended to stimulate and facilitate a future development towards an improved situation for a reliability based structural fire engineering design of timber structures. The state of the art is reviewed and a structure of a design guide or a model code is outlined. The document is written in a partially operational manner, allowing practical application for some types of timber structures. The need of further research and development is stressed and exemplified.

The study relates to research grant 81-4902 from the Swedish Board for Technical Development (STU).

1. GENERAL BACKGROUND

The development of the fire hazards and fire damages in the society depends on a number of overgrasping background factors. The most decisive are:

* The trend towards a generally more complex society with a rapidly expanding use of advanced technology,
* an accelerated increase in the total potential of hazards with the measures for fire prevention and fire fighting becoming more and more an integrated component of the overall concept of rescue services, and
* a continuously expanding international fire research.

As a result of the powerfully increased extent of the international fire research, more and more components and systems are now becoming amenable to analytical and computer modelling. Considerable progress then has been made concerning such phenomena and procedures as [1] to [5]:

* The fire growth in a compartment,
* the fully developed compartment fire,
* the reaction to fire of materials,
* the fire spread between buildings,
* the fire behaviour of building structures,
* the smoke filling in enclosures and smoke movement in escape routes and multistorey buildings,

* the interaction of sprinklers and a fire,

* the process of escape, and

* the systems approach to the overall fire safety of a building, in its most general form comprising human response models interacting with fire development models.

As a consequence of this progress, a rapid development now is going on in the field of codes, specifications and recommendations for a fire engineering design in a broad sense. Some typical trends in this development are:

* An improved connection to real fire conditions,

* an increasing extent of design, based on functional requirements and performance criteria,

* a development of new test methods, which are, as far as possible, material independent and directly related to well-defined properties and phenomena,

* an increasing application of analytical design - reliability-based in its most advanced form,

* an extended use of integrated assessments, and

* an introduction of goal-oriented systems of analysis of the total, active and passive fire protection for a building.

The most manifest, official verification of these trends of development probably relates to the fire engineering design of load bearing and separating structures. An analytical procedure for a determination of the fire resistance of structural elements is now approved by the authorities in several countries as an alternative to the internationally predominant design, based on the results of the standardized fire resistance test and related classification. In order to facilitate the practical application of such an analytical procedure, the European Convention for Constructional Steelwork (ECCS) has drawn up European Recommendations for an analytical design of steel structures, exposed to the standard fire, [6] and an associated manual [7]. A similar design basis for fire exposed reinforced concrete structures has been prepared by Comité Euro-International du Béton (CEB) [8].

In a few countries, the authorities also have taken the next step to permit a general practical application of a direct analytical design procedure, based on the natural compartment fire concept [9]. In order to stimulate a further development towards a reliability based structural fire design, the Fire Commission of the Conseil International du Bâtiment (CIB W14) has prepared a State-of-Art Report [10] and a Design Guide [11] on this subject as an aid in the future drafting of corresponding national regulations or recommendations.

Today, an analytical design can be completed for most cases, as concerns fire exposed steel structures. Validated material models for the mechanical behaviour of concrete under transient high-temperature conditions [12], [13] and thermal models for a calculation of the charring rate in wood exposed to fire [14]-[17], derived during recent years, have significantly enlarged the area of application of analytical design. To aid this application, design diagrams and tables have been computed and published, giving directly, on the one hand, the temperature state of the fire exposed structure, and on the other, a transfer of this information to the corresponding load bearing capacity of the structure - cf., for instance, [6]-[8], [18]-[43].

The most recent trend in the development of the structural fire design is to adopt the modern loading and safety philosophy and include a probabilistic approach, based on either a system of partial safety coefficients (practical design format) or the safety index concept [8], [10], [11], [43]-[52].

The research and development work presented has mainly focussed on structures and structural elements of steel or reinforced concrete. For timber structures exposed to fire, the fire resistance and load bearing capacity can at present be calculated approximately for beams and columns of solid cross section. For lightweight and composite timber structures, there is no analytical method available for a structural fire design. Probabilistic design of fire exposed timber structures is a research area to which very little attention has been paid up to now.

The following presentation is intended to stimulate and facilitate a future development towards an improved situation for a reliability based structural fire engineering design of timber structures.

2. DESIGN METHODS FOR STRUCTURAL FIRE SAFETY

2.1 Characteristics of a Reliability Based Structural Fire Design

As stated in Chapter 1, the modern development of functionally well-defined, analytical design methods for fire exposed structures includes a probabilistic approach [8], [10], [11], [43]-[52].

A reliability based structural fire design should originate from validated models, describing the relevant physical processes and connected to strictly specified functional requirements and criteria. For the probabilistic model to be integrated with the physical model, various levels can be distinguished:

* An exact evaluation of the failure probability, using multi-dimensional integration or Monte Carlo simulation,

* an approximate evaluation of the failure probability, based on first order reliability methods (FORM), and

* a practical design format calculation, based on partial safety factors and taking into account characteristic values for action effects and response capacities.

For practical purposes, an exact evaluation of the failure probability is not possible. Also, the FORM approximations are too cumbersome for everyday design and the more simplified practical design formats have to be used.

In the partial safety factor format, each of the variables X in the design process is represented by a characteristic value x_k to which a certain probability of exceedance or non-exceedance may be allocated - i.e., expressed as a specified fractile. From the characteristic values, design values x_d are derived by multiplication, as concerns exposure variables, or by division, as concerns response variables, with corresponding safety factors γ_x:

$$x_d = x_k \gamma_x \quad \text{for exposure variables} \tag{2.1a}$$

$$x_d = x_k/\gamma_x \quad \text{for response variables} \tag{2.1b}$$

The fundamental components of a reliability based structural fire design are

* the limit state conditions,
* the physical model,
* the practical design format, and
* deriving the safety elements.

Depending on the type of practical application, one, two or all of the following limit state conditions apply:

* Limit state with respect to load bearing capacity,
* limit state with respect to insulation,
* limit state with respect to integrity.

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

$$\min \{R_d(t)\} - S_d \geq 0 \tag{2.2}$$

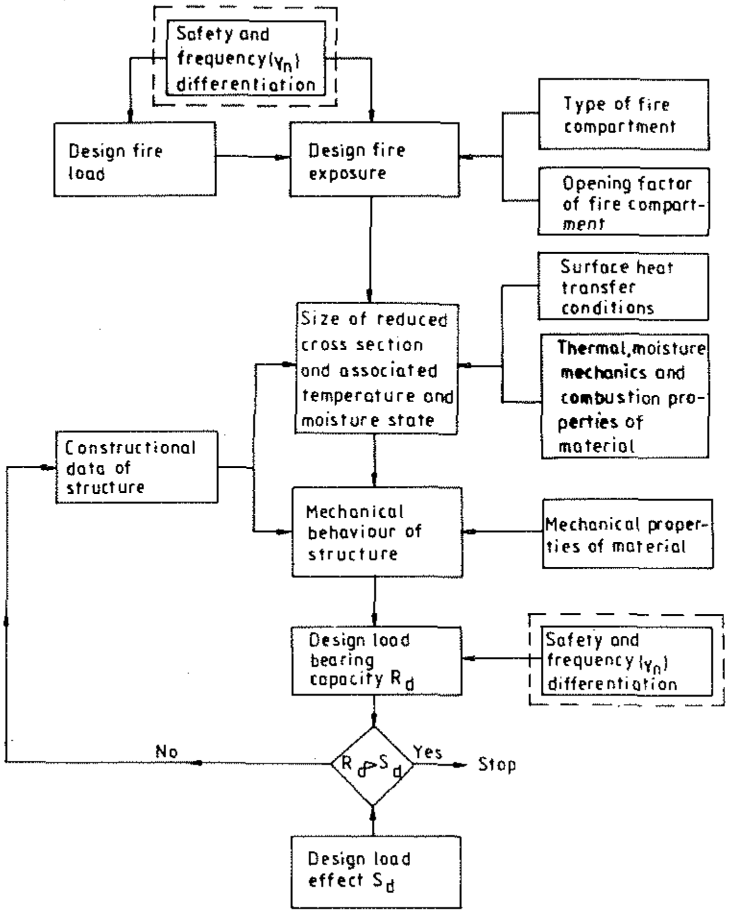
The criterion must be fulfilled for all relevant types of failure. The requirements with respect to insulation and integrity apply to separating structures. The design criterion regarding insulation implies that the highest design temperature on the unexposed side of the structure - max $\{T_{sd}(t)\}$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

$$T_{cr} - \max \{T_{sd}(t)\} \geq 0 \qquad (2.3)$$

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

The <u>physical model</u> comprises the deterministic model, describing the relevant physical processes of the thermal and mechanical behaviour of the structure at specified fire and loading conditions. Supplemented with relevant partial safety factors, the physical model is transferred to the <u>practical design format</u> - illustrated in Fig. 2.1 by a flow chart for a load bearing timber structure, exposed to a natural compartment fire.

From the design fire load and the geometrical, ventilation and thermal characteristics of the fire compartment (opening factor and type of fire compartment), the design fire exposure is determined either by energy and mass balance calculations or from a systematized design basis. Together with design values for the constructional data of the structure and the thermal, moisture mechanics and combustion properties of the structural materials at elevated temperatures, the design fire exposure gives the reduced cross section of the structure and the associated temperature and moisture conditions. With the mechanical properties of the structural material as further input data, the transient temperature and moisture state for the uncharred part of the cross section can be transferred to the related design load bearing capacity R_d for the lowest value of the load bearing capacity during the relevant fire process.



<u>Fig. 2.1</u> Procedure for a reliability based, analytical fire design of a load bearing timber structure, exposed to a natural compartment fire. The flow diagram shows two alternative allocations of the differentiation factor γ_n, defined by Equation (2.4)

The design format condition to be proved is given by Equation (2.2). Depending on the type of practical application, the condition has to be verified for either the complete fire process or a limited part of it, determined by, for instance, the time necessary for the fire brigade to attack the fire under the most severe conditions or by the design evacuation time for the building.

The probabilistic influences are considered by specifying characteristic values and related partial safety factors for the fire load density, such structural design data as imperfections, the thermal properties, the mechanical strength and the loading. In deriving the partial safety factors, the following probabilistic influences then have to be taken into account:

* The uncertainty in specifying the loads and of the model, describing the load effect on the structure,

* the uncertainty in specifying the fire load and the characteristics of the fire compartment,

* the uncertainty in specifying the design data of the structure and the thermal, moisture mechanics, combustion and mechanical properties of the structural material,

* the uncertainty of the analytical models for the calculation of the compartment fire and the related heat transfer to the structure, the size of reduced cross section and the associated temperature and moisture state of the structure and its ultimate load bearing capacity,

* the probability of occurrence of a fully developed compartment fire,

* the efficiency of the fire brigade actions,

* the effect of an installed extinction system, and

* the consequences of a structural failure.

The functional requirements, specified for the design, should be differentiated with respect to type of occupancy, type and size of building, number of floors, size and location of fire compartment, and the importance of structure or structural element to the overall stability of the building. This may be considered by a system of safety classes associated with different failure probabilities. In design verification, safety differentiation is accounted for by applying different partial safety factors for different safety classes or - more conveniently - by applying corresponding differentiation factors γ_{n1}.

For a certain occupancy, provisions employed for reducing the frequency of a fully developed fire for a particular project, i.e.

- envisaged alarm and sprinkler systems
- available force of fire fighting brigades

should be considered. In design verification, frequency differentiation is accounted for by applying different partial safety factors, depending on intended provisions and fire compartment size or - more conveniently - by applying corresponding differentiation factors γ_{n2}.

Summing up, the design verification must ensure that

$$R_{dn} = \frac{1}{\gamma_n} R_d(R_{d1}, R_{d2}, \ldots) \geq S_d(G_d, Q_{d1}, \ldots) \qquad (2.4a)$$

or

$$\frac{1}{\gamma_n} R_d(R_{k1}/\gamma_{r1}, R_{k2}/\gamma_{r2}, \ldots) \geq S_d(G_k, \psi_i, Q_{k,i}, Q_{k,ind}) \qquad (2.4b)$$

where

R_d is the design value of the ultimate load bearing capacity, determined by the lowest value of the ultimate load bearing capacity during the relevant fire process,

R_{di}, R_{ki}, γ_{ri} are design values, characteristic values and partial safety factors, respectively, related to the ultimate load bearing capacity, accounting for the uncertainties in heat exposure and structural response - cf. Fig. 2.1, and

S_d is the design load effect in fire, determined by considering an accidental load combination of the type

$$G_k + \sum_i \psi_i Q_{k,i} + Q_{k,ind} \tag{2.5}$$

where all actions are represented by their characteristic values

G_k = permanent loads (actions),
$Q_{k,i}$ = variable loads (actions), and
$Q_{k,ind}$ = indirect actions due to heat exposure,

with

ψ_i = combination coefficients (generally different for $i=1$ and $i > 1$),

and all other load factors are set to unity [11], [53], [54]

$$\gamma_n = \gamma_{n1} \gamma_{n2} \tag{2.6}$$

is a differentiation factor, accounting for different safety classes (γ_{n1}) and special fire fighting provisions (γ_{n2}) according to above. In Equation (2.4), the differentiation factor γ_n has been allocated to the design load bearing capacity R_d. Alternatively, γ_n may be applied as to affect the design fire load thus modifying the design fire exposure - as shown in Fig. 2.1.

For deriving the safety elements (partial safety factors), a probabilistic analysis, based on a first order reliability method (FORM) is necessary. In such an analysis, the design criterion requires that some minimum safety margin has to be maintained during the fire exposure with respect to the minimum load bearing capacity or, for a separating structure, the maximum temperature of the unexposed side. Expressed according to the "second moment code formats", this implies that the minimum value of the safety index for the structure during the relevant fire process β_{fm}, derived by a probabilistic analysis, has to meet the required value of the safety index β_r, i.e.

$$\beta_{fm} - \beta_r \geq 0 \tag{2.7}$$

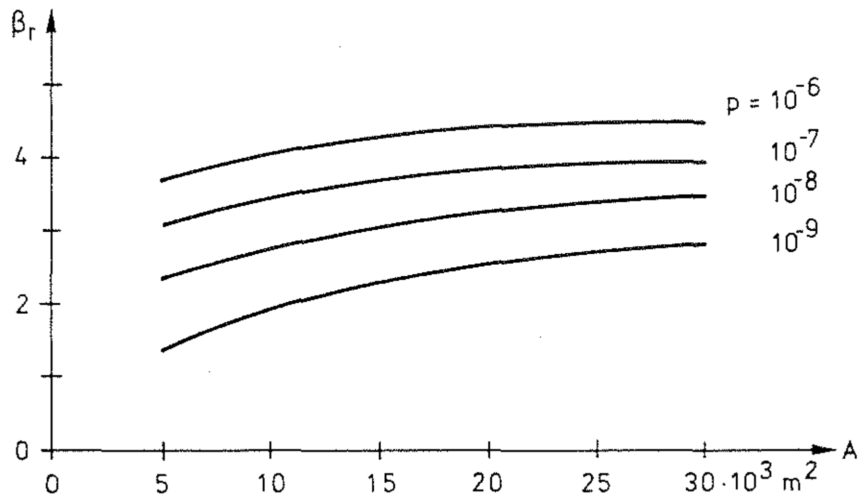


Fig. 2.2 Required values of safety index β_r as function of fire compartment area A and unit area probability per year p for industrial buildings and a safety class, representative of members of the main load bearing structure and separating structural members bounding the fire compartment [49]

The required value of the safety index β_r depends on the consequences of a structural failure, the probability of occurrence of a fully developed compartment fire, the efficiency of the fire brigade actions, and the effect of an installed fire extinguishment system, if any. For the detailed technique of deriving required values of the safety index β_r, see refs. [10], [46], [47], [50]. Fig. 2.2 exemplifies β_r values derived for industrial buildings and a safety class, representative of members of the main load bearing structure and separating structural members bounding the fire compartment [49]. The values are given as a function of the area of the fire compartment A and the probability of occurence of a fully developed compartment fire per year and unit area p.

The probability per unit area and year p may be described as

$$p = p_1 \; p_2 \; p_3 \tag{2.8}$$

where

p_1 = mean probability of occurrence of a fully developed compartment fire per unit area and year if the influence of fire brigade actions and extinguishment systems is not considered,

p_2 = factor to assess the efficiency of the fire brigade actions, and

p_3 = factor to include the effect of an installed extinguishment system, if any.

Example values of the probability p_1 are given in Table 2.1 and of the reduction factors p_2, p_3 in Table 2.2 [10].

Table 2.1 Example values of the mean probability of occurrence of a fully developed compartment fire per unit area and year p_1 [10]

	Germany	England	USA	
Dwellings	0.2	2.0	0.05-1	10^{-6}
Schools	0.5			10^{-6}
Hotels	0.5			10^{-6}
Shops	1.0			10^{-6}
Offices	0.5	1.0	1-5	10^{-6}
Industrial buildings	2.0	2.0		10^{-6}

Table 2.2 Example values of reduction p_2, p_3 of the mean probability of occurrence of a fully developed compartment fire p_1 for different types of active protection measures [10]

Average standard public fire brigade	10^{-1}
Adequately maintained sprinkler system	$2 \cdot 10^{-2}$
High standard residential fire brigade, combined with alarm system	$\geq 10^{-2}$ to 10^{-3}
Both sprinkler system and high standard residential fire brigade	$\geq 10^{-4}$

A probabilistic analysis according to a first order reliability method can be outlined as follows - see Fig. 2.3, which shows the procedure for a fire exposed, loadbearing timber structure.

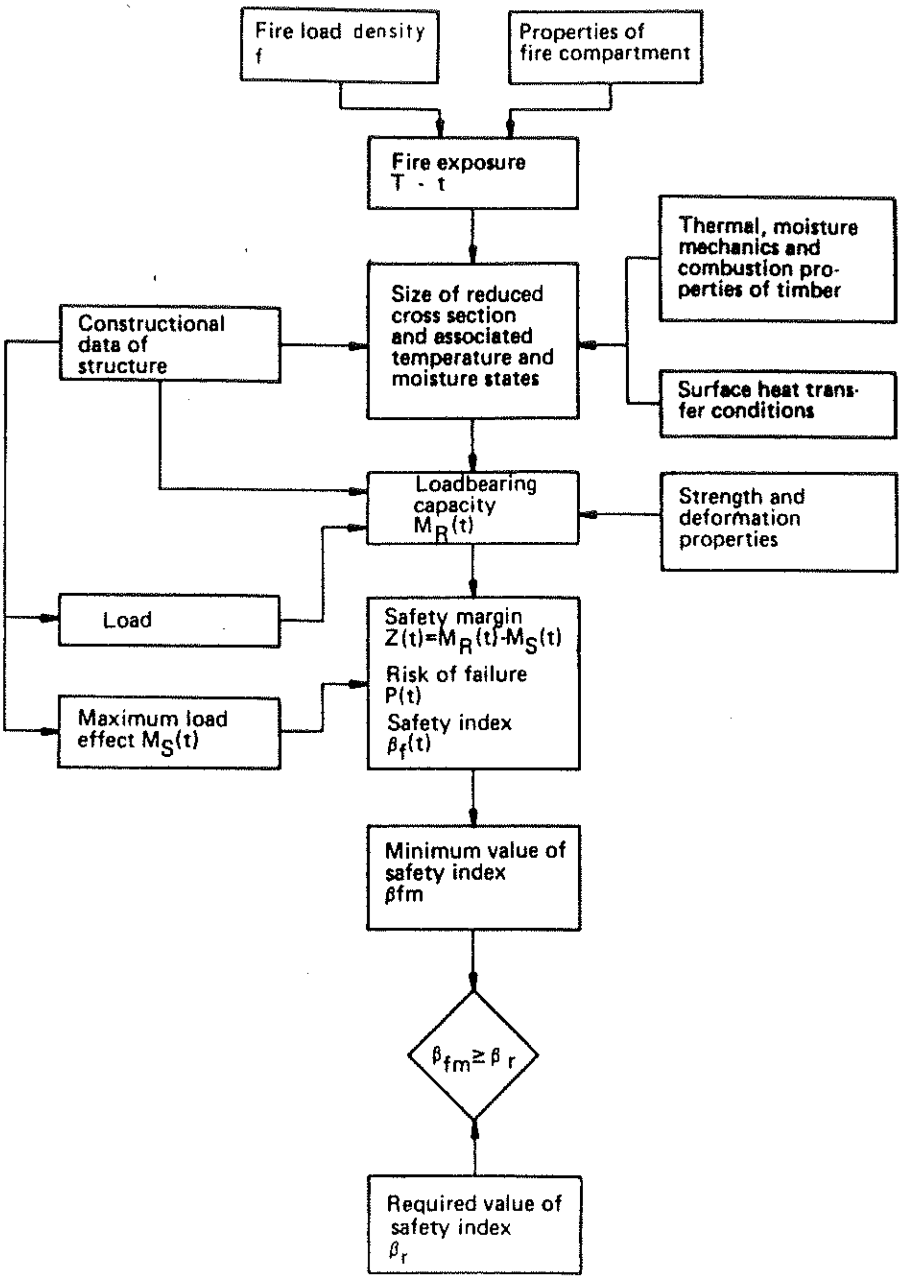


Fig. 2.3 Derivation of partial safety factors for a fire exposed, load bearing timber structure by a probabilistic analysis according to a first order reliability method (FORM)

The size and properties of the fire load density and the geometrical, ventilation and thermal characteristics of the fire compartment constitute the basis for a determination of the fire exposure, given as the gas temperature-time curve T - t of the fully developed compartment fire. Together with constructional data for the structure and information on the thermal, moisture mechanics and combustion properties of the structural material at elevated temperatures, the fire exposure gives the reduced cross section of the load bearing structure and the associated transient temperature and moisture conditions. With the strength and deformation properties of the structural material as further input data, the transient temperature and moisture state for the uncharred part of the cross section can be transferred to the time variation of the load bearing capacity during the fire exposure. This can be expressed, for instance, as bending moment $M_R(t)$ in a decisive section of the structure. The loading, statistically representative for the fire situation, gives a maximum load effect with a bending moment $M_S(t)$ in the section for the load bearing capacity $M_R(t)$.

The following formulae apply for the safety margin:

$$Z(t) = M_R(t) - M_S(t) \tag{2.9}$$

for the probability of failure

$$P(t) = \int_{-\infty}^{0} f_z[Z(t)]dZ \tag{2.10}$$

and for the safety index

$$\beta_f(t) = \Phi^{-1}[1 - P(t)] \tag{2.11}$$

where $f_z[Z(t)]$ = probability density function of safety margin Z, and Φ^{-1} = inverse of the standardized normal distribution. At the determination of the safety margin Z(t), the probability of failure P(t) and the safety index $\beta_f(t)$, all the probabilistic influences listed on 10 p. have to be taken into consideration, except the influences covered by the safety index β_r according to above.

As expressed by Equation (2.7), the design verification must ensure that the minimum value β_{fm} of the safety index $\beta_f(t)$ during the relevant fire exposure meets the required value of the safety index β_r.

Further guidance for the determination of the partial safety factors γ_r and the differentiation factor γ_n - Equations (2.4a) and (2.4b) - is given in appendix 5 of ref. [11] together with example values.

2.2 Summary Review of Internationally Applied Methods for a Structural Fire Design

The methods available at present for a fire engineering design of load bearing structures can systematically be characterized with reference to the matrix presented in Fig. 2.4 [10], [11], [41]. This is based on three types of models for the thermal exposure of the structure (models H_1, H_2 and H_3) and three types of models for the mechanical behaviour of the load bearing structure (models S_1, S_2 and S_3).

Models for thermal exposure

H_1 - thermal exposure according to the standard temperature-time curve as specified in the ISO Standard 834 [55] or in the corresponding national standards. This exposure is used to grade structural elements and the building codes and regulations require different grades of element depending on the circumstances and expressed by the fire resistance t_f.

Model for structure / Model for thermal exposure		S_1 Element	S_2 Substructure	S_3 Complete structure
H_1	ISO-834 (T, t_f)	test or calculation (deterministic)	calculation exceptionally testing (deterministic)	
H_2	ISO-834 (T, t_e)	test or calculation (probabilistic)	calculation, exceptionally testing (probabilistic)	calculation (probabilistic) should be avoided
H_3	real fire (T)	*calculation* (probabilistic)	*calculation* (probabilistic)	*calculation* (probabilistic) in special cases and for research

Fig. 2.4 Matrix of thermal exposure and structural models, characterizing available methods for a fire engineering design of load bearing structures

H_2 - the same thermal exposure as for model H_1, except that the length of thermal exposure t_e is determined in each individual case from the characteristics of the particular compartment fire. t_e is called the equivalent time of fire exposure and is defined to give the same decisive effect on the structural element with respect to the relevant limit state when the element is exposed to the standard temperature-time curve as it is when exposed to the natural compartment fire.

H_3 - thermal exposure determined by the fully developed compartment fire with due regard taken to the combustion characteristics of the fire load, the ventilation of the fire compartment and the thermal properties of the structures enclosing the compartment.

Internationally, a structural fire design method, based on the thermal exposure model H_1, H_2 or H_3 is referred to as a level 1, 2 or 3 method or, alternatively, as an assessment method 1, 2 or 3, respectively.

Models for structural behaviour

S_1 - single structural elements, e.g. beams, columns, walls, floors and roofs. The structural model may simulate either a structural element, which behaves as single in the real structure, or a structural element with simplified end conditions which in reality acts together with other elements of the complete structure.

S_2 - a substructure which approximately describes the mechanical behaviour of a part of the complete load bearing system of the building. Compared to the complete load bearing system, a substructure has simplified conditions of deformation at its outer ends or edges.

S_3 - the complete load bearing structure acting as, for instance, a two- or three-dimensional frame, a beam-slab system or a column-beam-slab system.

Comments

Assessment method 1 (model H_1) represents the internationally prevalent structural fire design. As mentioned, the method is related to a grading system with the fire resistance usually determined experimentally by the standard fire resistance test. Alternatively, the fire resistance can be evaluated analytically and manuals and other publications now available facilitate such an evaluation [6]-[8], [21]-[24], [26]-[29], [31]-[37], [39]-[41].

As specified in the ISO Standard 834, the standard fire resistance test is applicable to such structural elements as walls and partitions, columns, beams, floors and roofs. Hence, it follows that the thermal exposure model H_1 is only intended to be applied to structural elements, i.e. the structural model S_1. In some countries, also the model combination H_1-S_2 is applied and then usually by calculation. The model combination H_1-S_3 is characterized by a very great difference in schematization between the thermal exposure and structural models and should consequently not be used.

The rapid progress during the last decades in the development of analytical methods has considerably increased the possibilities of applying a structural fire design according to assessment methods 2 and 3 as an improved alternative to the conventional fire design.

An assessment method 3 design means an entirely analytical procedure, directly based on the natural compartment fire - exposure model H_3. Exceptionally, the design can refer to a full scale test. Depending on the individual practical application, the thermal exposure model can be combined with the structural model S_1, S_2 or S_3. The structural model S_1 then primarily has relevance if the structural element behaves as a single element in the real structure. If the real structure has a high degree of complexity, the ordinary procedure will be to split up the structure into well-defined substructures in the analysis. A structural fire design related to the model combinations H_3-S_1 and H_3-S_2 is facilitated by the availability of manuals, especially as steel structures and reinforced concrete structures are concerned [9], [19], [20], [25], [32], [38], [41].- [43]. A design according to the model combination H_3-S_3 normally requires the support of a computer.

A fire design in accordance to assessment method 2 (model H_2) is based indirectly on the natural compartment fire but the thermal exposure is specified by the standard temperature-time curve. The connecting instrument is the equivalent time of fire exposure t_e. When formulated as a model combination H_2-S_1, a level 2 design can be done either by calculation or by an evaluation based on results of the fire resistance test. For the model combination H_2-S_2, an analytical approach will be the normal case and testing will be confined to exceptional cases. For both model combinations H_2-S_1 and H_2-S_2, an analytical design is facilitated by the availability of manuals and other relevant publications - se references, given above in relation to assessment method 1. The model combination H_2-S_3 requires access to a computer. The combination can be questioned from a practical point of view since it does not give any simplifications in comparison with the more direct design according to the model combination H_3-S_3.

For a probability based structural fire design, it must be required that it originates from functionally validated models, describing the relevant physical processes and clearly specifying the inherent uncertainties and reliability levels. Of the fire design methods presented, only the assessment methods 2 and 3 fulfil these requirements from a conceptual point of view. Consequently, the fire design according to assessment method 1 should be limited to a deterministic approach.

In what follows, the summary review given of the internationally applied methods for structural fire design will be supplemented with an outline of the different models of thermal exposure in relation to the assessment methods 1, 2 and 3. Then, the procedure of a reliability based structural fire design is briefly described and commented on, as concerns the assessment methods 2 and 3. The description will be structured in such a way that it is directly linked to section 2.1, which mainly applies to assessment method 3.

2.3 Assessment Method 1 and Thermal Exposure H_1

The internationally prevelant fire design of load bearing and separating structural elements, related to national classification systems, is directly based on results of standard fire resistance tests. In the design, the results of such tests have to meet the corresponding requirements, specified in the building codes and regulations - Fig. 2.5.

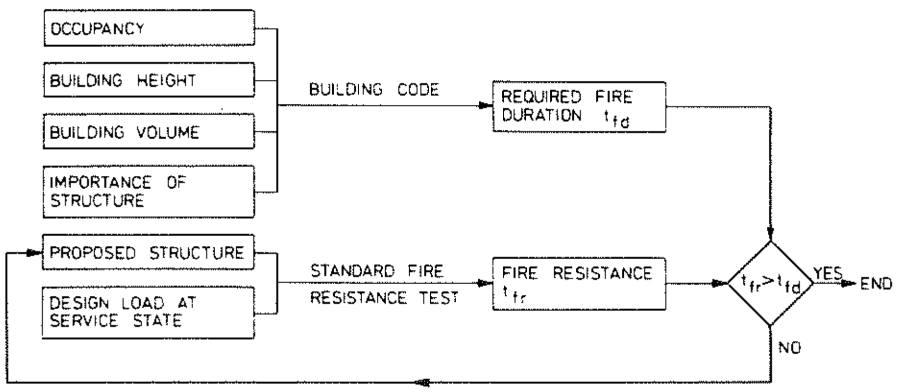


Fig. 2.5 Internationally conventional fire design of structural elements, based on classification and results of standard fire resistance tests

In the fire resistance test [55], the specimen is exposed in a furnace to a temperature rise, which shall be controlled so as to vary with time within specified limits according to the relationship - the standard fire

$$T_t - T_o = 345 \log_{10} (8t + 1) \qquad (2.12)$$

where

t = time, in minutes

T_t = furnace temperature at time t, in ^oC, and

T_o = furnace temperature at time t=0, in ^oC.

Internationally, the standard fire resistance test is considered to be one of the fire test methods most thoroughly dealt with. In spite of this, the test can be criticized. In its present form, the test procedure is insufficiently specified in several respects, for instance, concerning the heating and restraint characteristics, the environment of the furnace, and the thermocouples for measuring and regulating the furnace temperature. The specification of the test load is practically related to the national building codes and regulations and these can vary considerably with respect to the load level required from country to country.

Consequently, a considerable variation may arise in the fire resistance for one and the same structural element, when tested in different fire engineering laboratories with varying furnace characteristics and varying practice. These problems are thoroughly analysed within ISO/TC92/SC2/WG1 with the ultimate aim to arrive at a test procedure with improved repeatability and reproducibility.

The important progress in the development of computation methods for an analytical structural fire design has opened the door for the fire resistance to be determined by calculation in many practical applications. Fig. 2.6 shows a flow chart for this procedure. More and more countries are now permitting a classification of load bearing structures to be done analytically with respect to the standard fire, as an alternative to testing. A further development in this direction is stimulated and facilitated by the recent international recommendations and guidance documents, produced by European Convention for Constructional Steelwork (ECCS) [6], [7] and Comité Euro-International du Béton (CEB) [8], [36].

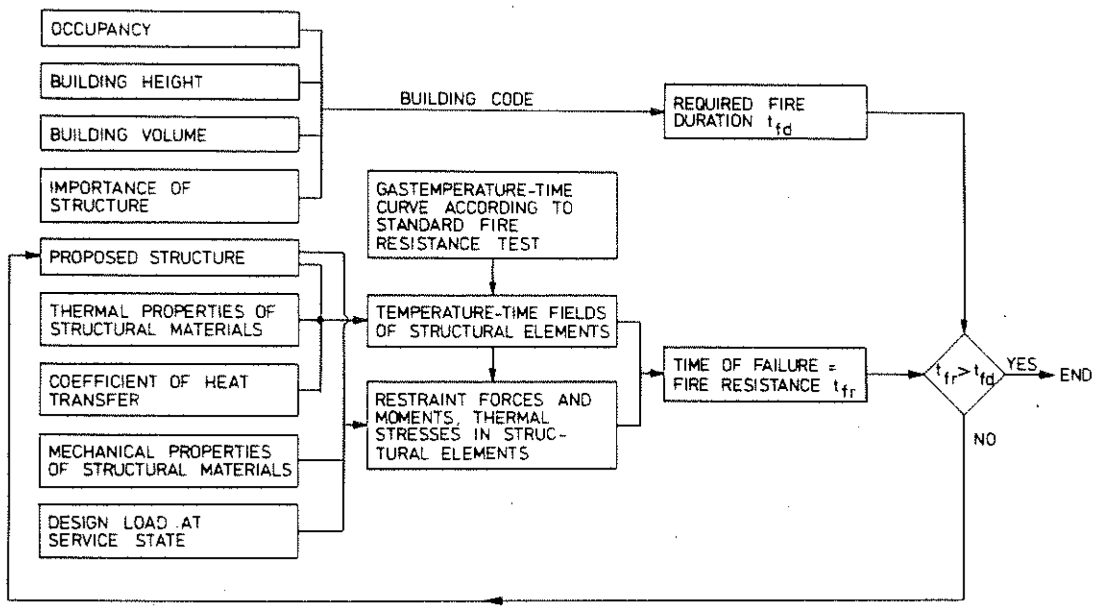


Fig. 2.6 Analytical fire design of load bearing structural elements, based on classification and thermal exposure according to Equation (2.12)

Irrespective of the fire resistance being determined analytically or by testing, it is important to consider that the standard fire resistance test does not represent the real fire exposure in a building nor does it measure the behaviour of the structural element as a part of an assembly in the building. What the test or the corresponding calculations do is to grade structural elements and the building codes and regulations then require different grading levels of elements depending on the circumstances.

2.4 Assessment Method 3 and Thermal Exposure H_3

Applying assessment method 3 means a structural fire design, directly based on a natural compartment fire exposure. The design procedure follows the flow chart according to Fig. 2.1 with the limit state criteria given by Equations (2.2) and (2.4) for load bearing structures and by Equation (2.3), as concerns the insulation function for separating structures.

The essential influences on the fully developed compartment fire are:

* Amount and type of combustible materials in the compartment - the fire load,
* porosity and particle shape of the fire load,
* distribution of the fire load in the compartment,
* amount of air per unit time supplied to the compartment,
* geometry of the compartment, and
* thermal properties of the structures, enclosing the compartment.

The fully developed compartment fire is the one most widely studied and during the past 20 years several analytical simulation models have been presented, primarily developed for the application to problems of structural fire safety. In a review paper [56] published 1983, HARMATHY and MEHAFFEY have classified 14 such mathematical models on the basis of 14 principal modelling aspects. The models included have been judged either to represent important steps in the evolution of knowledge or to offer unique concepts.

The fundamental characteristics for a complete description of the fully developed compartment fire are the time variations of the

(1) rate of heat release, RHR,
(2) gas temperature,
(3) geometrical and thermal data for external flames,
(4) smoke and its optical properties, and
(5) composition of the combustion products, particularly toxic and corrosive gases.

The simulation models, developed for structural fire safety purposes, then concentrate on the characteristics (1) to (3). Most models are partly theoretical and partly empirical with the empirical part focusing on data on the rate at which the fuel is consumed. The models generally appear to be based on the approximation that the temperature is uniform within the fire compartment.

For known combustion characteristics of the fire load, the time curve of the heat flux to an exposed structure or the gas temperature-time curve of the fire compartment can be calculated in the individual practical application from the energy and mass balance equations of the compartment fire - Fig. 2.7 [57]-[72].

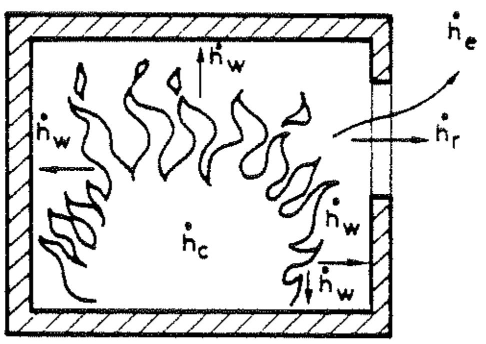


Fig. 2.7 Energy balance of a compartment fire

The energy balance equation reads

$$\dot{h}_c = \dot{h}_e + \dot{h}_r + \dot{h}_w + \dot{h}_g \qquad (2.13)$$

where

$\dot{h}_c$ = rate of heat release due to the combustion of the fuel (fire load),

$\dot{h}_e$ = energy removed per unit time by change of hot gases against cold air,

$\dot{h}_r$ = energy removed per unit time by radiation through the openings,

$\dot{h}_w$ = energy removed per unit time by heat transfer to the enclosing structures, and

$\dot{h}_g$ = energy stored per unit time within the fire compartment, usually negligible.

The corresponding mass balance of the fire compartment is described by the equation

$$\dot{m}_f = \dot{m}_{air} + \dot{m}_p \qquad (2.14)$$

where

$\dot{m}_f$ = mass outflow of hot gases,

$\dot{m}_{air}$ = mass inflow or air, and

$\dot{m}_p$ = rate of fuel pyrolysis.

As a simplification, fully developed compartment fires can be described by two types of behaviour - ventilation controlled or fuel bed controlled [73]. For the first type, the combustion during the active stage of the fire is controlled by the ventilation of the compartment with the burning rate approximately proportional to the air supply through the openings and does not depend on the amount, porosity and particle shape of the fuel in any decisive way. For the second type, the combustion is mainly controlled by the properties of the fuel and is fairly independent of the air supply through the openings. The boundary between the two types of fire behaviour is not clearly defined.

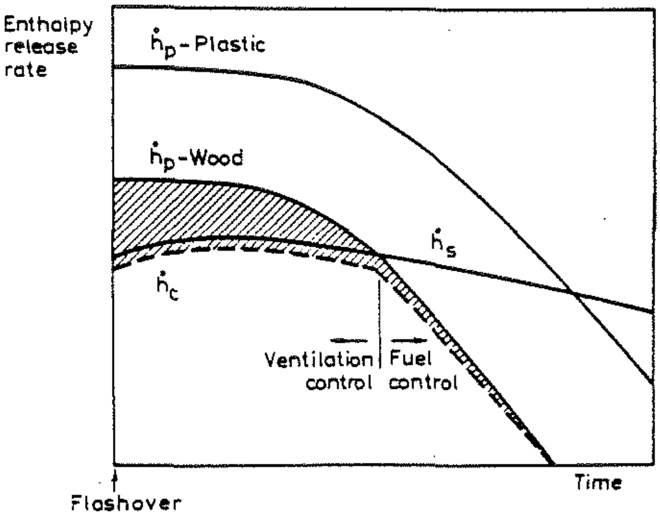


Fig. 2.8 Possible rates of enthalpy release in a fully developed compartment fire versus time for two types of fuel [62]

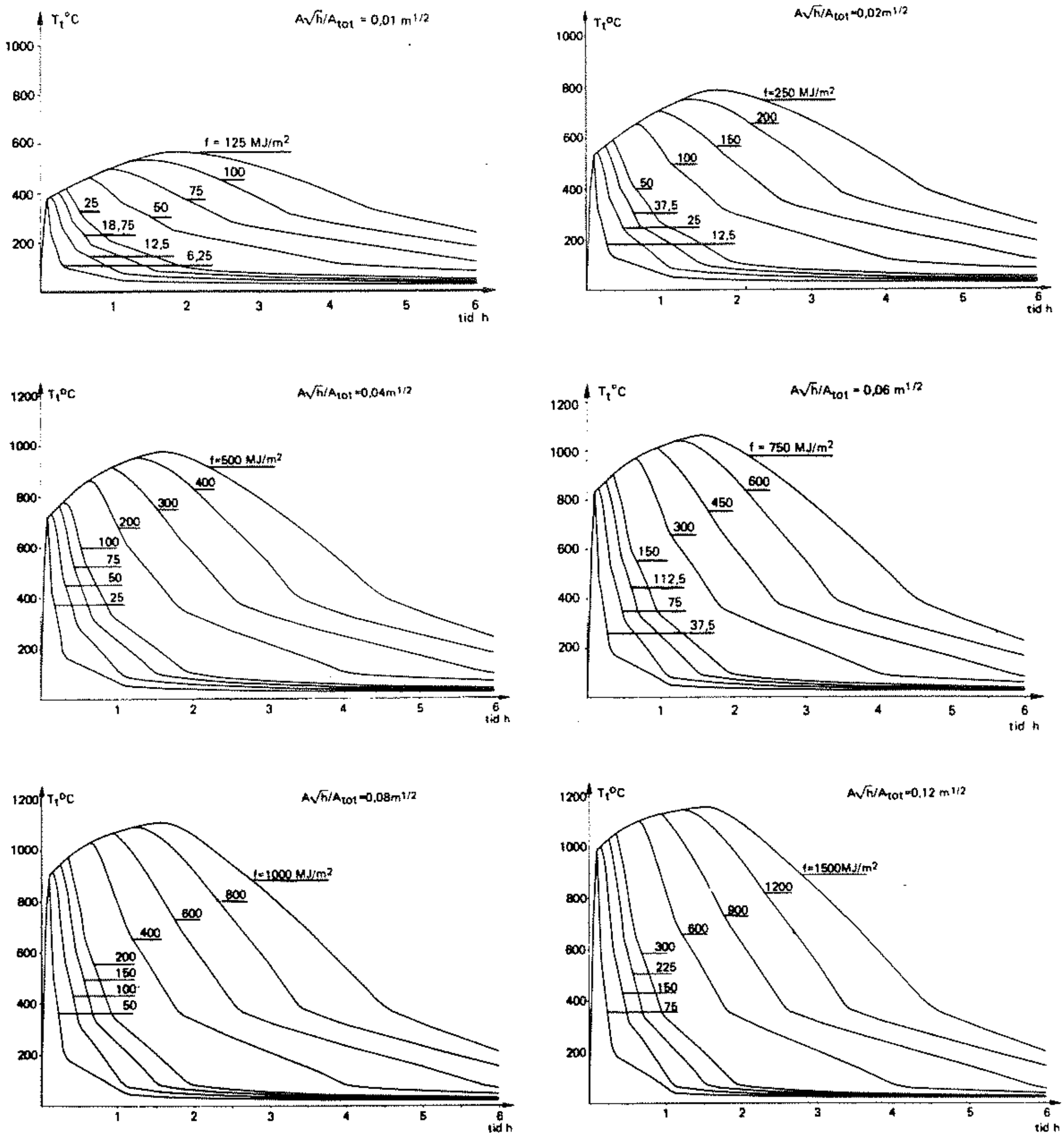
Fig. 2.8 illustrates the two types of compartment fires in a diagram, giving the rate of enthalpy release during the fire process versus time for two types of fuel [62]. In the figure, $\dot{h}_p$ denotes the potential rate of change of enthalpy of the gas, pyrolyzed from the fuel, i.e. the maximum fuel enthalpy release rate that would occur under ideal burning conditions. The term $\dot{h}_s$ denotes the rate of heat release for stoichiometric combustion. For a given compartment, $\dot{h}_s$ is primarily a function of the ventilation factor $A\sqrt{h}$ - where A is the area and h the height of the opening of the compartment - and the gas temperature and only slightly dependent on the type of fuel. The actual enthalpy release rate $\dot{h}_c$ will be the lesser of $\dot{h}_p$ and $\dot{h}_s$, reduced by a factor of maximum combustion efficiency b_p, which corrects for incomplete mixing, i.e.

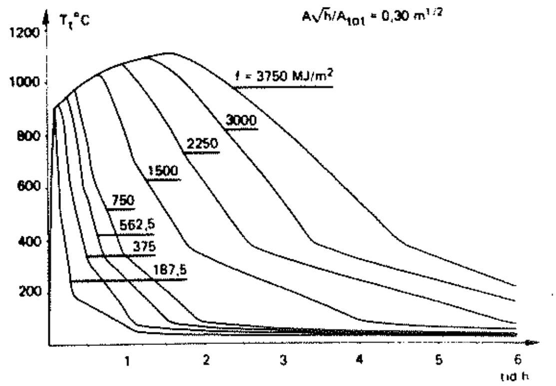
$$\dot{h}_c = \text{lesser of } \begin{cases} \dot{h}_p b_p \\ \dot{h}_s b_p \end{cases} \tag{2.15}$$

Fig. 2.8 shows two compartment fires with $\dot{h}_p > \dot{h}_s$ at flashover which means that the fires start as ventilation controlled. At a decreasing rate of pyrolysis during the fire, the $\dot{h}_p$ curve may cross the $\dot{h}_s$ curve after some time. At this point, the fire changes to be fuel controlled from then on. For $\dot{h}_p > \dot{h}_s$, more fuel is pyrolyzed within the fire compartment than can be burnt inside it. The difference $(\dot{h}_p - \dot{h}_s)$, shown hatched in the figure for the wood fuel fire, represents the excess pyrolysates, released from the compartment. For fuels with a high rate of pyrolysis, which is typical for flammable liquids and many plastic fuels, these excess pyrolysates can give rise to a considerable fire hazard outside the fire compartment, for instance, in corridors or at facades.

The practical use of the energy and mass balance equations of the fully developed compartment fire is facilitated by access to well-documented computer programmes, e.g., see [59], [65], [70]. A closed-form approximation, arranged to suit hand calculations, is presented in [66].

The available methods can be used for preparation of design aids for practical application. The gas temperature-time curves in Fig. 2.9 - cf. [9], [19], [25], [59] - exemplify such design aids for an analytical design of load bearing structures and partitions, exposed to a natural compartment fire. The curves are approved by the National Swedish Board of Physical Planning and Building for a general practical application [9].





g. 2.9 Example of gas temperature-time curves T_t-t of fully developed compartment fires for different values of the fire load density f and the opening factor $A\sqrt{h}/A_{tot}$. Fire compartment, type A - from authorized Swedish Standard Specifications [9], [19], [25], [59] Variables for the diagrams are the fire load density f per unit area of bounding surfaces of the compartment ($MJ \cdot m^{-2}$), and the ventilation characteristics of the compartment, expressed by the opening factor $A\sqrt{h}/A_{tot}(m^{1/2})$

where

A = total area of window and door openings (m^2),
h = mean value of the height of window and door openings, weighted with respect to each individual opening area (m), and
A_{tot} = total interior area of the surfaces, bounding the compartment, opening area included (m^2).

The fire load density f is given by the relationship

$$f = \frac{1}{A_{tot}} \Sigma\mu_\upsilon \; m_\upsilon \; H_\upsilon \qquad (2.16)$$

where

m_υ is the total mass of combustible material υ (kg),
H_υ its net calorific value ($MJ \cdot kg^{-1}$), and
μ_υ a fraction between 0 and 1, giving the real degree of combustion for each individual component υ of the fire load.

The diagrams in Fig. 2.9 apply to a fire compartment with specified thermal data for the bounding structures - fire compartment type A. Fire compartments with deviating thermal data can approximately be transferred to the fire compartment type A by using fictitious values of the fire load density and the opening factor according to the formulae

$$f_f = K_f f \qquad (2.17a)$$

$$(A\sqrt{h}/A_{tot})_f = K_f \; A\sqrt{h}/A_{tot} \qquad (2.17b)$$

The coefficient K_f then mainly is a function of the type of fire compartment. For some types of compartments, there also is an influence of the opening factor to be considered. The coefficient K_f is given in Table 2.3 [9] for 8 types of fire compartments.

The design basis referred was computed from the energy and mass balance equations of the fire compartment under certain simplifying assumptions, viz.

* the combustion of the fire load takes place entirely within the fire compartment,

* the fire process is ventilation controlled, and

* the temperature is uniform within the fire compartment at any time.

Systematic analyses have verified the reasonableness of the assumptions as a basis for the calculation of the load bearing capacity of fire exposed structures and structural elements located in fire compartments of moderate size, i.e. compartments with a size representative of dwellings, ordinary offices, schools, hospitals, hotels and libraries. For fire compartments with a very large volume - for instance, large industrial buildings and sports halls - the exemplified design basis as well as the energy and mass balance equations behind are giving an unsatisfactory description of the real fire exposure. For such compartments, a preflashover fire may locally expose a structural member - for instance, a beam, a column or a frame - more or less severely than would be the case, if the design is based on available models of the fully developed compartment fire. At present, no validated models are available for a phenomenologically correct representation of the fire exposure, as concerns fire compartments with a

Table 2.3 Coefficient K_f for transforming a real fire load density f and a real opening factor $A\sqrt{h}/A_{tot}$ to a fictitious fire load density f_f and a fictitious opening factor $(A\sqrt{h}/A_{tot})_f$ corresponding to a fire compartment, type A

$f_f = K_f f \qquad (A\sqrt{h}/A_{tot})_f = K_f\ A\sqrt{h}/A_{tot}$

Type of fire compartment	Opening factor $A\sqrt{h}/A_{tot}$ $m^{1/2}$					
	0.02	0.04	0.06	0.08	0.10	0.12
Type A	1	1	1	1	1	1
Type B	0.85	0.85	0.85	0.85	0.85	0.85
Type C	3.00	3.00	3.00	3.00	3.00	2.50
Type D	1.35	1.35	1.35	1.50	1.55	1.65
Type E	1.65	1.50	1.35	1.50	1.75	2.00
Type F[1]	1.00 - 0.50	1.00 - 0.50	0.80 - 0.50	0.70 - 0.50	0.70 - 0.50	0.70 - 0.50
Type G	1.50	1.45	1.35	1.25	1.15	1.05
Type H	3.00	3.00	3.00	3.00	3.00	2.50

[1] The lowest value of K_f applies to a fire load density $f > 500$ MJ m^{-2}, the highest value to a fire load density $f < 60$ MJ m^{-2}. For intermediate fire load densities, linear interpolation gives sufficient accuracy.

The different types of fire compartments are defined as follows:

Type A: Bounding structures of a material with a thermal conductivity $\lambda = 0.81$ W m^{-1} °C^{-1} and a heat capacity $\rho c_p = 1.67$ MJ m^{-3} °C^{-1}.

Type B: Bounding structures of concrete.

Type C: Bounding structures of aerated concrete (density $\rho = 500$ kg m^{-3}).

Type D: 50% of the bounding structures of concrete, and 50% of aerated concrete (density $\rho = 500$ kg m^{-3}).

Type E: Bounding structures with the following percentage of bounding surface area: 50% aerated concrete (density $\rho = 500$ kg m^{-3}), 33% concrete and 17%, from the interior to the exterior, of plasterboard panel (density $\rho = 790$ kg m^{-3}) 13 mm in thickness, diabase wool (density $\rho = 50$ kg m^{-3}) 10 cm in thickness, and brickwork (density $\rho = 1800$ kg m^{-3}) 20 cm in thickness.

Type F: 80% of the bounding structures of sheet steel, and 20% of concrete. The compartment corresponds to a storage space with a sheet steel roof, sheet walls, and a concrete floor.

Type G: Bounding structures with the following percentage of bounding surface area: 20% concrete, and 80%, from the interior to the exterior, of double plasterboard panel (density $\rho = 790$ kg m^{-3}), 2 x 13 mm in thickness, air space 10 cm in thickness, and double plasterboard panel (density $\rho = 790$ kg m^{-3}) 2 x 13 mm in thickness.

Type H: Bounding structures of sheet steel on both sides of diabase wool (density $\rho = 50$ kg m^{-3}) 10 cm in thickness.

For fire compartments, not directly represented in the Table, the coefficient K_f can either be determined by a linear interpolation between applicable types of fire compartment in the Table or be chosen in such a way as to give results on the safe side. For fire compartments with surrounding structures of both concrete and lightweight concrete, different values of the coefficient K_f can be obtained, depending on the choice between the fire compartment types B, C and D at the interpolation. This is due to the fact that the relationships, determining K_f, are non-linear. However, the K_f-values in the Table are such that a linear interpolation always gives results on the safe side, irrespective of the alternative of interpolation chosen. In order to avoid an unnecessarily large overestimation of K_f, that alternative of interpolation is recommended which gives the lowest value of K_f. At the determination of K_f, it is not allowed to combine types of fire compartments in such a way, that any of them gives a negative contribution to K_f.

very large volume. In [68], a preliminary investigation is presented which includes a non-uniform model of the fully developed *compartment fire - in its present version* consisting of 29 subvolumes and 60 surface elements on the boundary of the compartment. For a practical application to fire compartments of a very large volume, the model has to be supplemented by a model, describing the fire growth and the related energy release in the subvolumes, as well as by an internal flow model.

2.5 Assessment Method 2 and Thermal Exposure H_2

The concept equivalent time of fire exposure has been introduced as a mean to connect a natural compartment fire exposure (thermal exposure model H_3) and the heating according to the standard fire resistance test (thermal exposure model H_1). The concept can be used in practice, for instance, for giving an improved classification for fire ranking or grading of structural elements. In principle, the equivalent time of *fire exposure is defined as that length of the heating period* of a standard fire exposure which gives the same, decisive effect on a structural element with respect to a limit state as the complete process of the compartment fire.

The principle is illustrated in Fig. 2.10. The full-line curves show the time variation of the gas temperature T_t and the load bearing capacity R(t) of the structural element for a compartment fire exposure, determined by the fire load density, the opening factor and the thermal properties of the structures bounding the compartment. The dash-line curves give the standard fire temperature-time variation T_t, ISO, and the corresponding time curve of the load bearing capacity R(t), ISO. The minimum load bearing capacity of the structural element during the compartment fire, transferred to the same value of the load bearing capacity at the standard fire exposure, determines the equivalent time of fire exposure t_e.

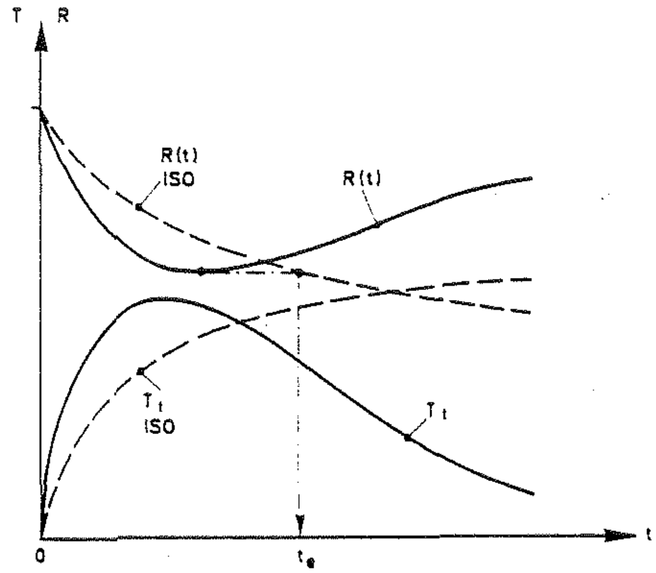


Fig. 2.10 Definition of equivalent time of fire exposure t_e. Full-line curves apply to a natural compartment fire exposure, dash-line curves to a thermal exposure according to the standard fire resistance test, Equation (2.12). T = temperature, R = load bearing capacity, t = time

For steel structures, it can normally be assumed that the minimum load bearing capacity is reached at the time for the maximum steel temperature $T_{s\ max}$. The definition of the equivalent time of fire exposure then is modified to the definition as shown in Fig. 2.11.

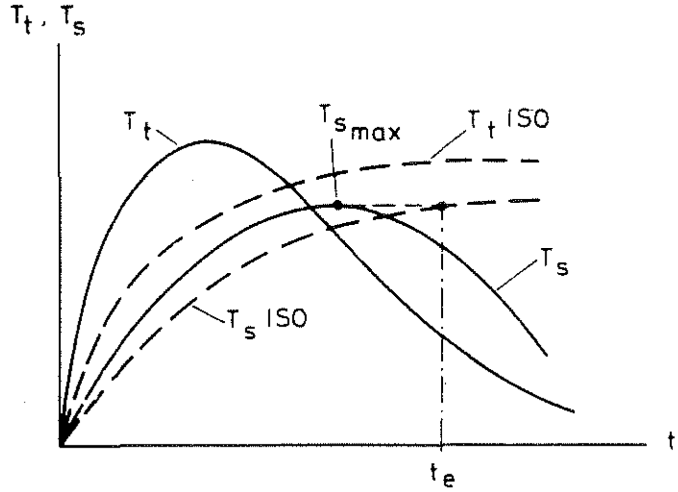


Fig. 2.11 Equivalent time of fire exposure t_e as defined by the maximum steel temperature $T_{s\ max}$, exemplified for a fire exposed, protected structural steel element

Defined in the described manner, the equivalent time of fire exposure t_e depends on the parameters influencing the compartment fire as well as on the structural parameters. For fire exposed steel structures, refs. [19], [25] and [74] give design aids which facilitate a practical determination of the equivalent time of fire exposure according to this definition. For fire exposed structures of reinforced concrete or wood, corresponding design aids are not available.

A simple formula, giving the equivalent time of fire exposure as independent of the structural parameters, was derived by LAW in the following way for protected steel structures [75]. For a given compartment fire exposure, those values of the structural parameters were chosen which gave a maximum steel temperature of a fixed value, e.g. 500°C. By repeating this procedure for different compartment fire characteristics, an approximate formula was obtained, which gives t_e as a function of only the fire load and the properties of the fire compartment. A similar formula with about the same level of accuracy was derived by THOMAS-HESELDEN [76]. Both formulae are confirmed by experimental results. A generalized approach is presented in [74], [77], giving the following approximation, derived for an insulated steel structure as reference type of element

$$t_e = 0.067 \frac{f_f}{(A\sqrt{h}/A_{tot})_f^{1/2}} \quad (\mathrm{min}) \tag{2.18}$$

where f_f and $(A\sqrt{h}/A_{tot})_f$ are the fictitious fire load density ($MJ \cdot m^{-2}$) and opening factor of the fire compartment ($m^{1/2}$), respectively, according to Equation (2.17) and Table 2.3. Written in this form, the equation enables the influence of varying thermal properties of the surrounding structures of the fire compartment to be taken into account.

The approximate formula according to Equation (2.18) has been verified for a practical application to fire exposed unprotected and protected structural steel elements, if the critical steel temperature with respect to failure is about 500°C. The formula can be used for deviating values of the critical steel temperature, too, provided that the opening factor of the fire compartment $A\sqrt{h}/A_{tot} > 0.05\ m^{1/2}$ [7], [74]. The formula has also been verified for reinforced concrete beams with a failure in bending on the condition that the failure starts by yielding in the reinforcement [77], [78]. For other types of load bearing structural elements and for partitions, there are very few studies reported on the accuracy of Equation (2.18). Consequently, an application of the formula to such types of structural elements must include a corresponding additional uncertainty in the design.

In [79], five different methods of calculating the equivalent time of fire exposure t_e are reviewed and compared in the light of some experimental data.

The applicability of the simple formula for t_e according to Equation (2.18) for fire exposed timber structures can be examined in the following way.

The minimum load bearing capacity at a natural compartment fire exposure is reached approximately when the maximum charring of the structure is obtained. This modifies the definition of the equivalent time of fire exposure t_e to the one shown in Fig. 2.12. The full-line curves refer to the gas temperature T_t and the charring depth β of the structure for a defined compartment fire exposure. The dash-line curves give the standard fire temperature-time curve T_t, ISO, and the corresponding time curve of the charring depth β, ISO. A transfer of the maximum charring depth β_{max} at the compartment fire exposure to the same β-value at the standard fire exposure, determines the equivalent time of fire exposure t_e.

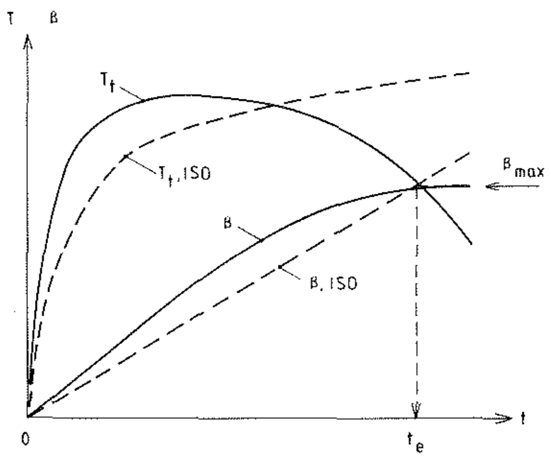


Fig. 2.12 Equivalent time of fire exposure t_e as defined by the maximum charring depth β_{max} for a fire exposed timber structure

For a thermal exposure according to the standard fire resistance test - Equation (2.12) - a large number of tests, made in different fire engineering laboratories, verify an approximately constant rate of charring $\dot{\beta}$, ISO of 0.6 mm $\cdot$ min^{-1} for solid and glued laminated timber beams and columns of pine. The value is applicable up to a charring depth equal to one quater of the cross-section dimension in the direction of charring. For a larger charring depth, the rate of charring increases.

Analytical models for a calculation of the charring rate and depth of wood at varying thermal exposure are presented in, for instance, refs. [14]-[17] and [80], cf. also [81]. The refs. [14], [15], [17] and [80] also include a model for determining the temperature distribution within the uncharred part of the cross section. In [16], diagrams are presented giving the charring depth β of a cross section at a natural compartment fire exposure, defined by the gas temperature-time curves according to Fig. 2.9. The diagrams apply to structures and structural elements of solid or glued laminated timber beams of pine. A curve fitting of the charring diagrams results in the following approximations for a calculation of the charring depth β (mm), [16]:

$$\theta = \frac{0.0175\ f}{A\sqrt{h}/A_{tot}} \tag{2.19}$$

$$\dot{\beta}_o = 1.25 - \frac{0.035}{(A\sqrt{h}/A_{tot})+0.021} \tag{2.20}$$

$$\beta = \dot{\beta}_o t \qquad \text{for } 0 \leq t \leq \frac{\theta}{3} \tag{2.21a}$$

$$\beta = \dot{\beta}_o(-\frac{\theta}{12} + \frac{3t}{2} - \frac{3t^2}{4\theta}) \qquad \text{for } \frac{\theta}{3} \leq t \leq \theta \tag{2.21b}$$

where

f = fire load density, per unit area of bounding surfaces ($MJ \cdot m^{-2}$) - Equation (2.16),
$A\sqrt{h}/A_{tot}$ = opening factor of the fire compartment ($m^{1/2}$) - section 2.4,
θ = time at which maximum charring depth is reached for particular values of f and $A\sqrt{h}/A_{tot}$ (min),
$\dot{\beta}_o$ = initial value of rate of charring ($mm \cdot min^{-1}$) and
t = time (min).

By using fictitious values of the fire load density f_f and the opening factor $(A\sqrt{h}/A_{tot})_f$ according to Equation (2.17) and Table 2.3, the influence of varying thermal properties of the structures bounding the fire compartment can be taken into account.

Equation (2.21b) gives for the maximum charring depth β_{max} the value ($t = \theta$):

$$\beta_{max} = \frac{2}{3}\dot{\beta}_o\theta \tag{2.22}$$

from which the equivalent time of fire exposure t_e can be determined according to Fig. 2.12, i.e., by the relationship

$$\beta_{max} = (\dot{\beta}, ISO) t_e \tag{2.23}$$

where $\dot{\beta}$, ISO is the rate of charring at a thermal exposure as applied in the standard fire resistance test. Fig. 2.13 shows the equivalent time of fire exposure t_e, calculated in this way with $(\dot{\beta}, ISO) = 0.6$ mm $\cdot$ min^{-1}, as a function of the fire load density f and the opening factor $A\sqrt{h}/A_{tot}$.

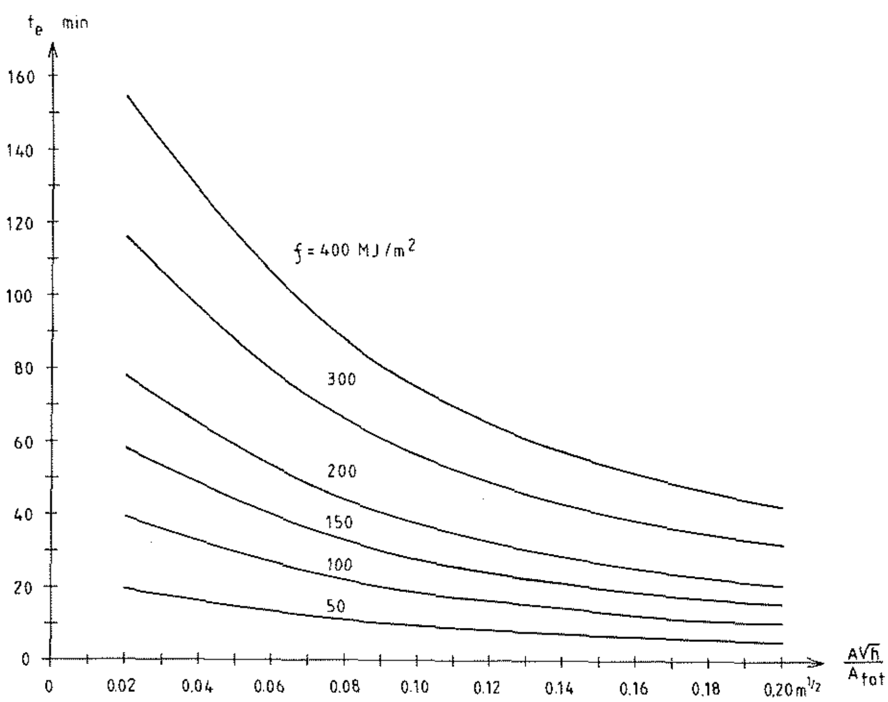


Fig. 2.13 Equivalent time of fire exposure t_e versus fire load density f and opening factor of the fire compartment $A\sqrt{h}/A_{tot}$ for solid or glued laminated timber structures of pine. The corresponding value of the maximum charring depth β_{max} is given by the relationship $\beta_{max} = 0.6\ t_e$ (mm)

The related applicability of the approximate formula for t_e according to Equation (2.18) can be investigated by transferring the data in Fig. 2.13 to a presentation as shown in Fig. 2.14, giving t_e primarily as a function of the parameter $f/(A\sqrt{h}/A_{tot})^{1/2}$. This results in a family of dash-line curves with the fire load density f as entrance parameter. The curves are relatively close to the straight line defined by Equation (2.18). Consequently, the simple formula for a quick determination of the equivalent time of fire exposure t_e can be used as an approximation also for solid and glued laminated timber structures of pine. As can be seen from Fig. 2.14, the formula then gives conservative values of t_e.

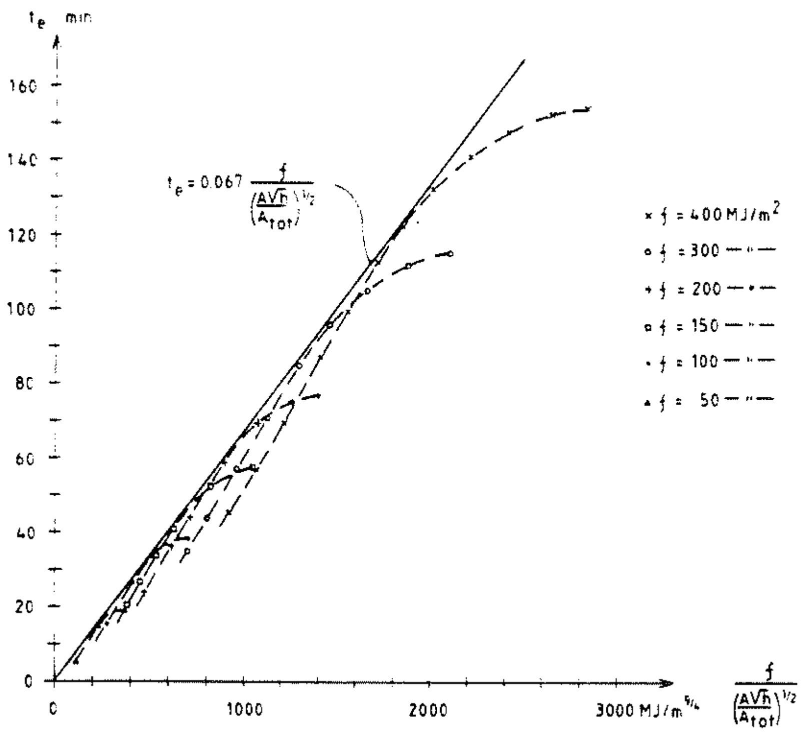


Fig. 2.14 Equivalent time of fire exposure t_e as a function of the parameter $f/(A\sqrt{h}/A_{tot})^{1/2}$ for different values of the fire load density f (dash-line curves). The curves verify the applicability of the simple formula for t_e as an approximation for solid and glued laminated timber structures of pine

2.6 Procedure of a Reliability Based Structural Fire Design According to Assessment Method 3

The general characteristics of a reliability based fire design of load bearing structures according to assessment method 3 has been dealt with in Section 2.1. The limit state condition and the criterion for the design verification are given by Equations (2.2) and (2.4). Fig. 2.1 describes the design procedure and the practical design format, including the physical (deterministic) model for the thermal and mechanical fire behaviour of the structure. The way of deriving the related partial safety factors by a first order reliability method (FORM) is outlined in Fig. 2.3.

In the flow diagram in Fig. 2.1, describing the design procedure, two alternative allocations are shown of the differentiation factor γ_n which accounts for the influences of the consequences of a structural failure (safety classes; safety differentiation factor γ_{n1}) and the frequency of a fully developed fire (frequency differentiation factor γ_{n2}). For the design procedure presented below, the safety and frequency differentiation will be allocated to the design fire load and fire exposure, which gives as a consequence that

$$\gamma_n = 1 \qquad (2.24)$$

in the design verification according to Equation (2.4).

The reliability based structural fire design procedure, described in what follows, is mainly in conformity to the principles of safety applied in the Swedish Building Code, Section 2A, Load Bearing Structures [82] which is being used voluntarily in practice from 1 January, 1980. The design procedure also is in close agreement with the specifications given for assessment method 3 in the Design Guide "Structural Fire Safety", prepared on behalf of CIB W14 [11].

2.6.1 Object and Scope

The design method comprises an assessment of the thermal and mechanical response of structures and structural elements exposed to a natural compartment fire. It applies to those structures and structural elements which surround the fire compartment or are located in it, as well as to structures and structural elements which are located outside the fire compartment, e.g., external columns and beams. The design situation may be a fire affecting the structure as a whole or only a part of it.

The fire design is based on the verification of adequate structural safety in case of a fully developed compartment fire. Adequate structural safety then may be assumed if the required function of the structure or structural element is maintained during the relevant part of the fire exposure with appropriate safety and differentiation factors considered.

The design method can be applied to fire compartments in buildings with specified occupancies. Reference can be made to either

* an individual assessment of a particular compartment and building, comprising a detailed individual appraisal of the various influence parameters or

* an assessment of a fire compartment and building considered as representativ for a certain type of building and occupancy with respect to the various influence parameters.

A certain standard of fire prevention and fire-fighting efficiency is presumed in the specification of the safety factors. Furthermore, some limitations are assumed on compartment sizes as stated in Section 2.4.

2.6.2 Required Information and Data

For the assessment, the following information and data are required:

* Type of building and occupancy,

* size of building, number of floors,

* size and location of fire compartments,

* type and amount of fire loads (permanent and variable fire loads), referring either to the particular compartment or to a representative compartment for a certain occupancy,

* ventilation conditions in the fire compartment and thermal properties of its surrounding structures (walls, floor and roof), again referring to either the particular compartment or a representative compartment for a certain occupancy,

* function of structure and structural elements with respect to compartmentation and overall stability of building,

* fire-fighting devices (detecting systems, sprinkler systems), and

* fire brigades and water supply.

2.6.3 Limit State Conditions

As specified in Section 2.1 with respect to load bearing and/or fire separating functions.

2.6.4 Loads

The appropriate design load for evaluating the fire behaviour and the ultimate load bearing capacity R_d is determined by considering an accidental load combination according to Equation (2.5). The partial safety factors γ_f then are given by Table 2.4 [82].

Table 2.4 Partial safety factors γ_f for the ultimate load bearing capacity at fire exposure [82]

Type of load	Load value	Partial safety factor γ_f
Permanent loads	G_k	1.0 and 0.8
Variable loads	ψQ_k	1.0
Fire induced loads	$Q_{k,ind}$	1.0

The γ_f values 1.0 and 0.8 for the permanent load are alternative values to be applied in such a way that the most unfavourable load effect is considered. Loads of the same type (e.g., dead load) shall always be given the same γ_f value. The number of variable loads with $\psi \leq 0.5$ may be limited to one. No corresponding limitation is allowed for the number of variable loads having $\psi > 0.5$.

Values of permanent loads G_k, variable loads Q_k and reduction factors ψ to be applied in the structural fire design are specified in [82].

2.6.5 Categories of Structures and Structural Elements. Design Fire Exposure

As stated above, 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. This can be done by dividing the structures or structural members into categories, with a related differentiation of the design fire load density f_d, and the length of the fire process, to be considered in the design.

In the version of the design procedure under development, four categories K0, K1, K2 and K3 have been introduced and defined according to Table 2.5. The table relates the different categories and the fire resistance in minutes (A30, B30, A60, B60, A90...) required in the current design, based on classification and results of standard fire resistance tests, which is to be seen as a procedure of a relative calibration.

For the different categories, the design fire exposure will be chosen according to Table 2.6, specifying the design fire load density f_d, in relation to the characteristic value of the fire load density f_k, and the duration of the fire process. The characteristic fire load density f_k is defined as that value corresponding to a probability in excess of 20%. For various types of occupancies and buildings, f_k values to be applied in the fire design are specified in [9].

Table 2.5 Definition of categories of structures and structural elements

Fire resistance in minutes, required in current design, based on classification	Category
-	K 0
A30, B30	K 1
A60, B60	K 2
$\geq$ A90	K 3

Table 2.6 Design fire exposure, expressed by its duration and the design fire load density f_d

Category of structural member	Design fire load density f_d	Duration of fire exposure
K 1	$1.0\ f_k$	$\leq$ 30 min
K 2	$1.0\ f_k$	complete fire process
K 3	$1.5\ f_k$	complete fire process

The thermal exposure on the structure or structural element during the fully developed compartment fire is determined by the energy and mass balance equations with due regard taken to the characteristics of the fire load, the ventilation of the fire compartment and the thermal properties of the structures enclosing the compartment - as further described in Section 2.4. The thermal exposure can be specified by the time curve of either the gas temperature within the fire compartment or other appropriate properties, e.g., the heat flux to the structure or structural element.

By Fig. 2.9, Equation (2.17) and Table 2.3, a set of gas temperature-time curves T_t-t of the fully developed compartment fire is defined which is generally approved by the National Swedish Board of Physical Planning and Building for a structural fire design in practice. The design basis is limited in application to fire compartments of moderate size, i.e. compartments with a size representative of dwellings, ordinary offices, schools, hospitals, hotels and libraries.

By specifying the design fire exposure as described, consideration is taken of

* the probability that the fire load density differs unfavourably from the characteristic value,

* the uncertainty of the analytical model for the determination of the compartment fire and its thermal exposure on the load bearing structure or structural element,

* the uncertainty in specifying the geometry and thermal properties of actual fire compartment materials,

* the safety level required for the respective categories of structure or structural member, including the influence of varying safety classes (differentiation factor γ_{n1}).

A rough estimation, carried out for some simple types of load bearing structural elements, shows that the probability of failure is about one tenth of an order of magnitude less at a design for $f_d = 1.5\ f_k$ than for a design where $f_d = 1.0\ f_k$ [48].

The probability of occurence and the consequences of a fully developed compartment fire are influenced by various types of active fire protection measures such as fire detection systems, sprinkler systems, smoke control systems, roof venting systems, fire alarm systems, and the fire fighting facilities of the fire brigade (frequencey differentiation factor γ_{n2}). The present version of the method does not allow for such influences to be included in any sophisticated way in the specification of the design fire exposure.

According to Table 2.2, the presence of an adequately maintained sprinkler system gives a reduction of the mean probability of occurence of a fully developed compartment fire which roughly can be accounted for by multiplication by a factor of the order of 10^{-2}. This verifies a simple procedure implying that the influence of an adequately maintained sprinkler sys-tem could be taken into account by transferring the structure or structural element to the next lower category.

2.6.6 Physical Model

The physical model comprises the deterministic model, describing the inherent physical processes of the thermal and mechanical behaviour of the structure or structural element at the specified fire and loading conditions.

For a fire exposed timber structure, the thermal behaviour is characterized by the time variation of the size of the reduced cross section and the associated temperature and moisture states - Fig. 2.3. The time variation of the reduced cross section can be approximately determined by Equations (2.19) - (2.21) for various values of the fire load density f and the opening factor of the fire compartment $A\sqrt{h}/A_{tot}$. By using fictitious values of the fire load density and the opening factor, the influence of the thermal properties of the structures bounding the fire compartment can be included. The maximum charring depth of the cross section β_{max} for the complete process of a fully developed compartment fire is given by Fig. 2.13. The equations and design curves quoted relate to solid or glued laminated timber structures of pine and do not consider any influence of the initial moisture content in the structure.

As concerns the time variation of the temperature and moisture states of the uncharred part of the cross section at a fire exposure, refs. [14], [15], [17] and [80] include a model by which the temperature state can be computed. Any model for a calculation of the connected moisture state has not yet been published.

A transfer of the thermal behaviour to the mechanical behaviour and load bearing capacity for a fire exposed timber structure requires in the general case access to validated analytical models for the mechanical behaviour of the structural material in the temperature and moisture ranges associated with fires. Available information in this respect is mainly limited to the compression strength, tensile strength, bending strength, shear strength, modulus of elasticity and shear modulus, parallel to and perpendicular to the grain, determined from tests with small specimens conditioned to different combinations of temperature and moisture content - see, for instance, [41], [83]. Furthermore, there are a few studies presented concerning the mechanical behaviour of wood at fire exposure conditions, characterized by a more general approach. The most comprehensive of these studies is the one carried out by SCHAFFER [84]. However, at present, there is no analytical model available for the mechanical behaviour of wood which can be applied for a description of the deformation process at simultaneous transient states of stress, temperature and moisture. This prevents a reliable calculation of the deflections of fire exposed timber structures to be performed and limits a structural fire design primarily to a determination of the ultimate load bearing capacity. The lack of a practically adaptable model for a calculation of the moisture gradient in the uncharred part of the cross section then requires a relatively rough approximation to be introduced at the estimation of the decrease in the ultimate bending moment of the reduced cross section due to increased temperature and moisture content during the fire. As a rule, this decrease is considered by multiplying the ultimate bending strength at normal temperature by a reduction coefficient μ with a value giving results on the safe side.

For solid and glued laminated timber beams and columns with rectangular cross section, there is a design basis available which enables a quick determination of the ultimate load bearing state at fire exposure, defined as the corresponding maximum charring depth β_{max} for various values of the quotient between the load of failure at normal temperature and the design load at fire [25], [41]. The design basis has been produced under the simplified assumption, mentioned above, with the reduction coefficient $\mu = 0.8$.

For slender beams with small lateral flexural rigidity and/or torsional rigidity, the risk of lateral-torsional buckling can be decisive in a structural design. In a fire, this risk is continuously increased since the width/height ratio of the cross section of the beam decreases by the charring. The risk will be further accentuated if intermediate supports of the beam fail during the fire exposure. A comprehensive design aid for fire exposed, solid and glued laminated timber beams of rectangular cross section with respect to this type of instability failure is given in [85].

For lightweight and composite timber structures, there is no analytical method derived for a determination of the mechanical behaviour and ultimate load bearing capacity at fire exposure. The urgency of the development of such a design instrument is evident.

2.6.7 Design Load Bearing Capacity

The determination of the ultimate design load bearing capacity R_d of a structure or structural element is based on the design strength values f_d of the actual structural materials. In applying the practical design format, the design strength f_d is given by the formula [82]

$$f_d = \frac{f_k}{\eta \, \gamma_m \gamma_n} \tag{2.25}$$

where

f_k = the characteristic value of the material strength,

η = a factor which considers the systematic differences between the material strength of a test specimen and the real structure,

γ_m = a partial safety factor, expressing the influence of the probability that the material strength differs unfavourably from the characteristic value, and

γ_n = a partial safety factor which considers the influence of the safety class.

Normally, the characteristic strength value f_k is put equal to the lower 5 percent fractile. For structural wood (konstruktionsvirke) and glued laminated wood (L-trä), the characteristic value f_k at ordinary room temperature may be assumed to be twice the permissible stress - for L-trä in bending or shear 2.4 times the permissible stress - as specified in Chapter 27 of the Swedish Building Code for normal case of loading.

By introducing various categories of structure and structural elements 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_n is to be made equal to 1 in the fire design.

A combined experimental and analytical study of reliability based design methods for timber structures at ordinary room temperature conditions was recently reported by JÖNSSON and ÖSTLUND [86]. This study recommends $\eta\gamma_m = 1.4$ for structural wood, primarily as concerns compression and tension parallel to the grain. For glued laminated timber structures, a lower value, $\eta\gamma_m = 1.2$, is reasonable when referred to a whole cross section.

The exposure of a structure or structural element to combined static loading and fire is considered as an accidental case. Consequently, the partial safety factor $\eta\gamma_m$ should be given a lower value in a structural fire design than those referred above. An appropriate choice then requires a supplementary probability study.

2.7 Procedure for a Reliability Based Structural Fire Design According to Assessment Method 2

2.7.1 Object and Scope

The design method comprises an assessment of fire compartments with respect to the appropriate fire resistance of structures and structural elements. The method applies only to those structural elements which are directly exposed in a fire, i.e., those elements which surround the fire compartment or which are located within it.

The fire design is based on the verification of adequate structural safety in case of a fully developed compartment fire. Adequate structural safety then may be assumed if the fire resistance of the structural elements is equal to or exceeds the equivalent time of fire exposure with appropriate safety factors and differentiation factors considered.

The design method can be applied to fire compartments in buildings with specified occupancies. Reference can be made to either

* an individual assessment of a particular compartment and building, comprising a detailed individual appraisal of the various influence parameters, or

* an assessment of a fire compartment and building, considered as representative for a certain type of building and occupancy with respect to the various influence parameters.

The approach can be applied for an experimental or an analytical evaluation of the structural response.

A certain standard of fire prevention and fire-fighting efficiency is presumed in the specification of the safety factors. Furthermore, some limitations are assumed on compartment sizes as stated in Section 2.4.

2.7.2 Required Information and Data

According to 2.6.2.

2.7.3 Limit State Conditions

Depending on the type of practical application, one, two or all of the following limit state conditions apply;

* Limit state with respect to load bearing capacity,
* limit state with respect to insulation,
* limit state with respect to integrity.

The limit states are expressed in the time domain (min) in terms of:

* The equivalent time of fire exposure t_e - cf. Section 2.5, and
* the fire resistance t_f with respect to the particular structure, type of structural component and limit state of concern with reference to a thermal exposure according to Equation (2.12).

For each limit state, the limiting condition is given by

$$t_{fd} - t_{ed} \geq 0 \qquad (2.26)$$

where the design values t_{fd} and t_{ed} are expressed by characteristic values and appropriate safety factors and differentiation factors.

2.7.4 Equivalent Time of Fire Exposure

According to Section 2.5. The applicability of Fig. 2.13 and the simplified formula (2.18) for the equivalent time of fire exposure t_e is limited to fire compartments of moderate size, i.e., compartments with a size representative of dwellings, ordinary offices, schools, hospitals, hotels and libraries.

2.7.5 Fire Resistance

The fire resistance t_f of the structure or structural element with respect to the limit state under consideration may be determined either

* experimentally, according to ISO 834 [55] - applicable to all limit states, or

* analytically, according to Fig. 2.6 - not applicable to the limit state with respect to integrity, or

* by interpolation or extrapolation and by analogy from experimental or analytical results, or

* by reference to catalogues, compiling experimental/ analytical results, possibly extended by interpolation and analogy.

For load bearing capacity, the fire resistance can be determined

* as a function of the mechanical loading, so that the decisive fire resistance for a structural element is evaluated taking into account the individual loading conditions in terms of Section 2.7.6, or

* for a specified design load, roughly accounting for representative loading conditions in terms of Section 2.7.6.

2.7.6 Loads

In conventional fire design, the fire resistance is determined for the design load corresponding to the normal, non-accidental design situation.

More consistently, the appropriate design load for evaluating the fire resistance should be determined by considering an accidental load combination according to Equation (2.5) and Section 2.6.4.

2.7.7 Design Verification

Expressed in the practical design format, the design verification reads

$$\frac{t_f}{\gamma_f} \geq \gamma_{n1} \; \gamma_{n2} \; \gamma_e \; t_e \qquad (2.27)$$

where

t_e = characteristic value of the equivalent time of fire exposure (min),

t_f = characteristic value of the fire resistance, determined experimentally or analytically according to Section 2.7.5,

γ_e = partial safety factor related to the equivalent time of fire exposure and covering the uncertainties of the fire load density and the fire compartment characteristics, including the uncertainties of the analytical models for the determination of the fire exposure and the related formula or design curves for t_e.

γ_f = partial safety factor related to the fire resistance and covering the uncertainties of the mechanical load and the thermal and mechanical material properties of the structural element, including the uncertainties of the analytical models for a determination of the load effect, the transient thermal behaviour and the load bearing capacity, if the fire resistance is evaluated analytically,

γ_{n1}, γ_{n2} = differentiation factors accounting for different safety classes (γ_{n1}) and special fire-fighting provisions (γ_{n2}) according to Section 2.1.

Guidance for deriving appropriate values of the partial safety factors and the differentiation factors as well as example values is given in refs. [10], [11] and [50]. In Appendix 2 of ref. [10], the statistical aspects of the experimentally determined fire resistance is dealt with.

REFERENCES

[1] FRIEDMAN, R.: Status of Mathematical Modelling of Fires. First Specialists Meeting of the Combustion Institute, University of Bordeaux (1981).

[2] THOMAS, P.H.: Modelling of Compartment Fires. Fire Safety Journal 5, pp. 181-190 (1983).

[3] THOMAS, P.H. and WICKSTRÖM, U. (Ed.): The Modelling of Pre-flashover Fires - The Report of a CIB W14 Workshop, Borås, Sweden, May 1983. CIB Report, Publication 81 (1983).

[4] MAGNUSSON, S.E.: Smoke Movement in Buildings: A State-of-Art Review and a Program for Future Swedish Research (In Swedish with an English summary). Report LUTVDG/(TVBB-3013), Division of Building Fire Safety and Technology, Lund Institute of Technology, Lund (1983).

[5] PETTERSSON, O.: Current Fire Research and Design - Particularly in View of Mathematical Modelling. Lecture, given at the CIB 9th Congress in Stockholm, 15-19 August, 1983, Report LUTVDG/(TVBB-3018), Division of Building Fire Safety and Technology, Lund Institute of Technology, Lund (1983).

[6] ECCS, Technical Committee 3, Fire Safety of Steel Structures: European Recommendations for the Fire Safety of Steel Structures - Calculation of the Fire Resistance of Load Bearing Elements and Structural Assemblies Exposed to the Standard Fire. Elsevier Scientific Publishing Company, Amsterdam-Oxford-New York (1983).

[7] ECCS, Technical Committee 3, Fire Safety of Steel Structures: Design Manual on the European Recommendations for the Fire Safety of Steel Structures. ECCS, Publication No. 35, Brussels (1985).

[8] CEB: Model Code for Fire Design of Concrete Structures. CEB, Bulletin d'Information, No 174, Lausanne (1987).

[9] NATIONAL SWEDISH BOARD OF PHYSICAL PLANNING AND BUILDING: Brandteknisk dimensionering (Fire Engineering Design). Comments on SBN (Swedish Building Code), No. 1976:1, Stockholm (1976).

[10] CIB W14: A Conceptual Approach Towards a Probability Based Design Guide on Structural Fire Safety. Report of CIB W14 Workshop "Structural Fire Safety", Fire Safety Journal 6, pp. 1-79 (1983).

[11] CIB W14: Design Guide - Structural Fire Safety. CIB W14 Workshop "Structural Fire Safety", Fire Safety Journal 9, pp. 77-136 (1986).

[12] ANDERBERG, Y. and THELANDERSSON, S.: Stress and Deformation Characteristics of Concrete at High Temperatures. 2. Experimental Investigation and Material Behaviour Model. Bulletin 54, Division of Structural Mechanics and Concrete Construction, Lund Institute of Technology, Lund (1976).

[13] SCHNEIDER, U.: Ein Beitrag zur Frage des Kriechens und der Relaxation von Beton unter hohen Temperaturen. Institut für Baustoffe, Massivbau und Brandschutz der Technischen Universität Braunschweig, Heft 42, Braunschweig (1979).

[14] FREDLUND, B.: Modell för beräkning av temperatur och fuktfördelning samt reducerat tvärsnitt i brandpåverkade träkonstruktioner (Mathematical Model of Wood Pyrolysis, Including Internal Moisture Transfer). Internal Report IR 79-2, Division of Structural Mechanics, Lund (1977, 1979).

[15] WHITE, R.H. and SCHAFFER, E.L.: Application of CMA Program to Wood Charring. Fire Technology 14, pp. 279-291 (1978).

[16] HADVIG, S.: Charring of Wood in Building Fires - Practice, Theory, Instrumentation, Measurements. Laboratory of Heating and Air Conditioning, Technical University of Denmark, Copenhagen (1981).

[17] FREDLUND, B.: A Computer Program for the Analysis of Timber Structures Exposed to Fire. Report LUTVDG/(TVBB-3020), Division of Building Fire Safety and Technology, Lund Institute of Technology, Lund (1985).

[18] LIE, T.T.: Fire and Buildings. Applied Science Publishers, London (1972).

[19] PETTERSSON, O., MAGNUSSON, S.E. and THOR, J.: Fire Engineering Design of Steel Structures. Swedish Institute of Steel Construction. Publication No. 50, Stockholm (1976) (Swedish edition 1974).

[20] PETTERSSON, O.: Theoretical Design of Fire Exposed Structures. Bulletin 51, Division of Structural Mechanics and Concrete Construction, Lund Institute of Technology, Lund (1976).

[21] GUSTAFERRO, A.H. and MARTIN, L.D.: PCI Design for Fire Resistance of Precast Prestressed Concrete , Prestressed Concrete Institute (PCI), Chicago (1977).

[22] INSTITUTION OF STRUCTURAL ENGINEERS, CONCRETE SOCIETY: Design and Detailing of Concrete Structures for Fire Resistance. Interim Guidance by a Joint Committee of the Institution of Structural Engineers, The Concrete Society, London (1978).

[23] BARTHÉLÉMY, B. and KRUPPA, J.: Résistance au Feu des Structures - Béton, Acier, Bois. Édition Eyrolles, Paris (1978).

[24] FRUITET, P.L.: Guide pour la Conception des Bâtiments à Structures en Acier. Office Téchnique pour l'Utilisation de l'Acier (OUTA), Paris (1978).

[25] PETTERSSON, O. and ÖDEEN, K.: Brandteknisk dimensionering - principer, underlag, exempel (Fire Engineering Design of Building Structures - Principles, Design Basis, Examples). Liber förlag, Stockholm (1978).

[26] HARMATHY, T.Z.: Design to Cope with Fully Developed Fires. ASTM Symposium "Design of Buildings for Fire Safety". ASTM Special Technical Publication STP 685, pp. 198-276, Washington (1979).

[27] AISI: Fire-Safe Structural Steel - A Design Guide. American Iron and Steel Institute (AISI), Ohio (1979).

[28] CSTB (Centre Scientifique et Téchnique du Bâtiment): Méthode de Prévision par le Calcul du Comportement au Feu des Structures en Béton. Document Téchnique Unifié, Paris (1980).

[29] TWILT, L. and WITTEVEEN, J.: Brandveiligheid Staalconstructies (Fire Resistance of Steel Structures). Staalcentrum Nederland (1980).

[30] DOTREPPE, J.C.: Modèles Numériques pour le Simulation du Comportement au Feu des Structures en Acier et en Béton Armé. Thèse d'Agrégation de l'Enseignement Supérieur, Université de Liège (1980).

[31] ACI (American Concrete Institute): Guide for Determining the Fire Endurance of Concrete Elements. Reported by ACI Committee 216, ACI 216R-81 (1981).

[32] THRANE, E.J.: Brandteknisk dimensjonering av bygningskonstruksjoner (Fire Engineering Design of Building Structures). Tapir forlag, Oslo (1981).

[33] KORDINA, K. and MEYER-OTTENS, C.: Beton-Brandschutz-Handbuch. Beton-Verlag, Düsseldorf (1981).

[34] REICHEL, V.: Brandschutz-Anforderungen an Baukonstruktionen. Staatsverlag DDR, Berlin (1981).

[35] MALHOTRA, H.L.: Design of Fire Resisting Structures. Surrey University Press, London (1982).

[36] CEB (Comité Euro-International du Béton): Design of Concrete Structures for Fire Resistance. Appendix to the CEB Model Code, Bulletin d'Information No 145, Paris (1982).

[37] CTICM (Centre Téchnique Industriel de la Construction Métallique): Méthode de Prévision par le Calcul du Comportement au Feu des Structures en Acier. Revue Construction Métallique, No 3, Paris (1982).

[38] FORSÉN, N.E.: Theoretical Study on the Fire Resistance of Concrete Structures. FCB-SINTEF, Report STF65 A82062, Trondheim (1982).

[39] KORDINA, K. and MEYER-OTTENS, C.: Holz-Brandschutz-Handbuch. Deutsche Gesellschaft für Holzforschung e.V., München (1983).

[40] Standard Building Code 1985, Appendix P, Calculated Fire Resistance. Southern Building Code Congress International, Birmingham, AL35213 (1985).

[41] JÖNSSON,R. and PETTERSSON, O.: Timber Structures and Fire. Swedish Council for Building Research, Document D3: 1985, Stockholm (1985).

[42] KIRBY, B.R.: Recent Developments and Applications in Structural Fire Engineering Design - A Review. Fire Safety Journal 11, pp. 141-179 (1986).

[43] ANDERBERG,Y., PETTERSSON, O., THELANDERSSON, S. and WICKSTRÖM, U.: Brandteknisk dimensionering av betong-konstruktioner (Fire Engineering Design of Concrete Structures). Manual (in preparation).

[44] MAGNUSSON, S.E.: Probabilistic Analysis of Fire Exposed Steel Structures. Bulletin 27, Division of Structural Mechanics and Concrete Construction, Lund Institute of Technology, Lund (1974).

[45] MAGNUSSON, S.E. and PETTERSSON, O.: Functional Approaches - An Outline. CIB Symposium "Fire Safety in Buildings: Needs and Criteria", held in Amsterdam 1977-06-02/03, CIB Proceedings, Publication 48, pp. 120-145 (1978).

[46] SCHNEIDER, U., BUB, H. and KERSKEN-BRADLEY, M.: Structural Fire Protection Levels for Industrial Buildings. Presented at the 1980 Fall Convention, American Concrete Institute, San Juan, Puerto Rico (1980).

[47] HOSSER, D. and SCHNEIDER, U.: Sicherheitskonzept für brandschutztechnische Nachweise von Stahlbetonbauteilen nach der Wärmebilanztheorie. Institut für Bautechnik, Berlin (1980).

[48] MAGNUSSON, S.E. and PETTERSSON, O.: Rational Design Methodology for Fire Exposed Load Bearing Structures. Fire Safety Journal 3, pp. 227-241 (1980/81).

[49] PETTERSSON, O.: Reliability Based Design of Fire Exposed Concrete Structures. Contemporary European Concrete Research, Stockholm (1981), pp. 143-169.

[50] DIN 18230, Baulicher Brandschutz im Industriebau. Vornorm, Teil 1 und 2, Berlin (1982).

[51] GROSS, D.: Aspects of Stochastic Modeling for Structural Firesafety. Fire Technology 19, pp. 103-114 (1983).

[52] HARMATHY, T.Z. and MEHAFFEY, J.R.: Design of Buildings for Prescribed Levels of Structural Fire Safety. Fire Safety: Science and Engineering, Symposium held at Denver, Co., 26-27 June 1984, ASTM Special Technical Publication 882, Philadelphia (1985), pp 160-175.

[53] CEC (Commission of the European Communities): Eurocodes 1-3, Industrial Processes: Building and Civil Engineering. Report (1984).

[54] CEB/FIP: Model Code for Concrete Structures. Comité Euro-International du Béton, Paris (1974).

[55] ISO 834, Fire Resistance Tests-Elements of Building Construction. Geneva (1975).

[56] HARMATHY, T.Z. and MEHAFFEY, J.R.: Post-flashover Compartment Fires: A Review. Fire and Materials 7, pp. 49-61 (1983).

[57] KAWAGOE, K. and SEKINE, T: Estimation of Fire Temperature-Time Curve in Rooms. Occasional Report No. 11. Building Research Institute, Tokyo (1963) - KAWAGOE, K.: Estimation of Fire Temperature-Time Curve in Rooms. Research Paper No. 29, Building Research Institute, Tokyo (1967).

[58] ÖDEEN, K.: Theoretical Study of Fire Characteristics in Enclosed Spaces. Bulletin 19, Division of Building Construction, Royal Institute of Technology, Stockholm (1963).

[59] MAGNUSSON, S.E. and THELANDERSSON, S.: Temperature-Time Curves for the Complete Process of Fire Development - A Theoretical Study of Wood Fuel Fires in Enclosed Spaces. Acta Polytechnica Scandinavica, Ci 65, Stockholm (1970).

[60] HARMATHY, T.Z.: A New Look at Compartment Fires. Part I, Fire Technology 8, pp. 196-217 (1972); Part II, Fire Technology 8, pp. 326-351 (1972).

[61] MAGNUSSON, S.E. and THELANDERSSON, S.: A Discussion of Compartment Fires. Fire Technology 10, pp 228-246 (1974).

[62] BABRAUSKAS, V. and WILLIAMSON, R.B.: Post-flashover Compartment Fires. Report No. UCB FRG 75-1, Fire Research Group, University of California, Berkeley (1975) - Post-flashover Compartment Fires: Basis of a Theoretical Model. Fire and Materials 2, pp. 39-53 (1978).

[63] THOMAS, P.H.: Some Problem Aspects of Fully Developed Room Fires. ASTM Symposium "Fire Standards and Safety", held at National Bureau of Standards, Gaithersburg, 5-6 April 1976. ASTM Special Technical Publication STP614, Washington (1977), pp. 112-130.

[64] BÖHM, B.: Fully Developed Polyethylene and Wood Compartment Fires with Application to Structural Design. Technical University of Denmark, Copenhagen (1977) (with data supplement).

[65] BABRAUSKAS, V.: COMPF2 - A Program for Calculating Postflashover Fire Temperatures. Technical Note 991, National Bureau of Standards, Washington (1979).

[66] BABRAUSKAS, V.: A Closed-form Approximation for Post-flashover Compartment Fire Temperatures. Fire Safety Journal 4, pp 63-73 (1981).

[67] BÖHM, B. and HADVIG, S.: Nonconventional Fully Developed Polyethylene and Wood Compartment Fires. Combustion and Flame 44, pp. 201-222 (1982).

[68] BÖHM, B.: Non-uniform Compartment Fires. Report No. 1, Preliminary Investigation of Fully Developed Fires. Laboratory of Heating and Air Conditioning, Technical University of Denmark, Copenhagen (1983).

[69] NAKAYA, I. and AKITA, K.: A Simulation Model for Compartment Fires. Fire Safety Journal 5, pp.157-165 (1983).

[70] MAGNUSSON, S.E. and JÖNSSON, R.: Calculation of Gas-temperature-Time Curves Using Recent Research Developments. Study on Behalf of the GEILINGER AG Company. Division of Building Fire Safety and Technology, Lund Institute of Technology, Lund (1985), (Private communication).

[71] WICKSTRÖM, U.: Application of the Standard Fire Curve for Expressing Natural Fires for Design Purposes. Fire Safety: Science and Engineering, Symposium held at Denver, Co., 26-27 June 1984, ASTM Special Technical Publication 882, Philadelphia (1985), pp. 145-159.

[72] HARMATHY, T.Z.: Postflashover Fires - An Overview of the Research at the National Research Council of Canada (NRCC), 1970-1985. Fire Technology 22, pp. 210-233 (1986).

[73] THOMAS, P.H., HESELDEN, A.J.M. and LAW, M.: Fully-developed Compartment Fires - Two Kinds of Behaviour. Fire Research Technical Paper No. 18, Ministry of Technology and Fire Offices Committee, Joint Fire Research Organization, HMSO, London (1967).

[74] PETTERSSON, O.: The Connection Between a Real Fire Exposure and the Heating Conditions According to Standard Fire Resistance Tests. European Convention for Constructional Steelwork, Chapter II, CECM-III-74-2E (1974). See also, Bulletin 39, Division of Structural Mechanics and Concrete Construction, Lund Institute of Technology, Lund (1975).

[75] LAW, M.: A Relationship between Fire Grading and Building Design and Contents. Fire Research Note 877, Joint Fire Research Organization, Borehamwood, Herts. (1971).

[76] THOMAS, P.H. and HESELDEN, A.J.M.: Fully-Developed Fires in Single Compartments. A Co-Operative Research Programme of the Conseil International du Bâtiment, CIB Report No. 20, Fire Research Note 923, Fire Research Station, Borehamwood, Herts. (1972).

[77] PETTERSSON, O.: Structural Fire Protection. Report of Group Session 5.2, CIB W14 Commission Meeting, Copenhagen, May 1978, Fire and Materials 4, pp. 1-16 (1980).

[78] SCHNEIDER, U. and HAKSEVER, A.: Bestimmung der äquivalenten Branddauer von statisch bestimmt gelagerten Stahlbetonbalken bei natürlichen Bränden. Institut für Baustoffkunde und Stahlbetonbau, Technische Universität, Braunschweig (1976).

[79] HARMATHY, T.Z.: On the Equivalent Fire Exposure. Fire and Materials 11, pp. 95-104 (1987).

[80] PARKER, I.P.: Development of a Model for the Heat Release Rate of Wood - A Status Report. Center for Fire Research, U.S. National Bureau of Standards, Gaithersburg (1985).

[81] FREDLUND, B.: Jämförelse av två modeller för analys av trä som pyrolyseras (Comparison of Two Models for Analysis of the Process of Charring of Wood). Report LUTVDG/(TVBB-3027), Division of Building Fire Safety and Technology, Lund Institute of Technology, Lund (1986).

[82] NATIONAL SWEDISH BOARD OF PHYSICAL PLANNING AND BUILDING: SBN, avd 2A, Bärande konstruktioner (Swedish Building Code, Section 2A, Loadbearing Structures). Stockholm (1979).

[83] GERHARDS, C.C.: *Effects of Moisture Content* and Temperature on the Mechanical Properties of Wood: An Analysis of Immediate Effects. Wood and Fiber 1, pp. 4-36 (1982).

[84] SCHAFFER, E.L.: Elevated Temperature Effect on the Longitudinal Mechanical Properties of Wood. Thesis, Engineering Mechanics, University of Wisconsin (1971).

[85] FREDLUND, B.: Structural Design of Fire Exposed Rectangular Laminated Wood Beams with Respect to Lateral Buckling. Report No. 79-5, Department of Structural Mechanics, Lund Institute of Technology, Lund (1979).

[86] JÖNSSON, R. and ÖSTLUND, L.: Säkerhetsproblem för träkonstruktioner (Safety Problems for Timber Structures). Report TVBK-3026, Department of Structural Engineering, Lund Institute of Technology, Lund (1987).

TABLE OF CONTENTS