TECHNICAL REPORT

ISO/TR 12471

First edition
2004-11-15

Computational structural fire design — Review of calculation models, fire tests for determining input material data and needs for further development

Conception de calcul des feux de structures — État des travaux des modèles de calcul et d'essais au feu pour la détermination des données de base requises et des besoins du développement ultérieur

Reference number
ISO/TR 12471:2004(E)

Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

In exceptional circumstances, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO/TR 12471 was prepared by Technical Committee ISO/TC 92, *Fire safety*, Subcommittee SC 2, *Fire containment*.

Introduction

Considerable advances have been made in recent years in understanding the behaviour of fires in their development and impact upon buildings. Coupled with developments in computational techniques, it is now possible to predict how structures will behave at the fire limit state (i.e. under fire conditions).

As a result of the high level of international fire research in recent decades, more and more components and systems are becoming amenable to analytical and computer modelling. Considerable progress has been made concerning such phenomena and procedures as:

— reaction of materials to fire;

— fire growth in a compartment;

— fully developed compartment fire;

— fire spread between buildings;

— fire behaviour of load-bearing and separating building structures;

— smoke filling in enclosures and smoke movement in escape routes and multi-storey buildings;

— interaction of sprinklers and fire, including sprinkler and fire venting interaction;

— process of escape; and

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

This progress in fire research has led to consequent changes in the field of codes, specifications, and recommendations for fire engineering. Some characteristic trends in these changes are:

a) improved connection to real fire scenarios;

b) increase in extent of design, based on functional requirements and performance criteria;

c) development of new test methods, that are, as far as possible, material-independent and related to well-defined phenomena and properties;

d) increase in application of reliability-based analytical design;

e) extended use of integrated assessments; and

f) introduction of goal-oriented systems of analysis of total, active and passive fire protection for a building.

The most manifest verification of these developing trends probably relates to the fire engineering design of load-bearing and separating structures. An analytical determination of the fire resistance of structural elements is being approved by authorities in more and more countries as an alternative to the internationally predominant design that is based on the results of the standard fire resistance test and connected classification. The further step to permit a general practical application of an analytical design, based on a natural compartment fire concept, was taken by Swedish authorities as early as 1967. Since then, a few other countries have been officially open to the possibility of structural fire design.

A significant contribution was made by the Fire Commission of the Conseil International du Bâtiment, CIB W14, in the form of a state-of-the-art report, in 1983. The report presented a conceptual approach towards a probability-based design guide on structural fire safety[1], supplemented in 1986 by a model code/design guide[2]. These design guides are important aids in drafting corresponding national regulations and recommendations. For European countries, the Eurocodes (see references [3] to [10] in the Bibliography) issued as European Prestandards and supplemented with national application documents, certainly will contribute to increased practical use of analytical structural fire design methods.

A problem arises between material-related codes and the general code. The material-related codes focus very strongly on the fire design, based on thermal exposure according to the standard fire resistance test. However, the general code, specifying the basis of design and mechanical and thermal actions on fire-exposed structures, also gives some guidance, in the form of informative annexes, regarding the alternate structural fire design, based on a parametric fire exposure determined by fire models or specified temperature-time curves.

An analytical fire engineering design can now be performed in most cases for steel structures. Validated material models for the mechanical behaviour of concrete under transient high-temperature conditions[11] to [13] and thermal models for a calculation of the charring rate in wood exposed to fire[14] to [16], developed in recent decades, have significantly enlarged the area of practical application of an analytical structural fire design. To support 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 further transfer to the corresponding load-bearing capacity of the structure, for instance see references [17] to [47] in the Bibliography.

The following clauses begin with a summary of internationally applied methods for a structural fire engineering design. With this survey as general background, the characteristics of a reliability-based approach are described. In order to review the need for further development of calculation models and for fire tests to get the input data required for the design, the design alternative, based on a simulated fire exposure, has been chosen for presentation. For other design alternatives, applied in practice, the need for calculation models and related input data is less comprehensive than for the more general approach being dealt with. The presentation is followed by a discussion about uncertainty in the design process.

Following this background presentation of the reliability-based design process and its inherent uncertainties, the remaining document is devoted to related deterministic models, comprising the fire exposure and the thermal and mechanical behaviour of the structure. These models are supplemented with a survey of the material input data required for the structural fire engineering design. Finally, conclusions are drawn regarding the need for further development of calculation models and tests to determine the input material data required for the structural fire design.

Computational structural fire design — Review of calculation models, fire tests for determining input material data and needs for further development

1 Scope

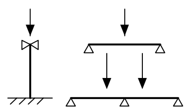
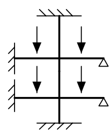
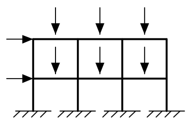
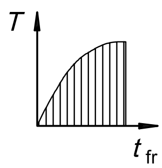
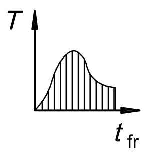
This Technical Report gives a review of the advances that have been made in measuring and understanding how structural materials respond to fire in terms of changes in their elevated temperature, and physical and mechanical characteristics, and to identify areas where further work is necessary to generate the data required. Analytical methods for heat transfer are combined with mechanical models to calculate structural behaviour from single elements up to complete frames under real fire and ISO Standard furnace heating conditions. This Technical Report reviews advances in computational analysis and indicates how these can be used with probabilistic analysis to provide a risk-based approach to structural fire engineering design.

2 Internationally applied methods for structural fire engineering design

The methods available at present for a structural fire engineering design can systematically be characterized with reference to the matrix according to Table 1 [1] [2] [37].

The matrix is based on two types of models for the thermal exposure of the structure (H1 and H2) and three types of models for the mechanical behaviour of the structure (S1, S2 and S3).

Table 1 — Matrix of thermal exposure and structural behaviour models, characterizing available methods for structural fire engineering design

Model for thermal exposure		**Model for structure**		
		S1	S2	S3
		Element	Substructure	Complete structure
				
H1	Nominal temperature-time curves 	Test or calculation (deterministic)	Calculation exceptionally testing (deterministic)	
H2	Real fire 	Calculation (probabilistic)	Calculation (probalistic)	Calculation (probabilistic) in special cases and for research

2.1 Models for thermal exposure

Model H1 describes the thermal exposure according to the standard fire resistance test of structural elements as specified in the ISO 834[48] and in corresponding national standards, or according to some other nominal temperature-time curve[3]. A fire design, based on this thermal exposure, represents the internationally prevalent situation for load-bearing and separating structural elements.

In the standard fire resistance test, the specimen is exposed in a furnace to a temperature rise that is controlled so as to vary with time within specified limits according to the standard temperature-time curve

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

where

t is the time, in minutes;

T_t is the furnace temperature at time t, in °C;

T_o is the furnace temperature at time t = 0, in °C.

For calculations, it is normally more favourable to use the following expression for the standard temperature-time curve

$$T_t - T_o = 1\,025\left(1 - 0{,}324e^{-0{,}2t} - 0{,}204e^{-1{,}7t} - 0{,}472e^{-19t}\right) \qquad (2)$$

that describes Equation (1) to a fairly high degree of accuracy, as shown in reference [49] in the Bibliography. In Equation (2), then t is time, in hours.

Other nominal temperature-time curves are the hydrocarbon curve

$$T_t - T_o = 1\,080\left(1 - 0{,}325e^{-0{,}167t} - 0{,}675e^{-2{,}5t}\right) \qquad (3)$$

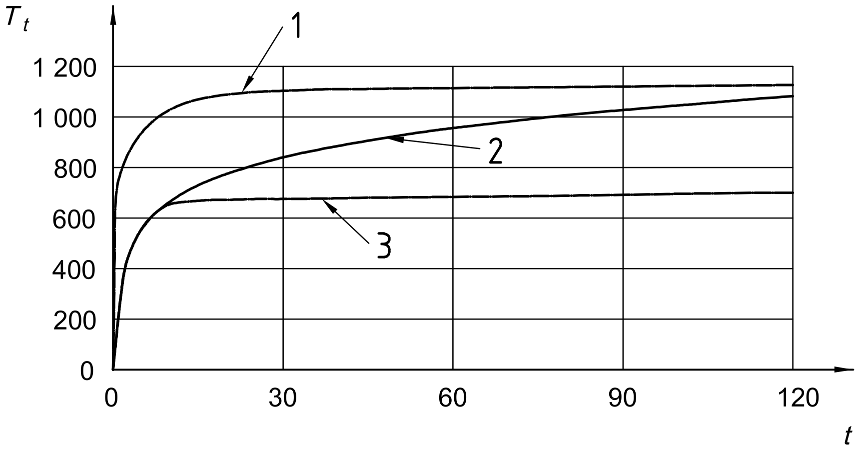
representing thermal exposure on structural members due to hydrocarbon type fires, and the external fire curve

$$T_t - T_o = 660\left(1 - 0{,}687e^{-0{,}32t} - 0{,}313e^{-3{,}8t}\right) \qquad (4)$$

representing thermal exposure on the outside of external walls and on other external members as beams and columns[3]. See Figure 1.

In the test, the time to reach the decisive limit state with respect to the load-bearing and/or separating function of the structural element defines its fire resistance, normally expressed in minutes. As an alternative, the fire resistance can be determined by calculation.

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, such as 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 national building codes and regulations, which can vary considerably with respect to the load level required from country to country. Current activities within CEN and ISO are aimed at improving the test specifications.



Key

t time, min

T_t temperature, °C

1 hydrocarbon

2 standard (ISO)

3 external

T_0 = 20 °C

Figure 1 — Temperature T_t as function of time t according to Equations (1) to (4)

Irrespective of the fire resistance being determined by testing or by calculation, 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. It is further essential to have in mind that the standard fire duration, applied in a test, does not represent the real fire duration. What the test or the corresponding calculations do is to grade structural elements. The building codes and regulations then require different grading levels of elements depending on the circumstances.

Model H2 describes a thermal exposure, based on a simulated real fire and either computed by solving the energy and mass balance equations of the compartment fire or determined from some systematized design basis, for instance, the parametric fire as specified in Eurocode 1[3], or the set of gas temperature-time curves, illustrated and explained later in connection with Figure 13.

The two examples of design bases for the fully developed compartment fire exposure are both derived under the assumptions that

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

— the fire process is ventilation-controlled, and

— gas temperature is uniform within the fire compartment at any time,

giving a conservative solution. The specified fire exposure considers the influence of the opening factor of the compartment $A\sqrt{h}/A_t$ and the thermal properties of the surrounding structures of the compartment, expressed by the thermal inertia $\sqrt{\lambda \rho c}$. A is the total area of the window and door openings, in m^2; h is the mean value of the heights of the openings, weighted with respect to each individual opening area, in m; A_t is the total area of the surfaces bounding the compartment, opening areas included, in m^2; λ is the thermal conductivity, in W·m^{-1}·°C^{-1}; ρ is the density, in kg·m^{-3}; and c is the specific heat, in J·kg^{-1}·°C^{-1}, of the compartment boundaries.

The parametric fire specifies the temperature-time curves of the heating phase of the compartment fire as the standard gas temperature-time curve according to Equation (2) with the real time t replaced by a modified time

$$t^* = t\Gamma \quad (5)$$

where

$$\Gamma = \left\{ \frac{A\sqrt{h}/A_\mathrm{t}}{0{,}04} \times \frac{1160}{\sqrt{\lambda \rho c}} \right\}^2 \qquad [\mathrm{J \cdot m^{-2} \cdot s^{-1/2} \cdot {}^\circ C^{-1}}] \qquad (6)$$

The duration of the heating phase is given by the modified duration time

$$t_\mathrm{d}^* = 1{,}3 \times 10^{-4} \frac{q_\mathrm{t} \Gamma}{A\sqrt{h}/A_\mathrm{t}} \qquad [\mathrm{h}] \qquad (7)$$

where q_t is the design value of the fire load density per unit area of the total surfaces, bounding the fire compartment, in $\mathrm{MJ \cdot m^{-2}}$.

For the decay period, the parametric fire exposure is specified by the following formulae:

$$T_t = T_{t,\mathrm{max}} - 625\ (t^* - t_\mathrm{d}^*) \qquad \text{for} \quad t_\mathrm{d}^* \leqslant 0{,}5\ h$$

$$T_t = T_{t,\mathrm{max}} - 250\ (3 - t_\mathrm{d}^*)\ (t^* - t_\mathrm{d}^*) \qquad \text{for} \quad 0{,}5 < t_\mathrm{d}^* < 2\ h$$

$$T_t = T_{t,\mathrm{max}} - 250\ (t^* - t_\mathrm{d}^*) \qquad \text{for} \quad t_\mathrm{d}^* \geqslant 2\ h \qquad (8)$$

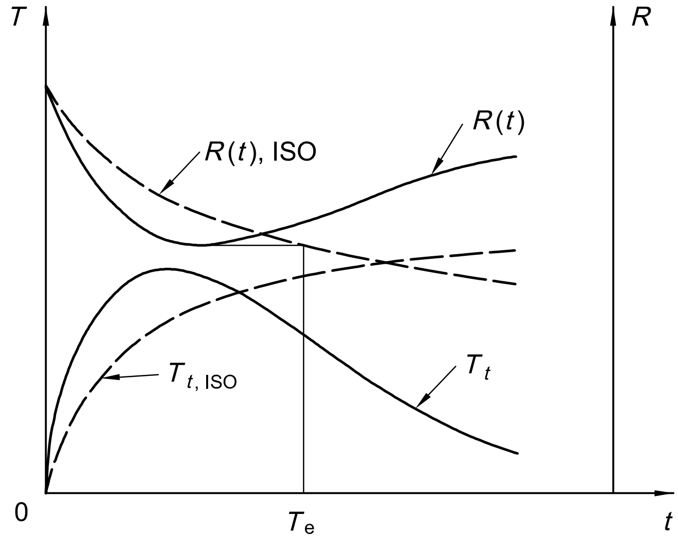
where $T_{t,\mathrm{max}}$ is the maximum temperature in the heating phase, i.e. for $t^* = t_\mathrm{d}^*$, in °C.

When applying a Model H2 description of the thermal exposure, the design normally consists of an analytical or numerical procedure. Exceptionally, the design can refer to a full-scale test.

As a means to connect the thermal exposure according to the standard temperature-time curve, Equation (1) or (2), and the thermal exposure, based on a simulated real fire (Model H2), the concept of the **equivalent time of fire exposure** has been introduced. In practice, the concept can be used, 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 the standard fire resistance test that gives the same decisive effect on a structural element with respect to a limit state as the complete process of a simulated real fire exposure. The concept is further explained by Figure 2, in which the full-line curves show the time variation of the gas temperature T_t and the load-bearing capacity $R(t)$ of a structural element for a simulated real compartment fire exposure and the dash-line curves the standard temperature-time curve according to ISO 834 $T_{t,\mathrm{ISO}}$ and the corresponding time curve of the load-bearing capacity $R(t)$,ISO. The minimum load-bearing capacity of the structural element during the simulated real fire exposure, transferred to the same value of the load-bearing capacity at the standard thermal exposure, determines the equivalent time of fire exposure t_e.

For steel structures, the minimum load-bearing capacity during a simulated real fire exposure normally corresponds to the maximum steel temperature $T_{\mathrm{s,max}}$, provided that the temperature can be dealt with as uniformly distributed over the cross-section of the structure. This simplifies the definition of the equivalent time of fire exposure as shown in Figure 3.



Key

t time

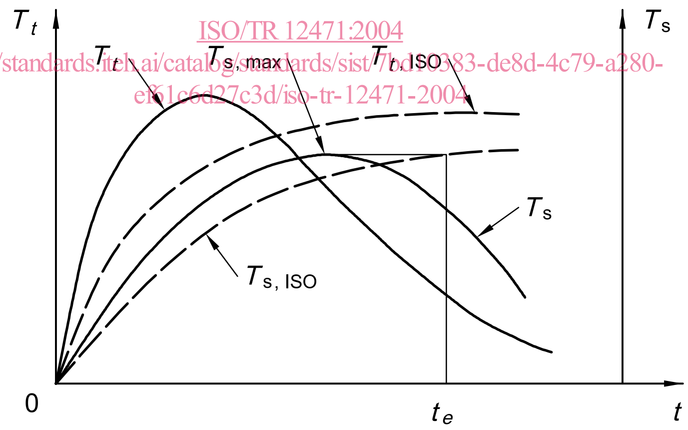
T temperature

R load-bearing capacity

——— simulated real compartment fire exposure.

– – – – thermal exposure according to the standard fire resistance test, ISO 834.

Figure 2 — Definition of equivalent time of fire exposure t_e



Key

t time

T_t gas temperature at time *t*

T_s steel temperature

Figure 3 — Equivalent time of fire exposure t_e as defined by the maximum steel temperature $T_{s,max}$ during a simulated real compartment fire exposure, exemplified for a protected structural steel element

When determined according to Figures 2 and 3, the equivalent time of fire exposure depends on parameters influencing the simulated real fire exposure as well as on structural parameters (for protected steel structures: the thermal material properties and the geometry of the protection and the steel profile). For fire-exposed steel structures, references [18], [23], [50] and [51] include a design basis for a direct practical determination of this differentiated form of the equivalent time of fire exposure.

For more rough estimations of the equivalent time of fire exposure t_e, the following formula has been derived, taking into account only the factors affecting the simulated real fire exposure[50], [52], [53]:

$$t_e = 0{,}067 \frac{q_{tf}}{(A\sqrt{h}/A_t)_f^{0,5}} \quad \text{[min]} \qquad (9)$$

where

q_{tf} is the fire load density per unit area of the total surfaces, bounding the fire compartment; in $MJ \cdot m^{-2}$;

A is the total area of window and door openings; in m^2;

h is the mean value of the heights of the openings, weighted with respect to each individual opening area, in m;

A_t is the total interior area of the surfaces, bounding the compartment, opening areas included, in m^2.

By using fictitious values of the fire load density q_{tf} and the opening factor $(A\sqrt{h}/A_t)_f$, the influence of varying thermal properties of the surrounding structures of the fire compartment can be considered[18].

Summing up, the formula given by Equation (9) connects in a simplified way the thermal exposure according to the standard fire resistance test, ISO 834, and the thermal exposure of simulated, fully developed compartment fires. The formula has been verified for application mainly to steel structures and those reinforced concrete structures, where the critical concern is yielding of the reinforcement under bending conditions. At very low opening factors, the formula may give a considerable overestimation of the fire severity. There is also a limitation of the validity of the formula to compartments of moderate size, i.e. compartments with a size representative of dwellings, ordinary offices, schools, hospitals, hotels, and libraries. The technical basis for the formula is for small compartments. A study of the applicability of available relationships for the equivalent time of fire exposure to buildings with large compartments is reported in reference [54]. In reference [55], formulae for the equivalent time of fire exposure, from Ingberg to Eurocode 1, are systematically reviewed and compared with experimental data for compartment fires.

2.2 Models for structural behaviour

Model S1 comprises single structural elements, e.g. beams, columns, walls, floors, and roofs. The model may simulate either a structural element or a single element isolated from the complete structure and described by simplified end conditions in the fire analysis.

Model S2 means a substructure, which approximately describes the mechanical behaviour of a part of the complete load-bearing system of the building. Compared to the real structure, a substructure is analysed with simplified boundary conditions at its outer ends or edges.

Model S3 describes the mechanical behaviour of the complete load-bearing structure of the building, acting as, for instance, a two- or three-dimensional frame, a beam-slab system or a column-beam-slab system.

In the matrix given in Figure 1, the thermal exposure models and the structural models are combined in the sequence of improved idealization. In principle, each element in the matrix then represents a particular design procedure. The matrix therefore can be considered as a type of classification system for methods of structural fire engineering design. It is, however, evident that not all models can be used in all combinations and the aim should be to provide a sensible pairing at each level of advancement. In the matrix, reference is made to these aspects. In principle, a structural fire engineering design offers a problem-oriented choice for the combination of the thermal exposure model and the structural behaviour model. The final choice may also depend on national preferences, the complexity of application, and the particular design situation.

3 Characteristics of a reliability-based structural fire engineering design [56]

Essential components of a rational design methodology include, in the ideal case[57], [58]:

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

For the probabilistic model to be integrated with the analytical model(s) of the relevant processes, the following 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 feasible. Also, the FORM approximations are too cumbersome for everyday design, but may be applied in special cases. For normal design, the practical design formats have to be used.

The procedure for a reliability-based structural fire engineering design, related to a FORM approximation and a practical design format calculation, is illustrated by flow diagrams in Figures 4 and 6, respectively. For generality, the procedure is demonstrated for a load-bearing structure of charring material, for instance, a timber structure[39], [59].

3.1 Structural fire engineering design based on FORM approximation

Following the flow diagram in Figure 4 for a structural fire engineering design, based on a FORM approximation, the characteristics of the fire load and fire compartment constitute the basis for determining the fire exposure, expressed by the gas temperature or the heat flow to the structure as a function of time and either computed by solving the energy and mass balance equations of the compartment fire or chosen from some systematized design basis.

Together with construction data of 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 structure and the associated transient temperature and moisture conditions. With the mechanical properties of the structural material as further input data, the transient temperature and moisture states for the uncharred part of the cross-section then has to be transferred to the time variation of the load-bearing capacity of the structure during the fire exposure, expressed, for instance, as the bending moment $M_R(t)$ in a decisive section. The load, 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 $M_R(t)$.

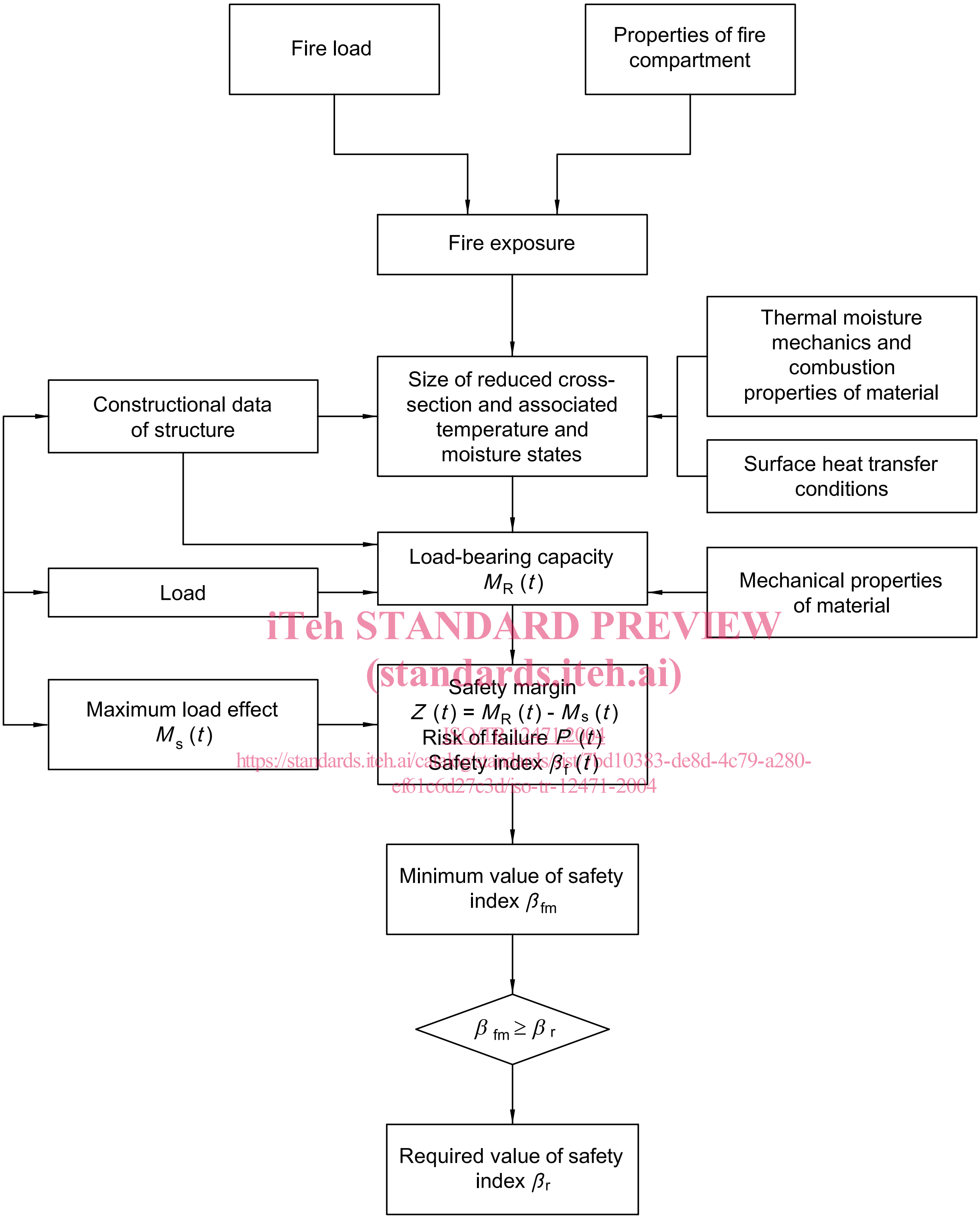


Figure 4 — Structural fire engineering design, based on first order reliability method (FORM)

The quantities $M_R(t)$ and $M_S(t)$ define the safety margin $Z(t)$, as

$$Z(t) = M_R(t) - M_S(t) \tag{10}$$

The related failure probability $P(t)$ and the safety index $\beta_f(t)$, defined as the quotient between the average safety margin and the standard deviation, can then be calculated by the formulae:

$$P(t) = \int_{-\infty}^{0} f_Z[Z(t)]\mathrm{d}Z \tag{11}$$

$$\beta_f(t) = \varphi^{-1}[1 - P(t)] \tag{12}$$

where

$f_Z[Z(t)]$ is the probability density function of the safety margin $Z(t)$;

φ^{-1} is the inverse of the standardized normal distribution.

The design criterion implies that the minimum value of the safety index for the structure during the relevant fire exposure $\beta_{fm} = [\beta_f(t)]_{min}$ shall meet the required value of the safety index β_r, i.e.

$$\beta_{fm} - \beta_r \geqslant 0 \tag{13}$$

At the determination of the safety margin $Z(t)$, the failure probability $P(t)$, and the safety index $\beta_f(t)$, the following uncertainties have to be taken into account:

— the uncertainty in specifying the loading and of the model for calculating 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; and

— the uncertainty of the analytical models for calculating the compartment fire and the related heat transfer to the structure, the size of reduced cross-section and the associated temperature and moisture states, and the load-bearing capacity of the structure.

The required value of the safety index β_r depends on the probability of occurrence of a fully developed compartment fire p_1; the reduction of this probability due to fire-fighting by the fire brigade p_2 and to the effect of an installed fire extinguishment system p_3, if any; and the consequences of a structural failure. For the detailed technique of deriving required values of the safety index β_r, see for instance references [1], [2] and [60] to [62]. Example values of p_1, p_2 and p_3 are given in references [1], [2] and [63].

In Figure 5, example values of β_r are for industrial buildings and a safety class, representative of the main load-bearing structure and separating structures bounding the fire compartment. The β_r values are given as a function of the floor area of the fire compartment A_f and the probability of occurrence of a fully developed compartment fire per year and unit area $p = p_1 p_2 p_3$.