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Fire safety engineering — Performance of structures in fire —

Part 1: General

Ingénierie de la sécurité incendie — Performances des structures en situation d'incendie —

Partie 1: Généralités

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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.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 92, *Fire safety*, Subcommittee SC 4, *Fire safety engineering*.

This first edition of ISO 24679-1 cancels and replaces ISO/TS 24679:2011, which has been technically revised.

The main changes compared to the previous edition are as follows:

— The document has been updated to properly structure as a normative document.

A list of all parts in the ISO 24679 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Fire is an extreme loading condition for structures, which can lead to significant effects on people, property and the environment. Part of the fire safety design of a built environment arises out of the need to provide design strategies that minimize the occurrence and spread of fire and its impact on life, property and the environment. Fire safety of structures is one important component of an overall fire safety design strategy. The role of fire safety of structures is to ensure that elements of a structure, (separating and structural elements) within a built environment, are capable of preventing or delaying fire spread and structural failure, so that the fire safety objectives, such as safety of life (for occupants and firefighters), conservation of property, continuity of operations, preservation of heritage and protection of the environment, are not compromised.

Traditionally, most designs for the fire safety of structures have been based on prescriptive requirements set by building regulations, building codes and associated standards. In prescriptive regulations, this is also known as *fire resistance*. The evaluation of fire resistance of construction elements is mainly determined by fire tests that involve:

— a single fire represented by a standard time-temperature curve (such as that given in ISO 834-1); and

— isolated elements or assemblies with defined boundary conditions and sizes.

In standard fire resistance tests, the thermal fire action continues to increase for the duration of the test according to standardized time-temperature fire curves. These thermal actions do not take into account the real conditions such as real fuel load, enclosure size, ventilation conditions, thermal properties of enclosure boundaries, active fire protection systems and firefighting actions. At the same time, from a mechanical point of view, these tests do not take into account the realistic boundary conditions and, consequently, the mechanical loads are not realistic. For example, possible redistribution of loads to other elements in a structure is not evaluated, since only single elements are tested. In addition, most test furnace facilities cannot take into account of the effect of restraint conditions that the tested element may undergo within a structure in real situation.

Such an assessment method is only able to provide a comparative rating of the construction products and cannot provide all the information required to perform a structural fire analysis of a given built environment.

With the recent advances in fire safety engineering and the opportunity for designers to take advantage of an engineering approach when evaluating the performance of structures in fire, it is becoming necessary to:

— refine the philosophy covered by the fire safety of structures, in the case of real fires, with respect to the whole structure;

— move beyond the sole consideration of individual elements and include the behaviour of the entire structural system;

— consider realistic thermal and mechanical load conditions; and

— include the cooling phase of the fire.

In the approach used in this document, solutions are based on engineering principles founded on a quantification of fire development, heat transfer and thermo-mechanical behaviour, on experts' judgement and on practicability.

An engineering approach offers many benefits, including:

— the provisions for better and more reliable fire safety in the built environment;

— potential cost-effective fire safety measures, and more options with regard to the choice of these measures; and

— better communication with other professionals involved in the design, construction process and approval process.

ISO 24679-1 is intended for use by fire safety practitioners who employ performance-based design methods. It is expected that users of this document be appropriately qualified and competent in the fields of fire safety and structural engineering. It is particularly important that users understand the limitations of any methodology used.

Each ISO standard supporting the global fire safety engineering analysis and information system includes language in the introduction to tie this document to the steps in the fire safety engineering design process outlined in ISO 23932-1.

ISO 23932-1 provides a performance-based methodology for engineers to assess the level of fire safety for new or existing built environments. Fire safety is evaluated through an engineered approach based on the quantification of the behaviour of fire and based on knowledge of the consequences of such behaviour on life safety, property and the environment.

ISO 24679-1 "Performance of structures in fire" standard form part of compliance with ISO 23932-1, and all the requirements of ISO 23932-1 (see Figure 1) apply to any application of this International Standard. For example, section "Selection of engineering methods and preliminary report" of ISO 23932-1 describes the procedure to select engineering methods used to assess the fire behaviour of structure, and section "Scenario-based evaluation of trial design" of ISO 23932-1 describes the procedure of quantification of the performance of structures in fire.

Fire safety engineering — Performance of structures in fire —

Part 1: General

1 Scope

This document provides a methodology for assessing the performance of structures in the built environment when exposed to a real fire.

This document, which follows the principles outlined in ISO 23932-1, provides a performance-based methodology for engineers to assess the level of fire safety of new or existing structures.

NOTE The fire safety of structures is evaluated through an engineering approach based on the quantification of the behaviour of a structure for the purpose of meeting fire safety objectives and can cover the entire time history of a real fire (including the cooling phase), and its consequences related to fire safety objectives such as life safety, property protection and/or environmental protection.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 834-1:1999, *Fire-resistance tests — Elements of building construction — Part 1: General requirements*

ISO 13943, *Fire safety — Vocabulary*

ISO/TR 16576, *Fire safety engineering — Examples of fire safety objectives, functional requirements and safety criteria*

ISO/TS 16733-2, *Fire safety engineering — Selection of design fire scenarios and design fires — Part 2: Design fires*

ISO 23932-1, *Fire safety engineering — General principles – Part 1: General*

3 Terms and definitions

For the purpose of this document, the terms and definitions given in ISO 13943, ISO 23932-1 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at https://www.iso.org/obp

3.1
building element
integral part of a built environment

Note 1 to entry: This includes floors, walls, beams, columns, doors, and penetrations, but does not include contents.

3.2
function
role and actions assigned to, or required or expected of, various parts of a structure to achieve a specified objective or task

3.3
load-bearing element
building element that is designed to resist mechanical actions

3.4
mechanical action
defined force impact on other elements due to strain or stress redistribution within a structure, or part of a structure, in fire

3.5
non-load-bearing element
building element that is not designed to resist mechanical actions besides its own weight

3.6
reliability
ability of a structure or structural element to fulfil the specific requirements, including working life, for which it has been designed

3.7
structure
assembly of materials forming a construction for occupancy or use to serve a specific purpose

Note 1 to entry: This includes, but is not limited to, buildings, open platforms, bridges, roof assemblies over open storage or process areas, tents, air-supported structures, and grand stands.

3.8
structural fire performance
extent to which a structure or structural element fulfils the specific requirements, including working life, for which it has been designed, when exposed to fire for a given time

3.9
thermal action
description of the variation of temperatures or heat fluxes as a function of time in an enclosure

Note 1 to entry: These temperatures or heat fluxes depend on fire load density, fuel arrangement, geometry of and openings within the enclosure.

4 Design strategy for fire safety of structures

4.1 General design process for fire safety of structures

Although many countries are still delivering fire safety design of structures based on prescriptive requirements and standardized tests, there has been a move towards using calculation methods to estimate the performance of structures in fires. This is due to an enhanced understanding of the behaviour of structures in fire and improved knowledge of thermal and mechanical responses of structures at elevated temperatures. This understanding and knowledge enable a better evaluation of what would happen in a built environment during real fires. However, many of the calculation methods are still at a stage where they replace standard fire tests, or are used to extend the results of these standard tests, in a bid to overcome the drawbacks of testing. Most of the existing calculation methods are simple models applicable to isolated elements and assemblies and cover mainly:

— heat transfer through load-bearing elements or non-load-bearing separating elements, when the thermal properties of the component materials and boundaries conditions are known;

— load-bearing fire performance for common construction materials such as steel, concrete and timber.

These simple calculation methods, just like the standard tests, are only able to provide data for ranking the various elements based on their ability to resist a standard fire. Although they do make accounting for some more specific parameters easier, they do not provide the necessary tools for assessing the performance of a structure in various possible real-fire scenarios, such as localized or fully-developed fires, including the cooling phase that can lead to certain failure mechanisms. For this reason, the current design approach for fire safety of a structure and its elements is still based on crude assumptions, which may lead to limited flexibility in design as well as very little or no opportunity for accurate optimization of fire safety measures in a built environment.

However, it is increasingly possible to either use advanced calculation methods or develop simplified calculation methods to deal with the behaviour of structure in real fire situations.

This document provides a methodology for applying an engineering approach to the assessment of fire performance of structures in real fires. An engineering approach for the design of fire safety of structures includes:

— defining the built-environment characteristics, including geometry, actions, materials, etc.;

— identifying clear objectives for the fire safety of structures;

— identifying performance criteria for elements of construction in the context of the objectives for fire safety of structures;

— defining a trial design plan for fire safety of structures;

— considering design fire scenarios that can develop in the built environment and challenge the structure and the enclosure boundaries;

— assessing the fire performance of the built environment (load-bearing and non-load-bearing) elements and the structure as a whole system; and

— examining the fire performance of the structure against the identified objectives and established performance criteria by taking into account realistic design fire scenarios.

Figure 1 is a flow chart showing the overall design process of fire safety engineering according to ISO 23932-1, while the details concerning fire safety of structures are provided in Clause 5 (see Table 1 and Figure 2) of this document.

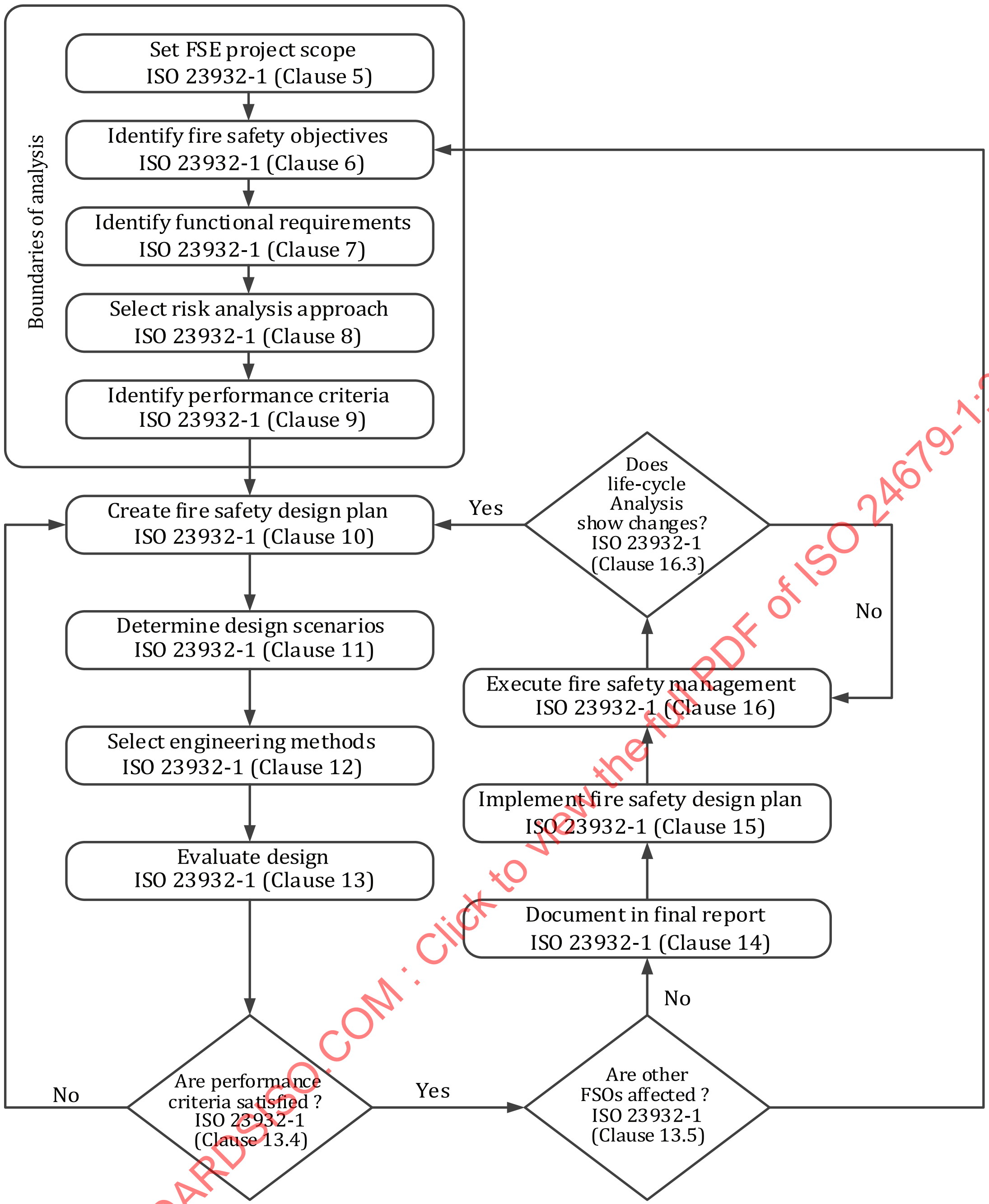


Figure 1 — Fire safety engineering — Design process according to ISO 23932-1

4.2 Practical design process guidance for fire safety of structures

Table 1 identifies the various steps and parameters to be considered when assessing the behaviour of structures subjected to fire exposure. The details of these steps are explained in Clause 5.

Figure 2 shows a flow chart detailing the methodology of the following four steps:

1) Determination of design fire scenarios and design fires;

2) Evaluation of thermal response of the structure;

3) Evaluation of the mechanical response of the structure; and

4) Assessment of responses against the fire safety objectives (Steps 4 to 7 of Table 1).

This flow chart helps to provide a detailed understanding of a rational approach to the fire safety of structures exposed to real fires. As illustrated in Figure 2, inputs are determined from Steps 1, 2 and 3 of Table 1 and outputs obtained for the assessment of Step 8 in Table 1.

If the fire safety objectives are not satisfied (see Figure 2, Step 7) with the first suggested strategy by the trial design plan (Step 3), then Steps 4 to 7 shall be repeated using a different strategy proposed at Step 3. This procedure shall be repeated until a solution that satisfies the fire safety objectives is found. If the found solution is not viable for the stakeholder, it is necessary to go back to Steps 1 and 2 in order to modify the scope of the project, and if possible, the fire safety objectives.

Table 1 — Steps of practical design process

Step No.	To consider	To determine or identify	Input	Factors of influence
1	Scope of the project for fire safety of structures	— Context and purpose of the design and/or the different parts — Mechanical actions, including initial structural loads on the elements of the structure or loads induced by the fire such as pressures — Fuel loads in compartments	— Built-environment characteristics: — Geometry — Lining materials — Openings — Quantity of fuel load — Dead and live loads — Active and passive fire protection systems	— Interested and affected parties — Structural systems to be analysed
2	Identifying objectives, functional requirements and perfor-mance criteria for fire safety of structures	— Objectives relating to: — Safety of life — Conservation of property — Continuity of operations — Preservation of heritage — Protection of the environment — Functional requirements relating to: — Limiting or preventing fire spread — Limiting or preventing structural failure — Performance criteria to fulfil the objectives and functional requirements	— Statements in codes, standards and guidance documents	— Type of occupancy of built environment to be designed — Interested and affected parties including code officials, owners, and fire safety professionals — Existence of active and passive fire systems and effectiveness of these systems — Escape time approach — Target reliability

Table 1 *(continued)*

Step No.	To consider	To determine or identify	Input	Factors of influence
3	Trial design plan for fire safety of structures	— Strategy for fire safety of structures — Design elements and functions to be considered for the fire safety of structures include structural stability, integrity, containment and compartmentation	— Objectives, functional requirements and performance criteria — Type and method of analysis	— Type of occupancy of built environment to be designed — Interested and affected parties — Fire protection system
4	Design fire scenarios and design fires (fire development)	— Thermal actions on the elements of the structure: — Heat release rates — Temperatures — Heat fluxes	— Fuel loads and distribution in compartments — Compartment characteristics (e.g., ventilation)	— Fire severity — Fire duration
				— Pressure in the fire enclosures
			— Reliability and response time of suppression systems	— Effectiveness of suppression systems — Fire safety management plan and procedures
			— Fire department response and intervention time	— Firefighting effectiveness
			— Criteria for fire spread: — Ignition by flames and/or smoke — Integrity — Thermal insulation — Others	— Effectiveness of fire separation — Paths of fire spread (openings and/or breaching of boundaries) — Temperatures and pressures in enclosures
				— Method of analysis chosen (e.g., deterministic fire analysis or probabilistic analysis)
5	Thermal response of the structure	— Temperatures in elements of the structure	— Temperatures in every enclosure — Heat transfer data for thermal response of the elements of the structure — Thermal properties of the elements of the structure	— Effectiveness of fire separation — Paths of fire spread (openings and/or breaching of boundaries) — Effects of temperatures and pressures in enclosures

Table 1 *(continued)*

Step No.	To consider	To determine or identify	Input	Factors of influence
6	Mechanical response of the structure	— Structural analysis (stability and deformation of separating elements and structural elements including connections) — Failure and time to failure of the different elements of the structure — Failure and time to failure of the whole structure	— Temperatures in elements of the structure — Mechanical properties of the elements of the structure — Characteristics of structural elements and connections — Restraint conditions	— Effects of connections on load redistribution and continuity — Effects of restraint — Structural determinacy
7	Assessment against the fire safety objectives	— Are the objectives defined in step 2 satisfied? — Yes, go to Step 8 — No, make changes in Steps 1, 2 or 3 (depending on reconsiderations) and repeat the process from the appropriate step	— Results of the analysis	— Interested and affected parties
8	Documentation of the design for fire safety of structures	— A document containing all the assumptions and calculations	— Results of the analysis	— Interested and affected parties

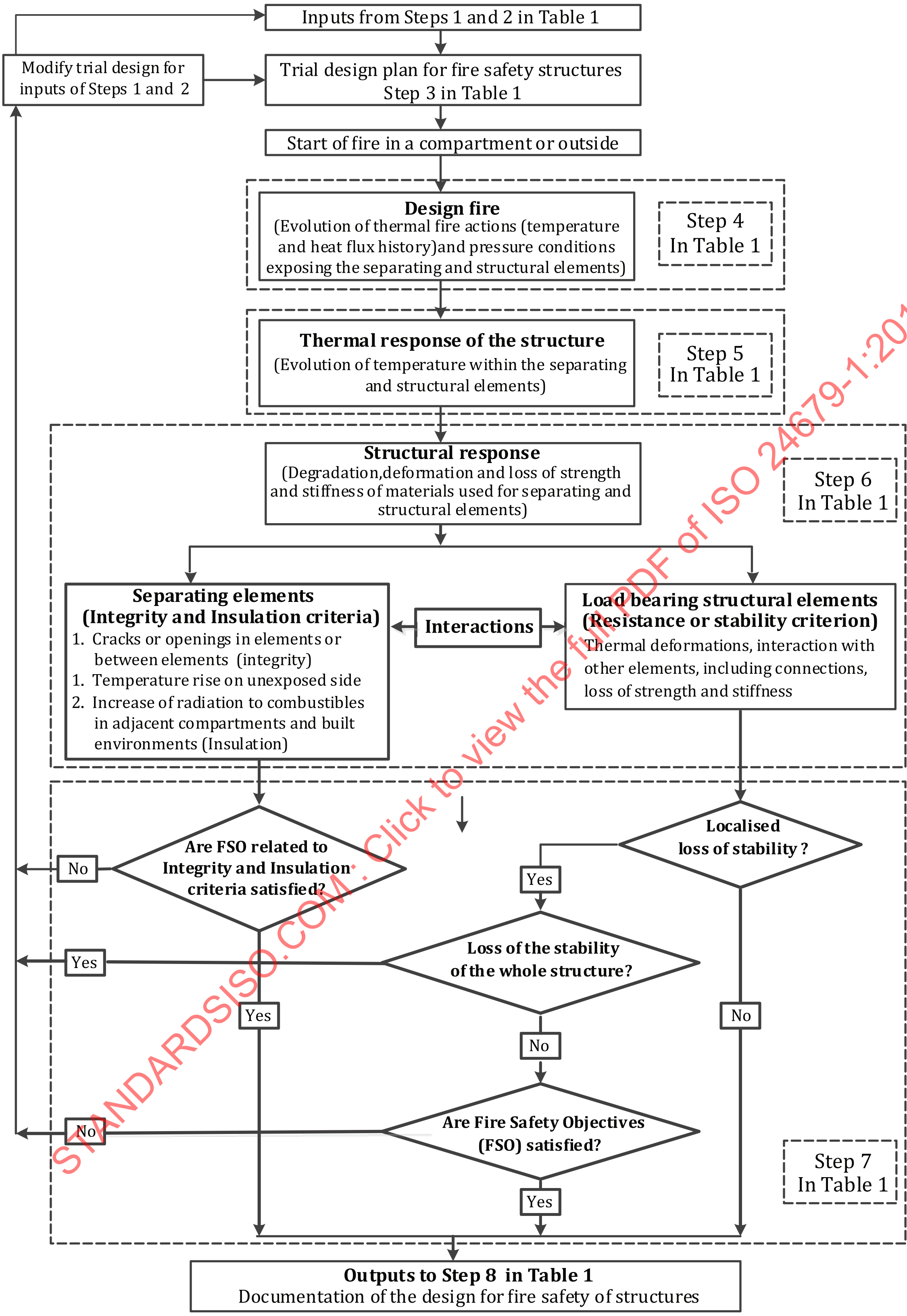


Figure 2 — Overview of a practical design process for Steps 4 to 7 for the fire safety of structures

The following subclauses provide more details on the steps highlighted in Table 1. This allows the reader to gain a better understanding of the structures' response to fire and to assess the fire performance of structures.

5 Quantification of the performance of structures in fire

5.1 Scope of the project for fire safety of structures

5.1.1 Built-environment characteristics

The project designer generally has knowledge of the general characteristics of the built environment and of the assumed enclosures of fire origin.

5.1.2 Fuel loads

In order to determine the appropriate design fire for the evaluation of the structure, fuel loads or fuel load densities are needed. These are determined from existing databases or from surveys of fuel in the built environment. Fuel load densities are generally expressed in megajoules per unit area. Fire loads are characterized by the kind of combustible materials (attached to the built environment or its content), their amount and their location.

5.1.3 Mechanical actions

When considering the mechanical actions due to applied loads, the probability of the combined occurrence of a fire in a built environment and the extreme level of mechanical loads can be considered as sufficiently low, since fire action on structures is an accidental action. In this respect, the loads to be used when assessing the fire behaviour of the entire structure, or part of it, are smaller than those used for normal design of structures.

An important concept that is used in fire design of structures is that of load ratio. The load ratio is the ratio of expected loads on a structure during a fire to the load-bearing capacity at ambient conditions. Lower load ratios give higher structural fire performance.

In general, other accidental actions should be considered in conjunction with fire. Therefore, in countries with high seismic risks, it may be necessary to account for the possibility of structural damage, damage to separating (load-bearing and non-load-bearing) elements, and the compromise of fire suppression systems and/or the supply of water due to an earthquake in the overall fire risk assessment.

In addition, the fire can induce mechanical actions, directly or indirectly, through the method of assessment. These include:

a) action due to the pressure of gases from the developing fire;

b) impact, if there is a risk of falling elements, on other structural or separating (load-bearing and non-load-bearing) elements;

c) impact of hose stream due to the possible action of fire-fighters, mainly on the unexposed side of separating (load-bearing and non-load-bearing) elements;

d) forces and moments induced by the restraint of thermal expansion or contraction at the boundaries of elements of a structure; and

e) deformation of elements (such as a beam or a floor) leading to the application of load on non-load-bearing separating elements or deflections that affect the integrity of separating (load-bearing and non-load-bearing) elements.

5.2 Identifying objectives, functional requirements and performance criteria for fire safety of structures

5.2.1 Objectives and functional requirements for fire safety of structures

Conducting a rational fire safety design of structures requires the establishment of fire safety objectives and functional requirements.

The fire safety objectives usually address life safety, conservation of property, continuity of operations, preservation of heritage, and protection of the environment (singly or in combination). They can be sub-categorised into fire safety sub-objectives (see ISO/TR 16576). As an example, some of them are presented in Table 2[1]. They can be also divided into mandatory and voluntary objectives (see ISO 23932-1).

The functional requirements for providing fire safety of structures are associated with the type of structure. Usually they are stated in terms of compartmentation and the stability of the structure.

The compartmentation of a built environment, as a means to prevent or to limit the fire spread, can be realised by load-bearing elements such as walls and floors, or by non-load-bearing elements, such as partition walls, doors, windows and so on. These elements have to satisfy functional requirements related to: integrity, insulation and resistance or stability[2].

The integrity function represents the absence of passage of hot gases and/or flames from a compartment to another one through a separating element.

The insulation function represents the limitation of the temperature increase on the unexposed surface of a separating element.

The resistance or stability function represents the ability of a structural element or a building to resist collapsing for a stated period of time or for the entire duration of the fire.

The load-bearing elements that contribute to compartmentation shall satisfy the three functional requirements related to integrity, insulation and stability, while partitioning (non-load-bearing) elements shall satisfy one or both of the separating functional requirements (integrity and insulation), depending on its function and location in the building. Load-bearing members that do not contribute to compartmentation need only satisfy the resistance or the stability function.

a) Compartmentation for the prevention or limitation of fire spread

   Compartmentation shall ensure the implementation of the following functional requirements:

   1) Prevent or limit fire spread within the built environment. As a result of the fire dynamics, but also due to pressure, thermomechanical deformation and heat transfer through components of the structure, fire (flames and smoke) can spread to other enclosures within the built environment, endangering life safety and adversely affecting the value of the built environment and its contents. In this case, a built environment is divided into fire enclosures (the concept of compartmentation) with barriers (usually floors or walls), which contain the fire in the enclosure in which the fire originated.

   2) Prevent or limit fire spread to other built environments and outside the built environment. Enclosure boundary walls, floors and roofs may contribute to such fire spread, either as a secondary fuel source for fire located on the outside of the built environment, where adjacent built environments and the natural environment are exposed, or through enclosure failure, creating a path for an interior fire to vent to the outside, again exposing adjacent built environments and the natural environment. The hazard is greater in the presence of materials that can sustain more intense fires or more toxic or corrosive pyrolytic products — for example, in the case of a warehouse containing hazardous materials or a chemical processing facility that uses or produces hazardous materials. Consequently, enclosure boundary walls, floors and roofs shall provide sufficient fire performance to resist secondary ignition and to contain an interior fire when no other strategy is employed to address the hazard. Another strategy consists in placing the built environment at sufficient distance from any potential exposure to prevent any significant risk of fire spread.

   3) Maintain the integrity of all types of separating elements of the built environment. This provision aims to increase the time available for escape, protect escape routes, facilitate

1) According to ISO/TR 16576.

2) In Europe, integrity, insulation and resistance (fire stability) are noted E, I and R, respectively.

firefighter access during rescue operations, limit the area of possible loss, reduce the impact of fire on the structure and its contents, separate different occupancies, isolate hazards, and contain releases of hazardous materials (during a fire and possibly after a fire).

b) Resistance or stability and/or resistance and integrity of the structure for the prevention or limitation of structural failure

Resistance, stability and integrity shall ensure the implementation of the following functional requirements:

1) Prevent or limit structural failure. For various reasons, including thermal deformation (expansion and contraction) and reduction of strength and stiffness resulting from heating exposed components of the structure, collapse may occur in one of two ways: through failure of heated portions of the structure or through failure involving non-heated portions of the structure. Collapse due to either mechanism creates a dangerous situation with respect to life safety (if anyone remains inside the built environment) and property protection. Therefore, structural elements shall have sufficient structural fire performance (in terms of resistance or stability for columns, beams and frames, and in terms of both integrity and resistance or stability for floors and walls) to prevent or delay failure. Prevention or delay of collapse is essential for load-bearing structural members.

2) Maintain the integrity and/or limit the deformation of the load-bearing structural elements of the built environment. In the absence of collapse, deformation may still affect exit paths, endangering life safety, and may cause considerable property damage. Prevention and/or limitation of deformation is essential for load-bearing structural members and for load-bearing barriers, which provide containment.

For the above-stated objectives and functional requirements for fire safety of structures, the time needed to achieve the objectives shall be defined by the interested/affected parties, for example, as the time to complete burnout, the time to complete evacuation or the time for the fire department to respond to and start controlling a fire. These are some examples and the interested/affected parties may specify other times.

In satisfying the functional requirements, consideration shall be given to the existence of active and passive fire control systems and their effectiveness.

Table 2 shows some examples of fire safety objectives, sub-objectives and functional requirements taken from ISO/TR 16576. The objectives and functional requirements shall be defined by the designer in consultation with the affected parties. Final approval may be required by regulatory authorities.

Table 2 — Examples of fire safety objectives and sub-objectives, as well as functional requirements

Fire safety objectives	Sub-objectives	Functional requirements
Life safety	Protection of occupants	No collapse of the load-bearing structures and no openings in or insulation failure of the partitions, walls and floors, in order to avoid fire spread and to maintain satisfactory conditions of tenability: — in the level of fire origin, — in the evacuation routes, and — in the refuge (secure waiting areas), where occupants awaiting evacuation are situated.
	Protection of fire fighters	No collapse of the load-bearing structures and no openings in or insulation failure of the partitions, walls and floors, in order to avoid fire spread and to maintain satisfactory conditions of tenability: — during all the time of the recognition phase, and — during the evacuation operations.
	Protection of third parties (outside of the building)	No collapse of the load-bearing structures and no openings in or insulation problems with the partitions, walls and floors, in order to avoid fire spread and to maintain satisfactory conditions of tenability: — during all the duration of fire, — during the time of evacuation of third parties, if necessary.
Protection of the environment	Protection of grounds, aquatic environments, groundwater and atmosphere	No collapse of the load-bearing structures and no openings in or insulation failure of the partitions, walls and floors, in order to avoid fire spread that can affect the maintenance of safety conditions related to the effluents linked to pollution — for example, fire-fighting water or toxic gases.
Conservation of property	Conservation of furniture or immovable properties of the building or construction work and third parties	No collapse of the load-bearing structures and no openings in or insulation failure of the partitions, walls and floors, in order to: — preserve a particular element inside the room of fire origin, — limit the fire damage to the room of fire origin, — limit the fire damage to the compartment or the floor of fire origin, — avoid the propagation of the fire to the third parties, — avoid the damage of the third parties.
	Conservation of strategic functions	No collapse of the load-bearing structures and no openings in or insulation failure of the partitions, walls and floors, in order to: — ensure the permanence of the strategic functions, — preserve the equipment or elements taking part in the strategic functions.
	Conservation from media impact	No collapse of the load-bearing structures and no openings in or insulation failure of the partitions, walls and floors, in order to avoid the media image related to a material, built environment or fire safety activity.

Table 2 *(continued)*

Fire safety objectives	Sub-objectives	Functional requirements
Preservation of heritage	Preservation of architectural, cultural and historical heritage	No collapse of the load-bearing structures and no openings in or insulation failure of the partitions, walls and floors. in order to avoid the damage of priceless buildings and objects or public works.
Continuity of operations	Preservations of activities and systems	No collapse of the load-bearing structures and no openings in or insulation failure of the partitions, walls and floors, in order to: — maintain a given activity, — preserve the total capacity of the activity, — preserve a particular system.

5.2.2 Performance criteria for fire safety of structures

Performance criteria shall be used to determine whether the objectives and functional requirements for the fire safety of structures have been satisfied.

Some candidate criteria for the fire performance of structures may be inferred from existing criteria employed in standard fire resistance tests in accordance with ISO 834-1. However, such criteria are generally expressed in prescriptive terms for a single element rather than in performance terms of a single element or the whole structure. In addition, although these performance criteria may still be useful, it is necessary to question their relevance and the way in which they are measured.

To allow for a more realistic assessment when using fire safety engineering design and analysis, performance criteria should not be stated as fixed values, in accordance with ISO 834-1, but should be expressed in terms of the fire safety and protection of people, property and contents, and the environment, and should take into account the interaction between the different elements within the structure.

Existing and new (relevant or more representative) performance criteria can be separated into categories to limit the harm or damage due to:

a) fire spread, using compartmentation (through separating elements and structural elements);

b) collapse of structural elements (for partial or total collapse).

The criteria relating to these two groups are presented in 5.2.2.1 and 5.2.2.2.

5.2.2.1 Performance criteria to limit fire spread (compartmentation)

The existing performance criteria relate to those found in ISO 834-1 and are as follows:

— Insulation criteria: in the form of a limited temperature rise of 140 °C on average, reaching a maximum of 180 °C, on the unexposed side of separating (load-bearing and non-load-bearing) elements. These limiting values are generally a very conservative means of assessing the risk of fire spread.

— Integrity criteria: assessed by igniting a cotton pad or through gaps formed through separating (load-bearing and non-load-bearing) elements. Neither the cotton pad test nor the gap test provides sufficient quantitative data.

The new (relevant) performance criteria are concerned with setting limit values so that enclosure boundaries meet the objectives and functional requirements for the fire safety of structures.

— A criterion for limiting heat transfer through separating (load-bearing and non-load-bearing) elements (or the surface temperature of the boundaries of adjacent enclosures), and thermal radiation emanating from these elements, in order to avoid any ignition of combustible material on the unexposed side of separating (load-bearing and non-load-bearing) elements, taking into account their relative location (penetrating materials, lining materials or any combustible materials in the adjacent enclosure), the kind of materials, and injury to occupants. Such a criterion can be measured in terms of heat flux or temperature of the unexposed side.

— A criterion for limiting the spread of hot fire gases through separating (load-bearing and non-load-bearing) elements in order to avoid both ignition of combustible materials on the other side of separating (load-bearing and non-load-bearing) elements and injury to occupants. Such a criterion can be measured in terms of leakage rate.

5.2.2.2 Performance criteria to limit structural damage (structural stability)

The existing performance criteria relate to those found in ISO 834-1 and are as follows:

— Load-bearing criteria dependent on a limited deflection/elongation and the rate of deformation. With regards to the stability of load-bearing elements, interaction with the boundary elements and other structural elements needs to be considered realistically, with the appropriate service load conditions.

The new (relevant) performance criteria are concerned with setting limit values so that load-bearing elements and the overall structure meet the objectives and functional requirements for the fire safety of structures. When setting the criteria, consideration should be given to:

a) the limits for structural collapse of a structure or part of it, and

b) the limits for deflection, elongation, contraction, etc. of elements of the structure and the impact of additional mechanical actions on adjacent separating (load-bearing and non-load-bearing) elements, liable to cause cracks and openings in them.

The levels of structural stability that should be considered are as follows:

— a criterion for providing sufficient structural stability of the load-bearing element for safe evacuation from the built environment;

— a criterion for providing sufficient structural stability of the load-bearing element for safe internal firefighting rescue and extinguishment activities in the built environment;

— a criterion for providing sufficient structural stability to critical elements of the structure (local failure of non-critical structural members is permitted);

— a criterion for providing sufficient structural stability to avoid any progressive or sudden global failure of the structure.

The criteria collectively need to address the question of reliability and other sources of uncertainty. This can be done by using safety margins in the direct calculation of the probability of structural failure per year, or associated risks when the relevant limit states are exceeded. The values used for reliability and uncertainty are usually based on historic data collected over a period of time. Results of risk assessment can also provide a rational basis for determining target reliability levels.

As far as the protection of people is concerned, the new (relevant) performance should be defined in relation to the Available Safe Escape Time (ASET)/ Required Safe Escape Time (RSET) approach, the extent of damage to the structure and the environment, and/or the maximum downtime allowed before reoccupying the built environment. Decisions about these performance criteria shall be made by the interested and affected parties as part of the initial design report and each time the performance criteria are refined.

5.3 Trial design plan for fire safety of structures

The trial design plan for fire safety of structures is an elaboration of the strategy for fire safety of structures and consists of a set of design elements for the fire safety of structures, such as stability and compartmentation.

This plan shall be described and documented in a fire design report and shall present detailed information in order to determine whether the fire safety objectives and performance criteria for fire safety of structures are met when assessed against the design fire scenarios. The design plan can define all the functions of the built environment in accordance with the strategy for fire safety of structures, taking into account, in its analysis, the interaction between all parts of the fire safety design.

ISO 23932-1 provides some useful information on the functions and design elements for consideration in a fire safety design.

5.4 Design fire scenarios and design fires (thermal actions)

5.4.1 General

Design fire scenarios and design fires are an important step in the assessment of the performance of structures in fire. It shall be noted that a design fire scenario is a specific qualitative description of the development of a fire whereas a design fire (thermal action) is a quantitative description of assumed fire characteristics within a design fire scenario.

See ISO 16733-1 and ISO 16733-2 for more information on the selection of design fire scenarios and design fires.

5.4.2 Design fire scenarios

The specification of appropriate fire scenarios is a crucial aspect of fire safety design. The selected fire scenarios have a major influence on all aspects of the design as they represent the input for most of the quantification processes.

There are an infinite number of possible fire scenarios for every built environment. It is impossible to analyse all likely scenarios, even with the aid of the most sophisticated computing resources. These possibilities shall be limited to a finite set of design fire scenarios that are amenable to analysis.

Characterization of a design fire scenario for analysis purposes involves a description of such things as initiation, growth and extinction of fire together with likely fire spread routes under a defined set of conditions. The impacts of fire on people, property, structure and environment are all part of the potentially relevant consequences of a design fire scenario and of the characterization of that scenario when those consequences are relevant to the specified fire safety objectives.

For the design of structures in fire, a fire scenario represents a particular combination of events and circumstances associated with factors such as:

— type of fire (e.g. location with respect to the load-bearing elements, size of fire);

— distribution and type of combustible materials;

— ventilation conditions; and

— status of the active systems and passive fire safety measures, and their performance and reliability.

As an example, a localized compartment fire may be located in a corner near a column. The compartment may have an open door, no sprinkler protection, and there may be no manual intervention (by the occupants or fire service) to extinguish the fire.

See ISO 16733-1 for more information on the selection of design fire scenarios.

5.4.3 Design fires (thermal actions)

Actions for consideration when assessing the behaviour of a structure in fire include thermal actions or design fires from realistic fire scenarios. Thermal actions or design fires are generally given either as time-temperature relationships or as time-heat flux relationships. To estimate the temperature or heat flux effects on separating (load-bearing and non-load-bearing) and structural elements, both convective and radiative heat effects should be accounted for.

Temperature in the volume affected by a fire is a function of time and space. The parameters to consider when determining the design fire (fire development) in a built environment include:

— built-environment geometry (surface area, height of storeys, enclosures, wall and floor types, sizes and positions of openings, types of glazing, etc.); and

— fire characteristics (fire load based on statistics or actual evaluation, ventilation conditions, glass breakage, and heat release rate determined from existing literature or tests).

In addition, the design fire is influenced by other factors such as human behaviour, active fire protection measures, such as sprinkler systems and firefighting operations. These factors should be taken into account for a better evaluation of the heat flux-time relationship or temperature-time relationship.

The design fire used in calculations should represent what is happening in a real fire; see Figure 3. When dealing with real fires, the key factor is the definition of the fire scenario for consideration in the design. It is possible to distinguish between different types of fires:

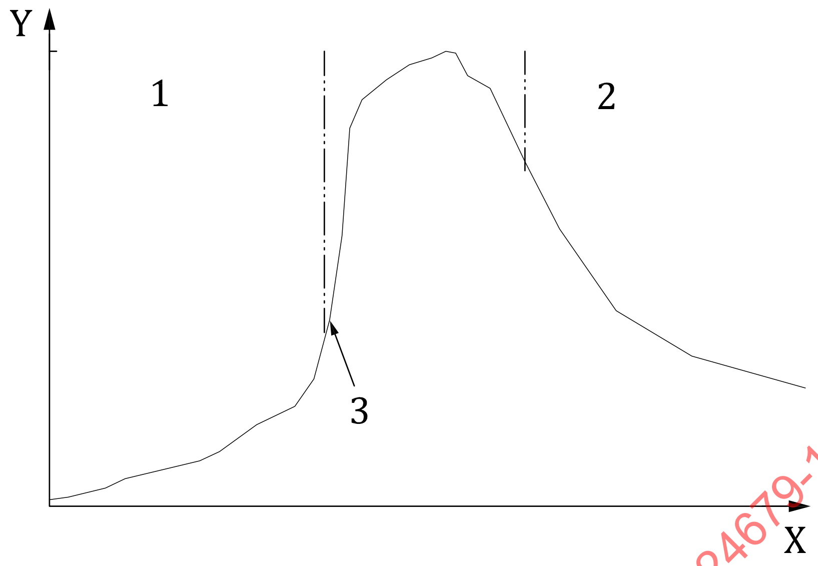
a) A nominal fire, which is expressed by a well-defined temperature-time curve, e.g. the standard ISO fire, the hydrocarbon fire, the external fire, etc. Although these curves are generally used in national regulations for testing and rating building components, how they relate to real fires is not well established and they should consequently not be used to assess the level of safety of structures.

b) An “analytical” fire, which takes into account the main parameters that have an influence on the gas temperature, but which is still only a rough approximation of a real fire, e.g. a parametric fire, a thermal exposure for external structural elements (flame coming from an opening or an outside fire such as wild land fires), a localized (plume) fire, etc.

c) A fire resulting from the calculation of the fire's development in one or more enclosures within a built environment and taking into account the geometry of the built environment, its ventilation (including window breakage) and the characteristics and distribution of the fuel, as well as from external fires exposing the structure from the outside.

d) A fire resulting from a test (but the designer should check the applicability of this fire to the real situation).

For fires reaching a fully-developed stage, the rate of combustion is limited either by the fuel or by the available ventilation. The ventilation-controlled rate of burning in a compartment is determined on the basis of the air flowing into the compartment. Fuel-bed-controlled fires occur less frequently than ventilation-controlled fires and are expected only in particular situations such as storage-type occupancies or external fires with a high level of ventilation.



Key
X time
Y temperature
1 ignition phase
2 decrease of the fire
3 flash over

Figure 3 — Real-fire characterization

To assess the different types of design fires for use in fire safety of structures, calculation methods or models may be used, including:

a) simple analytical formulae (e.g. for fire development in a single enclosure), which contain assumptions and approximate representations;

b) numerical calculations (e.g. for fire development in one or more enclosures) based on advanced calculation models including:

1) one-zone models, which are generally applied in post-flashover conditions;

NOTE Homogeneous properties of the gas are assumed in the enclosure.

2) two-zone models, which are based on the assumption that combustion products accumulate in a layer beneath the ceiling, with a horizontal interface with the lower cold layer;

3) field models that solve numerically the differential equations governing combustion and give calculated quantities for all points of the enclosure.

See ISO/TS 16733-2 for more information on the selection of design fires.

5.5 Thermal response of the structure

Structural design for fire safety requires the calculation of the temperature profiles in the elements subjected directly or indirectly to thermal actions. When the thermal conditions (e.g. heat flux, temperatures) on a load-bearing element or a non-load-bearing separating element are known, the temperature field can be calculated as a function of time, taking into account the following:

— heat transfer from flames and smoke to the structural elements through radiation and convection;

— heat transfer within the element (mainly by conduction in the case of a solid element, but also by convection and radiation when there are cavities within the element); and

— heat loss to adjacent elements, adjacent spaces or materials.

Temperatures can vary along an element, either because of the local action of the fire or because of heat transfer toward non-heated zones of the built environment. To calculate temperature profiles of elements, various assumptions/simplifications may be made:

a) with fully engulfed elements made from materials of high thermal conductivity (such as steel or aluminium alloys): uniform temperature through the cross-section;

b) with simple flat elements heated on one side (e.g. a flat concrete slab) or axisymmetric elements fully engulfed (e.g. a circular concrete or concrete-filled column): one-dimensional heat transfer;

c) to obtain the temperature field within a cross-section: two-dimensional (2D) heat transfer; and

d) to obtain the temperature field within an element with non-uniform temperature distribution along its axis or over its surface: three-dimensional (3D) heat transfer analysis.

The reference time-temperature relationship of surrounding gas and boundaries or time-heat flux (see 5.4.2) should be known, as well as the thermal properties of the materials involved. For the relevant reference temperatures, these thermal properties include thermal conductivity, specific heat, density (when it varies with temperature), melting points and other phase-changing points. Particular attention should be paid to the conditions in which the thermal properties were obtained; thermal properties suitable for a given fire severity (see ISO 834-1:1999, Figure 7) may not be suitable for another fire severity.

In addition, to obtain accurate temperature fields, mass transfer (due to the moisture content in many elements of the structure) may be considered, or at least the specific heat should be selected properly if accounting for mass transfer directly proves difficult. Additionally, the temperature field may be altered if spalling, melting or cracking of materials occur.

5.6 Mechanical response of the structure

The heating of structural elements may cause expansion (e.g. aluminium, steel, concrete) or contraction (e.g. wood), possible thermal gradients, and generally a reduction in mechanical properties such as stiffness and strength. These effects, along with the mechanical actions, lead to deformations. The purpose of the mechanical analysis of a heated structure is to assess:

— the load-bearing capacity after a given duration of fire exposure; and

— the deformation of the structure or part of it.

The load-bearing capacity decreases with temperature while the deformation generally increases with temperature. Both of these quantities require knowledge of mechanical properties according to temperature.

The analysis of the fire performance of structures is performed according to two possible representations:

a) A global structural analysis, which should take into account the relevant failure modes in fire exposure, the temperature-dependent material properties, and the effects of thermal expansion or contraction that may cause interactions between elements within the structure.

b) An analysis of parts of the structure. In this case the magnitude of loading and restraint, at boundaries between the part of the structure to be analysed and the remainder of the structure, is assumed to be time-independent during fire exposure, i.e. the effect of thermal expansion or contraction of heated elements is only considered within the part of the structure and not at its boundaries. Because some of the boundary conditions are kept constant during fire in this type of analysis, there are uncertainties in the calculations that the designer should bear in mind. In order to avoid these uncertainties, this type of analysis is typically used for symmetric structures if a whole structure is affected symmetrically by the same thermal actions.

The analysis of elements is applicable mainly when dealing with standard fire-resistance requirements (ISO fire or other nominal fire) and has been addressed in other ISO standards. In this case, the effects of thermal expansion or contraction, continuity and load redistribution are usually ignored. This analysis can be used for real localized fires but it is necessary to be careful with the boundary conditions in order to be sure that the results are on the safety side.

5.7 Assessment against the fire safety objectives

To assess whether or not the structure has, for a given fire scenario, an adequate level of fire safety (i.e. identified objectives are satisfied), the relevant performance criteria should be compared against the results of the analysis, test and/or judgement. This is achieved by comparing the maximum deformation of the components of the structure, or, if appropriate, the time to collapse.

The level of structural design for fire safety is evaluated using performance criteria relevant to the chosen strategy. For load-bearing functions the criteria can be:

a) the load-bearing capability for the entire duration of the fire or part of it;

b) the limit of the deflection/contraction/elongation with respect to the integrity of load-bearing separating elements; and

c) the limit of structural damage (spalling, corrosion, charring, deformation) at which a structure can be repaired after fire.

For non-load-bearing separating functions the criteria can be:

a) the limit of the unexposed surface temperature;

b) the limit of the radiation level from the unexposed surface of the element; and

c) the limit of cracks and boundary deformation in order to reduce leakage (e.g. flames and smoke) through the element.

For floors and load-bearing walls, both functions shall be satisfied.

5.8 Documentation of the design for fire safety of structures

Documentation concerning the assessment of fire safety of structures shall be provided to all interested and affected parties involved in the design process in order to foster greater understanding of the scope, the calculation methodology, the assumptions and the outcome of the assessment. The documentation shall provide details on the assessment of fire safety of structures, including the following:

a) Interested and affected parties involved: the participants in the assessment and their roles.

b) Scope of the project:

   1) description of the built environment, including type of occupancy, dimensions of the built environment, compartmentation, and openings;

   2) aspects relevant to fire safety performance, including type of structural material, building content (amounts and type of combustible material), occupant load, design structural loads, fire management and maintenance schedules;

   3) purpose of the assessment;

4) scope of the assessment, which shall also include the limitations and boundaries considered in the assessment.

c) Objectives, functional requirements and performance criteria for the fire safety of structures: the objectives, functional requirements and criteria used for the assessment, and how these were developed.

d) Trial design plan for fire safety of structures: this section of the documentation shall provide details on the strategy used to evaluate the fire safety of structures.

e) Design fire scenarios and design fires: the documentation shall state why the scenarios used are representative of the universe of scenarios to which the built environment is exposed and the design fires used in the evaluation process.

f) Assessment methods: the methods that were used for fire development, thermal analysis and structural analysis shall be outlined, including their appropriateness and limitations of use.

g) Data sources: the data sources that were used in the assessment, as well as the rationale underlying their suitability, shall be documented.

h) Evaluation of the assessment results: the documentation shall include the assessment results and the comparison against the performance criteria established at the beginning of the design. This shall attest to the appropriateness of the design for fire safety of the structure under consideration.

i) Summary and conclusions (if any).

5.9 Factors and influences to be considered in the quantification process

5.9.1 Material properties

5.9.1.1 Thermal properties

Heat transfer calculations shall consider relevant data for thermal properties as a function of temperature for each material involved, including:

— specific heat;

— thermal conductivity;

— density;

— moisture content.

The relevant materials are those used for construction, including any protective material, lining or acoustical products that may influence the temperature of the structural elements.

5.9.1.2 Mechanical properties

In general, materials within a built environment lose strength and stiffness at elevated temperatures, leading to a decrease in their load-bearing capacity and an increase in deformation.

Mechanical behaviour calculations shall consider relevant data for mechanical properties as a function of temperature for each material involved, including:

— stress-strain relationships at elevated temperatures;

— reduction factors for strength and stiffness;

— expansion or contraction due to elevated temperatures; and

— when necessary, the degradation of sections (by charring, spalling, etc.) due to the effect of temperature.

The materials considered are mainly those used for separating and structural elements, as well as any other materials that may influence deformation and stability.

5.9.1.3 Uncertainty of material properties

The thermal and mechanical responses of separating and structural elements are subject to the variability of the properties, which can be due to the source of the materials, the manufacturing processes, or the on-site construction methods.

For mechanical properties, it is normally assumed that the nominal properties featured in the relevant standard are adopted. In reality, the strength levels of structural materials in the as-received condition are different from the nominal values and this is usually reflected in the behaviour at elevated temperatures. For example, in the case of steel, the strength (yield and ultimate tensile strength) is typically above the value guaranteed in the standard, which follows through at elevated temperatures. The same applies to pre-cast products, which are delivered to the site, such as masonry and pre-cast concrete slabs. Where materials are produced on site (*in situ*), there is less control over the resulting properties. Timber products can have a relatively broad range of variability in characteristic properties compared to some manufactured materials, since wood is a natural product. For this reason, values quoted for characteristic properties can have a degree of uncertainty and conservatism.

The variation in thermal properties of structural materials is strongly influenced by characteristic parameters such as moisture content and phase changes. In concrete, the free-moisture content has a major impact on specific heat and on the dwell time at around 100 °C during which free moisture is converted into steam and heat is lost through the latent heat of vaporization. Care should therefore be taken to assign minimal moisture levels to heat transfer models to avoid underestimating heat transfer. Phase changes in the material are often accompanied by changes in heat content (latent heat). These are generally well established and the effects on, for example, specific heat and thermal conductivity are well known. Heat transfer is strongly dependent on the thermal emissivity of the materials' surface and this can change significantly during a fire. For example, the emissivity of steel is around 0,8 at ambient temperature, but, as the steel surface oxidizes during heating, the emissivity can rise up to 1,0. While thermal models usually take into account changes in specific heat and thermal conductivity, few consider changes in emissivity and instead adopt a single value.

Given that the material properties exhibit large variations, the designer shall take into account this uncertainty in the proposed values for the design.

5.9.2 Effect of continuity and restraint (interaction between elements and materials)

When assessing the fire behaviour of a structure [i.e. the risk of fire spread through separating (load-bearing and non-load-bearing) elements and/or the risk of collapse of the load-bearing structure], the possible interaction between materials within a given element or between elements having different degrees of heating should be considered. This can affect composite elements, made from a combination of materials, or the elements forming a system.

Fire behaviours obtained from a fire test performed on a structural element with a given time-temperature curve (e.g. ISO 834-1) are not easily translated into other thermal actions if no accurate calculation method is available.

Some of the physical phenomena that should be accounted for when assessing the fire performance of a structure are as follows:

a) Interaction of materials within a given element and behaviour of the different elements in the whole system, e.g. composite concrete-steel element connected with shear connectors.

b) Interaction between elements such as the elongation of a beam/floor at the top of a column/wall. Tests taking into account the interactions between elements, rather than isolated elements (beams, column, floors, walls), should be encouraged when determining the fire performance of a load-bearing structure. Indeed, in reality, the heating of a beam and/or floor and the resulting elongation create additional shear forces or increased bending moments at the top of the column due to restraint by surrounding elements. This adverse effect can cause an early collapse of the column. This should be considered in the fire performance design of the structure.

c) Full-scale behaviour. Full-scale tests performed in a realistic structure or part of a structure have shown that the use of computer models validated against “simple” laboratory test results (such as simply supported beams) may not correctly estimate the actual fire behaviour of an entire structure.

5.9.3 Use of test results

Separating and structural elements are mainly assessed by tests in accordance with ISO 834-1. The fire performance, with respect to the insulating and integrity failures obtained in this type of test, may not be accurate indicators of the performance of these elements in a real fire.

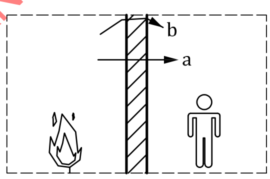
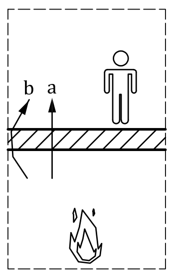
In general, it is necessary to perform tests with a relevant time-temperature curve representing the design fire or to use appropriate (and validated) calculation models to transfer a given result under a given fire curve to the expected result according to another fire curve.

5.9.4 Fire spread routes

There are many routes, both direct and indirect, by which fire can spread to adjacent enclosures or spaces with the attendant risk of secondary ignition and fire growth. Many of these routes are shown in Figure 4.

The figures illustrate some of the more common routes for potential fire spread. In many instances, in addition to identifying direct routes, designers should consider the potential for fire spread between adjoining enclosures via independent spaces. These fire spread routes often represent a combination of direct spread routes and should be viewed as a series of separate direct spread mechanisms.

All the potential routes for fire spread from the enclosure should be quantified and the time for fire spread to reach critical conditions should be determined. Any shortfall between this and the “required” fire spread time should be addressed by enhancing the fire and smoke containment capability of the relevant element. However, design effort may be reduced in situations where expert or engineering judgement can identify those routes most susceptible to rapid fire and smoke spread. It is important to remember that the fire spread is influenced by the environment, fire enclosure and adjacent spaces, as well as its susceptibility to secondary ignition.

WALLS	FLOORS
	
[a] **Spread route:** Through wall, or openings created in wall, or around edges.	[a] **Spread route**: Through floor, or openings created in floor, or around edges.
[b] **Spread mechanism:** Conduction [convection], direct pyrolysis (collapse or ignition).	[b] **Spread mechanism:** Conduction [convection], direct pyrolysis (collapse or ignition).

