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Fire safety engineering — Performance of structures in fire

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

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Foreword

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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 other circumstances, particularly when there is an urgent market requirement for such documents, a technical committee may decide to publish other types of normative document:

— an ISO Publicly Available Specification (ISO/PAS) represents an agreement between technical experts in an ISO working group and is accepted for publication if it is approved by more than 50 % of the members of the parent committee casting a vote;

— an ISO Technical Specification (ISO/TS) represents an agreement between the members of a technical committee and is accepted for publication if it is approved by 2/3 of the members of the committee casting a vote.

An ISO/PAS or ISO/TS is reviewed after three years in order to decide whether it will be confirmed for a further three years, revised to become an International Standard, or withdrawn. If the ISO/PAS or ISO/TS is confirmed, it is reviewed again after a further three years, at which time it must either be transformed into an International Standard or be withdrawn.

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/TS 24679 was prepared by Technical Committee ISO/TC 92, *Fire safety*, Subcommittee SC 4, *Fire safety engineering*.

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 regulation, 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.

Standard fire tests apply to fires with an inexhaustible fuel supply, where no distinction is made between enclosure size and ventilation, and which do not take into account realistic structural loads, the redistribution of load or conditions of structural restraint. Such an assessment method is only able to provide a comparative rating of the construction products but cannot furnish all the information required to make a fire safety analysis of a given built environment (e.g. smoke leakage, other types of fire, treatment of a full structure).

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 load conditions; and

— include the cooling phase of the fire.

This Technical Specification provides a methodology for applying an engineering approach to the assessment of fire performance of structures in real fires. In such an approach, the solutions are based on principles of reason, judgement, science, engineering and practicability. A rational 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.

This Technical Specification is intended for use by fire safety practitioners who employ performance-based design methods. Examples of users include fire safety engineers and structural engineers as well as authorities having jurisdiction, such as authority officials, fire service personnel and code developers. It is expected that users of this Technical Specification are appropriately qualified and competent in the fields of fire safety and structural engineering. It is particularly important that the users understand the limitations of any methodology used.

In addition to the standard clauses (Clauses 1, 2, 3 and Bibliography), this Technical Specification includes the following clauses:

— Clause 4 provides generic ways of describing design strategies for the fire safety of structures;

— Clause 5 presents the quantification of the performance of structures in fire, which includes guidance on the steps and engineering methods used to predict the thermal and mechanical responses of structural and separating elements exposed to fire and thereby evaluate the potential for fire spread and structural failure. Also included is a description of the factors that should be taken into consideration in the assessment and quantification process, namely fire spread paths and material properties at elevated temperatures;

— Clause 6 gives guidance on the use of the different quantification methods.

Fire safety engineering — Performance of structures in fire

1 Scope

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

This Technical Specification, which follows the principles outlined in ISO 23932, 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 referenced documents are indispensable for the application 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 23932, *Fire safety engineering — General principles*

3 Terms and definitions

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

3.1
building element
integral part of a built environment

NOTE 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
structural element
building element that is designed to carry loads besides its own weight

3.4
mechanical actions
defined force impacts 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 carry loads 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 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 actions
description of the variation of temperatures or heat fluxes as a function of time in an enclosure

NOTE 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 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 recently 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 enables better simulation 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 conventional fire 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:

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

— heat transfer, by conduction, through non-load-bearing separating elements, when the thermal properties of the component materials are known.

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 conventional 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 could 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 could 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 being made increasingly possible to either use advanced calculation or develop simplified calculation to deal with the behaviour of structure in real-fire situations.

This Technical Specification 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;
— considering design fire scenarios that could 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;
— 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 for the fire safety of structures. More details are provided in Clause 5 on quantification.

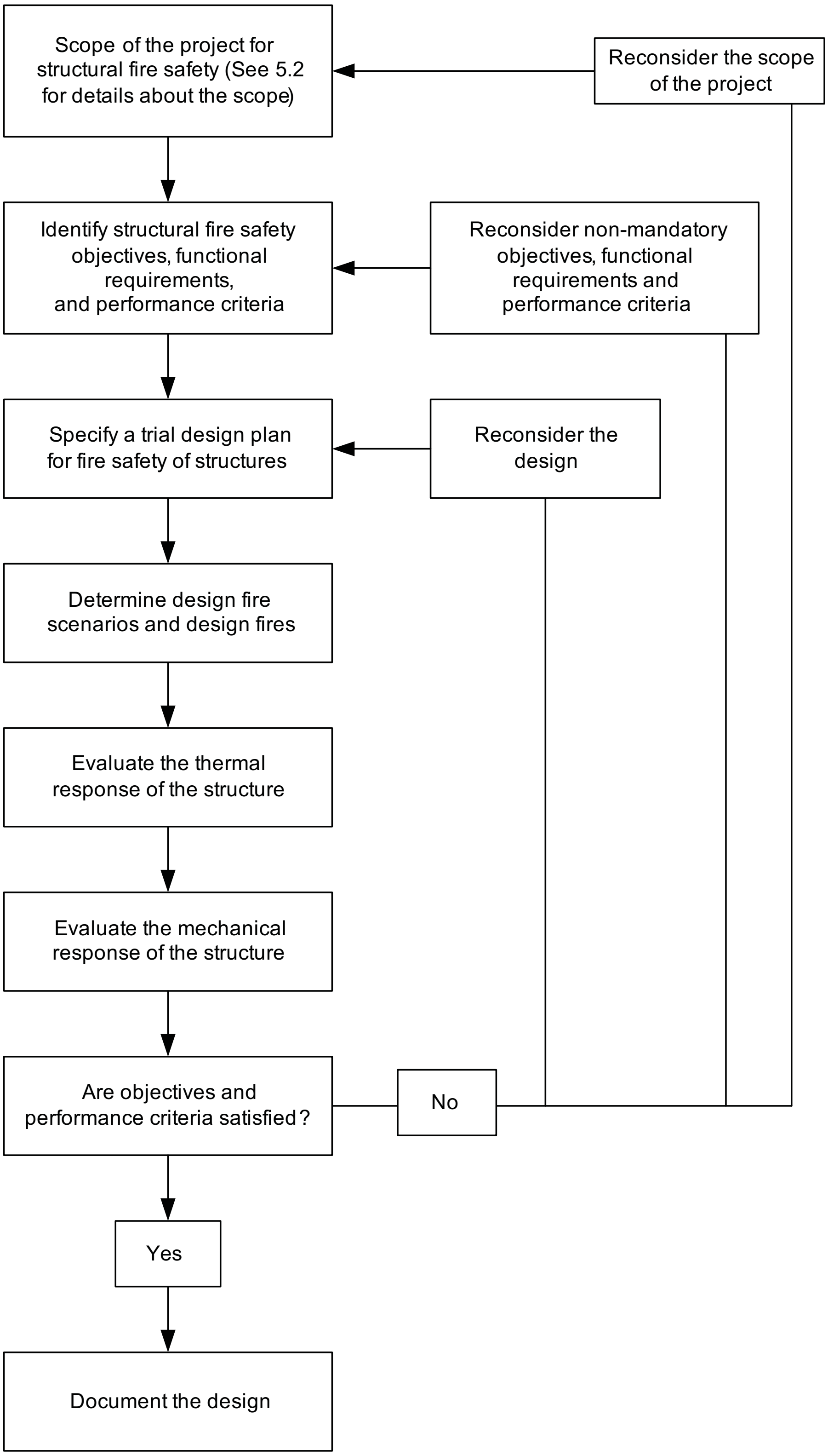


Figure 1 — Fire safety of structures — Design process

4.2 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).

The functional requirements for providing fire safety of structures, usually stated in terms of compartmentation, integrity and stability of the structure, are outlined as follows:

a) Compartmentation for the prevention or limitation of fire spread

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 (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 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 should provide sufficient fire performance to resist secondary ignition and to contain an interior fire. 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 the separating elements of the built environment. This provision aims to increase the time available for escape, protect escape routes, facilitate 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 even after the fire).

b) Integrity and stability of the structure for the prevention or limitation of structural failure

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 building) and property protection. Even in the absence of collapse, deformation may still affect exit paths, endangering life safety, and may cause considerable property damage. Therefore, structural elements should have sufficient structural fire performance (in terms of both integrity and stability) to prevent or delay failure. Prevention of collapse and/or limitation of deformation is essential for load-bearing structural members and for load-bearing barriers, which also provide containment. The main load-bearing structural elements, and secondary elements, which support or provide stability to barriers or main members, shall be given structural fire performance.

2) Maintain the integrity and/or limit the deformation of the structural elements of the built environment.

For the above-stated objectives and functional requirements for fire safety of structures, the time needed to achieve the objectives may be defined by the interested and affected parties 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 and affected parties may specify other times.

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

4.3 Performance criteria for fire safety of structures

Performance criteria are 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 may be separated into categories:

a) to limit the harm or damage due to fire spreading, using compartmentation (through separating elements and structural elements);

b) to limit the harm or damage due to the collapse of structural elements (for partial or total collapse).

The criteria relating to these two groups are presented in 4.3.1 and 4.3.2.

4.3.1 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 could 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 could be measured in terms of leakage rate.

4.3.2 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. As regards 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 ASET (Available Safe Escape Time) / RSET (Required Safe Escape Time) 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 should be made by the interested and affected parties as part of the initial design report and each time the performance criteria are refined.

5 Quantification of the performance of structures in fire

5.1 Fire performance of structures — Design process

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 later in the text.

Figure 2 shows a flow chart detailing the methodology of the three steps “Determine design fire scenarios and design fires”, “Evaluate the thermal performance of the structure”, and “Evaluate the mechanical response of the structure” in Figure 1 and Steps 4 to 6 of Table 1. This flow chart helps to provide a detailed understanding of a rational approach to the fire safety of structures exposed to a real fire. 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 7 in Table 1.

Table 1 — Design and quantification 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 existing 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 — — Dead and live loads — — Active fire protection systems	— Interested and affected parties — Structural systems to be analysed
2	Identifying objectives, functional requirements and performance 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 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
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
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)	
				— 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

Table 1 (*continued*)

Step No.	To consider	To determine or identify	Input	Factors of influence
			— 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 fire risk assessment)
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
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

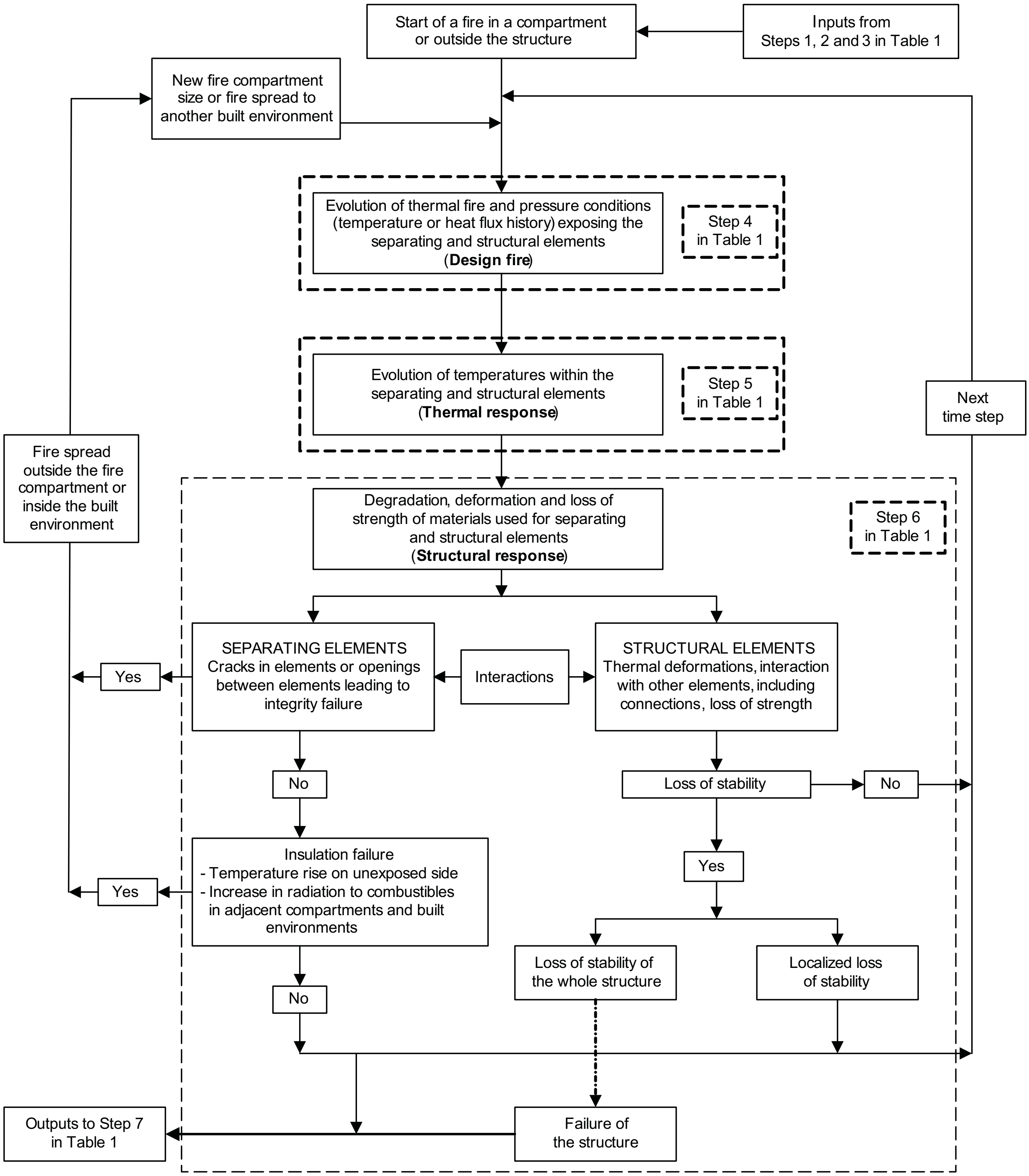


Figure 2 — Overview of a rational design process for Steps 4 to 6 in the fire safety of structures

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.

5.2 Scope of the project for fire safety of structures

This is the initial step in a fire safety design process for a new or an existing built environment. The main items included in this step are detailed in 5.2.1 to 5.2.3.

5.2.1 Built-environment characteristics

The project designer generally has knowledge of the general characteristics of the built environment and of the enclosure of fire origin. More specific characteristics are then usually developed (see 5.4).

5.2.2 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 load is characterized by the kind of combustible materials (attached to the built environment or its content), their amount and their location.

5.2.3 Mechanical actions

When considering the mechanical actions due to applied or weathering loads, the probability of the combined occurrence of a fire in a built environment and an extreme level of mechanical loads is considered sufficiently small, since fire action on the 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 the normal design of structures.

An important concept that may be 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, no other accidental actions should be considered in conjunction with fire. However, in countries with a high seismic risk, it might be necessary, in the overall fire risk assessment, to account for the possibility of structural damage, damage to separating (load-bearing and non-load-bearing) elements, and the threat to fire suppression systems and/or water supplies in the event of an earthquake.

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 firefighters, mainly on the unexposed side of separating (load-bearing and non-load-bearing) elements;

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

e) the 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.

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

Fire safety objectives are usually addressed in terms of life safety, conservation of property, continuity of operations, preservation of heritage, and protection of the environment. The functional requirements and performance criteria ensuring the fire safety of structures are usually stated in terms of compartmentation, integrity and stability of the structure. This step was detailed in Clause 4 and will not be repeated here.

5.4 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 should be described and documented in a fire design report and should 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 provides some useful information on the functions and design elements for consideration in a fire safety design.

5.5 Design fire scenarios and design fires

5.5.1 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 is a quantitative description of assumed fire characteristics within a design fire scenario.

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

5.5.2 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 should 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 could be located in a corner near a column. The compartment has an open door, no sprinkler protection, and there is no manual intervention (by the occupants or fire service) to extinguish the fire.

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

5.5.3 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:

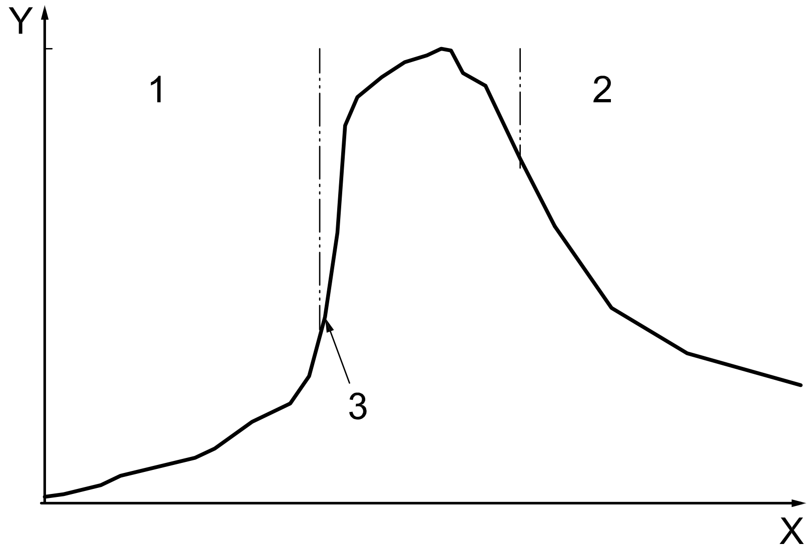
a) A nominal fire, which is expressed by a well-defined temperature-time curve, e.g. the standard ISO fire, the hydrocarbon fire, the external fire, etc. Although these curves are generally used in national regulations for testing and rating building components, how they relate to real fires is not well 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-flash over 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 16733 for more information on the selection of design fire scenarios and design fires.

5.6 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 5.5.2), 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.

5.7 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:

a) the load-bearing capacity after a given duration of fire exposure; or

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

The analysis of elements, applicable mainly when dealing with standard fire-resistance requirements (ISO fire or other nominal fire), is outside the scope of this Technical Specification and has been addressed in other ISO documents. In this case, the effects of thermal expansion or contraction, continuity and load redistribution are usually ignored.

5.8 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, they could be:

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

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

c) the limit of structural damage (spalling, corrosion, charring, deformation) at which a structure can be repaired after fire (re-serviceability or re-usability limit state).

For non-load-bearing separating functions, they could be:

— the limit of the unexposed face temperature;

— the limit of the radiation level from the unexposed face of the element; and

— 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.

5.9 Documentation of the design for fire safety of structures

Documentation concerning the assessment of fire safety of structures is 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 provides 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 should 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 should provide details on the strategy used to evaluate the fire safety of structures.

e) Design fire scenarios and design fires: the documentation should 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 should be outlined, including their appropriateness and limitations of use.

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

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

i) Summary and conclusions (if any).

5.10 Factors and influences to be considered in the quantification process

5.10.1 Material properties

5.10.1.1 Thermal properties

Heat transfer calculations should 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.

5.10.1.2 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 should 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.

5.10.1.3 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 planks. Where materials are produced on site (*in situ*), there is less control over the resulting properties. Timber is usually categorized as either softwood or hardwood. Using such a broad range in an attempt to cover all wood species introduces considerable variability in characteristic properties. For this reason, the nominal properties quoted normally have a degree of uncertainty and potential 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.

5.10.2 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. the ISO 834-1:1999, Figure 7) 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 underestimate the actual fire behaviour of an entire structure.

5.10.3 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.

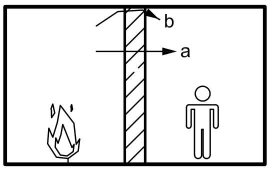
5.10.4 Fire spread routes

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 have already been identified in ISO/TR 13387-6. Figure 4 has been derived from the mechanisms and routes given in ISO/TR 13387-6:1999, Figure 2.

The figures illustrate some of the more common routes for potential fire spread. In many instances, in addition to indentifying 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. Whether or not fire spread takes place is influenced by environment, both within the fire enclosure and within the adjacent spaces, and its susceptibility to secondary ignition.

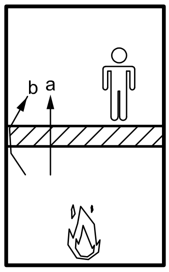
WALLS



[a] **Spread route:** Through wall, or openings created in wall, or around edges.

[b] **Spread mechanism:** Conduction [convection], direct pyrolysis (collapse or ignition).

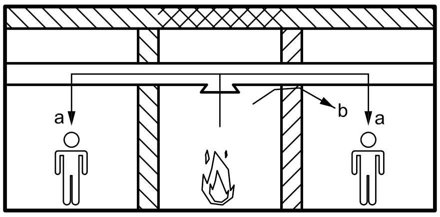
FLOORS



[a] **Spread route**: Through floor, or openings created in floor, or around edges.

[b] **Spread mechanism:** Conduction [convection], direct pyrolysis (collapse or ignition).

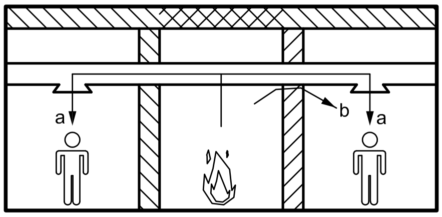
UNDAMPERED HORIZONTAL DUCTWORK (1)



[a] **Spread route:** Along or through horizontal duct.

[b] **Spread mechanism:** Conduction, convection.

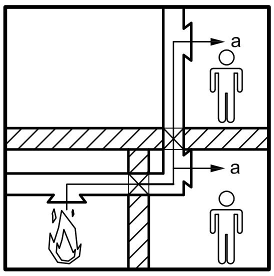
UNDAMPERED HORIZONTAL DUCTWORK (2)



[a] **Spread route:** Along or through horizontal duct.

[b] **Spread mechanism:** Conduction, convection.

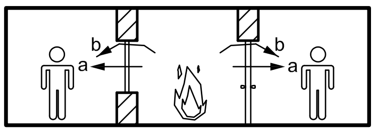
DAMPERED DUCTWORK



[a] **Spread route:** Through damper or openings created.

NOTE **Spread mechanism:** Convection, conduction.

PROTECTED OPENINGS

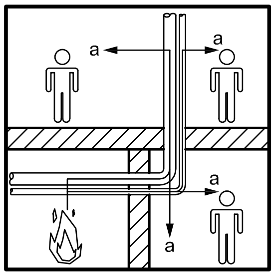


[a] **Spread route:** Through door, glazing, etc. and openings created in them or around edges.

[b] **Spread mechanism:** Conduction, radiation, direct pyrolysis (collapse or ignition).

Figure 4 (*continued*)

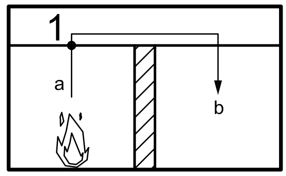
SERVICES (PIPES/CABLES AND SUPPORTS)



[a] **Spread route:** Fire transferred through service or via penetration to accommodate service.

NOTE **Spread mechanism:** Complex, including radiation, mass transfer, conduction.

SUSPENDED CEILING VOIDS



Key

1 void above ceiling

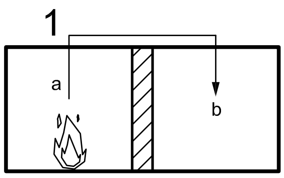
Spread route:

[a] Enclosure to ceiling void.

[b] Ceiling void to adjacent enclosure.

NOTE **Spread mechanism:** Complex, including pyrolysis, mass transfer and conduction.

ROOFS



Key

1 over external roof

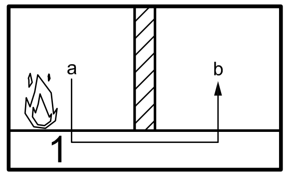
Spread route:

[a] Enclosure to roof.

[b] Roof to adjacent enclosure.

NOTE **Spread mechanism:** Pyrolysis, radiation.

RAISED FLOOR VOIDS (1)



Key

1 void

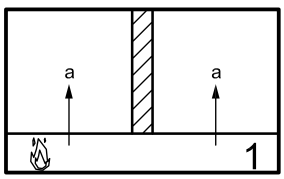
Spread route:

[a] Enclosure to floor void.

[b] Void to adjacent enclosure.

NOTE **Spread mechanism:** Complex, including pyrolysis, mass transfer, conduction and convection.

RAISED FLOOR VOIDS (2)



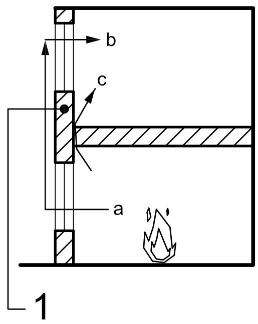
Key

1 void

[a] **Spread route:** Void to enclosure via floor.

NOTE **Spread mechanism:** Conduction and convection.

EXTERNAL WALLS/WINDOWS



Key

1 façade surface

Spread route:

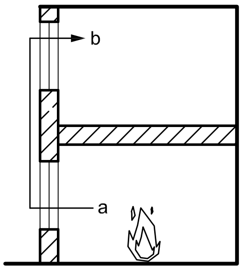
[a] Enclosure to façade surface.

[b] Façade to adjacent enclosure.

NOTE **Spread mechanism:** Complex, including pyrolysis of surface.

Figure 4 (*continued*)

EXTERNAL WINDOWS



Spread route:

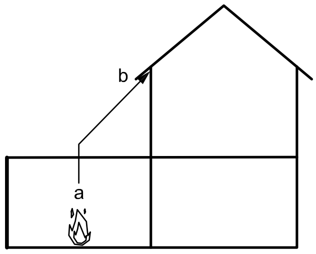
[a] Enclosure to outside.

[b] Outside to adjacent enclosure.

NOTE 1 **Spread mechanism:** Collapse, convection, radiation.

NOTE 2 Can occur horizontally between windows in certain conditions.

UPPER PARTS OF BUILDINGS



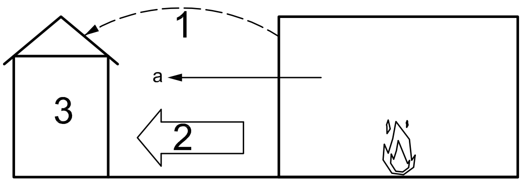
Spread route:

[a] Enclosure to roof outside.

[b] Roof flames through external envelope, e.g. window.

NOTE **Spread mechanism:** Pyrolysis (collapse/ignition), convection, radiation.

ADJACENT BUILDINGS



Key

1 flying brands

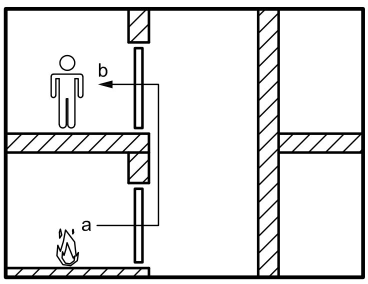
2 radiation

3 exposed building

[a] **Spread route:** Enclosure to space adjacent to enclosure.

NOTE **Spread mechanism:** Complex, including radiation, mass transfer.

LIFT SHAFT



Spread route:

[a] Enclosure to lift shaft.

[b] Lift shaft to enclosure.

NOTE **Spread mechanism:** Convection, conduction.

Figure 4 — Routes of fire spread

6 Guidance on use of engineering methods

Assessment of the behaviour of a structure, in real-fire situations, uses the following approaches:

— calculation methods;

— experimental methods;

— expert (or engineering) judgement.

Generally, the expected behaviour of a structure exposed to fire conditions is a combination of these three approaches. This is because, currently, no single approache is capable of providing the full necessary answer.

6.1 Using calculation methods

Calculation methods provide a convenient means of understanding the phenomena that can occur in situations of fire and to assess the behaviour of structures in a variety of fire scenarios. There are numerical simulation tools, which may be used to calculate the heat transfer, deformation and load-bearing capacity of the heated members in the structure. However, the user should be aware of their limitations which are due to:

— the limited number of validated calculation methods;

— the current impossibility of accurately modelling some of the physical phenomena such as spalling;

— the lack of information on the thermal and mechanical properties at elevated temperature of the materials used in elements constituting the structure.

Because of these limitations, a safer way of using calculation methods to assess the fire performance of structures is to first verify the ability of the model and of the input data to simulate the behaviour of given tested representative specimens by checking that the design and the thermal exposure is close enough to the final target.

Predicting the structural fire behaviour of non-load-bearing separating elements such as partitions, doors, dampers, etc. by calculation remains difficult. Although it is possible to make heat transfer calculations through multi-layer elements, it is still very difficult to predict with any accuracy the thermal distribution at boundaries as well as the performance in terms of integrity. For the time being, calculation methods only serve to provide a better understanding of the physical phenomena that can occur when changing the design or the size of a tested element. In all cases, a reference test result and expert judgement remain necessary for these partition elements.

6.2 Using experimental methods

As regards assessment by test, it must be recognized that experimentation on fire safety of structures is expensive and it is therefore generally necessary to limit the number, size and complexity of the specimens to be tested. Three possibilities should be considered:

a) The experimentation of isolated elements or assemblies of elements according to a given thermal action (design fire), leading to results closely connected to the expected behaviour in real fire. This method is mainly used where the design fire is accurately defined, where it is possible to reproduce with sufficient accuracy the boundary conditions to the tested element or assembly, and where the possible application of the tested element(s) is large enough to be worth the investment. This method applies to any thermal action (represented by a temperature-time relationship) and to any element (beam, column, partition, wall, door, ceiling, floor, as well as duct, damper, etc.) or assembly of elements for which assessment is required. In such a situation, the test result is directly used in the assessment and requires only minor interpretation.

b) The experimentation of isolated elements according to a standard fire (ISO 834-1 or other nominal fires). Since elements of a structure will continue to be tested according to this thermal action for compliance with prescriptive requirements or deemed-to-satisfy solutions, test results should be made available and should be used in the assessment. However, more limitations should be considered than in the previous situations:

   1) Mainly isolated elements are tested and test results are only seldom made available for assemblies.

   2) Depending on the relative fire development between the nominal fire used for testing and the design fire phenomena, such factors as those related to thermal deformation, strength and rigidity as a function of temperature, and shrinkage, should be considered when making an expert judgment on the behaviour of the built environment in the design fire.

   3) It is worth establishing rules for using these test results for fire engineering purposes. Existing or newly developed rules may be used to relate the results of standard fire testing to those of real-fire testing so that the existing standard data remain useful. One way of doing this is to develop an

evaluation method, check it against the test results, use it for assessing the same element for the relevant fire design, and then use it for assessing the element with other boundary conditions.

4) In addition, there is a need to improve the instrumentation of the many routine (standard) tests performed on a regular basis to provide more information on the fire behaviour of the elements of a structure. Additional data that may be obtained in these fire tests include initial stress conditions, distortion and deflection, temperature profile, restraining forces, heat flux from the unexposed surface and leakage of flames and/or smoke.

c) The experimentation using full-scale behaviour representing the entire structure. This kind of testing is very expensive and time-consuming and should be performed only in very rare cases for the purpose of studying real behaviour and collecting data that would be used to validate a numerical model, which in turn would be used to study the behaviour of structures. This type of testing should also be used to provide a direct answer for a given construction project.

6.3 Using engineering judgment

All this information, obtained by test and/or by calculation, will help the fire expert make a full assessment of the expected fire behaviour of a structure. One of the major concerns of the expert will be to evaluate the possible impact of different thermal actions (heating rate, maximum temperature reached, cooling phase) based on the failure criteria.

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