TECHNICAL REPORT

ISO/TR 13387-6

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Fire safety engineering —

Part 6:
Structural response and fire spread beyond the enclosure of origin

Ingénierie de la sécurité contre l'incendie —

Partie 6: Réponse structurelle et propagation du feu au-delà de l'enceinte d'origine

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Contents

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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 main task of ISO technical committees is to prepare International Standards, but in exceptional circumstances a technical committee may propose the publication of a Technical Report of one of the following types:

— type 1, when the required support cannot be obtained for the publication of an International Standard, despite repeated efforts;

— type 2, when the subject is still under technical development or where for any other reason there is the future but not immediate possibility of an agreement on an International Standard;

— type 3, when a technical committee has collected data of a different kind from that which is normally published as an International Standard (“state of the art“, for example).

Technical Reports of types 1 and 2 are subject to review within three years of publication, to decide whether they can be transformed into International Standards. Technical Reports of type 3 do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful.

ISO/TR 13387-6, which is a Technical Report of type 2, was prepared by Technical Committee ISO/TC 92*, Fire safety*, Subcommittee SC 4, *Fire safety engineering*.

It is one of eight parts which outlines important aspects which need to be considered in making a fundamental approach to the provision of fire safety in buildings. The approach ignores any constraints which might apply as a consequence of regulations or codes; following the approach will not, therefore, necessarily mean compliance with national regulations.

ISO/TR 13387 consists of the following parts, under the general title *Fire safety engineering*:

— *Part 1: Application of fire performance concepts to design objectives*

— *Part 2: Design fire scenarios and design fires*

— *Part 3: Assessment and verification of mathematical fire models*

— *Part 4: Initiation and development of fire and generation of fire effluents*

— *Part 5: Movement of fire effluents*

— *Part 6: Structural response and fire spread beyond the enclosure of origin*

— *Part 7: Detection, activation and suppression*

— *Part 8: Life safety — Occupant behaviour, location and condition*

Introduction

An important feature of design for fire safety, whether it is undertaken employing prescriptive regulations or fire safety engineering principles, is to ensure that building elements prevent (or delay) the spread of fire and prevent (or delay) structural failure. Measures must be taken to ensure the spread of fire and structural failure do not threaten the lives of occupants and firefighters, or compromise other fire safety objectives.

In prescriptive fire safety design, extensive use is made of the fire resistance of building elements as determined by the standard fire resistance test ISO 834-1. Inherent in this test are criteria concerned with load-bearing capacity, integrity and thermal insulation. Fire resistance requirements may be prescribed in national regulations and codes according to the use of the building, the size of fire compartments and the height of the building.

Design may also be undertaken employing fire safety engineering principles in which neither the temperature-time curve nor the duration of the exposing fire are prescribed. Instead, pertinent characteristics of the exposing fire are calculated to be representative of one (or several) fire scenarios envisioned for the building. The thermal and mechanical response of building elements subjected to such exposing fires are then calculated. Finally, the performance of building elements (specifically their ability to inhibit fire spread and structural failure) are assessed using criteria which, depending on the conditions at hand, may differ from the fire resistance criteria within ISO 834-1.

This part of ISO/TR 13387 is intended for use together with the other Technical Reports as described in clause 5. For some applications however this document alone may be sufficient.

Clause 6 describes and provides guidance on the approaches available to characterize the physical and chemical processes which govern the thermal and mechanical responses of building elements exposed to fire.

Clause 7 is a discussion of engineering methods to predict the thermal and mechanical response of building elements exposed to fire and thereby to evaluate the potential for fire spread and structural failure. It should be noted that whatever method is selected, it should be assessed and verified using the principles documented in ISO/TR 13387-3. Furthermore, special care should be taken when using input data published in the literature. The quantitative information may be related to specific test conditions and/or specific commercial products, and the application of the data under different conditions may result in significant errors.

Finally, in clause 8, guidance on interpreting the results of an analysis of the potential of structural failure and fire spread is provided. This includes guidance on the selection of criteria for assessing the effectiveness of fire safety measures meant to reduce the potential of structural failure or fire spread. The latter is only possible if the objectives of fire safety design have been clearly specified.

Fire safety engineering —

Part 6:
Structural response and fire spread beyond the enclosure of origin

1 Scope

This part of ISO/TR 13387 is intended to provide general guidance on the use of engineering methods for the prediction of fire spread within and between buildings, and for the prediction of the response of a structure exposed to fire. The report is not intended as a detailed technical design guide, but could be used as the basis for development of such a guide.

This part of ISO/TR 13387 provides a framework for critically reviewing the suitability of an engineering method for assessing the potential for fire spread and for fire damage to a building's structure. It also provides guidance for assessing the effectiveness of fire safety measures meant to reduce these potentials.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this part of ISO/TR 13387. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this part of ISO/TR 13387 are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

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

ISO 7345:1987, *Thermal insulation — Physical quantities and definitions*.

ISO/TR 10158:1991, *Principles and rationale underlying calculation methods in relation to fire resistance of structural elements.*

ISO/TR 12470:1998, *Fire resistance tests — Guidance on the application and extension of results*.

ISO/TR 13387-1, *Fire safety engineering — Part 1: Application of fire performance concepts to design objectives.*

ISO/TR 13387-2, *Fire safety engineering — Part 2: Design fire scenarios and design fires.*

ISO/TR 13387-3, *Fire safety engineering — Part 3: Assessment and verification of mathematical fire models.*

ISO/TR 13387-4, *Fire safety engineering — Part 4: Initiation and development of fire and generation of fire effluents.*

ISO/TR 13387-5, *Fire safety engineering — Part 5: Movement of fire effluents.*

ISO/TR 13387-7, *Fire safety engineering — Part 7: Detection, activation and suppression.*

ISO/TR 13387-8, *Fire safety engineering — Part 8: Life safety — Occupant behaviour, location and condition.*

ISO 13943, *Fire safety — Vocabulary*.

3 Terms and definitions

For the purposes of this part of ISO/TR 13387, the definitions given in ISO 13943, ISO/TR 13387-1 and the following apply.

3.1
building element
integral component of the structure or fabric of a building, including floors, walls, beams, columns, doors, etc. complete with penetrations, but does not include building contents

3.2
enclosure
space defined by boundary elements

3.3
integrity
ability of a separating element, when exposed to fire on one side, to prevent the passage of flames and hot gases or the occurrence of flames on the unexposed side

3.4
load-bearing capacity
ability of a building element (or structure) to sustain applied actions (loads) when exposed to fire

3.5
mechanical response
measure of fire induced changes to the deflection, stiffness and load-bearing capacity of building elements and the development of openings (cracks) in building elements during fire exposure as a result of the shrinkage (expansion) of materials, spalling, delamination, etc.

3.6
thermal diffusivity
thermal conductivity divided by the density and specific heat, expressed in $m^2 \cdot s^{-1}$, given by $\kappa = k/(\rho \cdot c)$

3.7
thermal inertia
product of thermal conductivity, density and specific heat (square of thermal effusivity according to ISO 7345), given by $k \cdot \rho \cdot c$,

It is expressed in $J^2 \cdot m^{-4} \cdot K^{-2} \cdot s^{-1}$.

3.8
thermal insulation
the ability of a separating element, when exposed to fire on one side, to prevent the transmission of excessive heat

3.9
thermal response
a measure of:

a) fire induced changes to the temperature profile within building elements; and

b) the development of openings in building elements during fire exposure as a result of the melting of materials

4 Symbols and abbreviated terms

c specific heat of a material, expressed in $J \cdot kg^{-1} \cdot K^{-1}$

k thermal conductivity, expressed in $W \cdot m^{-1} \cdot K^{-1}$

κ thermal diffusivity, expressed in $m^2 \cdot s^{-1}$

ρ density, expressed in $kg \cdot m^{-3}$

5 Subsystem 3 of the total design system

The approach adopted in this part of ISO/TR 13387 is to acknowledge that assessment of structural response and fire spread addresses only a subsection of the global objectives of fire safety design. Global design, described in more detail in the framework document, ISO/TR 13387-1, is divided into subsystems. The key principles of the global design approach are that interdependencies among the subsystems are evaluated and that pertinent considerations for each subsystem are identified. Structural response and fire spread is subsystem 3 (SS3) of the total fire safety design system.

In the framework document, global fire safety design is illustrated by an information bus analogy. The information bus has three layers: global information, evaluations and process buses. The global information includes data which are either transferred among subsystems or employed to make engineering decisions. SS3 links with the global information are shown in Figure 1. The second layer of the bus system depicts the evaluations which must be undertaken within SS3 to evaluate structural response and fire spread. The third layer elucidates the fundamental processes which come into play in each evaluation undertaken within SS3.

SS3 draws on other subsystems for certain input data and generates output data which are used by yet other subsystems. For example, SS1 provides predictions of the temperature and heat flux history (thermal profile) in the enclosure of concern. These data along with the description of building assemblies (building parameters) are employed by SS3 to predict the likelihood (and time) of fire spread, and the likelihood (and time) of structural failure. Once a prediction has been made “output” data describing the building condition are placed on the global information bus. Building condition data may subsequently become “input” data for evaluations undertaken by SS1 and SS2 to calculate, for example, the potential for fire spread (and the subsequent fire size).

The transfer of data between the global information bus and the evaluations undertaken in SS3 is depicted explicitly in Figure 1. As Figure 1 indicates it is necessary to calculate (evaluate) the thermal response and mechanical response of building systems and then determine whether fire spread will occur. Guidance on undertaking such calculations is given in clause 6.

The fundamental processes which come into play in these evaluations are also depicted in Figure 1. An engineering analysis will incorporate these fundamental processes to an appropriate level of rigour as discussed in clause 6.

It should be noted that Figure 1 has been constructed to elucidate the process involved in undertaking an evaluation of the potential for structural failure or fire spread. It is not intended to include all possible phenomena.

ISO TC 92/SC 4 FIRE SAFETY ENGINEERING BUS SYSTEM

Subsystem 3 (SS3) — Structural response and fire spread beyond the enclosure of origin

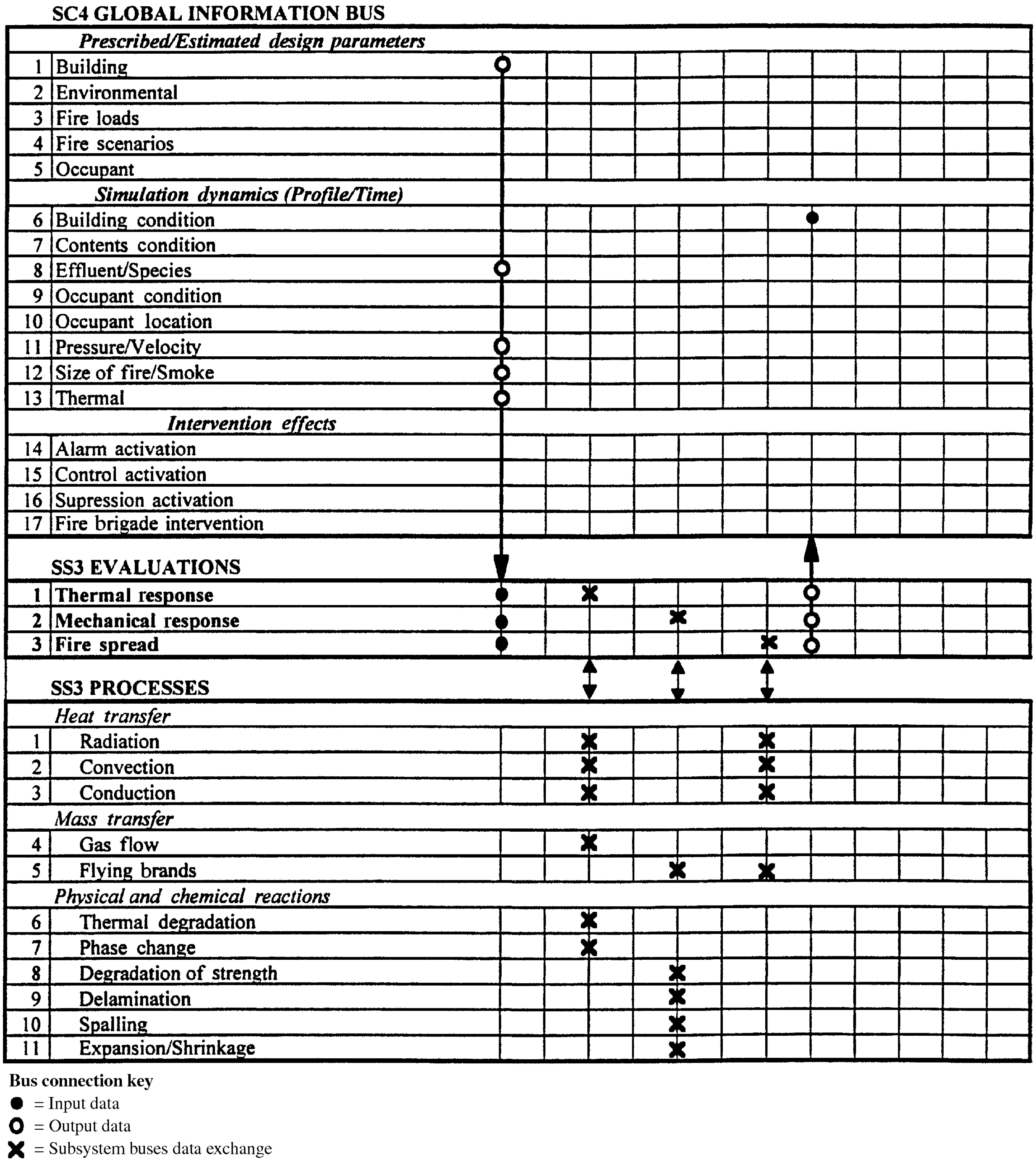


Figure 1 — Illustration of the global information, evaluation and process buses for SS3

6 Subsystem 3 evaluations

6.1 General

In this clause, guidance on predicting and evaluating the thermal and mechanical response of building elements and structures exposed to fire are discussed. Guidance on assessing whether fire spread will occur is also provided. The input data required to undertaken such evaluations and the possible output information are identified. Where possible, reference is made to literature which provides a more detailed discussion of the material presented in this clause.

6.2 Thermal response

6.2.1 Role in fire safety engineering design

This clause provides an overview of the assessment of the thermal response of building elements which are in one way or other exposed to heating from fire. The exposing fire may be a localized fire within an enclosure, a post-flashover enclosure fire, or perhaps an external fire. The nature of the exposing fire will have already been derived by SS1 or possibly specified as a design fire by ISO/TR 13387-2.

An accurate prediction of the thermal response of building elements exposed to fire is essential in fire safety engineering design. In the first instance, it allows for an assessment of the degree of thermal damage that may be sustained by building elements exposed to fire. This may be particularly important if a building is to be designed so that it can be re-used following a fire. Of more immediate concern, prediction of the thermal response of building elements is the first step in the assessment of their mechanical response and ultimately the potential for structural failure and/or fire spread.

Detailed discussions of the mechanical response and potential for fire spread are provided in 6.3 and 6.4 respectively. However, it note that for some applications an assessment of the thermal response of building elements coupled with well-defined performance criteria may suffice. This may be the case, for example, if a structural member can be assumed to fail when it reaches a specific temperature as is often assumed for structural steel elements. It may also be the case if it can be assumed that the spread of fire from one enclosure to another may occur because of either the excessive transmission of heat through enclosure boundaries or because of openings created by the melting of materials as both of these phenomena can also be tied to temperature rise criteria. The question of establishing appropriate thermal criteria is briefly discussed in clause 8.

6.2.1.1 Input

As depicted in Figure 1, evaluation of the thermal response of building elements requires the following input data from the global information bus:

— building parameters (dimensions, locations, thermophysical and thermochemical properties of building elements);

— size of fire/smoke (for localized or external fires: physical size and relative location of fire to key building elements);

— thermal (for all fires: the temperature-time profile of fire gases and the heat flux impinging on building elements);

— pressure / velocity (the velocity of the fire gases may be needed to assess convective heat transfer from the fire to building elements); and

— effluent species (smoke concentrations effect the emissivity of the fire gases. The emissivity may be needed to assess radiative heat transfer from the fire to building elements).

6.2.1.2 Output

Once the evaluation of the thermal response of building elements is completed, the following data are passed to the global information bus:

— building condition (temperature-time profile within and on the surface of building elements).

This output also becomes input for assessing the mechanical response of building elements and the potential for fire spread.

6.2.2 Modelling the thermal response of building elements

As indicated in 6.2.1.1, to model the thermal response of building elements, a reasonably detailed description of the exposing fire is necessary. This document is intended to be used as part of a fire safety engineering assessment in which SS1 has first calculated the pertinent properties of the exposing fire (whether it be an enclosure fire, a localized fire or an external fire). There are, however, applications for which the exposing fire can be chosen from a set of design fires. Care must be exercised when selecting an appropriate design fire as some constructions may be sensitive to high temperatures whereas others may be sensitive to high rates of temperature rise or to the duration of exposure. Further guidance on the use of design fires is found in ISO/TR 13387-2.

Once the exposing fire has been chosen an assessment of the thermal response of building elements can begin (see Figure 1). The calculation of heat transfer to and within the building elements undertaken by SS3 will need to be more detailed than the calculation already undertaken by SS1 where it was the temperature of the fire gases that was of primary interest.

If a building element is in direct contact with fire gases (for example, in a post-flashover enclosure fire), heat is transferred to exposed surfaces of the element by means of radiation (see reference [1] in the bibliography) and convection (see reference [2]). On the other hand, if a building element is some distance from flames or hot gases (for example, for exposure to fire in a neighbouring building), "exposed" surfaces may be heated by radiation but cooled by convection. Engineering methods for modelling radiative and convective heat transfer for fire safety engineering calculations are readily available (see references [1] and [2]).

In either case, heat is transferred from the hot surface deeper into the element by means of heat conduction (see reference [3]). As heat is conducted into the element, any absorbed water is vaporized (a phase change) and the element itself may experience melting (a phase change) or thermal degradation. These processes are commonly endothermic and hence slow down heat transmission. The vapours generated by vaporization of water and by thermal degradation of the element will migrate through the element further impacting on the heat transfer process. In principle, then, heat transfer and mass transfer (gas flow) are coupled. The equations governing these processes are complex and can only be solved by the use of numerical methods.

For some materials, the internal processes discussed above are not present or do not unduly impact upon heat flow so that heat transfer through the material can be assumed to obey the 3-dimensional heat conduction (see reference [3]). Nonetheless, the material's thermal conductivity (k), specific heat (c) and perhaps even density (ρ) are commonly temperature dependent. Despite these simplifications, the heat conduction equation with temperature dependent coefficients can also only be solved by the use of numerical methods.

Analysis can be further simplified if the material's thermal properties (k, c and ρ) can be assumed to be constant (or at least can be replaced by an average value) over the temperature range of interest. Due to the complex nature of radiative heating at the surface (boundary conditions) the heat conduction equation can still only be solved explicitly by the use of numerical methods. Nonetheless, the structure of the equation reveals interesting dependencies on the thermal properties. For example, in the early stages of the heating, the increase of the temperature of a surface exposed to radiative and/or convective heating as a function of time is proportional to $(k \cdot \rho \cdot c)^{1/2}$; that is, to the inverse of the square root of the thermal inertia. On the other hand, the time-dependent temperature profile within the material can be shown to depend upon the material's thermal diffusivity κ.

For materials which have very large thermal conductivity or which are very thin, it is sometimes possible to completely ignore heat conduction. In such cases, a lumped heat capacity model can be constructed whereby the entire element is assumed to be at a uniform temperature. Nonetheless, the element is still heated at the surface by radiation and convection.

Further discussion of engineering methods for modelling the thermal response of building elements exposed to fire is provided in clause 7 of this part of ISO/TR 13387 and in ISO/TR 10158.

6.3 Mechanical response

6.3.1 Role in fire safety engineering design

This subclause provides an overview of the assessment of the mechanical response of building elements and the building structure when exposed to heating from fire. This analysis is undertaken using as input data the time-dependent temperature profiles within elements which have been calculated following the procedures outlined in 6.2.

The term mechanical response is used to denote two important facets of a building element's response to fire. Firstly, it is a measure of fire induced changes to the deflection, stiffness and load-bearing capacity of the element. Secondly, it is a measure of the development of openings (cracks) in the element as a result of the shrinkage (expansion) of materials, spalling, delamination, etc.

An accurate prediction of the mechanical response of building elements exposed to fire is essential in fire safety engineering design. In the first instance, it allows for an assessment of the degree of mechanical damage that may be sustained by building elements exposed to fire. This may be particularly important if a building is to be designed so that it can be re-used following a fire. Of more immediate concern, prediction of the mechanical response of building elements is necessary step in the assessment of the potential for structural failure and/or fire spread.

Detailed discussions of the potential for fire spread are provided in 6.4. However, it should be noted that for some applications an assessment of the thermal and, then, mechanical response of building elements coupled with well-defined performance criteria may suffice. This may be the case, for example, if a structural member can be shown to undergo excessive deflection. It may also be the case if it can be assumed that the spread of fire from one enclosure to another may occur because of openings created by the shrinkage (expansion) of materials, spalling, delamination, etc. The question of establishing appropriate criteria is briefly discussed in clause 8.

6.3.1.1 Input

As depicted in Figure 1, evaluation of the mechanical response of building elements requires the following input data from the global information bus:

— building parameters (mechanical properties of building elements, structural loads supported by building elements);

— building condition (temperature-time profile within and on the surface of building elements); and

— pressure and/or velocity (pressure distributions may have an impact on integrity and structural performance).

6.3.1.2 Output

Once the evaluation of the mechanical response of building elements is completed, the following data are passed to the global information bus:

— building condition (integrity of building elements and load-bearing capacity of building elements).

This output also becomes input for assessing the potential for structural collapse and fire spread.

6.3.2 Modelling the mechanical response of building elements

As indicated in 6.3.1.1, to model the mechanical response of individual building elements or of the building structure, the time-dependent temperature profiles within the elements are necessary. Although it is likely that in a fire safety engineering analysis these profiles will have been calculated following the procedures outlined in 6.2, such profiles are also available in graphical form for some elements exposed to the standard temperature-time curve defined in ISO 834-1 and for certain simulated natural fires.

The mechanical properties of a building element, such as its modulus of elasticity or its yield stress, can be both temperature and thermal history dependent. Assessment of the structural response (in particular, assessment of thermal expansion, deflections or load bearing capacity) is often undertaken by incorporating the mechanical properties of materials at elevated temperatures into traditional (room-temperature) structural analysis (see reference [4]). The assessment of the structural response of building elements exposed to fire is described in detail in ISO/TR 10158.

Modelling the integrity of building elements, that is, the development of openings (cracks) in an element as a result of the shrinkage (expansion) of materials, spalling, delamination, etc., is not very advanced. In fire safety engineering calculations, this behaviour is often inferred on the basis of the element's performance in the standard fire resistance tests.

6.3.3 Effect of continuity and restraint

In modelling the mechanical response of load-bearing building elements, the restraint conditions experienced by elements must be properly treated.

Most fire resistance furnaces suffer limitations on the size of specimen that may be tested and the arrangements for imposing loads. Hence it is generally only possible to test specimens with idealized end conditions. Testing standards recognize this fact. In fire safety engineering calculations, structural elements need not be treated in isolation from one another so that the mechanical response of the member will be influenced by the effects of continuity and restraint from the surrounding structure.

Structural continuity allows redistribution of loads in the event of fire, which enhances the performance of the individual element. While restraint may not significantly alter the ultimate load-bearing capacity of the element under fire exposure, it will generally reduce its deflection. Full (or 100%) restraint allows large forces to develop in heated members due to restrained thermal expansion. Such forces which are often referred to as “thermal thrusts” can induce failure. However, restraint is generally beneficial. For example, in ISO 834-1 tests, the optimum fire resistance of flexural concrete members have been observed when tested under imposed end restraints of between 20 % and 80 %.

Restraint has two effects on the performance of columns in fire. Firstly, the resistance to free thermal expansion generates compressive forces within the column which reduce the rate of strength and stiffness loss at elevated temperature. Secondly, the failure mode of restrained columns may change from being a sudden buckling collapse to being one of progressively increasing deformation where load-bearing capacity is limited by strain capacity.

A further matter for consideration is that thermal gradients through the thickness of heated structural members can generate internal stresses as the thermal expansion of the hotter edge fibres is restrained by the cooler core. The magnitude of such stresses is dependent on the thermal properties of the material being heated. The effect is of particular concern for concrete members where high local surface stress levels can result in explosive spalling.

The mathematical representation of the behaviour of building structures exposed to fire needs more research and validation.

6.3.4 Structural failure

An important feature of design for fire safety is to ensure that structural failure does not threaten the safety of occupants and firefighters, or compromise other fire safety objectives. Building regulations often rely on structural fire resistance requirements to prevent (or delay) structural failure.

Structural failure occurs when a building element (or structure) is no longer able to sustain applied actions (loads) when exposed to fire. Its load-bearing capacity has been compromised to the point that the element collapses or experiences excessive deflection.

Before the potential for structural failure can be determined, an assessment of the mechanical response of building elements (or structures) exposed to fire must be undertaken following 6.3.2. Of particular interest are the fire induced changes to the deflection, stiffness and load-bearing capacity of the elements. Knowledge of the mechanical response of building elements coupled with well-defined performance criteria allow for a determination of whether structural failure will occur. The question of establishing appropriate criteria is briefly discussed in clause 8.

6.4 Fire spread

6.4.1 Role in fire safety engineering design

An important feature of design for fire safety is to ensure that the spread of fire does not threaten the safety of occupants and firefighters, or compromise other fire safety objectives. National building regulations often rely upon compartmentation to prevent (or delay) fire spread within a building. This entails dividing a building into compartments separated from one another by building elements with prescribed fire resistance ratings. The intent of this strategy is to confine fire to the compartment of origin and to keep fire from entering the escape routes.

Fire spread within a building can occur through openings existing before the fire or as a result of a thermal insulation failure, an integrity failure or a structural failure.

Thermal insulation failure occurs when a separating element exposed to fire on one side transmits excessive heat to the unexposed side. As a consequence, fire spreads from the enclosure of fire origin through the separating element to a neighbouring enclosure.

Integrity failure occurs when a separating element exposed to fire on one side permits the passage of flames and hot gases or permits ignition into flames on the unexposed side. As a consequence, fire spreads from the enclosure of fire origin through the separating element to a neighbouring enclosure. Integrity failure may arise as the result of the development of cracks or fissures.

Structural failure occurs when a building element (or structure) is no longer able to sustain applied actions (loads) when exposed to fire. Its load-bearing capacity has been compromised to the point that the element collapses or experiences excessive deflection.

There are other mechanisms of fire spread which must be considered. Flame spread along a facade can cause fire to spread from one floor to another. Fire may spread from building to building by means of radiant-heat transfer, direct flame impingement and/or flying brands.

6.4.1.1 Input

The evaluation of the potential of fire spread depends on the thermal and mechanical responses of building elements as well as any inadequacies resulting from design or poor maintenance. The evaluation depends on the following input data from the global information bus:

— building condition (temperature-time profile within and on the surface of building elements, integrity of building elements, load-bearing capacity of building elements).

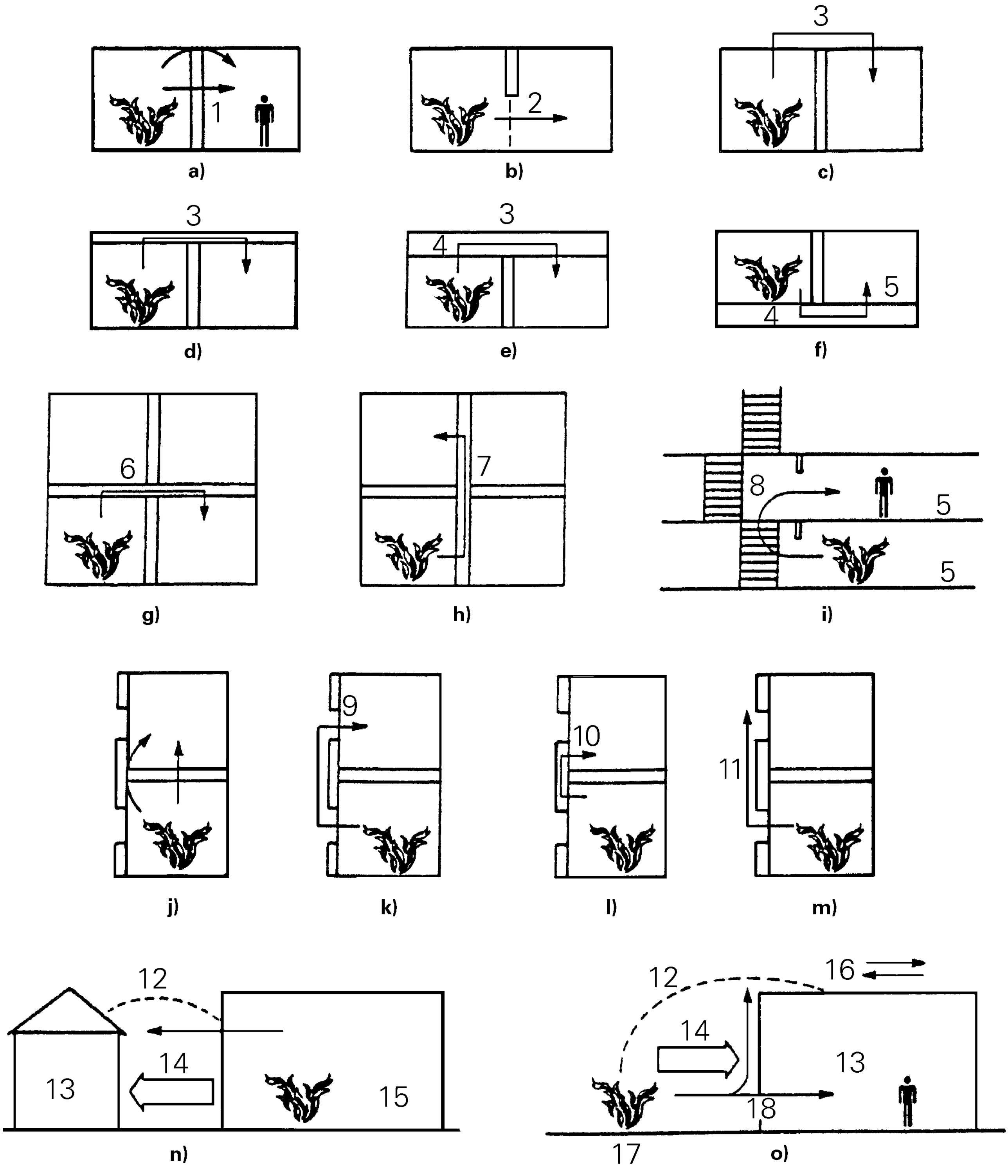
6.4.1.2 Output

Once the evaluation of the potential fire spread is completed, the following data are passed into the information bus:

size of fire and/or smoke (area involved in fire).

6.4.2 Fire spread routes

There may be several possible routes by which fire may spread and due attention should be paid to each. Examples of some major and frequently occurring fire spread routes are illustrated in the diagrams shown in Figure 2. The following notes relating to each of the diagrams are intended to clarify these routes and, where appropriate, the factors affecting them. The separations depicted in Figure 2 represent real assemblies complete with service penetrations for wiring, piping, etc. These assemblies may or may not be fire-rated.



Key

1 Wall
2 Wall opening
3 Roof
4 Void
5 Floor
6 Horizontal duct
7 Vertical duct
8 Shaft (lifts, staircases, etc.)
9 Window
10 Façades
11 Surface of façades
12 Flying brands
13 Exposed building
14 Radiation
15 Exposing building
16 Wind
17 External fire source
18 Flame spread

Figure 2 — Some frequently occurring fire spread routes

Figure 2 a): fire may spread:

a) directly through a wall by failure of integrity or of thermal insulation, or

b) between a wall and adjoining element (for example, a ceiling) through gaps which may be present before the fire or which develop because of the incompatibility of movement of the elements during fire.

Figure 2 b): fire may spread from one enclosure to another through an area of lower fire resistance (such as a door or damper).

Figure 2 c): fire may spread from one enclosure to another by breaking through the roof due to collapse or massive loss of integrity and entering the next enclosure by downward penetration caused for example by

a) radiation from flames above the roof,

b) fire spread across the upper surface of the roof, or

c) falling flaming molten or burning materials.

This mechanism can include fire spread through skylights.

Figure 2 d): fire or hot gases may penetrate into the roof construction and spread within the construction to the next enclosure by, for instance, combustion or melting of the core material.

Figure 2 e): fire or hot gases may penetrate into the void above the ceiling and pass to the next enclosure. This mode can occur where the wall does not penetrate above a suspended ceiling.

Figure 2 f): fire may penetrate the floor (which may be a raised floor to accommodate services), bypass the wall, and enter the next enclosure.

Figure 2 g): fire may enter a duct allowing fire to spread horizontally to a neighbouring enclosure.

Figure 2 h): in a similar fashion, fire may spread upwards inside a vertical duct. Such upward spread may be influenced by buoyancy and/or stack effects.

Figure 2 i): fire may spread to upper floors by entering a shaft containing, for example, a lift or staircase.

Figure 2 j): fire may spread directly through a floor by failure of integrity or of thermal insulation, or between a floor and adjoining element (for example, a wall) through gaps which may be present before the fire or which develop because of the incompatibility of movement of the elements during fire.

Figure 2 k): fire may spread to an upper level via windows or other openings in the external wall. Flames (and hot gases) from the lower window and/or opening may be of such a length and severity to produce a heat flux sufficient to cause ignition of materials at an upper level. This can happen without the contribution to flame spread from combustible materials on the facade surface [compare with Figure 2 m)].

Figure 2 l): fire may spread behind or within a facade and then to an upper level.

Figure 2 m): combustible material on the surface of the facade may propagate flames vertically up the building. This route assumes that flames have emerged from the window or another opening in the external wall of the lower room.

Figure 2 n): fire may spread from building to building by means of radiant heat transfer, direct flame impingement and/or flying brands.

Figure 2 o): a fire outside the building may spread to the building via the mechanisms described in Figure 2 n).

The effects on the building of the heat impact associated with the fire spread routes shown in Figure 2 are not always amenable to calculation. It is often necessary to rely on test data. For example, tests may be appropriate for routes shown in Figure 2 c) through 2 j) (bypass routes), 2 l) and 2 m). The effects of the heat impact associated with routes shown in Figure 2 a) (direct), 2 b), 2 n) and 2 o) can usually be calculated.

When using Figure 2, engineering judgement is effective in assessing different possible fire and/or smoke routes. An event tree analysis (see ISO/TR 13387-2) can help find the probabilities of failure routes in fire barriers. Statistical data from real fires are needed to estimate the different failure rates.

6.4.2.1 Fire spread (enclosure to enclosure)

Fire spread from enclosure to enclosure can occur through openings existing before the fire commences. Such spread is more appropriately addressed by SS1.

Fire spread from enclosure to enclosure can also occur as a result of thermal insulation failure, integrity failure or structural failure of the building element separating the two enclosures. Calculation of the thermal and mechanical condition of the separating element following 6.2 and 6.3 provides input data needed to make an assessment of the likelihood of fire spread.

For example, thermal insulation failure can be considered to have occurred if the thermal analysis predicts that the temperature on the unexposed side of the separating building element exceeds a critical temperature.

Integrity failure can be considered to have occurred if the thermal analysis predicts openings have developed in the separating building element because of the melting of materials or the mechanical analysis predicts that openings have developed due to the shrinkage (expansion) of materials, spalling or delamination.

Structural failure can be considered to occur if the thermal and mechanical analyses predict the separating building element (or another element which supports it) is no longer able to sustain the applied actions (loads).

6.4.2.2 Fire spread (exterior routes)

Figure 2 k) and 2 m) identify routes for fire spread from floor to floor along the exterior of the building. In both cases, fire has destroyed windows and flames project through the window. Buoyancy and entrainment of air will cause these projected flames to be in contact with or, at least, in close proximity to the facade above the window.

The vertical and horizontal components of this flame projection depend upon the rate of burning within the enclosure, and the dimensions of the window. If the shape of the flames has not been determined by SS2 it can be estimated using simple correlations (see reference [5]).

A calculation of radiative and/or convective heat transfer from the projected flame to the facade together with the properties of the facade will determine whether it will ignite and spread flame vertically to the next storey.

A calculation of radiative and/or convective heat transfer from the projected flame to (through) the window on the next storey will determine whether fire can break into the next storey even if the facade is not combustible.

It should be noted that exterior steel columns which form part of the structure of the building can also be heated by direct flame impingement or by radiation. An engineering analysis of heat transfer to these columns can be undertaken in a fashion similar to that for the facade itself.

6.4.2.3 Fire spread (building to building)

Figure 2 n) identifies routes for fire spread from building to building. Fire may penetrate the external wall of a building as a result of the failure of the glazing or burn-through of areas of low fire resistance. The amount of emitted radiation may be sufficient to cause piloted ignition (with the assistance of flying brands) or spontaneous ignition of materials on the outside or inside of an exposed building nearby. Fire spread between buildings in this way can be modelled from a knowledge of the emitted radiation intensity, the configuration factor and the ignitability of materials exposed on the neighbouring building (see reference [6]).

There is little technical guidance available on the spread of fire by flying brands in the absence of radiation. The size of brands generated depends upon the size of the fire in the burning building. It is likely that small brands go out (extinguish) while “flying” and large brands fall to the ground before “flying” far. This means the greatest danger is from medium brands which may “fly” some distance while still burning. The risk of ignition of combustible materials on a neighbouring building can be assessed based on:

— the size of the brands;

— the trajectory of the brands; and

— local cooling conditions.

7 Engineering methods

7.1 General

A number of practical engineering methods (see reference [7]) have been developed to predict the thermal and mechanical response of building elements exposed to fire and hence to assess the potential for fire spread within and between buildings, and to predict the response of structures exposed to fire. The purpose of this clause is to give general guidance on the selection, use and limitations of engineering methods. The types of methods considered below include estimation formulae, computer models and experimental methods.

If a mathematical model (estimation formula or computer model) is selected for an application, it should be assessed and verified using the principles documented in ISO/TR 13387-3. This should aid in evaluating the limitations of the model. Furthermore, special care should be taken when using input data published in the literature. The quantitative information may be related to specific test conditions and/or specific commercial products, and the application of the data under different conditions may result in significant errors.

7.2 Estimation formulae

Estimation formulae (or hand calculations) are often derived from an analysis of highly simplified physical situations or are empirical correlations based on experience or test data. They can be used to check the results of computer calculations, for preliminary calculations, or if detailed computer calculations are unnecessary or unavailable.

Estimation formulae for predicting fire spread between enclosures are generally based on the standard fire resistance test ISO 834-1, and are therefore only applicable to conditions similar to those in the test. The component additive calculation procedure for assessing the performance of wood-frame assemblies is a typical example (see reference [8]).

The shape of a flame projecting through a window can be estimated by hand calculation (see reference [5]). A calculation of radiative heat transfer from the projected flame to the window on the next storey will determine whether fire can break into the next storey.

The potential for fire spread from building to building due to radiant heat transfer is also amenable to hand calculation. The potential for fire spread can be calculated from knowledge of the emitted radiation intensity, the configuration factor and the ignitability of materials exposed on the neighbouring building (see reference [6]).

7.3 Computer models

Computer models which predict the thermal and mechanical response of building elements exposed to fire are simply mathematical representations of the physical and chemical behaviour that constitute fire processes. Some of the most important factors governing the predictive capabilities of computer models include the level of the assumptions and simplifications of the physical and chemical processes that constitute the models and the data that must be input at the start of the calculations. As a general rule, a thermal model is first run to calculate the temperature-time profile within elements. This output from the thermal model becomes input for the mechanical model.

The governing heat transfer and solid mechanics equations that form the basis of these computer models typically require a numerical solution using either finite element or finite difference methods. Finite difference methods are used in problems with simple geometry and reasonably homogeneous materials. For more complex geometries and for heterogeneous materials, finite element methods are advisable.

A more detailed discussion of computer models which predict the thermal and mechanical response of building elements is found in ISO/TR 10158 and in the literature (see reference [7]).

7.4 Experimental methods

Over the years, the fire-resistance ratings of many building elements have been determined by subjecting specimens to the standard fire resistance test ISO 834-1. Listings of fire-resistance ratings are useful when demonstrating compliance with prescriptive regulations. Such data may also be useful for fire safety engineering analyses. For example, the fire performance of building elements in real fires can be inferred from knowledge of their fire-resistance rating together with a model for representing a post-flashover fire as a standard fire of "equivalent" duration (see ISO/TR 13387-2). This approach can be particularly useful for building elements for which estimation formulae and computer models are not available. For example, detailed computer simulation of the performance of dampers exposed to fire requires modelling both 3-D heat transfer and the deflection of blades, and is beyond the capability of current models.

Other practical information has been derived by subjecting building elements to the standard test ISO 834-1. For instance, thermophysical property data can be inferred from thermal resistance data measured during fire tests. For some products, such data may be the best high temperature data available for the use in fire models.

Care should, however, be exercised when applying the results of a fire resistance test to a construction which is larger than the test specimen. An example is a specimen which is susceptible to thermal bowing at elevated temperatures. Thermal bowing of a specimen 3 m high may have negligible effect on the structural stability of the specimen in a furnace test. In a similar construction two or three times higher (i.e., 6 m or 9 m high), thermal bowing is a factor of four or nine times greater, respectively. This greater thermal bowing can lead to instability especially in tall fire walls in single-storey buildings which can be 30 m high. Guidance for the application and extension of fire resistance test results is provided in ISO 12470.

For some applications it may be desirable to design an ad hoc test to assess the thermal and mechanical response of separating or load-bearing elements. Whether the scenario of interest involves a localized fire or a post-flashover enclosure fire, every effort should be taken to ensure the thermal exposure in the ad hoc test is representative of that expected in the actual facility. For a post-flashover fire, the fire load, physical scaling, thermal properties of surface finish and ventilation conditions should replicate those in the facility of interest. Guidance for conducting ad hoc enclosure fire experiments is provided in references [9] and [10].

8 Guidance for setting criteria

Care must be taken in selecting acceptance or failure criteria. Such criteria may be quite different for fire safety engineering design than for design employing prescriptive regulations.

For example, fire resistance is an important property affecting fire spread and is often referred to in national regulations. Fire resistance criteria are concerned with thermal insulation, integrity and load-bearing capacity (stability). These criteria may need to be reconsidered in a fire safety engineering assessment. The thermal insulation and integrity criteria for an external wall attacked by fire from inside the building can be relaxed making them less onerous depending upon the fire risk near the external wall. For instance, if the external wall is acting as a flame shield (in order to prevent radiation emitted from the external wall from causing ignition of a nearby building) it may be onerous and unnecessary to adopt the traditional fire-resistance thermal insulation criterion which requires that the unexposed face of the construction should not experience a temperature rise of more than 180 °C at any point: a higher temperature can be accepted if radiation is the primary consideration. Again, it may be onerous to apply the standard integrity criterion chosen to prevent ignition of stored goods in contact with or very close to the unexposed face if the external wall is spaced away from buildings nearby. In such cases the size of holes (or temperature of the unexposed surface) which can be tolerated could be calculated from a knowledge of the acceptable level of radiation intensity incident on the exposed risk, the configuration factor and the level of emitted radiation intensity.

It is common to express the thermal insulation criterion for a separating building element in terms of a temperature rise on the unexposed side of the element. In fire safety engineering calculations, the criterion in ISO 834-1 may be considered to be too stringent. Instead, the ignition of materials in contact with or even some distance from the exposed side of the element, which may occur when they reach their piloted-ignition temperature, can be adopted as the measure of excessive heat transmission. On the other hand, for some applications, the criterion in ISO 834-1 may not be considered sufficiently stringent. For example, if the separating wall is intended to protect magnetic tapes from excessive heat transmission, a temperature rise criterion well below that employed in ISO 834-1 may have to be selected.

In prescriptive building regulations, the criterion to prevent fire spread from building to building by radiation is often expressed implicitly in terms of heat flux. For example, there may be a requirement for combustible materials on the facade of the exposed building not to experience a heat flux greater than the critical radiant heat flux for the ignition of wood. In fire safety engineering calculations, this criterion may be considered to be too stringent. If, for example, superlative firefighting capabilities are at hand or if the facade has much better ignition resistance than wood, a moderately higher heat flux at the facade of the exposed building may be acceptable.

For fire safety engineering calculations, the structural failure criteria in ISO 834-1 may not be considered reliable, but should instead be tailored for a given application. Such criteria can be expressed in terms of a critical temperature rise, load-bearing capacity, thermal expansion or excessive deflection. The deflection criterion, in particular, needs to be carefully selected for large-span flexural elements. It is important to recognize that, what is regarded as structural failure or limit of deflection in the fire resistance test, can be significantly different in real structures. In this context, the interaction of large beam deflections on the stability and/or integrity of compartment walls must be considered as an integral part of the analysis.

Finally, criteria for fire spread from storey to storey can be expressed in terms of one or more of the following:

— a critical heat flux though the upper storey window (with or without glass) which prevents ignition of combustibles;

— a critical temperature which prevents breakage of the window on the upper storey;

— a critical flame length which prevents exposure of the upper window; and

— a critical heat flux which prevents flame spread on the facade.

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