RATIONAL FIRE SAFETY ENGINEERING APPROACH TO FIRE RESISTANCE OF BUILDINGS

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TO
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CIB W014

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PREFACE

The great progress of fire research during the last decades of the 20th century has made it possible to treat fire as a phenomenon governed by the same laws of nature as other physical and chemical phenomena. The *art* of fire has been changed to *science* of fire.

Recent research results have been turned into design tools with which engineers can assess the consequences of fire in different scenarios. Recent changes in building regulations in many countries have begun to allow a performance-based approach to fire safety design.

Despite the general trend towards rational design for fire safety, the regulatory systems in most countries do not encourage calculation of fire resistance, which is most often assessed only by standard tests. The fire resistance requirements for parts of buildings vary significantly and non-systematically between different countries, being based on historical development rather than science.

Fire resistance requirements often influence construction costs significantly. Excessive fire resistance is an unnecessary cost. The recent development of fire safety engineering and the trend toward performance based fire regulations open up new possibilities for optimising building design without compromising safety.

In the mid 1990’s, CIB W014:Fire formulated a Work Programme with clear objectives to support the development of fire safety engineering in performance based fire regulations. To meet the objectives, several projects have been initiated, workshops arranged, and conferences co-sponsored. After the highly successful First International Conference on Performance Based Codes and Fire Safety Design, held 24 - 26 September 1996 in Ottawa, Ontario, Canada, it was recognised that there was a need to take a fresh look at the issue of fire resistance in buildings. As a consequence, CIB W014:Fire decided to establish a Sub-Group " *Guidance for a Rational Approach to Fire Resistance"* under the leadership of Dr Joel Kruppa of CTICM, France.

This document **"Rational Fire Safety Engineering Approach to Fire Resistance of Buildings"** is a result of team work with a large number of CIB Members and non-members. The document has been written by the following individuals:

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A large number of other members of CIB W014 have supported the work by reviewing the drafts and participating in the discussions during the Sub-Group meetings.

The document is aimed at helping all interested parties, including regulators, architects, design engineers, and construction companies, to increase their understanding of what fire resistance is really for and how it can be assessed. This document is by no means "the last word" on fire resistance. The ongoing research on this topic will increase our understanding leading to better regulations and new tools for engineers.

Matti Kokkala
Co-ordinator of CIB W014: Fire

1. INTRODUCTION

Modern architecture continues to evolve in pursuit of spatial function and users needs. Buildings are no longer designed as a series of rooms connected by a circulation route, and it is common to see open spaces linked vertically and horizontally through the full extent of a building. The role of fire resistance in the building regulations has not been keeping pace with these developments, particularly where extensive internal landscaping of building is concerned.

The traditional view of "fire resistance" being provided by static and robust “passive” elements must be extended to a complementary relationship with “active” fire protection measures, to provide safety in real buildings in real fire situations.

This document - **'A Rational Fire Safety Engineering Approach To Fire Resistance in Buildings '** - presents pre-normative technical guidance which is intended to appeal not only to experts, specialists, practitioners, regulators and controllers in the fire community, but also to other professionals working in mainstream building design and construction.

Many people involved in the process of design, construction, or maintenance of buildings, view compliance with fire safety legislation merely as an obstacle to be overcome with minimum cost and effort. Legislation for fire safety in buildings varies greatly from country to country, and is sometimes not effectively monitored or controlled due to lack of resources. The scope of the legislation also varies greatly, with some jurisdictions having inadequate allowance for important matters such as property protection, safety of fire fighters, or evacuation of disabled people. It is strongly recommended, therefore, that the reader interpret the views and opinions expressed here in the context of local building practices and relevant local legislation.

A rational engineering approach for designing fire resistance is to establish clear objectives for overall fire safety, and to examine the role of fire resistance in meeting those objectives, considering all likely scenarios. The solutions should be based on principles of reason, common sense, science, engineering and practicability [1,2].

The benefits offered by such an approach include :

- the provision of better, and more reliable [3], fire safety in buildings **;**
- more cost effective safety and protection measures, and more options with regard to their choice and specification **;**
- better communication with other professionals involved in the design and construction process.

Real fires

From the outset of this approach, it must be clearly understood that reality, or the realistic end condition, is a 'real' fire in a 'real' building which is occupied by 'real' people,

The fire safety objectives should be developed in consultation with all interested parties, being aware of the limited safety objectives in prescriptive legislation, before the development of any fire safety strategy. It is only after the objectives have been clearly stated, that a cost-effective fire safety strategy can be designed which will effectively meet the requirements of the client's brief for the project.

Three aspects of fire resistance performance will be dealt with in the body of this document:

- **Fire Separation** - ensuring that a fire, including heat and smoke, cannot move, or spread, from Point A in a building to Point B within a specified time period**;**

- **Smoke Separation** - ensuring that the spread of smoke is prevented or restricted. Smoke can move very quickly over large distances in a building, including into hidden spaces and construction cavities, only to re-appear where least expected [4] **;**

- **Structural Reliability** - ensuring that the structural system of a building continues to operate effectively for the full duration of a fire, and for a minimum period thereafter [3].

Reliability

To achieve improved levels of fire protection for people who may have to remain in a building for longer periods during a fire, one issue which is becoming increasingly critical is that of 'reliability'. The following are some questions which influence performance reliability, and should be taken into account by a fire safety engineer in the detailed development of a fire safety strategy:

(i) Can we confidently depend on an installed product, component or building system to perform as expected whenever a fire may occur, at any stage in the life cycle of that building [5, 6]?

(ii) Precision of fire test methods - a fire performance rating obtained in one test laboratory may be different to those obtained in another laboratory for the same component [7]?

(iii) Installation alterations on site. Have any changes been made to a product since originally tested ? Have any of the fixing details been altered ? Have any changes been made on site in order to ensure a good fit ? If assemblies do not fit, how have resulting larger gaps and clearances been handled by the building contractor ?

(iv) Workmanship - is it good, bad or ugly ? Has it been competently supervised, or not ?

(v) Has an installed product been interfered with by other trades at later stages in the construction process ?

(vi) Servicing and maintenance - will any be carried out, by somebody competent to do so ?

(vii) Could there be improper use or abuse of materials by the building's occupants?

(viii) What information is available about the management system, personnel, and reporting relationships in a building ? Are they effective / efficient / competent ?

The answers to these questions can be, to some extent, taken into account using a probability based fire safety engineering approach. Reliability Based Structural Fire Design is discussed in chapter 9.

2. DESIGN PROCESS

2.1 GENERAL

In traditional design in a prescriptive regulatory environment, fire safety is usually achieved by designing various components in isolation. The building layout must usually meet certain requirements, such as maximum compartment size and minimum/maximum dimensions of the exit routes. The building fabric, structural elements and other building components only have to meet prescriptive requirements. Any possible interactions between different fire protection measures are not considered, unless explicitly allowed as acceptable trade-offs (alternative prescriptive solutions).

Fire resistance can be included in the design process in one of two ways:

- The method promoted in this Report is to establish the appropriate fire resistance requirements by considering the actions and acceptable consequences of various fire scenarios.
- The traditional method is to design the structure to meet code-specified fire resistance requirements without considering the effects of possible real fires

2.2 PROCESS DESCRIPTION

Figure 2.1 depicts a performance-based fire safety design process. The presentation here is a modification of that by SFPE [8], which in turn is building on the earlier works in Australia [9, 10], New Zealand [11], UK [12], and ISO/TC92/SC4 [14]. The process is described for the case where the fire safety engineer has an active role.

In many current designs, the fire safety engineer is only involved in parts of the process and has no interaction with decision making, even if it significantly influences the subsequent fire safety measures. The sooner the fire safety engineer is included in the design process, the larger the potential benefits, such as the possibilities for optimising the quality and cost of the fire safety measures.

(A) The project scope defines the purpose of the building, which affects many items such as size, compartmentation, characteristics and number of occupants, type and amount of fire load. The project scope also limits the design budget and time available to do the work. The traditional prescriptive fire safety requirements can in most cases be established from the specification of this phase.

(B) The fire safety engineer normally enters the design process after the draft plans have been prepared. The first step in the fire design is to clarify the goals and fire safety objectives (see Chapter 3). This often requires consultation with a number of interested parties, including the building owner or developer, the users of the building, the relevant authorities, and the rest of the design team.

(C) After agreeing on the fire safety objectives, the fire safety engineer needs to develop a fire safety strategy in consultation with the other interested parties. The strategy may be based on passive fire protection, (including compartmentation, separating elements fire-resisting load-bearing structures, and materials with limited combustibility) or active fire protection measures (including suppression and detection systems), or a combinations of active and passive fire protection. The role of the occupants and fire fighters also need to be considered, as well as any special requirements emerging from safety legislation other than the building regulations (e.g. safety at work place).

(D) Once the fire safety strategy has been agreed on, the performance requirements and acceptance criteria must be quantified. The performance requirements, including legal requirements and other requirements specific to the particular project, will be based on tolerable risk for people and property, in the case of the worst credible design fire scenarios. There is an interdependency between the engineering design methods to be used and the quantitative acceptance criteria. The safety factors or the safety margins may be determined only after the design methods have been selected.

(E) A crucial step in the fire safety design is the selection of design fire scenarios. The ignition time, location, growth rate, ventilation conditions, number of people threatened, etc. need to be established for a suitable number of scenarios specific to each project. The scenarios are selected by the fire safety engineer, in consultation with other relevant experts (insurance, fire service, experts on the operation of the building in use). Depending on the size and type of the project, this may be done through systematic risk analysis or expert judgement and experience from other similar projects.

(F) With the architect's design and the constraints set by the other interested parties as a starting point, the fire safety engineer develops a design proposal. The fire safety engineer should confirm that the suggested solutions in the design proposal are acceptable to the developer, the user of the building and the architect, before starting detailed design. As in other fields of engineering, the greater the expertise of the fire safety engineer, the better optimised the first design proposal should be, and the less work that is required during the following stages of the process.

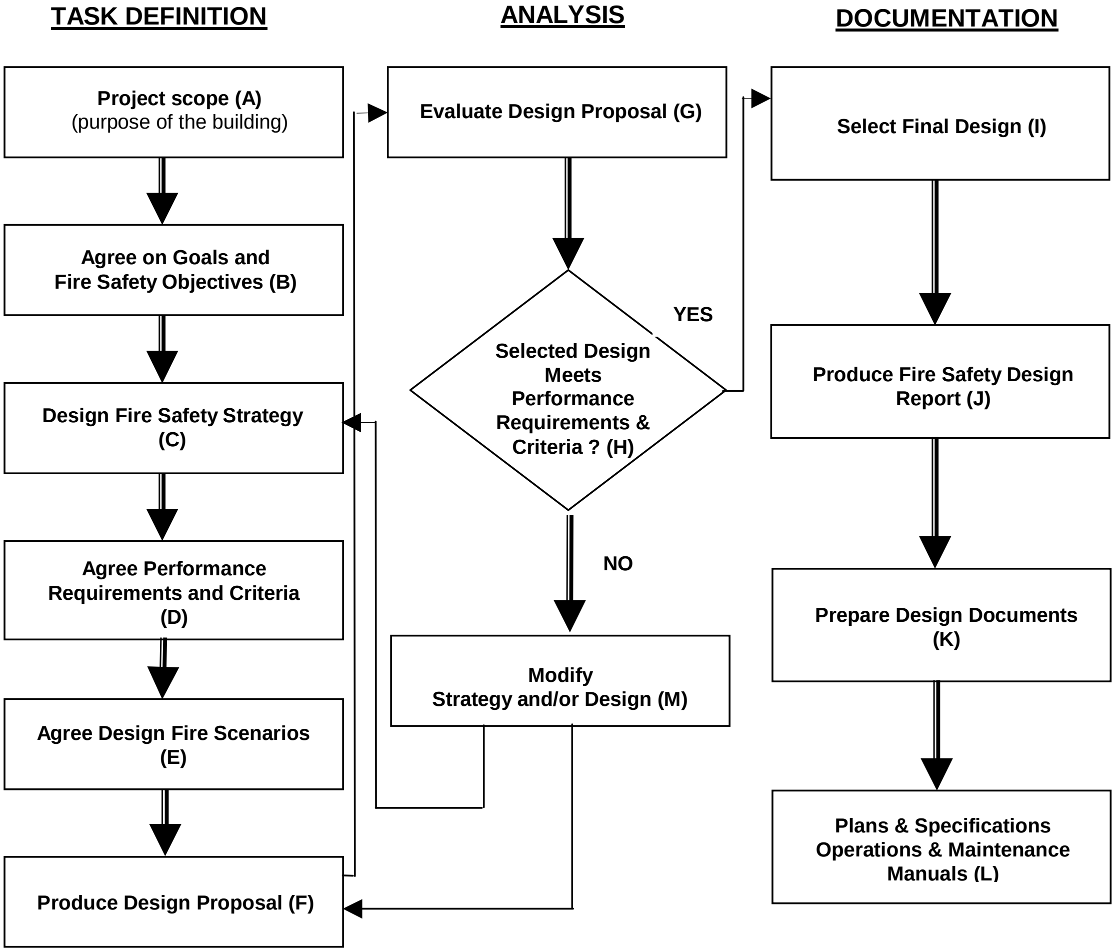
(G) The design proposal is then analysed quantitatively. For each design fire scenario, the fire safety engineer assesses the consequences, i.e. the fire environment as a function of time, the time for the conditions to become threatening or untenable, evacuation of the occupants, and performance of active and passive fire protection. There is also a need to consider, whether the initial assumptions about the design fire scenario are realistic. Assessment of the reliability of various fire protection measures, and the consequences of failure of critical components also form part of the evaluation of the design proposal.

(H) As the quantitative assessment is being completed, the results are compared with the criteria agreed earlier. If the criteria are not met, there are two alternatives ways for proceeding. When the source of nonconformity is evident, the design may be changed to remove the problem, e.g. if the evacuation time has been found to be too long due to too narrow stairs, a solution may be to make the stairs wider. If no evident reason exists, the whole fire safety strategy may need to be revisited. After the alterations have been made, the assessment is repeated until the proposed design meets the performance requirements and acceptance criteria.

(I) Once the final design has been selected, the fire safety engineer produces a fire safety design report,

(J) documenting the assumptions made and identifying any possible constraints for future renovations. The fire safety engineer, in co-operation with the rest of the design team, prepares the final design documents (K), which will form part of the plans and specifications for the construction team, and also the operation and maintenance manuals (L) for the building users.

Figure 2.1 : Overview of the Performance-Based Fire Safety Design Process



2.3 ROLE OF DIFFERENT PROFESSIONALS

Since fire safety engineering is a new field of expertise, it is highly recommended that the fire safety engineer will have a continuing key role during the construction of the building. Even small alterations may introduce a threat to fire safety causing a loss of the value of the agreed investments in fire safety.

Modern fire safety engineering design is an integral part of the entire building design process from the conceptual phase to the supervision of related construction. The fire safety engineer not only needs to design the building for a given range of fire scenarios, but also needs to consider the possible feedback of the proposed building design on the fire scenarios. Understanding the interactions between all possible fires with the building layout and building services requires a specialised knowledge of fire phenomena and behaviour of construction products. A specialised group of fire safety engineers has emerged with the capability to provide this knowledge to the rest of building design team.

The architect typically first makes a draft design of the building based on the owner's objectives. As the building design evolves, with the input of the structural engineer and the building services engineer, the fire safety engineer selects and designs appropriate components of a fire safety system to satisfy the functional fire safety objectives. The fire safety engineer may significantly influence the design of the building by proposing alternatives to the building services or the building layout to achieve the fire safety objectives. It is important for the fire safety engineer to be involved in the early stages of the design process.

Selecting or designing the structures or structural elements is typically handled by structural engineers. Assessing the fire severity and quantifying the fire resistance requirements should be the task of a qualified fire safety engineer. The fire resistance requirements may be greatly influenced by the building layout and other fire protection measures. The reliability of passive fire protection, including fire resisting construction, also needs to be considered [13].

In addition to the fire safety requirements, the design also needs to meet the functional, aesthetic and economical requirements of the owner, and other essential requirements imposed by the authorities. . Prescriptive fire resistance requirements often add a significant cost to the structures and, therefore, a common task of a fire safety engineer is to develop alternative designs which provide sufficient safety without increasing the cost, possibly by changing the layout or adding other innovative fire safety features.. There may be cases, where the acoustic insulation requirements or the requirements for other loads already guarantee sufficient fire resistance without further action.

3. FIRE SAFETY OBJECTIVES

A rational system for fire safety design of a building requires the safety objectives to be identified explicitly. Fire safety objectives identified for a specific project must also be the basis for the specification of the fire resistance properties of the separating or load-bearing structural elements. Fire resistance is usually necessary but it is not the only method available to meet fire safety objectives. Cost-effective construction normally requires a balanced use of various strategies.

The fire safety objectives which need to be addressed in design of a building may be related to the safety of life, property, environment, cultural heritage or social activity [14]. A different set of objectives may apply to each building depending on the use, location and available resources. The five categories of objectives are discussed in more detail below.

3.1 PROTECTION OF HEALTH AND LIFE SAFETY

Life safety is often the primary goal of fire safety design. A long term trend throughout the world is the increasing value of human life, so life safety issues must be considered with special care. Life safety objectives are typically divided into the safety of occupants and the safety of fire-fighters.

a) The health and life safety of occupants in case of fire

All buildings must be designed so that in the event of fire, the occupants can either remain in place, evacuate to another part of the building (place of relative safety), or totally evacuate the building without being subject to unhealthy, hazardous or untenable conditions. The life safety requirement applies both inside and outside of the building.

Usually, the building designer only needs to be concerned about the safety of people remote from the point of ignition, because the ignition seldom occurs within the building structure or fabric but normally within the contents of the building. The main purpose of fire resisting structures is to limit the damage in the case where the fire grows big enough to threaten parts of the building outside the compartment of fire origin.

It is apparent that historical development has been based on the need to prevent multiple death fires. Even today society is much more tolerant of fires with single, or only a few casualties, than of fires with tens of casualties and a rational approach to fire resistance must recognise this societal goal. Special groups of people may need additional protection. Permanently or temporarily disabled people are not expected to be able to evacuate with the same speed as the majority of population. A defend-in-place strategy may need to be adopted. Small children need assistance and more time even if assisted.

Designers should also note that life safety requirements may appear in different legislation. Especially in Europe, the legislation covering safety at work may require an assessment of fire safety.

b) The safety of fire-fighters

Fire fighting is an essential component of fire safety strategies in practically all countries and local communities. Fire-fighters are expected to assist in evacuation where necessary, to effect rescue, and to prevent extensive uncontrolled spread of fire.

Even though fire-fighters may be prepared to take higher risks than the building occupants, an appropriate level of fire protection must be provided for them to carry out their task as expected. Appropriate fire resistance levels are needed to facilitate safe fire fighting for the purpose of controlling the fire, even if the expected time needed for evacuation would be short. Sudden changes in the exposure conditions should be prevented. Progressive collapse both inside the building and outwards from the building should be prevented during the time required for fighting the fire.

Political decisions may dictate that fire fighting be not considered when designing buildings for fire safety. For example it may be decided to limit the cost of construction in remote places,or a community may not wish to provide a specified level of fire service protection for each building, even though the same jurisdiction may demand that the safety of fire fighters be taken into account.

3.2 PROTECTION OF PROPERTY

Protection of property from fire damage is an essential part of the well-being in every society. Most societies expect a minimum level of property protection even though it may not be explicitly mentioned in the building codes. For commercial reasons, property protection requirements may be increased to a level where the owner (with the aid of insurance companies) is assumed to be able to bear the consequences of the potential losses.

The property protection objectives may be divided into the following groups :

a) Protection of the structure and the fabric of the building

The goal of protection of the structure and the fabric of the building is to limit any fire damage so that the building could be repaired and reconstructed in the shortest possible time and with minimum cost. A common functional requirement is to ask for the building to be designed to resist the whole duration of an uncontrolled fire. The objective behind this requirement may be either to make the rebuilding easier, or to protect fire fighters and others in the vicinity of the fire.

b) Protection of the contents of the building

In many cases, the value of the contents of the building is much higher than the value of the building itself. Therefore, for example, insurance companies pay special attention to the protection of the contents. The indirect consequences need also to be considered.

c) Protection of property in the immediate vicinity of the building

Society is generally less tolerant to damage caused to somebody else’s property. Therefore, the protection of property in the near vicinity, i.e. adjacent buildings and facilities, needs to be considered.

d) Protection against business interruption

In the modern world , the cost of business interruption may be much higher than the cost of direct damage to the contents and the building itself. A large high-tech company may not be able to deliver product for several weeks after a fire in a critical production plant causing permanent loss of market share.

e) Protection of public image

In many fields of industry, a good public image is essential to success in business. A fire loss may damage public image and lead to detrimental long term consequences. For example, a fire in only one hotel of a large international company may tarnish the image of the whole company, impacting on hotels which operate in a completely different cultural environment and under a different regulatory system.

3.3 PROTECTION OF ENVIRONMENT

Although many of the long term consequences of the environmental impact of fires may not be well known, the societal goal to avoid these consequences is becoming more apparent. The objectives of environmental protection in case of fire may be divided into two main groups as follows, bearing in mind that the best way to reduce the environmental impact is to prevent ignition, or to suppress small fires.

a) Minimised impact on the environment caused by release of hazardous fire effluent to the atmosphere

In most fires, large amounts of gaseous and particulate effluent are released into the atmosphere. The main combustion products of water, carbon dioxide and carbon monoxide are not a serious hazard but the effluent may contain other substances with long-term effects on the biosystem. Fire resisting separating elements are one means of limiting the size of the fire by confining it to a predetermined space in the building, thereby limiting the production of hazardous effluents and their spread to the environment.

b) Reduction of hazardous solid or liquid waste at the site of the fire

In fires there are often serious releases of possibly hazardous solid or liquid fire residues to the ground or to the waste water system, which may consequently damage the ground water or nearby lakes or rivers. Wastewater can be contained and treated if a bunded water-collection area is available around the building. Solid combustion residues may become a problem if they contain substances with long term environmental impact. Limiting the maximum size of the fire will influence the requirements for the capacity of the wastewater reservoir.

3.4 PROTECTION OF ARCHITECTURAL, HISTORICAL OR CULTURAL VALUES

Old buildings, and some new buildings with architectural, historical or cultural importance may have values which cannot be measured on a monetary scale. Their protection against the damage caused by fire is considered to be one of the basic moral duties of society. Often historic buildings are also of direct measurable value to the society, e.g. as places of worship or sights attracting tourists.

In engineering terms, the protection of cultural heritage may not be very different from protection of any other values. However, due to the values being expressed in qualitative terms only, the fire safety provisions need to be considered with special care.

3.5 PROTECTION OF INFRASTRUCTURE

In some cases, a fire may seriously damage systems essential to normal social activities. For example, a small fire in a telecommunication centre may cause large loss of service to critical private or business connections, a fire in a bank may cause loss of critical data, or a fire in an administration building may cause operational loss of vital public services.

With the development of increased networking, the fire protection of social activities will increase as a fire safety objective in the future and fire resisting components may have a role to play in it.

4. FIRE SAFETY STRATEGY

The following phenomena, typical of fires in buildings, may endanger one or several of the fire safety objectives identified in Chapter 3:

a. **Propagation of smoke and toxic gases within the building**
Smoke and toxic or corrosive gases can travel over long distances within a building, driven by the thermal effects and forced ventilation of a fire, depending on factors such as wind, dimensions and geometry of a building.Smoke and toxic gases may thus seriously endanger life safety and contribute significantly to property loss, especially with respect to the building contents. This can occur even with relatively cool smoke and gases from a smouldering fire or a small flaming fire.

b. **Propagation of smoke and toxic gases outside the building**
Smoke and toxic gases can emerge into the open via facades and roofs, thus endangering the environment, or neighbouring occupants. This may be particularly relevant in situations in which large amounts of hazardous materials are stored (chemical plants, industrial warehouses, etc.).

c. **Propagation of fire in terms of heat transfer within the building**
Fire spread within a building is primarily caused by the fire dynamics but can also be due to thermal/mechanical deformations and heat transfer through building components. Fire spread may greatly endanger life safety and the value of the building together with its contents.

d. **Failure of building elements, particularly if this leads to progressive collapse**
Structural failure may occur due to thermal deformations and reduction of strength and stiffness – normally resulting from heating of exposed building components. If structural failure could lead to progressive collapse, a dangerous situation may result, both with respect to life safety and property protection (building & contents).

Items **a** to **c**, above, call for performance requirements with respect to the separating function of building elements such as floors, wall, roofs and facades under fire conditions . The last item (**d**) calls for a load bearing function to be maintained under fire conditions. In many cases a combined load bearing and separating function will be required, e.g. in the case of floors and load-bearing walls.

The above phenomena are described in physical terms only. It is important to realise that they may also be affected by human behaviour, including intervention by fire services. When considering life safety during a fire, not only the regular occupants are at risk , but also visitors who are unfamiliar with the building and fire brigade personnel

Fire safety can be provided by active measures (e.g. detection, automatic suppression, smoke control) that will provide early warning or diminish the fire severity. Alternatively, or in addition, *passive* measures such as fire resistance may also provide means for meeting several of the objectives.

Limitation of damage using a strategy based on fire resistance may be divided into the following categories, with increasing time of fire resistance required, and increasing thermal exposure to the fire resistive structure:

- Resistance to spread of hot gases, to provide safe evacuation and limitation of damage to the building contents
- Resistance to spread of a localised or fully developed fire for evacuation purposes
- Resistance to spread of a localised or fully developed fire for evacuation purposes and to allow fire fighting access
- Containment of a fully developed fire for the purpose of loss reduction, with the assistance of fire fighters
- Containment of a fully developed fire for complete burnout for the purpose of loss reduction, with the assistance of fire fighters
- Containment of a fully developed fire for complete burnout without any assistance from fire fighters.

A design strategy based on fire resistance is usually considered to be more robust and to require less maintenance than a strategy based on active systems. The designed-in fire resistance performance of structural elements may, however, be easily nullified by poor workmanship or poorly sealed penetrations, or by wedging open of doors.

5. PERFORMANCE CRITERIA

When establishing performance criteria for fire resistance of building elements, it is necessary to consider all possible failure modes to agree on the relevant figures, considering the fire safety objectives. The performance criteria must take into account safety factors or safety margins (see Chapter 9).

5.1 FAILURE MODES

Propagation of smoke and toxic gases, within the building or into the open, will occur if a significant quantity of combustion products is able to pass through separating elements. This leads to the limit state condition resulting from **smoke leakage**.

Fire can spread through a barrier by thermal propagation if the temperature at the non-exposed side of the fire barrier becomes so high that combustible materials ignite, either by direct contact with the hot surface, or by radiation. This leads to the limit state condition of **thermal insulation.**

Fire spread can also occur if combustible gases pass through the barrier after the formation of cracks or gaps. This leads to the limit state condition **integrity**.

Structural failure of building elements occurs if the load bearing capacity becomes less than the actual loading, as result of a reduction in the mechanical strength of the building materials at elevated temperatures and the redistribution of the mechanical loading.As well as providing load bearing capacity, building elements need to be protected against excessive deflection, either to ensure integrity, or to allow subsequent salvage of the building. This leads to the limit state condition of **load bearing capacity**.

In a functional manner, the above limit state conditions can be defined as follows:

Smoke leakage:

Smoke leakage is the failure of an element to prevent the passage of gases or smoke from one side of the element to the other. The quantitative limit for acceptable leakage depends on the development of smoke concentration in the enclosure on the unexposed side. The propensity to leakage depends on the resistance to flow of fire effluent through the element under different fire exposure conditions. In standard tests, in which the exposure conditions are assumed to be well-defined, the propensity to leakage is usually expressed as volume flow rate (leakage rate) in units of m^3/h. Smoke flow in a standard test depends on the furnace pressure. No standardised procedures are available for alternative fire exposure conditions.

Integrity:

Integrity is the ability of a construction element with a separating function to withstand fire exposure on one side, without the passage of significant quantities of flames or hot gases to the unexposed side, thereby causing ignition of the non-fire exposed surface or any material adjacent to that surface, or leading to untenable conditions for people.

Integrity failure is characterised in a direct manner in a fire resistance test (actual penetration of combustible gases through the separating element). Integrity failure may also be characterised in an indirect manner by defining conditions under which such penetration may occur, particularly considering the dimensions of openings within a separating element or at its boundaries. No calculation methods are available to reliably predict integrity failures. Some empirical methods may be used, for example in the case of some lightweight separating walls, a lower critical unexposed temperature may be applied to predict the time of integrity failure.

Thermal insulation:

Thermal insulation is the ability of a separating element to withstand fire exposure from one side without significant transfer of heat by conduction to the unexposed side, which could either lead to the spread of fire or cause injury to people.

In a fire resistance test of a separating element, the limiting value with respect to thermal insulation is expressed either in terms of temperature reached [°C] on the unexposed side or in terms of radiation emitted from the unexposed side. Apart from the surface temperature, other factors such as the dimensions of the elevated temperature area or emissivity of the surface may also play a significant role.

Load bearing capacity :

Two kinds of limit state have to be identified.

- **Ultimate limit state**
  In the ultimate limit state, the element of construction must have sufficient load bearing capacity to withstand fire exposure, on one or more faces, for a prescribed period of time, without any loss of structural stability.

- **"Deformation" limit state** or the re-serviceability limit state
  In the deformation limit state, the fire performance of an element of construction is evaluated by considering the maximum allowed deformation, either to avoid any adverse effect on adjacent separating elements, or to reduce the cost of reinstatement after a fire. The limiting values are given in terms of deflection and rate of deflection. Distinction is made between flexural members (floors, beams, etc.) and axially loaded members (columns, etc.).

When considering the categories mentioned in Chapter 4, with increasing thermal attack on the fire resisting structure, it is possible to identify the relevant failure modes, as shown in the Table below:

Purpose of construction element	Failure modes
Resistance to spread of hot gases for evacuation and limitation of damage to the building contents	Smoke leakage and integrity
Resistance to spread of localised or fully developed fire for evacuation or to prevent damage to the building fabric	Smoke, integrity and thermal insulation
Resistance to spread of localised or fully developed fire for evacuation and fire fighting access	Smoke leakage, integrity, thermal insulation and load bearing capacity (see "no progressive collapse" in § 5.2)
Containment of a fully developed fire for the purpose of loss reduction, with the assistance of fire fighters	Integrity, thermal insulation and load bearing capacity
Containment of a fully developed fire for complete burnout for the purpose of loss reduction, with the assistance of fire fighters	Integrity, thermal insulation, load bearing capacity related to deformation limit state
Containment of a fully developed fire for complete burnout for the purposes of loss reduction, without any assistance from fire fighters	Integrity, thermal insulation, load bearing capacity related to deformation limit state

5.2 ACCEPTANCE CRITERIA

As stated above, when establishing performance criteria for fire resistance of building elements, it is necessary to consider all possible failure modes, considering the overall fire safety objectives. The limiting values selected for design depend not only on the limit state under consideration, but also on the specific fire safety objectives which need to be satisfied.

For specific fire engineering design, the failure criteria need no longer to be expressed as fixed values as is used with the standard fire conditions; they can be expressed as relative values regarding the risk and the fire safety objectives. In general, the limiting values will depend on the time during which a critical situation is maintained.

Smoke leakage and integrity
With respect to smoke leakage and integrity, the critical values depend very much on the actual design situation. For a design aimed at life safety inside the building, these values will be significantly more critical than if the design is aimed at environmental protection. For safety of people, the limiting value will depend on the leakage rate through the boundaries of the compartment of fire origin, the nature of effluents, the volume of the adjacent room, and the duration of the stay of people in this room. This limiting value can be expressed in terms of critical concentration of gas (oxygen, carbon monoxide, toxic gases ..) or a critical optical density. For property protection or environmental protection, the concentration of toxic or corrosive gases also needs to be established. To prevent fire spread and resulting damage to property, it is necessary to restrict the leakage rate of hot gases through separating elements, to prevent ignition of combustible materials on the other side of the element. The critical level is a function of the type, amount and relative location of these combustible materials, rate of heat release, and the expected temperature that the separating element is exposed to.

Thermal insulation
With respect to thermal insulation, the criteria will be different for life safety and property protection. For life safety, it may be necessary to limit the surface temperature of separating elements to avoid skin burn and to limit the level of thermal radiation from these elements to people, depending upon the expected duration of exposure. The latter can be related either to the safety of people within a building or to the definition of safe distances from a building in a fire. For property protection the limitation of heat transfer through separating elements and thermal radiation from them needs to be set to avoid any ignition of combustible material on the unexposed side. Any other damage that may be caused by high temperatures also has to be considered.

Load bearing capacity
With load bearing capacity, a criterion has to be established to avoid any sudden or progressive collapse of a building or parts of a building that could endanger people located within the area but not directly involved in fire. This criterion will also, in some circumstances, be of importance to avoid spread of fire and loss of goods.

When dealing with a "deformation" limit state condition the following should be considered:

- deflection, elongation, contraction of elements can lead to additional mechanical actions on adjacent separating elements, which can cause cracks and openings in them, and
- when the load bearing elements are playing a role as separating elements, it is necessary to ensure compatibility with acceptable deformation limits of other adjacent components.

6. DESIGN FIRE SCENARIOS

6.1 INTRODUCTION

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.

A design fire scenario [14] is a qualitative description of the course of a particular fire with respect to time and space. It includes the impact of the fire on all parts of the building, including the occupants and the fire safety systems. The design fire scenario considers the ignition source and mechanism, the growth of fire on the first item ignited, the spread of fire, the interaction of the fire with its environment and its decay and extinction. It could also include the interaction of the fire with the building occupants and the interaction with the fire safety systems within the building.

There is an infinite number of possible fire scenarios in each building. It is impossible to analyse all likely scenarios even with the aid of the most sophisticated computing resources. This huge set of possibilities needs to be reduced to a finite set of design fire scenarios that are amenable to analysis. Design fire scenarios for analysis should be based on a range of reasonable worst-case fire scenarios. Some extreme fire scenarios which have a very low probability of occurring cannot be accommodated, and therefore the risk and consequences of such extreme scenarios must be borne by society.

It is desirable that all the interested parties are involved in the selection of the relevant design fire scenarios.

There is a wide range of computational models for estimating the growth, duration and severity of design fires. The level of accuracy of calculation methods used for quantifying the design fires depends greatly on the design scenarios, and the design objectives. According to the level of sophistication of the calculation methods the following stages can be identified:

1- with sophisticated calculation methods which can calculate all aspects of fire growth and fire spread beyond the room of origin, the only assumption needed in the design fire scenario is the first item ignited, provided that a complete description of the room and its contents is available

2- with calculation methods dealing with more global information for fire growth and able to consider spread of fire beyond room of origin; then an assumption of the combustible products to be involved in fire and their rate of heat release is necessary. It is also necessary to differentiate between a localised fire and a fully developed fire,

3- with calculation methods dealing only with spread of fire beyond the room of origin; then an assumption on the time-temperature curve for the fully developed fire is necessary for the rooms where fire could occur, and

4- when calculation methods are not able to predict the spread of fire beyond the room of origin, assumptions are needed on the reliability of the separating elements, to obtain the time at which the fire could involve another room, for a given fire development.

6.2 FACTORS TO BE CONSIDERED

A description of a fire scenario also includes data that cannot be obtained by calculation. Some of these concern the fire itself (size and type of ignition source, distribution and type of fuel, fire load density, fire spread, etc). Others may include the factors influencing the fire development, such as internal ventilation conditions, external environmental conditions, state of doors, breakage of windows, building air handling system, fire compartment size, fire compartment wall properties and the influence of the active fire control systems. Finally, structural engineering factors such as the position of the fire relative to bracing systems, columns, or other loaded elements, need to be considered.

All the above-mentioned information needs to be identified in a systematic manner for the whole building. For example, for the fire itself, a systematic review should be conducted to establish the potential fire hazards within the building. The review should take account of factors such as:

(a) general layout,
(b) potential ignition sources,
(c) nature of the activities,
(d) anticipated occupancy,
(e) materials and forms of construction,
(f) combustible contents,
(g) any unusual factors.

Figure 6.1 illustrates a design fire by giving a rate of heat release as a function of:

- the fire growth rate measured by the parameter t_o.
- the fire load density q_f
- the fire area A_{fi}
- the ventilation conditions

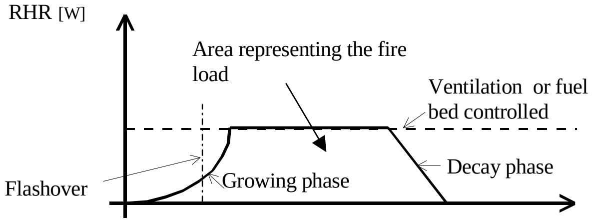


Figure 6.1

In specific large spaces such as an exhibition halls or airport concourses, the fire area A_{fi} can be easily defined by the layout of the combustible materials. Otherwise the fire area A_{fi} is equal to the fire compartment area A_f.

The first stage of fire, when temperatures are below 100°C can, generally, be neglected in the design fires used for the evaluation of fire resistance, since these temperatures are generally too low to affect the structural elements. It is only when the fire reaches certain levels of severity that load bearing structures and separating elements can be affected. Such levels are, for example, when the localised gas temperature is more than 400°C or when flashover occurs in a room.

Flashover is the transition from the growth stage of a fire to the fully developed stage (full room involvement). It is widely accepted that flashover occurs when the temperature in the hot gas layer of a compartment reaches 500°C to 600°C or radiation from this layer reaches 20 kW/m^2 to 25 kW/m^2. After flashover, all pyrolysis gases cannot burn inside the compartment due to lack of oxygen, and flames appear through openings in the boundaries.

6.3 FIRE COMPARTMENT LAYOUT

Details of the compartment of fire origin are usually known from the project of the designer and very few assumptions are needed. However, depending on the sophistication level of calculation methods used for quantifying the thermal actions (see § 7.2), some estimations may be necessary for compartment boundaries, windows and other openings, and other factors.

6.3.1 Consideration of compartment boundaries

For the quantification of the thermal effects of the design fire and its possible propagation to adjacent rooms, it is necessary to understand the behaviour of boundary elements of the room of fire origin under relevant fire conditions.

The behaviour of boundary elements can be assessed by:

- Experimental fire exposure
  For a given design fire scenario, the element is exposed to an assumed time-temperature curve, simulated in a furnace. It is necessary to test a specimen representative of the actual element. In addition, when the experimental results are known, the accuracy of the assumed time-temperature curve used has to be verified. This approach could lead to a large number of expensive fire tests if the complete range of reasonable worst-case scenarios were to be quantified.

- Calculation
  This approach makes use of the available test data for separating elements (mainly obtained under standard (ISO-fire) conditions). The behaviour of elements under design fire conditions can be assessed by calculation if enough knowledge is available on the thermal and mechanical properties for the range of temperatures being considered. Integrity failure cannot, for the time being, be accurately predicted by calculation, so assumptions have to be made on whatever test results are available.

- Standard fire test exposure
  National prescriptive rules require a certain standard fire resistance of walls and floors, depending on their use and geometry. These rules are based on the assumption that fire will not grow beyond the fire compartment, if the boundaries meet the specified fire resistance rating. In this case any assumptions made in the design fire scenarios are only related to the necessary fire resistance rating designed to avoid spread of fire beyond the room of origin.

The first option can only be used for a very limited number of special cases, due to the high costs of assessment. The second option, using calculation, can lead to an improvement in the fire design of buildings. If the third option is used, then the comments made in § 8.3 and §8.4 need to be carefully considered.

If the fire starts in an enclosure with a boundary of unknown fire rating, it is necessary to assume two scenarios. One possibility is to assume that this boundary is destroyed at the beginning of the fire, leading to a larger room of origin. The second possibility assumes that the fire will stay in the enclosure for some time (linked with the expected quality of the boundary) and after that the fire will spread beyond the boundaries. It is necessary to consider both possibilities since it is generally difficult to know which is the most onerous situation as far as the fire behaviour of load bearing and separating elements is concerned.

6.3.2 Consideration of compartment openings

Openings in an enclosure can consist of windows, doors, roof vents etc. The severity of the fire in an enclosure depends on the size, shape and number of openings in the enclosure. For defining the fire scenarios, the following rules are proposed:
- Doors are assumed to be closed if the enclosure has other openings.
- Doors are assumed to be opened if the enclosure has no other openings.
- Glazing without fire rating is assumed to be broken from the start of the fire. If the size of the window or glazing in a certain wall is high compared to the total height of that wall, only a given percentage of the upper part of the window or glazing assumed to be broken. This assumption is proposed because the greatest fire severity is generally not reached for the whole glazing area broken.
- Normal glass will break at relative low temperatures; say 100 to 200 °C. For glazing with a fire rating, the same approach as with compartment boundaries can be used (experimental fire, calculation or direct use of standard fire tests).
- Simple models can use the so-called opening factor to model the openings in an enclosure. More complex models can use a flow calculation based on the actual flow through each opening.
- The opening factor can be calculated for enclosures with one vertical opening, with multiple vertical openings and with a combination of horizontal and vertical openings. Complex models (solving mass/heat balance equations) are also available.

The heat in an enclosure can be lost from the enclosure by radiation and by convection. The convection part can be calculated with a simple model (using the opening factor) or complex models (solving mass/heat balance equations).

7. ACTIONS / LOADS

Actions to be considered in the assessment of the behaviour of a building in the case of fire are:

- mechanical actions, due to self weight, activities in the building, or actions induced directly or indirectly by the fire.
- thermal actions, from design fire scenarios.

7.1 MECHANICAL ACTIONS

When considering the mechanical actions due to applied loads, wind loads or snow loads, the probability of the combined occurrence of a fire in a building together with the extreme level of mechanical actions can be considered as negligible, because fire action on structures is an accidental action. In this respect the load level to be used when assessing the fire behaviour of an entire building or part of it has to refer to specific safety factors and not those used for normal design of buildings. The general formula which can be used to calculate the relevant effects of mechanical actions is :

$$E_{fi,d,t} = \sum \gamma_{GA}.G_k + \psi_{1,1}.Q_{k,1} + \sum \psi_{2,i}.Q_{k,i} + \sum A_d(t) \qquad (1)$$

where :	G_k	characteristic value of permanent action ("dead load")
	$Q_{k,1}$	characteristic value of one (the main) variable action
	$Q_{k,i}$	characteristic value of other variable actions
	$A_d(t)$	design values of actions from fire exposure (mainly indirect actions due to thermal expansion, if not taken into account by the calculation models)
	γ_{GA}	partial safety factor for permanent actions in the accidental situation (a value of 1.0 is suggested)
	$\psi_{1,1}$, $\psi_{2,i}$	combination coefficients for building - see table for instance [15 & 16]

For structural elements, this leads generally to a maximum load level during fire exposure of 65 to 70 % of the ultimate load bearing resistance at room temperature.

Some other independent accidental actions, such as earthquake, do not need to be considered in conjunction with fire. However for the particular case of fire following earthquake, for specific design in countries with high seismic risks, it is necessary to take into account possible damage to buildings due to earthquake (like destruction of water supply and damage to fire resisting construction) before making the fire resistance analysis.

Other mechanical actions induced directly or indirectly by the fire, have also to be considered when evaluating the fire resistance of parts of buildings :

- action due to the pressure of the developing fire; in a fully developed fire the vertical pressure gradient is of the order of 8Pa/m.
- impact, if there is a risk of collapse of surrounding elements on the fire exposed side.
- impact of hose stream due to the possible action of fire fighters, mainly on the unexposed side of separating elements.
- the forces and moments induced by the thermal elongation or shrinkage of surrounding elements also need to be considered, when assessing the behaviour of individual elements, or part of a structure.
- the deformation of single elements (such as a beams or a floors) which can lead to the application of load on non-load bearing separating elements, or the distortion of suspended services (such as ducts or service pipes).

7.2 THERMAL ACTIONS / DESIGN FIRES

From the design fire scenario (see Chapter 6), requirements expressed by interested parties, and the degree of accuracy to be looked for, the following types of design fires could be used to determine the thermal actions on the building components:

- data from an experimental fire, in direct conjunction with the layout of the relevant part of the building and the related fire load,
- a fire resulting from numerical calculations (simulated fire – see § 7.2.2),
- a parametric fire, taking into account the main parameters which have an influence on the gas temperature. It must be recognised that parametric fires are only a rough approximation of real fires (see § 7.2.3),
- when performance levels are expressed in terms of fire duration, a nominal fire (see § 7.2.4).

Only in the case of the first two alternatives it is possible to consider the fire development in more than one compartment.

Not all fires reach sufficient severity to will endanger the load bearing structure. Several factors in addition to those that can have an influence on the fire development, (e.g. detection, automatic extinguisher system, fire brigade) need to be taken into account for a better evaluation of the time-temperature relationship.

Some of the parameters to be used for making calculations are as follows:

- building geometry (surface area, height of storeys, wall and floor composition, compartmentation, size of openings, type of glazing),
- Type and amount of fire load (from statistics or based on an anticipated use, for the full life cycle of the building),
- rate of heat release of fuel items (from literature or ad hoc test results),
- thermal behaviour of boundary elements.

In some cases, agreement from authorities on some of these parameters will need to be sought, since the level of safety is a function of the design value of the variable parameters.

The following thermal actions, expressed mainly in terms of time-temperature curves, can be used, depending on the accuracy required for the assessment of the structural behaviour and the freedom of the designer to use fire safety engineering in lieu of a nominal fire.

7.2.1 Experimental fires

The thermal actions on structural elements can be established by performing a burn test representative of the design fire scenario. All the parameters mentioned above must be taken into account in the design of the test. It has to be recognised that the test set up will be a simplification of reality, in which case any simplifications should lead to results on the safe side. Full scale experimental fire tests can only be used in special situations because they are very expensive.

7.2.2 Numerical models

The effect of all parameters controlling a fire in a compartment could only be partially estimated by tests. Numerical models could, however, consider the complete range of variables. A wide range of different models, more or less complicated, can be used, depending on the design fire scenario.

7.2.2.1 Field model: computational fluid dynamic

Field models [17] divide the space of a fire compartment into small volumes and solve numerically the differential equations using the input thermodynamic and aerodynamic variables for the compartment. The output includes the temperature and velocity of gases (and chemical species concentration) in all parts of the compartment throughout the fire.

The complexity and the time needed for calculations using field models invariably limits the application of such codes for fire resistance purpose. Field models are often used for early fire growth and development, but they are not considered accurate for fully developed post flashover fires.

7.2.2.2 Two zone model

The two-zone model [17] (figure 7.1) is based on the assumption of accumulation of hot combustion products in a layer beneath the ceiling, above a cold layer, with a horizontal interface. In this hot upper layer, uniform characteristics of the gas are assumed. Other zones are defined i.e. the lower layer, the fire and its plume, the external gas and walls. The exchanges of mass, energy (and chemical species) are calculated between these different zones. The model represents a pre-flashover condition.

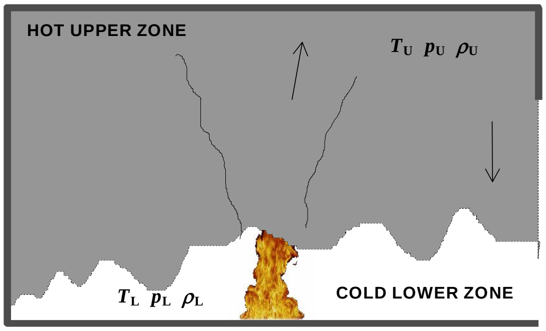


Figure 7.1: Pre-flashover fire (2 zones)

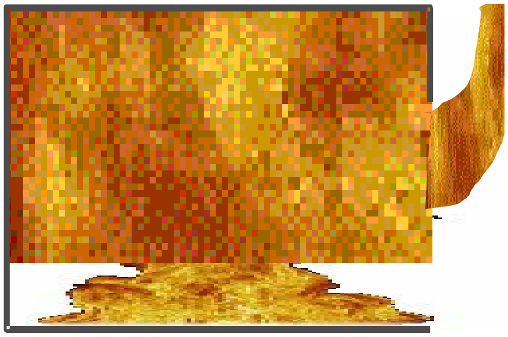


Figure 7.2: Post flashover fire (1 zone)

7.2.2.3 One zone model

The one-zone model [18] (figure 7.2) is generally applied for a fully developed post-flashover fire. Homogeneous properties of the gas are assumed in the compartment. These properties are temperature, optical properties, and chemical composition.

The temperature is calculated considering the resolution of mass conservation and energy conservation throughout the fire. Mass transfer occurs with the external gases (by openings) and the fire (pyrolysis rate). The energy released by the combustion process is released to surrounding walls and floors (by conduction), and transported through the openings (by convection and radiation).

7.2.3 Analytical models

Analytical models are used to estimate the temperatures in real fires expected to occur in buildings. They take into account the main parameters which influence the growth of fires: size of the compartment, amount of fire load, type of surrounding walls and floors, opening factor. However, since they are expressed in an analytical manner they still contain some assumptions and idealizations or approximations.

It is necessary to differentiate between:

- fully developed fire in a compartment (after flashover),
- localised fire in a compartment,
- flames coming from openings

7.2.3.1 Fully developed design fire

Parametric formulae can be used to estimate the uniform gas temperature within a compartment having a floor area not larger than 500 m², as a function of time, as done in Eurocode 1 part 2.2 [19,20] or in the ECCS Model Code [21,22].

An example of results [21] (fire load = 230 MJ per m^2 of the total surface area of the enclosure, opening factor O from 0.01 $m^{1/2}$ to 0.20 $m^{1/2}$) is shown on figure 7.3.

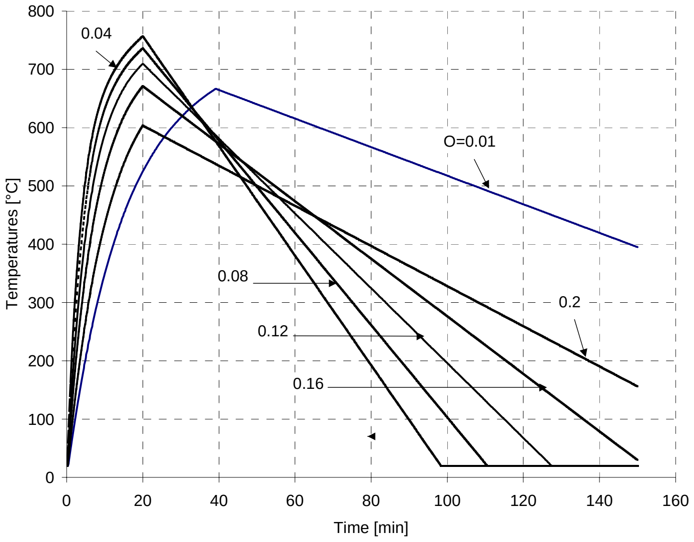


Figure 7.3: Example of parametric fires

7.2.3.2 Localised (plume) design fire

Estimates of the temperature effects of a localised fire can be made, knowing the relative height of the flame and of the ceiling (figure 7.4): the gas temperature distribution depends on whether the flame impinges the ceiling [23] or not [24].

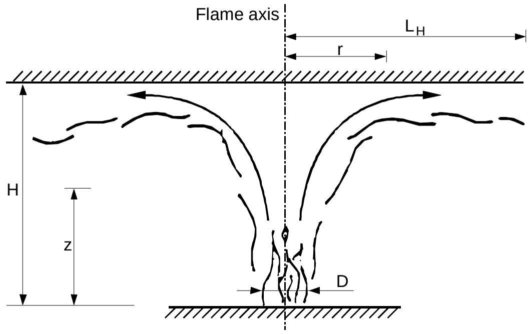


Figure 7.4 : Plume fire

The thermal flux received by the ceiling above a localised fire can be expressed by a formula [23].

When the flame is not impacting the ceiling, the temperature along the symmetrical axis and the visible flame length from the fire are relative to the diameter and the rate of heat release of the fire [24].

7.2.3.3 Flames from openings

In conjunction with temperature increases in a fire compartment, flames are often projected outside the building through openings in the facade or roof. These flames are due to unburned combustible gases produced by the fire load inside the building due to the lack of oxygen. The size of these flames mainly depends on :

- the opening factor
- the rate of heat release of the fire load,
- the size of the openings,
- the wind conditions,
- the draught conditions of the compartment (forced or not).

Proposals for calculating the heat transfer to external load bearing structural elements or to other buildings from external flames is given in several documents [19,25,26]

7.2.4 Nominal fires

Nominal fires are called up in Structural Eurocodes [19], which have to be followed in furnaces for experimental fire tests. It is important to note that the temperature mentioned is not the real gas temperature, but the one recorded by the thermometers placed in the heated volume.

Four different nominal curves (figure 7.5) are generally used [19,27,28]:

- Standard time-temperature curve

  $$\theta_g = 20 + 345 \log_{10}(8t + 1) \qquad (2)$$

  with t, time in minutes

  This curve is mainly related to cellulose fires in buildings as offices, flats, shops. This fire curve was standardised by ISO [27] and is very similar to curves in national codes (e.g. ASTM E119)

- Hydrocarbon curve

  $$\theta_g = 1080.(1 - 0{,}325 e^{-0{,}167t} - 0{,}675 e^{-2{,}5t}) + 20 \qquad (3)$$

  with t, time in minutes

  This curve can be used when the fire load is mainly made by hydrocarbon materials as in off-shore platforms, refineries, petrol stations,…

- External curve

  $$\theta_g = 660.(1 - 0{,}687 e^{-0{,}32t} - 0{,}313 e^{-3{,}8t}) + 20 \qquad (4)$$

  with t, time in minutes

  This curve is valid for assessing external walls against flames coming from openings in the fire compartment beneath.

- Smouldering curve

  during 20 min :

  $$\theta_g = 154.\sqrt[4]{t} + 20 \qquad (5)$$

  with t, time in minutes

  followed by the standard curve for a further 20 min.

  This curve could to be used for reactive materials, used either for fire protection of load bearing structures or for sealing of gaps, which would need a fast heating rate for reaction to occur.

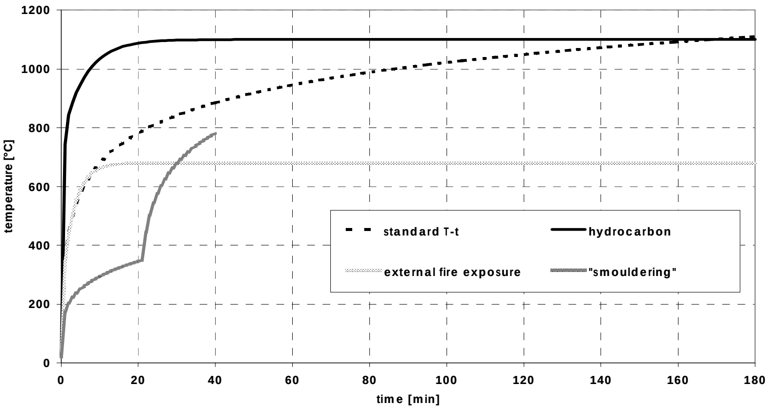


Figure 7.5: Nominal fires

Since these curves have no defined end time, their use needs to be related to fire durations expressed by national rules, the insurance company or the building owners.

7.2.5 Heat transfer to structural elements

On the basis of defined time-temperature thermal action, the heat flux to surrounding structural members can be calculated using an appropriate heat transfer equation.
The equation has to consider the relevant parameters as:

- the radiative heat flux,
- the convective heat flux.

The radiative heat flux should be determined by taking into account:

- radiation temperature of the environment of the member (e.g. gas temperature, boundary temperature, flame temperature, …),
- surface temperature of the member,
- emissivity and absorbtivity of the radiating elements,
- the view factor between the heat source and the target.

The convective heat flux component should be determined by taking into account:

- coefficient of heat transfer by convection,
- gas temperature of the environment of the member in fire exposure,
- surface temperature of the member.

In many situations it can be conservatively assumed that the surface temperature of the member is the same as the fire gas temperature.

8. SUBSTANTIATION OF STRUCTURAL AND THERMAL PERFORMANCE

Structural design consists of identifying all of the potential failure modes [29] and providing resistance to avoid failure. Both safety and economy are important considerations. A major part of the professional service of a structural engineer is the skill in identifying appropriate loading conditions and the associated failure modes for the construction conditions.

The ways in which structural members fail depend upon the materials, geometry, loading conditions, and support conditions. The anatomy of the entire structural systems is an important aspect of the analysis and design process. An advanced analysis will include the interaction between different elements and substructures.

8.1 GENERAL

The behaviour of building structures or building elements under fire can be assessed by one or more of the three following approaches:

- Calculations
- Tests and field application of test results
- Engineering judgement

Having in mind that the final aim is the accurate evaluation of the expected behaviour of entire buildings in real fires, no one of these methods can currently provide all the necessary answers. The behaviour needs to be assessed by a combination of the three approaches.

Calculations
One target to make calculation methods available for simulating each physical phenomenon needed in the fire assessment of a building. The use of calculations is an easy way to understand and quantify the phenomena that can occur in a fire situation and to assess the behaviour of buildings for a variety of fire scenarios. However there are some limitations on the use of calculation methods. Some of these limitations can be overcome by verifying existing calculation methods with available test results. The limitations include:

- Limited information on the thermo-mechanical properties at elevated temperature of materials used in building elements.

- The current limited number of validated calculation methods. (They are mainly available for individual load bearing members in steel, concrete or timber structures, whereas the number of methods for whole structures or separating members is limited.)

- The difficulty of modelling three-dimensional structures exposed to fires. This modelling needs very specialised finite element computer programs.

- The current lack of methods to accurately model some physical phenomena like internal combustion, spalling, mass transfer and water migration.

Tests
Regarding assessment by tests, it must be recognised that all experiments for fire resistance are rather expensive. Consequently it is generally necessary to limit the number, the size and the complexity of the parts of the building to be tested.

Engineering judgement
Engineering judgements use all information, obtained by tests and/or by calculations and/or by learning from real building fires, to make a full assessment of the expected fire behaviour in a building. One of the major concerns of the fire expert is evaluation of the possible impact of different thermal actions (rate of heating, maximum temperature reached, cooling phase) and of physical phenomena, which can not yet accurately be modelled.

8.2 ASSESSMENT BY CALCULATION

Performance-based fire engineering design for fire resistance of buildings needs to consider [13, 30]:

- the function of the building structure and its elements: load bearing (resistance R) and/or separating (insulation I, integrity E),
  the way of assessing the fire behaviour of the building: by considering individual elements, parts of building (assemblies of elements), or the entire building,
- the necessary models for performing the assessment.

When the thermal action (fire development) is defined for a given fire scenario, two sets of models have to be used for the assessment of fire resistance:

- heat transfer model,

- mechanical model.

The purpose of the calculation models is:

a. to determine the temperature field history (thermal response) of each building component,

b. to estimate the mechanical behaviour of the building, taking into account the interaction between different parts of the structural system, in order to determine the risk of fire spread and building collapse,

c. to allow the fire engineer to compare the "real" behaviour of the building as far as the failure criteria are concerned with the functions and the level of performance requested.

8.2.1 Calculation Models

There is a wide range of calculation models, from very simple to very advanced. They are generally categorised as follows:

- tabulated data,
- simplified calculation methods,
- advanced calculation methods.

Tabulated data can be considered as a "calculation model" because it is a first step which may be sufficient in many cases. Tabulated data should be conservative because it will often be used by designers with limited knowledge of the subject.

Tabulated data and simple calculation methods are rather easy to use, minimising the risk of misuse. However, due to this simplicity, their field of application needs to be clearly stated, since they are generally not valid outside the range for which they were developed.

Advanced calculation models need to be based on fundamental physical behaviour to give a reliable approximation of the expected behaviour of the structure in case of fire [13]. Advanced calculation models will be used only by a small number of expert designers, using specialised computer software.

8.2.2 Thermal Response

Heat transfer calculations need to consider relevant data (as a function of the temperature) for each material involved, concerning:

- specific heat
- thermal conductivity
- unit mass/density

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

The calculation of the temperature field within a section can be based on finite element or finite difference analysis or on simplified models given in standards and literature [13, 30]. In elements composed of various layers of different materials including air voids a calculation can be difficult and the performance of such elements may largely depend on detailing and quality of manufacturing. In such cases engineering judgement and testing may be necessary.

For moist materials the calculation of temperature increase may be made with mass transfer models, by considering a peak of specific heat around 100°C, or by allowing for a time delay in the rise of the material temperature when it reaches 100°C.

8.2.3 Mechanical Response

In general building materials lose strength and stiffness at elevated temperature leading to a decrease in their load bearing capacity and an increase in deformation.

Mechanical behaviour calculations need to consider relevant data (as a function of temperature) for each material involved, concerning:

- stress strain relationships at elevated temperatures
- reduction factors for strength, and stiffness
- elongation due to elevated temperatures

The materials to be considered are mainly those used for load bearing and separating members, including any other materials that can have an influence on deformation and stability.

The load bearing capacity of a member, structure or part thereof, is assumed, within a period of time "t", when:

$$\text{Min}\ (R_{fi,d}) \geq E_{fi,d,} \qquad (6)$$

$E_{fi,d,t}$ is the design effect of actions for the fire situation (see chapter 7.1).

$R_{fi,d}$ is the design resistance of the member or the structure for the fire design situation from 0 to time t

The calculation of the mechanical response of an entire structure or a part thereof needs to be performed with advanced calculation methods (such as those based on finite elements). Simplified models or tabulated data can be only used for the assessment of individual structural elements.. These simple models are generally based on limiting temperatures which may not exceeded during the fire.

When the expected failure mechanisms cannot be properly assessed by the analysis model, then either the construction detailing has to be modified to avoid such failure mechanisms, or the assessment of the mechanical response has to be made by carrying out a fire resistance test on a representative specimen.

8.3 ASSESSMENT BY TEST

8.3.1 General

It is recognised that a very large amount of experimental fire resistance data is available for testing in accordance with the standard fire (see § 7.2.4). More will be available in the future.

Whereas it is desirable that any elements incorporated into a real building should be tested for all the possible fire scenarios which could occur during the life of the building, it is obvious that this will never be possible. Therefore, methods should be developed to enable extended application of data from standard tests to other fire exposure conditions.

A standard fire test performed in a laboratory gives only a limited indication [31] of:

(a) the likely performance of a particular building product, material or component when exposed to 'real' fire conditions
(b) the suitability of a product, material or component for a particular end use.

In addition, one of the problems associated with the use of standard fire resistance test results as a measure of fire safety is that the criteria are fixed (absolute) and the quantifiable measurements are limited.

When considering the functional objectives associated with fire resisting construction, Chapter 6 identifies the need for the performance to be adapted or ‘tuned’ to satisfy the use of the building. With the existing approach this is difficult to introduce because of poor understanding of the fire risk associated with the various modes of failure. For instance, the fire safety engineer needs to have data available which allows the tenability of the conditions on the protected side to be established in respect to life safety, and the likelihood of secondary ignition occurring in this space in the case of property protection.

The important mechanisms needed to establish this include;

- how the separating element distorts under fire conditions,
- how hot the separating element gets,
- how much heat radiation can be transmitted through, or emitted from, the separating element during the fire,
- whether the separating element contains any combustible materials which may eventually ignite,
- the smoke leakage characteristics of the separating element, and
- whether or not degradation of the separating element itself may release combustible or toxic gases,

It is particularly important to recognise how the element may behave differently if the thermal exposure conditions are different from those in the test.

Elements of construction are made of different materials. The way materials react when exposed to fire is invariably different and often complex, but one very simple difference that must be taken into account when applying the information generated during tests is the following;

- Some materials are primarily temperature dependent, including rate of heating,
- Some materials are primarily time/duration dependent.

As a result some materials may achieve an extended fire resistance period when exposed to the standard temperature/time relationship, but may melt or significantly change state (e.g. strength, or ductility) should the temperature be elevated by 10 or 15% above the maximum value reached. In some cases, the change in behaviour can be dramatic, not just shortening the period of protection by a few minutes, but only providing a few minutes protection before failing.

Additionally, there are many products that are ‘energy’ dependent, which will not react badly to either temperature or time in isolation, but will fail when exposed to a critical input of energy.

Similarly, when applying any of the information generated from fire tests, particularly that which may be generated following improved instrumentation as recommended in this section, the magnitude of the thermal energy input needs to be considered. Where it can be established that the standard temperature/time conditions are not appropriate then alternative exposure conditions may be needed, if a full understanding of the hazard resulting from the structural response is to be fully quantified. An obvious alternative temperature/time regime is the hydrocarbon fire exposure (see § 7.2.4), but as this is designed to represent a free burning liquid hydrocarbon based fuel fire, this may be over-severe for building fires. Experimental fires using various timber crib fire sources may be more suitable. It is important, however, that the relationship between the test fire and the likely ‘real’ fire is known.

It is proposed that improved instrumentation of the many routine fire resistance tests performed on a regular basis could start to provide much of this information.

8.3.2 Improvement of test methods

In order to get more useful information from fire resistance tests some possible improvements in the measurements and observations carried out during these tests are suggested.

Temperature profiles

The construction specimen should be fully instrumented throughout its thickness with appropriate thermocouples so that full temperature profiles can be established. Differential temperatures in a structural element can cause thermally induced deflection (thermal bowing), so information on temperature profiles is useful for calculation of deflections or load-bearing capacity. In the case of official tests for product approval or certification, it is necessary to make sure that the additional measurements do not influence the product performance.

Temperature rise on unexposed surface

To have a better knowledge of any weak point on the unexposed surface, it is recommended that greater use be made of the roving thermocouple, although an improved device needs to be developed with a faster response, improved contact and possibly incorporating electronic “trend analysis” circuitry.

For instance, infrared thermal imaging cameras are able to identify the distribution of temperature on the unexposed face of heated elements. If they can be calibrated, they might give more information on the cold face temperature. The variation of the emissivity of the surface as function of position and time may cause significant problems to the accuracy of the temperature measurements.

Radiative heat flux

In a homogenous, plain element, the heat flux is normally measured by a single centrally positioned heat flux meter or radiometer. Where an element incorporates a number of zones with different thermal characteristics and hence surface temperatures, the use of a single meter is impractical and probably meaningless when the results are to be applied in practice to elements with different configurations of sub-elements. It is then recommended that heat flux data be obtained from each of these zones.

Escape of hot gases and smoke

A quantitative method of measuring the hot gas flow, preferably expressed in terms of gas temperature and rate of flow, is required.

The only way that this can be achieved in practice is to use a gas collector chamber on the unexposed face which allows the hot gases to be evaluated with respect to both temperature and flow. These gases include those which are escaping through gaps, the convective air flow up the unexposed face of non-insulating or partially insulating elements and any products of combustion being evolved by the element itself. It is important that the collector chamber/hood does not influence the behaviour of the element by denying the construction the normal ability to lose heat from the unexposed fire.

Information is also needed regarding the pressure conditions within furnace, when performing fire resistance test.

Smoke spread and associated hazards

The toxicity of the smoke or its obscuration ability may have to be measured on the unexposed face of the specimen, as well as the corrosiveness of the smoke. The knowledge of the toxicity of the leaking gases/smoke and the likely ability of this smoke to obscure evacuation routes and exit signs, etc, would make a valuable contribution in quantifying the level of protection an element is able to provide when subjected to fully developed fire enabling the results to be applied in terms of anticipated performance in support of the life safety objectives.

Distortion and deflection

The ability of an actual compartment to maintain a fire and smoke resisting enclosure is very dependant upon the elements' ability to interface with the adjacent elements in a compatible way. Deflection, elongation and distortion measurements have to be made on structural elements to help the designer to establish the best methods to prevent such deflections in practice.

It is important to recognise that the permitted levels of deflection in standard tests for load-bearing elements, particularly for horizontal elements, may result in imposed loads during tests being less than the realistic loads which could result in catastrophic failure in a real fire.

Restraining forces

The use of load cells to quantify the level of restraint that may be needed to resist expansion or lateral movement of a tested construction is recommended. If the construction is to be used in a similar manner as in a real building then it is important to know the amount of restraint that will be required to be provided if a similar result is to be assured in reality.

Interactive elements

A serious limitation of fire resistance tests is the fact that elements are tested in isolation as single elements. In practice, each fire enclosure is bounded by at least six elements (including the floor) which need to interact with each other if fire compartmentation and separation is to be maintained. It is recommended that the behaviour of a construction in respect of fully developed fire, as simulated by fire resistance test, be determined in a 3-dimensional manner, interfacing with adjacent elements as they would in practice. This will highlight the need for both good sealing between elements and for each adjacent element to be able to provide the required levels of fixity or restraint.

8.4 ENGINEERING JUDGEMENT IN THE DESIGN PROCESS

The design of structures for fire safety requires a number of engineering judgements to be made. For example, the introduction to §8.3 shows that a judgement will need to be made as to what the relevant exposure conditions should be. Other cases needing are, for instance:

- assumptions of calculation methods (fire scenarios, heat transfer conditions, schematisation of the structure, etc)

- definition of representative testing conditions and interpretation of the test results.

When the information generated from calculations and tests are fully analysed, engineering judgement can be used to establish compliance with the requested fire safety criteria. For example:

- when the conditions in the space protected by the element result in the area becoming untenable in terms of life safety for those who remain in, or have to pass through that space.

- when the conditions in the protected space become critical in respect of the likelihood of further ignitions or explosions.

In each case it is necessary to know enough about the volume and the boundary conditions of the protected space to establish how tolerant the space is to the heat or gases flowing into it. In particular engineering judgement should take into account any anticipated increase in the flow of combustion gases as a result of an "extrapolation" to those levels expected from larger full size elements by means of extended application procedures.

Should the leakage of gases and smoke render the protected space untenable while people are occupying it, there are two alternative strategies. Firstly the structural elements should be of enhanced construction, such that they will be able to resist the leakage of smoke and hot gases for longer. Alternatively, the smoke or combustion gases may be managed by means of extract systems, vents or reservoirs, to either dilute the gas concentrations or to restrict the spread.

In respect of the likelihood of fire spread into the protected area the materials used in the construction of this protected space could be selected with a higher ignition temperature or with a greater tolerance to the heat flux received. Alternatively the heat flux into the space may be reduced by enhancing the integrity, insulation/radiation performance of the fire separating element.

As most real buildings and fire compartments are larger than those which can be tested, further engineering judgement is needed to apply test results to full size structures. There may be many cases where a specific expert in a given field of fire resistance will be asked to make an expert judgement on the expected behaviour of a building or a fire safety system.

In any case engineering judgement is not a guess, but needs to be based on logical thinking, considering the bulk of information available on a given subject. Engineering judgement also needs to be quantifiable as far as possible.

9. CHARACTERISTICS OF A RELIABILITY BASED STRUCTURAL FIRE DESIGN

A reliability based structural fire design should originate from validated models, describing the relevant physical processes and connected to strictly specified functional requirements and criteria [32, 33]. For the probabilistic model to be integrated with the physical model, various levels can be distinguished:

- an exact evaluation of the failure probability, using multi-dimensional integration or Monte Carlo simulation,
- an approximate evaluation of the failure probability, based on first order reliability methods (FORM), and
- a practical design format calculation, based on partial safety factors and taking into account characteristic values for action effects and response capacities.

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

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

$x_d = X_k \gamma_x$ for exposure variables (7a)

$x_d = X_d/\gamma_x$ for response variables (7b)

The fundamental components of a reliability based structural fire design are :

- the limit state conditions,
- the physical model,
- the practical design format, and
- the safety elements provided.

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

- limit state with respect to load bearing capacity.
- limit state with respect to insulation.
- limit state with respect to integrity.
- or any others relevant limit state to a specific structure

For a load bearing structure, the design criterion implies that the minimum design value of the load bearing capacity $R_{fi,d,t}$ during the fire exposure shall meet the design load effect on the structure $E_{fi,d}$, (see formula (6))

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

$T_{cr} - \max \{T_{sd,t}\} \geq 0$ (8)

For the integrity requirement, there is no analytically expressed design criterion available at present. Consequently, this limit state condition has to be proved experimentally, when required, in either a fire resistance test or an ad hoc test designed for a specific purpose.

The physical model comprises the deterministic model, describing the relevant physical processes of the thermal and mechanical behaviour of the structure at specified fire and loading conditions. Supplemented with relevant partial safety factors, the physical model can be transferred to the practical design format.

The design format condition to be proved is given by equation (6). Depending on the type of practical application, the condition has to be verified for either the complete fire process or a limited part of it, determined by, for instance, the time necessary for the fire brigade to attack the fire under the most severe conditions or by the design evacuation time for the building.

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

- the uncertainty in specifying the loads and of the model, describing the load effect on the structure.
- the uncertainty in specifying the fire load and the characteristics of the fire compartment,
- the uncertainty in specifying the design data of the structure and the thermal. moisture mechanics. combustion and mechanical properties of the structural material.
- the uncertainty of the analytical models for the calculation of the compartment fire and the related heat transfer to the structure, the size of reduced cross section and the associated temperature and moisture state of the structure and its ultimate load bearing capacity,
- the probability of occurrence of a fully developed compartment fire.
- the efficiency of the fire brigade actions,
- the effect of an installed extinction system, and
- the consequences of a structural failure.

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

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

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

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

Summing up, the design verification must ensure that

$$R_{fi,d,n} = \frac{1}{\gamma_n} R_{fi,d}(R_{fi,d1}, R_{fi,d2}, ...) \geq E_{fi,d}(G_d, Q_{d1}, ...) \qquad (9a)$$

or

$$\frac{1}{\gamma_n} R_{fi,d}\,(R_{k1} / \gamma_{r1}, R_{k2} / \gamma_{r2}, ...) \geq E_{fi,d}\,(G_k, \psi_{j,i}, Q_{k,i}, A_{ind}) \qquad (9b)$$

where

$R_{fi,d}$ is the design value of the ultimate load bearing capacity. determined by the lowest value of the ultimate load bearing capacity during the relevant fire process,

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

$E_{fi,d}$ is the design load effect in fire, determined by considering an accidental load combination of the type given in equation (1)

All other load factors are set to unity [34, 35, 36].

$$\gamma_n = \gamma_{n1}\ \gamma_{n2} \qquad (10)$$

is a differentiation factor, accounting for different safety classes (γ_{n1}) and special fire fighting provisions (γ_{n2}) according to above. In Equation (4), the differentiation factor γ_n has been allocated to the design load bearing capacity R_d. Alternatively, γ_n may be applied as to affect the design fire load thus modifying the design fire exposure.

Related to the probabilistic influences to be considered, listed before, the partial safety factors take account of the first five influences and the differentiation factor of the last three, as in Eurocode 1 – part 2.2 [19].

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

$$\beta_{fm} - \beta_r \geq 0 \qquad (11)$$

The required value of the safety index β_r depends on the consequences of a structural failure. the probability of occurrence of a fully developed compartment fire, the efficiency of the fire brigade actions, and the effect of an installed fire extinguishment system, if any. For the detailed technique of deriving required values of the safety index β_r, see refs [37, 38, 39, 40].

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

$$p = p_1\ p_2\ p_3 \qquad (12)$$

where

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

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

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

A probabilistic analysis according to a first order reliability method (FORM) can be outlined as follows – here exemplified for a load bearing timber structure.

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

The following formulae apply for the safety margin:

$$Z(t) = M_R(t) - M_S(t) \quad (13)$$

for the probability of failure

$$P(t) = \int_{-\infty}^{0} f_Z[Z(t)]dZ \quad (14)$$

and for the safety index

$$\beta_f(t) = \phi^{-1}[1 - P(t)] \quad (15)$$

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

As expressed by Equation (11), the design verification must ensure that the minimum value β_{fm} of the safety Index $\beta_f(t)$ during the relevant fire exposure meets the required value of the safety index β_r.

Further guidance for the determination of the partial safety factors γ_r and the differentiation factor γ_n – Equations (9a) and (9b) - is given in appendix 5 of ref. 33 together with example values.

10. DOCUMENTATION OF ASSESSMENT

The format of the report on the fire behaviour of the structure of a building will depend on the nature and scope of the fire engineering assessment but it should typically contain the following information [11, 14]:

a) objectives and scope of the assessment;

b) description of the building and its fire safety installations;

c) fire safety objectives;

d) basis for selecting design fire scenarios;

e) acceptance criteria agreed;

f) analysis of results, detailing:
    1) assumptions;
    2) description of models used and their limitations;
    3) input and output data for each models;
    4) engineering judgements made and their basis;
    5) calculation procedures
    6) results;

g) comparison of results of analysis with acceptance criteria;

h) fire protection installations;

i) management requirements - including Fire Safety Manual;

j) conclusions, giving explicitly:
  1) requirements for fire protection;
  2) any limitations on use;

k) references:
  1) drawings;
  2) design documentation;
  3) technical literature.

APPENDIX I

VOCABULARY

Assembly : An aggregation of components arranged together for a specific purpose.

Compartmentation : The division of a building into fire-tight compartments, by fire resisting elements of construction, in order

- (i) to contain an outbreak of fire, to prevent damage internally to other adjoining compartments and/or building spaces, and to prevent harm externally to the environment;
- (ii) to protect a compartment interior from external fire attack.

Component: A building product, formed as a distinct unit, having specified (ISO 1791) sizes in three dimensions.

Cool smoke: Smoke, remote from the scene of a fire, which has cooled and is drifting at low levels.

Cost - effectiveness: To achieve a defined objective at the lowest cost or to achieve (IEC Treaty, 1994) the greatest benefit at a given cost.

Design fire: A quantitative description of assumed fire characteristics within the Design Fire Scenario. Typically, an idealised description of the variation with time of important fire variables such as heat release rate, fire propagation, smoke and toxic species, yield and temperature.

Design fire scenario: A specific fire scenario on which an analysis will be conducted.

Disabled: Those people, of all ages, who are unable to perform, independently and without aid, basic human tasks or functions because of physical, mental or psychological impairment, whether of a permanent or temporary nature.

Doorset: A component consisting of a fixed part (the door frame) , one or more movable parts (the door leaves) , and their hardware, the function of which is to allow, or to prevent, access and egress.

Element of construction: A functional part of a building, constructed from building (ISO 1791) materials and/or building components.
Examples are floor, roof, wall, etc.

Engineering judgement: The process exercised by a professional who is qualified by way of education, experience and recognised skills to complement, supplement, accept or reject elements of a quantitative analysis.

Environmental impact: Any effect caused by a given activity on the environment, (IEC Treaty, 1994) including human health and safety, flora, fauna, soil, air, water, climate, landscape and historical monuments or other physical structures or the interactions among these factors **;** it also includes effects on cultural heritage or socio-economic conditions resulting from alterations to those factors.

Evacuate a fire building: To withdraw, or cause to withdraw, all users from a fire building, in planned and orderly phased movements, to a place of safety.

Field model: Numerical model to simulate fire development, using partial differential equations to give in all points of a compartment, thermodynamic and aerodynamic variables.

Fire compartment: The compartment of fire origin.

Fire protection: The use of building design, construction, services, systems, personnel and equipment in order to control and extinguish fire, and minimize its effects on people, property and the environment.

Fire resistance: The inherent capability of a building assembly, or an element of construction, to resist the passage of heat, smoke and flame during a fire. (Note: This definition is broader than that in ISO 13943:2000 Fire Safety – Vocabulary).

Fire safety design: The art and science of the design , supervision of related construction , and maintenance of fire safety in the built environment.

Fire safety objectives: An expression of the fire safety design intent for a building, in the form of specific subordinate purposes, towards which the production of a fire defence plan is directed.

Fire safety strategy: A coherent and purposeful arrangement of fire protection and fire prevention measures which is developed in order to attain specified fire safety objectives.

Fire severity: A measure of the destructive potential of an enclosure fire on the constructional elements which form the enclosure boundaries

Fire scenario: A qualitative description of the course of a fire with time identifying key events that characterise the fire and differentiate it from other possible fires. It typically defines the ignition and fire growth process, the fully developed stage, decay stage together with the building environment and systems that will impact on the course of the fire

Fully developed (or engulfed) fire: Fire in a compartment with all surfaces of combustible material burning

Local fire severity parameter: A function of the energy available per square metre to inflict damage on the surface of a constructional component [46]

Localised fire: Fire concerning combustible materials in a localised area of an enclosure.

One zone model: Nnumerical model to simulate fire development, based on the assumption of a well-stirred reactor leading to homogeneous properties of gas in an enclosure.

Penetrating service: Any building service, e.g. cable, conduit, trunking, pipe, flue, duct or shaft, etc., which penetrates a fire resisting building assembly or element of construction.

Penetration sealing assembly: An assembly consisting of one or more penetrating services and their support construction, fire resisting damper assembly, penetration barrier and/or fire sealant, etc., the function of which is to restore the original fire resistance capability of a building assembly or an element of construction.

Performance: Performance is a quantitative expression (value, grade, class or (EU Directive 89/106/EEC) level) of the behaviour of a works, part of the works or product, for an action to which it is subject or which it generates under the intended service conditions (for the works or part of the works) or intended use conditions (for products).

Safety: Freedom from unacceptable risk of harm. (ISO/IEC Guides 2 & 51).

Shutter assembly: An assembly consisting of one movable part (a curtain of horizontal interlocking steel slats) , and its hardware (a suspension system, guide rails, etc.) , the function of which is to allow, or to prevent, access and egress.

Simulated fire: Fire development estimated by numerical or analytical model .

Smoke: The visible suspension of solid and/or liquid particles in gases resulting from fire or pyrolysis.

Smoke resistance: The inherent capability of a building assembly to resist the passage of smoke during a fire.

Structural reliability: The ability of a structural system to fulfil its design purpose, for (ISO 2394) some specified time, under the actual environmental conditions encountered in a building.
In 'hot form' structural design, our concern must be that the structure will fulfil its fire safety design purpose, both during the fire - and for a minimum period immediately following the fire incident.

Two zone model: Numerical model to simulate fire development, based on the assumption of accumulation of combustion products in a homogeneous layer beneath the ceiling.

APPENDIX II

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International Council for Research and Innovation in Building and Construction

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CIB is a world wide network of over 5000 experts from about 500 organisations, who actively cooperate and exchange information in over 50 Commissions and Task Groups. Their scopes extend to all fields in building and construction related research and development. They are listed on the next page.

They are actively engaged in initiating projects for R&D and information exchange, organising workshops, symposia and congresses and producing publications of acknowledged global repute.

It is in their ability to bring a multi-national and multi-disciplinary approach to bear on the subject matter delineated in their Terms of Reference that is their strength.

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CIB Task Groups (TG) and Working Commissions (W)
(as at 1st October 2001)

Task Groups
TG19 Designing for the Ageing Society
TG21 Climatic Data for Building Services
TG23 Culture in Construction
TG25 Facade Systems and Technologies
TG27 Human-Machine Technologies for Construction Sites
TG28 Dissemination of Indoor Air Sciences (joint CIB-ISIAQ Task Group)
TG29 Construction in Developing Countries
TG31 Macro-Economic Data for the Construction Industry
TG33 Concurrent Engineering in Construction
TG34 Regeneration of the Built Environment
TG36 Quality Assurance
TG37 Performance Based Building Regulatory Systems
TG38 Urban Sustainability
TG39 Deconstruction
TG40 Informal Settlements
TG41 Benchmarking Construction Performance
TG42 Performance Criteria of Buildings for Health and Comfort (Joint CIB – ISIAQ Task Group)
TG43 Megacities
TG44 Performance Evaluation of Buildings with Responsive Control Devices
TG45 Performance Indicators for Urban Development (Joint FIG – CIB Task Group)
TG46 Certification in Construction
TG47 Innovation Brokerage in Construction
TG48 Social and Economic Aspects of Sustainable Construction

Working Commissions
W014 Fire
W018 Timber Structures
W023 Wall Structures
W040 Heat and Moisture Transfer in Buildings
W051 Acoustics
W055 Building Economics
W056 Sandwich Panels (joint CIB - ECCS Commission)
W060 Performance Concept in Building
W062 Water Supply and Drainage
W063 Affordable Housing
W065 Organisation and Management of Construction
W067 Energy Conservation in the Built Environment
W069 Housing Sociology
W070 Facilities Management and Maintenance
W077 Indoor Climate
W078 Information Technology for Construction

CIB Task Groups (TG) and Working Commissions (W) (cont)
(as at 1st October 2001)

W080 Prediction of Service Life of Building Materials and Components (also RILEM SLM)
W082 Future Studies in Construction
W083 Roofing Materials and Systems (also RILEM MRS)
W084 Building Non-Handicapping Environments
W085 Structural Serviceability
W086 Building Pathology
W087 Post-Construction Liability and Insurance
W089 Building Research and Education
W092 Procurement Systems
W094 Design for Durability
W096 Architectural Management
W098 Intelligent and Responsive Buildings
W099 Safety and Health on Construction Sites
W100 Environmental Assessment of Buildings
W101 Spatial Planning and Infrastructure Development
W102 Information and Knowledge Management in Building
W103 Construction Conflict: Avoidance and Resolution
W104 Open Building Implementation
W105 Life Time Engineering in Construction
W106 Geographical Information Systems

CIB HOME PAGE

WWW.CIBWORLD.NL

The CIB home page contains the following main and publicly accessible sections:

1. General Information
2. Newsletter
3. Databases

General Information

Included is General Information about CIB in the following sub-sections:

- Introduction, including among others: CIB in the past and present
- Mission Statement
- Membership which includes information on the various types of CIB Membership and on developments in the composition of the CIB Membership
- Organisation, including the composition of the CIB Board and its Standing Committees and of the CIB General Secretariat and links with the CIB Partner Organisations
- Programme of Activities
- Services to Members, and in addition the possibilities for Members to participate in CIB's Programme of Activities
- Fee System and How To Join, including the description of the current Membership Fee Levels and the option to electronically request a Membership Application Form

Newsletters

In this section electronic copies are included of the various issues of INFORMATION, the CIB Bi-Monthly Newsletter, as published over the last couple of years. Also included is an Index to facilitate searching articles on certain topics published in all included issues of Information.

Databases

This is the largest section in the CIB home page. It includes fact sheets in separate on-line regularly updated databases, with detailed searchable information as concerns:

- ± 500 CIB Member Organisations, including among others: descriptions of their Fields of Activities, contact information and links with their Websites
- ± 5000 Individual Contacts, with an indication of their Fields of Expertise, photo and contact information
- ± 50 CIB Task Groups and Working Commissions, with a listing of their Coordinators and Members, Scope and Objectives, Work Programme and Planned Outputs, Publications produced so far, and Schedule of Meetings
- ± 100 Publications, originating to date from the CIB Task Groups and Working Commissions, with a listing of their contents, price and information on how to order
- ± 250 Meetings, including an indication of subjects, type of Meeting, dates and location, contact information and links with designated websites for all CIB Meetings (± 50 each year) and all other international workshops, symposia, conferences, etc. of potential relevance for people interested in research and innovation in the area of building and construction

Searchable Data: an Example

Searching for certain publications in the Databases in the CIB home page can be done in the following three ways:

1. In the home page itself a pre-selection is included of all recent CIB publications (published in the last 4 to 6 months). By clicking on "New Publications" the respective list will appear. By clicking on a title in this list the information fact sheet about this Publication will appear, including the option for an electronic order if it concerns a publication produced by the CIB Secretariat.
2. In the description of a Task Group or Working Commission in the database "Commissions" a pre-programmed selection is included of all publications produced under the responsibility of each Commission.
3. In the database "Publications" one can search, for example, for all publications on a certain topic, by simply typing the word that covers this topic in the box "Title" in the search page that appears when one asks for this database.

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