Fire Safety
and
Concrete Structures

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Choice of concrete, regulations, fire resistance, fire risk, "Fire Safety Engineering" and repair of concrete after fire

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Preamble

The dramatic Innovation fire in Brussels in 1967 revealed the absolute necessity for regulations in the field of fire resistance and a better knowledge of the behaviour of materials and structures in fire.

It was followed by unprecedented work in these areas. It was and is being carried out to meet the preoccupation of any building user or designer: optimum fire safety.

More recently, fires have occurred in mountain tunnels, then under the Channel and in New York on 11 September 2001. Fires also occurred even more recently in Madrid and at Mons on our Belgian motorway network. All resulted in greater vigilance and led to people considering the various components of fires and asking questions about the behaviour of structures in fire.

This publication is aimed at construction professionals, be they project designers, architects or research offices, authors of specifications, building contractors, insurers or public authorities.

The document:

- introduces the basic concepts used to discuss fire and fire safety;
- describes the notion of fire risk;
- demystifies terms such as active protection and "Fire Safety Engineering";
- puts the regulations into context;
- describes the behaviour of concrete and steel materials during and after a fire;
- shows that concrete integrated into a structure in the form of reinforced concrete, prestressed concrete or masonry gives such structures remarkable fire resistance and good prospects for renovation after fire.

It is our hope that this document will provide answers to your many questions, as well as helping to improve understanding of this extensive and interesting field.

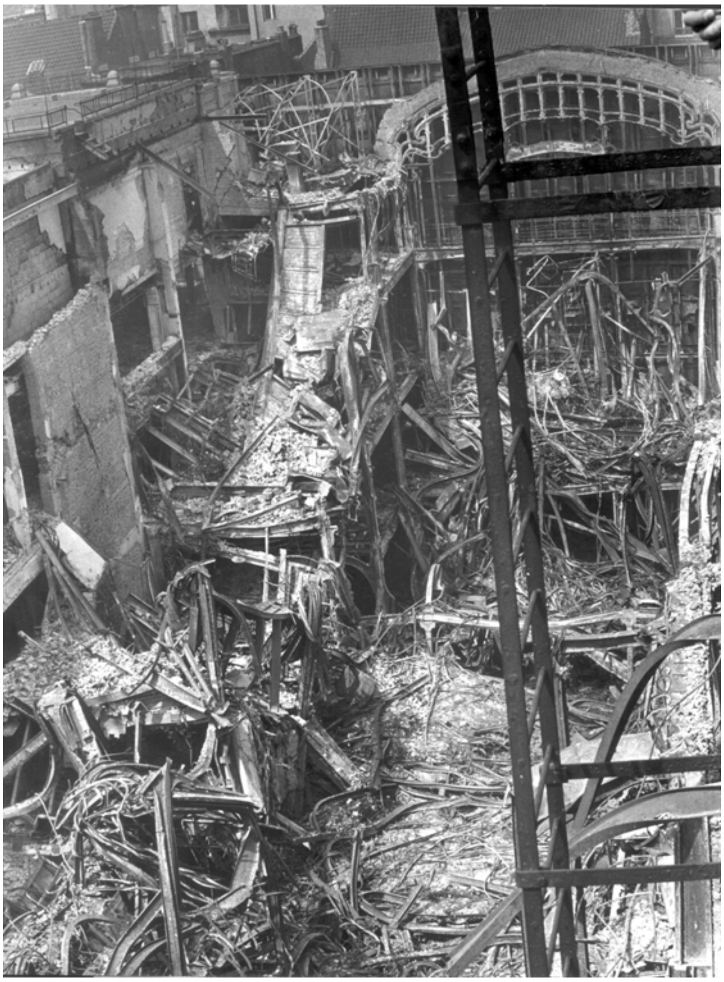
The document can be downloaded from www.febelcem.be

It served as reference document for drafting bulletin nr 37 entitled
"Fire protection by concrete constructions" (20 pp.)
which can also be downloaded from the same website.

Table of contents

A. Introduction

The tragic fire [1] at Innovation in Brussels in 1967 cost the lives of more than 250 people. Hindsight shows that this had to happen sooner or later. In case of fire, several public buildings of the period would be transformed into death-traps.



After the fire, all that remained of Innovation was a pile of twisted steel

At Inno, for example, there was no fire detection system and no sprinklers; no compartmentalisation; no emergency exits; the metallic structure was not protected, highly inflammable cardboard panels covered the walls and were used as false ceilings; the fire service's access to the flaming building was severely hampered by the advertising hoardings that blocked the windows on the façade and by the narrowness of the street congested by heavy traffic and many parked cars.

The shock caused by the catastrophe forced the authorities to take action. Very quickly, the Ministry of the Interior finalised a series of laws, royal decrees and ministerial circulars, and the Belgian Institute for Standardisation (IBN) in turn published standards.

Belgium's case was not unique; all other European countries had to face up to the same problem. Just about anywhere, laboratories were hastily established and series of tests undertaken.

In 1988, the "Construction Products Directive" issued by the Council of the European Communities recognised fire safety as one of the six essential requirements which constructions works must satisfy.

Today, after dozens of years of gestation, genuine harmonised European "product" standards are finally appearing, along with European calculation standards. These are intended to serve as a basis for national regulations.

Even if concrete remains "the" material *par excellence* which has the best fire resistance, we felt it was vital to first visit or revisit the basics of the physics of fire. In the highly emotional way fires are perceived, this should provide elements for assessment and improve our understanding of the behaviour of structures in fire.

It is vital that buildings and structures are designed and built which protect both persons and goods thoroughly and effectively. The annual statistics for deaths caused by fires in homes and elsewhere bring us back to the harsh, sad reality. At the same time, these events allow us to gather information on fire safety for the design of constructions.

An impressive body of national and international legislation exists to protect us from the risks of fire. It is constantly being updated. Relevant and introductory information should be available for construction professionals, be they project designers, architects or research offices, authors of specifications, entrepreneurs, insurers or public authorities. This publication is aimed specifically at these people, who need a summary of the importance of fire safety in the design of buildings and the role concrete can play in that. This summary covers buildings and structures. Reference is made to the tunnels and other extreme configurations in which concrete is used.

"No more disastrous fires"

We can read on the plans for the Hennebique bridge (Paris, 24 November 1904) built in Liège in 1905. This inspired designer, inventor of the stirrups for reinforced concrete, had quickly understood the extraordinary appeal of this material. He turned it into his advertising slogan.

Why choose a concrete structure?

Concrete is specified in buildings and civil-engineering projects for several reasons: questions of cost, of speed of construction, of aesthetic or architectural appearance. Nevertheless, one of the key inherent benefits of concrete is its performance in fire at no extra cost, an aspect which can prove decisive in relation to the factors affecting the decision-making process when designing a project.

Concrete [21] and concrete structures present particularly favourable characteristics:

- Along with masonry, concrete is the only load-bearing material capable of remarkable resistance to fire, **with no additional protective measure** of any kind whatsoever, such as a coating of plaster or intumescent paint. Its properties in relation to its behaviour in fire do not alter over time. They remain **permanent**, with no additional maintenance costs. Simply choosing concrete constitutes a significant element in the preventive safety measures against fire;
- Concrete offers the required resistance in an economic way: more often than not all that is required is to verify **the concrete cover** and the minimum dimensions given in the calculation standards tables. This simple table-based approach avoids the need to get embroiled in the complex art of “Fire Safety Engineering”;
- Concrete load-bearing structures offer extremely high resistance in fire. For example, in large, multi-storey buildings, it **reduces risks** for the occupants of this type of building and for the fire-fighting services. These can enter the building and take action at close quarters and therefore effectively;
- Thanks to their **thermal inertia** and **massivity**, concrete elements, in contrast to unprotected metal sections, withstand high temperatures for a very long time, with a minimum of deformation. Reinforced concrete slab reinforcements only reach their critical temperature of 500 °C after 2 hours, at a depth of 3,5 cm. A lightweight aggregate concrete can satisfy even greater demands. It constitutes an effective barrier against the spread of fire;
- The high thermal inertia of concrete walls is also of considerable interest to **delaying flash-over**;
- Concrete is **not combustible**: in a fire, no element detaches itself from it or drips from it. It does not melt. Concrete does not propagate fire and does not give off smoke or toxic gases, even in the most extreme temperature conditions;
- Concrete fire walls perfectly combine **fire resistance**, **sound insulation and thermal inertia**. The effective compartmentalisation of large spaces using concrete floors and walls reduces the risk of total loss as a result of fire. These elements together with concrete stairwells provide safe, simple and economic **escape routes**;
- Thanks to their intrinsic safety in fire, concrete constructions provide greater **architectural freedom**. Fire demands weigh heavily on other materials that have to be protected by coverings or require active protective measures that do not apply to concrete. In this way the architect can concentrate fully on his architectural creation;
- Concrete structural elements generally have **reserves of protection** against fire that can be used at no extra cost if the fire protection requirements are tightened up, notably if the building is reconverted, as is often the case;
- Concrete’s excellent properties in fire are valued by property insurers: concrete buildings benefit from the cheapest **fire insurance premiums**;
- Concrete **is not afraid of water**, which is often used in large quantities to put out fires;
- Thanks to its use in the compartmentalisation of spaces, concrete prevents fires from spreading, thereby reducing the associated **environmental** impact. Concrete does not generate any toxic residues when attacked by fire;
- Because of the protection it offers, concrete allows **activities to continue** in installations of vital importance. It also protects the compartments that house our **cultural heritage**;
- The use of prefabricated concrete elements allows **speed of execution**, which is greatly appreciated;
- Concrete floors are subject to **little deformation** compared with other materials;
- After a fire, concrete also offers **simple restructuring** at little cost.

The reader will note that this document **does not constitute a complete guide** to fire safety. Rather, it is a general view of the key aspects of fire safety and the behaviour of concrete in constructions. This document is therefore a good introduction to Eurocodes 1 and 2 fire part.

A list of the various publications, standards and sites is provided at the end of the document for all those who might require **more detailed technical information**.

The reader looking for "**A short but relevant document**!" will benefit from the above introduction and the texts in the ochre boxes, such as that on the use of concrete façades in industrial buildings (see p69) or concrete roadways in tunnels (see p71). He will note the examples of the fire behaviour of concrete structures in fire. These examples can be found at the end of the document (see p73).

Regulations (see p22) are the subject of a chapter which may be read independently. In the chapter devoted to the Royal Decree of 1997 (see p25), everyone can profit from a brief reminder of the provisions imposed by Belgian regulations on **stairwells, lift shafts, aprons and piers**.

B. Fire safety

1. Purpose of fire safety: protection of persons and goods

The purpose of fire safety [18], [20] is the effective protection against the risks of fire of persons and goods. More specifically, this concerns

- Saving the lives of the occupants of the building
- Protecting the lives of the emergency services
- Protecting the integrity of the building
- Saving adjacent buildings

In the absence of a specific insurance policy covering production stoppages, in industrial buildings, insurance premiums adjusted according to the risks run only cover loss of goods, and not production stoppages. This becomes extremely important when you consider that almost 50 % of business that suffer a major fire go bankrupt [6].

The basic requirements of fire safety consist in

- reducing the development of the fire;
- avoiding spread of fire;
- ensuring the speedy evacuation of occupants in relative safety;
- facilitating the intervention of the fire service.

The following table [33] shows how concrete elements satisfy these basic requirements of fire safety.

Fire safety [32] cannot be absolute. It consists of reducing the risks by taking a series of measures. Each of these measures is insufficient in itself, but a high degree of safety can be achieved by combining them.

In many European countries, there is a tendency [33] to reduce the requirements placed on the fire protection of buildings. This directly affects the resistance to fire required of structural elements. The main reason for this attitude stems from the belief that only the resistance to fire necessary to protect persons need be regulated by the public authorities. Responsibility for protecting buildings and goods is therefore transferred to the general public. In its annual report for 1999, the World Fire Statistics Centre presented an international comparison of the costs associated with fires. This comparison reveals the importance of fire protection:

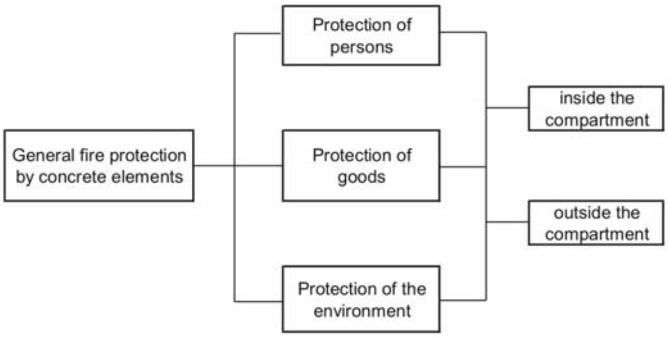
- The total cost of fire damage is between 0,2 and 0,3 % of gross national product;
- The number of deaths caused by fires varies per 100 000 inhabitants from 0,55 in Switzerland to 1,32 in Belgium and 2,12 in Finland.
- The sum of the costs associated with protective measures and fire damage amounts to 0,6 % of gross national product on average.

basic requirements of fire protection			
reduce the development of the fire	avoid the **spread** of the fire	ensure **the speedy evacuation** of occupants in relative safety.	facilitate **the intervention** of the fire service
↓	↓	↓	↓
preventive and protective measures			
e.g. Using non-combustible walls, floors and ceilings	e.g. Using highly effective fire walls both internally and externally	e.g. Escape routes consisting of highly fire-resistant elements that can be used for long periods	e.g. Highly fire-resistant load-bearing structures that allow the fire to be tackled effectively within the building

Relationships between basic fire protection requirements and protective measures

These figures show the need for general fire protection. Reducing the number of deaths by fire and the costs associated with fire damage should be undertaken as an indisputable social and economic aim.

Limiting pollution caused by smoke, toxic gases and contaminated fire-fighting water should in turn help protect the environment.



The overall effects of fire protection involving the use of concrete elements (Neck, 2002)

The reports of the NFPA [41] (National Fire Protection Association) state that in the United States between 1977 and 2002, the average financial loss per fire affecting the structure rose by 51 %. This increase is linked to a relaxing of the safety requirements specifically for the protection of buildings. These direct or indirect losses, such as the relocation of residents or the activities of the company, can have an enormous economic impact on the community. Regulations should take this impact into consideration.

To fight fire effectively, the fire-fighting services must be able to operate inside the building [23]. In this respect, concrete structures are the most reassuring both at the evacuation stage and the fire-fighting stage.

According to observations [32] made in England of 840 fires, the probability of the structure being destroyed is low (1 %) (taking all structural materials together!), while the localised destruction of a structural element is greater (15 %). This gives an idea of the importance of being able to repair structures.

The concrete sector is involved in efforts to optimise the **safety** and e**conomy** of projects. The presentation in this document of the scientific approach used by "Fire Safety Engineering" is worth risking opening. It thus hopes to provide an objective view of the problem. Most certainly it will reject simplistic or compartmentalised and non-integrated approaches. The interests of the parties concerned: owners, architects, building contractors, product manufacturers, insurers, occupants of buildings and visitors, do not necessarily converge. Balanced regulations should provide for the training and acceptance of people for calculations and inspections.

A lack of measures and means on the part of the public authorities should be a clear indication that reliable solutions should be favoured, and responsibilities assigned to those with both the will and the capability to take them on.

2. Fire physics - basic concepts

2.1. Terminology: fire and “a fire”

Fire involves combustion [4]. This is found in furnaces and boilers in the form of **controlled combustion**. “A fire” involves **uncontrolled combustion**. It then assumes such a size that it can cause a **fire.**

There is a fundamental difference between fire and a fire. **Fire experts** master a controlled combustion which corresponds to the scenario defined by a predetermined thermal programme. These are found in the glass industry, the ceramics industry and other industries, as well as in test laboratories, all places where fires are produced in furnaces or test chambers, where smoke is channelled so as not to inconvenience operators. The **fire experts** that are firemen in turn have to try and master an uncontrolled combustion which corresponds to a scenario strewn with unforeseen aspects, with human lives that have to be saved, who also have to save, intervene, and so on.

2.2. The course of a fire

2.2.1. The fire triangle

For a fire to start [5], three elements must be present simultaneously: oxygen (21 % volume in air), combustible materials and a heat source. These make up what it is convenient to call the **fire triangle,** shown in the figure below. The first two elements [19] combust when the inflammation temperature is reached. The combustion of carbon produces carbon dioxide CO_2 and, if there is a lack of oxygen, it produces the well known gas CO, which is highly dangerous to man.

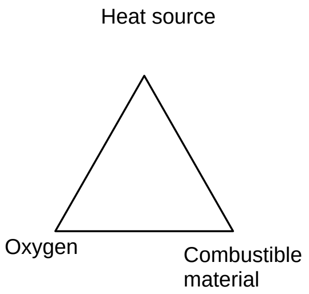


figure : the fire triangle

2.2.2. The development of a fire – flash-over

A fire involves a development phase in which the temperature increases, then a decline phase in which this temperature drops.

A heat source causes a fire to start in a quantity of materials. The first gases and smoke appear. In a closed environment, under the action of the increasing heat, the smoke rises to the ceiling in a plume. At this point, it spreads radially along the ceiling until it reaches a wall and continues downwards where it stagnates in an upper layer beneath the ceiling.

In general, the room contains a cool lower layer composed of ambient air, gas and a warm upper layer (two-zone model). A temperature in the order of 200 °C causes windows to break, creating a sudden influx of fresh oxygen which gives the fire a new lease of life. The upper layer moves closer to the floor because it increases in volume as a result of being fed by plumes of smoke.

During the development of a fire there may be a time when the temperature of the gaseous mixture of the upper layer is so high that it causes any combustible element in the compartment to ignite. This phenomenon is known as **flash-over**. It generally corresponds to a temperature of 500 to 600 °C. The extremely rapid rise in temperatures in the compartment and the increase in the release of heat cause the smoke to be stirred up where the layers mix (single-zone model). The fire is then said to be “fully developed”.

These different phases in the development of a fire are depicted in the next graphic, showing the evolution of the temperature in the compartment as a function of time.

The fire will be controlled by the fuel if there is sufficient oxygen available for combustion. It will be controlled by ventilation if there is insufficient oxygen.

The fire resistance of columns, beams, walls and slabs must prevent the spread of the fire and the collapse of the structure to allow the extinguishing operations to pass off smoothly without the firemen being exposed to excessive risks.

When more or less 70 % of the fuel has been consumed, the temperature of the gas drops. For information, the carbonisation speed of wood is between 3 and 6 cm an hour depending on its species.

2.3. Nominal curves – the ISO curve

The simplest way of representing a fire is to use nominal curves giving the evolution of the temperature of the gases as a function of time.

Historically, nominal curves were developed to test structural elements experimentally with a view to establishing a relative classification for both their resistance and reaction to fire (see §2.4 below). It is highly desirable for elements tested in different furnaces to be subjected to the same thermal action. In terms of modelling a fire in a building, these curves constitute a conventional reference.

For reasons of history and simplicity, they remain by far the most common method of representing a fire in practical applications.

The notion [32] of time of resistance conforms to the performance-based concept: no type of material is excluded and the performance of the element is prescribed.

The curves most frequently used are shown in the figure below. They were produced from experience of real fires, belonging to one of the three main categories, namely buildings, petrochemicals/oil rigs and tunnels.

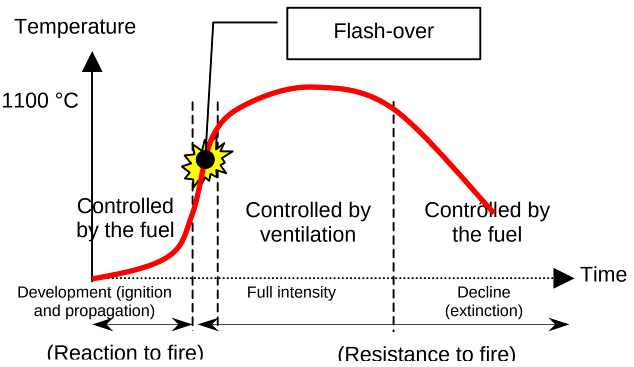


Figure: phases in the development of a fire

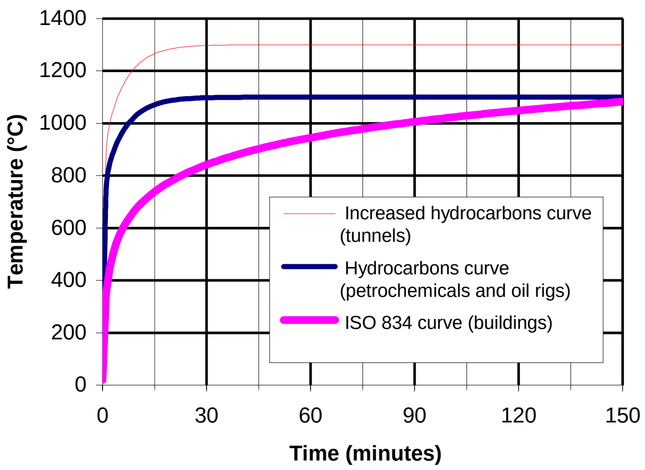


Figure: Different temperature curves

The standard ISO curve: $\theta_g = 20 + 345 \log_{10}(8t+1)$

Where θ_g = temperature of gases in the compartment in °C

t = time in minutes

For the ISO curve it is easy to remember that, after ¼ hr., the ambient temperature reaches around 745 °C and continues to increase by around 100 °C each time the time is doubled.

In this equation, the two phases [5] that occur during a fire can easily be identified: the flash-over period in which there is a very rapid increase in temperature to around 800 °C, then the period when the fire is fully developed.

The hydrocarbons curve [55] developed in the 1970s by the petrol company Mobil shows a very rapid increase in temperature with a temperature of 900 °C in the first 5 minutes and a plateau at 1100 °C. This research was begun to perfect a test procedure to evaluate fire protection materials for oil rigs and petrol complexes.

More severe hydrocarbon curves have been perfected more recently following the wave of major fires in tunnels, which revealed that more severe fire scenarios had to be considered. The Netherlands have perfected the "RWS" curve, simulating the behaviour in fire of tankers transporting petrol with a calorific power of 300 MW, generating a temperature of 1350 °C and causing a fire that lasts 2 hours. The Netherlands developed this curve as a realistic and essential thermal calculation reference to guarantee the behaviour of their tunnels passing beneath their hydraulic works.

The Germans have developed their curve: the RABT curve (sometimes known as the ZTV), less severe than the RWS curve, rising to 1200 °C for 1/2 hour before falling linearly to the ambient temperature after 170 min.

A new curve, different from the RWS and RABT curves, known by the name "increased hydrocarbons curve" (IHC), has finally been created by increasing the hydrocarbons curve by 18 %. The temperature plateau is therefore 1300 °C.

Concrete elements can easily withstand an ISO fire of 1 hour. A greater resistance can easily be obtained, which is anything but the case with unprotected metal elements. After 10 to 15 minutes, steel reaches 500 to 600 degrees and its resistance declines rapidly. Boards and paints are available which insulate steel, but poor site execution and reported degradation of these materials can have dramatic consequences.

2.4. Reaction and fire resistance

Reaction to fire [18] applies to construction materials. It measures all the properties of construction materials in relation to the birth and development of a fire. It is characterised by calorific potential [5], non-combustibility, inflammability, the means of propagation of flames on the surface of materials, where applicable by other properties such as the formation of smoke and the production of toxic gases.

Resistance to fire applies to structural elements. It is a measure of their ability to perform the role assigned them despite the action of a fire.

These two notions are therefore completely different. The first concerns the birth and development of the fire, while the second occurs in the full intensity phase. Neither area can be neglected in fire prevention. The instructions therefore include requirements relating to both aspects.

Thus, wood [5] is a material that does not react well to fire – wood burns – while wooden beams and columns are structural elements with a significant resistance to fire.

Conversely, steel is a material with a good reaction to fire, while steel elements are structural elements with a very poor resistance to fire.

Finally, concrete combines the two qualities. This is why it is "the" preferred material for structural elements where good fire behaviour is sought.

Because they are more permanent, the choices that improve the fire resistance of structural elements offer greater safety for preventing fires. Each modification (renovation, enlargement) is subject to a new building permit or a revision of the operating licence where the fire services are consulted.

The same is not true of finishes, especially in residential buildings, where the owner/tenant of the property can alter the content of the building and the nature of the claddings to such an extent that the load and risk of fire are fundamentally changed.

2.4.1. The reaction to fire of construction products - Classification

With regard to the reaction to fire mentioned in CE marks, every construction professional owes it to himself to get to grips with a minimum of European language to understand the new tests and classification standards.

This system of classification [40] was the subject of decisions by the European Commission on 08-02-2000 [61], [63] and 26-08-2003. As the decrees implementing this marking appear, manufacturers have to check that their products comply with the new European requirements and if necessary modify these products.

The number of classes, the logic which enabled their construction and some of the tests used differ from current Belgian practice, so much so that there is no correspondence between current Belgian classification and the system of Euroclasses.

Construction products are separated into two main families [12]: that of floor coverings and that of other products. This distinction is explained by the fact that the scenarios of exposure to fire and the behaviour of the materials differ in both cases. In each of these groups, the Euroclasses, which number seven, defined in NBN EN 13501-1:2002 [105], are as follows:

- $A1_{Fl}$, $A2_{Fl}$, B_{Fl}, C_{Fl}, D_{Fl}, E_{Fl}, and F_{Fl} for floor coverings (Fl for "floor")
- A1, A2, B, C, D, E, and F for other construction products.

Classes A1 and A2 (or $A1_{Fl}$, $A2_{Fl}$) are assigned to products with a low or very low organic fraction which are therefore hardly or not very combustible.

Classes B to E (or B_{Fl}, E_{Fl}) are assigned to combustible products which contribute significantly to fire development, for both floor coverings and other products. Class E applies to products that meet the minimum German marketing criterion and class F applies to unclassified products or those that have failed the least severe test.

Alongside the reaction itself, some construction products are given two additional qualifications:

- s1, s2 or s3 for the **production of smoke** (s = 'smoke': the higher the number, the more smoke is emitted):
    - s3: no limit for smoke emission;
    - s2: the total emission of smoke and the speed of emission are limited;
    - s1: stricter requirements than for s2.
- d0, d1 or d2 for behaviour faced with **falling droplets and burning particles**: (d = 'drop': the higher the number, the more drops are produced):
    - d2: no limit;
    - d1: production of droplets / incandescent particles over a specific period;
    - d0: no production of droplets / incandescent particles

The table [51] below allows reaction to fire classes to be transposed between the old French classification and the new European classification (EN 13501-1):

Classes to NF EN 13501-1 new classification			Requirement of old classification
A1	-	-	Incombustible
A2	s1	d0	M0
A2	s1	d1	M1
A2	s2 s3	d0 d1	
B	s1 s2 s3	d0 d1	
C	s1 s2 s3	d0 d1	M2
D	s1 s2 s3	d0 d1	M3 M4 (non-dripping)
All classes other than E-d2 and F			M4

In 1996, the European Commission published a regulatory list of construction materials [34], [61] which may be grouped together into protection class A1 without further examination. This list contains the different types of concrete or mineral constituents used in concrete. For the materials on this list, this classification is linked to the requirement of a level of organic constituents evenly distributed of less than 1 %.

Concrete, a mineral construction material [33], satisfies the requirements of class A1 because in fact it is not inflammable and does not catch fire at the temperatures encountered in fires. No burning element is released by or runs off concrete.

According to this system, construction materials belonging to class A2 are not considered inflammable but typically contain inflammable constituents which could therefore burn in a fire and cause damage.

The behaviour in fire of a product largely depends on the thermal stress scenario to which it is subject. To reproduce the fire scenarios most frequently encountered in buildings, three levels of thermal exposure are envisaged. These correspond to three stages of possible development of a fire:

- attack by a small flame;
- attack by a fully developed fire in the adjacent room or by a burning object;
- attack by a fully developed fire in the room.

The Euroclasses are subject to 5 types of test, on samples, 4 of which are new, notably the SBI (single burning item).

2.4.2. Reaction to fire – Attestation of conformity

The table [64] below explains the different levels of attestation of conformity required, depending on the products and their classes. These attestation systems allow the presumption of conformity with “product” standards to be obtained in relation to the fire safety stake.

Class	systems of attestation of conformity
A1*, A2*, B*, C*	1
A1**, A2**, B**, C**, D, E	3
(A1 to E)***	4

* products undergoing a treatment to improve their reaction to fire
** products without treatment
*** products “deemed to satisfy”, classified without test

The table below details the tasks dedicated to each party for the different levels of attestation of conformity:

Systems	Tasks dedicated to approved bodies	Tasks dedicated to producer
1	- initial type tests - initial inspection of the factory	- production control - supplementary tests
3	- initial type tests by the approved laboratory	- production control
4		- initial type tests - production control

2.4.3 Fire resistance of structural elements

The ability of a concrete construction to retain its load-bearing function for the required duration is expressed as follows:

$$E_{d,fi}(t) \leq R_{d,fi}(t)$$

where: $E_{d,fi}(t)$ is the calculated value of the effect of actions, loads at the time (t) of the fire;

$R_{d,fi}(t)$ is the calculated value of the construction's resistance to high temperatures at time (t).

The fire resistance of structural elements is measured in tests under the thermal stress described by the ISO curve. It comprises the three criteria that apply to most construction elements:

- stability **R** (load-bearing capability);
- flame integrity **E;**
- thermal insulation **I.**

In some Member States, the performance requirement **W** (limited radiation) may be required. To this are added supplementary criteria: **M** (impact resistance), **C** (automatic closure) and **S** (smoke integrity) as well as suffixes providing specific details relating to the configuration of exposure to the fire and the field of application of the test results.

The degree of resistance REI of the element is the time immediately below the observed duration, chosen from the values 15, 20, 30, 45, 60, 90, 120, 180, 240, 360 minutes, [61], [62].

By way of example, a test on a load-bearing wall gives the following results:

	Time	Classification
Load-bearing capacity	130 min	R 120
Fire integrity	92 min	RE 90
Thermal insulation	46 min	REI 45

The wall therefore enjoys classifications R 120 / RE 90 / REI 45

The "stability" criterion (R) of an element indicates the time during which its mechanical resistance is guaranteed under the static load defined in §6.1 and during which its deformations remain compatible with its function in the stability of the construction (generally 1/30th of its span). It corresponds to the French denomination of "Stable au Feu SF".

The criterion of "flame integrity" (E) is no longer satisfied when a cotton cloth, placed at a distance of 2 to 3 cm from an opening, spontaneously combusts.

The French denomination "Pare-Flamme PF" corresponds to the RE. criteria.

The criterion of "thermal insulation" (I) is satisfied if the increase in temperature of the unexposed surface of the element remains below 140 °C on average and 180 °C occasionally.

The French denomination "Coupe-Feu CF" corresponds to the REI criteria.

These last two criteria enable inflammation of materials in contact with this face to be avoided.

In load-bearing structural elements such as beams, columns, walls and slabs, the resistance R prevents the structure from collapsing. In general, the separating function (E and I) applies to elements that form an integral part of the walls and envelope of the compartment: i.e. the walls and slabs.

For the load-bearing capacity function, it is worth evaluating all modes of failure, such as rupture by flexion, by shearing load, by buckling or rupture of the anchoring of concrete element reinforcements.

The ISO curve test does not take into account links with neighbouring elements, which allow stresses to be redistributed to less exposed sections or elements.

Some phenomena, in particular the expansion of the entire structure under the influence of high temperatures, are not taken into consideration in the ISO curve test, yet these may be decisive in reality.

The concrete elements of buildings can satisfy all fire resistance classes defined by the European "Fire Safety" Directive "without any additional protective measure whatsoever (plaster coating, intumescent paint, etc.).

Attention! The fact that a structural element has withstood a fire does not mean that the element has not suffered damage, or that the element does not need replacing. It simply means that the structural functions of the element were fulfilled under the thermal and mechanical loads supported.

If a calculation is made for a required period of fire resistance, there is no need to worry about the behaviour of the structure beyond this period nor, a fortiori, after the structure has cooled down to ambient temperature.

The tests include limits: costly, they only allow elements of limited length to be tested, generally without being able to reproduce at their extremities the ties to the structure.

To avoid [37] a fire-resistance test being necessary for each construction product, calculation methods have been perfected to define the thermal (§6.2) and mechanical (§6.1) stresses and thereby evaluate the resistance to fire (§8.1) of structures made from concrete, steel mixed steel/concrete, wood, brick and aluminium. These calculation methods can be found in the section of the Eurocodes on fire behaviour. The aim of these documents is to define with a common manner through the whole Europe the structures withstand to the fire.

Based on these design standards, an European product standard has been drawn up specifically for each type of element. Thus false ceilings, service ducts, façades, walls, valves, concrete hollow core slabs, etc. have a specific standard. This provision is not that which prevailed in Belgium where, previously, all these elements were dealt with within a single standard.

The denominations R, E and I are not included in the Belgian basic standard but are currently included internationally, notably by the CEN, the European Committee for

Standardisation. The denomination R_f in hours of the standard NBN 713.020 will be adapted to the denomination REI in minutes, in accordance with CEN standards. The texts have already been prepared in this sense by the FPS Home Affairs.

At present, furnace tests have been standardised at European level to ensure they can be reproduced from one furnace to the next.

Previously, results could vary considerably [1], for example from two to more than five hours for the same hollow core slab element in different furnaces. By comparing the increases in temperature [5] measured on the exposed face of an identical element placed in 14 European furnaces respecting the ISO curve, the temperature of 800 °C is reached after times of between 28 and 48 minutes. Belgian furnaces are among the most severe.

The differences were due, among other things, to the radiation of the flames and the walls of the furnace, to the overpressure imposed in the furnace, and to the support conditions. Belgium was the only country to impose such a high gas overpressure value (20 Pa). This difference significantly alters the fire-resistance times of elements which have a separating function but not the resistance of load-bearing elements completely surrounded by the fire.

3. Regulations

3.1. European directives and Eurocodes.

3.1.1. European directives

If we wish to understand the far-reaching changes in the market and fire regulations, we have to understand the overall context.

The "Construction Products Directive", the CPD, [2] distinguishes between six essential requirements (ERs) for which the Member States are allowed to regulate construction works:

1. mechanical resistance and stability;
2. fire safety;
3. health;
4. hygiene and the environment;
5. safety of use;
6. energy savings and thermal insulation.

As its name suggests, the CPD is imposed by the European Union on PRODUCTS placed on the European market, delivered to sites, but NOT on STRUCTURES built on sites with these products: the requirements relating to structures remain within the competence of the Member States.

ER 2 of fire safety is regulated at federal level in Belgium. The regulation of ER 1 currently rests on the decennial responsibility of the designer and entrepreneur. ER 6 is the subject of a European Directive on the energy performance of buildings recently transposed into our regional regulations.

This "Construction Products" Directive is one of the "new approach" directives enacted following on from the Treaty of Rome of 25 March 1957 establishing the European Economic Community. The main aim behind creating it was to remove the obstacles to the free movement of people, services and goods (and therefore products) between Member States. An interpretative document, drafted by the European Commission in collaboration with European experts, is linked to each of the essential requirements. Following the general objectives released in the interpretative document for the ER fire, the building [107] must be designed and constructed such that in case of fire:

- the propagation of the fire and of smoke in the building is limited;
- the structural elements retain their function for a predetermined time;
- the fire is prevented from spreading to adjacent buildings;
- people can vacate the building or be rescued in some other manner;
- the safety of the fire services is guaranteed.

It should be pointed out that the protection of goods as well as the preservation of production stops do not in themselves constitute objectives of the CPD. The European Commission leaves it up to each country to determine the level of safety for people in their country. The additional information specific to NBN EN 1992-1-2 [107] specifies that each country is at liberty to impose criteria in its regulations which take into account the protection of directly exposed goods for economic and/or environmental reasons. The regional authorities in charge of economic development and those in charge of the environment may be aware of the aspect of the preservation of production stops and the environment. Obviously these aspects also fall within the competence of the building owner (see §1. devoted to fire-safety objectives).

Still [107] according to this interpretative document n^{r}2, the essential requirement can be respected by following the various possibilities for fire-safety strategies in force in the Member States, such as conventional (standardised fires) or "natural" (parametrised fires) fire scenarios, which include passive and/or active protective measures against fires.

The required functions [107] and levels of performance may be specified, either in terms of degree of resistance to a standardised (standard) fire, as is the case in Belgium, or by referring to engineering fire-safety studies to evaluate the passive and active protective measures. See NBN EN 1991-1-2 [106] (see request for dispensation in Belgium)

Supplementary requirements [107] concerning, for example:

- the possibility of installing and maintaining sprinkler systems;
- the conditions of occupation of the building or of a fire compartment;
- the use of approved insulating or cladding materials, including maintenance thereof

are not included in the EC1 fire, as they must be the subject of specifications emanating from the competent authority.

For a long time, the CPD stumbled on perfecting fire-reaction standards, since each country has its own procedures. However, three-quarters of construction products are concerned by fire safety.[12]

Many construction products, for example hollow core slabs and concrete blocks, are the subject of a harmonised European product standard. It is said to be harmonised as soon as it has an appendix Z and this is included in the European list of harmonized standards. This appendix lists the various characteristics which any producer must declare in its CE mark. This mark is affixed to products or included in the documents accompanying products. A "harmonised" product sold within the European Economic Area **must** bear this mark. The characteristics to be declared must comply with the standard and be certified in accordance with attestation system 1+, 1, 2+, 2, 3 or 4. 1+ corresponds to certification by a third party, while 4 corresponds to a simple declaration of conformity by the manufacturer.

Since like most Member States Belgium possesses fire regulations, all construction products whose standard is harmonised **must**, in order to be used, include in their marking a declaration relating both to reaction and resistance to fire.

The **product standards** refer to a great many **test standards** prepared by the European Committee CEN TC 127. They are beginning to replace the tests described in Belgian standard NBN 713-020.

Colruyt Ghent [58]: (source ERGON)

This building has a 3000 m^2 car park on the lower level for customers as well as an unloading bay for deliveries. The actual store is situated above the car park and the staff premises are located on an intermediate level.

The columns have been fitted with various accessories allowing both cellular concrete façade elements and prefabricated fire-escape stairways to be attached.

The TTPL 840 slabs of the floor of the shop extend beyond 17 m and can take a load of 1200 kg/m^2. The roof consists of IV beams.

The columns of the central axis are fitted with a downpipe for rain water dia. 160 mm.

The structure was installed in around twenty days.

3.1.2. The Eurocodes

The product standards are based on European **design standards** known as Eurocodes, 58 in number, produced by the TC250 Technical Committee of the CEN, the European Committee for Standardisation. It was the European Commission which delivered a mandate to draft these standards. Thus, to date, the design standards relating to concrete subjected to fire and published by the IBN between 1995 and 1999 which apply in Belgium are:

- NBN ENV 1991-2-2 + NAD "Actions on structures exposed to fire";
- NBN ENV 1992-1-2 + NAD "Design of concrete structures" fire part;
- NBN ENV 1994-1-2 + NAD "Design of mixed steel-concrete structures" fire part;
- NBN ENV 1996-1-2 + NAD "Design of masonry" fire part.

It is more usual to talk of Eurocodes 1, 2, 4 and 6, fire part. These Belgian standards are European pre-standards, supplemented by their National Application Document (NAD).

These pre-standards (ENV) will soon be replaced by European standards (EN), combined with their national appendix (ANB for Annexe Nationale – Nationale Bijlage - National Appendix).

It should be noted that the first number just after the EN or ENV acronym does not correspond to a date! Unfortunately the CEN assigned the series 1990 to 1999 to the Eurocodes. The publication date of the standard is given at the end of the name of the standard (see example hereunder).

What do the terms "informative and normative annexes" mean?

When an appendix to a standard is made normative, the designer must comply with the calculation method described in this appendix if he has to have recourse to it. If it is presented as informative, the designer, if he wishes to have recourse to it, may draw their inspiration from this appendix, with the approval of the client and the competent authorities. It is only compulsory to apply it if required by the client.

Each member country of the CEN sets safety levels and classes via parameters to be determined at national level (known as "National Determined Parameters", NDP). The national appendix to standard NBN EN 1991-1-2:2003 "Actions on structures exposed to fire" will be published this year.

What about standardisation at European level? [13]

The project anticipates providing European Member States, within the near future, with EN standards on calculating the behaviour in fire of structural works. Within a prescribed time limit, each country must transpose them into national standards. For example, in the informative appendices, each country will be free to adopt different fire loads. The choice of safety level falls within the competence of the States. The publication of approved fire Eurocodes could see the light in 2007 (Belgian Official Journal). We should emphasise that these standards become compulsory only by contract or administrative or legal deed.

NBN EN 1992-1-2:2005 "Design of concrete structures," fire part was published by the IBN at the beginning of 2005.

The European pre-standard, coupled with its national application document (NAD), NBN ENV 1992-1-2, is currently in force in Belgium.

The European standard NBN EN 1992-1-2:2005 is currently being translated into Dutch.

Its national annexe (ANB) should be available this year for use in conjunction with concrete product standards.

After a public enquiry and publication, it will enjoy a maximum period of co-existence of three years with the ENV, at the end of which time the ENV will be withdrawn.

3.2. Status of Belgian fire regulations

Safety in the event of fire falls under the responsibility of the building owner. They determine with the architect the active and passive measures that will protect their building.

3.2.1. General context

Legislating [40] in the field of fire prevention in Belgium is no easy matter. In legal terms, fire prevention is said to be an accessory competence. In common parlance, this means that there is not one minister in charge of fire prevention but several. For this subject area, new building projects are subject to regulations spread across several levels of competence:

1. The commune which, since 1790, has had the general task of preventing and stopping fires through communal regulations and building permits;
2. The Communities, notably competent for hotels;
3. The Regions, notably competent for rest homes;
4. The Federal Government, which has successively regulated the fire safety of workplaces (RGPT, since 1947), hospitals (1979), electrical installations (RGIE, 1981) and tall new buildings (1972), then medium and tall (1994), low (1997) (revised basic standards in 2003).

At federal level, the job of determining **basic standards** for prevention common to one or more categories of construction, independently of their destination, lies with the FPS HOME AFFAIRS. Still at federal level, for the application of certain requirements relating to fire prevention, competence lies with other ministers via other regulations. The table above shows the allocation of competences as an example.

Federal				Communities			Regions		
FPS Home Affairs	FPS Employment - Labour	FPS Economy	FPS Public Health	NL	FR	D	Flanders	Brussels	Wallonia
Basic standard	Legislation on Welfare at Work, RGPT (schools included)	RGIE - DPC	Hospitals et psychiatric institutes	Hotels			Town and country planning		
							Homes		

Table: As an example: distribution of competences in the field of fire prevention in Belgium

Moreover, when this regulation is revised, the term “basic standards” should disappear in favour of the term “General Regulation”, so as not to maintain confusion by the term “standards”. A standard summarises good practice in a field. It only becomes compulsory if established as such in a regulation.

There are [40] several sites containing detailed information, notably: www.previ.be [66], www.previlex.be, www.normes.be [7], www.anpi.be [60]. These sites are full of information. However, it is always wise to check the information published on these sites and to make sure it is up to date.

3.2.2. Basic standards of fire and explosion prevention

3.2.2.1. Field of application and reference date

The Appendices to the Royal Decree (RD) of 19 December 1997 [201] establish the basic standards in terms of fire and explosion prevention. These must be satisfied by multi-storey **new buildings** and also, for the single extension, **extensions to existing buildings.**

Until 04 April 2003 [40], the basic standards also applied, for the renovated part, during **renovations of existing buildings.** The repeated problems associated with the way in which the basic standards had to be applied in case of transformation led renovations of existing buildings to be excluded from the field of application from this date. A specific regulation for renovations is currently being studied.

As part of the procedure of granting a development licence, despite the exclusion of renovations, safety measures may be required. They will have to be based on the provisions of the basic standards. If some provisions of the basic standards are difficult to apply to a renovated building, they can be reduced and compensated for by others, based on a decision taken at local level (the mayor, advised by his fire service).

The RDs of 94 and 97 do not apply to single-family houses, industrial buildings and buildings with up to two levels covering a total area less than or equal to 100 m^2.

It is the date of the acknowledgement of receipt by the commune of the complete development licence application file that determines which version of the basic standards applies.

In summary:[8]

Building permit	Low buildings	Medium buildings	Tall buildings
Before 1972	N/A	N/A	N/A
22/12/1972	N/A	N/A	RD 04/04/1972 including NBN 713-010
1980	N/A	NBN S 21-201,2,3	NBN S 21-201,2,3
26/05/1995	N/A	RD 07/07/1994	RD 07/07/1994
01/01/1998	RD 19/12/1997	RD 19/12/1997	RD 19/12/1997
04/04/2003	RD 04/04/2003	RD 04/04/2003	RD 04/04/2003

Table: Reference dates for the application of modifying decrees *[101], [102], [103], [104].*

3.2.2.2. Royal Decree (RD) of 1997

Appendices 1 to 5 of the Royal Decree (RD) of 1997 are

1. Terminology;
2. Low buildings (LB) $h < 10$ m;
3. Medium buildings (MB) 10 m $\leq h \leq$ 25 m;
4. Tall buildings (TB) $h > 25$ m;
5. Reaction to fire of materials.

The height limits correspond to the sizes of the fire service's small and large ladders. The height (h) in question is the distance between the level of the floor of the highest storey and the lowest level of the streets surrounding the building that can be used by the fire service. In general [5], the requirements are:

- 2 h for TBs and underground levels of MBs;
- 1 h for floors of MBs and LBs;
- ½ h for roofs of LBs.

The requirements [20] for basements are stricter than for ground floors and upper floors of the same building, give the greater problems to intervene in the event of a fire in the basement.

The provisions of these basic standards that apply to buildings concern:

- location and access roads;
- compartmentalisation and evacuation;
- certain construction elements;
- the construction of the buildings and evacuation areas;
- the construction of certain premises and technical areas;
- the equipment of the buildings.

The classification for reaction to fire included in appendix 5 of the basic standards comprises 5 classes: A0 to A4. The document also puts forward requirements for reaction to fire according to type of premises. A new version of this appendix, introducing the new European classification, is currently being finalised.

Specifically, for insulating materials, a correlation table of past and present reactions to fire was drawn up in two different versions. In the absence of a consensus within the High Council, two different proposals were drafted and sent to the Minister for Home Affairs to allow him to choose one of them.

Obviously the few architectural provisions to be retained and included below cannot replace the complete text of the basic standards (110 pages) [11]:

The **horizontal distance** between a building and an opposing building shall be 6 m for LBs, 8 m for MBs and TBs, except if the walls satisfy the requirements defined for contiguous buildings. This distance does not apply to buildings that are separated by existing streets or lanes, etc. belonging to the public domain.

Walls that separate contiguous buildings shall have an Rf of 1 h for LBs, 2 h for MBs and 4 h for TBs.

Buildings shall be divided into **compartments** whose **area** shall be less than 2500 m^2, except for car parks. For **atriums**, the compartment which extends over several levels must be equipped with an automatic extinguishing system and a heat and smoke exhaust system. The presence of these installations allows the limit of 2500 m^2 to be exceeded.

Lintels (part below the floor)**, aprons** (part above the floor and below the window) **and piers** (part of façade between two windows): the sum of the dimensions, as given in the following figure, shall be greater than 1 m (MBs and TBs)

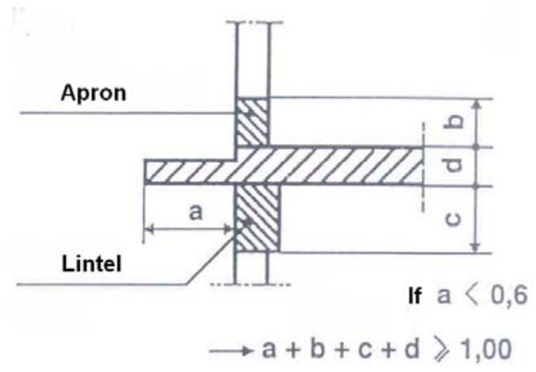


Figure: apron [18]

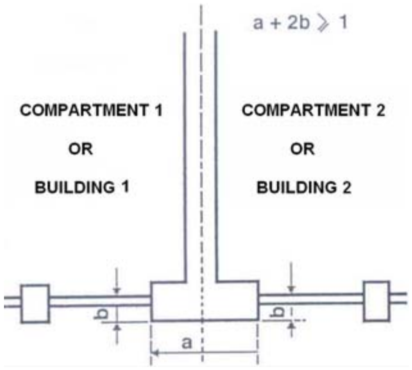


Figure: pier [18]

Even if the external observer does not realise it, glass curtain walls must also satisfy these requirements relating to aprons and piers.

Stairwells and lifts

- For external stairs giving access to an evacuation level: no resistance to fire is required but the material shall be of class A0 (non-combustible);
- Stairwells serving basements may not be a direct extension of those serving levels situated above an evacuation level except in the presence of a wall and Rf door separating them;
- For LBs, on each level, communication between the compartment and the stairwell shall be guaranteed by an Rf door.

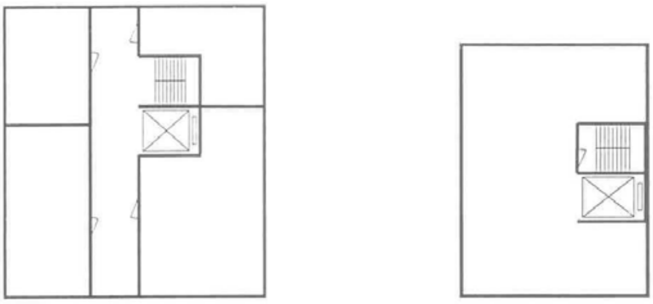
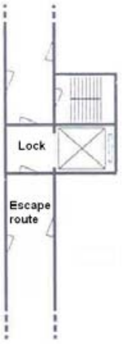
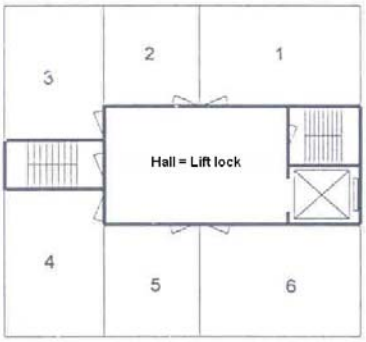


Figure: LB general case [18]

- For MBs, the landing of the lift(s) may be included in the escape route;
- For MBs that do not have more than 6 apartments per level, served by the same internal stairwell, the shared hall of these apartments may constitute the lift lock;

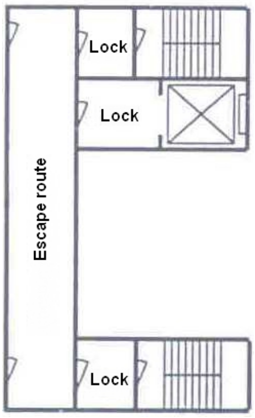


MB general case [18]



MB - 6 apartments [18]

- For TBs, the access landing of the lift(s) must be separate from the landings and locks of the stairwells. They must not be included in the escape route, except in the cases listed in the basic standards (complex cases with 4 and 6 apartments per level not included here).



TB general case [18]

3.2.2.3. Royal Decree (RD) of 4 April 2003

The arrival on the market of new technologies, the noting of certain inaccuracies in the initial text and the amendment of the regulations on other levels persuaded the legislator to introduce a new amending decree. The Royal Decree of 4 April 2003 [202] allowed several changes to be made, relating in particular to:

- Existing buildings: see §3.2.2.1 above;
- Circular staircases allowed if tread of 24 cm on line of stair flight;
- Boiler rooms: requirements according to power of heating system;
- Lifts: distinction of types with specific requirements;
- Electrical installations: availability of lifts for people of reduced mobility;
- Fire-resistant valves: new, clearer provisions;
- Behaviour in fire of roofs: according to European classification, the surface materials of roof coverings shall be of class A1 or class BROOF (t1).

3.2.2.4. The proposed new regulations

3.2.2.4.1. Industrial buildings

New industrial buildings are not yet covered by the federal regulations on new buildings. Their regulation was the subject of very long discussions to end up at a draft basic standard, the future Appendix 6. It was never published in the form of an RD but most fire services are aware of the document and, in the absence of an applicable regulation in this area, use it to draw up their prevention reports in relation to industrial buildings.

Among other things, this draft included a classification from a standard on automatic extinguishing systems or sprinklers based on the type of activities in these buildings. This RD was rejected by the Council of State, which argued namely that the type of activity in these buildings fell within the competence of the Regions and not the Federal authorities.

To make up the lack of regulation in this area and based on a proposal from Agoria and Technum, passed on by the FEB, an ad-hoc group of the High Council for Safety against Fire and Explosion has drawn up a new draft of annexe 6 which is currently being approved. It is based on a classification of industrial buildings according to their characteristic fire load density. It establishes:

- a maximum permissible calorific load per compartment, from which is deducted the maximum area of the compartments,
- a fire resistance for the walls of compartments as well as for other structural elements,
- minimum distances from neighbouring buildings,
- the requirements to be satisfied for evacuating the occupants and the safety of fire teams.

Appendix 7 including the general objectives has been abandoned.

3.2.2.4.2. Façades

Rules for the design of façades are currently being studied by a working group of the High Council. They will detail the provisions already included in the current basic standards.

3.2.2.4.3. Wall crossings

Recommendations on the construction of wall crossings by fluid or electricity conduits have already been distributed to the fire services in the form of a circular. A procedure for amending the basic standards has already been begun. It includes these recommendations.

3.2.3. Building permits - fire resistance

Currently, fire resistance is determined either by tests in furnaces to NBN 713-020 or by calculation, as allowed by the basic standards (appendix 1 of the RD of 19-12-97), in accordance with a calculation method approved by the Minister for Home Affairs.

To use this calculation method, the following may be taken into account:

- examination of conventional fire scenarios;
- examination of natural fire scenarios, with examination of the role of extinguishing systems, firemen and fire-detection systems;

As of today, no method has yet been approved. The Dispensations Commission authorises them on a case-by-case basis. In practical terms, designs made with the ISO curve are accepted if they are produced on the basis of our “NAD” part 1-2 of the Eurocodes and if these have been correctly applied. The revision of the fire basic standards should standardise this procedure. Design offices verify the required fire resistance by calculation. It is mentioned explicitly on construction plans. Architects and building owners concentrate on technical compliance with the provisions of the regulations and the requirements of both the fire services and insurance companies.

Prior to the granting of the building permit [8], the plans of the future construction are sent to the locally competent fire services. These then provide a recommendation, in the form of a report, which will be appended to the building permit application for a decision by the town-planning department of the commune concerned. At the end of the work, the fire services make a final visit to check that the construction does indeed comply with what was specified on the plan and that the building has no major shortcomings.

According to the RD of 1997, **doors** have their fire resistance certified by the Benor-ATG mark. They must be installed by fitters approve by our Minister for Home Affairs.

This dual requirement was quashed by the Council of State in 2004, following a complaint concerning the use of approved fitters. The paragraph of the Decree listing the two requirements was removed at a stroke, while the safety requirement relating to Benor-ATG certification could be remained. The FPS Home Affairs has drafted a text to fill the current void.

3.2.4. Fire detector regulation for residential accommodation

+ Scandinavian countries

In the Scandinavian and Anglo-Saxon countries, smoke detectors have long been required because many houses were made of wood and the need for warning seemed more basic: - wherever detectors are fitted, there has been an average reduction in the number of deaths and serious injuries of 80 %.

Smoke detector (source [8])

Issued in 2004, the decree of the Brussels government requires, from July 2005, smoke detectors in all houses let in the Brussels Region.

In Wallonia, since 20-11-2004, all new houses must be fitted with smoke detectors, whether let or occupied by their owner. All other houses must also be fitted with detectors since 01-07-2006.

The detector must carry the CE label and be approved by BOSEC or an equivalent European body. It must be guaranteed for 5 years by the manufacturer. Installation is undertaken by the owner and any replacement of batteries by the tenant. In this respect, the choice of lithium batteries with a life of 5 years allows you to leave their replacement to the occupants, which can often be uncertain. When the battery reaches the end of its life, the device emits an acoustic warning signal.

To cover their furniture and house by fire insurance, everyone agrees to give 300, 500, 600 EURO.

To protect people, the basic price of an approved detector is around ten EUROS. It would be ridiculous and irresponsible to think twice about making this investment.

In Flanders, there are no regulations relating to detectors in houses.

In France, detectors are not yet compulsory.

3.2.5. Old buildings

Old buildings… a problem all their own [8], [9], [10]

On Wednesday 20 February 2003, during the night, a fire is deliberately started in an apartment block in Mons. The consequences are dire: seven dead, including a child.

This fire captures public opinion: the public feels concerned and, the day after the drama, a lot of housing and management companies send requests for inspections to the fire services to determine whether their building satisfy current safety criteria. They also want to supplement the training of their community officers, concierges or other people in positions of responsibility. In Brussels alone, in a matter of weeks, more than 22 000 applications are recorded. Others are still regularly received.

Even if today a recommendation from the fire services is attached to building permit applications and in this case has the force of law, this is only the case for new buildings. And yet this is where the problem lies: most requests for inspections concern old buildings, as they no longer satisfy current fire-prevention requirements. The risks are therefore real in these buildings and we must not take them lightly, as demonstrated by the drama of the fire in Mons. The main buildings concerned are social housing buildings, that are often grouped together to form a “city”. The problems caused by cheap construction are made worse by the problem of vandalism, which contributes as much to the causes of fires, often deliberate, than to the dilapidated state of the buildings. For example, any new extinguishers fitted would be ripped off the next day or used by a malicious hand.

Unfortunately, none of the legislation mentioned above can be applied retroactively: all buildings built before 1972, which often present the greatest risk, are not governed by any regulations, except for any extensions built at a later date.

4. Protection and risks

4.1. Fire: risks, factors, origin and propagation

In a well-protected building there is a balance between danger and protection. The **risk** is therefore defined by the relationship between danger and protection. The danger is greater in tall buildings because, more than in other buildings, the fire has to attack from the inside. It is also greater in buildings that contain people with reduced mobility, whom it is more difficult to evacuate. The greater the danger, the stricter the safety rules must be.

The **factors** [38] to consider in the **development** of a fire are:

- the probability of a fire starting;
- the intensity of the fire;
- the speed at which the fire may spread;
- the existence of specific risks (toxic products).

The probability of a fire **starting** depends on:

- heating systems and electrical equipment;
- the presence of inflammable gas;
- certain industrial chemical processes;
- the presence of dust that could create explosions.

With regard to the last point, waste such as wood shavings, dust etc. must be removed regularly to counter a serious danger of fire. We should also mention the spontaneous combustion of rags saturated in oil, the auto-inflammation of steel wool by batteries, etc.

The **origin** of the fire danger may be:

- internal, linked:
  - to the building itself and its contents;
  - to the activities carried on therein (industrial activities);
  - to the people who occupy the building (smokers, waste).
- external, linked:
  - to adjacent buildings (via windows, for example);
  - to neighbouring installations (liquefied gas);
  - to gas mains beneath the public highway.

Its **development in the compartment** is limited by:

- the choice of materials in the buildings (see §2.4 reaction to fire) and
- the reliability of the technical active-protection installations such as detectors, alarms, sprinklers, heat and smoke exhaust systems.

Its **propagation beyond the compartment** is limited by the resistance to fire of the compartment (passive safety).

4.2. Passive and active protection… and human behaviour

Preventive measures are classically divided into passive and active preventive measures:

- the first are put in place when the building is constructed and are operational at all times;
- the second may be put in place during or after construction of the building and only become operational in the event of a fire.

4.2.1. Passive protective measures - compartmentalisation

Concrete occupies a very broad area in the field of passive protective measures. Thanks to its recognised fire resistance, it allows the construction of **highly secure compartmentalisation**, thus preventing the fire from spreading. This compartmentalisation allows occupants to be evacuated or taken safely to another compartment. It facilitates the access of the emergency services, thereby contributing considerably to their safety while fighting the fire. Compartmentalisation should be studied when drawing up the building plans.

Concrete allows the continuity of activities in installations of vital interest.

Continuity is paramount in buildings of public interest such as power stations, railway stations, hospitals, general government offices.

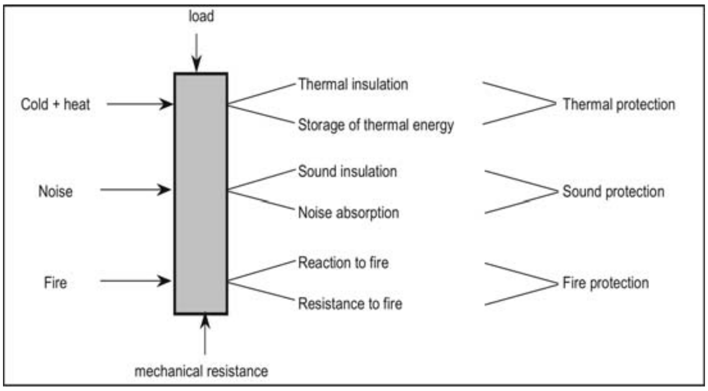
In warehouses, hotels, industrial sheds, office complexes, distribution centres, fires interrupt not only the running of the enterprises operating them but also:

- the service to the people who use them
- the productivity of the enterprises or organisations that revolve around the activities of the affected enterprise.

Apart from its load-bearing function, concrete combines fire protection, thermal protection and sound protection

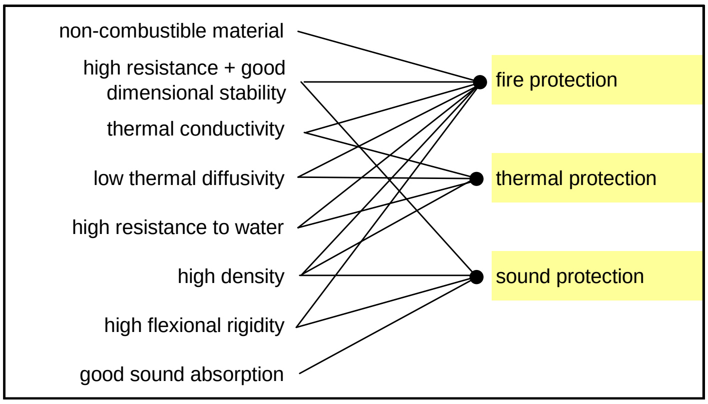
The interior walls, exterior façades and floors of buildings are subject not only to mechanical loads but also to the thermal stresses of the climate, ambient noise and fires.

The figure below shows the actions on a compartment wall and the associated properties necessitated by these actions, fulfilling the appropriate protective functions.



(Neck, 1999)

The figure below repeats the properties of the material and the structural properties of the components thanks to which the latter satisfy the requirements of fire protection, thermal protection and sound protection.



Fire prevention is based on

- a choice of materials with a good reaction to fire;
- the use of compartmentalisation enabling the fire to be confined in the place it started;
- sufficient exists to evacuate people: number of exits, width, continuous balconies, etc.

The weak points of compartmentalisation cannot be detailed here (consult [5]). They involve firstly doors (Benor-ATG): we shall come back to this point in the chapter on regulations. They also concern crossings for ducts and conduits, local deforcements (switches etc.), basements (air supply), façades (aprons + lintels + balconies) as well as roofs.

“If it is not closed, the best fire door [5] is useless in a fire. When the legislator requires door-closers, it is often observed that in reality, these doors are kept open to facilitate the use of the building.” BS 7974: PD7 [111] also provides reference values relating to the reliability of these doors: the probability of these fire doors being blocked while open is 30 %. The probability of automatic doors not closing correctly is 20 %. “The use [5] of closing devices, linked to a detection system, allows this situation, which endangers the entire desired effect of compartmentalisation, to be avoided.”

Non re-faced wall in an EI wall, at the level of the heating ducts crossing it (source [8])

Avoid! An opening in an EI wall for passing electric cables through and which has not been repointed (source [8])

Walkways running along the entire façade of the building (source [8]). These continuous balconies constitute escape routes for people.

4.2.2. Active protective measures

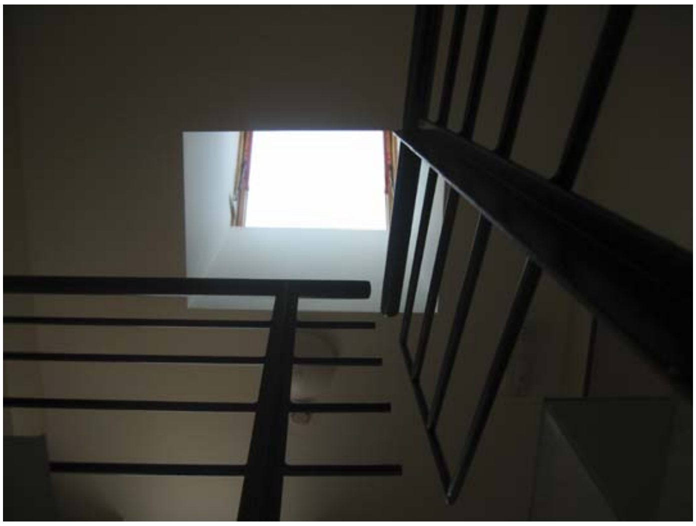
The active protective measures taken into account by 'Fire Safety Engineering' allow fires to be tackled by:

- automatic detection linked to an alarm system;
- extinguishing systems (extinguishers, automatic sprinkler system enabling the size of the fire to be controlled);
- heat and smoke exhaust systems (HSE): can be partly passive and partly active;
- the on-site fire teams, the fire intervention services.

Distinction between announcement, alert and alarm

As mentioned in the final paragraph of Appendix 1 to the Royal Decree of 1997 on basic fire standards, Belgium distinguishes between announcement, alert and alarm:

- **the announcement** which is the message to the fire services that a fire has been discovered or detected;
- **the alert** which is the message sent to the people concerned in the organisation that a fire has been discovered or detected;
- **the alarm** which is the message to the occupants of one or more compartments that they must evacuate their compartment.



Smoke extraction openings at the top of the stairwell (source FEBELCEM)

This corridor contains a large number of elements of active protection: alerting unit, hose reel, signalling panel, smoke detector, emergency lighting (source: FEBELCEM)

The performance of sprinklers [41]**,** normally highlighted for their operational reliability, is evaluated in the USA in laboratory test conditions where, in 96 to 99 % of cases, the sprinkler is activated when the temperature is reached at head level. But this approach does not consider real situations, where this same level of performance of controlling or extinguishing the fire is not achieved. The statistics reported by M. Rohr of the NFPA in September 2001 in "U.S. Experience with Sprinklers" indicate that, for fires of such a size that the sprinklers should have been activated, the system failed in its mission in 13 % of apartments, 17 % of hotels, 20 % of hospitals and offices, 26 % of public places, with a national average of 16 % failures. (We shall return later to the value of sprinkler reliability!). Based on these figures, the actual performance is therefore **10 times lower than announced.**

How can we define the success of a sprinkler system?

The area of operation or of calculation of the sprinklers varies according to the risk. Risk classes are defined for low, ordinary (OH) or high risks. Each class has a sprinkled area that must be kept under control. This means that the fire must not spread beyond this area. The following table from NBN EN 12845 gives the definition of these areas of operation, combined with a number of sprinkler heads and a minimum flow rate per sprinkler head:

Risk classes	Number of sprinkler heads	Area of operation (m²)	minimum flow rate per sprinkler head (l/m²/min)
Low	1 / 21 m²	84	2,25
Ordinary	1 / 12 m²	72 to 360	5
High except HHP4	1 / 9 m²	260	7,5 to 12,5

Sprinkler (source [8])

In Canada, the regulations in Ontario have led to the use of smoke detectors and fire alarms in combination with compartmentalisation. The principle is that fire alarms provide a suitable evacuation time and therefore the expenses and problems associated with sprinkler failures are removed. If the regulations are maintained as they are, it is because it has been shown that, for the safety of people and goods, the combination of fire alarms and fire-resistant compartmentalisation presents no more of a risk that that of fire alarms and sprinklers.

An in-depth discussion of the use and performance of sprinklers can be found in Appendix 1 (see Chapter E.) of this document.

The choice of concrete walls and floors for increase resistance to fire constitutes a key choice. These elements also allow the transmission of noise through walls and floors to be reduced (fewer light floors or partitions). They improve thermal comfort, reduce the owner's maintenance costs and improve durability. These characteristics are translated into a better resale value for owners, a financial gain linked to a lower fire insurance premium while reducing the risk of exposure to danger of the emergency services and the indirect expenses incurred following a fire.

The responsible attitude of a certain number of designers, developers and owners who voluntarily improve fire safety in their building beyond the regulations deserves to be highlighted. At the same time, for other buildings, these same people, under the cover of maintaining competitiveness, are invited to reduce to a minimum the regulatory requirements of fire safety. We are thinking particularly of those who obtain dispensations allowing them to construct projects that satisfy lesser requirements than those set out in the prescriptive regulations for constructions.

The effectiveness of sprinklers is reduced when the measures taken by the operator for the storage of products differ from those initially planned (different materials stored, different locations, different method of storage).

To benefit from the advantages of active measures, it is advisable for this usage to be conditioned by appropriate measures of maintenance, training, certification and approval of persons.

ACTIVE PROTECTIVE MEASURES: A SIGNIFICANT SHARE OF THE CONSTRUCTION COSTS OF INDUSTRIAL BUILDINGS [6]

"All too often the share taken by 'fire safety' costs in the budget for the construction of an industrial building is underestimated," states Bruno Robberechts. "All the same, for standard industrial warehouses, developers should reckon on 15 to 20 % of the total investment. The sprinkler system represents a large part of these costs. Two fixed costs should be taken into consideration in this connection: the local pump and the tank…. A local ESFR pump has to be provided with two diesel pumps and a tank for 12 sprinkler heads for an operating time of 60 minutes. The costs associated with the sprinkler system network also have to be considered …" "Not forgetting the maintenance costs: a periodic inspection and a check-up of a sprinkler system are mandatory nowadays," affirms Bruno Robberechts. "But that can also lead to a reduction in fire premiums," concludes Alain Georges.

4.2.3. Human behaviour

The behaviour of the occupants of the buildings and that of visitors has a significant effect on the occurrence of fires and the operation of protective systems.

Schedule anti-fire exercise sessions (evacuation and initial intervention), do not leave bulky objects in escape routes, do not lock emergency exits, etc. are all aspects that increase safety.

An attempt [8] to evaluate the risk of fire was recently carried out for buildings with several apartments. It is concerned with the safety of people and is based on points-system evaluation sheets. It relies on the basic Belgian standards relating to fire (RD 1997) and on the experience of the fire services. Each criterion is relatively simple to verify and requires no complicated techniques to be evaluated. It suggests a balanced weighting between the different parameters that limit the risk of fire: 2/3 for passive protection, 1/9 for active protection and 2/9 for the behaviour of the occupants and people in charge of buildings.

To be avoided: This cupboard is preventing escape via the walkway. (source [8])

To be avoided! Newspapers lying about in a basement passage, the perfect fuel for any malicious act (source [8])

The acknowledged importance of human behaviour is confirmed by the Canadian experience where, thanks to an extensive information campaign, the number of apartment fires has fallen sharply in recent years.

It should be noted that from the time fire safety no longer concerns establishments intended for access by the public, the regulations do not provide any measures that allow the measures taken to prevent fires to be followed up and verified.

Regulatory pictograms indicating the presence of a hydrant, hose reel, extinguisher or emergency exits

Does active safety not compensate for the weak points of steel structures? [13]

"Active safety takes account of the presence of sprinklers, automatic detection systems, the availability of an adequate supply of water, the proximity of the emergency services, the type of activity carried on in the building. These elements are used in fire engineering to artificially reduce fire-resistance requirements. It would be rash not to retain a reasonable minimum structural safety level in the building (passive safety) to withstand external faults.

Active safety can only be envisaged as a supplement to passive safety. We are thinking of the increase in arson attacks and a possible breakdown in the inspection and maintenance which lie in human hands. **This active safety strategy bestows on the building owner and occupier a responsibility they are not always capable of taking on, through lack of awareness, training and control.** Works managed by an unconcerned building owner often build up a cascading series of negligences that can prove dramatic.

We are repeating an extract from the **talk by Commandant J. Rahier** [39] dating from 2004, which we will title "Active protection and human behaviour":

"…A common characteristic of active safety techniques is immediately apparent: it is the need for human intervention to take note of the event and react according to the information received:

- the automatic detection system will never put out a fire and will never organise an effective evacuation;
- left to itself, the automatic extinguishing system will not put out the fire, and can cause excessive "collateral" damage;
- the HSE system will never put out a fire and, on the contrary, will cause one.

This characteristic is also one of the weak points of active safety systems: without an appropriate human reaction, without trained staff, they lose a large part if not all of their effectiveness.

The second characteristic common to the three techniques is that of being intimately linked to the spatial organisation of the premises and the technical organisation of the buildings.
A detection head, a sprinkler head or a smoke extraction grille cannot just be placed anywhere.

And any change to the premises (creation of new walls, opening up of certain walls, modification of the air-conditioning system, etc.) must result in a re-evaluation of the active safety protection

This second common characteristic shows the importance of regularly maintaining these systems. These systems fear the harmful effect of the couple formed by the commercial and financial managers (if you add a decorator to this couple you have an explosive mixture) who for reasons of their own are going to alter the arrangement of the premises and techniques: what counts is the commercial layout of the store, the beauty of the furniture in the director's office, the introduction of a new technique which changes completely the way the work is organised. And obviously it is in maintenance budgets that the financial manager will think he can make drastic cuts: why maintain an electrical installation that never does anything anyway (at least we hope not) ?…

The two characteristics I have just discussed: the obligation of human action and the obligation of continual maintenance are the reasons why prevention officers, in contrast to certain high priests of Fire Safety, think that these techniques do not constitute a panacea and that in many cases they cannot be used in isolation. On the contrary, fire prevention must be a clever balance between these three techniques (HSE, sprinklers and detection) and between passive fire safety measures and active safety measures. …

It is in day-to-day life that the importance of redundancy in terms of fire safety becomes clear. I will cite just one example: the fire at the Mabelpap plant in Verviers on 06-08-2002: when the fire causes an explosion and the sprinkler system is operating at less than 1 m from the ground, when the outlets are unable to open, and so on, it is down to the R_f compartment walls to limit the spread of the fire. An aerial view of the premises after the fire is full of information. …

Detection systems have become more reliable. We can say this, even if we are rather deprived of statistics. There are more developments to come, for example detectors that communicate with the control centre by electromagnetic waves. Perhaps the danger lies in integrating the automatic detection system in a super-computer which manages the "risk" of a building, enterprise or, if we keep on refining the servo-controls, we will end up no longer knowing precisely what is happening. Too many procedures kill human initiative: the management of nuclear power stations has clearly shown that. …

It is man who designed all the systems we have just spoken about. It is man who will have to install them so that they are as efficient as possible, who will test them in every possible configuration, who will have to maintain them.
Above all it is man who will take the information and determine what action to take to fight the fire effectively.

"I am furious when I hear people say that man is always the weak link in a safety chain. This is because, when everything goes belly up - if I may use the expression - it is on the shoulders of the staff present on which rests the proper management of the incident. At this point it is too late to ask: was he well trained, did we devote enough of the budget to him (ed.: level of supervision during the night in homes), have we given him enough initiative, have we organised simulation exercises?

Believe me, the role of man is paramount. When intervening in a fire the role of the initial intervention team member is fundamental, when he makes the first gestures, when he informs the outside emergency services accurately and in detail.

Talking of domestic accidents and fire in particular, the emergency services would be happy to have as much time as the road safety services…"

Figure : 7200 m² industrial warehouse North Rognac (France) - Saturday 15th June 1996 (source CIMBETON) : The concrete fire walls isolated the fire perfectly and prevented it from spreading to adjacent warehouses.

5. Thermal mechanisms

5.1. Heat transfer mechanisms

There are three basic mechanisms [38] of heat transfer:

- convection;
- radiation;
- conduction.

The three mechanisms interfere with each other during a fire. One or other will predominate to a lesser or greater degree according to time and place.

Convection is the means by which heat is transferred to a solid through movements of the gas surrounding it. At the start of the fire, it is predominant between the surrounding milieu and the construction element. The heat flux q_c - expressed in W - exchanged between the gas at a temperature T_g and 1 m^2 of wall at a temperature T_p is:

$$q_c = \alpha_c \,.\, (T_g - T_p)$$

where α_c = exchange coefficient by convection, varying from 4 to 50 W/m^2°C according to the face of the wall in question (exposed to the fire or not) and the chosen temperature curve.

Radiation is a transfer of energy by electromagnetic waves and does not require the presence of a milieu between the heat source and the recipient. This mechanism is predominant as the fire spreads and when it reaches full intensity. The heat flux q_r exchanged between the environment (wall + gas) at a temperature T_g and 1 m^2 of wall at a temperature T_p is:

$$q_r = \Phi.\varepsilon.\sigma_0.(T_g^4 - T_p^4)$$

where

Φ = form factor of the profile of the element. It equals 1 if the section is rectangular or circular. It is less than 1 in all other cases. This concept is based on the actual energy flux which reaches the surfaces exposed to the hot gases;

ε = conventional factor representing the global relative emissivity between the environment and the wall. According to fire European standards (EN) , it equals 0, 8 by default, 0,7 for a concrete surface, 0,8 for a steel surface, 0,4 for stainless steels. It should be noted that European pre-standards (ENV) gave values of 0,8.0,7=0,56 (by default)

σ_0 = Stefan-Boltzmann constant = 5,68.10^{-8} W/m^{2}K^4,

T_g and T_p are absolute temperatures expressed in kelvins.

Conduction is the means of transfer in solids. The thermal conductivity λ characterises the ability of a material to conduct heat. Conductivity values for different materials are given in the table in §5.2.3. In the case of a unidimensional heat flow, the heat flux q_λ which crosses a surface of 1 m^2 perpendicular to the direction of flow is:

$$q_\lambda = \lambda.(\partial T/\partial x)$$

where

λ varies from 2,0 to 0,6 W/m°C for concrete according to temperature. This variation is explained in §7.2.1.

$\partial T/\partial x$ represents the thermal gradient inside the wall.

The internal material of the walls will heat up as the temperature rises. The amount of heat absorbed per second and per m^3 of material of a density ρ is:

$$q_m = \rho.c.(\,\partial T/\partial t)$$

where

c = specific heat (J/kg) which varies according to temperature. This variation is explained in §7.2.1 .

ρ = density (kg/m^3)

The temperatures within construction elements are determined by resolving either by fine differences or by finished elements the linked equations:

$$½\, dx \,.\, q_m = (q_c + q_r) - q_\lambda$$

expressing the heat balance in the superficial wall layers and

$q_m = -\,\partial q_\lambda/\partial x$ or $\rho.c.(\,\partial T/\partial t) = -\partial(\lambda.(\partial T/\partial x))/\partial x$ (equation 1)

expressing the heat balance inside the walls.

5.2. Main factors affecting the temperature of gases

The development of a fire [38] and therefore the temperature of gases is linked to three main factors: the size of the combustible load and its maximum rate of heat release, the surface area of the compartment's openings onto the outside and the thermal properties of the walls.

5.2.1. The fire load and rate of heat release (RHR)

If there is a sufficient supply of air, which leads to a fire controlled by the fuel, it is the size of the fire load, linked to its rate of heat release, and its disposition that have a decisive influence on the severity of the fire.

The fire load density is defined as:

$$q = (\Sigma M_i P_i) / S$$

With S = surface area of compartment (in m^2)
M_i = mass of material i (in kg)
P_i = calorific potential of material i (in kJ/kg)

This sum applies to all materials of the compartment, including those of the building itself. Concrete, being non-combustible, does not contribute to the heat load.

For historical reasons and reasons of simplicity, the above-defined load is occasionally replaced by a "wood equivalent load". (1 kg of wood corresponds to 17,5 MJ). For the ease of the reader, we will use this wood equivalent rather than MJ.

In reality, the value of the fire load defined above should be modified by a working coefficient which takes account of the fact that most materials do not burn away completely and therefore do not release all the energy they contain. This is linked to the material itself, its geometry, its surface exposed to the flames, etc. The fire load that actually contributes to combustion lies between 50 and 90 % of the theoretical fire load defined above. In the case of materials made mainly of cellulose, in accordance with Appendix E to NBN EN 1991-1-2 [106], the assumption of a coefficient of combustion m=0,8 is permitted.

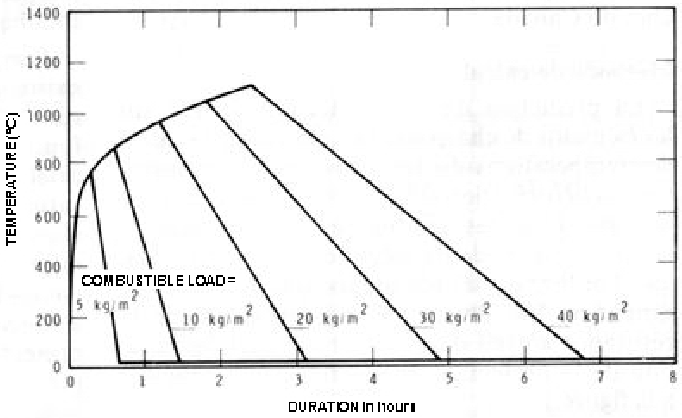


Figure: Effect of the combustible load on the temperature curve of the fire. [57]

To clarify matters, this standard stipulates, in its informative Appendix E, fire load density values. Converted to an equivalent in kg of wood per m², the mean combustible loads are determined for buildings according to the different types of occupation:

Type of occupation	mean combustible loads (kg of wood /m²)
library	86
residence	45
shopping centre	34
office	24
hotel	18
theatre cinema	17
school (class)	16
hospital	13
transport	6

Table: heat load densities [106]

The theoretical fire load [5] cannot be used as an absolute criterion for fire danger. Materials differ by the ease with which they can be set on fire and by the speed at which they burn, i.e. by the amount of heat they can release per unit of time. The first characteristic influences the frequency with which fires can occur, while the second determines the intensity of any fire.

Experience shows that, if other factors are constant, the duration of a fire is proportional to its fire load density. This means that an increase in a normal fire load will generally lead to an increase in the duration of the fire, but not particularly the maximum value of the mean temperature in the premises.

The way materials are stored conditions the speed of combustion. For example, rolls of paper lose their sheets: they have to be stored horizontally (see §8.4.1 activities in industrial buildings).

To this end, the two factors t_α and RHR_f allow the distribution of combustible materials to be characterised:

t_α = the time required to reach a rate of heat release of 1 MW and

RHR_f = RHR for Rate of Heat Release: the maximum rate of heat release produced by 1 m² of fire in the case of a fire controlled by the fuel. By way of information, see the table below:.

Type of storage – of occupation	RHR_f (kW/m²)	t_α (s)
Wooden pallets stacked to a height of 0,5 m	1250	
Wooden pallets stacked to a height of 3,0 m	6000	
Plastic bottles in boxes stacked to a height of 4,6 m	4320	
Rigid polystyrene foam panels stacked to a height of 4,3 m	2900	
Retail stores, library, shopping centre, theatre and cinema auditorium	500	150
Offices, residences, hospitals, hotel room, classroom, etc.	250	300

Table: maximum rate of heat release produced by m² of fire [42].

A high fire development speed is obviously characterised by a low t_α . This is true of a library, shopping centre, theatre and cinema. At the same time, a high maximum rate of heat release is found in these places.

The rate of heat release RHR can be limited by ventilation. This is determined by a “single zone” program (see §6.2.3.1 below), where the EC1 fire gives a simplified expression of this limited maximum rate of heat release.

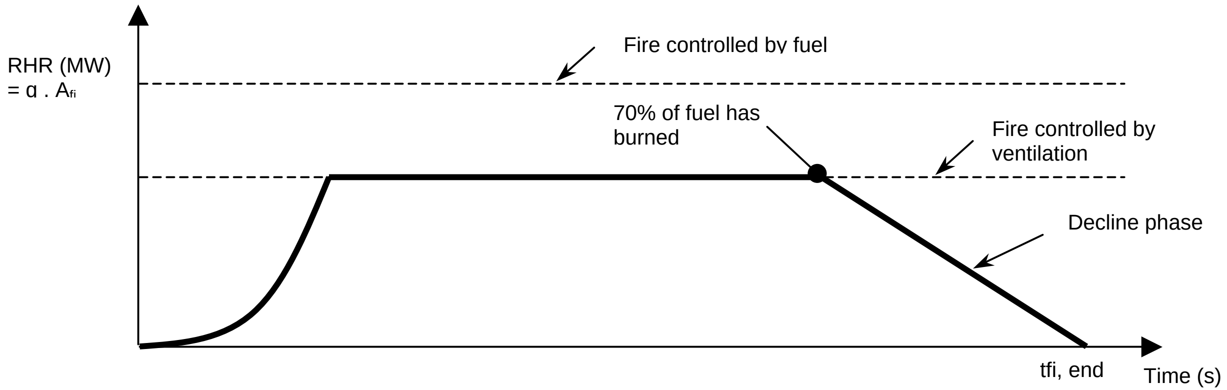


Figure: rate of heat release as a function of time

The diagram hereabove shows the classic representation of rate of heat release as a function of time. This rate increases according to a parabolic law, remains constant until 70 % of the fire load has been consumed then decreases linearly. The area under the curve represents the total accessible heat load.

5.2.2. Ventilation

Ventilation has a significant effect on the development of a fire. The phenomenon is no different from a wood stove where the air supply can be modulated, modifying the development and maximum intensity of the fire. The ventilation flow is directly proportional to the ventilation factor, also known as the opening factor O:

$$D = C^{te} . O = C^{te} . (A_v/A_t) . (h_{eq})^{0,5}$$

where

A_v = total area of openings on all walls (m^2),
A_t = total area of compartment (walls, ceiling and floor, including openings) (m^2),
h_{eq} = weighted average of window heights on all walls (m),
O = opening (in $m^{0,5}$),
D is expressed in kg of air/s.

Increasing the opening areas allows better ventilation and is therefore translated by higher temperature peaks and a faster decline phase.

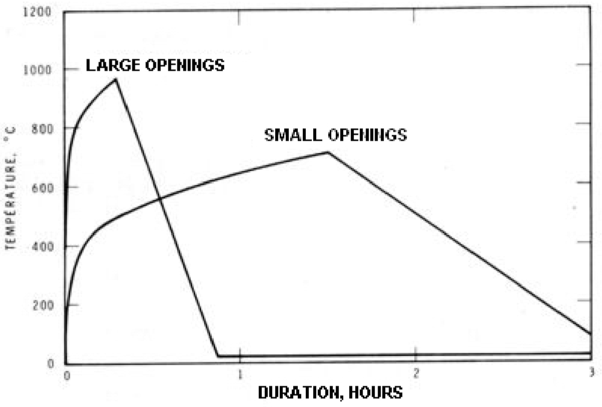


Figure: effect of openings as a factor on the fire temperature curve. [57]

Where smoke extractors are used, activated automatically by temperature-sensitive elements, the resulting inflow of extra air activates the fire. Practice has shown that the effect is extremely positive: better visibility offers the chance of the emergency services intervening more quickly. In addition, thanks to the lesser extension of the smoke, the smoke damage as well as the risk of intoxication for the occupants are reduced.

5.2.3. Thermal characteristics of walls

These characteristics influence the development of the fire, but to a lesser extent than fire load and ventilation.

The heat produced at the start of the fire is partly carried outside by the ventilation and partly absorbed by the floors, walls and ceiling.

The temperature in the room is determined by the heat balance between production and transport of heat.

The amount of heat that must be supplied to the material to increase its temperature depends on its **thermal effusivity**

$$Eff = (\lambda.\rho.c)^{0,5}$$

The effusivity provides a picture of the thermal inertia of the walls. The greater it is, the more it will absorb energy when exposed to fire. The speed of temperature increase of the walls will be slower the greater the inertia.

If one face of the walls is subject to a sudden variation in temperature T, which is then maintained for a time t, the total amount of heat Q absorbed by the wall satisfies the equation:

$$Q = 2.T.(t/\pi)^{0,5}.Eff$$

The calculation [5] shows that, with a cladding applied to a concrete wall and to a wall covered with a layer of low-density insulating material, the ratio between the generalized fire development time is 10, while the ratio of effusivities is close to 30.

The high thermal effusivity of concrete walls is therefore interesting both in terms of thermal comfort and for slowing down flash-over.

Thermal diffusivity

$$a = \lambda /(\rho.c)$$

is a measure of the speed at which the temperature changes in the material. This grandeur appears in equation 1 given in §5.1. The greater it is, the faster the material heats up.

Photo : RASTRA

The length of diffusion L_{diff} is the depth x at which the variation in temperature equals almost half the sudden variation in temperature on the surface. The equation:

$$L_{diff} = (a.t)^{0,5}$$

ignores any phase changes in the actual material.

The table below gives an overview of the thermal properties of several types of material:

In a permanent situation, the transfer of heat in the material is directly proportional to thermal conductivity while in a temporary situation it is, as demonstrated above, directly proportional to thermal effusivity. In the field of fire, it is therefore the high thermal effusivity $Eff = (\lambda.\rho.c)^{0,5}$, combined with the massiveness of the concrete elements, which proves particularly favourable in the evolution of **temperatures of gases** (delay of flash-over).

In a permanent situation **the temperature gradient** in the material is inversely proportional to the conductivity value, while in a temporary situation the temperature field is a function of thermal diffusivity. In the field of fire, it is therefore the low thermal diffusivity $a = \lambda/(\rho.c)$, combined with the massiveness of the concrete elements, which is particularly favourable in the evolution of **temperatures within the material**, rather than simply the thermal conductivity of the concrete.

5.3. Fire severity

In summary, the severity of the fire is characterised by the following factors:

- the duration of the fire, determined by fire load and ventilation;
- the average temperature in the compartment, determined by the ventilation and thermal insulation of the compartment;
- the speed with which the fire developed and with which the temperature rises, influenced by the thermal behaviour of the walls.

Material	fusion temperature (°C)	α (x 10^{-6}/°C)	ρ (kg/m³)	λ (W/m°C)	c (kJ/kg°C)	Eff (J/m²s^{0,5}°C)	a (m²/s.10^{-6})
concrete	1200 to 1400	12 to 18	2400	0,6 to 2,0	1	1200 to 2200	0,25 to 0,8
terracotta	-	5 to 7	1500	0,4 to 0,5	0,84	710 to 800	0,3
steel	> 1500	12 to 17	7850	50 to 60	0,45	13300 to 14600	15
timber	300 $^{(*)}$	3 to 5	400 to 1000	0,12 to 0,16	1,2	240 to 440	0,1
rockwool	1200	-	10 to 200	0,03 to 0,04	0,8	15 to 80	0,2 to 5
plaster	-	10 to 12	1500 to 1800	0,5 to 0,8	0,84	800 to 1100	0,4

* combustion temperature

α = thermal expansion coefficient,
ρ = density,
λ = thermal conductivity,
$c_p(\theta)$ = specific heat,
$Eff = (\lambda.\rho.c)^{0,5}$ = thermal effusivity,
$a = \lambda / (\rho.c)$ = thermal diffusivity.

6. Actions

A presentation of mechanical actions is necessary to understand the fire resistance of structures which involve the concept of loading rate. Taking this factor into account allows more refined dimensioning.

The purpose of presenting thermal actions is to understand "natural fires" in the approach of "Fire Safety Engineering". This approach takes account of the physical phenomena and intervention conditions encountered for the building in question.

The performance of the concrete structural elements in fire allows the building designer who so chooses not to burden himself with additional protective measures or not to have recourse to complex evaluations and requests for dispensation.

In the same vein, the use of concrete more often than not gives fire resistances that exceed those obtained with the nominal curves, at no additional expense. The degree of safety with other models is often less than that achieved with the ISO curve. The exception is the situation where the fire loads are extremely high, for example in libraries, provided fire-load reduction coefficients have not been applied to take account of active safety measures!

6.1. Mechanical actions

Actions on structures subjected to fire are classed as accidental actions. Consequently, the combinations of actions to be consideration are those whose load-weighting coefficients are reduced in relation to those that are used in cold dimensioning. The probability of a fire and extreme loads occurring simultaneously is extremely small.

Thus to make things clear:

the combination when cold $1{,}35G + 1{,}5Q$

becomes when hot $G + \psi_1 Q + A_d$

With,

$\psi_k =$ $\psi_2 = 0{,}3$ for private, residential and office buildings;
$\psi_2 = 0{,}6$ for commercial buildings open to the public and places open to the public;
$\psi_2 = 0{,}8$ for storage loads (libraries etc.).
$\psi_2 = 0$ for the snow ;
$\psi_k =$ $\psi_1 = 0{,}2$ for the wind ;
$G =$ dead weight;
$Q =$ live load and or climatic load and
$A_d =$ the value of the calculation of the indirect thermal action due to the fire (restraint, movement).

In general, applying these combinations leads to a load in a fire situation in the order of 50 to 70 % of that taken into account in cold dimensioning.

The highest hot loading rate η_{fi} there can be is 1/1,35 or 0,74. In practice, there is always a small live load which gives the loading rate of 0,7.

We will use this notion again in presenting the tabulated values method (§8.1.1 and §8.1.2).

6.2. The different models for thermal actions

There are several ways of modelling a fire [18] inside a building. In increasing order of complexity, the models most commonly used are:

- nominal curves;
- parametric curves;
- zone models;
- CFD models

and finally localised fire models which do not uniformly affect the surface of the compartment.

They are developed in the standard EC1 fire: the ISO curve in the body of the standard and the other models in the informative appendices.

6.2.1. Nominal curves

Nominal curves, including the ISO curve, were presented above. They all have the following characteristics:

- the temperature in the compartment is uniform;
- the only factor on which they depend is time;
- there is no cooling phase.

The ASTM nominal curve used in the United States is very similar to the ISO curve.

6.2.2. Parametric curves

A parametric curve also shows the evolution of the temperature of combustion gases as a function of time. The temperature in the compartment is uniform but, in contrast to nominal curves, the relationship is calculated on the basis of three main factors: fire load, ventilation and properties of the walls.

It should be noted that these curves can only be used at the predimensioning stage, as they are occasionally uncertain. This is mentioned in our future national annexe (ANB) to Eurocode 1, part 1-2. At the implementation stage, a calculation following a zone model must be carried out if the designers wish to go beyond the ISO curve.

6.2.3. Zone models

These models use the parameters developed in §5.2.

6.2.3.1. Single-zone models

Single-zone models are numerical models that calculate the evolution of the temperature of gases as a function of time, by integrating the ordinary differential equations expressing mass and energy balances. They assume that the temperature in the compartment is uniform. An example is given in the following figure.

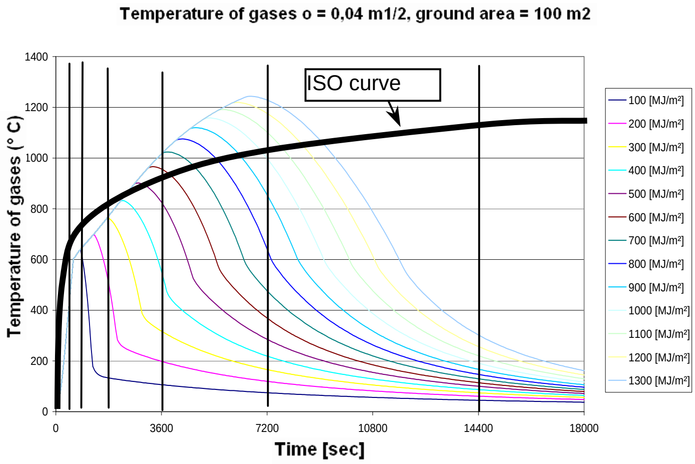


*Figure: example of the curve obtained by a zone model for different design fire loads $q_{fi,d}$ for a compartment of 10 m*10 m*3 m (=h) with concrete walls of 12 cm covered in 1,5 cm of plaster in the case of an RHR_f of $250kW/m^2$*

6.2.3.2. Two-zone models

Two-zone models are numerical models that calculate the evolution of the temperature of gases as a function of time in the lower and upper layer, using mass and energy balances written for each of the two layers within which the temperature is assumed to be uniform.

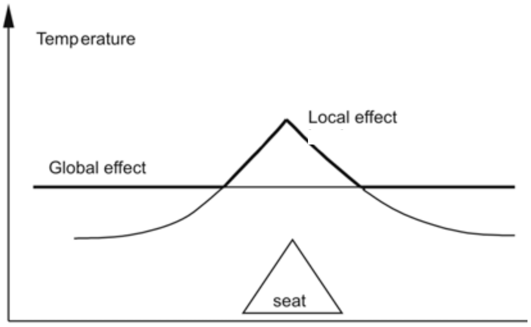
A fire may be grasped by a two-zone model which will itself tip towards a single-zone model at the moment of flash-over. These models have been developed more specifically by the University of Liège, notably as part of the OZONE program.

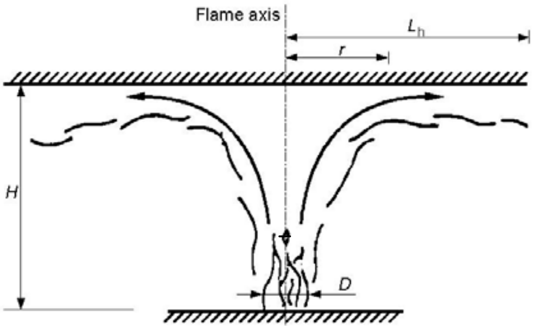
These models are used when the fire is small compared with the size of the room.

The thickness of the lower layer remains at a fairly low temperature and does not contain any combustion products. It is very important in assessing the survival conditions of the occupants of the compartment.

6.2.4. Localised fire models

The standard EC1 fire also provides for the possibility of performing a calculation of the local heating of gases at the point of a localised fire which might develop. In the same way as a generalised fire, this type of fire may cause the destruction of a building.





Localised fire: Hasemi model [106]

6.2.5. CFD (Computational Fluid Dynamics) models

The methods advanced in Fluid Dynamics (CFD for Computational Fluid Dynamics) analyse systems including the flow of fluids, transfers of heat and associated phenomena, by resolving the fundamental equations of Fluid Mechanics.

These equations constitute a mathematical representation of the physical laws of conservation.

In these models, the differential equations of thermodynamics and aerodynamics are resolved in a very large number of points of the compartment to determine, among other things, the temperatures and velocity components of smoke. Highly complex to use and extremely sensitive to hypotheses, these models are reserved for research. They are mainly used to study the dispersion of smoke and heat, rarely to evaluate in terms of heat flux the impact of fire on structural elements.

6.2.6. Which curve, what model?

Our current regulations only accept the use of nominal curves. Special dispensation needs to be applied for from the Federal Public Service if the designer wishes to justify the resistance to fire of his building by means of other curves.

In the design of buildings, dimensioning according to parameter or zone curves rather than the ISO curve significantly influences the risk of the works collapsing in case of fire: an ISO fire of 2 hrs in residential buildings, offices or any other building with a low fire load density is more severe than a fire calculated using parameter curves or zone models. The use of these curves is expanded further as part of dimensioning by "Fire Safety Engineering".

It is advisable to retain a critical attitude towards the fire-load values given in literature: other orders of magnitude than those given by the informative appendix to the EC1 fire (see §5.2.1) are presented in document [25] (1983) (See next table). For administrative buildings (USA, Germany, France, Netherlands) the fire loads are 50 kg of wood /m^2 and, in 95 % of cases, less than 90 kg/m^2.

Types of building	Mean fire load density (kg of wood/m^2)	Maximum fire load density (kg of wood/m^2)
housing	15	35
schools	15	50
hospitals	20	50

Certain acknowledged differences command caution. We would suggest that in Belgium a more precise analysis reinforces the most recent figures. The categories of offices, among others, should be more detailed.

The conditions of a rise in temperature over half an hour according to the standard curve can generally be obtained in numerous premises. The requirement of ½ hour corresponds very roughly to a fire load of around 40 kg of wood per square metre. It enables the stability of buildings used as accommodation, in which loads of between 15 and 60 kg/m^2 are encountered, to be guaranteed. A figure in excess of the mean fire load or indeed unfavourable ventilation conditions will generate a higher risk of the structure of the building collapsing.

For buildings used as accommodation, the requirement of 1 hour offers a low risk of the structure collapsing.

The requirement of two hours is justified for compartments with high fire loads. These loads are found in libraries, archival depots. This requirement is also justified for tall buildings where the fire services have to intervene via the interior of the building. The consequences of a collapse are also very serious for the vicinity.

By choosing ventilation factors which require the least possible fuel, we can calculate that ISO fire durations of 30, 60, 90 and 120 minutes are achieved for fire loads of 40, 80, 120, and 160 kg wood/m^2.

7. Materials

7.1. Physical and chemical phenomena in concrete

Although the standards provide simple and also more complex rule to use, it is important to understand the properties of concrete when subjected to fire.

A word about test results [55]

For tests exploring concrete, especially to characterise mechanical properties, rates of temperature rise in the order of 2 °C a minute are too low. They do not simulate the conditions of a fire. They are nevertheless used by scientists and recommended by the RILEM committee to, as far as possible, disassociate the material from the structural effects resulting from the heating of a reduced sample (e.g. 6 cm in diameter and 18 cm tall).

More than in other areas, the results obtained in relation to the behaviour of concrete exposed to fire are heavily dependent on a large number of factors:

- The thermal cycle imposed plays a major role: heating, high temperature plateau, resistance to heat, cooling, residual resistances after cooling to ambient temperature, "post-cooling" resistances, a certain lapse of time after cooling, second heating, etc.;
- The variation in the loading level during the rise in temperature influences mechanical characteristics in particular;
- The confinement conditions ("sealed" = no exchange of humidity with the outside or the opposite "unsealed") of the samples influence the pressure distributions of water vapours.

Physical and chemical phenomena

In the event of a fire, a very sharp rise [27] in temperature may trigger physico-chemical changes in the concrete, such as dehydration by drying of the concrete and decarbonatation. These phenomena can cause shrinkage, losses of resistance and rigidity of the materials.

Dehydration and decarbonatation are endothermic reactions: they absorb energy and therefore slow down heating. They therefore go hand in hand with absorption of heat which slows down the heating of the material exposed to the fire.

A dehydration and vaporisation front forms from the heated surface where the temperature barely exceeds 100 °C (see figure). If the capillary pores are too fine, the steam pressure that builds up may generate tensile stresses in the concrete at this point such that the concrete's limit of resistance is exceeded. This phenomenon is all the more pronounced because the humidity of the concrete is high and the rise in temperature rapid. Fragments of concrete can thus be thrown out from the surface of the element with more or less violence (see "spalling of concrete" below).

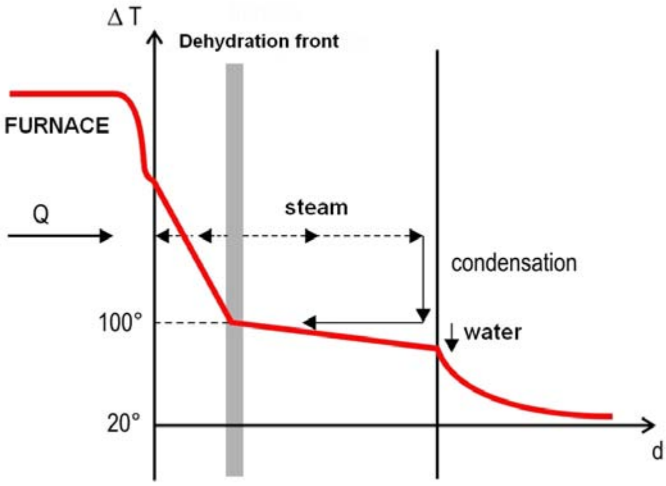


Figure: Temperature in a concrete wall exposed to fire. (Source [5])

For concrete, the loss of resistance results mainly from the formation of internal cracks and the degradation/disintegration of the cement paste. The paste in fact contracts while the granulates expand. Apart from these internal cracks, at these very high temperatures cracks can be seen to form between the cement paste and the aggregates. As described above, several transformations resulting from the significant increase in temperature occur in the cement paste, causing a loss of cohesion.

The concrete changes in an extremely complex manner during a fire (see table below).

Bulletin nr 37 [69] of the cement dossier published by FEBELCEM presents in two pages in §5 the physical and chemical phenomena encountered for concrete subjected to fire. The residual resistances of concretes and steels are also given.

Generally speaking the negative effects of heat mentioned above only act on an external layer 3 to 5 cm thick.

It is worth remembering that, even damaged, concrete acts as an insulating layer, a thermal shield. It protects the load-bearing core from the full effect of the high temperatures.

The changes [55] that occur in concrete at "low" temperature (< 300 °C) mainly reflect changes in the cement paste, as almost all current aggregates are relatively stable up to 350 °C. It has been shown that river gravel, "Thames gravel", bursts at this temperature, in contrast to the excellent behaviour of other aggregates.

The behaviour of cellular concretes

We should mention the excellent behaviour of air-cellular concretes, which are moreover used in furnaces to produce masonry around fire doors that require testing!

The explosive blow-out of concrete ("spalling") could occur in prestressed concrete girders where the thermal stresses resulting from the dehydration front superimpose themselves on the very high stresses present in the concrete and where the web is restrained by more massive slabs. The restraint of a construction element is the action of impeding, of blocking deformations of this element. Analysis of the stability of a construction element should take account of the superimposition of these stresses.

To avoid explosive blow-out, the Eurocode limits the compressive stress in concrete by imposing on girders a minimum core thickness depending on the desired resistance time (see table in §8.1.2.4.). This imposition is aimed at avoiding the sudden rupture of the core of the girder.

Physical behaviour of concrete elements: For a column exposed to fire [5] on four sides, for example, the concrete heats up rapidly on the surface and wants to expand. Its expansion is prevented by the core of the column, which remains cold. Tensile stress is applied to the core and compressive stress to the outside of the column.

As the thermal stresses superimpose themselves on the stresses resulting from the loads applied, the outer concrete, whose resistance drops as the temperature rises, is subjected to extremely high stresses close to the ultimate resistance. These stresses, combined with the effects resulting from the dehydration front and the expansion of the bars, explain the concrete blow-outs observed during tests.

These blow-outs chiefly concern concrete covering corner reinforcements, followed by concretes on the faces of columns. They reduce the section of the column and increase the flexure because the eccentricity of the load increases locally. Furthermore, the exposed reinforcements heat up more quickly than at points where they remain protected by the concrete.

This behaviour is taken into account in the verification of structural elements by the Eurocodes.

Reactions of concrete to a thermal attack	
Temperature in the concrete (°C)	Reaction of concrete
< 100	As a general rule this temperature is inoffensive to concrete. Simple expansion.
> 100	The concrete loses its free water. The water which is not chemically bonded evaporates from the capillary pores.
100 to 800	The concrete loses its chemically bonded water from CHS.
> 300	The paste in fact contracts while the granulates expand. Long-term heating at this temperature significantly reduces resistance to traction. The concrete begins to disintegrate.
400 to 600	Calcium hydroxide ($Ca(OH)_2$) is broken down into calcium oxide (CaO) and water (H_2O). The water vapour may bring about a phenomenon of local flaking.
± 575	Spontaneous transformation of quartz α into quartz β which goes hand in hand with an increase in the volume of the concrete.
>700	The transformation of limestone ($CaCO_3$) into calcium oxide (CaO) or “quicklime” and carbon monoxide (CO_2) begins.
1150 to 1200	The concrete begins to melt. First the cement paste, then the aggregates.
1300 to 1400	Bonding of the lime with SiO_2 and Al_2O_3. The concrete appears as a molten mass.

7.2. The mechanical and thermal characteristics of concrete and steel

To check concrete elements we must know the thermal and mechanical behaviour of concrete and steel. These properties, which are presented below, have been taken from Eurocode 2 part 1-2, NBN EN 1992-1-2:2005 [107]. This standard will not apply in Belgium before 2007, when its ANB will be drafted. In the meantime NBN ENV 1992-1-2 [113], supplemented by its NAD which applies stricto sensu. In reality, the results of the EN are already used for high-resistance concretes, on a case-by-case basis (for the transitional period see §3.1.2 on Eurocodes).

Only the properties of resistance are used in simplified calculation methods.

In advanced calculation methods, thermal properties and properties of deformation are also used. This is why it is worthwhile describing the stress-strain relationship in detail.

7.2.1. Normal concrete

The resistance of normal concrete (up to C50/60)

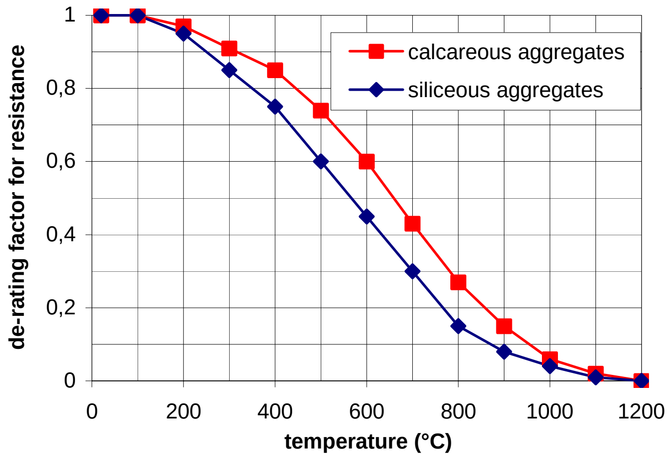


Figure: Evolution of the resistance of concrete as a function of temperature θ and the type of aggregate to NBN EN 1992-1-1:2005.

EC2 fire clearly specifies:

Concretes containing at least 80 % in mass in calcareous aggregates are deemed to be calcareous aggregate concretes.

When using tabulated data (see farer) no checks are required concerning spalling of concrete of normal weight concrete.

Where the axis distance to the reinforcement is 70 mm or more and tests have not been carried out to show that falling-off does not occur, then surface reinforcement should be provided. The surface reinforcement mesh should have a spacing not greater than 100 mm, and a diameter not less than 4 mm.

If others calculation method are used, spalling phenomena has to be considered.

Explosive spalling is unlikely when the amount of water in the concrete is less than k % of the total weight of concrete. Above k %, it is advisable to study more specifically the influence of water content, type of granulate, permeability of the concrete and rate of temperature rise.

In each Member State of the European Committee for Standardisation, the CEN, the value of k to be used will be given in its National Appendix. The draft Belgian ANB makes normative the value k=3 which is the recommended value at European level,

It can be assumed that when the elements are designed for internal use (environmental class EI to NBN B 15-001 [117]), the amount of water in these elements is less than k % of the concrete weight, with 2,5 % < k < 3,0 %.

Attention! "Explosive spalling" must not be confused with occurrences that could be described as "minor" such as flaking, the bursting of aggregates or of edges.

The deformation of concrete

The stress-strain relationship shown in the figure below is defined by three factors:

- compression resistance, $f_{c,\theta}$;
- strain $\varepsilon_{c1,\theta}$ corresponding to $f_{c,\theta}$;
- strain $\varepsilon_{cu1,\theta}$ defining the limit of the descending part of the curve.

with,

θ the considered temperature.

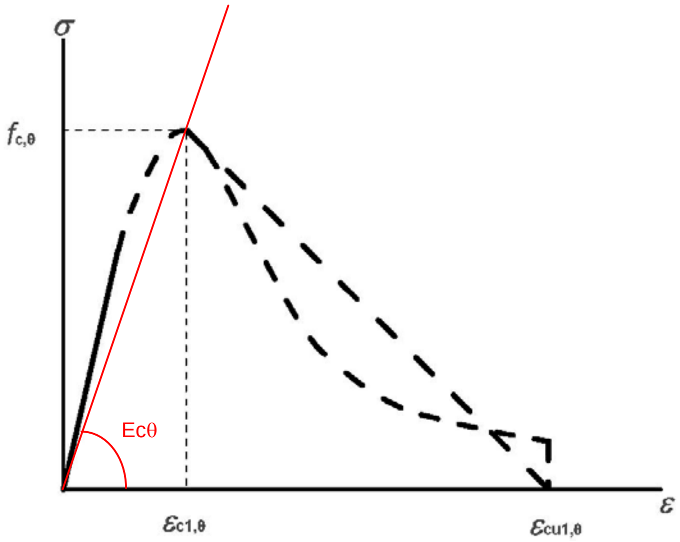


Figure: Mathematical model of the stress-strain relationship of concrete compressed at high temperatures. For questions of numerical stability, it is advisable to adopt a descending part. Linear or non-linear models are allowed. [107]

Inhibited expansion will not cause either concrete or steel to rupture. The extension of concrete that includes silica aggregates, resulting from free expansion, is less than $\varepsilon_{c1,\theta}$. Similarly, the expansion of steel bars resulting from free expansion is less than $\varepsilon_{sy,\theta}$, as the following figure shows: ε_{sy} is defined in §7.2.5.

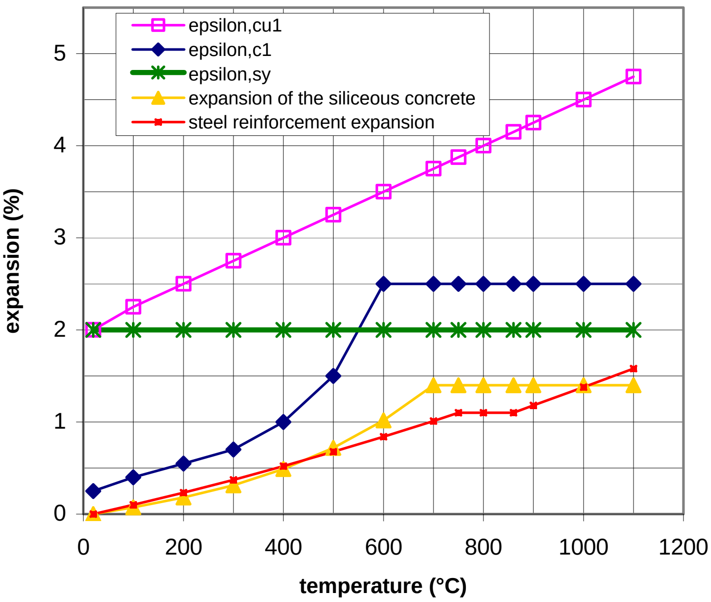


Figure: Evolution of extensions of steel and concrete as a function of temperature (source FEBELCEM)

The plastification of concrete is the key phenomenon to understanding the reason for concrete's resistance to the intense compressive stresses created when the skin of the concrete heats up and in general for any restrained concrete.

The thermal expansion of concrete

The thermal deformation $\varepsilon_c(\theta)$ of concrete as a function of temperature is illustrated in the following figure.

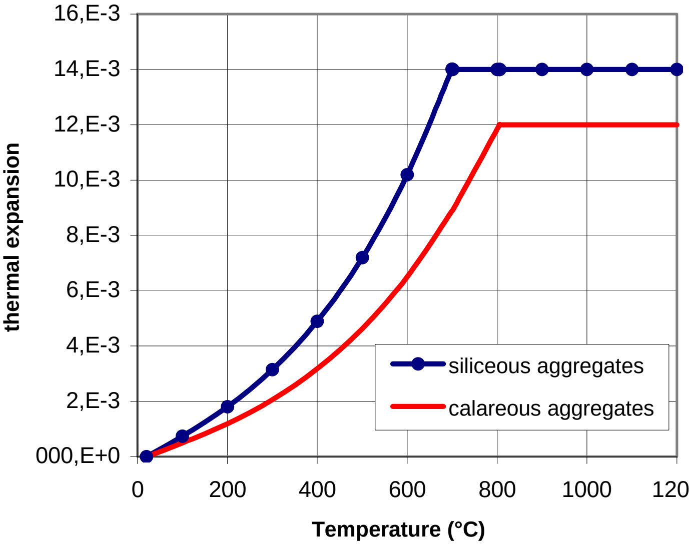


Figure: Thermal expansion of concrete as a function of temperature [107]

The specific heat of concrete

The variation in the specific heat $c_p(\theta)$ of concrete as a function of temperature and water content is illustrated in the following figure.

The peak observed between 100 and 200 °C corresponds to the heat needed to evaporate the water contained in the concrete.

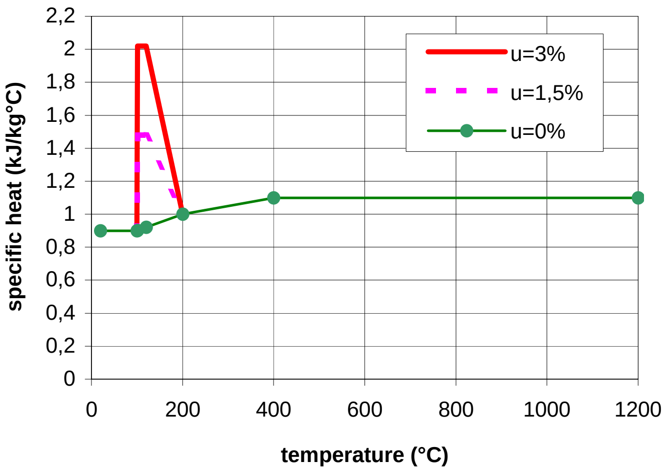


Figure: Specific heat of concrete, $c_p(\theta)$, as a function of temperature for 3 different water contents, u: 0 %, 1,5 % and 3 % of the weight of the concrete [107]

The thermal conductivity of concrete

The variation in the upper and lower limits of the thermal conductivity λ_c of concrete, as a function of temperature, is illustrated in the following figure.

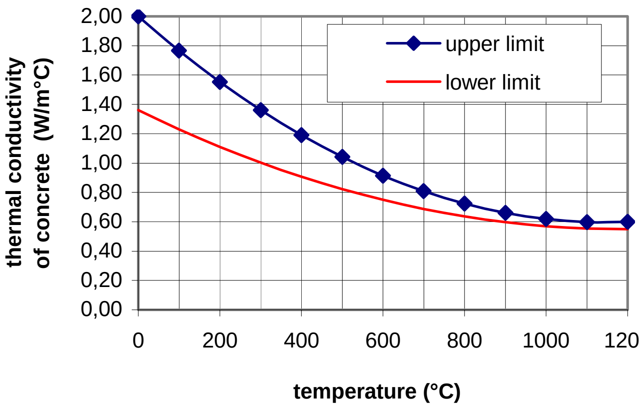


Figure: Variation in the upper and lower limits of the thermal conductivity of normal concrete as a function of temperature [107]

The thermal conductivity value will be provided by the National Appendix. This value will lie within the interval defined by the upper and lower limits.

The lower limit of thermal conductivity was obtained from comparisons with temperatures measures in fire tests on different types of concrete structures. The lower limit gives more realistic temperatures for concrete structures than the upper limit, which was obtained from tests on composite steel/concrete structures.

At 20 °C, the thermal conductivity curves taken from ENV 1992-1-2 produce a thermal conductivity for calcareous concretes of around 20 % less than that of silica concretes.

7.2.2. Light concretes

The properties of light-aggregate concrete are not given in NBN EN 1992-1-2. Because of that, they are taken from NBN ENV 1992-1-2 [113].

Thermal expansion of lightweight concrete

The thermal deformation $\varepsilon_c(\theta)$ of concrete as a function of temperature is illustrated in the following figure:

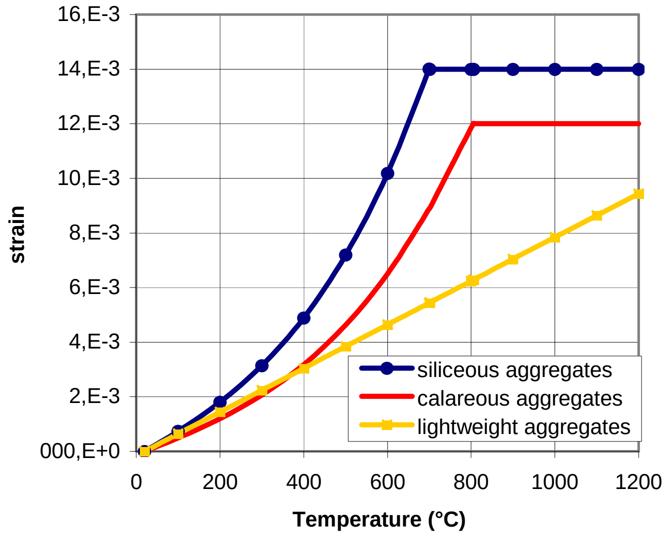
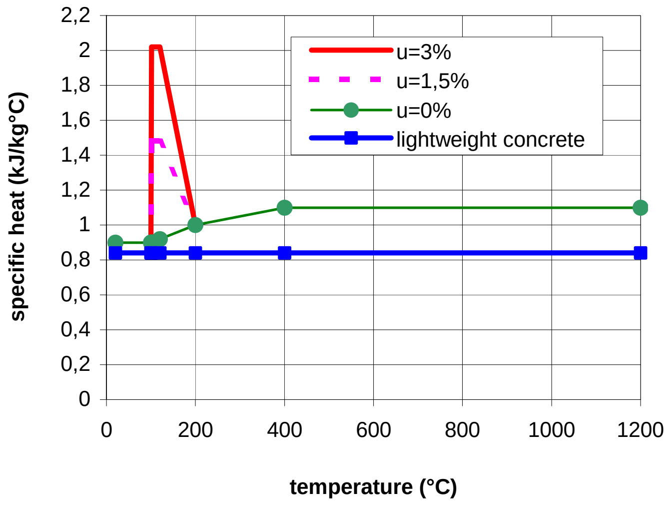


Figure : Thermal deformation $\varepsilon_c(\theta)$ of lightweight concrete according to [113]

The specific heat o flight concrete

The variation in the specific heat $c_p(\theta)$ of light concrete as a function of temperature and water content is illustrated in the following figure:



The upper curve corresponds to normal concrete [107] and lightweight concrete [113]

The thermal conductivity of lightweight concrete

The variation in thermal conductivity λ_c of lightweight concrete as a function of temperature is illustrated by the following figure:

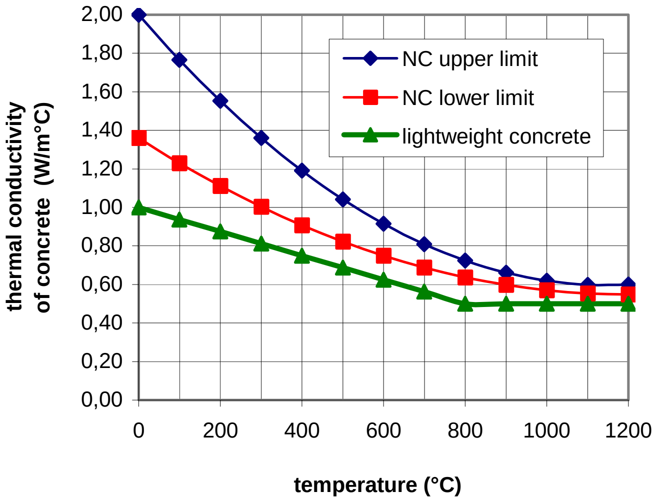


Figure: Thermal conductivity of normal concrete (NC) [107] and concrete with lightweight aggregates [113]

7.2.3. High-strength concretes

The consideration of high-strength concretes in EC2 is entirely new for calculating both "cold" and "hot" concretes.

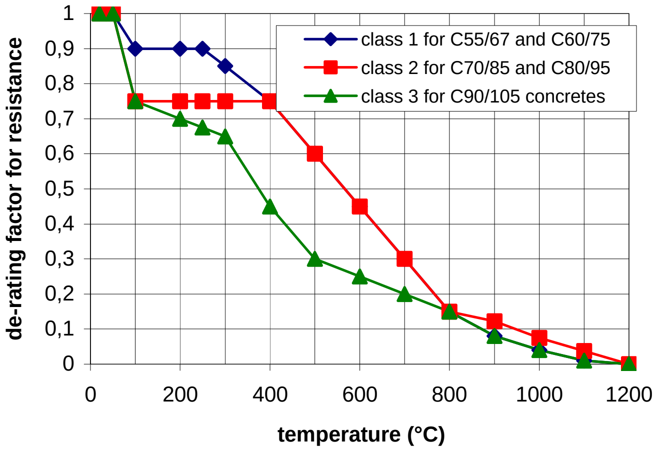


Figure: De-rating factor for compressive strength for the recommended classes for *high-strength concretes in accordance with EC2 fire [107]*

It is advisable to check that the concrete is not too good, in other words that its **actual strength** is not too high in relation to the desired result. The gain in strength would not compensate for the reduction in strength linked to the lower permeability of the concrete. When the actual characteristic strength of the concrete is likely to be of a class greater than that specified in the calculations, it is advisable, in the calculations, to use the relative reduction in resistance to fire in the higher class.

The **thermal characteristics** given for normal concrete can also be applied to high-strength concrete.

The rules of Eurocode 2 fire also specify the cases in which special measures must be taken against the spalling:

For concrete classes C55/67 to C80/95, the rules given for normal concrete above for the spalling apply, provided the maximum level of silica fumes is less than 6 % of the weight of the cement. For higher levels of silica fumes, the rules given for concrete classes C, with C80/95 < C ≤ C90/105 apply.

For concrete classes 80/95 < C ≤ 90/105, it is advisable to apply at least one of the following 4 methods:

Method A: place a mesh of reinforcements with a nominal cover of 15 mm. It is best for this mesh to include wires with a diameter greater than or equal to 2 mm, with a pitch less than or equal to 50 x 50 mm. It is best for the nominal cover of the main reinforcement to be greater than or equal to 40 mm.

NOTE: We advise against this method because it is not certain that this mesh will be able to be kept in place during concreting. The mesh may be close to the surface in the 20 mm superficial zone of the concrete with the associated risks of carbonation. The prescribed nominal cover is less than those prescribed in EN 1992-1-1 for all exposure classes.

Method B: use a type of concrete for which it has been shown (by local experience or by tests) that there is no risk of the concrete spalling when exposed to fire.

Method C: use protective casings for which it has been shown that there is no risk of the concrete spalling when exposed to fire.

Method D: use a mix of concrete which contains more than 2 kg/m³ of monofilament polypropylene fibres.

This last method is the one we recommend in the absence of a demonstration by methods B and C.

7.2.4. Self-compacting concretes

These concretes do not require vibrating to be installed. For more details on the technology of these concretes, we refer the reader to the cement bulletin nr 36 [59] which deals specifically with this subject.

The small amount of experimental results show that the reduction in compressive strength and behaviour on blow-out do not present any significant differences in relation to vibrated concretes of a similar composition. Tests carried out in France allowed them to be used.

7.2.5. Steel

Resistance of steel for reinforced concrete

The de-rating factor for the characteristic strength of the steel in reinforced concrete as a function of temperature θ is illustrated in the following figure. This factor varies according to the type of steel (hot- or cold-laminated) and according to the steel strain:

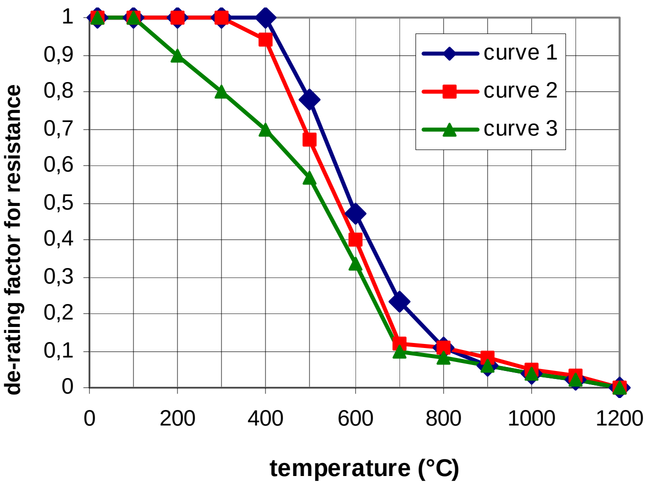


Figure: de-rating factor $k_s(\theta)$ applicable for the characteristic strength (f_{yk}) of tension or compression reinforcement (class N = recommended class) [107]

Legend:
Curve 1: tension reinforcements (hot-laminated steel) for strain ≥ 2 %;
Curve 2: tensioned reinforcements (cold-formed steel) for strain ≥ 2 %;
Curve 3: compression reinforcement or tension reinforcement for strain < 2 %.

The difference between the curves is linked to the fact that the experimental results show that the plateau of plasticity of steels disappears when hot, and therefore that the factor $k_s(\theta)$ depends on the elongation at rupture.

Curve 1 is the same as in NBN ENV 1993-1-2 [112] for the calculation of profiles in steel frame constructions.

Why are the deformations of the compression reinforcement limited (curve 3)?

In more concrete terms, in columns or in support zones of continuous beams, reinforcements may be situated in high-temperature zones where the concrete can cope with greater deformations, beyond the elastic deformation limit of 0,2 % for steel. In limiting the strains, the use of curve 3 warns against the danger of premature buckling of reinforcements between stirrups, thereby guaranteeing the compatibility of the deformations of concrete and steel.

Resistance of pretensioning steel

The drop in strength is much more rapid in pretensioning steels. This explains the increase of concrete cover in the tabulated value methods compared to ordinary steels: 10 mm for bars and 15 mm for strands.

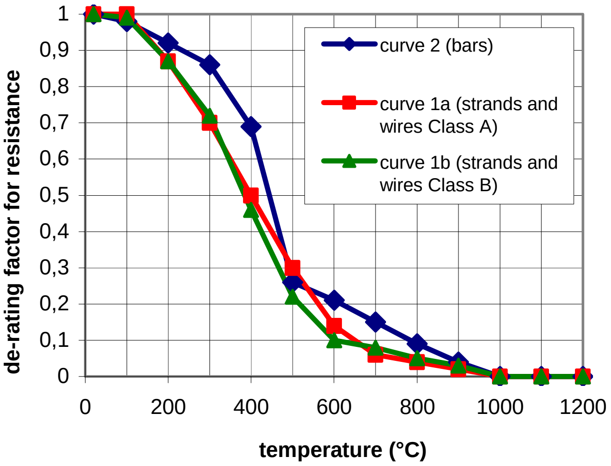


Figure: De-rating factor $k_p(\theta)$ of the characteristic strength ($\beta\times f_{pk}$) of pretensioning steel [107]

These classes correspond to safety classes. Each country can determine its choice of safety: the level of safety is a national competence.

Deformation of steel

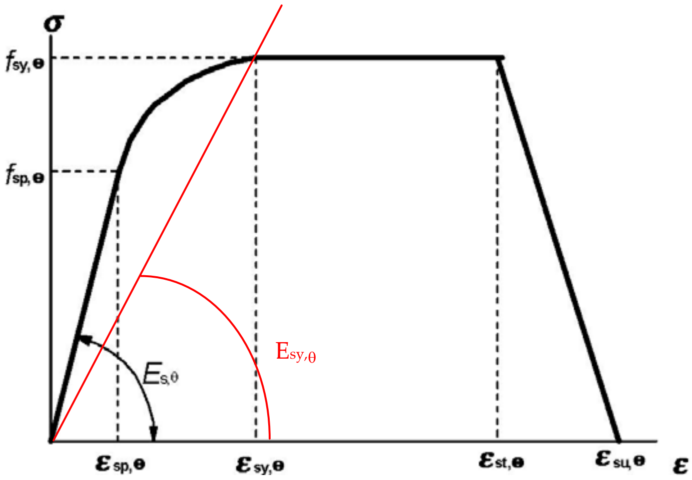


Figure: the stress-strain relationship is defined by three parameters: [107]
- *the gradient of the linear elastic zone $E_{s,\theta}$*
- *the limit of proportionality $f_{sp,\theta}$*
- *the maximum stress $f_{sy,\theta}$*

$\varepsilon_{sy,\theta} = 2\%$, $\varepsilon_{st,\theta} = 5\%$ *and* $\varepsilon_{su,\theta} = 10\%$

The formulation of the stress-strain relationship can also be applied to compressed reinforced concrete steel.

Thermal expansion of steel

The variation in thermal expansion $\varepsilon_s(\theta)$ as a function of temperature is illustrated in the following figure:

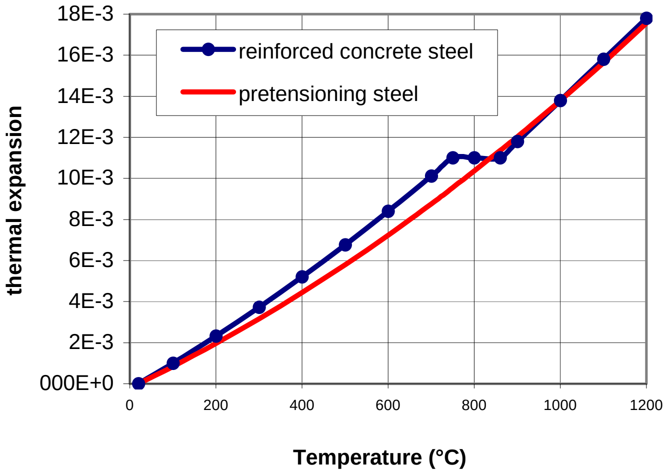


Figure: Thermal expansion of steel [107]

Specific heat of steel

The thermal properties of steel are not defined in Eurocode 2. They are not generally needed, except where the percentage of steel is high. Reference can be made to the values given in Eurocode 3 [112].

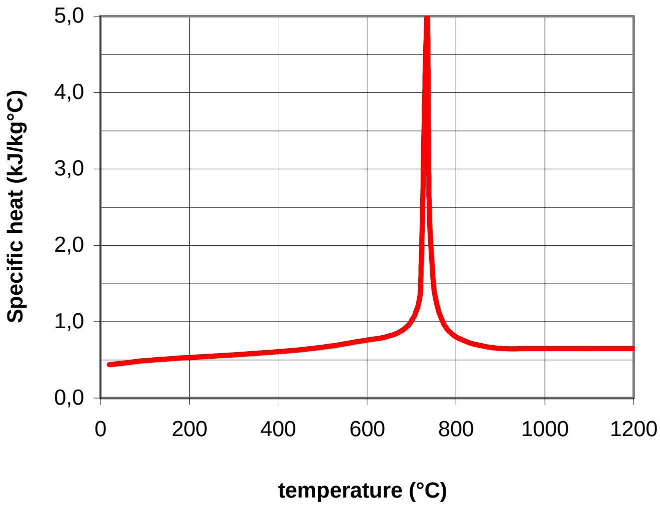


Figure: Specific heat of carbon steel, as a function of temperature [112]

Thermal conductivity of steel

The variation in the thermal conductivity λ_s of steel as a function of temperature is illustrated in the following figure:

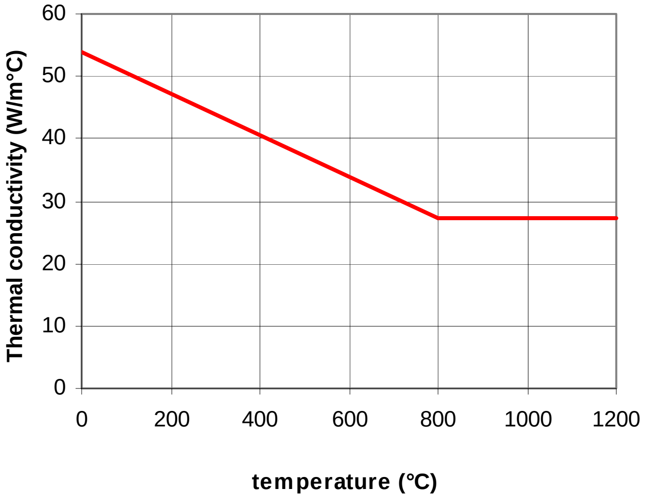
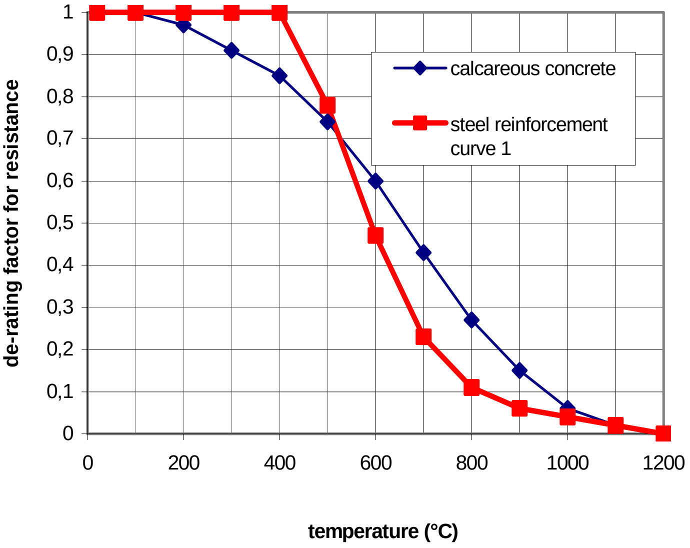


Figure: Thermal conductivity of carbon steel as a function of temperature [112]

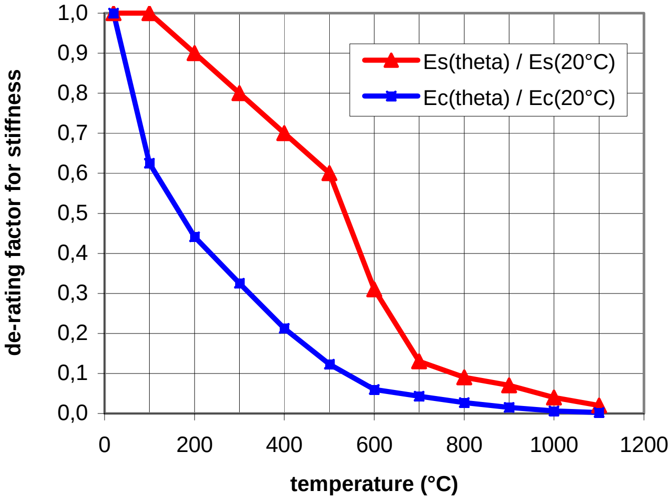
7.2.6. Comparison of the mechanical characteristics of steel and concrete

The losses of strength in concrete and steel are shown below on the same graph. For steel, it is curve 1 (deformation of steel greater than 2 %) which is shown on the graph.



According to NBN EN 1992-1-2 [107]

The losses in rigidity of concrete and steel are shown below on the same graph:



$E_{s,\theta} / E_s$ (20 °C) see §7.2.5
$E_{c,\theta} / E_c$ (20 °C) see §7.2.1

(source FEBELCEM)

The above graph is not common: it shows that the relative loss of rigidity is greater for concrete than for steel! This reflects the capability of concrete, as expressed above, to tolerate the restraint.

This significant drop in the rigidity of concrete at high temperatures has relatively little influence on the rigidity of compressed elements in concrete as only the first few centimetres from the surface are affected.

Conversely, the thermal diffusivity of steel, 25 times greater than that of concrete, combined with a low massivity of the pieces, has a serious influence on the buckling behaviour of steel pieces.

8. Protection and risk calculations

8.1. Verification of fire resistance: calculation

8.1.1. Three methods, three levels

It is important that architects and prescribers distinguish between the existing of 3 methods, each associated with a level of calculation. Only method 1 will be described in detail below. It offers maximum relevance and simplicity for concrete structures. For the other methods, readers may consult reviews [37] or NBN EN 1992-1-2 directly [107]

The fire part of the Eurocodes presents three types, three levels of model for calculating the fire resistance of structures [37]. At Federal level, a text has already been drafted on the acceptance by the competent authorities of calculation notes according to these different methods. This text will be the subject of a Royal Decree [52]. From the simplest to the most complex:

Level 1: calculations by tabulated values

The use of this method would be the responsibility of the design office controlled by the commune, itself advised by the fire services.

European standard EC2 part 1-2 allows girders, columns, walls and slabs made from reinforced or prestressed concrete to be verified for an ISO fire. This standard is based on tables (tabulated data) which give the minimum dimensions of sections as well as the distance from the axis (axis distance) of reinforcements to the nearest facing. The values given in these tables were calculated either after calibrating the characteristics of the material and the calculation models or deduced from empirical formulae calibrated from tests.

Eurocode masonry part 1-2 specifies the minimum thickness to be given to walls according to the type of blocks used.

Since the tables take account of the loading rate for walls and columns made from reinforced or prestressed concrete they allow the result to be refined.

This type of verification is considered as accessible as a cold calculation.

For concrete, this level 1 allows **immediate verification** for girders and slabs. A conservative approach in the guise of predimensioning, taking a loading rate of 0,7, **immediately gives the minimum sections** of columns and the thicknesses of walls.

The methods of levels 2 and 3 allow the results to be refined and the structural reserves offered by the possible hyperstaticity of the structure to be taken into account: the continuity of the upper reinforcements to the right of the supports and the beneficial effects of the membrane in monolithic floors are just some examples.

Designers of metal or mixed steel-concrete structures make maximum use of these last methods when demonstrating the behaviour of steel buildings in fire

Level 2: simplified calculation models

The use of this method would also be the responsibility of the design office, controlled by the commune advised by the fire services on the basis of certificates of conformity:

- either the design office is certified by a BELAC accredited certification body (EN 45013) and itself certifies the conformity of its calculation note;
- or the design office is not certified and conformity has to be attested by a BELAC accredited certification body (EN 45004).

A more advanced level 2 calculation uses the same approach as for cold dimensioning. It also integrates the loss of resistance of the concrete and reinforcements as a function of their temperature. For an ISO fire their temperature is determined either using graphs or using a programme that carries out a thermal analysis of the section being studied. If the capacity for resistance is greater than the loading, the structural element will have a fire-resistance time at least equal to the desired time.

The table below shows the safety coefficients on concrete and steel materials:

	Cold	Hot
Concrete	1,76(*)	1
Reinforcement steel	1,15	1
Steel structures	1,1 (**)	1

Safety coefficients on materials
(*) 1,76 = 1,5 / 0,85
(**) According to ENV 1993-1-1 [116]

This type of calculation requires a thorough knowledge of FSE. It is available to design offices whose calculation notes require certification.

Level 3: advanced calculation models

Calculation notes that use these advanced models are only accepted on a case-by-case basis by the Dispensations Commission of the Federal Public Service Home Affairs.

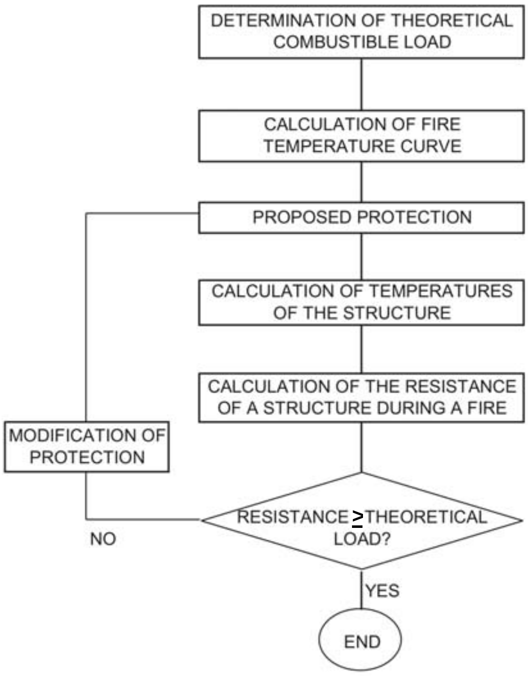


Figure: Method of calculating theoretical fire resistance [57]

These advanced models require sophisticated calculation programmes, necessitating a high level of knowledge. These models can perform a thermal analysis of elements in natural fires. The thermal loading may be linked to a complete mechanical analysis of the structure, among other things by finite elements. It is advisable to consider large movements, to take account of second-order stresses. The software SAFIR of the University of Liège is currently used.

The first two methods refer to the standard ISO curve of temperature rise. Only the level 3 methods can take other considerations into account. Furthermore, the Eurocodes give constructive provision rules which must be followed.

A strict calculation of steel structures through intensive use of FSE leads to a safety limit with no reserve. In contrast, concrete structures often present a large safety reserve at no extra cost which exceeds the minimum requirements imposed.

8.1.2. Tabulated values method (level 1)

The tabulated data of NBN EN 1992-1-2 are given for columns, girders, floors and walls, whether load-bearing or not.

This method is based on the hypothesis of siliceous aggregates, the most conservative hypothesis.

8.1.2.1. Field of application

- EN 1992 fire part is applicable to normal weight concrete up to strength class C90/105 and for lightweight concrete up to strength class LC55/60.
- The tables cover periods of exposure to the standardised fire of the ISO curve up to 240 minutes;
- The values given in the tables apply to the normal weight concrete (between 2000 and 2600 kg/m^3) made with siliceous aggregates.
- In the case of calcareous aggregates, the minimum dimensions of the sections may be reduced by 10%, except for columns;
- The use of this method dispenses with any additional verification of torsion, shearing load, anchorage of the reinforcements and spalling (while retaining the possible imposition of “skin netting”: see §7.2.1). It should be noted that ruins by shearing load are extremely rare.
- Attention nevertheless: in the case of HPC (of a class greater than C50/60), the use of tables is conditioned by supplementary rules.

8.1.2.2. Reading the tables

Depending on the required fire duration, and possibly the loading level, the tables give pairs of values of the type 200/35. The first value corresponds to the minimum dimension of the transversal section of the piece (b_{min}). The second value corresponds to “a”, the distance from the axis of the longitudinal reinforcement to the nearest facing.

Several minimum dimension / distance to the axis combinations are proposed. A larger dimensioned section could correspond to a smaller distance to the axis, and vice versa. In a more massive section, the heat could be transferred more to the core of the section instead of accumulating in the peripheral zone where the reinforcements are situated.

This distance “a” is a nominal value. The associated nominal cover is therefore (a-Φ/2- the diameter of the eventual stirrup). Let us remember that the cover that is mentioned on plans is the nominal cover. It corresponds to the height of the spacers). It is fixed equal to the minimum concrete cover + the installation tolerance (classically 10 mm for cast in situ concretes and 5 mm for precast concretes) from which is deduced 5 mm for high-strength concretes and slabs. (see NBN EN 1992-1-1 [100]). The minimum cover is linked to environmental classes (cf. NBN B 15-001 [117] or the book of “Concrete Technology” published by the GBB [70]).

For each type of structural element, the standard details the applicable conditions of the tables.

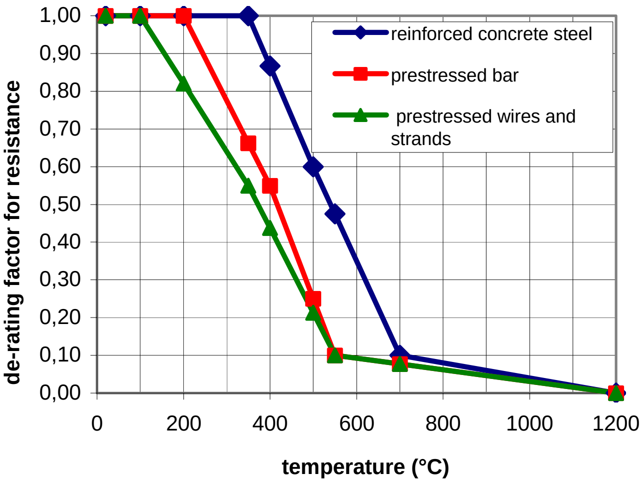
8.1.2.3. Axis distance

- In the case of **several layers of steel reinforcement** (notably in girders), "a" designates here "am" = distance between the centre of gravity of steels and the nearest concrete surface. Each bar must nevertheless respect a minimum "a";

- In the case of girders with a single layer of steel reinforcement, the value "a" of the **angle reinforcements** will have to be increased by 10 mm in relation to that given in the tables;

- The tables are based on a **"critical" temperature** of the steel: 500 °C for reinforced concrete steels, 400 °C for prestressed rods, 350 °C for prestressed wires and strands. This difference in critical temperature may be translated by an increase in cover in the case of prestressed concrete.

  The de-rating factor of the characteristic strength of steels in reinforced and prestressed concrete as a function of the critical temperature θ_{cr} to be used with the tables is illustrated by the reference curves in the figure below. They differ slightly from those given in §7.2.5 (as they have been deduced from tests carried out according to different procedures).



(source [107])

- What is the origin of these critical temperature values?

For a loading rate of 0,7 in fire situation (this was developed previously in mechanical actions see §6.1) and all other things being equal, steels will only work at 70 % of their allowable stress in cold situation.

When hot, steels can work at a stress 1,15 times greater than when cold. This results from safety coefficients of steel: 1,15 cold and 1,00 hot.

So that the steels support the load, the residual strength fraction required when hot is given by the loading rate in fire situation divided by the safety coefficient of the steel in cold situation, namely:

$$k_{s,\ necessary} = \eta_{fi}/(\gamma_s/\gamma_{s,fi}) = 0,7/(1,15/1,0) = 0,609$$

This value corresponds to a temperature of 500 °C., according to curve for RC steel given above.

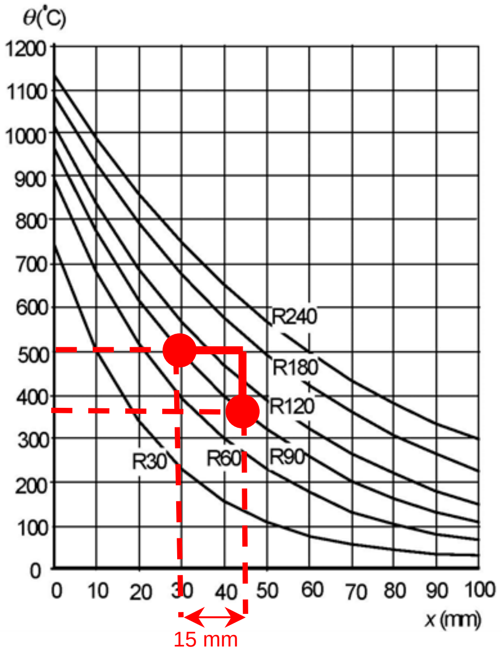
This same value corresponds to a temperature of 400 °C, according to curve "2" for prestressed rods. According to curve "3" for prestressed strands and wires, this same value corresponds to a temperature of 350 °C.

- In the case of **prestressed steels**, the same tables can be used, increasing the distance "a" by

  - 10 mm for prestressed rods and
  - 15 mm for prestressed strands and wire.

How are these two increases in distance explained?

The graph below, taken from EC2, gives the temperature distribution for a one-dimensional heat flow, which distribution applies to slabs. These same curves are used for hollow core slabs.



Legend: x is the distance from the exposed surface

Figure: Distribution of temperatures in slabs (height h = 200 mm) for R 60 to R 240 (source [107]

The temperature of a point situated 30 mm from the surface after 90 minutes' exposure of the element is 500 °C. At this same time, the temperature of a point situated 15 mm deeper, at 45 mm, is 350 °C.

Thus, to obtain the nominal axis distances "a" for prestressed strands, simply increase the distances given for RC reinforcements by 15 mm.

- Adjustment of axis distance: for girders and slabs, when the section of **reinforcement is overabundant in ambient temperature and for a loading rate** η_{fi}, the EC provides for a simple procedure based on critical temperatures. For tension elements on bent elements on simple supports, it allows the axis distance given in the tables to be reduced. By developing the equations put forward in the EC, the distance "a" from the reinforcement to the surface of the concrete obtained by the tables can be reduced by subtracting the value Δa defined as follows:

1. For reinforced concrete :

$$\Delta a = 24 \,.\, (1 - \zeta)\ (\text{mm}) \leq 20\ \text{mm}$$

2. For prestressed concrete with :
   - bars

$$\Delta a = 18 \,.\, (1 - \zeta)\ (\text{mm}) \leq 15\ \text{mm},$$

   - wires and strands (adherent)

$$\Delta a = 24 \,.\, (1 - \zeta)\ (\text{mm}) \leq 20\ \text{mm}$$

- where

$\zeta =$ $(A_{s,req} / A_{s,prov}) \,.\, (\eta_{fi} / 0{,}7)$, with

$A_{s,req} =$ the section of steel required for the ultimate limit state to NBN EN 1992-1-1, and

$A_{s,prov} =$ the section of steel actually put in place.

The limits of 15 et 20 mm correspond to the case where k_s and $k_p = 0{,}1$ and $\zeta = 1/6$.

Example of application:

1st part

Imagine a reinforced concrete floor (C25/30) 20 cm thick on simple supports intended for an office block situated in Belgium. What is the practical height of the spacers for reinforcements to obtain a fire resistance of 2 hours? The main lower reinforcement consists of steel rods 12 mm in diameter:

The height of the spacers is the nominal cover of the reinforcements. It is simply the one that should be indicated on the plans.

The nominal cover of the reinforcements is immediately deduced from the previous figure: on curve R 120 the abscissa x = a = 35 mm corresponds to the ordinate of 500 °C. The nominal cover is $c_{nom} = a - \text{diam}/2 = 35 - 12/2 = 29$ mm.

Let us verify compatibility with the requirements of durability. The minimum cover is that imposed for the interior environment class EI.

The nominal cover of the reinforcements is obtained by adding an execution tolerance of 10 mm and is therefore:

$$c_{nom} = 15 + 10 = 25\ \text{mm}$$

NBN B 15-002:1999 [115] and NBN EN 1992-1-1:2005 [100] authorise a deduction of 5 mm in the case of slabs:

$$c = 29\ \text{mm} > c_{nom} = 25 - 5 = 20\ \text{mm} \Rightarrow \text{OK for 29 mm}$$

2nd part

Knowing that for reasons of standardisation, the planned section of steel exceeds by 18 % the section of steel that is strictly necessary, what is the minimum acceptable nominal concrete cover?

Let us calculate the value of ζ.

Standard NBN EN 1991-1-1-ANB:2005 [114] specifies the live loads applicable in Belgium for offices in table 6.2 ANB, namely:

$$Q = 3{,}0\ \text{KN/m}^2.$$

The permanent load is:

$$G = 24 \,.\, 0{,}2 = 4{,}8\ \text{KN/m}^2$$

Standard NBN EN 1990-ANB:2005 [110] specifies the coefficient ψ_2 applicable in Belgium for category B offices in table A1.1 ANB: namely 0,3

The loading rate is therefore:

$$\eta_{fi} = (G + \psi_2 Q) / (1{,}35G + 1{,}5Q)$$

$$\eta_{fi} = (4{,}8 + 0{,}3 \,.\, 3{,}0) / (1{,}35 \,.\, 4{,}8 + 1{,}5 \,.\, 3{,}0) = 0{,}52$$

Therefore:

$$\zeta = (A_{s,req} / A_{s,prov}) \,.\, (\eta_{fi} / 0{,}7) =$$

$$\zeta = (1 / 1{,}18) \,.\, (0{,}52 / 0{,}7) = 0{,}63$$

Thus:

The reduction $\Delta a = 24 \,.\, (1 - 0{,}63) = 9\ \text{mm} \leq 20\ \text{mm}$

$\Rightarrow c_{nom}$ acceptable $= 29 - 9 = 20$ mm ≥ 20 mm $\Rightarrow$ OK

8.1.2.4. Isostatic girders

The following EC2 fire table provides the minimum dimensions and distances from the axis of the reinforcements to the surface for reinforced and prestressed concrete girders on simple supports without moment on supports.

Specifically for the girders in I, when the value "b" of their heel is greater than 1,4 times the actual thickness of the web and this heel is not sufficiently massive, it is advisable to increase the axis distance "a" given in the following table according to the formula given in EC2 fire [107].

Resistance to standardised fire	Minimum dimensions (mm)						
	Possible combinations of a and b_{min}, a being the mean distance from the reinforcement axes to the facing and b_{min} being the width of the girder				web thickness b_w		
					Class WA	Class WB	Class WC
1	2	3	4	5	6	7	8
R 30	b_{min}= 80 a = 25	120 20	160 15*	200 15*	80	80	80
R 60	b_{min}= 120 a = 40	160 35	200 30	300 25	100	80	100
R 90	b_{min}= 150 a = 55	200 45	300 40	400 35	110	100	100
R 120	b_{min}= 200 a = 65	240 60	300 55	500 50	130	120	120
R 180	b_{min}= 240 a = 80	300 70	400 65	600 60	150	150	140
R 240	b_{min}= 280 a = 90	350 80	500 75	700 70	170	170	160
a_{sd} = a + 10 mm (see note below)							

For prestressed girders it is advisable to take account of the increase in the distance from the axis of steels to the facing in compliance with §8.1.2.3.

a_{sd} is the distance from the axis of steels to the lateral wall of the girder in the case of angle reinforcements (or cable or wire) of girders with a single layer of reinforcement. For values of b_{min} greater than those given in column 4, no increase in the value of a_{sd} is required.

* The cover required by NBN EN 1992-1-1 is normally decisive.

Table: Minimum dimensions and axis distance for simply supported beams made from reinforced and prestressed concrete (source [107])

8.1.2.5. Continuous girders

EC2 fire provides a table similar to that for isostatic beams with reduced axis distances "a"

We shall content ourselves with noting the importance, in continuous structures, of extending across the entire span the upper reinforcements planned at the supports, at least in part, to meet the appearance of negative moments. These appear in mid span following thermal gradients in the sections:

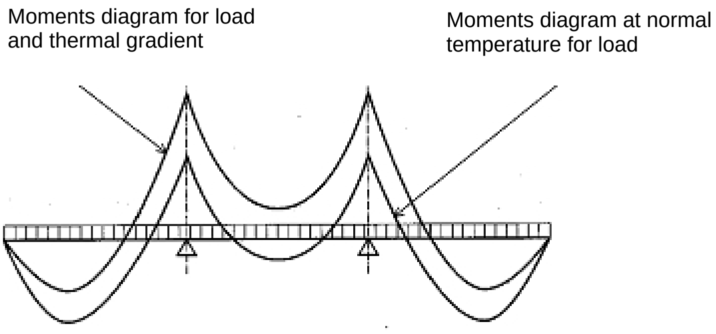


Figure: Raising of moments diagram for continuous structures [68]

8.1.2.6. Slabs

EC2 fire part gives tables for

- reinforced and prestressed concrete simply supported one-way and two-way solid slabs;
- continuous solid slabs;
- flat slabs. These are floors resting on columns;
- ribbed floors in one or two directions. A wafel floor, for example, is a ribbed floor in which the ribs and lower reinforcements are arranged in the two supporting directions.

8.1.2.7. Columns

Two methods are provided for verifying the resistance to fire of columns: A and B. The two methods can be used indiscriminately in their field of application. They take into account:

- the size and slenderness of the columns;
- the load level;
- the first-order eccentricity;
- the resistance of the concrete;
- the reinforcements,
- the distance from the axis of the rods to the facing and finally,
- the number of longitudinal bars (4 or 8)

The tabulated values are given purely for non-sway structures. Thus, columns in a building that support floors linked to a central core are typically non-sway. A note relating to unbraced structures will appear in the Belgian national annexe.

Method A

Method A was perfected by the University of Liège and previously existed in the NAD of the pre-standard. It has now been incorporated into the European standard. A series of tests on 80 columns, carried out by 4 different laboratories across the globe, allowed a formula to be calibrated which predicts the duration of fire resistance as a function of the various factors mentioned above.

The field of application of method A limits its use to

- maximum 450 mm square columns or 450 mm diameter circular columns;
- an eccentricity e/b of first order of 0,4 and,
- a buckling length of 6 meters in case of fire.

In the European standard, this formula was then translated into table form. The length of slenderness of the column was fixed at 3 metres.

To obtain other pairs of value b_{min}/a, an interpolation can be used or, for greater accuracy, the formula can be used directly.

The Belgian national annexe provides extended tables which allow the user to read solutions directly without recourse to an interpolation.

The values of the tables of the European standard and our ANB are different because they were calculated with different values for the parameter α_{cc} (respectively = 1,00 and 0,85)

Method B

This rests on the results of a mathematical model. The two methods A and B have been intensively compared and present a good correlation with the tests carried out on the 80 columns.

This method has a less limited field of application, especially if Appendix C to EC2 fire is used.

- slenderness of columns up to 80 and
- eccentricity "e/b" of the first order up to 0,5.

The difficulty of interpolating in the tables may be got around by a simple programme.

8.1.2.8. Walls

EC2 fire part gives tables for

- bearing walls
- non-bearing walls (EI requirement)
- fire-resistant walls (meeting the supplementary requirement of resistance to shocks).

8.2. Fire Safety Engineering

There is no absolute definition, but the following definition nevertheless seems acceptable (Purkiss, 1996):

> "Fire Safety Engineering" may be defined as the application of scientific and engineering principles to the effects of fire: the risks and dangers run are quantified, both with a view to reducing loss of life and damage to property and with a view to providing an optimal solution to the application of preventive and protective measures.

The approach of "Fire Safety Engineering" may lead to "natural fires" being used to describe the evolution of temperatures in compartments and to verify the behaviour in fire of the structure. Natural fires encompass the parameter curves and zone models developed above.

This approach was introduced in the informative Appendices to the standard Eurocode 1 part 1-2 [106]. It cannot currently be used in Belgium without departing from the regulations. The national application document (ANB) will include a very important note on this subject:

"The temperature curve to be applied has to be authorised by the competent public authorities either officially in the regulations or, for each individual case, on the basis of a supporting study."

> The different approaches to fire calculations are:
>
> - classification based on the standard ISO curve,
> - the use of parametric fires and
> - the use of natural fire curves coupled with reducing coefficients on fire loads. This is one of the developments of Fire Safety Engineering
>
> **They do not give the same level of safety**.
>
> Building owners and insurance companies have to realise that concrete structures are normally classified according to the standard ISO curve. They are robust, can be repaired after a fire and it is possible to make changes during the life of the building.
>
> According to European Prestandards, the critical temperature of steel structures without fire protection is 540 °C when the loading rate is 0,7. The critical temperature is reached in current profiles in 10 to 15 minutes or more depending on the massiveness of the elements and their loading rate. This is why the steel industry has developed calculation methods to show that temperatures are sometimes lower than those encountered in an ISO fire. This industry also shows that mechanical loads may be less than those required for standard classification according to the ISO curve. The timber industry shares the same interests.
>
> Even if the requirements can be satisfied by means of parameter curves or FSE, building owners have **more safety and flexibility for the same price if they choose concrete** with a standard classification.

In the national Belgian annexe, an opening towards different curves is given for the case of large compartments with reduced combustible loads in which flash-over can clearly not occur. In this specific case and only if authorised by the competent authorities, the ISO curve is abandoned in favour of the localised fires detailed in Appendix C.

The ANB makes Appendices C, D and G normative (see §3.1.2 p23). Appendices A, B, E and F remain informative. These appendices are brand new compared with pre-standard NBN ENV 1991-2-2 [118] and are the result of the latest FSE developments.

Appendix A develops parameter curves.

Appendix D develops advanced fire models (one and two zones).

Appendix E, which has received most criticism, deals with fire load densities, speeds of fire propagation to be incorporated into the models defined in the other appendices. At ANB level it includes a certain number of amendments that are the result of a constructive dialogue within the ad-hoc group charged with drafting it.

Annexe F develops the method of equivalent time of exposure to fire. It does not allow the maximum heat release rate to be taken into account.

In the annexes, the fire load density considered in the design is not the average European value encountered in the type of building studied. Nor does it correspond to the 80 % fractile, i.e.

a value for which 80 % of buildings contain a lower fire load. Nevertheless, this value is used as a conventional reference.

FSE gives probabilities of collapse in a fire situation, but there is no clear acceptability criterion.

FSE consultants have used the following interpretation:

$$p_{f,fi} \,.\, p_{fi} < p_t$$

with,

$p_{f,fi}$ = probability of collapse in case of a severe fire;

p_{fi} = probability of a severe fire developing;

p_t = target probability for the rupture of a structural element when calculating at the ultimate limit states as explained in NBN EN 1990 'Basis for design'[109].

The fire design load density is thus evaluated such that the risk of severe fire multiplied by the probability of collapse in case of a severe fire is less than the risk which is commonly accepted during calculations for a structure at normal temperature, or a probability of the structure being ruined of 1/1 000 000 a year, specifically 5.10^{-5} for a building life of 50 years.

This is a "personal" interpretation (in the sense of "private"): this appears entirely implicitly in Appendix E to EN 1991-1-2. Determining the level of safety falls under the responsibility of the 'fire' legislator (FPS Home Affairs in Belgium).

The drawback to the above interpretation lies in the fact that the probability of collapse in case of fire depends on the probability of a severe fire developing, which in turn depends on the use of the building.

For a building life of 50 years, this leads to a collapse rate of a little more than 5 buildings in 100 000. To give an idea, taking a probability:

- of a fire occurring of 1/100 000 = 10^{-5} per year and per m$^{2;}$
- of the fire being extinguished by the occupants of 6/10;
- of the fire being controlled by the fire services of 9/10;

the probability of a severe fire occurring is

$p_1 = 10^{-5} \,.\, (1\text{-}0{,}6) \,.\, (1\text{-}0{,}9) = 4.10^{-7}$ per year and per m^2

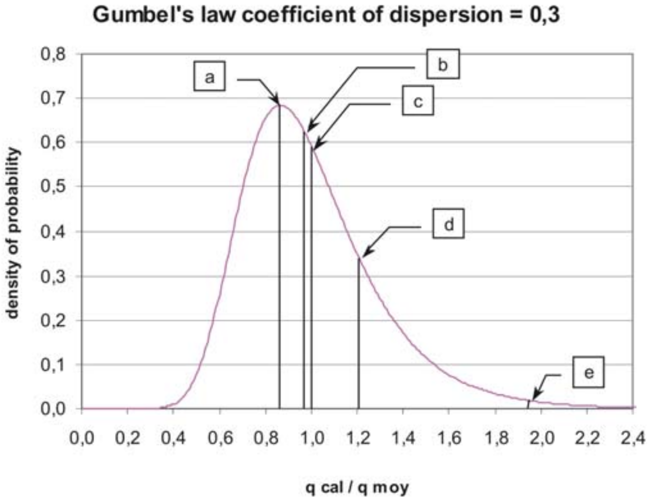
(see Figure: example of event tree §8.3.2.3 p63)

This means that if a fire breaks out in a compartment of 200 m^2, the fire load density in question will be determined such that the probability of failure will be

$$5.10^{-5} / (4.10^{-7}.200.50) = 1{,}25\ \%.$$

This means 1,25 building in 100 will be ruined in case of severe fire (=uncontrolled, with flash-over for example).

It has been shown that fire load densities follow a Gumbel type-I law. This law is used in several areas (in particular finance and credit) as it allowed asymmetrical statistics to be represented, which seems to be the case with fire load densities: there is necessarily a minimum of mobile fuel in housing, but conversely there is no maximum. As a consequence, the mean (c) is out of line in relation to the median (b = 50 % fractile) and in relation to the most likely fire load density (a) (see figure below):



Law of density of probability of the fire load as a function of the fire load density of the compartment in question, related to the mean fire load density for buildings of this type.

a = value with the greatest chance of being achieved (0,87. q_{mean});
b = median of 50 % fractile (0,95. q_{mean});
c = mean (q_{mean});
d = 80 % fractile (1,22. q_{mean});
e = 99 % fractile (1,93. q_{mean}).

The area under the curve and to the left of the vertical lines represents the probability of the fire load density being less than a given fractile.

The coefficient of dispersion represents the ratio of the standard deviation to the mean.

The design fire load density which in the case of a severe fire leads to a probability of ruin of 1 building in 100 is that which is exceeded in 1 % of the life of the building.

In our case, the fuel load resulting from this approach would correspond, based on a Gumbel statistical distribution, to the target fractile

(100 %-1 %) = 99 % = 1,58 . 80 % fractile

or:

1,93 . mean,

i.e., in a dwelling, an equivalent of

1,93 . 45 = 87 kg of wood/m^2.

Taking a coefficient of combustion $m=0,8$, the design fire load density then rises in our example to

0,8 . 87 . 17,5 = 1218 MJ/m^2

Finally, the fire load $q_{f,d}$ may be calculated according to two levels of complexity:

- the general method: as in the above example, by reasoning in terms of probability, to deduce a global coefficient which assigns the 80 % fractile
- the simplified method: for each factor (area of compartment, type of occupation, effect of sprinklers, etc.), use a partial coefficient. Their product then conservatively gives a global coefficient which assigns the 80 % fractile.

By developing the simplified method, we can demonstrate that to obtain the target fractile, we have to multiply the load corresponding to the 80 % fractile by a coefficient which depends on the floor area of the compartment (δ_{q1}) and the type of occupation of the building (δ_{q2}). These coefficients are shown in the table below:

Floor area of compartment	**Coef. δ_{q1}**	**Examples of types of occupation**	**Coef. δ_{q2}**
25	1,10	Art gallery, museum, swimming pool	0,78
250	1,50	Offices, residence, hotel, paper industry	1,00
2 500	1,90	Machines and engines factory	1,22
5 000	2,00	Chemical laboratory	1,44
10 000	2,13	Fireworks or paint factory	1,66

Coefficients δ_{q1} and δ_{q2} (table E.1 taken from NBN EN 1991-1-2)

The NFSC research report [42] states that, for each type of building or activity, a specific study should be drawn up to determine the probability p_1 of a severe fire developing. For example, in terms of probability in the case of offices intended for activities within the fireworks industry, the risk is multiplied by a factor of 1000. In terms of coefficients acting on fire loads, this factor 1000 is translated by an activation factor of 1,66. The rough evaluation of this activation factor, linked to the lack of sufficient statistical data, should encourage the greatest possible caution.

Within the framework of protecting heritage, the inestimable value of certain pieces or collections housed in certain art galleries and museums can lead to a higher consequences class being considered. Switching from class CC2 to consequences class CC3 divides by 10 the acceptable percentage of ruin. A supplementary coefficient of 1,22 is therefore applicable to the fire load density.

In the ANB, an amendment seems appropriate for a better understanding of the risk associated with the use of a building: the entire building is taken into account in the case of several superimposed compartments and not just one of these compartments. If the destruction of the compartment in question could result in the destruction of other compartments, a safety approach to the evaluation δ_{q1} may be based on the addition of surfaces of these compartments.

It should be noted that despite its appearance, this amendment does not take account of the financial consequences of the collapse of a building irrespective of its size. It is possible to adjust the fire safety factor to minimise the total cost, represented by the cost of fire safety and the weighted value of the building, its contents and any indirect losses. This gap in the Eurocodes approach is explained in greater detail in the paragraph on quantitative methods of evaluating risk. A tentative and rough modulation of the target probability of failure is possible, using the consequences classes given in the Eurocode "Bases of design for structures" [109]

The exhaustive consideration of active protective measures

We have shown how to take account of the intervention of occupants and firemen, the area of the compartment, its type of occupation and the consequences class. Designers takes the approach of FSE further: to take account of active measures such as the use of detectors and automatic transmissions, sprinklers, independent water supplies, extremely short intervention times by the emergency services, they currently allow themselves to reduce fire loads, still in the semi-probabilist approach described above.

These developments in "Fire Safety Engineering" are used to compensate for a lack of inherent fire resistance in certain structures.

These tools are relatively new [50] and **only highly qualified and well-informed people should use them**.

Furthermore, dispensation must be currently obtained from the competent authorities to reap the benefits.

For fire walls, it is prudent to demand fire stability for the entire duration of the fire without taking account of active protective measures and human intervention. This requirement is satisfied by fire walls REI 120, REI 240 or REI 360 depending on the fire conditions.

In June 2005, Professor Jose Torero (University of Edinburgh), one of the world's leading experts in "Fire Engineering" (FE) responded in this manner to the label of "black art" which is sometimes attached to FE [50]:

"Industry should use FE with caution. FE bases itself on a science which has not yet been digested to the point where we have reliable, solid and user-friendly tools that can be used by all. At this stage, it remains a matter for specialists. Industry should look for specialists with appropriate references and a solid training. Many people without suitable qualifications practice FE; it is these who introduce "sorcery" as a substitute for actual knowledge. Industry should be very cautious and surround itself with competent professionals when a project requires the use of FE"

The probability [42] of a severe fire per year to endanger the structural stability may be expressed as :

$$p_{fi} = p_1 \,.\, p_2 \,.\, p_3 \,.\, p_4 \,.\, A_{fi}$$

with,

p_1 = probability of a severe fire including the effect of occupants and public fire brigade (per m^2 and per year).

p_2 = additional reduction factor depending on the fire brigade types and on the time between alarm and firemen intervention.

p_3 = reduction factor if automatic fire detection (by smoke or heat) and / or automatic transmission of the alarm to the public fire brigade are present.

p_4 = reduction factor if sprinkler system is present.

A_{fi} = surface area of the fire compartment.

Thus, the use of sprinkler systems with an efficiency of 98 % (95 %) allows the heat loads to be multiplied by a partial coefficient δ_{n1} of 0,61 (0,70).

We must insist on the fact that all these factors are only applicable inasmuch as a semi-probabilist approach is accepted. Thus, if the fire load density is constant (case of the permanent part of the load which is known), it is advisable to take this load without modifying it by factors of increase or decrease. This part of the total load requires a "determinist" approach.

If the semi-probabilist type of approach can be justified in the eyes of insurance companies that spread their losses and profits across a large number of accidents for a given set of buildings, it is much more difficult to have it accepted by an owner or operator. For example, in terms of differentiating between the reliability of active measures, an increase use of steel structures would probably increase the loss expectancy of buildings. These constructive changes would easily be absorbed by insurers, by raising their premiums, as long as the standard is happy to average the statistics. A performance-based differentiation should be introduced.

In this approach, the successes of active measures are assumed to be independent. It is this that allows the product of probabilities to be performed (see also the example of the event tree in §8.3.2.3 relating to the description of quantitative methods).

The hypothesis of the independence of the success of the fire being extinguished by the fire service and the success of a sprinkler system is debatable. The result of the action of the fire services depends on the operation of the sprinklers.

In reality, the event tree given in §8.3.2.3 is not entirely correct. Moreover, this is explicitly acknowledged in the definition of factors p_3 and p_4. They are not failure probabilities of associated active measures but failure reduction factors for fire-fighters in their fight against the fire.

This is perfectly clear in the cases of detectors that are never going to put out a fire. Operational reliabilities of 72 % to 84 % (i.e. failure rates of 28 % to 16 %) for smoke detectors are reported in the study undertaken in [53] in the bibliography. **Therefore, it does not appear possible to obtain factors**

$$p_3 = 0{,}25 \,.\, 0{,}25 \,.\, 0{,}25 = 1{,}56\ \%$$

as mentioned in EC1 fire: p_3 must at least be greater than 16 %!

One of the difficulties of introducing FSE lies in the debatability of the hypotheses adopted in an approach which does not converge towards unanimity. The probabilities of a fire occurring, the behaviour of occupants and visitors, the success of fire-fighting operations (size of teams, knowledge of the premises): all factors that are functions of human behaviour, of regulations specific to each country, both in terms of design and operational inspections of installations, distributions of fire loads.

It is worthwhile pointing out that according to the NFSC report [44], an average success rate for the fire services of 9/10 corresponds to the intervention of an emergency team of professionals within a time of between 10 and 20 minutes after receiving the call. This same average success rate would be achieved during the intervention within a time less than 10 minutes for an emergency team made up of volunteers.

The notion of effective intervention time can cover very different realities, especially during a high-risk situation: is it from the arrival on site of the emergency services, the deployment of the first hose or of "n" hoses during a gradual deployment?

Extending the intervention times would obviously reduce the success rate.

Calibrating the parameters of the law of statistical distribution of the fire load density poses certain difficulties, notably with coefficients of dispersion greater than 0,3. This is why our ANB limits itself to adopting a single dispersion.

In the case of a fire resulting from a short-circuit or a malicious act, the building that is especially far away from a fire station or is unoccupied during the night (industrial hall, office) is calculated, according to FSE hypotheses, with an intervention of the occupants and firemen which is not effective. Quite often, the action of the latter has to limit itself to preventing the fire from spreading to neighbouring buildings. Thus, implicitly, the fixed level of safety is not identical, for goods and activities, to that obtained for people. In reality, malicious acts affect almost 30 % of buildings subjected to fire.

The fire loads [49] currently considered by FSE when it models "natural" fires are **average loads on the compartment**. They are rarely distributed uniformly through a building. Consequently, a local concentration of combustible materials will be able to bring about the collapse of a load-bearing element following its localised thermal action. It will also lead to the compartment being ruined.

Thus, the techniques and hypotheses of FSE, which take account of active measures, still have to prove themselves and respond to a certain number of objections before being able to constitute a sufficiently solid base to be included in the normative part of EC1 fire and, a fortiori, in a regulation. Several European countries, such as France and Germany, to mention just a couple of large neighbouring countries, have not retained this approach in their national appendix to the standard EC1 fire.

In addition, the structure could be verified using parametric curves or zone models:

- until all the fuel has been burnt or
- until a time t corresponding to a fixed period, for example that fixed in our current regulation referring to an ISO fire. The behaviour of the structure after this time is not examined: what does it matter that the building collapses?

The second solution obviously offers a lesser degree of safety than the first. It would constitute a planing down of fire safety of which we should beware. The draft ANB of NBN EN 1991-1-2 has not retained this solution, happily, by not defining a time limit. Moreover, it should be noted that, if this second solution was open in EC1 fire, in almost all publications relating to natural fires, the structures are studied for the complete fire cycle, including the cooling phase.

If we consider [49] that, for an industrial building, the cost of the structure only represents 10 to 30 % of the total cost of the building, not to mention the value of the contents, we can wonder about the usefulness of such methods.

The general method (probabilist approach)

We must remember that the general method which underpins Appendix E (probabilist approach) leads to a much more shocking result:

Let us consider a usage as office, accommodation or place of production with a "risk of activation" less than or equal to 1,00 (this is explained below): if the efficiencies put forward in Appendix E for the intervention:

- of the firemen (failure = 0,1);
- of the occupants (failure = 0,4);
- of the sprinkler system (reduction failure factor of firemen and the occupants = 0,02);
- of the smoke detectors (reduction failure factor of firemen and occupants = 0,0625) and
- of automatic transmission to the public fire brigade (reduction failure factor of firemen and occupants = 0,25)

are correct (**see the comment of previous page about the detectors**), then the probability of all these measures failing is

$$0{,}1 \cdot 0{,}4 \cdot 0{,}02 \cdot 0{,}0625 \cdot 0{,}25 = 1{,}25 \cdot 10^{-5}$$

or one case in 80 000. The probability of a severe fire occurring and therefore a building of 8000 m^2 equipped with all these measures being ruined is

$$p_{occ} \cdot p_{défaillance} = (10^{-5} \cdot 50 \cdot 8\,000) \cdot 1{,}25 \cdot 10^{-5} = 5 \cdot 10^{-5} \leq 5 \cdot 10^{-5}.$$

Since this probability of ruin is less than the target probability, the structure should not therefore offer any intrinsic resistance to fire for any surface area less than 8 000 m^2, if the competent authorities accept an approach other than the ISO approach.

If automatic transmission is not included, the failure rate drops to 1 case in 20 000, and the structure should not present any intrinsic resistance to fire for any surface area less than 2 000 m^2.

It is only if the probability of the building being ruined is greater than the target probability that the structure should be checked with a reduced fire load density

For a building of 2 000 m^2, the application of the general method means no fire resistance is required of the structure in the event of a severe fire.

Conversely, the application of the partial-coefficient method results in the structure being required to survive in the event of a severe fire in 61 % of cases. These are the cases where the fire load density is less than q (61 %). In fact,

$$1{,}90 \cdot 0{,}61 \cdot 0{,}73 \cdot q(80\,\%) = 0{,}74 \cdot q(80\,\%) = 1{,}03 \cdot q_{moy} = q(61\,\%)$$

Thus, as much as the conservative method of partial coefficients of Appendix E to the Eurocode can give results which seem reasonable in our example (minimum resistance corresponding to the 61 % fractile), so the application of the general method creates the opposite impression (no minimum requirement).

The general method has not been presented in the Eurocode because it refers to notions of probability and reliability which the authors felt were too complex for "basic" users. The "reassuring" results obtained by applying the coefficients method of Appendix E overshadow the "less reassuring" results which could be obtained by FSE experts.

It is clear that in case of a night-time fire (70 % outside working hours for warehouses: short-circuits, criminal acts, vandalism), the efficiency of smoke detectors will fall dramatically; the efficiency of firemen will also see itself reduced and the probability of a generalised fire will exceed 1/20 000. The method is clearly unsafe. It still has to convince. It is thus that the report of the US National Institute for Standards & Technology (NIST) - June 2005 - tones things down for this type of approach.

The NIST report (11 September: death of fire engineering ?) [54]

This official and colossal final report on the collapse of the World Trade Center consists of 43 sections (10 000 pages). It is the result of an investigation by the NIST. It will have taken 3 years and cost close on EUR 15 million.

World Trade Center (source www.nceplus.co.uk)

The group of experts charged with this investigation produced 30 recommendations to improve the safety of high-rise buildings. The five most relevant recommendations within the context of our publication concern:

- design to avoid progressive collapse;
- **verification so that an uncontrolled fire cannot unfold without causing local or global structural collapse;**
- improving the performances and redundancy of active protective systems against fire;
- tightening up regulations on sprinklers and escape routes in existing buildings;
- the maximum distance between emergency staircases; the reinforcement of stairwells and the adoption of coherent signing.

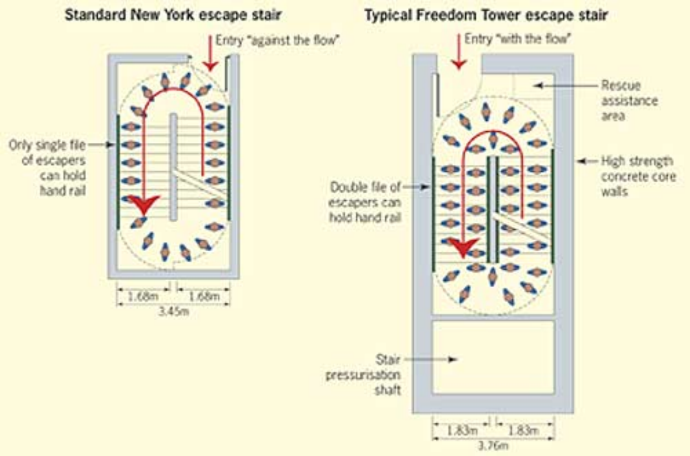
The other recommendations can be read on the site http://www.nceplus.co.uk/ and are moving notably, **while the research is not complete, towards the non-use of concepts of fire safety based on a performance-related approach.**

We feel it is important to reiterate that standards form the basis of the technical aspects of regulations [3]. It is only when standards, after having proven themselves, have acquired a certain degree of maturity that they can be integrated into regulations. It would be inopportune to cut corners. This path may represent around twenty years.

The key words of these recommendations are: development, analysis of regulations, methods, tests, research, conditions in service, design tools, system of communication, training, inspection, certification, recording, collaboration between architects and fire experts.

The new "Freedom Tower" will have a central core made from C80/95 high-strength concrete with walls 900 mm thick and will pride itself on being the safest office skyscraper in the world, with:

- its two risers of water rising up the core and linked at the summit to allow supplies to be maintained if one of the risers breaks off;
- a higher density of sprinklers: $1/15m^2$(OH) instead of $1/22m^2$ (LH) (see §4.2.2), with maintenance of flow for 60 min instead of 30 min, and much more spacious and solid stairwells



(source:www.nceplus.co.uk).

To boost its competitiveness [13], the steel industry has sought to refine dimensioning, almost always in the direction of a reduction in fire load (function of the quantity of inflammable material in the building). This lead to safety being limited to what is strictly necessary, taking into account a series of hypotheses. To take account of a fire load adapted to each particular configuration of buildings, other temperature curves have been developed: they chiefly take account of fire load and openings, for example windows. These fires are mostly less severe than the ISO curve fire. Great care is required when applying these curves, as the fire load varies considerably from one building and one country to another. Furthermore, in the case of a change in use during the life of a building, the fire loads or openings may vary from the initial design. In this case, the choice of curves other than the ISO curve could necessitate a major review of the structure.

8.3. Fire risk

8.3.1. Performance and prescriptive regulations

Traditionally in regulations [36], the working out of fire safety has largely rested on prescriptive rules. This is particularly true for the safety of people in case of fire.

The improved understanding of the phenomenon of fire, the demands of increased flexibility in the design of buildings, the cost/efficiency research and the implementation of new technologies have led to performance-based, and not prescriptive, regulations being produced. This has occurred in several countries over the past 20 years, such as Sweden in 1994. A performance-based regulation defines the design objectives but without detailing the way in which these objectives are to be achieved.

For classic buildings, tabulated or simplified methods are the most effective. For more exceptional buildings, incompatibilities regularly appear between fire protection and other architectural or structural aspects or aspects relating to the commercial activities of the building. In these situations, recourse to methods based on methods of risk analysis constitutes a solution.

8.3.2. Methods of assessing fire risk

The risks in "Fire Safety Engineering" (FSE) [36] can be defined as a combination of frequency or probability of occurrence with regard to the consequences of a specific event. It is therefore important [8], [16], to be able to assess the probabilities and consequences.

Just as describing the different methods in detail lies outside the scope of this document, so we felt it was important to give an overview of the methods used in FSE.

The acceptability [35] of the risk may be assessed by comparison with predefined upper limits. We consider the cost/benefit ratio or the efficiency of expenses. The current risk assessment methods are based on the principle known as ALARP ("As Low As Reasonably Practicable").

In terms of the risk to people during fires in industrialised countries, the statistics reveal an annual number of deaths of between 0,4 and 2 per 100 000 inhabitants. The public [35] would be more reticent to accept a small number of major accidents than the same risk spread over a larger number of smaller accidents. In many studies and methods of risk assessment, the perception and therefore the acceptance of risk decreases with the square of the number of potential victims [16]: thus, for 3 victims, the acceptability is 10 times less than that for 1 victim. Similarly, for 10 victims, the acceptability is 100 times smaller than that for 1 victim. This can help us understand one of the reasons which push the legislator to impose higher fire resistances for high-rise buildings than for low-rise ones.

Several working methods have been developed, based on calculations. They constitute a vital aid in assessing the risk of fire according to a large number of factors. These methods of analysing risk can be classified according to three types: qualitative, semi-quantitative and quantitative methods. However, they do not claim to be able to replace the reasoning and judgement of people authorised to define protective measures.

8.3.2.1. Qualitative methods

Qualitative methods are often used informally, when a compromise is envisaged and the effects on the fire safety strategy are limited. The experience and feeling of the designer are often enough to make slight changes to existing recognised solutions or to classify quantitatively the performances of the various safety measures. The criterion of performance used in the verification is relative and is expressed in terms of "as safe as" or "no worse than".

8.3.2.2. Semi-quantitative methods

Semi-quantitative methods constitute a simple tool in many situations where fire safety must be assessed and time or money are lacking to carry out a detailed quantitative analysis of the risks. In managing industrial risks, **points lists with weighting** [20] as well as **index methods** have been widely used to classify and give priorities to different preventive safety measures.

Points lists methods

In Sweden, for example, methods based on points lists have been developed for hospitals. They serve as a tool for the fire inspection services. However, this type of method has not yet been used in the design phase of fire safety, as to date the only thing implicitly admitted is the search for a compromise between the difference safety objectives of the regulations. Moreover, it is not clear how to deal with aspects not covered by the regulations, for example organisational aspects and training. They nonetheless affect fire safety in a building.

Index methods

Over the years, different approaches have been used to develop classifications: thus the GRETENER system and the NFPA methods.

The NFPA procedures apply to different types of building built in the tradition of buildings in the USA.

In Sweden, a classification procedure has been developed for hospitals. It follows methods used in the UK. It assigns a weighting according to the preferences of the decision-makers, combined with categories of parameters which allow the risk to be assessed. The SAW ("Simple Additive Weighting") method is the most commonly used method.

The GRETENER system is based on the statistics of Swiss insurance companies. It was initially used for industrial applications.

- 1970: method of M. GRETENER (Swiss ANPI): it only allows an evaluation of the risk for goods. It is widespread in Switzerland and Austria.
- 1978: ERIC method (*Evaluation du Risque d'Incendie par le Calcul* - Evaluation of Risk of Fire by Calculation) in France: this method is no longer aimed at protecting merely goods, but also people.
- 1981: E. DE SMET (Belgian ANPI) presents a detailed version of the GRETENER method, known as the FREME method: Fire Risk Evaluation Method for Engineering.
- 10 years later E. DE SMET perfects a new version of the FREME method, known as FRAME (Fire Risk Assessment Method for Engineering), revealing a third aspect of fire risk: the operating loss, in other words the risk to activities carried on in the building in question. It is widely taught in Belgium in the advanced course of the ANPI as well as to architect-engineers at the University of Ghent. The method has already been accepted by the Belgian authorities (fire services, technical inspection) for applications where legal provisions could not be applied as they are. An official request for the method to be recognised was made to the Ministry of Home Affairs in 2001. The results can vary considerably for a similar project and depending on the expert who enters the data.

The FRAME method is based on three main concepts:

1. In a well-protected building there is a balance between danger and protection. The risk is therefore defined by the index equal to the Danger / Protection quotient. A value less than 1 reflects good protection of the building; a value greater than 1 indicates poor protection.
2. The danger is defined by the index equal to the quotient of two values: "the potential risk P" and "the acceptable risk A";
3. The protection can be calculated from specific values for the techniques of protection: extinction by water, evacuation, resistance to fire, manual and automatic means of intervention.

Three calculations can be developed: a first calculation for the building and its contents, a second for the people occupying it and a third for the economic activity carried on in the building. In these three calculations, the factors of influence do not intervene in the same way because the potential risk and the acceptable risk are not the same for people, goods or economic activities.

8.3.2.3. Quantitative methods

Fire safety calculations are based on thresholds for the level of risk which the solution may not exceed. Truly quantitative risk assessment methods explicitly include the combined effect of the frequency and consequences of possible accidents. The method described in Appendix E of Eurocode 1, taking into account active fire protection measures, does not explicitly associate the consequence of accidents to their probability.

Similarly, the Eurocode "Basis for calculation" [109] only gives a rough classification, in terms of consequences classes per type of construction: high, average or low consequence relative to loss of human life, or economic, social or environmental consequences in case of structural failure.

The majority of structures fall into class CC2 corresponding to a situation where the consequences of a structural failure would be "average". Classes CC1 and CC3 correspond to low and high consequences respectively (concert halls, stands).

Each consequences class has its own reliability index β. Some Scandinavian countries assign a different minimum reliability index for each type of element in a construction. The reliability index of a column must be greater than that of a secondary girder: this displays a more acute concern to take account of the consequences of structural failure.

The methods can vary from a simple quantitative analysis of the performance of an element (the fire resistance of an element, the response time of a particular type of fire detector, etc.) to a complete quantitative analysis of the risk, including various scenarios of chains of events and the explicit consideration of uncertainties.

Event trees are often used to take account of human behaviour and the reliability of the fire protection systems installed. To each event is assigned a probability. This approach has been used in the method described in Appendix E to Eurocode 1 fire part.

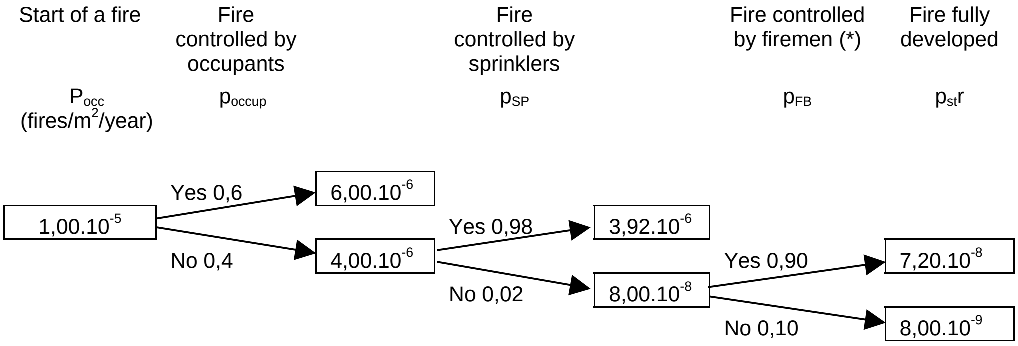


Figure: example of event tree

The standard quantitative analysis methods (QRA) do not provide a measure of the uncertainty of the result obtained, and yet this measure is of paramount importance to allow a rational decision to be taken. The probability of failure depends on the uncertainty of data, models, hypotheses given and even the consequences of failure. A first solution consists of dealing with uncertainties by simplification, using conservative hypotheses on the characteristic values of data by the addition of safety coefficients.

The extended quantitative method combines the traditional analysis of uncertainties and the standard quantitative method. By varying the parameters of fire loads, conditions of ventilation, response time (= Monte-Carlo simulation), risk profiles can be presented in terms of average profiles, supplemented by confidence intervals. These translate in more explicit terms the variation in risk, the variation in the probability of certain consequences.

8.4. Industrial buildings

8.4.1. Classification of activities and fire risks for industrial buildings

European standard EN 12845 [108] lists in its appendices the classes of risk defined by the European Federation of National Insurance Federations (*Comité Européen des Assurances* = CEA). In document CEA 4001:2003 [65] this Federation gives a classification of activities carried on and fire risks for industrial buildings. Automatic sprinkler systems in these buildings are determined using this classification. They are classified in low calorific potential risk (LH="low hazard"), ordinary risk (OH1 to OH4) or very high risk (HH). Very high risks are the subject of a distinction between buildings where a production activity is carried on (HH/P1 to HH/P4) and storage buildings (HH/S1 to HH/S4).

In the case of storage buildings, the figure affecting the denomination of risk represents the category of goods stored (defined as a product and its packaging). It is a function of the rate of heat release (kW) of the goods. It is simply the product of the combustion heat (kJ/kg) of the goods and its speed of combustion (kg/s). The combustion heat depends on the material stored and its speed of combustion is a function of the material and its method of storage.

To categorise products, this method first considers the material in question to specify a material factor which is then modified, if necessary, according to the storage configuration.

Storage configurations involving stacking, on pallets or shelves, are the subject of a classification for which limitations and requirements are set. Storage heights, the width of aisles, the size of storage blocks are addressed.

It is vital that the architect and building owner, as well as the competent authorities, take note of this classification.

In concrete terms, the same product [49] may belong to different categories according to its method of storage: rolls of bitumeous paper or cardboard boxes burn more easily stored vertically than horizontally.

What architect, what building owner is aware of the danger and consequences of this classification? The temptation is great to choose the class that corresponds to the lowest fire resistance, for economic considerations. But what operator will remember that he should store his rolls of bitumeous paper horizontally? Or that his building was designed for light cardboard packaging? A lack of knowledge that could have serious consequences both legally and criminally in case of injury or death and which risks leading to endless discussions with insurance companies!

Any change in storage (material or configuration) can alter the risk: the sprinkler protection system then has to be adapted, since it may no longer satisfy the requirements of insurance companies and regulations.

Similarly, if the structure is initially dimensioned using natural fires, the resistance of the structure must be verified under new heat loads.

People are talking increasingly of durable constructions. Durable buildings allow compartments to be modified, activity to be changed or a new façade to be installed, while retaining the structure.

The reserve of fire resistance of concrete structures offers greater flexibility in storage changes and in changes to the use of buildings. The life of concrete structures, without maintenance, is important.

There are excellent materials for constructing fire walls, but what are they like in practice?

Often, the stability of these fire walls, which must withstand fires for 2 to 4 hours, is provided by a structure which offers barely 15 minutes of resistance. If the wall does not come down in the collapse of the structure or is damaged by the collapse of the adjacent structure, it will often find itself in such an unstable position that it represents a real danger to the emergency services.

Fire walls are necessary but they must be correctly designed.

Honda – Alost [58]: (source ERGON) The 50 metre mark is passed. Compartmentalisation is by girders, without openings.

To make the work more flexible and construct the most multifunctional storage hall possible, the width of 50 m was exceeded, without any intermediate columns, in this hall 150 m in length and with a free height of 10 m.

8.4.2. Warehouse fires

In 2001 René Dosne synthesised [48] a study of warehouse fires.

This study of warehouse fires is structured solely around cases experienced by René Dosne, during his 43 years of working alongside Parisian firemen. These cases are illustrated for the review ALLO 18 (…) of these firemen.

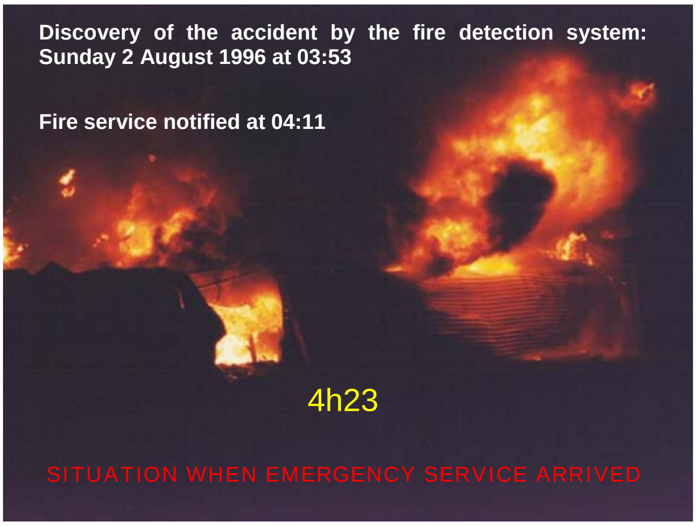
This study was also supported by 24 years of collaboration on the review “FACE AU RISQUE” of the C.N.P.P. through the production of the “instructive fire” section, totalling 180 accidents, including a large number of warehouse fires (…)

“Having many times experienced the dramatic struggle against a violent accident seeming to exceed the possibilities of the emergency services, measured the incredible violence of the fire and its inexorable development making light of the efforts of the emergency services, after having detected the warning signs of the flash-over of a warehouse which the firemen left at the last minute before being engulfed by flames, it emerged that solutions needed to be integrated at the time the building was designed.

How many firemen, watching a fire progress through a building, have imagined a solid brick wall suddenly rising up, to give them time to set up their hoses! (…)

Warehouse fire on the Loire (source CIMBETON)

The risks of collapse are permanent and the risks of pollution are real (source CIMBETON)



Discovery of the accident by the fire detection system: Sunday 2 August 1996 at 03:53

Fire service notified at 04:11

4h23

SITUATION WHEN EMERGENCY SERVICE ARRIVED

Fire at Grenoble Logistique Distribution

Fires in industrial buildings: generally speaking, these fires cause interventions requiring the deployment of most fire-fighting resources (source CIMBETON)

The lightness of some constructions, the massive calorific potential they house, the imposing dimensions, the non-application or poor application of the applicable regulations, the inadequacy of the means of fight faced with the violence of these accidents result in costly destructions: 750 000 EUR on average per accident in France, added to the billion of EUROS in operating losses (...)

Too often, for economic concerns, these constructions are light and ruined in the first half-hour, not allowing the emergency services to take effective action inside the building.

Sometimes, while the fire could still be attacked effectively and perhaps controlled, firemen have to decide, faced with the risk of collapse of certain structures, to use their hoses from a distance, from the entrances. Their effectiveness is hugely compromised.

The absence of minimum stability is the first finding. There is often 20 to 30 minutes between a fire being discovered and the first hose being turned on. The structure, if made from unprotected steel, is already swaying, while transmitting its stresses to the peripheral walls. Firemen can no longer penetrate the cell in question. One hour of resistance to fire would be reasonable (…)

Rotations of goods in warehouses are rapid. They are at 30 days maximum. It is impossible for firemen to know if the safety measures that apply to the warehouse correspond to the goods in it... and which will not be in it tomorrow (…)

Cf. the example of the furniture depository fire in Nanterre, where the operator “also” stored aerosols and 10 000 l of fuel ! It is rolls of flames worthy of a hydrocarbon warehouse fire, 15 m above the rooftops, which will betray the presence of barrels in amongst the Louis XV armoires...

Causes:

Fires (70 %) mainly occur outside working hours, at night or at the weekend. 26 % are of criminal origin, to which percentage must be added some of indeterminate cause.

At night and outside of working hours, fires are discovered when they appear on the outside. When the emergency services arrive, the situation is then too far gone to attempt effective action before flash-over and collapse.

Depending on the zones, the delay before the first hoses are deployed is put at 20 to 50 minutes.

The warehouse must be able through its design to participate in its protection while facilitating the intervention of the emergency services.

Roofs and annexes:

A modern warehouse is a box open on one side, with a row of doors, topped off with one or two floors of offices.

The structure is made from concrete or steel, the façades from curtain walls or prefabricated concrete slabs. The roof is almost always the same: steel trough covered with an insulating watertight covering, often bitumeous.

In case of fire, (…) the high temperatures reached beneath the roof will liquefy the bitumeous covering by conduction of the steel troughs. Their deformation will allow them to flow into the warehouse and sometimes to start secondary fires.

If it can be said that this supply of fuel is of little importance in relation to the massive calorific potential stored, conversely, its propagatory role is real beyond the limits of the cell on fire (…).

Bitumeous roof coverings, when not interrupted by the protruding of a fire wall, could perhaps see themselves "chequered" by non-combustible strips of a width to be defined (…)

The reality of the danger presented by bitumeous coverings, as these currently exist, is illustrated by the destructive accidents which had their origin in work by hot spots on roofs and which, despite occurring above the warehouse, led to its complete destruction after having "fallen" into the building.

"There is no fire that hasn't been put out!" say firemen. Extinction time and area covered make all the difference. Determining the maximum cell area for which the fire remains controllable is a difficult exercise.

It is accepted that beyond several hundreds of m² on fire, the cell is lost, especially if it is full. Stopping the fire is particularly tricky if it is not possible to lean on an existing structure (wall) or a wide strip free from goods.

A fire will be more easily controllable in a cell of 10 000 m² with low storage, spaced out, provided with an effective smoke extraction system, rather than a cell of 2 000 m² filled to the rafters (…)

For an accident to remain controllable by the emergency services, its area must allow the overlapping of hose jets from the façades. (35/40 m of useful range). The greatest lengths should not therefore exceed 80 m, and entrances should exist on at least two opposite sides.

The areas of outlets should be much larger than they are at present, in view of the extreme fume-producing power of modern products. The problem of fumes does not last long in warehouses with metallic skeletons and roofs made from steel troughs or asbestos-cement: they are swiftly removed, letting the fire create the outlet that suits it. Conversely, it is trickier for warehouses with roofs made from concrete elements.

This last roof, if its outlets are inadequate, will retain fumes and hot gases without giving way. These fires in enclosed spaces create a furnace effect which soon makes any entry impossible, and can lead to flash-over.

Compartmentalisation:

The fire wall should overreach the roof in order to break up the combustible continuity of the cover, a major source of "spillovers" into adjacent cells.

Even if it is traditionally independent of the load-bearing structure, the fire wall can be affected by the proximity of a metallic structure which, by losing its shape, will bring about its partial or complete ruin.

During several accidents, it has been observed that the closure of a fire door had been prevented by the overly low positioning of the fuse controlling its closure. The wall had been deformed beforehand, or debris had fallen, blocking its movement. The fuse or detector must be placed as high as possible below the roof to activate the closure of the door without delay.

Contents:

(…) The storage method stacked on pallets, film-wrapped, placed on metal shelves: veritable ventilated pyres where the fire will develop with ease.

Storage height should be limited below the ceiling, to delay the occurrence of flash-over very often seen during the development of a fire.

Shelves should be arranged perpendicular to the façade and thus have greater access or openings, to make it easier for hose jets to penetrate. In large warehouses, it has often been noted that a large central area remains out of reach of the hose jets, most of which are limited to a useful range of 40 m.

The time between the discovery of a fire and the intervention of the fire services is difficult to reduce. Other factors may prolong the time, such as the distance from the fire station to the fire and the travel conditions (traffic, weather, etc.).

When the firemen arrive, the situation is often already very far gone and the risks of collapse prevent them from entering (...)

The action of the firemen:

Fire already too violent, entrances blocked, (safety curtains to be forced), ruin of the structure preventing the emergency services from effectively gaining entry, dimensions of warehouses not allowing hoses to cover the area on fire, inadequacy of access on all 4 sides: firemen are forced to remain on the limits of the building and to spray the fire ineffectively over façades with no openings.

These accidents demand on average water supplies of 400 to 600 m³/hr, which are far beyond the capabilities of the local network.

Too many industrial zones do not have a fire network adapted to the risk they generate. Their fire hydrants, badly or sometimes not (!) connected, are known as "flowerpot hydrants" by firemen. The phenomenon is not uncommon...

Refrigerated warehouses and buildings insulated by sandwich panels:

Each year, several establishments that make widespread use of polyurethane core panels go up in flames. They can be M4 or M1 (see p18), the method of installing these panels turns them into a wick that is difficult to curb in case of accident, because the fire runs in the walls

This combustible continuity simply has to be broken, either by inserting a non-combustible plate between assemblies, or by integrating, in a continuity of panels, several panels insulated with mineral wool or foamed glass, which is non-combustible. These fire-retardant zones would allow the emergency services to rest their appliances on a solid base.

Warehouses and pollution:

From Sandoz in Basel, to Nantes, Rhône Poulenc to Péage de Roussillon, the emergency services have been faced with a choice: water a fierce fire that is generating toxic fumes and pollute through the extinguishing water or limit watering so as not to overflow the retention areas and prolong the production of fumes…

Fire resistance of structures, roofs, coverings, compartmentalisation, automatic extinguishing, smoke extraction... these means must not be considered in isolation, but integrated into a coherent design. What is the point of a non-combustible covering if the swift ruin of the framework drags it into the fire? What is the point of an automatic extinguishing system if stocks are chaotic, too dense, too high, partially neutralising its action? What is the point of outlets dimensioned for goods that have nothing in common with those currently stored? ...

For a fire to have a chance of remaining at the incident stage, what is required, apart from a design within the rules in terms of compartmentalisation and smoke extraction, is an intelligently conceived stocks organisation in terms of height below ceiling, width of aisles, creation of islands of several hundreds of m² surrounded by wider aisles in large-sized units True, a little volume will be lost! (…)"

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Metal-skin sandwich panels

Concrete panels do not generate pollution during fires. Conversely, the incomplete combustion [67] of the polyurethane foam of sandwich panels generates harmful and irritating fumes, thereby complicating evacuation and extinguishing operations.

The good insulating properties of sandwich panels are responsible for a rapid increase in temperature in the premises and therefore for the accelerated appearance of flash-over.

Joining panels

The installation of sandwich panels is very important and should be carried out with all possible care. The foam must in no way be exposed, otherwise it risks coming into contact with sparks, flames, embers floating in the air, etc. The use of a special frame around openings of doors and windows allows this risk to be countered.

But a building is alive: openings are made in sandwich panels, partitions are added and removed, exposing the synthetic core of the panels.

Several catastrophic fires in buildings using sandwich panels with a synthetic core have gradually increased awareness among constructors, building owners, architects and company bosses.

The use of sandwich panels in, among others, the agri-foodstuffs industry does not provide an appropriate and effective solution to the problem of fire safety in this type of building. There are still too many unknown factors!

Importance of large-scale tests

The comparison between the euroclasses fire and the large-scale tests method shows that classification according to euroclasses is clearly overly optimistic compared to that employed according to large-scale tests.

This is one of the reasons why insurance companies in particular are increasingly requiring the application of large-scale tests to ensure safety in buildings.

Below are several points for consideration which should be of concern to the various interested parties:

The position of insurance companies [56]

To assess the risks and calculate insurance premiums, insurers base themselves on 7 different criteria:

1. the smaller or larger risk of a fire activation, generated by the activity of the enterprise;
2. insulation in relation to third parties;
3. the nature of the constructions, taken into account in a building classification method which studies each section of the construction according to the stability and combustibility of the construction elements. This method assigns a construction code, according to the

nature of the materials. It allows entry to a table giving the "constructions" surcharges or discounts applicable to the building. The variations range from -25 % to +50 %.

The difference in cost of insurance premium between a building whose skeleton and covering are made from concrete and another in steel, is in the order of 30 % in favour of concrete

4. the method of heating the buildings;
5. the quality of the electrical installations;
6. accident prevention: surveillance, bans on smoking, waste management, liquids, gases, maintenance of technical installations, fighting malicious actions;
7. fire protection: staff training, sprinklers, extinguishers, smoke extraction, water supplies… and **compartmentalisation.**

"An overall design taking these principles into account allows the insured party to significantly reduce the amount of their fire insurance premium, but also to limit the human and economic consequences of this type of accident. It is therefore advisable when designing the work for a new building, an extension or a conversion to contact your insurance company."

The APSAD rules in France (Assemblée Plénière des Sociétés d'Assurances Dommage) relating to separating fire walls (CF 2 h or 4 h), explain the overhangs to be respected for roofs and on the sides of the building.

The same is true for openings in fire walls fitted with fire doors as well as openings for electric cables, ducts, conduits and conveyor belts.

The fight against fire.

The effectiveness of the emergency services depends initially on the speed with which the fire services are notified.

In the case of a warehouse fire, there are several additional difficulties:

Difficulty of penetration, size of the fire when help arrives, risks of collapse of structures limiting the effectiveness of the hoses, larger water supplies required.

The fight against a warehouse fire is not played out by the external emergency services, whatever their resources, speed of intervention with good water supplies. It is in the design of the building that the fire risk must be taken into account. However, too many warehouses encountered are merely "umbrellas" with no other ambition than to protect the goods from bad weather and theft.

In an urban environment, where the emergency services are quickly on site with many and powerful resources, the same destruction is seen as in rural areas. A greater number of hoses are deployed more quickly, but the fire cannot be prevented from developing in the cell of origin if there is no "permanent" screen on which to rest the hose system.

Façades

The intense heat radiation of a fire forces a certain distance to be planned for between the warehouse studied and neighbouring buildings, to avoid collateral damage to these buildings and also, clearly, to retain access zones for the fire services.

Given the cost of land or more simply the constraints of sitting a building, it could prove interesting to limit this distance:

- by the use of an embankment built from excavated earth for the construction of the building;
- by the use of concrete fire-retardant façades.

The use of concrete fire-retardant façades limits the heat flux for adjacent buildings, the fire services and their equipment. It is vital that these façades are self-supporting or joined to a structure with the same degree of resistance. Concrete structures are without doubt the favourites.

Propagation by façades (source CIMBETON).

The intense heat radiation of a fire forces the fire services to keep their distance from the metal-skin sandwich construction façade with polyurethane insulation in fire. (source CIMBETON).

In France, to carry out danger studies, heat radiation limits were fixed at 3, 5, 8, 16 and 30 kW/m^2 by the Ministry of the Environment. A heat flux of:

- 3 kW/m^2 will produce significant burns on an unprotected person exposed for 1 min.;
- 5 kW/m^2 is the threshold for significant destruction of windows;
- 8 kW/m^2 is the threshold for domino effects corresponding to the threshold for serious damage to structures.

In general [5], this intensity should be limited to a value in the order of 10 to 15 kW/m^2.

In France, domino effects are fixed:

- for the effects of heat: at 8 kW/m^2 corresponding to the start of risks of propagation, and
- for the effects of pressure (explosion): at 140 mbar corresponding to the start of risks for structures.

In France, warehouses containing fire loads in excess of 500 T or with a building volume greater than 50 000 m^3, e.g. 5 000 m^2 x 10 m (=h) are subject to the SEVESO directive, which states that a danger study must be carried out.

These danger studies have shown that the use of fire-retardant façades for these warehouses allows the withdrawal distance to be reduced by an average of 40 %.

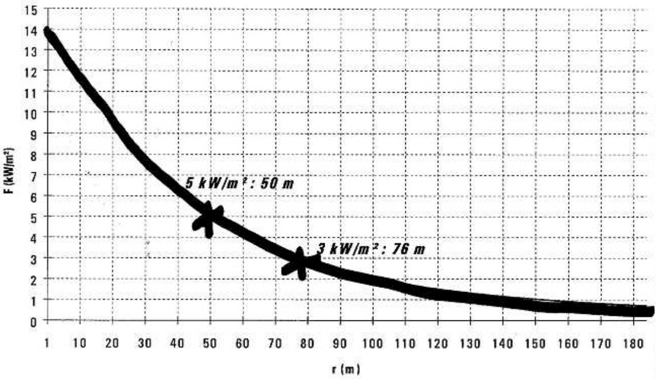

Figure: Cell of 5000 m^2 - Heat flux ***without*** *fire wall (source CIMBETON).*

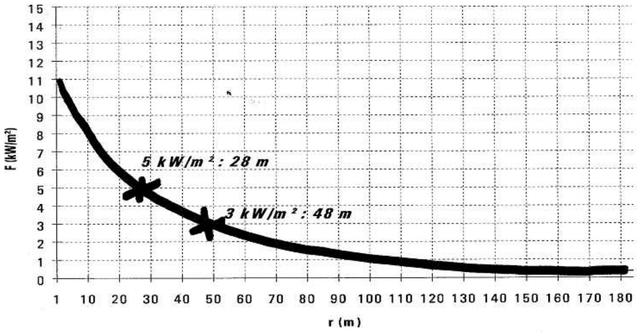

Figure: Cell of 5000 m^2 - Heat flux with fire wall (source CIMBETON).

Fire-retardant façades (source: CIMBETON)

Concrete curtain walls (source: CIMBETON)

Concrete curtain walls with CF 2hr heat shield (source: CIMBETON)

Accessibility

Since many warehouse fires break out outside working hours (majority of cases), the entrance to the premises poses major problems for the fire service. Since the fight against intruders often preoccupies operators more than the fight against fire, the emergency services have to use cutting equipment used for cutting into vehicles! Dozens of minutes which the fire uses to push deeper into stocks...

Thus firemen can only walk around the building noting the signs of an imminent flash-over, without being able to take any effective action.

This shows it is unrealistic to apply a mean probability of a 90 % success rate for the emergency services for this type of building.

Hydrants

Stand pipes are sometimes too close to the façades, subjected to the radiation of the fire and to the risk of collapse. Pump engines, in principle connected by a 10 m pipe, are subjected to radiation. Some have to be sprayed with water to continue their job, others have to be disconnected, with all the consequences of the interrupted supply to the hoses...

The danger study should highlight the risks:

- of fire and explosion;
- of pollution (soil, water and air)

and put forward solutions to limit the risks:

- prevent the fire spreading:
  - partitioning (walls CF 2 h exceeding the roof - self-supporting);
  - storage rules (aerosols, separation of products);
  - Walls CF 2h minimum;
- avoid pollution:
  - putting in place of retention of residual fire water;
  - surface of smoke outlets (properly dimensioned).

This conclusion enables us to realise that fire safety can be strongly influenced by a multitude of factors which should be taken into account from the design stage and before commissioning.

8.5. Tunnels

The temperatures [46] encountered in tunnels during fires may exceed 1000 °C. In the case of the Mont-Blanc tunnel, on 24 March 1999, the Italian lorry situated 300 metres from the front of the flames caught fire spontaneously under the effect of heat radiation (+-20kW/m^2). It was the tyres, rubber parts and plastic components that caught fire.

To give an idea, the following table shows the spontaneous combustion temperatures of certain solids and liquids. To reach this surface temperature in the material, the gases must be carried, in transient condition, at a higher temperature:

Solids or liquids	**Temperature of spontaneous combustion (°C)**
Hard wood	295
Engine oils	350 to 500
Paper	230
Polyethylene	350
Polystyrene	490
Gas oil	330

Tables are available which provide the permissible heat thresholds for firemen and users, in terms of temperature ranges, heat radiation, intervention times, effects on man following the temperatures of inhaled air.

We should point out that the latest-generation of clothes are being studied to protect firemen against the thermal effects of a flash-over.

Breach in a fire wall (source CIMBETON)

This advantage of concrete combines with the limited maintenance of concrete pavements. The good behaviour of the pavement during the fire will allow shorter closures of the tunnel and a reduction in roadworks. Closures with diversions cause a nuisance in terms of pollution. Roadworks in turn, with traffic flowing around them, expose the people working on the site to accidents.

In road tunnels, concrete will therefore be used optimally as a road surface.

A joint BIBM, CEMBUREAU and ERMCO publication develops this subject. It is entitled: "Improving Fire Safety in Tunnels: The concrete pavement solution". The French and English versions can be viewed and downloaded on the FEBELCEM site (www.febelcem.be in the "publications" tab) or the CEMBUREAU site (www.cembureau.be in the "concrete" tab)

Tunnels and concrete pavements

The laboratory of the University of Cergy Pontoise [47], in France, carried out comparative fire tests on the behaviour at high temperature of samples of asphalt. The types of asphalt used were those currently used for pavements. The tests were carried out in accordance with the ISO curve presenting a lesser thermal load than the hydrocarbon curve to be used normally in tunnels. The results of these tests showed that:

- asphalt catches fire for values between 428 °C and 530 °C after only 8 minutes' heating;
- the first vapours given off are noticed 5 minutes after the asphalt starts to heat up. The gases given off are toxic and some of them are asphyxiating (CO_2) and carcinogenic;
- asphalt loses its mechanical characteristics and can no longer fulfil its primary function. Only aggregate remains, but without being bonded by the asphalt.

Concrete in turn does not burn, does not go soft and does not produce opaque or toxic fumes during a fire. This behaviour facilitates the intervention of the fire services. The fire load contribution of other types of pavement can amount to 25 % of the total fire load. A lesser fire load will reduce the duration of the fire and consequently the damage to structures and the associated direct and indirect financial costs.

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Cointe tunnel (E25-E40 link) at Liège, in Belgium: use of a concrete pavement for improved safety in the tunnel.

C. Examples of the fire behaviour of concrete structures during fire incidents

1. “Instructive fires”

(source: photos from J. C. López Agüí)

1.1. What happened in Madrid?

[50] (source: Pal Chana, British Cement Association).

The key facts:

- The WINDSOR, an emblematic 29-storey skyscraper in Madrid, remained standing despite the fire that lasted for 26 hours, spreading through numerous floors.
- The steel perimeter columns were the only part of the building to collapse. They supported the flooring on the upper floors.
- The NIST’s (US National Institute for Standards & Technology) interim report on the World Trade Center disaster recommends the presence of “strong points” in the design of the building’s structure. The strong points of the WINDSOR building in Madrid were the two “technical” concrete floors and the system of a central concrete core which helped the building survive a fire of exceptional intensity.

- This case is an example of the excellent performance of concrete structures designed using traditional methods and subjected to an intense fire. It also highlights the risks when active fire protection measures fail or are not included in the steel structures.

“Completed in 1978, the WINDSOR building totalled 32 floors, with 29 above ground and 3 below. Its occupants included Deloitte accountants and the Spanish firm Garrigues but the building was undergoing renovation, which meant it was empty when fire broke out around 23:00 on Saint Valentine's Day 2005.

A concrete core and a concrete frame supported the first 20 floors. Above, a central support system of concrete columns supported the concrete floors with steel perimeter columns.

Two “technical floors” in concrete gave the building greater strength: a floor situated just above the ground level and the other on the 20th floor.

The tower was built using normal strength concrete, before the issue of recent fire-proofing standards, and had no sprinkler system. The tower was undergoing renovation including

- ironically enough – the installation of active and passive fire prevention measures.

The fire began on the 21st floor and rapidly spread both upwards and downwards. The fire services had to limit themselves to taking action to confine the fire. The fire ended after battling for 26 hours, leaving the building completely burnt out above the 5th floor. The steel-glass façade was completely destroyed, exposing the concrete perimeter columns. The steel columns situated above the 20th floor suffered complete collapse. They were partially resting on the upper technical floor.

The striking fact was the building remained standing."

The collapse of the façades and the metallic structures around the perimeter of the upper floors did not cause the concrete floor to break. It was burning debris which set fire to the lower floors, falling through the windows of these floors.

The insurance value of the total damage caused was estimated at EUR 122 million.

Fire prevention in the case of fires of this extent can only be limited to the protection of neighbouring buildings. The fire spread by means of gap between the floors and the façades. Belgian regulations impose special measures to the designers in an effort to prevent fire spreading in this manner. It was the concrete frames that resisted.

(source: photos from J. C. López Agüí)

1.2. The Trois Fontaines viaduct

Beneath the bridge deck after the fire (source: ANPI).

The 3 Fontaines [27] viaduct, built in 1981, is situated along the E411 motorway at the entrance to Brussels.

During the night of 6 and 7 December 2003, the bridge perfectly withstood the fire which started in the large hut just beneath the 22,5 metre long main girders.

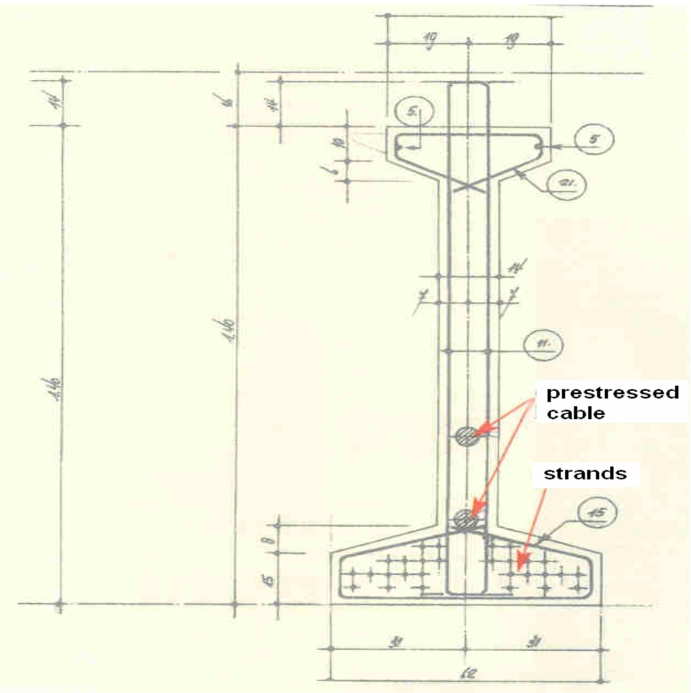
It was the subject of an extensive localised fire, which started in a 195 m² wooden hut and a tank containing a minimum of 750 l of heating oil. The rooftop, sealed with bitumeous layers, was situated 8,3 m above the ground.

This last point is fundamental. In a localised fire, when the flames do not impact the ceiling, the temperature of the gases above the flame does not exceed 520 °C. Here, since the height between the viaduct and the roof of the hut were reduced, the girders and the apron came into direct contact with the flames. By applying the fire model proposed in appendix C of Eurocode 1, part 1-2, the surface of the material would have reached a temperature of 750 °C.

Following visual inspection, the Brussels Capital Region decided to completely replace the damaged bay situated above the destroyed hut and to take this opportunity to carry out extensive maintenance works on the other bays. It did not proceed with the usual tests nor did it carry out a simple load test. The girders were cut up and left close to the viaduct (see photo opposite).

In several places, the girders show shattered concrete on the flanges and the webs (shattered edges). In certain places, prestressed strands are visible as well as reinforcements. On the lower side of the deck, pieces of shattered concrete (pieces breaking off) are also visible, with exposed reinforcements.

The girders with prestressed strands (see diagram below) suffered from damage to the anchorage zones for the strands as well as a possible relaxation of these parts.



Sketch of the reinforcement of the main girders (source: ANPI).

Spalling of the concrete on the main girders (source: FEBELCEM).

2. Building design

North-Galaxy towers in Brussels (Source: ERGON).

ERGON [31] proposed an alternative in reinforced concrete for the construction, in 2003, of the two 30-storey North-Galaxy towers, situated next to the Centre Rogier in Brussels. This alternative not only turned out to be more economical than the initial solution of a concrete clad steel structure, but also much faster. Furthermore, it met the technical conditions of the initial project, concerning the dimension of the elements, the space available for the techniques and fire resistance. [58]

The use of high-strength concrete and the implementation of new TT components lie behind the success of the construction in precast concrete.

The rapid execution of the works was also a determining factor: the assembly of the precast components went like clockwork, at a rate of two storeys every eight working days. No other tower in Belgium can boast of such a rapid assembly.

The stability of the two towers is ensured by a rigid core cast in-situ with the help of climbing framework.

The complete prestudy became extremely complex owing to additional strict requirements issued by the contracting authority relating to the risk of progressive collapse, imposed following the events of 11 September 2001.

The fire resistance of the columns in HPC was justified through the calculation made by the University of Liege with the help of its SAFIR programme, classed as an advanced method.

Limiting use to HPC C80/95 concrete, with a maximum silica fume content of 6 % of the weight of the cement, means it is not necessary to use monofilament polypropylene fibres, in accordance with the rules of standard Eurocode 2 part 1-2 [107]. See §7.2.3 relating to the characteristics of high-strength concrete.

The use of precast concrete elements in tower blocks confirms the advantages compared with other systems:

- assurance of two hours of fire resistance without any additional protection;
- rapid turnaround time;
- limited deflection of the floors;
- floors have better sound insulation;
- more competitive price.

These advantages have all been confirmed in the field in numerous constructions such as:

- the Vazon tower in Luxembourg (19 storeys);
- extension of the Madou tower in Brussels (15 storeys);
- extension of the Botanique tower in Brussels (18 storeys);
- North-Galaxy project in Brussels (30 storeys).

3. Fire tests for buildings

Fire tests on individual structural elements are useful to improve knowledge relating to the effects of fire on these construction elements. A realistic fire test is rarely performed on a whole building or on a major part that includes all these elements, thus allowing us to study their interaction.

3.1. Ghent 1974

A voluntary fire [30] was conducted in Ghent on 13 June 1974 on an industrial type building. The building had a surface area of 12 x 8 m and a clear height of 6 m.

(Source: FEBE).

All the elements were precast. The roof beams had a span of 18 m. The roof was composed of various types of concrete: heavy aggregate, light and cellular concrete. Two walls were done in block masonry and the other two were composed of façade panels in cellular concrete and light concrete.

The fire load of 125 kg of wood per m^2, which was completely consumed, produced an intense fire for an hour. The building was particularly resistant to the fire.

The three main prestressed beams resisted this major fire remarkably well. They were repaired and subjected to a load test later on. These beams showed a greater resistance than the three beams which had not been exposed to the fire. These tests were commissioned by the Belgian authorities.

The film "Concrete is Fire Safe", which is downloadable from the Association of Concrete Industry, the FEBE (www.febe.be > febefast > publications > Video), shows a recording of this test.

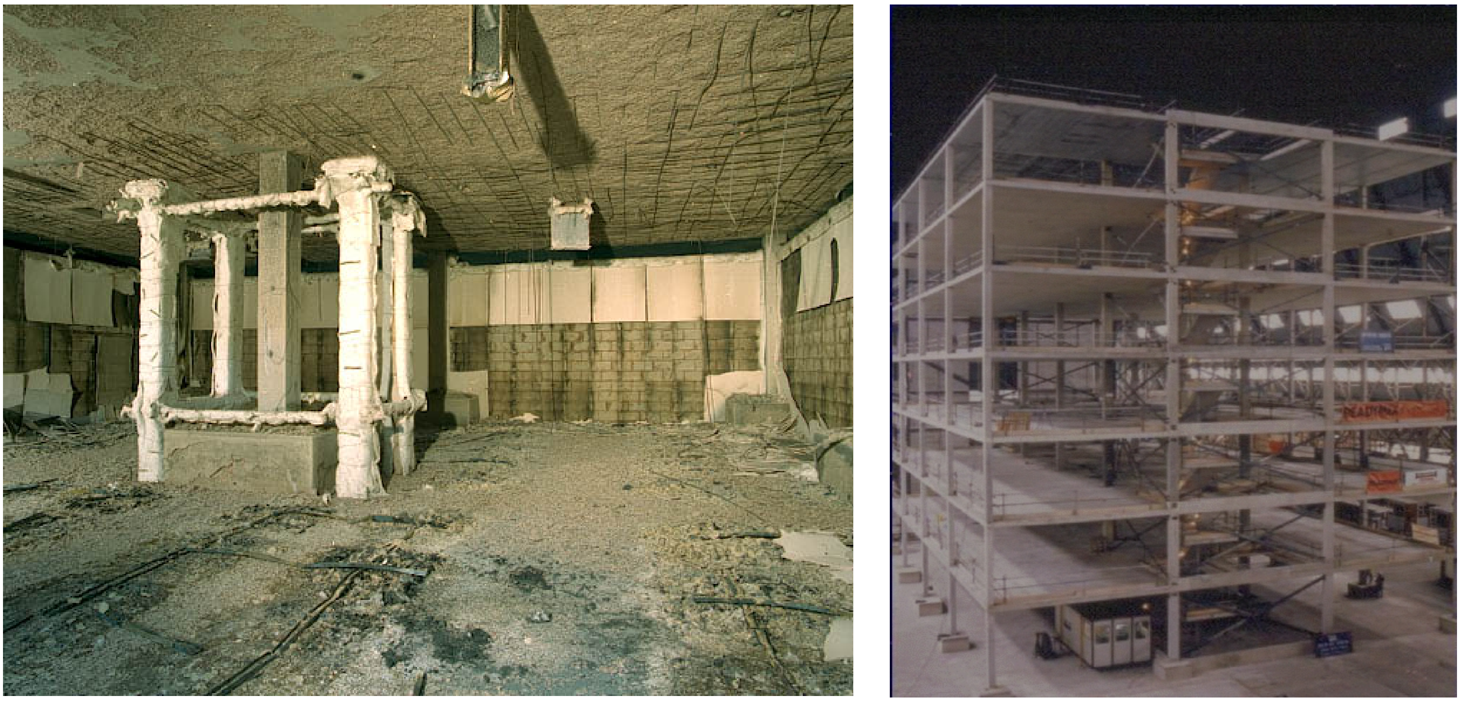
3.2. Cardington 2001

(source BCA)

The Building Research Establishment (BRE) carried out a fire test on a compartment situated on the ground floor of a six-storey building in reinforced concrete, in Cardington (UK) on 26 September 2001. This test was part of the "European Concrete Building Project" and was financed, in particular, by the British Cement Association [28], FEBELCEM (Association of Belgian Cement Industry) and CEMBUREAU (Federation of European cement industry).

This concrete building had 7 levels, each of them 22,5 m x 30 m. Each storey had 12 (3 x 4) bays (7,7 m x 7,7 m).

Despite exposing the lower reinforcements, this test showed the good behaviour of the flat slab, and the good performance of its central column in high performance concrete, equipped with polypropylene fibres.



(source: BCA).

D. Repair of concrete structures

What we have learnt from fires [14], [22]

The "Concrete Society" (UK) investigated a significant number of different concrete structures damaged by fire in Great Britain. The investigation included detailed information on the performance, assessment and repair of more than 100 structures including housing, offices, warehouses, factories and car parks. The constructions were either one-storey or multi-storey. The types of constructions examined included flat slabs and others resting on a network of beams, associated beams and columns for structures that were both cast in situ and precast, and reinforced as well as prestressed. The examination of the list of damages and repairs showed that:

- the majority of structures were repaired. Amongst those that were not, very many could have been but they were demolished for reasons other than the damage they suffered;
- nearly all the structures behaved correctly during and after the fire.

In general, concrete structures that are burnt can be restored whereas structures made from other materials would be irremediably damaged, even by lesser fire loads.

This is nearly literally what is stated in the ANPI's MAG 169 text [27]

A construction made from concrete exposed to high temperatures can be damaged. In certain cases, the damage can be repaired. In other cases, it is irreversible and the construction must be demolished.

1. Inspection methods

After a fire, the first thing to do is to proceed with an assessment of the structural integrity of the construction in concrete. This assessment will determine if it is possible to safely enter the building. Then, it is necessary to assess the extent of the damage and see whether the building can still be repaired.

1.1. Visual observations

During an initial inspection, spalling, the flaking of the concrete, the formation of major cracks and the distortion of the construction are relatively easy to detect. This can be seen just by looking at it.

Concrete is made from limestone or siliceous aggregate: its colour changes when subjected to heat. The change of colour is due to the presence of certain ferriferous components. Subsequently, it varies according to the type of concrete. This modification in colour is permanent: it is therefore possible, on the basis of the colour of the concrete, to make an approximate assessment of the maximum temperature reached during the fire. The different colours of the concrete are as follows:

- pink or red for temperatures between 300 °C and 600 °C;
- grey-white for temperatures between 600 °C and 900 °C;
- dull or light yellow for temperatures over 900 °C.

This means that it is also possible to assess the resistance of the concrete after a fire. In practice, we can confirm that any concrete that turns pink is suspicious. A temperature of 300 °C corresponds, more or less, to concrete that has lost a permanent part of its resistance. A grey-white colour indicates concrete that is fragile and porous.

Furthermore, a permanent distortion of the construction indicates an overheating of the reinforcement.

1.2. Test methods

Below are the methods available:

- examination of compressive strength, for instance with a sclerometer;
- carrying out acoustic measures to detect the formation of internal cracks;
- boring and extracting core samples to carry out compression tests and carry out both petrographic and microscopic examinations.

2. Repair options

After a fire, it is sometimes necessary to carry out major repair works. To repair a construction made from concrete, it is practically impossible to provide standard solutions. Each situation must be examined individually and the best solution chosen for each case. In this respect, the following factors must nevertheless be taken into account:

- the resistance of the construction after the fire;
- the permanent distortions;
- the durability after the fire and repairs;
- the aesthetic aspect.

The choice of the solution is largely dictated by economic considerations: what is the most advantageous economic solution? Replacing or repairing damaged elements? In general, for a construction in concrete, which is distorted in some way following a fire, the most logical solution consists of replacing the elements of construction or demolishing the building.

If the reinforcement has not been subject to high temperatures, stripping the damaged concrete back to the healthy concrete is largely sufficient. In practice, a good solution consists of repairing the damaged concrete using shotcrete, though work of this type must be performed by professionals. By sticking metal plates or carbon fibre strips to the surface of the damaged concrete, it is sometimes possible to strengthen a reinforcement that has been weakened locally. This type of work must also be carried out by specialists. In the case of damage to the aesthetics of a building, the most obvious solution is to apply a rendering.

Shotcrete

Shotcrete is often used for repairs, renovations or for a particular type of construction. Within the context of "Fire safety and concrete structures", shotcrete is more particularly used to repair the elements of a structure where the reinforcement has been exposed. In the case of shotcrete, the mortar is sprayed under pressure. There are two spraying techniques: dry-mix shotcreting and damp-mix shotcreting.

Dry-mix shotcreting

The dry mortar is directed towards a high-pressure pipe. This pipe transports the dry mix towards the spraying head where water is injected to transform it into concrete, which is then sprayed onto the surface for repair. It is a relatively complicated technique which requires heavy equipment. It is only applied for voluminous elements.

Damp-mix shotcreting

Before spraying, the mixture of cement and sand, and possibly aggregate, is introduced into a mixer where it is mixed with water. This mixture is then sprayed onto the surface to be treated using a plunger pump and then worked. This technique is particularly used for small elements and for elements where thin layers must be sprayed. It is a simple technique that requires lighter equipment.

When it is heated up [13], concrete can spall: this is not the case for steel.

"In a closed building, the level of humidity (see §7.2.1) in the concrete is classically lower than the threshold at which it spalls. Moreover, high-performance concrete (60 to 100 MPa) will behave correctly providing particular attention is paid to its composition, the incorporation of polypropylene fibres or surface reinforcement such as mesh. The Channel Tunnel, a reinforced concrete structure (100 MPa concrete with no particular precautions) was nevertheless subjected to a fire lasting nearly 9 hours with a maximum temperature of almost 1100 °C. We are not speaking about the same thing when we speak of a resistance of ¼ h for steel which reaches approximately 600 degrees."

E. Appendix

Appendix 1 - Discussion on sprinkler systems

In the United States, in multi-family dwellings (including hotels, motels, crèches, homes for the elderly), dividing the building into compartments capable of offering resistance for one or two hours between all the living quarters as well as the public spaces and the living quarters should be redundant [41] with automatic smoke detection systems and sprinklers.

The concept of redundancy is opposed to the concept of substitution. It should be regarded as a combination of two complementary means of achieving an increased level of fire protection.

It would be instructive to investigate whether, in Belgium, there are the same trends as in the US, where fires affect multiple-apartment buildings 2,6 times more often proportionally than single or two-family dwellings. This figure becomes 1,6 if the statistics for people killed are analysed. It is 3,6 for people injured. The level of damage per apartment is more than twice as high as for single-family dwellings.

What are the causes of such a high level (16 %) of sprinkler failures?

The National Fire Sprinkler Association (NFSA) insists on the need for sprinklers to undergo thorough inspections in accordance with the current standard “Inspection, Testing and Maintenance of Water-Base Fire Protection Systems”. The Association recommends that the water-supply valves should be checked weekly to make sure they are in the open position. Even with this inspection, if the valve is closed, the supply to the sprinklers may be cut for a whole week. The NFSA recommends that a qualified expert should carry out an in-depth inspection of the whole sprinkler system.

According to the NFSA: “Sprinkler systems are designed for the conditions which exist or which can be expected in a building where the sprinkler system is installed. After any modification is made to the building or its usage, an analysis should be made to determine whether the sprinkler system is still satisfactory. Similarly, even if the building and its usage are unchanged, modifications to the water supply or to the equipment in the sprinkler system require system re-evaluation.”

An adequate supply of water to the building is critical for the efficient operation of automatic sprinkler systems. Any reduction in or interruption to the supply can reduce its efficiency. Urban development can reduce the water quantity and pressure in the water distribution system supplying buildings. Interruptions to water distribution can arise for a number of other reasons such as the maintenance of water pipes inside and outside the building, including sprinkler system maintenance. Then there are natural causes such as earthquakes, storms, and interruptions caused by arsonists or simultaneous fires in several buildings (deliberate attacks, exploding gas pipes, etc.).

Human intervention can also reduce the operational effectiveness of sprinklers. The NFSA recommendations are:

- Never paint sprinklers;
- Never hang anything from any part of the sprinkler system;
- Never store anything close to sprinklers (the top of any stacks should be more than 45 cm below the sprinklers);
- Always report any damage to the sprinkler system immediately;
- Always make sure the control valves are in the open position.

Is the public [41] generally aware that the level of safety in buildings may not be what they imagine?

Probably not. All they can see is the number of sprinkler heads, whether these are functional or not. An investigation carried out by an independent third party for the Alliance for Fire Safety has shown that the public do not generally feel safe when they are made aware of the 16 % sprinkler failure rate. If sprinklers are present, almost all regulations allow for significant reductions in other fire-protection systems. This include a reduction in the fire-resistance time of the compartments, an increase in the size of the compartments and an increase in the distance from the emergency exits, all within the framework of an ISO fire (see §2.3)

But sprinkler systems can also fail as a result of an interruption to the water supply, inappropriate maintenance, criminal arson, manufacturing faults in the sprinkler heads, physical obstacles at the same level as or close to the sprinkler heads, and paintings or other items hung from sprinkler heads. This makes compartmentalisation necessary to prevent the spread of the fire if the sprinklers fail.

The National Institute of Standards and Technology (NIST) published its conclusions on 03-03-2005, following a serious fire in 2003, on the subject of fire design in buildings balancing active and passive protective measures. The report recommends:

- in the case of buildings fitted with sprinkler systems, to eliminate agreed concessions when it comes to the factors influencing the time taken to evacuate the buildings;
- the "Model Codes" and regulations should require redundant active and passive fire-protection systems in order to guarantee adequate performance of the structure in the event of one or more protective systems being compromised by inappropriate actions on the part of the owner or occupants (namely disabling the sprinklers for maintenance).

Reducing the design fire load density in presence of sprinklers is explained in the frame of the Fire Safety Engineering approach (see §8.2).

We would now like to return in detail to sprinkler reliability figures and illustrate in a tangible and explicit manner the problems of quantifying active measures. The mistrust and suspicion surrounding FSE, taking mathematical account of the presence of active measures, stem from the great variation in reliability and poor understanding of active measures. This is the case, among other things, with sprinklers from different sources and countries. Allowing for an average higher figure sacrifices numerous buildings unacceptably and penalises others. Thus, in addition to the values taken from the report of 2001 from the NFPA for the USA:

- According to the concept of fire safety based on natural fire (NFSC for Natural Fire Safety Concept) [42] which contributed to the publication of Appendix E to Eurocode 1, part 1-2, we should be able to count on a reliability of 98 % for installations which conform "to the regulations".
- In Australia, statistics relating to sprinklers give reliability figures of 99,5 % (!). This is explained by:
    - An automatic alert to the emergency services if sprinklers open. It should be noted that this does not improve the reliability of the sprinklers but does increase the probability of success by the emergency services;
    - All plans for sprinkler systems are checked by evaluation organisations;
    - Installed sprinkler systems are tested against their specifications by evaluation organisations;
    - Sprinkler systems are **checked weekly** (control valve, water supply, alarm), and documented in a written report;
    - An electronic scanner is installed in high-rise buildings.
- In Switzerland, all alarm valves are connected to the emergency services. The closure of the main valve triggers an alert to the emergency services, preventing the closed valve syndrome and closure of the valve in the event of criminal arson.
- According to BS 7974[111], the recommended values are from 75 to 95 % (values also cited in the report from Warrington Fire Research [43]);
- According to the WG4 report from the NFSC study [44], in France, a value of 95 % would apply. Half of all faults are linked to human error;
- The statistics from the European Insurance Committee as per regulation CEA 4001 indicate that all cases taken together involve control of the action area in 94 % of cases. Regulation CEA 4001 is the equivalent of standard NBN EN 12845 [108], relating to the design, installation and maintenance of sprinkler-type automatic fire-extinction systems. The equivalent of the CEA in the USA is the NFPA. In the past in Belgium, all fires were declared thanks to a zero excess system. At present, following the introduction of excesses, insurance companies no longer have the previously reliable statistics which interest us. Some large store and distribution chains have excesses as high as 1,2 million euros.
- According to the results from the NFPA relating to the statistics from 1925 to 1996, taking all classes of risk as a whole, 96 % of fires are extinguished. A single head was triggered in 28 % of cases, two heads in 18 %, three in 10 %, and four in 8 %.

What are we to make of this?

In a document [45] commissioned by the Alliance for Fire Safety, Mr Koffel summarises 20 studies on the subject:

- Numerous studies relate to periods more than 15 years ago, unlike the recent study from the NFPA which covers an observation period during the 10 last years;
- The percentage of fires extinguished by sprinklers given by the NFPA drops to figures varying from 8 to 33%. In reality, control of the size of the fire by the sprinkler system (successful action) is generally sufficient to allow complete fire extinction by the emergency services;
- The statistics from the NFPA do not cover minor fires which do not trigger at least one sprinkler head, nor those not reported to the emergency services. Thus, the figure of 87% success given by Mr Ramachandran (New York) would amount to 94% if we assume that 1/3 of all fires are not reported.

Because of a lack of proof to support this hypothesis, the NFPA has adopted an operational reliability of 84 %. This report seems to indicate that the reliability of automatic sprinkler systems stated at around 96 % is overestimated the reliability.

It should be emphasised that in the event of fire, even if system reliability is 84 %, these systems reduce dramatically the loss of human life and destruction of property.

We talked to Mr Briers from ANPI, the convenor of the WG5 at European level, on the subject of sprinkler standards. He explained Belgian practices:

- What is meant by basic water supply for sprinkler systems?

NBN EN 12845 [108] mentions that the water supply must remain effective for a specific period (see §8.4.1 Classification industrial risk: for LH 30 min, OH 60 min, and above 90 min). Local water-distribution authorities never guarantee flow/pressure curves: measurements are carried out when the system is proposed. The supply is considered satisfactory in Belgium if the curve resulting from a levy of 3 000 l/min to supply the fire-fighters leaves a sufficient supply for the system to operate. A curve is established on the basis of the town water supply when the sprinkler system is devised. A measurement is also made at each biannual inspection. If the results are unsatisfactory (linked to the distributor or the establishment of major new enterprises in the area), the supply has to be augmented, using booster pumps, for example. Networked systems are more reliable than those without loops.

- What are the water supply requirements of sprinkler systems?

For slight or ordinary risks of types OH1 and OH2, insurers require a normal water supply (= basic supply). In the case of risks equal to or higher than OH3 (OH3, OH4, dangerous production facilities and storage depots), insurers may require a high-reliability supply, that is, a supplementary, independent basic water supply or the presence of a public network capable of supplying 100 % of the flow on each side.

- How is the capacity of the water supply checked?

A flow/pressure curve is established at installation. An end of line test is carried out during the ANPI inspection every 6 months. The sprinkler in the least favourable position in the pressure network is triggered. A check is carried out to ensure that the control point on the main line does in fact trigger the alarm.

When new companies are established in an industrial zone, for example, the flow/pressure curve may be inadequate. When it carries out its 6-monthly inspection, the ANPI informs those companies already equipped with a sprinkler system. They are advised to install a supplementary, independent source of supply.

The ANPI advises companies to test the supply regularly every 3 years and redo the flow/pressure curve. This is not required by NBN EN 12845 but is quite easily done if there is a pump fitted with a measurement device from the outset.

It should be noted that 90 % of sprinkler systems are “wet” systems, where all piping always contains water. The other 10 % are “dry” systems in which the water only circulates if a signal is sent to a control valve following the opening of a sprinkler head.

- How are local authorities involved?

The fire brigade requires a system in accordance with the standard and requests a report from ANPI confirming conformity to NBN EN 12845. The fire brigade does not carry out any on-site checks after that.

- Is there a dispensation system?

The ANPI does not grant any dispensations. These may be granted by a dispensation commission composed namely of insurers.

- How can you guarantee the control valve remains open?

Traditionally, this valve is always sealed or maintained in the open position using a padlock. An enquiry is initiated if the ANPI finds that the seal has been broken. The authorities in the matter, the fire brigade or the insurer, may, depending on the risk, require monitoring of this valve by dispatcher, control post or centralised remote surveillance. Any rotation of the pump is detected and the presence of circulating water reported directly to the monitoring service. An annex to NBN EN 12845 is devoted to system monitoring.

- Does standard NBN EN 12845 apply?

Yes. This is a harmonised product standard which also includes an Annex Z. The problem of “kits” has triggered long discussions.

- What about the reliability of sprinkler systems?

It’s a bit of a mixed bag.

In the case of Europe, if you look at sprinkler success rates by risk class, the statistics show:

- for office risks (slight): 97,4 % success;
- for business risks (ordinary): 97,2 % success;
- for timber industry risks (high): 90,8 % success.

The statistics from the CEA relating to the period from 1985 to 1996 for industrial buildings (OH1 to HP4 and HS4) taken altogether indicate that control of the action zone was successful in 94 % of cases, and than in 73 % of cases, the fire was confined to less than half the area of the action zone.

The statistics of the CEA relating to a very recent period show that this probability even falls to 90 % instead of 94 % mentioned above. This drop can be explained specifically by the increasingly frequent use of plastic packaging.

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