Steel and fire safety

A global approach

Edited by
Steel Promotion Committee of Eurofer
Square de Meeûs, 5, bte 9, B-1040 Brussels, Belgium

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This brochure is an initiative of the Steel Promotion Committee of EUROFER which brings together the Steel Information Centres from Belgium-Luxemburg, France, Federal Republic of Germany, Great-Britain, Italy, the Netherlands, Switzerland and Austria.

It has received the financial support of the Research Directorate ECSC-Steel of the Commission of the European Communities.

This brochure has been written with the aim of making architects, non-professional decision-makers, investors, insurers and fire authorities aware of the many important factors which determine the fire safety of steel constructions. Special care has been taken to present a global and coherent approach in a novel and easy way and to provide information of a high density in few pages.

More elaborate information on fire safety of steel constructions can still be obtained by the Steel Information Centres of the West European countries, the list of which is given at the end of this brochure.

Those responsible for steel promotion in the Community countries hope that this Fire Brochure will result in a more objective and realistic approach of fire safety and promote fruitful dialogues between fire Authorities and decision-makers, building owners, architects and designers, allowing modern, fire safe and cost-effective steel structures to be realised.

P. BORCHGRAEVE,
Centre Belgo-Luxembourgeois d'Information de l'Acier, Brussels, Belgium,
Chairman.

J.P. BOUILLETTE,
Office Technique pour l'Utilisation de l'Acier, Paris La Défense, France.

J.P. FAVRE,
Gebäudeversicherung des Kantons Bern, Bern, representing Schweizerische Zentralstelle für Stahlbau, Zürich, Switzerland.

J.T. ROBINSON,
British Steel, General Steels, Redcar, Cleveland, representing The Steel Construction Institute, Ascot, United Kingdom.

P. SETTI,
Politecnico di Milano, Structural Engineering Dpt, Milan, representing
Centro Promozione e Sviluppo Federacciai, Milan, Italy.

L. TWILT,
TNO-IBBC Institute for Building Materials and Structures, Delft, representing Centrum Staal, Rotterdam, the Netherlands.

H. WITTE,
Instruct Ingenieur GmbH, Wiesbaden-Sonnenberg, representing Stahl-Informations-Zentrum, Düsseldorf, Federal Republic of Germany.

J. ZUCKA,
Centre Belgo-Luxembourgeois d'Information de l'Acier, Brussels, Belgium.

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In many parts of the world, structural steel is the first choice of architects and engineers for the frame work of single and multi-storey buildings. Steel construction offers many advantages such as fast erection, wide clear spans, light foundations and the cost can be compared very favourably with other methods of construction. However steel structures are often still treated with a particular and unjustified distrust with regard to fire safety. Steel structures can be designed to withstand any level of fire resistance and much research has been carried out in recent years to quantify the behaviour of fires in buildings and structures in fire.

Fire safety is an international concern and although the behaviour of fires and structures is consistent from one country to another, experience has shown that there are difficulties in understanding the principles and processes of fire safety throughout all the Community countries in addition to differences in national and local standards and regulations.

Based on the available international literature and on the research carried out with the help of the ECSC during the last twenty years, the present brochure has been prepared with a threefold objective:

- to help to provide a better understanding of global fire safety by supplying a guide for architects, non-professional decision- makers, investors and other concerned people, such as architectural and engineering students;
- to help the Authorities responsible for the enactement and enforcement of the regulations by providing a summary of fire safety measures, taking into account recent developments;
- to promote communications between architects, designers and Fire Authorities with regard to fire safety requirements.

CHAPTER I

contents that fire safety in buildings is concerned with achieving two fundamental objectives: to reduce the loss of life and to reduce the property or financial loss.
Official data indicate clearly the causes of deaths and property/financial losses in case of fire. They allow the following main conclusions to be drawn:

- The choice of structural material for a building is quite irrelevant with regard to both types of losses.
- Taking only fire resistance measures into account does not automatically ensure sound fire safety levels.
- The design of fireproof buildings requires an integrated approach.

A systematic approach to identify all possible actions to be considered in order to achieve the above objectives is therefore used.

CHAPTER II

gives an analysis of fire risk and of the measures to overcome it.
The acceptable level of risk may be evaluated in terms of the probability of a fire occurrence and the probable loss expectation.
Both active and passive fire precaution measures may be used to prevent and limit risks. The consideration of integrated fire precaution measures leads to three fire safety concepts, the common structural concept and the two alternative concepts of monitoring and automatic extinction. These two alternative approaches, for which there is growing acceptance in many european countries, offer increased levels of fire safety, even if bare steel or steel with a limited passive fire protection is used.
A cost-benefit analysis approach is outlined which allows designers and decision-makers to realise optimum fire safety.

CHAPTER III

discusses the way to assess the correct level of structural fire resistance requirements, in the absence of active measures. Furthermore it shows the way to take into account active measures chosen for a given building with its fire risk situation.
The approach indicates:

- methods of ensuring structural stability by taking into account real fire conditions;
- methods of defining the correct level of fire resistance.

Traditional methods of assessment are based either on the Standard fire curve or on the concept of equivalent fire duration. Quantitative more sophisticated methods based on natural fire modelling are a further development. These engineering design methods represent a modern, reliable and realistic approach to define the correct level of structural fire resistance.

CHAPTER IV

deals more specifically with steel structures. Correctly designed, these are always able to achieve satisfactory fire resistance levels. Three main factors govern the fire resistance of steel structures: the level of load, the dimensions and the temperature profiles of the steel members.
Different methods to delay or to limit the speed of heating and to increase the critical temperature of the steel elements are surveyed in a simple and easily accessible way. Criteria for choice of optimal protection are also given.
Simple calculation methods and computerized calculation models which are available to assess the fire resistance of bare steel or insulated steel structures are also surveyed.

AS A CONCLUSION

three main statements may be resumed as following:

- The fire safety of a steel building can be optimised in relation to its occupancy;
- Bare steel, fireproof buildings are feasible, aesthetic and cost-effective;
- Fire resistant steel structures can be achieved by a wide range of cost-effective methods.

1. OBJECTIVES OF FIRE SAFETY

Fire safety in buildings is concerned with achieving two fundamental objectives:

1) to reduce the loss of life in, or in the neighbourhood of, building fires
2) to reduce the property or financial loss in, or in the neighbourhood of, building fires.

In most countries the responsibility for achieving these objectives is divided between government or civic authorities who have responsibility for life safety via building regulations, and insurance companies who are concerned with property loss through their fire insurance policies.

Often the two objectives are thought to be incompatible, even occasionally conflicting. For example, sprinklers and automatic detection devices tend to be regarded as property protectors rather than life protectors and insurance companies will commonly offer substantial premium discounts when they are used. They do not figure highly in most national building regulations, yet the evidence that is available suggests that they are extremely effective in preserving life.
In fact the actions required to achieve life and property preservation are very similar.

The objective of fire safety can be broadly stated as:

1. to reduce the loss of life in, or in the neighbourhood of, building fires

2. to reduce the property or financial loss in, or in the neighbourhood of, building fires.

2. CAUSES OF LOSSES (LIFE AND FINANCIAL)

If the objectives are to be achieved in the most effective manner it is clearly necessary to determine where and how casualties and property losses occur.
To gain an overall perspective of the risk of life loss due to fires in buildings it is possible to compare fatality statistics from other accidental causes.
The data of table 1 have been drawn from a number of sources. [1], [2], [3].

Activity	Fatal accident rate per person and for a mean lifetime of 70 years
Average for disease (USA)	0,7
Travelling by car (USA)	0,6
Travelling by car (UK)	0,4
At home - average (excl. sickness)	0,02
At home - total able bodied persons	0,01
Fires in hotels (UK)	0,01
Fires in dwellings (UK)	0,001
Natural disasters (USA)	0,0001

Table 1. Comparison of fatality statistics from different accidental causes.

Although the risk of life loss in fire is low in comparison with other causes of death, there is a tendency for an incident involving multiple fatalities, over about 5 deaths, to attract a high level of news coverage. In this sense building fires tend to be regarded in the same high profile way as air crashes or earthquakes. Nonetheless it is important that the causes of fire fatalities should be examined with a view to public safety.
Accurate comparison of fire data from different countries suffers from difficulties caused by different statistical bases and methods of recording. However, general trends and broad patterns can be perceived.

a) Life loss

Table 2 gives a breakdown of fatal casualties by fire location. The UK figures are a ten year average, 1972/82, the figures for France are a five year average, 1977/81.

	Domestic Buildings	Other Buildings	Other Fires eg. outdoors
France [4]	84,7 %	9,2 %	6,1 %
UK [5]	77,1 %	10,3 %	12,6 % *

Table 2. Location of fatal casualties
(* The UK figure for "Other fires" includes casualties in derelict, unoccupied buildings).

The French data have been analysed in detail by l'Institut Technique du Bâtiment et des Travaux Publics and the results show that almost three-quarter of the deaths in non domestic premises occur in public buildings, hotels, shops etc..., and only 2 % in places of work such as offices or industrial premises.

The causes of fire deaths are shown in table 3 below:

	heat & smoke	other causes
France [4]	94,7 %	5,3 %
Germany [6]	74,0 %	26,0 %
United Kingdom [5]	97,0 %	3,0 %

Table 3. Cause of death in building fires ("unknown causes" have been eliminated from the figures).

By far the greatest cause of death in fire is smoke inhalation, not structural collapse.

These data show that fire deaths in buildings are most likely to occur in the home rather than in public buildings or in the workplace and that when casualties occur they are far more likely to be caused by smoke or heat than by any other cause and death will occur at a temperature much below that required for structural collapse.

By far the greatest number of deaths occur in the home, not in the place of work or public buildings.

b) Property / Financial losses

It is considerably more difficult to obtain comprehensive information on financial losses than on casualties in fire, though it is generally accepted that whereas the greatest loss of life is in domestic premises the greatest financial loss is in industrial buildings, in particular in warehouse and storage buildings.
A survey of low-rise industrial building fires in the Netherlands and France [7] conducted by TNO and CTICM showed that the financial loss of building contents outweighs the cost of building damage.

Building Contents	Consequential Losses	Building Structure
43 %	36 %	21 %

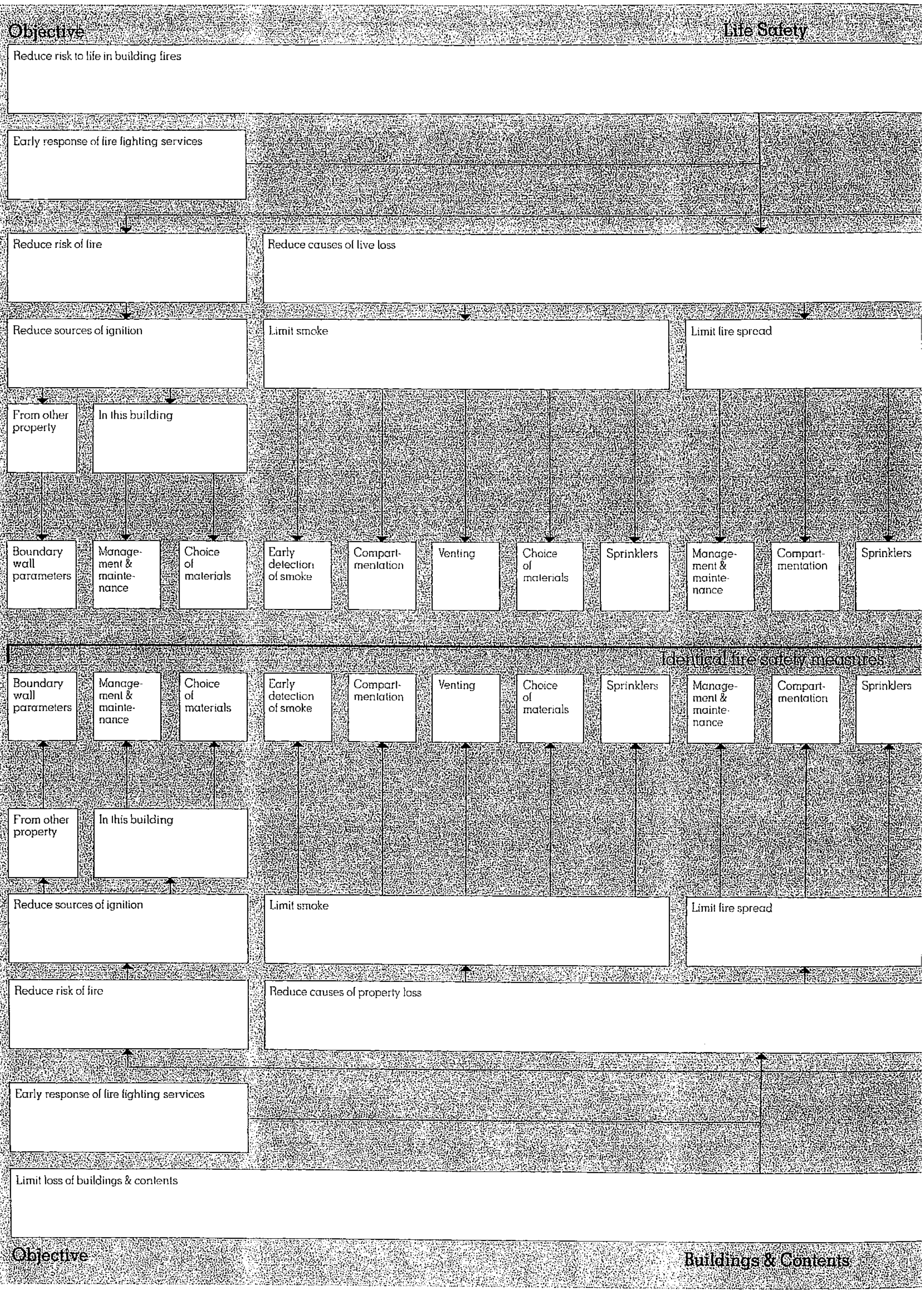
Table 4. Distribution of financial losses.

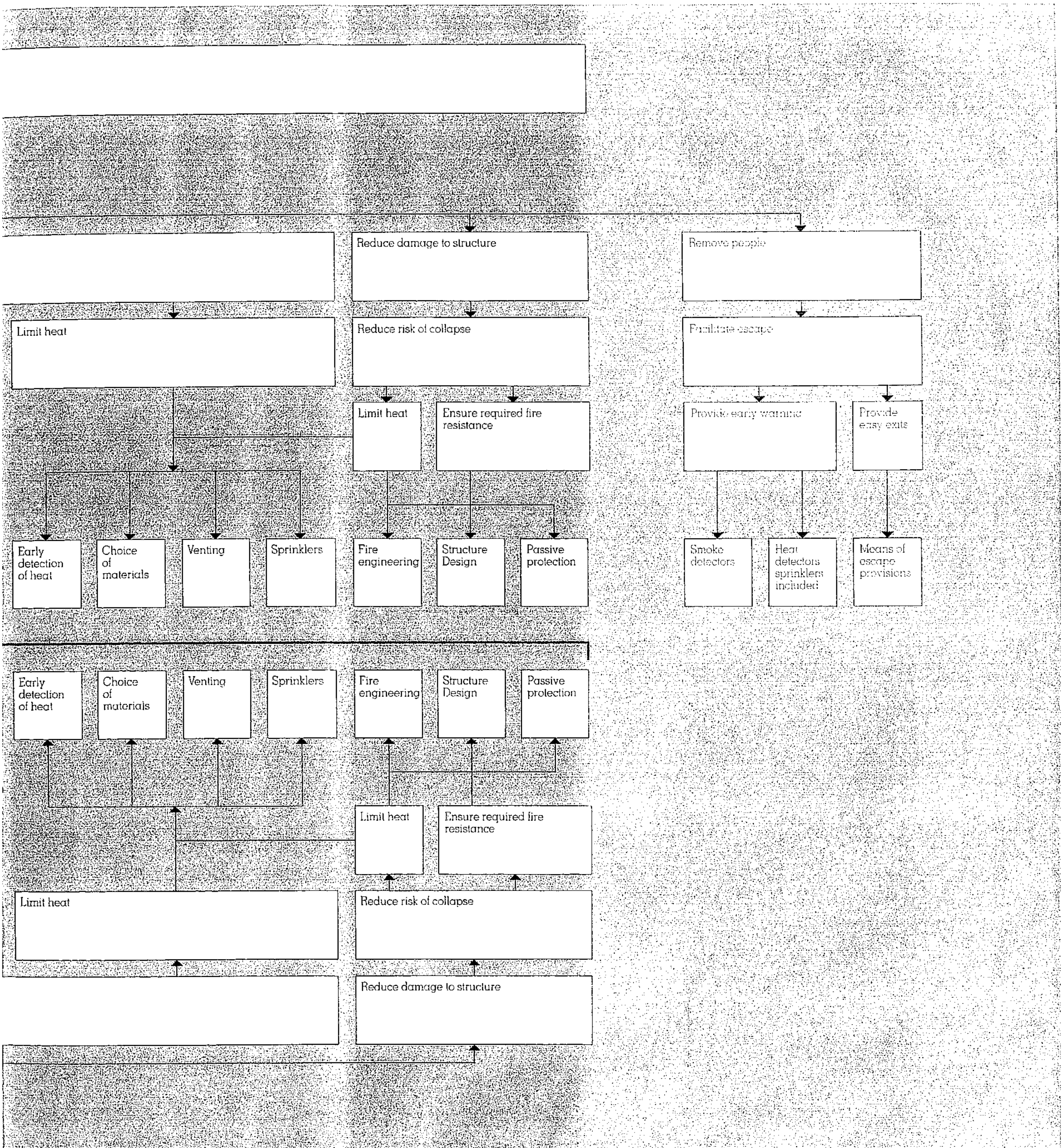
The greatest financial loss in fire arises from loss of contents and working facilities, not from damage to the structure.

The indication is that damage to contents and consequential losses are more significant financial factors than damage to the structure.

3. HOW CAN THE OBJECTIVES BE ACHIEVED

Figure 1 uses a systematic approach to identify the major options available for the designer to reduce on the one hand life loss and on the other hand financial loss. Progressive analysis of each objective leads, through a serie of sub-goals, to a set of possible actions that can be taken to achieve it.
Some options occur more than once. "Compartmentation", for example, serves to limit fire spread and also to limit smoke.
There are in all 12 discrete options 11 of which are common to both objectives. Only provisions for the escape of occupants are specific to life safety objective.


Objective
Life Safety
Reduce risk to life in building fires
Early response of fire fighting services
Reduce risk of fire
Reduce causes of live loss
Reduce sources of ignition
Limit smoke
Limit fire spread
From other property
In this building
Boundary wall parameters
Manage-ment & mainte-nance
Choice of materials
Early detection of smoke
Compart-mentation
Venting
Choice of materials
Sprinklers
Manage-ment & mainte-nance
Compart-mentation
Sprinklers
Identical fire safety measures
Boundary wall parameters
Manage-ment & mainte-nance
Choice of materials
Early detection of smoke
Compart-mentation
Venting
Choice of materials
Sprinklers
Manage-ment & mainte-nance
Compart-mentation
Sprinklers
From other property
In this building
Reduce sources of ignition
Limit smoke
Limit fire spread
Reduce risk of fire
Reduce causes of property loss
Early response of fire fighting services
Limit loss of buildings & contents
Objective
Buildings & Contents
Fig. 1



Life Safety Provisions

Note that the means of escape provisions are the only difference

a) prevent ignition

(applies to life and property protection)

1) Choice of material
Materials for both the structure and the fittings and furniture should, as far as possible, be non-flammable to reduce the risk of ignition, fire spread and heat and should generate a minimum amount of smoke to retain visibility for escape of occupants and to reduce the risk of asphyxiation.

2) Building management and maintenance
Building operators have a role to play in reducing the risk of ignition. Provision of secure storage for inflammable materials, adequate maintenance of electrical wiring, adequate means of disposal of smoking materials, provision of fire extinguishers, correct use of self-closing fire doors etc. are all necessary but more important is that adequate provision be made for staff training in fire safety.

b) facilitate escape

(applies to life protection only).

3) Means of escape.
The ability of occupants to escape rapidly from burning buildings is well recognised as the most effective means of minimising casualties. Escape provisions, to ensure safe exits, feature in all national building regulations. If casualties are to be reduced from their present levels other aspects of building evacuation need to be considered. In particular, since most casualties occur in domestic buildings at night when occupants are likely to be asleep, consideration could be given by legislators to provision of fire detectors to increase escape time.

4) Education and training
Studies of human behaviour in fire [8] indicate that there is frequently a slow response to early indications of danger and also administrative confusion in terms of who should take action. Staff training is important for public premises, where most casualties in non domestic buildings occur, but so too are clearly signed exit routes and smoke control. Marshall and Heselden [9] report that in their home surroundings people would pass through smoke of only 3-5 m visibility to escape fire. In stores and public buildings, where large numbers of people were not familiar with the layout they would not attempt to escape before visibility was reduced to 15-20 m.

c) prevent fire development and spread

(applies to life and property protection).

5) Sprinklers
Sprinklers not only help to extinguish fires and limit fire spread but they also reduce smoke, thus enhancing life safety and reduce temperatures, thus limiting destruction of contents, structural damage and consequential losses.

6) Detection of smoke and heat.
Fire alarms provide early warning to building occupants and maximise escape time. Detection systems are being developed having greater reliability and with reduced risk of false alarms than has been possible in the past. They insure a rapid intervention of fire brigade and by this strongly reduce the probability of flashover and important losses.

7) Boundary wall conditions.
Boundary walls or façades facing other buildings should be designed with sufficient stability, integrity and insulation and with suitable attention to the size of windows and separation distance to reduce the risk of ignition from fires in neighbouring property.

8) Compartmentation
Division of building interiors by fire and smoke retaining barriers is well recognised as a mean of limiting the consequences of fire. Compartmentation is a feature of all national building regulations.

9) Venting
Releasing smoke and heat to the atmosphere is preferable to retaining them inside the building where they can endanger the occupants and hinder fire brigade action.

d) prevent structural collapse

(applies mainly to property protection).

10) Passive protection
Normally only applied to steel and timber frameworks but sometimes to concrete structures. For most buildings insulation of the structural frame to prevent collapse is the least effective way of reducing casualties or financial loss. If the temperature in a burning compartment reaches a level at which the structure is in danger of collapse the costs, both in terms of lives and contents loss, will have already occurred. The CTICM/TNO report [7] for low-rise buildings concludes that the fire resistance of the load-bearing structure is an insignificant factor in structural damage, fire propagation and monetary losses due to fire.

11) Structure design
Significant levels of fire resistance can be achieved in steel framed structures even without passive protection. Research is showing that the designer can influence fire resistance by his choice of member stresses, connections, interaction between members, interaction between members and other elements of construction and location of members inside or outside the structure.

12) Fire engineering
Quantitative methods of assessing the temperatures that will be generated in natural fires are now available. These techniques make it possible to determine fire resistance requirements more precisely than by traditional methods based on the standard fire. In particular it allows the designer to determine with greater accuracy the amount, if any, of passive protection required to ensure structural stability.

The influence of fire services on life and property preservation is extremely important but is not emphasized here because this document is mainly concerned with building design and fire prevention. In domestic fires, which are the largest single source of fire deaths, the fire brigades provide almost the only effective means of protecting life and property. For fires in low-rise industrial buildings the TNO/CTICM survey indicated that the time of arrival of the fire brigade is one of the most significant factors in limiting fire propagation, fire losses and structural damage. There was no loss of life inside any building in the study.

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4. PRIORITIES FOR ACTION

The priorities for action to achieve each of the objectives are similar :

Reduce risk to life	Reduce financial loss
1) Reduce risk of ignition	1) Reduce risk of ignition
2) Remove occupants	
3) Early fire brigade action	2) Early fire brigade action
4) Limit fire spread	3) Limit fire spread
5) Limit fire severity	4) Limit fire severity
6) Limit causes of death	5) Limit causes of losses
in order of priority	in order of priority
a) Smoke	a) Heat and smoke
b) Heat	b) Water
c) Collapse	c) Collapse.

Apart from provision of adequate means of escape the methods and priorities to limit life loss and property loss are the same.

1. ANALYSIS OF THE RISK

The usual way to measure the risk of fire for a given type of building or occupancy is expressed by the formula

$R = P_o \times L_x \leqslant R_{accepted}$

R = actual risk
R accepted = targeted risk
P_o = probability of occurrence of a fire.
L_x = probable extent of loss (direct and indirect losses per fire, human losses per fire).

The risk R can never be zero and we have to accept a certain level of risk for every type of building and/or occupancy. This level will depend on the number of persons, their ability to escape and the value of content exposed to fire.
Table 5 gives some indications of the occurrence of fire in different types of building.

Type of building occupancy	Source	Number of fires per million m^2 floor area and per year
Industrial Buildings	United Kingdom [11]	2
	Germany [12]	2
	CIBW14 [13]	2
Offices	United Kingdom [11]	1
	USA [14]	1
	CIBW14 [13]	0.5 ÷ 5
Dwellings	United Kingdom [11]	2
	Canada [15]	5
	Germany [16]	1
	CIBW14 [13]	0.05 ÷ 2

Table 5. Occurence of fires.

The probability of fires getting out of control is strongly related to the type of active measures available, as indicated in table 6 below (reference CIB W14 Workshop Structural Fire Safety). [13]

Type of active measures	Probability of fires getting out of control
Public fire brigade	100/1000
Sprinkler	20/1000
High standard residential fire brigade combined with alarm system	≥ 10/1000 ÷ 1/1000
Both sprinker and high standard residential fire brigade	≥ 1/10 000

Table 6.

The degree of risk that may be tolerated will depend on the importance of one or more of the following objectives:
- to avoid fatal casualties and injuries
- to reduce monetary losses caused by
  - loss of content
  - interruption of production
  - damages to neighbouring buildings
  - failure of the building.

Type of building

The actual risk depends on the type of building, the kind of use and type of occupancy. In the "Swiss Risk Evaluation" [17] three types of buildings are defined :

- buildings with a large volume as shown in fig.2 where fire spread is possible in both vertical and horizontal directions,
- buildings with large areas as shown in fig.3 and 4 where fire spread is possible in a horizontal direction only,
- buildings consisting of a large number of fire cells as shown in fig.5 where only limited spread is possible.

Proper fire safety levels should be a reflection of the risks, which are a function of the type of building and the type of occupancy.

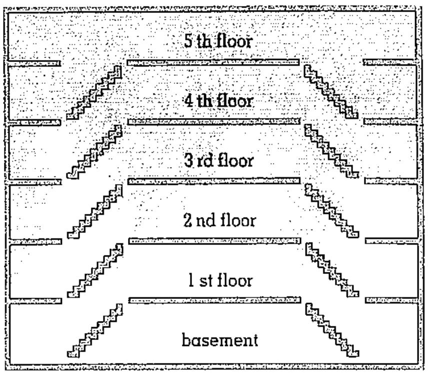


Fig. 2 Building with a large volume (elevation)

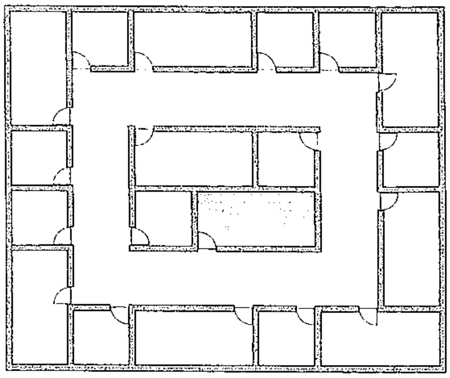


Fig. 5 Building with a large number of fire cells (plan)

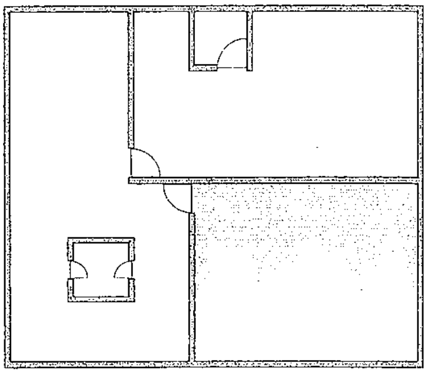


Fig. 3 Building with large areas (plan)

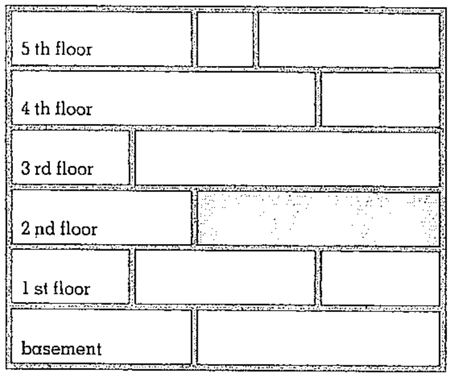
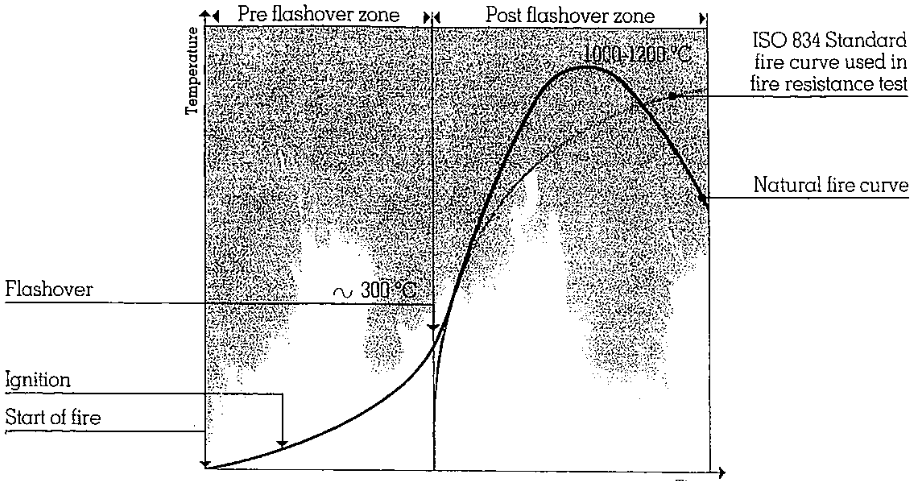


Fig. 4 Building with large areas (elevation)

Type of occupancy

The kind of use will determine the fire load density, for example a library has a higher fire load density than a metal fabricating facility. The occupancy gives some important indications for the probability of fatal casualties. This may be explained by an example. In the industrial field most buildings have only one storey. Normally there are active healthy people inside the building, who are familiar with the building layout. In case of fire they will escape quickly and fire protection of the structure is normally unnecessary. In residential buildings or hospitals, which may be multistorey, occupants may be asleep or incapacitated when fire occurs and thus unable to escape quickly. In such cases improved fire safety provisions are necessary. It is well known that the risk of fire occurrence is relatively small. But in assessing fire precautions the potential severity of a fire and the probable loss amount should be considered.



Key words	Ignition	Smouldering phase	Heating	Cooling phase
Phases governed by	Inflammability	Temp. + smoke development	Fire load density	Ventilation conditions

Fig.6 Development of an uncontrolled fire.

There is no risk of structural damage unless "flashover" occurs.

There is no risk of life loss if adequate escape facilities are provided.

During the phase of ignition the risk to life or property is not very high. This phase is, however, of vital importance since it allows early detection and suppression. The phase of slow fire growth in which the thermal effects are only local, will cause burning of combustible materials and production of smoke. This is a crucial phase where the occupants are in danger and which may also produce financial losses due to smoke damage. The structural damage of the building is still small. Only the glass in the windows may be destroyed.
The dangerous point is the flashover which marks the transition from the local fire to the fully developed fire. The temperature for a flashover depends on combustibility of the material. For cellulose products it will be approximately 300°C. A post flashover fire will cause temperatures typically of 600-1000°C with the risk of structural failure. Fire fighting in the compartment is then totally impossible. Fire fighters are only able to protect the neighbourhood.

2. ACCEPTANCE OF RISK

A method of evaluating acceptable risk levels is given by the Swiss Risk Evaluation [17] using the following categories which relate to the safety of individuals:

■ occupancies with a large number of persons at risk
- office buildings and hotels (high density of human occupation)
- shops, theatres, exhibition rooms (possibility of panics)
- hospitals, homes for the elderly (physically handicapped occupants)
- prisons (no possibility to escape)
- high-rise buildings (difficulty of evacuation)

■ occupancies with a normal number of persons at risk
- industrial buildings (healthy people)

■ occupancies with a restricted number of persons at risk
- storage buildings (few people).

Additionally the number of storeys, which influences the escape duration, is taken into account.
For structural safety the CIB Design Guide [18] proposes different safety classes relating to:
- the expected number of fatalities in case of fire (depending on the type of occupancy)

• the expected economic losses (depending on the values of building and content exposed to fire)
This type of reasoning may be represented in a simplified, qualitative way as shown in Table 7.

EXPECTED NUMBER OF HUMAN FATALITIES	EXPECTED ECONOMIC LOSSES LOW	MEDIUM	HIGH
LOW 1 FATALITY PER TEN STRUCTURAL FAILURES	VERY LOW LEVEL	LOW LEVEL	MEDIUM LEVEL
MEDIUM 1 FATALITY PER STRUCTURAL FAILURE	LOW LEVEL	MEDIUM LEVEL	HIGH LEVEL
HIGH 10 FATALITIES OR MORE PER STRUCTURAL FAILURE	MEDIUM LEVEL	HIGH LEVEL	VERY HIGH LEVEL

Table 7. Required levels of structural fire safety.

3. FIRE SAFETY CONCEPTS

In order to develop possible Fire Safety Concepts it is essential to examine the usual development of an uncontrolled fire as shown on page 16 (fig. 6). The influence of fire precaution measures may be visualised by reference to figure 7.

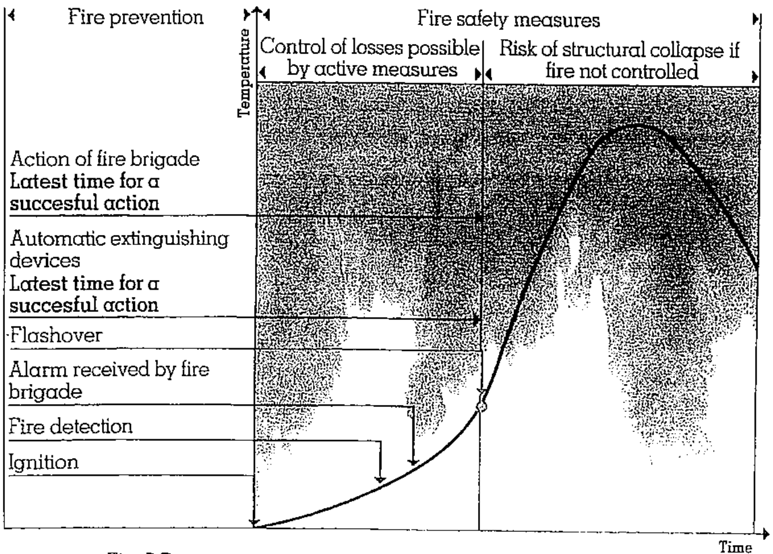


Fig. 7 Fire precaution measures, conditions for effective control.

A fire safety concept is defined as an optimal package of integrated structural, technical and organisational fire precaution measures which allows well defined objectives agreed by the owners, the fire authority and the designer to be fulfilled. Three approaches to fire safety, namely the "Structural concept", the "Monitoring concept" and the "Extinguishing concept" are described as follows.

A fire safety concept is an optimal package of integrated structural, technical and organisational fire precaution measures.

3.1 Structural concept

A Structural concept comprises compartmentation combined with an adequate fire resistant structure; it may be the best choice as long as the normal (cold-design) use of the building allows compartmentation by fire resistant floors and walls.

It is admitted that the fire may reach flashover conditions before fire fighting action begins.
The necessary time of fire resistance should be determined by the condition that the fire should not spread outside the fire compartment. Hence the separating and (possibly) load-bearing function of the relevant building components should be maintained during the anticipated duration of the fire.

KEY WORD: NO STRUCTURAL COLLAPSE THROUGH FIRE RESISTING STRUCTURES AND COMPARTMENTS

Result/risk acceptance
- No structural collapse
- Loss of content
- Business interruption
- No guarantee about reserviceability and repairability of compartments involved in the fire

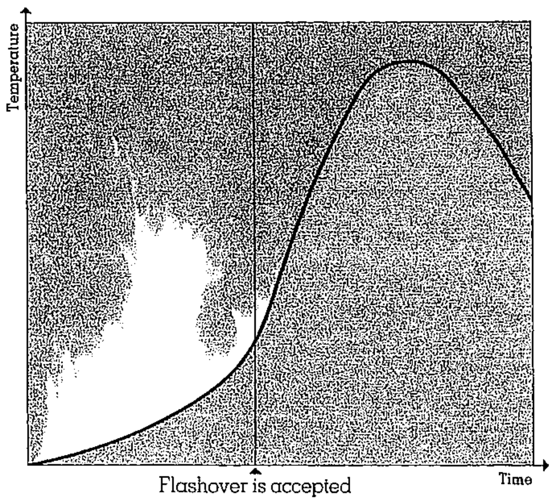


Fig.8 Structural Fire Safety Concept.

STRUCTURAL FIRE SAFETY CONCEPT

It is assumed that flash over will occur, giving rise to excessive heat and smoke.

Compartmentation anc structural fire resistance may be necessary t limit fire losses.

Whenever possible fire spread should be limited by fireproof partition walls and floors. Also combustible building components should be designed or treated to prevent fire spread by smouldering, e.g. in two layer built-up roofs the combustible layer should be covered by a non-combustible one. Partition walls, which are designed as shown in fig. 9 protect a building against fire spread from inside and from outside at the surface of the roof.
Also the design of the façade can prevent flames climbing into an upper storey.

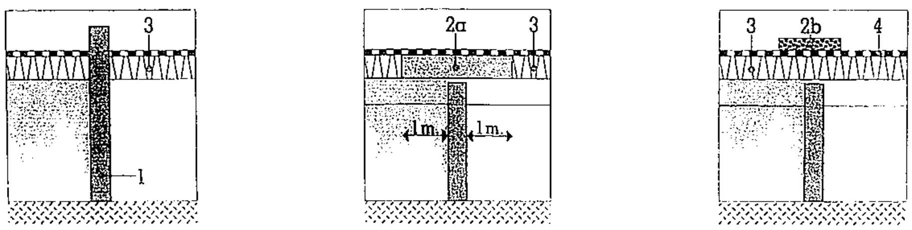


Fig.9 Prevention of fire spread. 1) partition wall - 2) non-combustible material - a. mineral wool - b. gravel 3) combustible material - 4) roofing

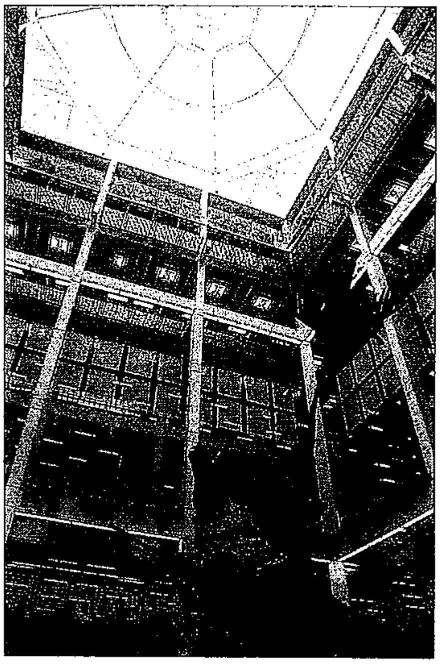
Fire resistance of the building components is usually prescribed in the building codes where it is normally expressed in units of time.
The required time for fire resistance is usually expressed in terms of multiples of 30 minutes : for example 30, 60, 90 minutes, related to ISO 834-fires. This means that a component is able to fulfil its function during the required time under a temperature exposure according to ISO-fires. Actual office buildings realized in London are excellent examples of this type of concept. Another example is an office building realized for the European Community in Luxembourg.
The time-temperature relationship in the standard fire may significantly differ from that in a real fire but modern fire design procedures allow fire resistance to be determined for natural fires as will be shown in Chapter III.
The time criterion should not be interpreted as an escape time for occupants or an intervention time for the fire brigade.
It is however often more effective to use ALTERNATIVE CONCEPTS based on the avoidance of flashover by means of non-structural active fire measures.
Fire resistance requirements may then be reduced, the extent of reduction should be determined in relation to the probability of fire occurrence and the acceptability of risk.
Active measures are based on a monitoring or an extinction concept.

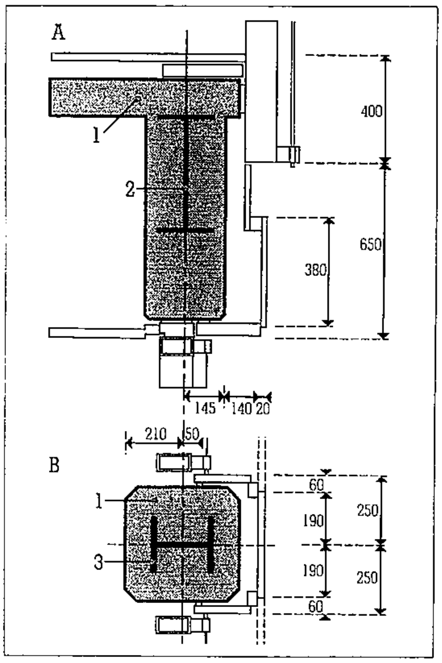
EXAMPLE

FINSBURY AVENUE, LONDON (GB)

• Steel frame designed using beam and column sections, floor slab constructed on profiled steel sheeting (composite action of the concrete with the sheeting and the frame beams).
• Office building, basement + 9 floors.
• Fire safety concept: structural
• Protection measures:
a. Passive protection. Steelwork above suspended ceiling: sprayed, vermiculite cement. Columns and beams to the atrium and columns in office areas: clad in steel sheet faced, fire resistant board.
b. Escape provisions: 4 external escape stairs including firemen's lifts.
c. Venting: the roof light span is raised to provide 2 m high vertical glazed opening side lights which give a large smoke vent area. An octagonal cupola in the centre of the roof provides additional venting.

A Section detail - B Plan detail
1 Concrete
2 Perimeter Steel Beam
3 Steel Column



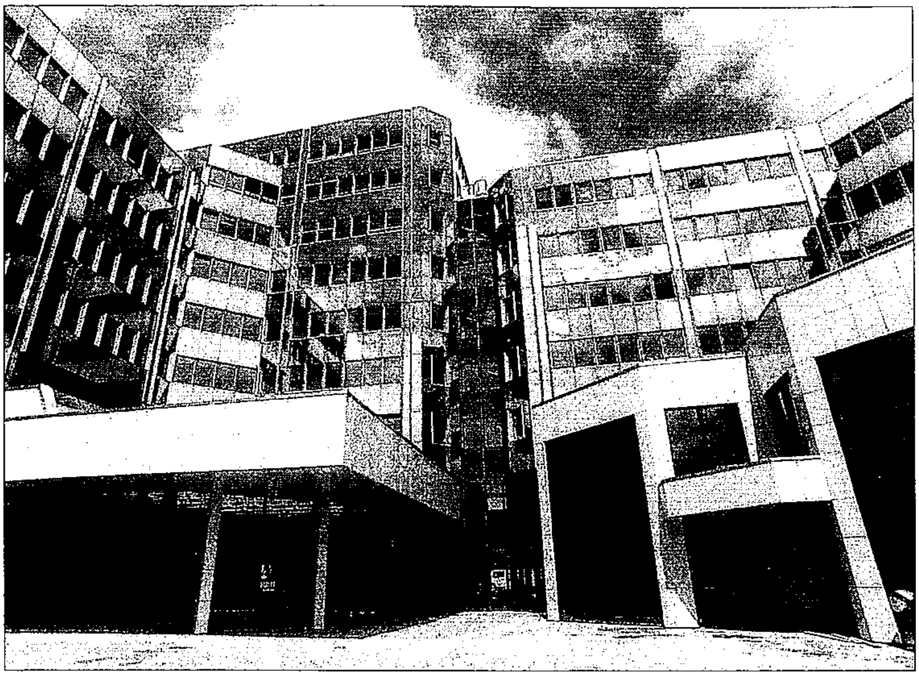


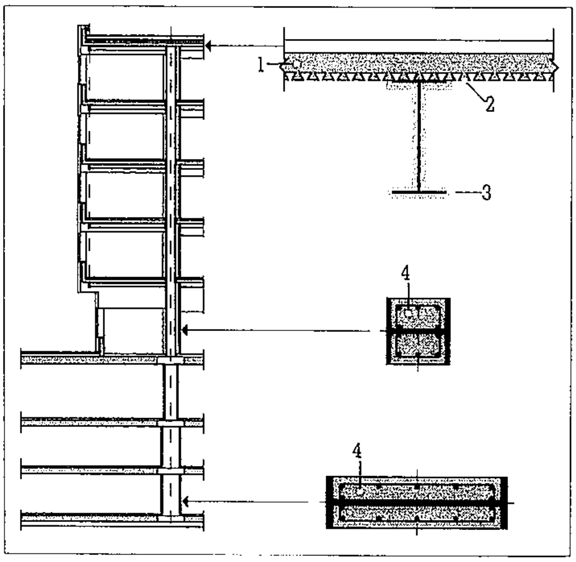
EXAMPLE

ADMINISTRATION OF THE EUROPEAN PARLIAMENT, KIRCHBERG (L)

• Structure using beams and columns of hot rolled steel sections.
Floors: reinforced concrete slab poured on profiled steel sheeting.
• Office building, 3 basement levels + 8 floors. Total volume 195.000m³

• Fire safety concept: structural
• Protection measures: F 90* passive protection: beams, sprayed system; columns, concreting the steel sections between the flanges (composite sections).





1. 12 cm concrete slab
2. Profiled steel deck
3. Sprayed fire protection
4. Filled with B 35 concrete

*F 90 = 90 minutes of fire resistance

3.2 Monitoring concept

The Monitoring concept is based on automatic detection devices and automatic alarm transmission to an adequate fire brigade (around the clock), preferably to an on-site fire brigade.

MONITORING FIRE SAFETY CONCEPT

Flashover is avoided by automatic alarms and early intervention by fire fighting services. Heat and smoke generation are limited. Compartmentation and structural fire resistance requirements may be reduced.

KEY WORD: NO FLASHOVER TROUGH EARLY DETECTION, AUTOMATIC ALARM TRANSMISSION AND EARLY ACTION OF FIRE BRIGADE

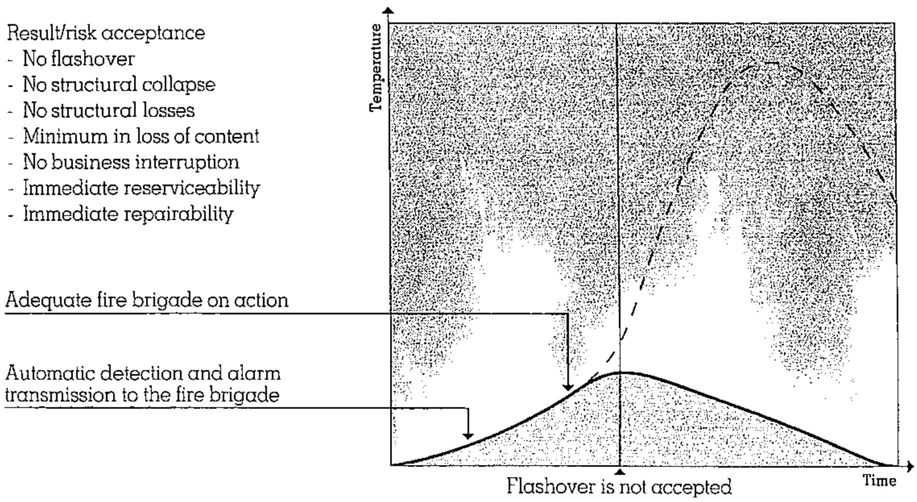


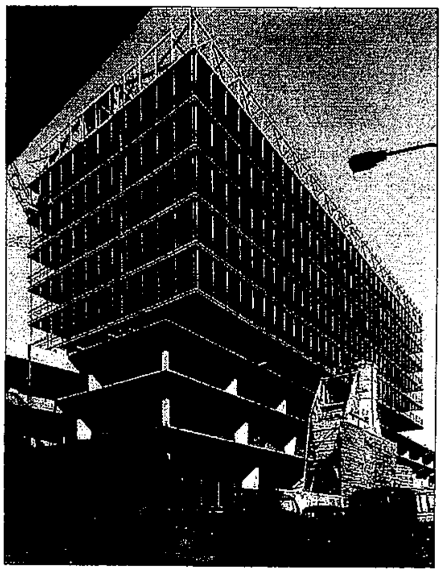
Fig. 10 Monitoring Fire Safety Concept.

A Monitoring Concept (shown in Fig.10) which involves limited or no structural fire resistance may represent the best choice when the normal (cold-design) use of a building calls for a minimum of compartmentation. It is most applicable for occupancies with reduced fire load densities, for low to medium-rise buildings in which fires may be expected to develop slowly and where an effective and quick-responding fire brigade is available.
The office building "Place Chauderon" built in Lausanne is an excellent example of a Monitoring Concept.

EXAMPLE

TWO BUILDINGS, PLACE CHAUDERON, LAUSANNE (CH)

- Bearing system: two main welded plate steel girders supported by four reinforced concrete cores and series of transverse lattice steel trusses supported by main girders.
Floor structure: hot rolled I-sections supporting profiled steel sheeting and concrete deck.
- Commercial and office buildings, 4 basement levels + 5 floors.
Ground area 1.717 m^2.
- Fire safety concept: Monitoring
- Protection measures:
a. No passive protection, bare steel structure.
b. Automatic detection with automatic transmission to the fire brigade of Lausanne located in a neighbouring building.
c. Escape provisions: 2 closed F 90 internal staircases.

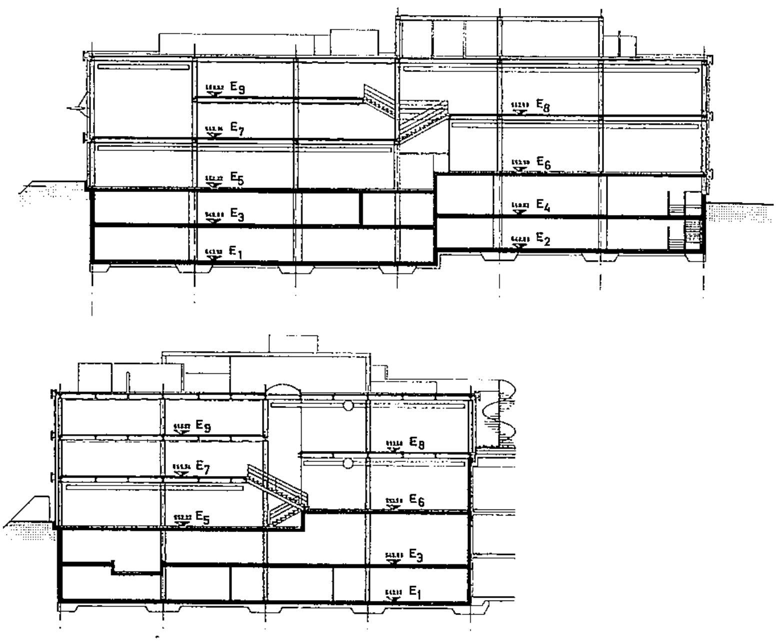


EXAMPLE

HELFER ARCHITEKTEN AG, BERN (CH)

- Structure of hot rolled steel sections, floors made of reinforced concrete slab poured on profiled steel sheeting.
- Architects' Office, 5 levels. Volume 30.000 m³. Ground area: 2.500 m².
- Fire safety concept: Monitoring.
- Protection measures:

a. No passive protection, bare steel structure.
b. Automatic detection devices with automatic alarm transmission to the professional fire brigade of the city of Bern.
c. Escape provisions: 1 staircase, 1 external escape stairway.
d. Venting: Heat and smoke vent over the staircase.



Longitudinal and cross sections.

• Fire detection

Automatic alarm systems are activated by smoke, heat or flames. They work mechanically or by electric or electronic systems. Preference is given to smoke detection, since this is -in general- by far the most effective way. When detectors begin to operate, an alarm is automatically set off. For maximum effectiveness, the alarm should be transmitted day and night to a nearby fire brigade station. Alarm systems with sound generating sirens are almost the only means against deliberate fires. Sprinklers act as extinguishing devices and as a "slow" alarm system (heat detectors).

• Fire fighting

The effectiveness of fire fighting mainly depends on the time of arrival of the fire brigade and the access to fire.

The easiest means is the use of hand fire extinguishers, if there are people who detect the fire and who are skilled enough to use an extinguisher.

Fire fighting services may be either public fire brigades or work (on-site) fire brigades. Work fire brigades have the advantage of being acquainted with the locality and having shorter distances to reach the fire, but for all fire brigades it is essential to have access routes for their vehicles. For sprinklers as well as for fire brigades a sufficient water supply is necessary, and special precautions may be necessary in winter time. In a compartment the effective radius of action for firemen is up to 20 metres.

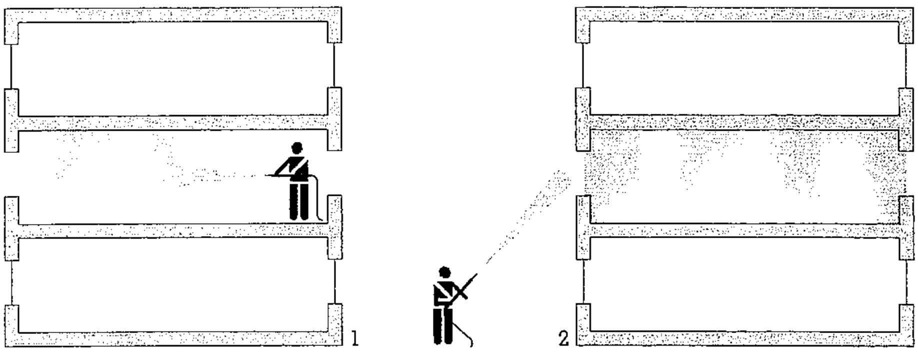


Fig. 11 Limiting for fire fighting.

If flashover conditions are reached on limited areas (say less than 200 m²), the fire brigade will be able to enter the fire compartment (1) and to extinguish the fire. For flashover conditions over areas of say more than 400 m², entering the fire compartment will be impossible and fire fighting will be limited to action from outside and to the protection of the neighbouring fire compartments (2).

Fig. 12 Limiting for fire fighting.

3.3 Extinguishing concept

The Extinguishing concept is based on automatic extinguishing devices such as sprinklers, CO_2 or Halon-Systems with automatic alarm transmission to an adequate fire brigade. It is illustrated in figure 13.

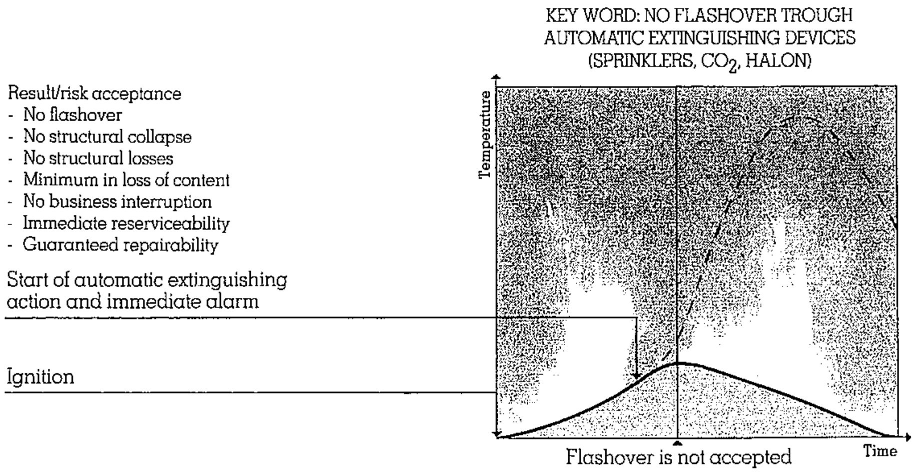


Fig. 13 Extinguishing Fire Safety Concept.

EXTINGUISHING FIRE SAFETY CONCEPT

Flashover is avoided by automatic extinguishing devices. Structural fire resistance requirements are unnecessary.

The extinguishing concept with limited or no structural fire resistance may represent the best choice when the normal (cold-design) use of a building calls for a minimum of compartmentation. It is most applicable for occupancies with medium or high fire load densities and fast developing fires.

Building owners often are afraid of the damage which these systems may cause by the water poured on the stored material or the manufacturing machines. But sprinklers open their valves only at the spot where temperature reaches a critical limit of 70° to 140°C. It has to be noted that 75% of all fires in premises with sprinklers devices are controlled by 1 to maximum 4 sprinkler heads. This represents approximately 50 m^2 watered by opened sprinkler heads. By means of an automatic alarm transmission system, they inform owner and fire brigade at once. It is important to know that automatic detection and extinguishing systems have to be maintained once or twice a year by specialists.

System	Measures and working method	Application
Sprinklers	Water, cooling	Stores, warehouses, high storage racks factories, offices and public buildings
Water deluge systems	Sprayed water, cooling	Theatres, petrochemicals
Fire extinguishing by foam	Foam of water and chemicals, cooling and stifling	Storage tanks, chemical industry, petrochemicals
CO_2-systems	Displacing CO_2 and stifling	Computer systems
Halon-systems	Halogenated hydrocarbon, prevention of chemical reactions between burning material and oxygen.	Inflammable liquids, computers.

Table 8. Fire extinguishing systems, working methods and application.

The alternative concepts of monitoring and/or extinguishing are gaining more and more acceptance in many countries. Table 9 gives a survey of how far these alternative concepts with no or reduced fire resistance requirements are internationally accepted.

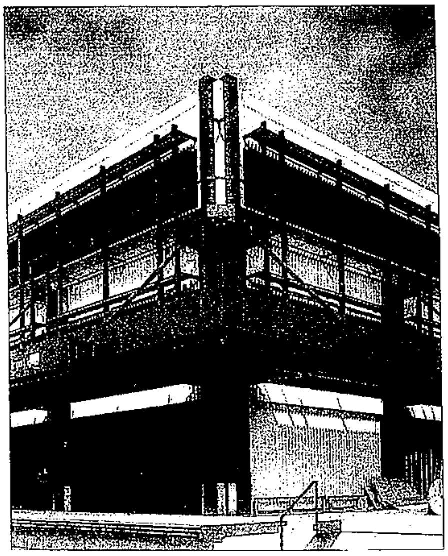
The new building for Airport Storage Facilities erected in Geneva is an excellent example of an Extinguishing Concept.

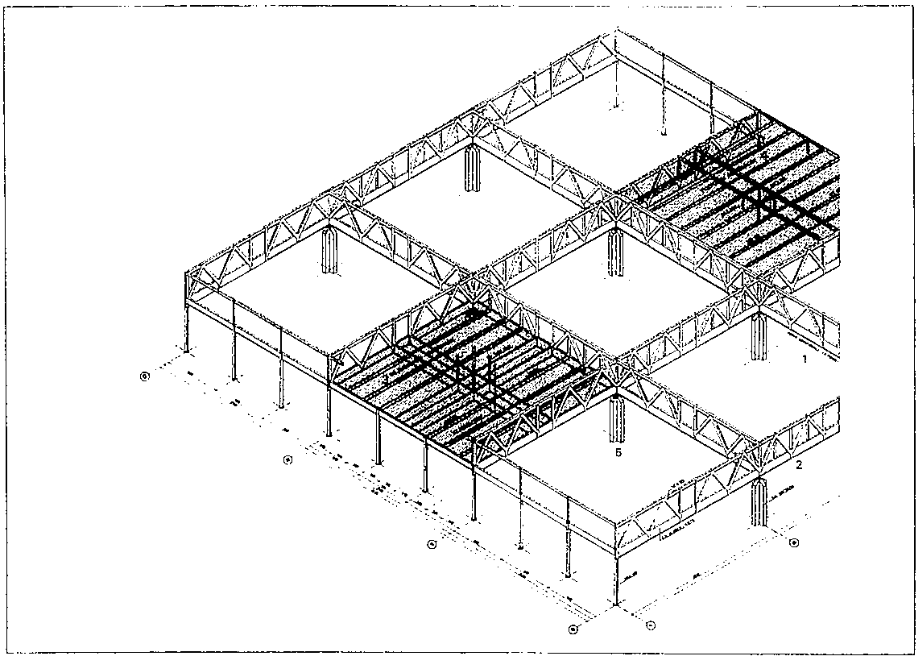
EXAMPLE

AIR FREIGHT HALL, GENEVE COINTRIN AIRPORT (CH)

- Three independent blocks. Bearing steel structure: continuous lattice main beams with three 27 m spans.
- Storage buildings. 2 basement levels + 2 floors. Volume 388.000 m^3. Ground area: 19.800 m^2.
- Fire safety concept: Extinguishing.
- Protection measures:

a. No passive protection, bare steel structure.
b. Adequate fire compartments.
c. Automatic sprinkler devices with automatic fire transmission to the professional fire brigade of Geneve City and Geneve Airport.
d. Escape provisions: numerous staircases.



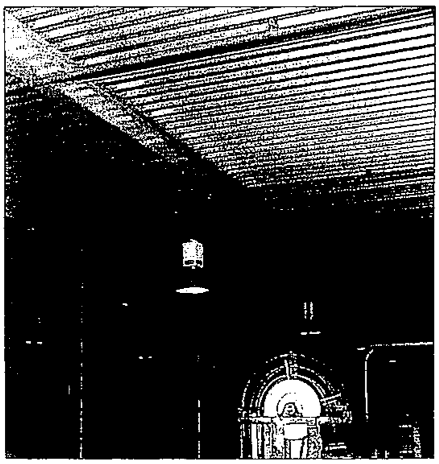


EXAMPLE

CARNAUD EUROCAN FACTORIES, MECHELEN (B)

- Three buildings with tubular welded steel structure, steel sandwich panel walls and roofs.
- Industrial buildings: fabrication of steel cans. 1 floor. Ground area: over 22.000 m^2.
- Fire safety concept: Monitoring + Extinguishing.
- Protection measures:

a. No passive protection, bare steel structure
b. Automatic sprinkler devices with automatic electric alarm transmission to work fire brigade.



Countries		Austria	Belgium	Canada	Switzerland	Czechosl.	Fed. Rep. Germany	Denmar
Acceptance of alternative concepts/active measures versus passive measures	Yes				■	■	normally limited on industrial buildings	
	Some Limitations			■			■	
	Strong Limitations	■	■				with extensions to other occupancies	■
	Not admitted							
Basic methodology or philosophy governing the acceptance of alt. concepts				Probabilistic approach model code	Fire risk evaluation method	Modified T-equivalent method	Probabilistic T-equivalent method DIN 18230	
Who decides about the practical acceptance		Provincial government	Minister of labor	Provincial government	Cantonal fire Authority	National fire code	Special Authority Bauaufsicht Fire brigade	Building Authorit Fire brigade
Alternative concepts allow for major reductions of fire resistance requirements in connection with:	Autom. sprinkler devices		■	■	■		■	■
	Autom. detection devices		■	■	■			
	Work fire brigade 24/24				■		■	
	Heat and smoke vents	○	■				■	
Alternative concepts allow for major increases in the size of fire compartment in connection with:	Autom. sprinkler devices	■		■	■	■	■	■
	Autom. detection devices	■		■	■	■		
	Work fire brigade 24/24	■			■	■	■	
	Heat and smoke vents	■	■		■	■	■	
Acceptance of the T-equivalent concept as an improved approach allowing to define correct levels of fire resistance requirements		No	No	Not yet	Yes	Yes	Yes	Yes
Acceptance of fire modeling as an improved approach allowing to define optimal fire resistance levels (for instance localized in huge fire compartments)		No	No	Not yet	Yes	Yes	Yes case by case	No

■ = accepted

○ = accepted in some cases

[■] = reduction of 30 minutes in fire resistance requirements

Fig. 9

France	Gr. Brit.	Italy	Japan	Luxemb.	Norway	Netherland	Portugal	Sweden	Finland	Un. States
										Limited
					■	■			■	■
	■	■		■			■	■		On precise occupancies
■			■							
Currently in evaluation	Statistical fire risk evaluation	In evaluation, probably T-equivalent	National project not yet finalized	In evaluation. Fire modelling			CIB W 14 structural fire safety			National method in evaluation
Building Authority Special Authority	Building Authority Fire Authority	Fire brigade	Ministry of Construction	Local fire brigade Minist. of Construction		Local fire brigade	Special Authority	Spec. Auth. Bldg. Auth. Fire brig. Code	Building inspection	
	◙	[■]			[■]	■	◙	[■]	■	◙
				◙			◙		■	
				◙	[■]					
									■	
	■	■	■		■	■	■	■	■	◙
	Doubling the size				■	◙	◙	■	■	
						◙		◙		
	◙			◙		■		■	■	◙
No	[Yes] in very special cases	Not yet. Codes partially based on fire loads	No	Not yet	Yes	No	No	Yes	[Yes] under discussion	No
Perhaps 1990	No	No	Yes	No	Yes case by case	Not yet	No	Yes case by case	Yes	No

Sweden, Switzerland, Germany and Czechoslovakia are accepting alternative concepts. CIB, ECCS and CEB are starting projects to promote these new approaches in Europe and worldwide. The methods used to quantify the fire risk and the necessary fire protection measures are given in the bibliography.[12,13,18,19,20,21].
As an example it is interesting to realize that Switzerland with its high acceptance of alternative concepts, accepting multi-storey bare steel structures combined with detection or sprinkler devices, has had an excellent safety record in its fire statistics for 20 years. Fire statistics give 6 human fatalities and 60 injured persons per million head of population and year, and 2.0 ‰ of the Gross Domestic Product for direct losses. These figures show that the most important goal is and remains the avoidance of flashover, and prove that alternative safety concepts lead to safety levels which are at least as high as traditional purely structural concepts, but at reduced cost and greater security.

Alternative concepts are gaining more and more importance leading to safety levels at least as high as traditional structural concepts, but at reduced cost and with savings on insurance premium.

4. COST-EFFECTIVENESS

The type of occupancy and the choice of the structural "cold-design" are the main variables governing the amount of fire protection measures necessary and thus the cost of the total FIRE SAFETY CONCEPT. A detailed analysis of the main sub-variables is given earlier. The cold-design concept and the Fire Safety Concept should be integrated from the beginning in order to obtain an optimum safety level with a minimum of investment. This aim can only be reached through a dialogue between the designers of a building and the fire authority at a very early stage of the planning.
An outline cost-benefit analysis indicates that the return on investment in fire precautions is variable.

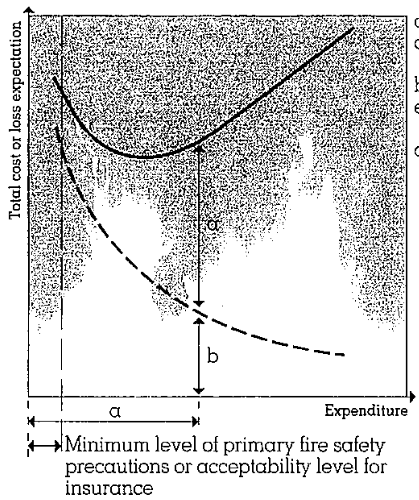


Fig. 14 Relation between expenditure on preventive measures and loss expectation (schematic).

In this diagram as the expenditure level, and therefore also the level of safety precautions, is chosen higher, the loss expectation due to fire will decrease. This relation is indicated schematically by the broken line. The loss-expenditure curve has a hyperbolic shape which means that, beyond a certain point, there is little benefit in increasing the level of protection.
From the relation between expenditure and loss expectation it is possible to deduce the relation between expenditure and overall cost due to fire (= loss expectation + expenditure). See the solid curve, the minimum of which corresponds to the optimum solution.
In this context it should be pointed out that in general the expenditure must not fall below a certain minimum, having regard to the requirements of life safety and/or the minimum level of acceptability for purposes of insurance. These aspects are also indicated in the figure.

There is a balance between expenditure for fire precaution measures and loss expectation, which corresponds to the optimum solution.

Finally, attention must be drawn to the criteria by which the behaviour of the structure under fire conditions will have to be judged. In applying measures with a view to improving the fire safety of a building it will certainly be necessary to consider what the ultimate effect of such measures will be. It is known from experience that major building fires may damage the structure to such an extent that demolition of the building becomes necessary even though it has not collapsed. The money spent on protecting it from collapse will then have to be regarded as lost. In such a case it would be better either to limit the precautions merely to a level where escape of the occupants in the event of a fire is ensured, or to choose an alternative fire safety concept.
In order to undertake a detailed COST-BENEFIT ANALYSIS a differentiated approach is necessary, in which all aspects are taken into account. A rough listing gives the following main items:

INVESTMENTS (I) Basic investment

- Building costs governed by the "cold-design" concept
- Fire protection costs governed by the "cold-design" concept and the derived fire precaution concepts
- Operational costs.

MAINTENANCE (M) repetitive costs per year

- Maintenance of the building: governed by the "cold-design" concept and the occupancy or the type of production.
- Maintenance of fire protection measures: governed by chosen type of measures including annual fees for alarm transmission in conjunction with detection and sprinkler devices.
- Maintenance of the production capacity

SAVINGS (S) repetitive savings or increases per year

- Savings or increases in production costs: governed by the cold-design and the fire safety concept
- Savings or increases in insurance premiums
  - Fire
  - Acts of God
  - Liability
  - Business interruption

These savings or increases are governed by the type of occupancy (risk), the chosen active fire precaution measures and the type of cold-design concept.
The optimum will be determined by comparing the value of the annual charges for different basic concepts.

Σ (I) x mortgage rate in percent + Σ (M) - Σ (S) = ANNUAL CHARGES

In order to proceed in a realistic way through such an optimization some fire precaution costs and premium levels must be known. However fire precaution costs differ widely from country to country and also in time.

Cost analysis

In order to visualize the main cost differences existing between the three fire safety concepts, some cost indications are given in the following table.

	Investments (I)	Maintenance (M)	Savings (S)
TRADITIONAL CONCEPT			
Structural concept			
	Traditional cladding or spraying systems cost approximately 10-30 ECU/m² floor. Through early design and proper choices it may be significantly reduced by using multifunctional systems such as specially designed fire resistant suspended ceilings. The use of composite load-bearing systems also allows significant reductions in fire resistance costs.	Almost no cost, just some repair costs for damages caused by lorries, trucks and elevators (localized mechanical damages)	SAVINGS: limited, do not have any effect on insurance premiums. INCREASES: possibly on production costs, due to partitionning as a barrier to flexibility and rationalisation of production.
ALTERNATIVE CONCEPTS			
Monitoring concept			
	Including automatic alarm transmission devices to an adequate fire brigade 7-11 ECU/m² floor for a modern building to be built 11-15 ECU/m² floor for existing old and complex buildings	Important: 2-4% of investment. These costs include yearly mandatory control costs. The annual fees for the automatic alarm connection to the fire brigade must be added.	Important savings on fire insurance premiums. 5-35% according to the type of fire brigade (municipal and/or on-site fire brigade) and the reliability of the chosen alarm transmission system
Extinguishing concept			
	Including automatic alarm transmission devices to an adequate fire brigade. 10-15 ECU/m² floor for new buildings 15-20 ECU/m² floor for existing buildings The connection to the municipal water supply network or the installation of a reservoir and sprinkler pumps includes variable costs which must be determined from case to case.	Insignificant maintenance costs. Including the twice a year mandatory control they should not exceed 0,5% of the investment costs.	Important savings on fire insurance premiums 40-80% according to the type of fire brigade (municipal and/or work fire brigade and the reliability of the chosen alarm transmission system

REMARKS

a. On-site fire brigades

They are often mandatory and may help to gain acceptance of alternative fire protection concepts. The costs of fire brigades differ so much in terms of their equipment and organisation that no proper cost figure can be given either for investment or for maintenance costs. On-site fire brigades always induce some reduction on fire insurance premiums (5 - 20%).
An on-site fire brigade is an excellent reason for choosing a Monitoring Concept.

b. Insurance premiums

The level of premium rebates is governed by :

- the type of active measure
- the reliability of this active measure
- the percentage of protected area
- the type and reliability of the fire brigade

The same level of rebates is applicable to premiums for building, content and business-interruption.
It is recommended that the final premium levels be discussed with an authorized insurance company. The european insurance market is governed by high levels of competition and it may happen that initial premiums may be "rebated" without special measures, so that additive non-structural, active measures will then not induce the total rebate.

c. Sprinkler devices

Modern risk analysis should be accepted by fire authorities and insurers leading to interesting alternative concepts in using bare steel structures or steel structures with reduced structural fire protection in conjunction with reliable non-structural, active measures. These alternative concepts allow an optimal return of investment.

1. AIMS AND BASIC PRINCIPLES

The following refers to buildings designed according to the STRUCTURAL FIRE SAFETY CONCEPT i.e. to withstand post flashover conditions.

The overall performance of a building must provide firstly means to isolate a fire within a compartment and secondly prevent local failure leading to collapse of the whole structural system. In order to meet the first objective, the structural components surrounding the fire compartment should be designed to prevent fire spread. The second objective calls for a proper arrangement of the structural system, taking into account the possibilities of load redistribution in case of local failure. It follows that in a structural fire safety design, the following two functions of the fire exposed structure are of vital interest:
- the separating function;
- the load-bearing function.

Both functions may be related to the total time of fire duration or to a limited period in order to provide sufficient time for escape and rescue operations.

For non-load-bearing building components such as partitions, the separating function will not be fulfilled if the temperature at the non-exposed side exceeds a certain critical level, or, if due to the formation of cracks and/or fissures, combustible gases may pass through compartment barriers. This gives rise to the limit states of thermal insulation and integrity respectively.

In the case of load-bearing elements with a separating function (e.g. floors), the limit state of load-bearing capacity is to be added to the limit states of thermal insulation and integrity.
The load-bearing capacity is important, not only as a necessary condition for the separating function, but also as a function on its own. This obviously holds for load-bearing elements with no separating function (e.g. columns, beams), and in particular for situations where there is a risk of progressive collapse.

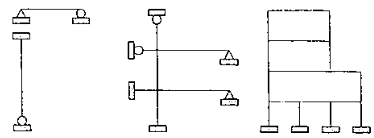
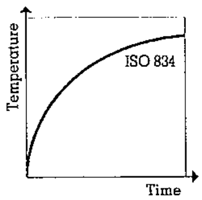
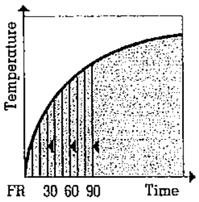
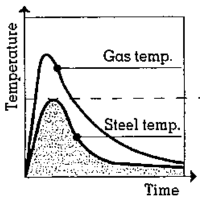
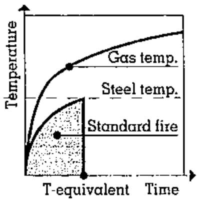
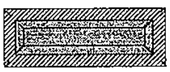
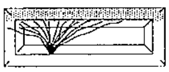
For steel elements, only the load-bearing function is relevant.

It will be clear that for structural steel elements as such, only the load-bearing function is relevant. The correct level of resistance depends very much on the situation and on the other precautions taken. For buildings in only one or two levels, for example, the load-bearing capacity during a fire is generally of limited value and often no explicit fire resistance requirements are necessary. Even for multi-storey buildings, the introduction of active fire safety precautions (monitoring or extinguishing fire safety concept) may justify a significant reduction or removal of the structural fire resistance requirements.

2. OVERVIEW ON ASSESSMENT METHODS OF STRUCTURAL FIRE RESISTANCE OF LOAD-BEARING ELEMENTS

Fire Resistance is governed by two basic models :
a. Heat model
b. Structural model
which normally have three to four levels of sophistication.
Traditional methods of assessment are based on the STANDARD FIRE CURVE as far as HEAT MODELS are concerned, but more quantitative methods are available based on natural fires.
Table 11 illustrates the three existing assessment methods [18]

Fire resistance may be determined:
- on elements, sub-frames or structures
- by test or calculation
- under standard (ISO 834) fire conditions or natural fire conditions.

			HEAT EXPOSURE MODELS	FIRE RESISTANCE REQUIREMENTS F-REQUIRED		STRUCTURAL MODELS Isolated elem.	 Sub-system	 Global struc.	VERIFICATION
									
GRADING METHODS	1	STANDARD FIRE			Function of number of storeys of possible occupation	Fire tests and calculation			F ≥ F Isolated struct. element Requir.
	2	NATURAL FIRE			Function of fire load density of possible ventilation Therm. prop.	Fire tests and calculation	Fire tests and calculation		F ≥ F Isol. str. element or sub-system Requir. Equival.
ENGINEERING METHODS	3 a	NATURAL FIRES (MODELS)	 Gastemp. f (Time)	The structure must remain stable under the action of fire. Numerous variables involved	Homogeneous temp. distribut.	Calculation	Calculation	For research only	P ≥ P Ultimate load under action of fire Applied accidental load combination
	3 b		 Gastemp. f (Time, position)		Zone field-models	Calculation	Calculation	For research only	
ASSESSMENT METHODS						No interaction between neighbouring elements is considered	A reasonable interaction between neighbouring elements is considered	All interactions of the global structural system are considered	

Notice: 3b is the only allowing to predict the growth and development and effect of local fires in huge fire compartments.

Table 11 Overview on assessment methods
F = fire resistance classes expressed in minutes

ASSESSMENT METHODS 1 and 2 are GRADING SYSTEMS
F-required and F-element are usually graded in catalogues or obtained by calculation in FIRE-RESISTANCE CLASSES starting with 15 and 30 minutes and continuing by steps of 30/60/90... minutes

ASSESSMENT METHODS 3 (a + b) are ENGINEERING METHODS
using models of real fire, the proof of the stability of the structure has to be shown.

The next paragraphs discuss each method and the improvements that a closer approach to reality will bring.

3. CURRENT FIRE RESISTANCE REQUIREMENTS. ASSESSMENT METHOD 1

If we speak of Current Fire Resistance Requirements we always mean the values fixed by NATIONAL CODES. They always use Fire Resistance classes (15/30/60/90... minutes) which represent the time an isolated element will resist the action of a STANDARD FIRE as defined by the heat exposure given by ISO-834. The level of requirements is function of the number of storeys and, depending on the country, can be function of the occupancy of the building and of the fire load.

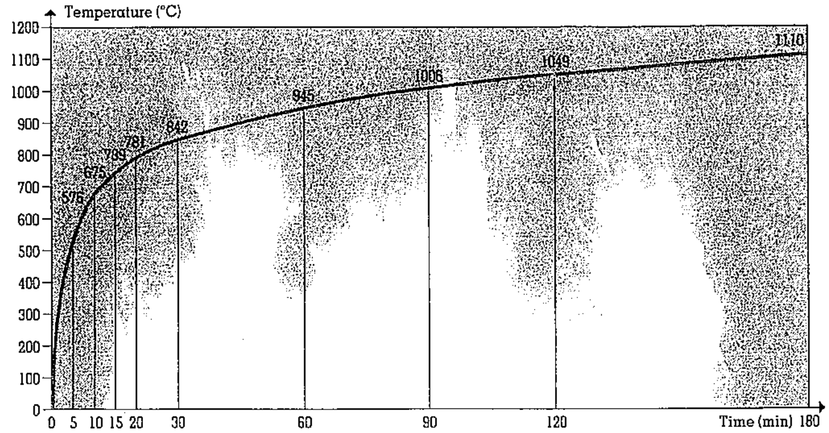


Fig.15 Standard fire curve

If we try to give an overview of European requirements as a function of the number of storeys, we find the following data

Type of building	Requirements	
one storey	NO REQUIREMENTS	possibly up to F30
2 to 3 storeys	NO OR LOW REQUIREMENTS	possibly up to F60
more than 3 storeys	MEDIUM REQUIREMENTS	F 60 to F 120
tall buildings	HIGH REQUIREMENTS	F 90 and more

Table 12. Variations in fire resistance requirements.

Numerous countries limit requirements to a maximum of 90 or 120 min.
Most national fire regulations pay insufficient attention to fire loads, to the way natural fires develop and to the effect of active non-structural measures.
However, modifications are at present accepted in numerous countries, still on the base of National Codes directly related to Standard Fire Exposure.

They are:
1. NO Fire Resistance Requirements for low-rise buildings and roof structures
2. NO Fire Resistance Requirements for all occupancies and premises with a fire load less than 15-20 kg wood equivalent per m^2 floor area or, in other units, 250-350 MJ/m^2
3. NO Fire Resistance Requirements for two and three storey buildings with fire proof staircases in sufficient number and adequate compartmentation over all storeys
4. Differentiation in Fire Resistance Requirements according to the importance of the load-bearing element considered.

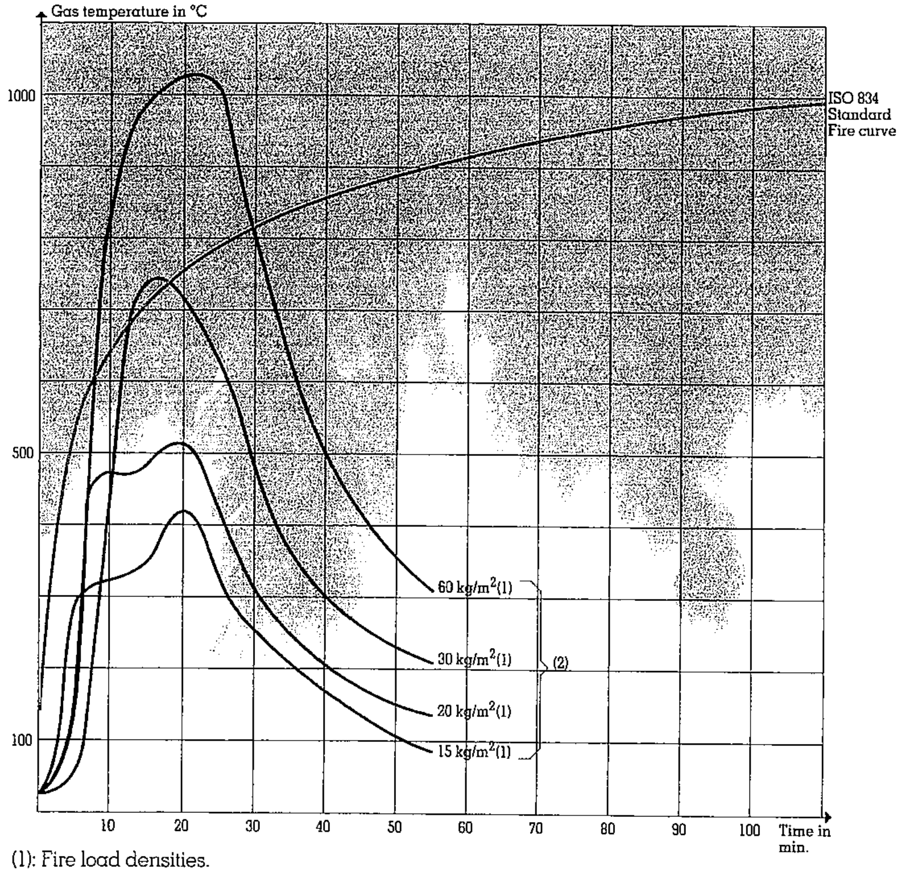
Fire resistance is not required for:
- low-rise buildings
- roof structures
- occupancies with fire load density less than 15-20 kg wood equivalent per m^2 floor area

These modifications are quite positive for steel construction and the designer should always try to use them if more sophisticated methods are not accepted. Furthermore the designer should always try to introduce calculation of the fire resistance for given elements under their PROBABLE load in case of fire (see Chapter IV).

For the quickest and most cost-effective construction the target must be the use of bare steel elements and composite systems by designing with more accurate and comprehensive knowledge of the behaviour of steel structures in fire. Examples of countries accepting all or parts of these improvements are Switzerland, United Kingdom, France and the Netherlands.

4. FIRE RESISTANCE REQUIREMENTS BASED ON T-EQUIVALENT. ASSESSMENT METHOD 2.

The comparison of the traditional standard fire curve with the natural fire curves induced the idea to combine tradition and new knowledge.
The result was the introduction of the T-equivalent concept.



(1): Fire load densities.
(2): Natural fire curves (fully developped compartment fires) for a ventilation factor =0,157m$^{1/2}$

Fig. 16 Standard Fire versus natural fires.

Note: Occupancies such as dwellings, hotels, offices are about 45 kg/m² wood equivalent

This concept of equivalent or effective fire duration provides a first but important step towards a more differentiated approach. The equivalent fire duration is a quantity which relates a non-standard or natural fire exposure to the standard fire, in a way as is shown in Fig.17 and can be calculated if the fire load density and the ventilation conditions of the fire compartment are known.
In more advanced concepts of the equivalent fire duration the effects of the thermal properties of the building components surrounding the fire compartment are accounted for.

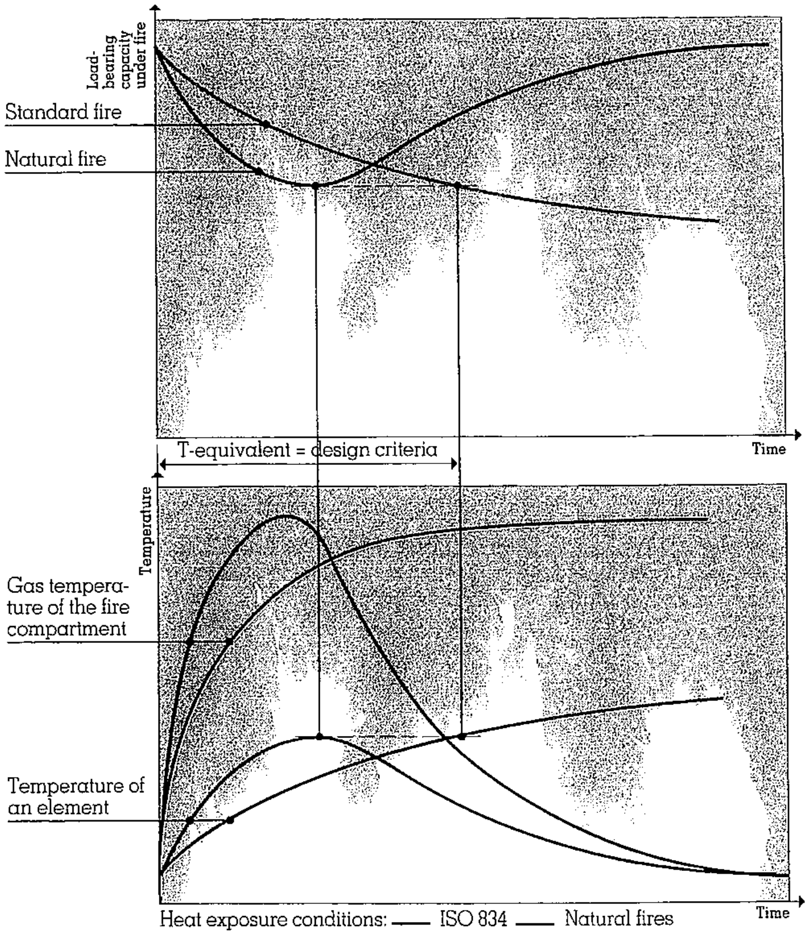


Fig. 17 T-equivalent concept.

For current occupancies and fire compartments this method gives a reasonable approach to the reality of fire. The required fire resistance is F-required = γ T-equivalent, γ being a safety factor. Normally, the safety factor is taken as being equal to 1 when the full fire load density is considered.

For most occupancies such as offices, dwellings, hospitals, homes, schools, etc these methods are aimed to ensure that elements designed for γ T-equivalent will resist the action of a natural fire without collapsing even if no fire brigade action occurs. This is the main feature of the T-equivalent concept.
An important advantage of this concept is that the tremendous amount of knowledge and data given by past fire testing can be used to verify the results of any calculation. Many countries have already officially adopted this T-equivalent Method in a more or less sophisticated way.

In Switzerland and the Netherlands for example the fire resistance requirements have been simplified as follows:
Fire duration in minutes = fire load density in kg/m^2 wood equivalent.
This is normally given in steps of 30 minutes. For fire loads more than 15 and less than 30 kg/m^2 wood equivalent the requirement therefore will be 30 minutes. In addition for normal risks most countries limit requirements to a maximum of 60 or 90 minutes, knowing the quick response and quality of action of their fire brigades. However for other reasons, for example special safety risks or socio-economic considerations, more stringent requirements may be asked for.

Many codes allow the fire resistance requirements to be reduced when active non-structural fire precautions are installed.

Most national codes emphasise element tests under standard fire conditions and fire resistance requirements for the same building may vary from one country to another.
In some countries more realistic assessment methods can be adopted.

The T-equivalent Method has been introduced internationally by the CIB W14 Workshop on Structural Fire Safety [13] and detailed in its "DESIGN GUIDE". [18]. Active measures are taken into consideration.

National code requirements and T-equivalent requirements are both related to standard fire exposure. As for improved national codes, differentiated requirements could be introduced to reflect the importance and function of different structural components and natural fires.

5. ENGINEERING DESIGN METHODS BASED ON NATURAL FIRES. ASSESSMENT METHOD 3

5.1. Introduction

These methods will only be introduced as the most sophisticated method of defining the correct level of structural fire resistance.
Modern computer-assisted calculation methods are available which allow any Heat Exposure Model to be introduced.

Two types of models are currently used:
- the compartment fire model with a uniform temperature distribution in the fire compartment after the occurrence of flashover.
- models with non-uniform temperature distribution in the fire compartment (Zone and Field Models)

All these engineering methods combine a Heat Model with a Structural Model and allow structural stability to be evaluated under the action of a real fire for the loads present at the time of the fire.
It is emphasized that with slight modifications Assessment Method 3 can also be used for buildings where only a limited time period, sufficient only to provide time for a safe escape and rescue, is required.

Interest in these engineering fire design methods will certainly be strengthened by the new generation of EUROCODES which will incorporate an "ULTIMATE LOAD DESIGN" of structures and a "PROBABILITY BASED LOAD CODE" with fire as an accidental case.

5.2. Compartment Fires. Assessment Method 3a

This method applies for fire compartments of a size usually found in hotels, offices, schools, dwellings, etc. with an equal distribution of the fire load. The assumption of a uniform distribution of temperature in the fire compartment is then correct.

This method introduces the following main variables:
- the amount of equally distributed combustible materials in the fire compartment = mean fire load density (fixed and mobile)
- the combustion rate of variable combustible materials
- the geometry of the fire compartment
- the ventilation of the fire compartment
- the thermal response of walls and floors enclosing the fire compartment.

Some variables may be approximated or even ignored. Two variables will always have a strong influence
- the fire load density
- the ventilation of the fire compartment

The influence of fire load density and ventilation on compartment gas temperature is illustrated in figures 18 and 19.

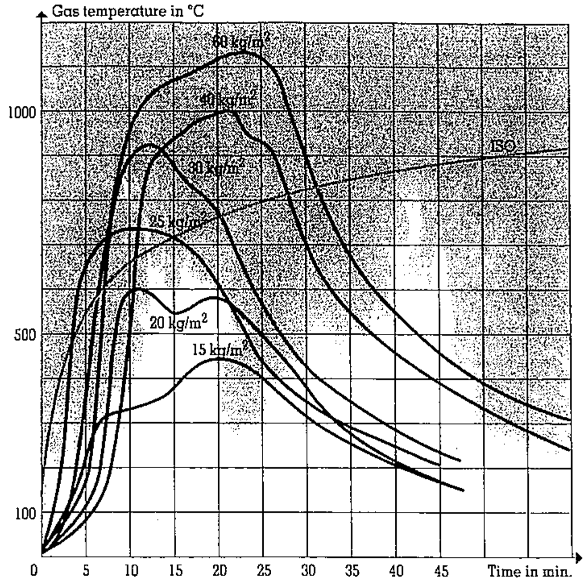


Fig. 18 Evolution of the gas temperature for different fire load densities - ventilation factor $f_v = 0{,}091\ m^{1/2}$

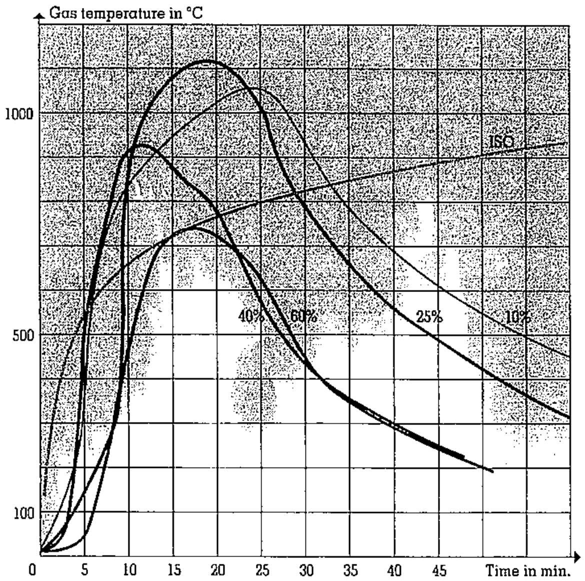


Fig. 19 Evolution of the gas temperature in function of the ventilation (ratios of areas of openings to total area of frontal façade expressed in percentage) - fire load $q = 30\ kg/m^2$ of wood of surface area

The diagrams correspond to a simplified compartment fire theory as a basic heat exposure model for engineering fire design. Current compartment fire theories neglect the pre flashover period, the structural response being mainly governed by post flashover temperature evolution.

5.3. Fire modelling. Assessment Method 3b

These methods seek to evaluate the evolution of fire as a non-uniform problem where for a given compartment and a known localized fire load temperature will be governed by

- the location of a local fire
- the growth of such a local fire
- the size, geometry, ventilation and thermal inertia of the fire compartment.

Therefore the temperature evolution will be function of

- time and
- location of a given structural element in this compartment

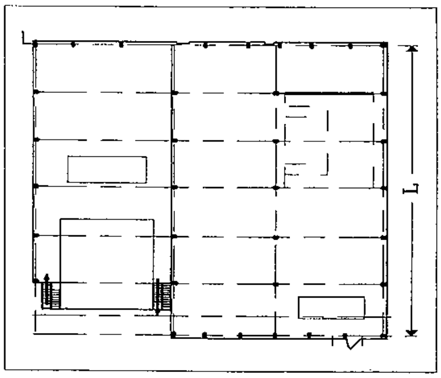
These methods must be calibrated. International tests have been carried out either in large fabrication halls (ex. p. 39) or in test facilities with large compartments

(Finland/Espoo) which allowed the temperature evolution of natural fires to be measured at different points.
These methods are useful for all cases of localized fires in large compartments or large spaces. This new approach is essential because steel is often used for buildings with large compartments and because it is the only way to assess rationally the effect of local fires. It may allow stability in fire of bare steel structures to be proven.
As an example it is interesting to notice that a simplified method developed in Switzerland proved that for a multi-storey car park built above the railway station of Winterthur a bare steel structure calculated with a resistance of 15 minutes under standard fire conditions, would not collapse under anticipated real fire conditions.
Car parks, railway stations, exhibition halls, industrial production plants, huge atria etc. with localized fire load area are excellent examples for the appropriate use of such modern methods.
Far more sophisticated fire models (zone and field models) are internationally under development. Their application will depend on the ability of the model builders to simplify the input data, to develop simple programs and to prove the reliability of their modelling of fire.

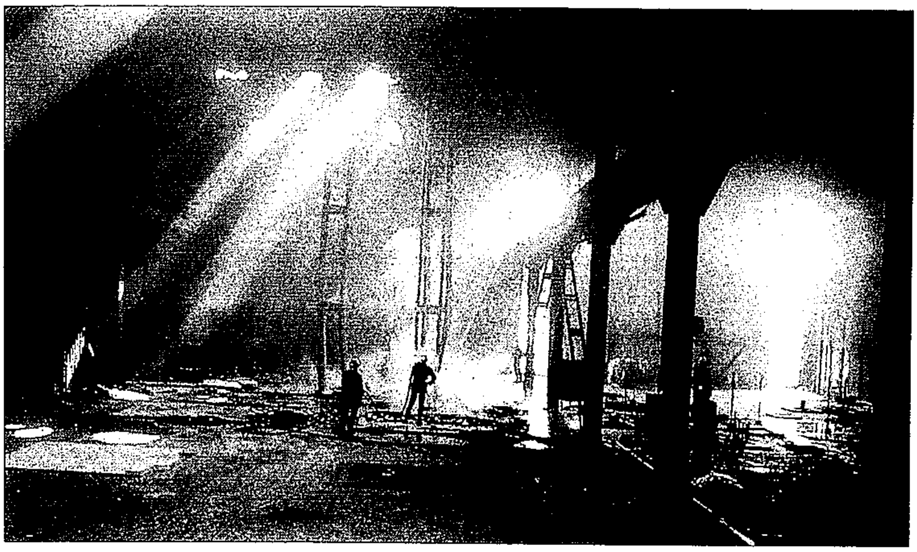
EXAMPLE

PARC DE LA VILLETTE, PARIS (F)

Large compartment of 10.000 m^3 building intended to demolition. Unprotected bearing steel structure. Tests carried out in 1983 by the Centre Technique et Industriel de la Construction Métallique in co-operation with the Office Technique pour l'Utilisation de l'Acier, have confirmed the results of former research work and investigations: natural fires do not follow the same law as standard fires.
Although the raised temperatures in fire compartment have reached 1100°C, the most heated bearing elements of the structure have never exceeded 350°C.
It must be emphasized that natural fire does not systematically lead to collapse of a structure, especially when the fire load is too low to imperil the unprotected bearing steel elements.



L. = 39 m divided into 6 spans of 6.50 m, height 10 m.

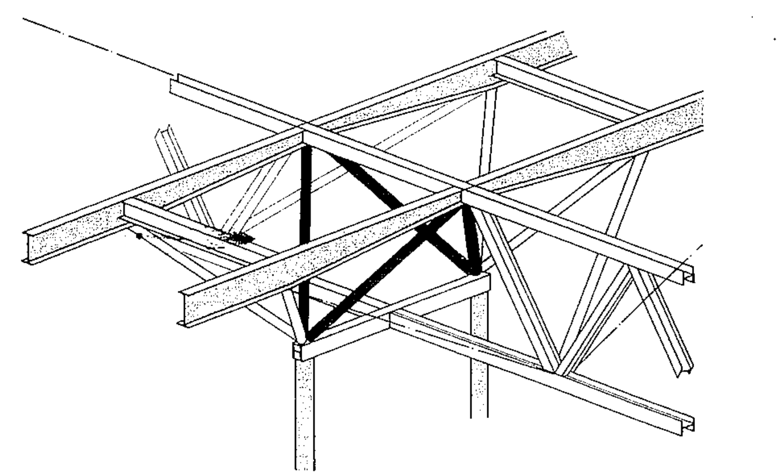


EXAMPLE

RAILWAY STATION + CAR-PARK, WINTERTHUR (CH)

- Lower part of the steel structure: continuous lattice main beams parallel to the platforms and secundary beams perpendicular to main beams and circular hollow section columns. Upper part three spans rigid frames.
- Ground floor + 2 park decks. Ground area: 10.300 m².
- Fire safety concept: Structural.
- Protection measures:

a. No passive protection, bare steel structure.
b. Large compartments: fire modelling proves that the structure resists to all possible fire scenarios.
c. Escape provisions: numerous safety stairways.



Bearing structure at double-column

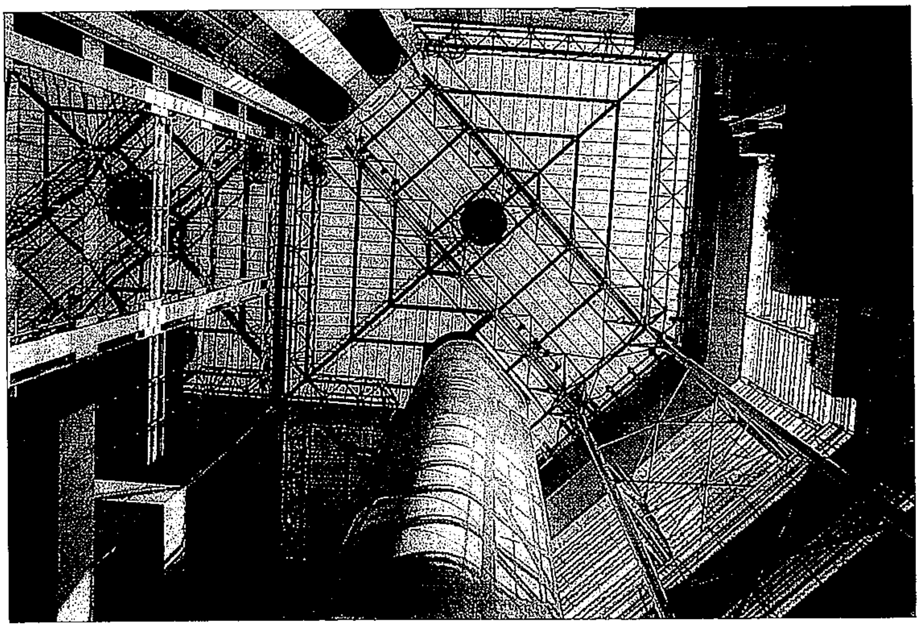
EXAMPLE

LLOYDS CHAMBERS, LONDON (GB)

- Steel structure with composite profiled steel sheeting and in situ poured concrete floors. The atrium is the dominant architectural feature. Aesthetic requirements were for exposed tubular steel frame supporting glas wall and roof.
- Office building, basement + 10 levels. Ground area: 3.652 m^2.
- Fire safety concept: Structural + Extinguishing.

- Protection measures:

General structure:
a. Passive protection by insulation F 120. A number of methods of fireproofing were adopted: concrete, lath and plaster, various sprayed media and dry boarding.
b. Sprinkler devices throughout.
Atrium:
No passive protection, bare steel structure, large compartment.



6. SOME THOUGHTS ON FIRE RESISTANCE REQUIREMENTS CONSIDERING THE EFFECT OF ACTIVE FIRE PROTECTION.

It has to be noted that the fire modelling assessment method is an appropriate way to prove the effectiveness of ALTERNATIVE FIRE SAFETY CONCEPTS. In fact the dependency of structural fire requirements on potential structural hazards is uncritically accepted whilst the dependency on non-structural measures (governing the frequency of severe fires) is often not generally acknowledged as a design parameter. Fire modelling will ultimately allow the influence of extinguishing actions (automatic devices such as sprinklers and fire brigade actions) to be quantified and incorporated into the assessment.

An increasing number of countries like Sweden, Switzerland, and Germany allow reduced or no fire resistance requirements when the probability of avoiding flashover or of localising a fire in a small area is high enough. Some other countries are moving to this direction. These alternative concepts will normally be limited to occupancies which will not undergo significant change of use and to buildings with a limited number of storeys. The major argument brought forth against these alternative concepts refers to the reliability of the active measures in the sense that, if they fail to suppress an initial fire, then a reduced fire resistance of the structure could exhibit a considerable hazard. We should however consider the risk of failure case by case.

In some countries, when active measures are employed, fire resistance requirements are reduced or zero rated.

The first argument in favour of active systems is that they are all submitted to a periodic mandatory control.
The second argument is that the probability of failure of well designed and controlled active measures is about 1 to 3% whereas the probability of severe fires in buildings without active measures is about 10 - 20%.
Thirdly the incidence of life loss in buildings without active measures far exceeds the loss in buildings where active systems are installed.

This approach can only be successful when treated as PROBABILISTIC CONCEPTS to Fire Engineering. The CIB Design Guide for Structural Fire Stability [18] gives an excellent overview.

7. FLOW CHART AS A HELP FOR DESIGNERS TO DEFINE CORRECT FIRE RESISTANCE LEVELS.

Define the main data of a project, optimize the "cold-design".

DOES THE NATIONAL CODE CALL FOR FIRE RESISTANCE ?

IT DOES NOT	IT DOES	
▼	▼	▼
Use bare steel freely	and no active fire precaution measures are possible	and active fire precaution measures are possible
▼	▼	▼
	Introduce the T-equivalent philosophy.	Introduce alternative risk assessment methods. Prove the probability of success of active measures. Prove that the escape of all persons involved and the safe access through fireproof staircases for fire brigade is guaranteed.
▼	▼	
	Introduce calculation methods on localized fire in large fire compartments when you have these particular conditions.	
▼	▼	▼
		Introduce calculation methods on local fires in large fire compartments with the influence of active measures.
▼	▼	▼
TARGET	TARGET	
▼	▼	▼
Design of bare steel structure with a reasonable behaviour of the whole building under the action of fire.	Determination of a correct level of fire resistance ▼ Optimization of the steel structure following the survey given in Chapter IV.	

Table 13.

CHAPTER IV
HOW CAN STEEL WITHSTAND FIRE RESISTANCE REQUIREMENTS ?

1. INTRODUCTION

The present chapter will show that steel structures are always able to withstand defined fire resistance levels, and defines ways to choose the best method to ensure this structural fire stability. Although attention is focused on the ISO-fires, the same procedure can be used for natural fires.
Structural performance in fire can be based either on fire tests or on calculation. A short overview of both methods is given. First it is necessary to define the factors which influence the fire resistance of structural steelwork.

Steel structures are able to face correctly any fire resistance level.

2. BEHAVIOUR OF STEEL ELEMENTS IN FIRE

The mechanical properties of all common building materials decrease with elevation of temperature. Although steel is an uncombustible material without any release of smoke or toxic gases, it is also a good heat conductor and thin sections follow very closely the elevation of temperature in the fire compartment.
Beyond approximately 250° the mechanical strength of both steel and concrete falls rapidly and when the temperature reaches values above 450°, may lead to collapse. The collapse temperature may be known as CRITICAL TEMPERATURE and varies due to differences in cold-design criteria and methods of cold-design (allowable stress philosophy or ultimate load philosophy). For simply supported beams and one storey columns the collapse temperature is clearly given for a fixed load level derived from cold-design rules. The level of this COLLAPSE TEMPERATURE is approximately 500°C for a load level of 60% of the cold ultimate load. This is true for any steel quality and type of structure as long as a uniform temperature distribution is maintained.

Fire resistance can be derived by test or by calculation.

3. FACTORS GOVERNING THE FIRE RESISTANCE TIME OF STEEL STRUCTURES

Two main groups of factors influence the fire resistance time of a steel structure: one group influences the critical temperature, the other one the steel heating rate. To satisfy fire resistance requirements, the temperature developed in a steel member at the required time must be less than its collapse temperature. This is shown in fig. 20.

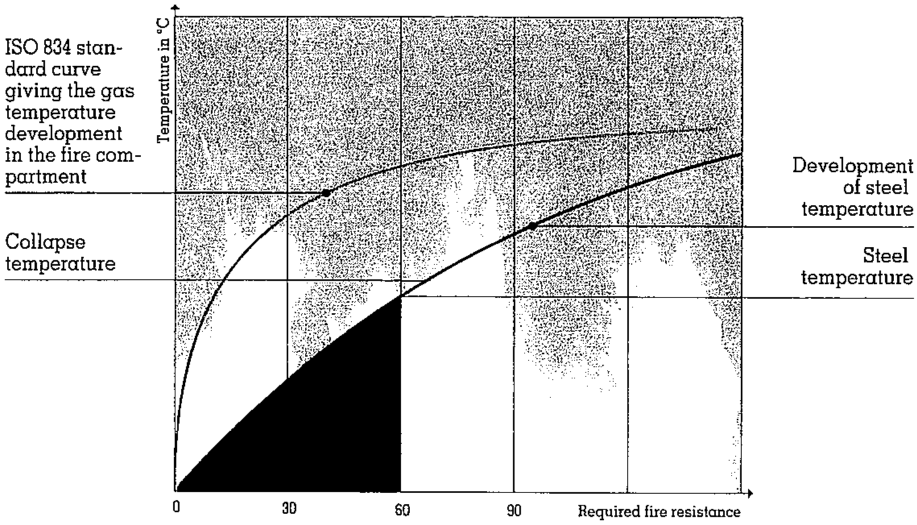


Fig. 20. Relationship between the temperature developed in steel member and collapse temperature.

3.1. Factors influencing the collapse temperature

The collapse temperature depends upon
- the load level
- the cold-design theory
- the temperature distribution
- the section dimensions

It should be noted that if the fire is restricted to a part of the structure or element, the other part which is cold may contribute to improved performance.

The collapse temperature of a steel member varies according to:
- the load it carries
- its dimensions
- the temperature distribution through the cross section.

3.2. Factors influencing the heating rate in the steel.

FOR BARE STEEL SECTIONS the heating rate is governed by the massivity of the chosen steel member. It is clear that the more massive the section, the more energy is needed to heat it.
In order to take account of this effect reference is made to so called section factor P/A m^{-1} in which P(m) is the perimeter of the member directly exposed to the fire and A(m^2) is the cross sectional area of the same member. The higher the ratio P/A, the faster is the rate of temperature rise.
It follows therefore that the rate of temperature rise in a small thick section will be slow whilst in a large thin section it will be more rapid.
In calculating the section factor (P/A) values, the full cross sectional area (A) is used as the whole of the steel section will be receiving heat.
Perimeter (P) however is the exposed perimeter.
In the case where a beam supports a concrete floor for example, the perimeter is reduced by the width of the top flange which is protected by the floor itself.

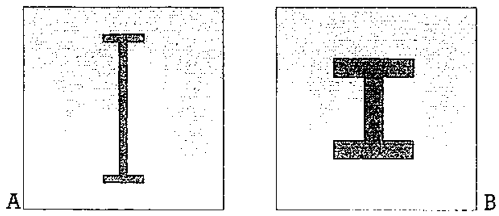


Fig. 21 P/A concept: A = high P/A; B = low P/A

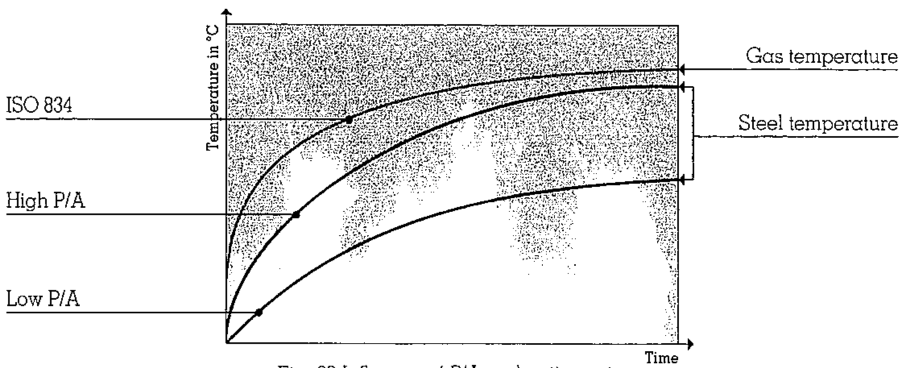


Fig. 22 Influence of P/A on heating rate.

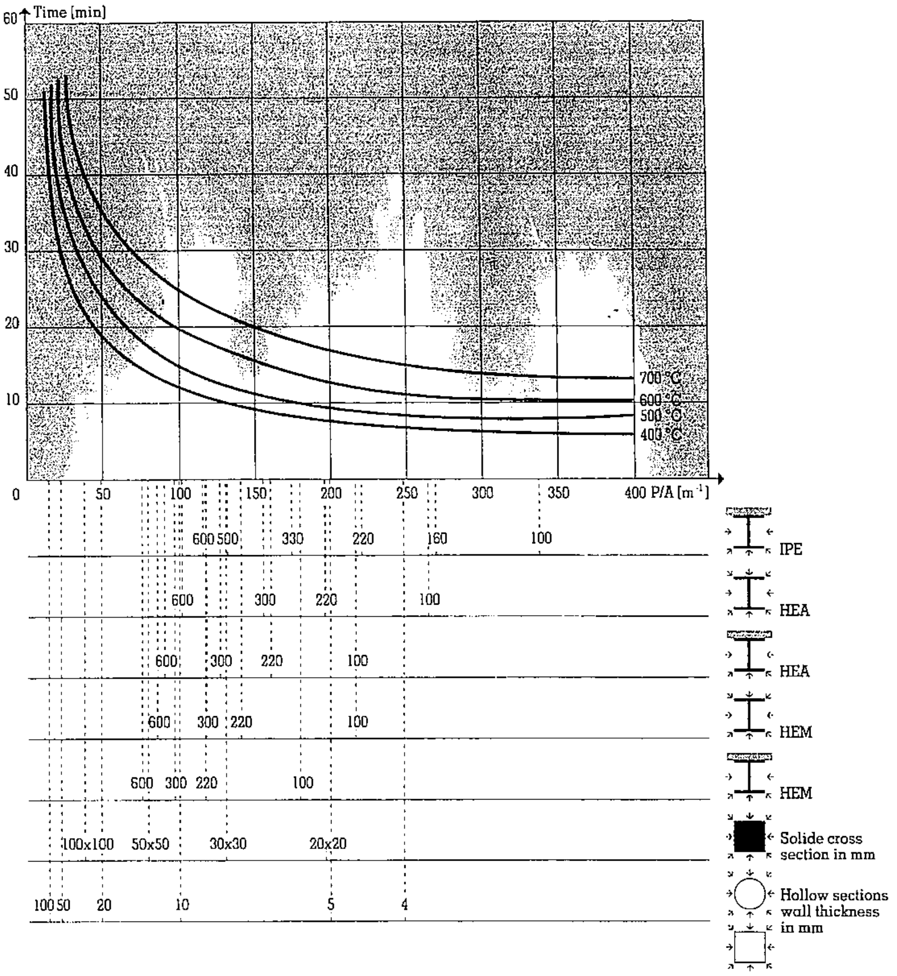


Fig. 23 Time taken for unprotected members to reach a defined temperature when exposed to standard fire, as a function of their section factor.
Some typical sections are presented in line with their section factor P/A. [22]

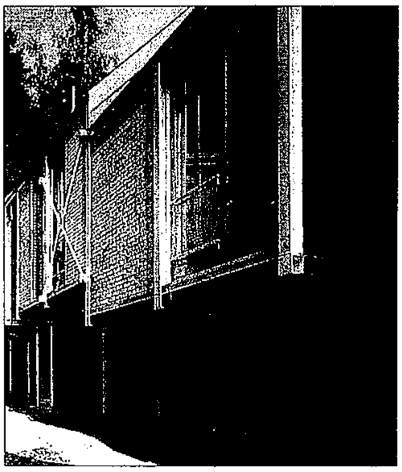
EXAMPLE

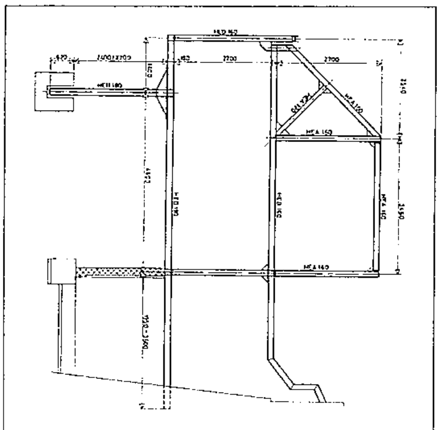
SINGLE FAMILY HOUSING, ZURICH (CH)

- Frames of hot rolled steel sections.
- Six houses. Ground floor + 1 or 2 floors.
- Fire safety concept: Structural
- Protection measures:

a. No passive protection, F 30 by overdimensioning (massivity) of the steel elements.

b. Escape provisions: 1 open staircase + external escape way.





View of bearing steel structure

This figure clearly shows the effect of the section factor on the development of the steel temperature and furthermore the influence of the choice of profile on the section factor and through this on the temperature evolution.
Data are typical but can vary from furnace to furnace.

FOR INSULATED STEEL SECTIONS the development of the steel temperature is, apart from the section factor, also dependent on the coefficient of heat conduction (λ) and the thickness (d) of any applied insulation material (fig.25).

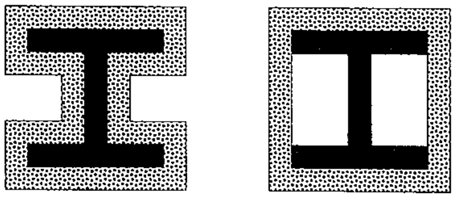


Fig. 24 Section factor for insulated steel sections

(1) Contour encasement or spraying: $P/A = \frac{\text{perimeter of steel section}}{\text{steel cross section}}$

(2) Hollow encasement: $P/A = \frac{\text{interior perimeter of encasement}}{\text{steel cross section}}$

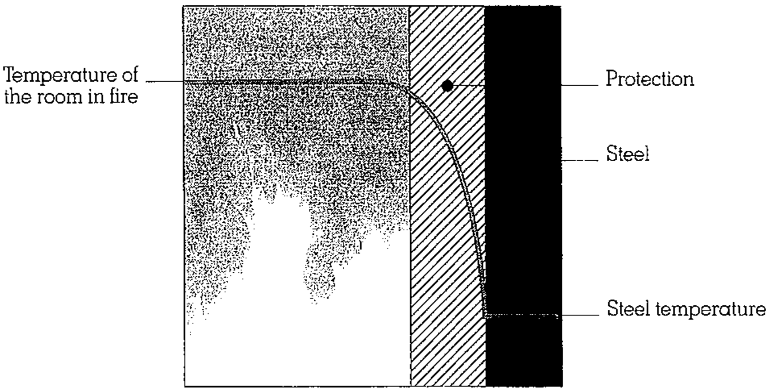


Fig.25 Temperature distribution in insulation materials and steel.

A small value for λ in combination with a high value for d will -for a given fire exposure and section factor- result in a relatively slow temperature development in the steel section. The insulation characteristics may be represented by the quantity d/λ. The values of λ to be used in a fire engineering design are different from those normally given in references on heat transfer for room temperature conditions. Special procedures have been developed to determine the insulation characteristics under fire conditions. However, if no detailed information is available and if only an approximate answer is required, the analysis may be based on average values of λ, assumed to be valid for the whole temperature range during a fire. It may be shown that under such circumstances the time to attain a certain steel temperature is governed by the factor $\frac{d \cdot A}{\lambda \cdot P}$

The fire resistance for a given load level varies according to:

- the section dimensions (P/A)
- the thickness of insulation (if any) and its thermal conductivity.

For standard fire conditions and practical levels of the critical steel temperature, i.e. 400, 500 and 600°C, the relationship between this factor and the time to attain the critical temperature is shown in Fig.26. This time is the fire resistance time.

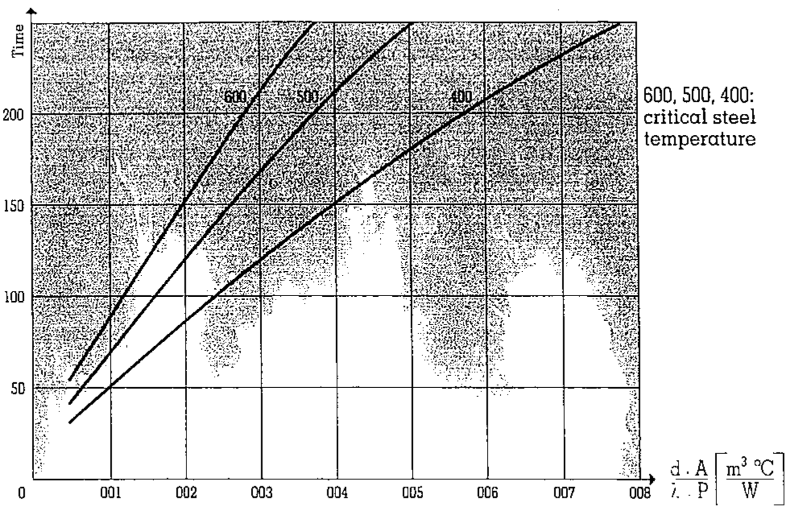


Fig. 26 Calculated fire resistance times for members with insulation (Source: Design Manual ECCS, Brochure n°35) [22].

For COMPOSITE STEEL-CONCRETE STRUCTURES several design choices will influence the temperature development of steel. Firstly the position and mass of concrete, secondly the possibility of redistribution of internal stresses to protected cold parts of the section.

For HOLLOW STRUCTURES FILLED WITH WATER the steel temperature will be limited between 100-200°C as long as the water can effectively remove heat from the steel. The main problem is one of satisfactory design of the water supply and circulation.

For EXTERNAL STRUCTURAL ELEMENTS, the effect of fire may be less severe, and hence it is not realistic to consider standard fire conditions.

4. SURVEY OF THE MEANS OF ACHIEVING STRUCTURAL FIRE RESISTANCE OF STEEL STRUCTURES

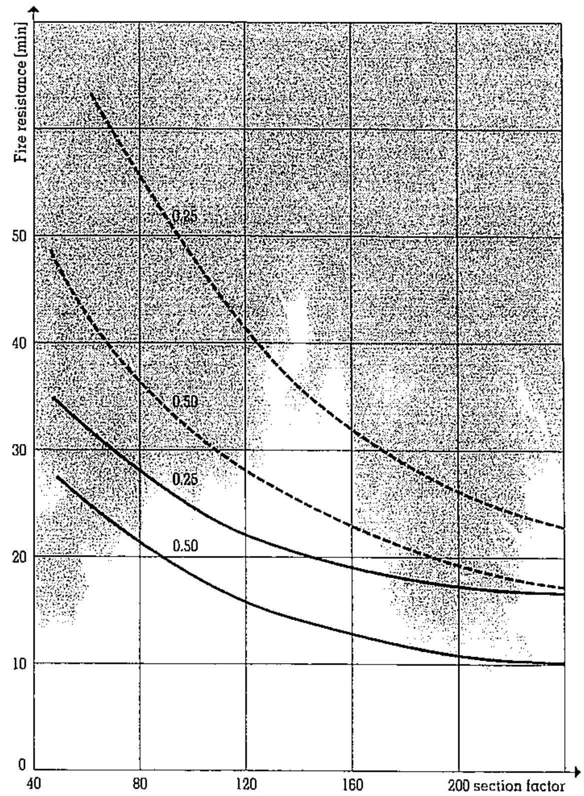
4.1. Bare steel structures

Bare steel structures may meet fire resistance times of 30 or 60 minutes if one or more of the following conditions are met:

- low load level;
- low value of the section factor;
- high degree of static redundancy.

In Fig. 27 the fire resistance of bare steel beams is given as a function of the section factor, for different values of the ratio between the actual load and the collapse load under room temperature conditions.
The solid curves are calculated on basis of the European Recommendations for the Fire Safety of Steel Structures, issued by ECCS Technical Committee 3 and hold for continuous beams [23].

The rules given in the European Recommendations are on the conservative side if compared with the results of a comprehensive series of fire tests recently carried out in the UK on simply supported bare steel beams [24] which are presented in Fig. 27 as the dashed curves. Reasons for the discrepancy include non-uniform temperature distribution over the height of the steel section in the case of bare steel beams and different furnace characteristics. In the European Recommendations the effect of these are only approximately taken into account.



——— European recommendations

- - - - - - Recent UK-test

Load ratio $= \frac{P_{actual}}{P_{ult.20°C}}$

Fig.27 Fire resistance of bare steel beams as a function of the section factor and for different load levels.

4.2. Insulated steel structures

When structural steel members are required to have a certain fire resistance and bare steel is not able to meet it, they can be protected by applying an insulating material which slows down the heating of the members (Fig. 25)

The temperature, reached at certain time, of an insulated steel element exposed to fire depends on the following factors:

- the ambient temperature development,
- the section factor,
- the nature and thickness of insulating material and the method of applying it.

The nature and properties of insulating materials are defined in several publications. Tables and monograms of their thickness for imposed fire resistance are also published.

There are different systems of protection by insulation in particular sprays, boards, intumescent coatings, encased members.

- SPRAYED SYSTEM (FIG.28).

This system, which may be called also "wet", consists of projecting a material in the wet state, usually in several layers (according to the thickness required) on the members to be protected. The insulating material can be vermiculite particles, mineral or slag fibers etc., added with a binder.

ACCORDING TO THE COMPOSITION AND THE THICKNESS OF THE LAYER, ANY DESIRED RESISTANCE LEVEL CAN BE OBTAINED. SOME PRODUCTS ALSO ENSURE CORROSION PROTECTION.

This system of protection is generally applied to hidden elements. But it may be also possible with the aid of the color effects to integrate these elements to the architectural aspect of the structure.

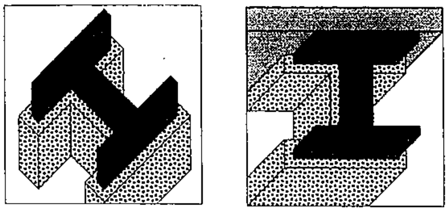


Fig.28. Sprayed system. (1) Column (2) Beam

• BOARDED ENCASEMENTS. (FIG.29).
The most used materials for boards are: plaster, vermiculite, mineral fibers.

DEPENDING ON THE THICKNESS AND THE COMPOSITION OF THE BOARD, ANY DESIRED LEVEL OF FIRE RESISTANCE CAN BE ACHIEVED.

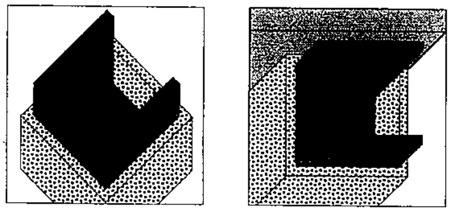


Fig.29 Boarded encasements. (1) Column (2) Beam

The boards may be fixed either directly to the steel surface (following the profile) or in the form of box encasements.
These last are particularly used when the members to be protected have complicated external surfaces e.g. profiles with stiffeners. They may be fixed to the surfaces of the profiles by mechanical methods (screw, straps and/or galvanized angles) or by heat resistant adhesive bonding (which eliminate any possibility of thermal bridges). In both cases a careful examination of joints is necessary in order to avoid local heating of inadequately covered parts.

• INTUMESCENT COATINGS (FIG.30).
Intumescent materials, mastics and paints foam and swell under the influence of heat to form an insulating protective layer of char. These products can be applied by brush, spray or trowel.
They are usually applied in situations where the shape of the steel structure remains visible.

THE INTUMESCENT COATING AT PRESENT CAN PROVIDE FROM 30 TO 60 MINUTES FIRE RESISTANCE IN ACCORDANCE TO STANDARD TEMPERATURE-TIME CURVE ISO834.
Research for a superior fire resistance is in progress.

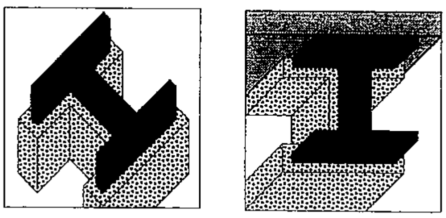


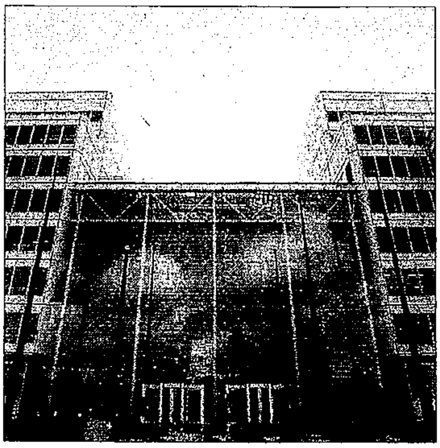
Fig.30 Intumescent coatings. (1) Column (2) Beam

EXAMPLE

COTTONS, LONDON BRIDGE CITY, LONDON (GB)

- Steel structure of hot rolled steel sections. Floor with profiled steel sheeting and semi light-weight concrete.
- Office building, basement + 9 floors. Ground area: approx. 8.000 m².
- Fire safety concept: Structural.
- Protection measures:

a. Passive protection, F 120 Cementitious spray applied directly to unpainted beams, "Clip-on" pre-finished dry casing on columns.
b. No passive protection, F 60 for bare soffit of the composite steel deck.

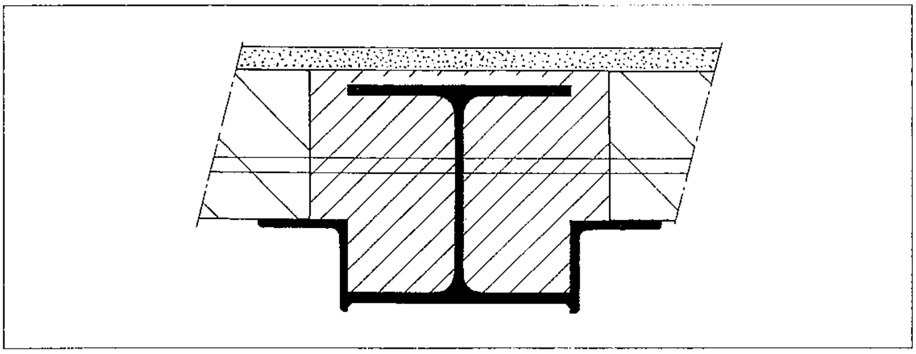


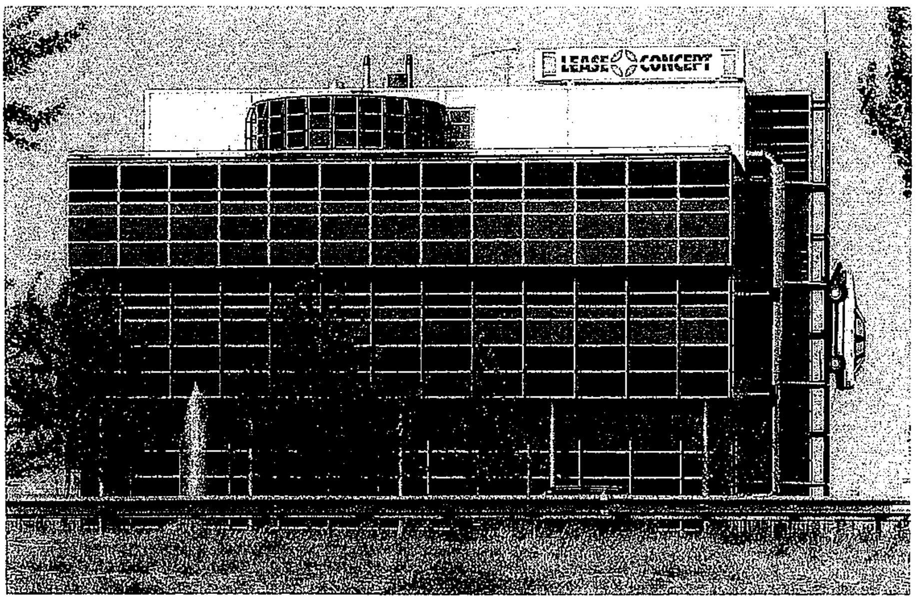
EXAMPLE

MEES LEASE BUILDING, AMSTERDAM (NL)

- Steel structure of tubular concrete filled sections and hot rolled sections. Floor with precast concrete slabs.
- Office building, ground floor + 4 floors. Ground area: approximately 1820 m².
- Fire safety concept: Structural.
- Protection measures:

Passive protection: concrete filled tubular sections and in concrete slabs embedded hot rolled beams. (HEA 300): F 60





4.3. Composite steel-concrete structures

• CONCRETE ENCASED STEEL COLUMNS (FIG.31).
When steel members are embedded in concrete it has usually been assumed that concrete provides thermal insulation only.
Developments in the design of composite steel-concrete elements permit the load-bearing contribution of the concrete to be taken into account.
The cross section of this type of column is composed of a steel profile placed at the centre of an appropriate reinforced concrete block.

THE FIRE RESISTANCE DEPENDS ON THE CROSS SECTION OF THE ENCASED PROFILE AND THE EXTERNAL DIMENSIONS OF THE CONCRETE BLOCK:
IT IS NORMALLY 90 MINUTES OR MORE.

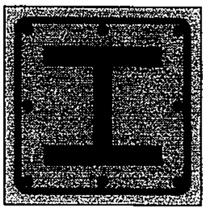


Fig.31 Cross section of a column with encased H-steel profile reinforced with longitudinal steel bars.

• CONCRETE FILLED HOLLOW STEEL COLUMNS (FIG.32).
Generally the cross section of this type of column is either rectangular or circular.
The inside concrete may be reinforced or not.

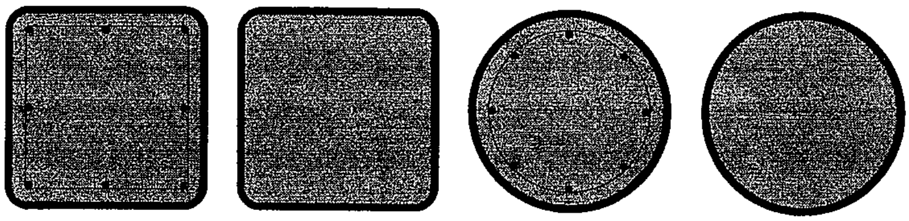


Fig.32 Concrete filled hollow steel sections.

During the fire, the mechanical properties of the steel element decrease and the concrete core, still retained by the steel envelope, gradually takes over the load-bearing function.

IN CASE OF NON REINFORCED CONCRETE, THE FIRE RESISTANCE IS AT LEAST 30 MINUTES; IF THE CONCRETE IS REINFORCED THE FIRE RESISTANCE CAN REACH 120 MINUTES.

• STEEL CORE COLUMNS (FIG.33)
The column cross section consists of a steel core encased in concrete with outer circular or rectangular steel envelope.

THE FIRE RESISTANCE OF THIS TYPE OF COLUMN VARIES FROM 60 MINUTES TO ANY HIGHER VALUE ACCORDING TO THE THICKNESS OF THE CONCRETE LAYER.

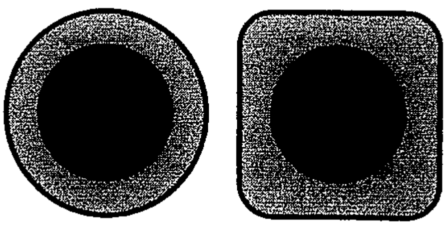
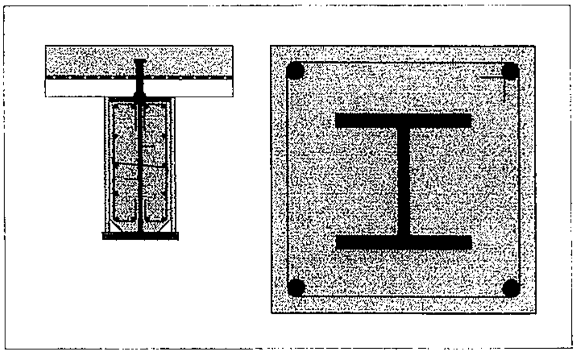


Fig.33 Circular and square steel core columns.

EXAMPLE

RESEARCH AND DESIGN CENTRE FOR BMW, MUNICH (D)

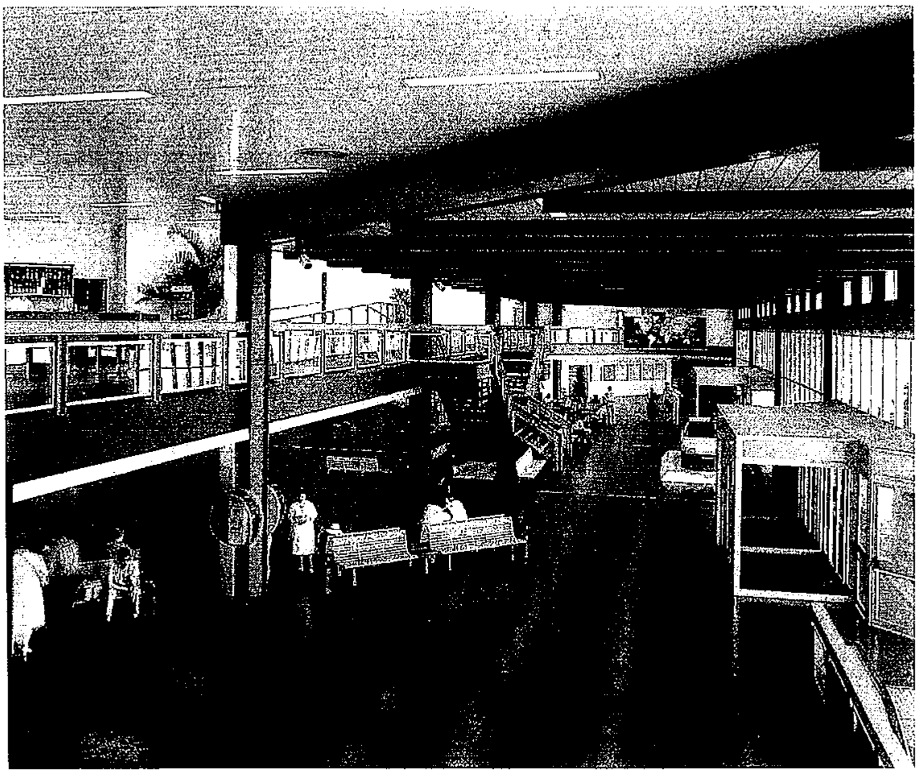
- Steel frame using composite steel-concrete prefabricated elements with floor slab on profiled steel sheeting.
- Basement + 4 floors. Volume: 225.000 m^3. Ground area: 7.200 m^2.
- Fire safety concept: Structural.
- Protection measures: passive protection, F 90 composite structure: girders with steel sections concreted and reinforced between the flanges, columns with concrete encased steel sections.



EXAMPLE

C. COLOMBO AIRPORT BUILDING, GENOA (I)

- Steel structure with pinned connections and reinforced concrete bracing towers; beams and columns of hot rolled and welded steel plate sections.
- Main building of the airport, with 5 loading bridges; basement + 3 floors. Ground area: 6000 m^2.
- Fire safety concept: Structural.
- Protection measures: passive protection: intumescent coatings: 1000 μm thickness, in services building: F 120 750 μm thickness, in air terminal: F60.



• COLUMNS AND GIRDERS WITH THE STEEL PROFILES CONCRETED AND REINFORCED BETWEEN THE FLANGES.(FIG.34).
The concrete between the flanges is used as an insulating and load-bearing material. The vertical (columns) or horizontal (girders) reinforcing bars substitute, during the fire, for the heated flanges of steel profile.

SUCH COMPOSITE SECTIONS MAY REACH ANY DESIRED FIRE RESISTANCE LEVEL.

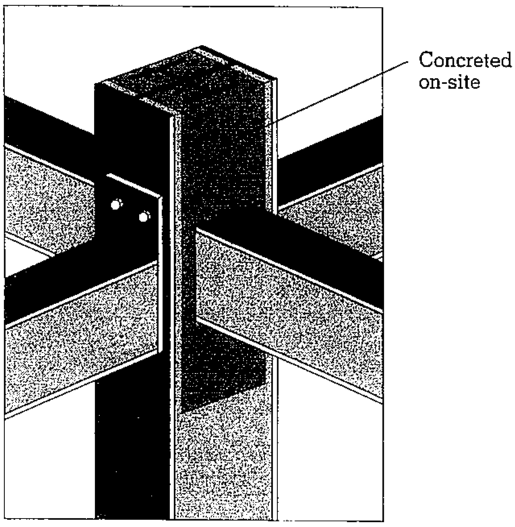


Fig. 34 Configuration of connection of steel girders and column concreted between the flanges.

Significant levels of fire resistance can be achieved in structural members without insulation when they are combined with other materials e.g. composite members, partially embedded members, water and concrete filled hollow members.

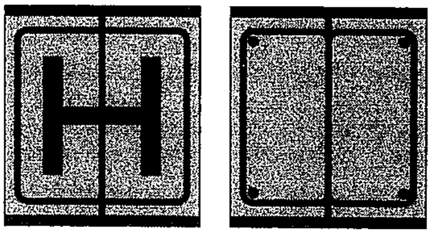


Fig. 35 Cross section of Fig.34

• PARTIALLY EXPOSED MEMBERS (FIG.36)
Members partially exposed because they are embedded in walls, floors or other elements of the structure, achieve a significant fire resistance by redistribution of stress from hot regions to cooler areas of the section. Research and analysis are in progress to quantify this effect.

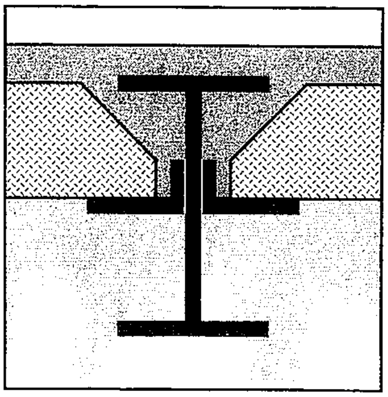


Fig.36 Beam embedded in concrete floor slab.

4.4. Waterfilled hollow sections (Fig.37)

Fire resistance of structures may be attained by waterfilling of hollow section columns and also of other bearing members.

IN THIS SYSTEM STEEL MEMBERS DO NOT NEED EXTERNAL PROTECTION SO THAT THEY MAY REMAIN VISIBLE.

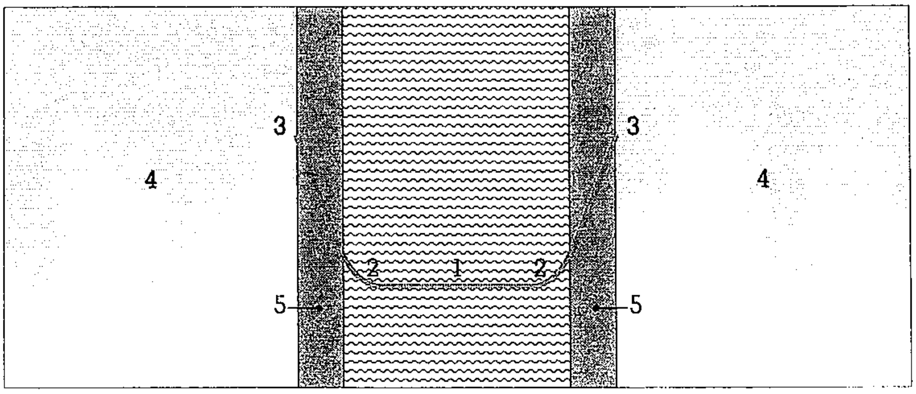


Fig.37 An example of distribution of temperatures in waterfilled column [25]

1. Water temperature 170C° - 2. Steel temperature at interior face 190°C. - 3. Steel temperature at exposed face 225°C - 4. Fire area 1090°C - 5. Column wall thickness 25,4 mm

The functioning principle is simple: when the waterfilled columns are exposed to the fire, warm water rises and is replaced by cold water from below (principle of thermosiphon) which cools the heated parts of the column.
Tests and calculations have proved that with an adequate functioning of the system the temperature of the column walls remains low. (Usually under 250°C).
The water evaporation is compensated by supply of fresh water from a header tank.

4.5. External columns (Figs. 38 and 39)

The position of the steel structure in relation to the fire influences its fire resistance. Columns positioned outside a building will remain cooler during the fire than those positioned inside the same building.

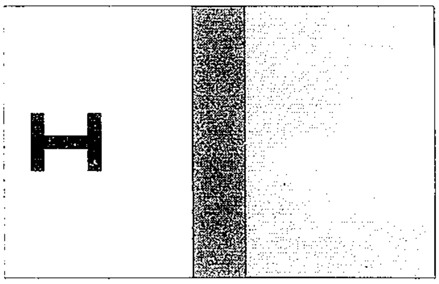


Fig.38 External column-wall

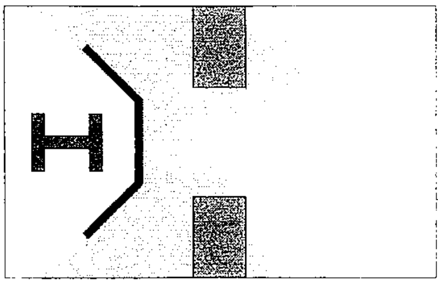


Fig.39 External column with shield

The use of external bare steel columns requires a fire resistant façade and a sufficient distance from the building and any opening. When the column is positioned directly in front of an opening, a shield may be necessary.

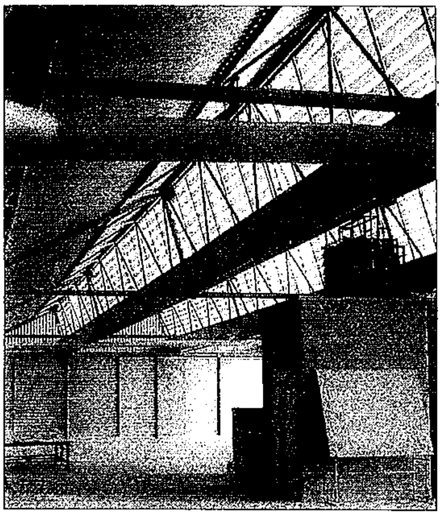
Further information may be obtained from published documents.

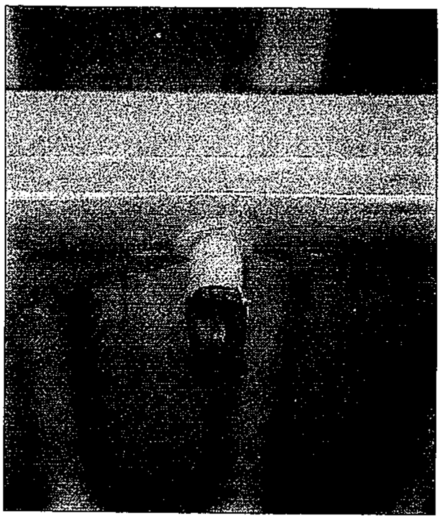
EXAMPLE

CATALA PAPER-MILL, RUISBROEK (B)

• Roof structure with circular hollow steel sections (CHS).
• Paper-mill, 3 floors. Ground area: 10.000 m².

• Fire safety concept: Structural + Extinguishing.
• Protection measures: Bare structure, CHS are permanently waterfilled and used to supply incorporated sprinklers.

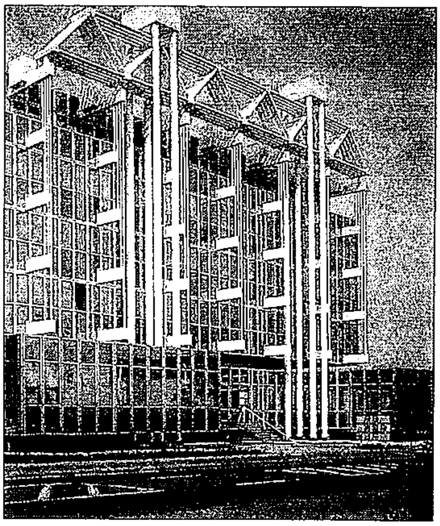


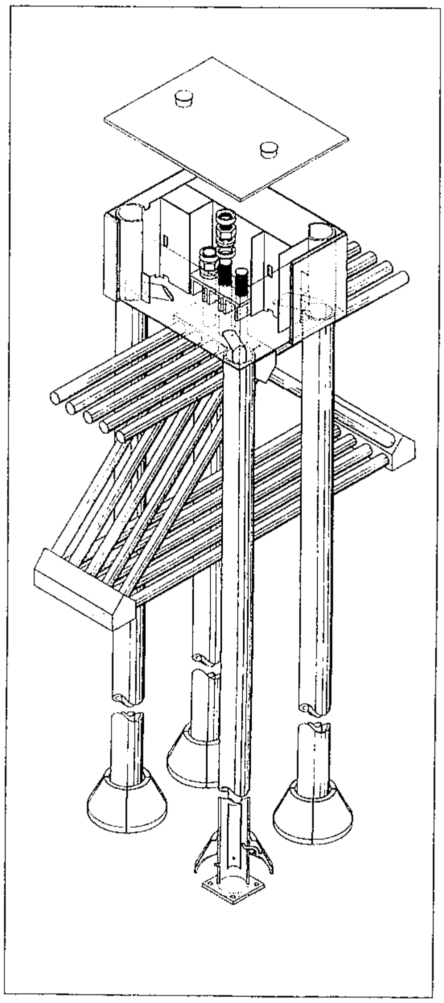


EXAMPLE

NORCONHAUS, HANNOVER (D)

• Composite steel decking floors, suspended by external hangers of circular hollow sections and two giant tubular lattice girders. The girders are supported by four external columns of circular hollow sections.
The water tanks are part of the architectural concept.
• Office building, 5 floors, Ground area: 1.200 m².
• Fire safety concept: Structural.
• Protection measures: F 90.
Lattice girders by insulation, hangers and columns by waterfilling.





4.6. Protection by screens

This kind of protection consists either of suspended ceilings or of partition wall panels (Figs.40 and 41) and offers the advantage of cost reduction by combining the function of fire protection with other functions such as partition, thermal and sound insulation and aesthetics. When necessary the screens must be able to ensure the integrity and insulation so that the fire cannot spread into the void. Special attention should be paid to the method of assembly and in particular to the joints and connections.

ANY DESIRED RESISTANCE LEVEL CAN BE OBTAINED.

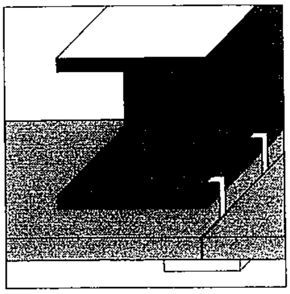


Fig. 40 Suspended ceiling

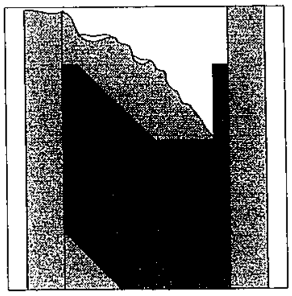


Fig.41 Partition wall panels

4.7. Composite floors with concrete slabs and profiled steel sheets

Although the above discussion is related only to load-bearing steel members with regard to fire, it should be noticed that nowadays composite floor slabs and profiled steel sheets are very frequently used in buildings. These floors exhibit a significant fire resistance, even if no additional fire safety precautions are taken. Calculations based on large experiments have proven that the fire resistance time of this type of floor will be in excess of 30 minutes without any insulation. For higher fire resistance times up to 2 hrs, additional reinforcement of the concrete may be necessary.

Metal deck floors have significant fire resistance without insulation.

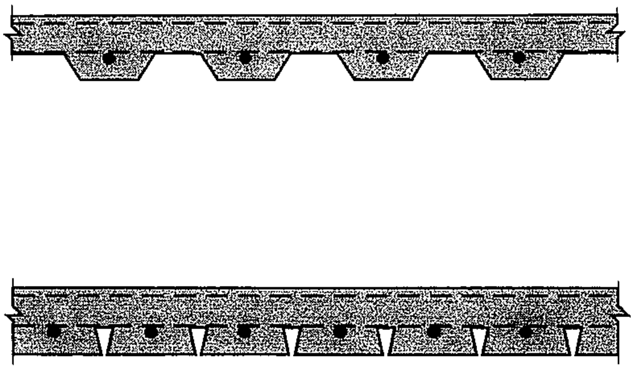


Fig.42 Typical cross sections of composite steel-concrete floors.

5. CALCULATION METHODS FOR STRUCTURAL FIRE RESISTANCE

5.1. Simple methods

During the last decades, important progress has been achieved in the development of simple calculating methods allowing the fire resistance time to be determined by analytical methods.

This allows the following factors to be taken into account

- material strength
- load level in case of fire
- thermal characteristics of protection materials
- real end conditions of the built-in steel element

Normally, the calculation procedure is based on a uniform temperature distribution. See

- European Recommendations for the fire safety of steel structures - Level I Calculation of the Fire Resistance of Load-Bearing Elements and Structural Assemblies exposed to the standard fire. ECCS, brochure n° 30 [23].
- Design Manual on the European Recommendations for the fire safety of steel structures. ECCS, brochure n°35 [22].

Tests have shown that members subject to non-uniform temperature distribution attain significantly higher level of fire resistance than uniformly heated ones.
In due course analytical models and design guidance will be generated to allow these effects to be incorporated into fire resistant designs.
The above Design Manual shows in a very clear manner that it is possible to transform the effect of real fires (natural fires or compartment fires) to standard fire requirements through the time-equivalent philosophy, the required fire resistance time being a function of

- the fire load density
- the geometry of the fire compartment
- the ventilation of the fire compartment
- the thermal characteristics of the fire compartment.

The ECCS Technical Committee 3 -Fire Safety of Steel Structures - has issued other important publications:

- Calculation of the Fire Resistance of Composite Concrete Slabs with Profiled Steel Sheets Exposed to Standard Fire (1984), brochure n° 32 [26].
- Calculation of the Fire Resistance of Centrically Loaded Composite Columns exposed to the Standard Fire (1988) (brochure n° 55) [27].

5.2. More advanced methods

The analysis of the fire resistance of a structure is made complex by the number of variables involved.
Recent developments in the computer technology allow a reliable computer aided design of fire resistant structures.
The aim of these new methods is to assess directly the real behaviour of fires (Natural Fires) and structures. They use sophisticated computerized thermal and mechanical analysis.
Programmes can be established for any type of structure.
The input of natural fires additionally could be governed by FIRE MODELLING.
The advantages of the numerical methods are that they permit the designer to take into account the various heat transfer problems, the changes in material properties, the dynamic character of the fire environment and the reaction of the structure to the thermal loadings and variations in loadings.

EXAMPLES:

- FIRES-T: a finite element programme for transient thermal analysis (two-dimensional). Options for different materials, fire types and fire boundary conditions. (Source: CIT, Berkeley). Micro-computer application.
Wuppertal University, Institute for Structural Engineering and Fire Safety Engineering, Germany.

- TASEF/2 Temperature Analysis of Structures Exposed to Fire: a three dimensional finite element heat transfer programme, available at the Swedish National Testing Institute, Boras, Sweden.

- TEMPCALC: a two dimensional finite element heat transfer programme, developed by the Institute of FIre Safety Design, Lund, Sweden.

- FIRES-T3 FIre REsponse of Structure-Thermal-3 Dimensional Version [28,29]: a three dimensional finite element heat transfer programme developed at the University of California, Berkeley, USA.

• CEFICOSS Computer Engineering of the Fire resistance for Composite and Steel Structures) [30]:
gives the evolution of thermal fields and stress fields inside the cross section of bearing elements and simulates the progression of the deformations for all types of structures.
Considers geometric and physical non linear effects. Has no limitations regarding material, cross-section and fire-types.
Allows the prediction of the real physical failure (buckling, plastic zone and/or mechanism) for whole structural systems. Gives the effect of a local fire on overall structural behaviour.
Developed under the leadership of ARBED Departement Recherches, Luxemburg, together with the Department of Structural Engineering of the University of Liège, Belgium.

• COMSYS-T: Ultimate load-bearing capacity of structural elements in fire case; Single beam elements (beams with or without slab connection), columns, complete frames); Geometrically and physically non linear; Plastic hinges and plastic zones; No limitations for materials, cross section design and fire type; Calculation up to complete system failure.
Wuppertal University, Institute for Structural Engineering and Fire Safety Engineering, Germany.

• STABA-F: a computer programme for the determination of load-bearing and deformation behaviour of uni-axial structural elements (beams, columns) under fire action. The influence of mechanical (non linear moment/curvature relationships) and geometrical (2nd order theory) non linear interaction between load and deformation is taken into account. The programme includes temperature dependent stress-strain relationships for concrete, structural steel, reinforcing steel and prestressing steel.
Institute for Building Materials, Concrete Structures and Fire Protection, Technical University of Braunschweig, Germany.

• SBDEF: a programme for Deflection Analysis of Steelbeams under non uniform temperature distribution across the steelprofile developed at the Swedish Institute of Steel Construction, Stockholm, Sweden.

• STEELFIRE: a programme for the non linear analysis of steel frames subjected to fire,available at the Lund Institute of Technology, Sweden.

• FASBUS II Fire Analysis of Steel BUilding Systems [28,29]: a structural analysis programme specifically designed to analyse the fire endurance of building floor systems framed with structural steel beams and girders. The model utilizes the finite element method of analysis developed by the American Iron and Steel Institute, Washington, USA.

• DIANA DIsplacement method ANAlyser: a general purpose finite element programme, suitable for the calculation of geometrical and physical non linear problems.
The temperature distribution in a construction can be determined by means of a two- or three dimensional transient-state potential flow analysis. Temperature dependence of mechanical and thermal material properties can be taken into account.
Applications: calculation of the behaviour of steel, reinforced concrete and composite steel-concrete construction elements under fire action.
Developed by TNO-IBBC, the Netherlands.

6. FLOW CHART FOR THE DESIGN OF STRUCTURAL FIRE RESISTANCE

6.1. Bare Steel

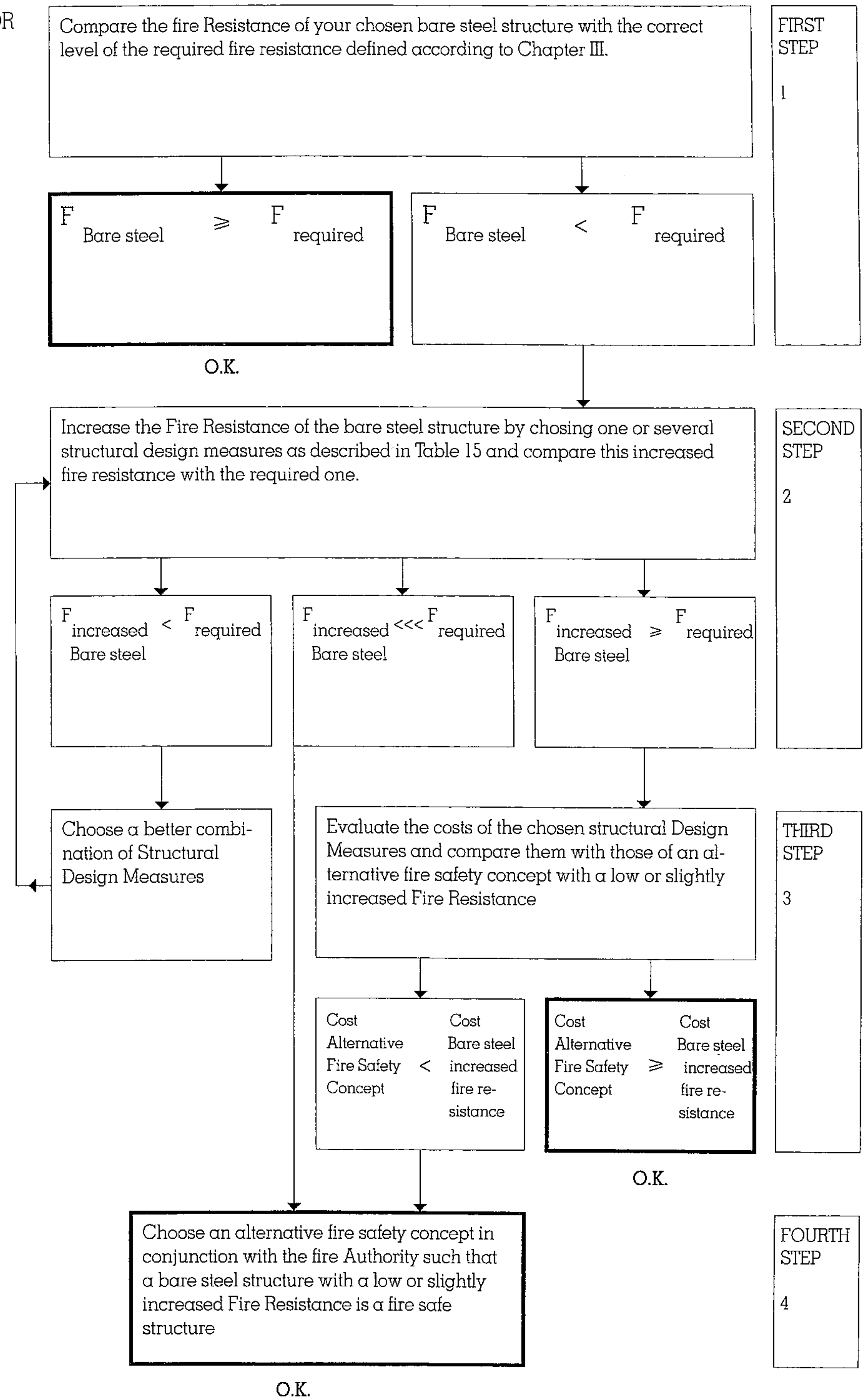


Table 14

Possible and reasonable structural choices allowing the fire resistance of bare steel elements to be improved.	Examples of possible combinations of structural choices allowing the fire resistance to be improved.																		
	A	B	C	A B	A B C	D	E	B E	C E	B C E	E	C G	A G	B G	C G	A C G	B C G	A B C G	F
A. Choice of low section factors.	■			■	■								■			■		■	
B. Overdesigning of structural elements (reduction of load factor).		■		■	■			■		■				■			■	■	
C. Introduction of accidental load combinations under the action of fire foreseen by Eurocode.			■		■				■	■		■			■	■	■	■	
D. Use of shielded elements eg. external columns with shielding distances in function of the required fire resistance levels.						■													
E. Choise of hollow sections filled with concrete (if necessary with reinforcement bars)/R/.							■	■	■	■	R ■	R ■							
F. Choice of hollow sections filled with water.																			■
G. Choice of partially exposed sections.													■	■	■	■	■	■	

Level of fire resistance which might be reached by the given combination of structural design measures.

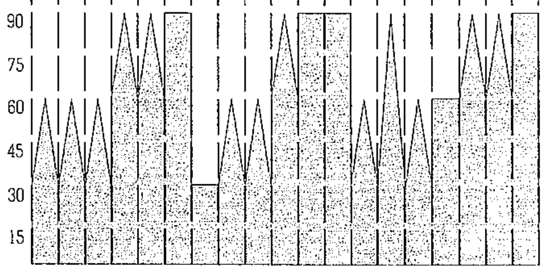


Table 15

Structural design measures allowing the fire resistance of bare steel structures to be increased.
Attention! Check always your costs.

6.2. Protected Steel Structures

WAYS TO OPTIMIZE THE PROTECTION

First step:
Negociate again the lowest possible fire resistance requirements as shown in Chapter III

Second step:
Choose the cheapest protection by combining aesthetical, functional and fire resistance aspects

Range of applications	30 min	60 min	90 min	≥120 min
Sprays	■	■	■	■
Boarded systems	■	■	■	■
Intumescent coatings	■	■		
Composite systems	■	■	■	■
Waterfilled columns	■	■	■	■

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ABBREVIATIONS

AISI = American Iron & Steel Institute.
CEB = Comité Euro-International du Béton.
CIB = Conseil International du Bâtiment.
CTICM = Centre Technique Industriel de la Construction Métallique.
DIN = Deutsches Institut für Normung.
ECCS = European Convention for Constructional Steelwork.
ECSC = European Coal and Steel Community.
ISO = International Standards Organisation.
TNO = Technisch Natuurwetenschappelijk Onderzoek.

STEEL INFORMATION CENTRES OF WESTERN EUROPE:

Centre Belgo-Luxembourgeois d'Information de l'Acier
Belgisch-Luxemburgs Staalinfocentrum
rue Montoyerstraat 47, B-1040 Bruxelles-Brussel

Federacciai, Centro Promozione e Sviluppo
Piazza Velasca 8, I-20122 Milano

Centrum Staal
Stationsplein 45 - Postbus 29076, NL-3001 GB Rotterdam

Office Technique pour l'Utilisation de l'Acier
Elysées La Défense 19 Le Parvis, F-92072 Paris La Défense 4

Österreichischer Stahlbauverband
Larochegasse 28, A-1130 Wien

Schweizerische Zentralstelle für Stahlbau
Centre Suisse de la Construction Métallique
Seefeldstrasse 25, CH-8034 Zürich

Stahl-Informations-Zentrum
Breite Strasse 69 - Postfach 1611, D-4000 Düsseldorf 1

The Steel Construction Institute
Silwood Park, GB-SL5 7 QN Ascot, Berks

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