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Fire resistance tests — Guidelines for computational structural fire design

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National foreword

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TECHNICAL REPORT

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Fire resistance tests — Guidelines for computational structural fire design

Essais de résistance au feu — Lignes directrices sur la conception statistique des feux de structures

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Foreword

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The committee responsible for this document is ISO/TC 92, *Fire safety*, Subcommittee SC 2, *Fire containment*.

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Introduction

In recent years significant advances have been made in the scientific community in understanding the behaviour of fire in building structures and as a result there is an increasing activity in the development of computer models that are capable of describing and predicting many of the different aspects of fire safety engineering.

As a result of this research, design codes have been prepared that enable practising engineers to undertake this type of analysis which can be applied to comply with prescriptive requirements as specified in National Building Regulations, or, to develop performance based fire safety strategies and often involving complex computational analysis.

In particular, analytical procedures and computer models have been developed in the areas of:

— reaction of materials to fire;

— fire growth in a compartment;

— fully developed compartment fire;

— fire spread between buildings;

— fire behaviour of load-bearing and separating elements and building structures;

— smoke filling in enclosures and smoke movement in escape routes and multi-story buildings;

— interaction of sprinklers and fire, including sprinkler and fire venting interaction;

— process of escape; and

— systems approach to the overall fire safety of a building, in its most general form comprising fire development models interacting with human response models.

This progress in fire research has led to consequent changes in the field of codes, specifications, and recommendations for fire engineering. Some characteristic trends in these changes are:

— improved relationship between standard tests and real fire scenarios;

— increased use of fire safety engineering principles to meet functional requirements and performance based criteria;

— development of new test methods, that are, as far as possible, material-independent and related to well-defined phenomena and properties;

— increase in the application of reliability-based analytical design;

— extended use of integrated assessments; and

— introduction of goal-oriented systems of analysis of total, active and passive fire protection for a building.

One of the most rapidly developing trends relates to the structural fire engineering design of load-bearing and separating structures. An analytical determination of the fire resistance of structural elements is being accepted more widely by the Approving Authorities in many countries as an alternative to the internationally prescriptive based approaches based on the results of the standard fire resistance test and connected classification.

A significant contribution to the analysis of building structures in fire has been made by the development of the European Structural Eurocodes which enable practising engineers to follow agreed design procedures for application in individual members states. During the mid 1990s, these Codes which covered; Fire Actions and individual structural materials (Concrete, Steel, Composite Steel and Concrete, Timber, Masonry, Aluminium) were published as ENV's (or pre-standards). These Codes had the status of Draft for Development, and were supplemented with National Applications Documents (NAD's), which

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permitted member states to ascribe certain factors to many of the calculations and input variables in order to align with National experience.

During the last five years, considerable progress has been made in converting these pre-standards into full European Design Codes for application in the European Community member states. The Codes are now divided into two separate parts:

— **Normative** - in which members states are obliged to follow.

— **Informative** - usually consisting of a series of Annexes in which acceptance is voluntary by individual member states.

In addition, there is still provision to apply individual National Determined Parameters (NDP's) to align more closely with National experience. The interaction of the Eurocodes are summarized in Figure 1.

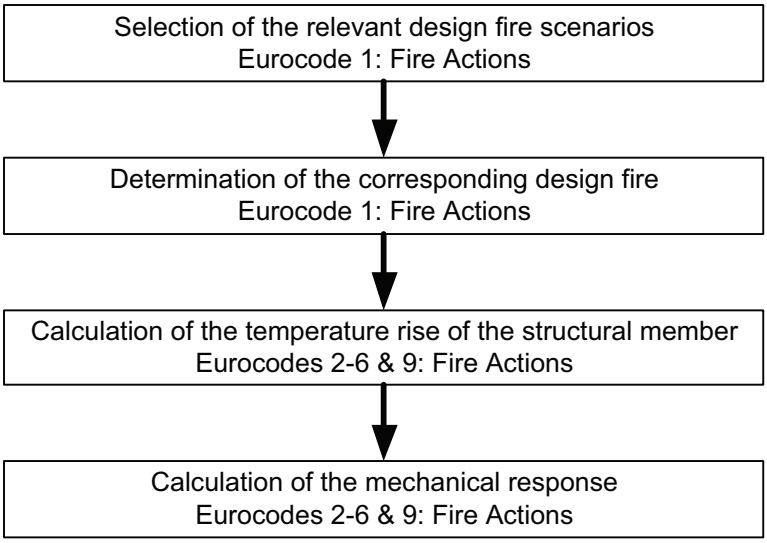

Figure 1 — Interaction of the Structural Eurocodes

The structural Fire Engineering design models have been reviewed in Reference [1] and essentially they can be presented in a simple form as three succinct design steps shown in Figure 2:

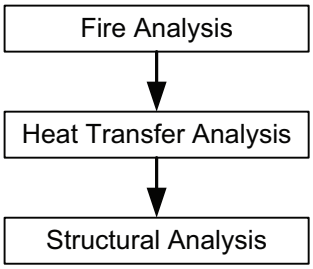

Figure 2 — Three stages to structural fire design

This report examines each of the above under separate headings. In each case, internationally applied methods for a structural fire engineering design are discussed.

For fire models or thermal actions the report considers:

Furnace tests:

— according to ISO 834: cellulosic, hydrocarbon, external and smouldering curves.

— tunnel heating curves according to RWS and the French National curve.

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Natural fires:

— single zone or parametric fires in so far as they may be used in a standardised way to provide characteristic occupancy related standard tests. This also includes time equivalent relationships for quantifying real fires into an equivalent period of heating in the standard ISO 834 test.

For heat transfer models the report considers:

— Heat transfer for uniform temperature distribution

— Non-uniform temperature distribution for

  — one dimension

  — two dimensions

  — three dimensions

For structural models the report considers:

— Single member analysis

  — Sub-frame assembly analysis (sub-frames and assembly of members)

  — Global structural analysis in which load redistribution occurs.

The report also considers **Combination Models** for thermal and structural analysis and the performance of structural glass, plastics and resins.

In addressing structural models relevant thermo-physical and mechanical properties are presented for each loadbearing material. While these are presented for use in calculating the thermal response under standard furnace heating conditions for the most part the same properties will invariably be appropriate for natural fires.

This Technical Report is one of a series of Technical Reports being developed that provide guidance on important aspects of calculation methods for fire resistance of structures. Related documents include

— ISO/TR 15655, *Fire resistance — Tests for thermo-physical and mechanical properties of structural materials at elevated temperatures for fire engineering design*,

— ISO/TR 15656, *Fire resistance — Guidelines for evaluating the predictive capability of calculation models for structural fire behaviour*, and

— ISO/TR 15658, *Fire resistance tests — Guidelines for the design and conduct of non-furnace-based large-scale tests and simulation*.

Other documents, which have been produced in ISO/TC92/SC2, provide data and information on the determination of fire resistance. In particular, these include

— ISO 834 (all parts), *Fire resistance tests — Elements of Building Construction*,

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

— ISO/TR 12471, *Computational structural fire design — Review of calculation models, fire tests for determining input material data and needs for further development*, and

— ISO/TR 10158:1991[1)], *Principles and rationale underlying calculation methods in relation to fire resistance of structural elements*.

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Fire resistance tests — Guidelines for computational structural fire design

1 Scope

This Technical Report provides an overview of the advances that have been made in understanding how structures respond to fire. This is reviewed in terms of heat transfer to the structural elements from primarily nominal (furnace) fires changes in the elevated temperature, physical and mechanical characteristics of structural materials, and how the information is used in the analysis of structural elements for the fire limit state. In reviewing the fire scenarios the report concentrates primarily on standardized heating curves but includes the basis of characteristic curves, which may at some time in the future be adopted in a standardized way. Reference is made to time equivalent as a recognized methodology in relating a natural or characteristic fire, to an equivalent period of heating in the ISO 834 furnace test.

This Technical Report is the result of the development of European Structural Eurocodes for application by member states in the European Community. These Codes enable practising engineers to follow agreed design procedures for application in individual members states irrespective of whether these are for building projects either inside or outside their own National boundaries.

The current UK national structural codes and the European (Eurocodes) are listed in Annex A.

2 Basic principles

2.1 Primary objectives of fire safety design

The primary objectives for fire safety design are

— Life safety - Regulatory requirements for the occupants, fire fighters and rescue services

— Property protection - Regulatory, societal, economic and insurance requirements

— Environmental protection - Regulatory, societal and insurance requirements

— Heritage - Regulatory and societal requirements

In order to limit the impact of fire risk accepted levels are reflected in national fire safety codes, which are generally expressed in terms of requirements and recommended measures. These set out to control the risk of ignition, fire growth and flashover, as well as their consequences and encompass the following strategies:

a) reducing the risk of occurrence,

b) control of fire (heat, flames, smoke and toxic gases) at an early stage,

c) ensuring a safe evacuation of people (and possibly of property), or safe areas of refuge,

d) preventing fire spread (heat, flames, smoke and toxic gases) beyond a certain area (compartmentation),

e) providing for safe and efficient operating conditions for the fire brigades and rescue services,

f) avoiding premature structural failure or limiting structural damage with respect to reinstatement,

g) minimising business interruption and financial losses,

h) minimising the impact upon the environment.

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Structural fire safety design is directly concerned with strategies involving items (c) to (h) since these will come into play if the fire is not controlled at an early stage in its development.

The level of structural fire safety provided should be considered in terms of:

— the risk of fire occurring, which is considered as an accidental situation,

— the development of fire through:

  — compartment geometry

  — ventilation

  — fire loading

— the reduction in risk by introducing structural measures,

  — engineering design

  — materials selection

  — passive protection

— the reduction in risk by introducing fire compartments or containments that prevent fire spread beyond the surrounded area for a specific time. For some buildings, a complete floor may be regarded as a single compartment.

— the reduction in risk by the introduction of active protection measures (detection, alarm, sprinklers, smoke control, fire brigade).

2.2 Performance criteria

The level of structural fire safety can be evaluated by performance criteria depending of the strategy chosen.

For load-bearing structures, these are:

— load-bearing function for the whole duration of fire or a part of it (ultimate limit state),

— limit on the extent of deformation (deflection, displacement, contraction, elongation) with respect to the integrity of separating elements, or, for the fire protection material to remain attached to the load-bearing structure (deformation limit state),

— limit of structural damage (limit of the overall deformations and other effects such as spalling, corrosion, charring occurring during the heating and the cooling phases) to allow reparability of building after fire (re-serviceability or reusability limit state).

For separating elements, they include:

— limit on the temperature rise of the unexposed surface, (+140 °C average, +180 °C max);

— limit on the leakage of hot gases through gaps created in the element (movement of gap gauge, cotton wool pad);

— limit on the thermal radiation from the unexposed face, (for escape routes 3 kW/m^2).

The human skin can only tolerate a certain level of heat flux for a certain time. The higher the incident heat flux level the shorter the tolerable exposure time. Some typical critical values are presented in Table 1.

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Table 1 — Examples of human tolerance and physiological damage from exposure at ambient temperature to various levels of incident radiant heat flux from a remote emitter

Incident radiant heat flux kW/m^2	Physiological Effect
1.0	Maximum for indefinite tolerability
4.0 - 5.0	Sufficient to cause pain to personnel if unable to reach cover in 20 seconds. Blistering of the skin (second degree burns) is likely, 0 % lethality
10.0	Intolerable pain after 12 seconds
12.5 - 15.0	1 % lethality in 1 minute, first degree burns in 10 seconds
25.0	100 % lethality in 1 minute; significant injury after 10 seconds
35 - 37.5	100 % lethality in one minute; 1 % lethality in 10 seconds
41.8	Skin necrosis to 0.05 mm depth after 2 seconds

More detailed information is given in the publication Risk-Informed, Performance Based Industrial Fire Protection (ISBN 1-882194-09-8).

Other criteria may be based upon the incident heat flux to cause ignition on different types of materials as shown in Table 2.

Table 2 — Incident radiant heat flux from a remote emitter for ignition after 10 minutes exposure at ambient temperature

Material	Incident radiant heat flux kW/m^2
Polystyrene	18
Polymethyl methacrylate	18
Polyethylene	20
Polypropylene	20
Paper	20
Polyvinyl chloride	21
Nylon	29
Wood	32

The criteria may also depend upon the ability of certain types of products to withstand specific temperatures as presented in Table 3. These are indicative only.

Table 3 — Effect of temperature on selected materials

Material	Typical Examples	Damage Conditions	Approximate Temperature °C
Polystyrene	Thin walled food containers, foam, light shades, handles, curtain hooks, radio casings	Collapse Softens Melts and flows	120 120 - 140 150 - 180
Polyethylene	Bags, films, bottles, buckets, pipes	Shrivels Softens and melts	120 120 - 140
Critical temperatures may be dependent upon the rate of heating. in particular, glass products are also dependent upon the impact of water as well as the framing and glass condition.			

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Table 3 *(continued)*

Material	Typical Examples	Damage Conditions	Approximate Temperature °C
Polymethyl methacrylate	Handles, covers, skylights, 'glazing'	Softens Bubbles	130 - 200 250
PVC	Cables, pipes, ducts, linings, profiles, handles, house ware, toys, bottles	Degrades Fumes Browns Chars	100 150 200 400 - 500
Cellulose	Wood, paper, cotton	Darkens	200 - 300
Paint surface- resinous or oil based	-	Deteriorates Destroyed	100 250
Annealed soda-lime-silica glass	Window glass, doors and internal glazing	Cracking due to thermal gradients leading to falling out Softening pointWorking point Practical melting point	Thermal gradient typically 160°C 720°C 1010°C
Wired glass	Window glass, doors and internal glazing	Cracks as for annealed but wires ensure pieces stay in place	
Toughened (or tempered) soda-lime-silica glass	Impact safety glazing	Subject to unpredictable catastrophic thermal shock failure If integrity retained, softening as above	Thermal gradient typically in range 150°C to 280°C (see note)
Laminated soda-lime-silica glass	Security and safety glazing, with pvb interlayer	Glass layers crack and behave as above Organic interlayer starts to degrade leading to smoking and ignition	Starts from ~180°C accelerating from ~300°C onwards
Critical temperatures may be dependent upon the rate of heating. in particular, glass products are also dependent upon the impact of water as well as the framing and glass condition.			

3 Design process

In order to evaluate the performance of a structure or a part of it, the assessment has to be carried out in three stages:

Stage 1: Analysis of the thermal actions/exposure - fire model

Stage 2: Analysis of the heating rate and temperatures attained by the structural components - heattransfer model

Stage 3: Analysis of the mechanical/load bearing performance of the member/s - structural model

These are described as follows:

3.1 Fire model

The thermal exposure (design fire) is generally described by a temperature-time relationship but can also be described by a time dependent – incident radiant condition, which could be simulated as by a temperature-time relationship. The fire model can therefore be a nominal (furnace) fire, or, a fire simulating a real scenario, or even an experimental fire.

The first stage of fire (pre-flashover phase) is generally regarded the most critical for human life since during this stage smoke and toxic gases are produced. When dealing with structural fire resistance, this phase has in the past, been ignored, since the temperatures reached although critical for human beings,

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are generally too low to seriously affect the mechanical behaviour of a structure. However, with the use of aluminium, structural plastics and resins becoming more widely employed in situations where their performance in fire can be critical, the pre-flashover fires should not be ignored. Aluminium and/or alloys virtually lose all their strength at around 400 °C. Structural plastics can char in a very similar manner to timber at temperatures below 300 °C.

In the future it is expected that pre-flashover fires may be simulated into a furnace test in a standardised way or as incident radiant heat flux with time.

However, when a fire occurs, it is not obvious that it will reach such a severity that it will endanger a load-bearing structure. A wide range of factors such as detection, automatic extinguisher system, fire brigade action etc., need to be taken into account (generally by using a probabilistic approach) in order to provide a more representative evaluation of the fire exposure conditions and resulting structural fire response.

The design fire used to assess the fire resistance assessment of a structural member/s can be based upon:

— A nominal fire, which is expressed by a well - defined temperature-time relationship. This would be typically a Standard furnace test upon which national Regulations are set, although it is primarily used for ranking of products and systems rather than reflecting reality.

— A natural fire, based upon a simple formula or a set of temperature-time curves, taking into account the main parameters that influence the time temperature response within the compartment. These are often referred to as single zone fire models or parametric fires and would be used in simple easily defined compartment geometries.

— A fire determined using complex numerical calculations such as multi-zone models or **C**omputational **F**luid **D**ynamics. This type of advanced analysis would be required in very large compartments, compartments with complex geometries and possibly high and irregular ceilings.

For a more comprehensive review of design fire scenarios and design fires reference should be made to ISO/TS 16733.

3.2 Heat transfer model

The heat transfer analysis is carried out to determine the temperature rise and distribution within the structural members. Thermal models are based on the acknowledged principles and assumptions of the theory of heat transfer. They may present various levels of sophistication according to the assumptions and needs. Models vary in complexity and may be used simply to determine a uniform temperature distribution, or, more complex temperature distributions in which thermal gradients may be calculated in 1, 2 or 3 directions.

The formulation of transient state heat conduction problems differs from that of steady cases in that the transient problems involve an additional term representing the change in the energy content of the medium with time. This additional term appears as a first derivative of temperature with respect to time in the differential equation, and as a change in the internal energy content during Δt, in the energy balance formulation. The nodes and the volume elements in transient problems are selected as in the steady case. For convenience, it is assumed that all heat transfer is into the element.

The energy balance on a volume element during a time interval Δt can be expressed as:

$$\begin{pmatrix} \text{Heat transfer into the} \\ \text{volume element from} \\ \text{all of its sides during} \\ \text{a time interval } \Delta t. \\ \sum \dot{Q} \end{pmatrix} + \begin{pmatrix} \text{Heat generated within} \\ \text{the volume element} \\ \text{during a time} \\ \text{interval } \Delta t. \\ G \end{pmatrix} = \begin{pmatrix} \text{The change int the} \\ \text{energy content of} \\ \text{the volume element} \\ \text{during } \Delta t. \\ \Delta E / \Delta t \end{pmatrix}$$

or

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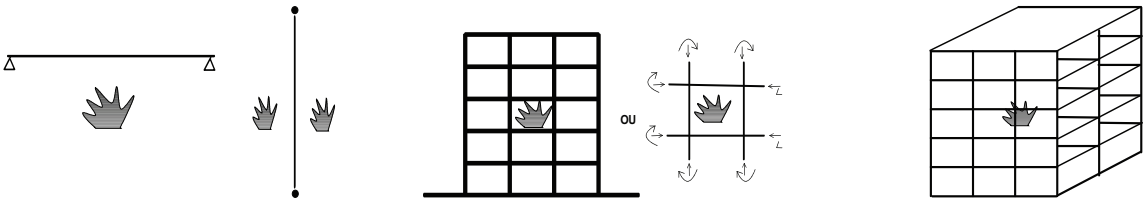
$$\sum \dot{Q} + G_{element} = \Delta E_{element} / \Delta t$$

The rate of heat transfer $\dot{Q}$ normally consists of conduction terms for interior nodes, but may involve heat flux (convection and radiation)for boundary nodes. The sum of Q is zero except at the boundaries.

Materials that incorporate free moisture should consider the effect of migration of moisture through the system in order to provide an accurate representation of the thermal distribution with time. This can be handled in the thermal analysis by incorporating mass transfer in the model. Where this is used, additional information can be provided on pressure field due to steam being produced and also to provide useful information on materials that are subject to the phenomena of spalling.

3.3 Structural model

The structural analysis/model used very much depends upon the structural form that is being analysed and can broadly be described as follows and shown in Figure 3.



a) Example of member analysis **b) Example of sub-assembly analysis** **c) Example of global analysis**

Figure 3 — Examples of types of analyses

Single member analysis, (e.g. beams, columns, floors, walls) are usually considered when verifying standard fire resistance requirements although they can be considered in real fire scenarios. The restraint conditions at the supports that exist at the beginning of a test (time = 0) generally remain unchanged throughout the fire exposure period. Only the effects of thermal deformation resulting from temperature gradients created through the cross-section need to be considered. Thermal expansion effects are usually ignored.

Sub-assembly analysis (e.g. sub frames and assembly of members). The conditions set at the beginning of a test will change upon heating. In particular, forces that are developed either through expansion or contraction (during cooling) will be considered as well as load transfer to other parts of the structure when one or more members loose their load bearing capacity. However, the effects of restraint from the rest of the frame particularly in respect of expansion effects and local failure, are only considered in a minor way. Sub-frame analysis can be carried out under both nominal and real fire scenarios.

Global structural analysis (of the whole structure in which a fire occurs). This takes into account heat transfer conditions, relevant failure modes, temperature-dependent material properties, stiffness as well as effects of thermal expansion effects where relevant. Load distribution is generally considered unchanged during the whole of the fire exposure period. While a global analysis is primarily carried out under natural fire heating conditions it can also be applied under furnace heating conditions although the effects of the cooling phase on the structural response would not normally be considered.

3.4 Combination models

Use of the models for fire, heat transfer and structural analysis, have to be considered in terms of the level of sophistication required. There is little point in conducting exact heat transfer analysis if when it comes to the structural analysis a very coarse approach is adopted unless it can be shown an insensitive coarse model is sufficiently accurate within the context of the outputs required.

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There are some combinations of thermal and structural analysis where it would be impracticable to carry out other than for calculation purposes. Figure 4.

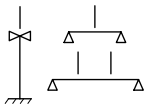
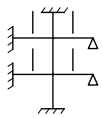
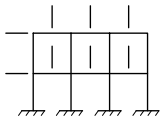
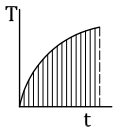
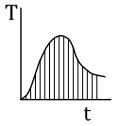
Model for structure / Model for thermal exposure		S_1	S_2	S_3
		Element	Substructure	Complete structure
				
H_1	Nominal temperature-time curves 	test or calculation (deterministic)	calculation, exceptionally testing (deterministic)	
H_2	real fire 	calculation (probabalistic)	calculation (probabalistic)	calculation (probabalistic) in special cases and for research

Figure 4 — Combination of thermal and structural analysis

Thermal Model H_1 describes the thermal exposure according to the standard fire resistance test of structural elements as specified in ISO 834 and in the corresponding national standards, or according to some other nominal or characteristic temperature-time curve. A fire design based on this thermal exposure, represents the internationally prevalent situation for load bearing and separating structural elements. It would be applied to single elements or simple sub-frames.

Thermal Model H_2 describes a thermal exposure based on a simulated real fire and either computed by solving the energy and mass balance equations of the compartment fire or determined from some systematized design basis. For example, Eurocode 1: Actions on structures exposed to fire, presents a set of parametric equations. These are very similar to the gas temperature-time curves based upon energy and mass balance equations of the fully developed compartment fire for which computer codes are available (SFIRE, COMPF-2 and BRAND). These models can be applied to single elements, sub-frames as well as to the complete structure. Furnace tests are currently being considered that represent the heating conditions of occupancy related fires scenarios.

Structural Model S_1 comprises single structural elements, e.g. beams, columns, walls, floors, and roofs. The model then may simulate either a structural element, which behaves as a single element in the real structure, or an element, which in reality acts together with other elements of the complete structure, but is cut out of this and described by simplified end conditions in the fire analysis.

Structural Model S_2 refers to a substructure, which approximately describes the mechanical behaviour of a part of the complete load bearing system of the building. Compared to the real structure, a substructure is analysed with simplified boundary conditions at its outer ends or edges.

Structural Model S_3 describes the mechanical behaviour of the complete load bearing structure of the building acting as, for instance, a two or three dimensional frame, a beam-slab system or a column-beam-slab system.

In the matrix presented in Figure 4, the thermal exposure models and the structural models are combined in the sequence of improved idealization. In principle, each element in the matrix then represents a particular design procedure. The matrix can therefore be considered as a type of classification system for methods of structural fire engineering design. It is, however, evident that not all models can be used in all combinations and the aim should be to provide a sensible pairing at each level of advancement. In

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the matrix, reference is made to these aspects. In principle, a structural fire engineering design offers a problem oriented choice for the combination of the thermal exposure model and the structural behaviour model and the final choice may also depend on national preferences, the complexity of application and the particular design situation.

3.5 Material properties

The material properties required for thermal and structural models including any fire protection materials can be broadly divided into two areas and generally may be used during heating under standard furnace test or representative occupancy related characteristic fires. They are not necessarily appropriate for structural analysis during the cooling phase.

3.5.1 Thermo – physical properties

The solving of the equations of transient heat flow to and within a fire exposed structure, requires information on the following properties for the structural materials and insulation/protection where appropriate

— emissivity of the fire exposed surfaces of the structure (a value of 1 is normally assumed for any applied fire protection),

— thermal conductivity of the structural materials and the fire protection,

— specific heat of the structural materials and the fire protection,

— thermal energy due to phase changes at various temperature levels of the structural materials and for some protection materials,

— rate of internally generated heat in the structure and fire protection,

— thermal expansion/contraction of the structural materials,

— density of the structural materials and fire protection.

For structures of combustible material, additional information on the rate of charring is required.

The properties must be known as a function of temperature for the heating as well as the subsequent cooling-down phase of the compartment fire. More advanced analysis, consisting of a solution of inter-related heat and mass transfer equations, requires information on a considerable number of additional properties such as:

— permeability of the structural materials,

— diffusion coefficient of adsorbed water and vapour in the structure,

— void fraction of the structure,

— equilibrium water content in the structure,

— crystalline water content in the structure,

— reaction rate and heat of reaction in the process of pyrolysis for structures of combustible materials,

— heat of reaction at the oxidation at the surface of structures of combustible material, and

— specific heat and dynamic viscosity of water vapour and volatile pyrolysis products.

For most fire protection materials the thermal properties are significantly different in the cooling phase.

3.5.2 Mechanical properties

A reliable calculation of the mechanical behaviour of a fire-exposed structure based upon the transient temperature state requires validated models for the mechanical behaviour of the materials involved

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within the temperature range associated with fires. These include mathematical relationships with respect to temperature that describe:

— elastic modulus,

— compressive strength,

— tensile strength,

— shear strength, including strength of shear connectors,

— torsional strength, and

For reinforced structures: strength with respect to bond and anchorage, as a function of temperature and, when relevant, stress history.

For a determination of the deformation behaviour and the ultimate load with respect to instability failure of fire-exposed structures and structural members, additional information is required for these properties:

— stress-strain relationship,

— steady-state and transient creep,

— steady-state and transient shrinkage,

— thermal expansion,

— relaxation

In structural models, it is not unusual to find that the material model for the mechanical behaviour is specified by temperature-dependent stress-strain curves that either neglect or indirectly include the creep strains and transient strains. The stress-strain curves are determined either from small-scale material tests or from full-scale tests on that type of load-bearing structure, for which the computational procedure is developed.

Fundamental parameters for determining the mechanical material properties at elevated temperatures are the rate of heating, load application and the control of strain. Practically, information on the material models can be referred to different testing regimes as shown.

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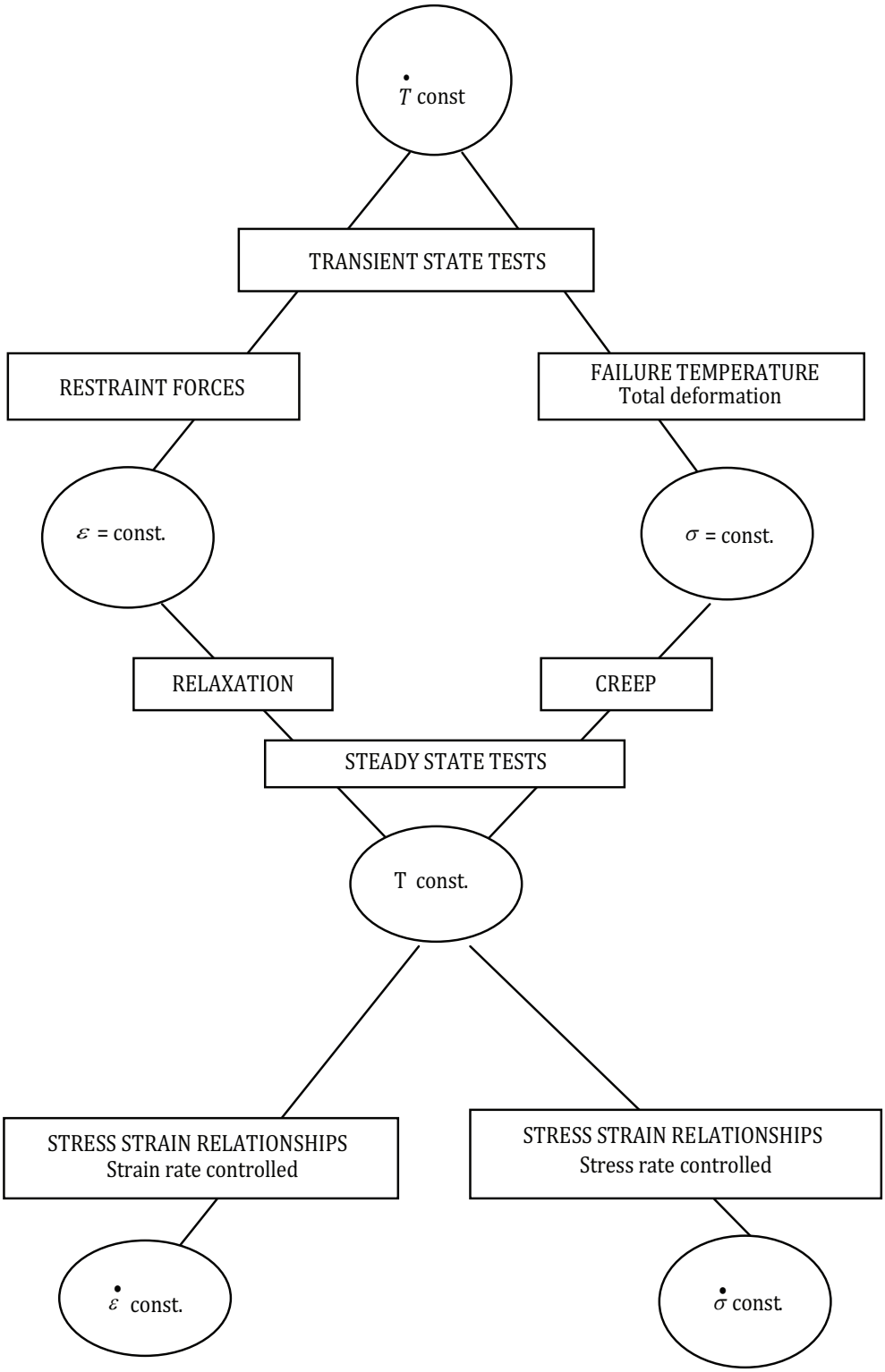

Figure 5 — Various testing regimes for determining the mechanical properties of materials at elevated temperatures

Much of the information used in either thermo-physical, and mechanical models are given in the Eurocodes 2 - 6 and 9, see Annex A. Other data are given in CIBSE (Chartered Institute for Building Services Engineers) Guide E (UK) and SFPE Handbook on Fire Protection Engineering.

For separating elements and fire protection materials, similar thermo-physical and mechanical properties are required that cover for example: gypsum, calcium silicate, mineral wool, vermiculite cement etc.

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Material properties are required over a range of temperatures depending upon the environment under which they may be used or the exposure conditions. For building fire scenarios and hence furnace tests temperatures are unlikely to exceed much above 1200 °C. The exception would be the heating conditions that relate to tunnel fires whereby some materials may be exposed to temperatures up to 1350 °C.

The design values of the material properties are obtained by using partial safety factors. Design values of thermal and mechanical material properties $X_{fi,d}$, are defined as follows:

Thermal properties for thermal analysis:

If an increase of the property is favourable for safety then:

$$X_{fi,d} = X_{k,\theta} \times \gamma_{M,fi} \tag{3.1}$$

If an increase of the property is unfavourable for safety then:

$$X_{fi,d} = \gamma_{M,fi} \times X_{k,\theta} \tag{3.2}$$

where;

$X_{fi,d}$ is the design value of thermal and mechanical property

The X can be any property of interest for thermal or mechanical calculations.

The X is meant to be substituted with properties like λ (thermal conductivity), C (specific heat), E (modulus of elasticity), f (strength), ρ (density), w (moisture content).

The subscripts have the following meaning:

fi = Fire design

d = Design

The use of X is a general way of explaining the influence of a partial coefficient or factor on the property of interest. It depends on the type of property whether an increase of the property is favourable for safety. An increase in λ (thermal conductivity) is not favourable for safety, where an increase in f (strength) is favourable.

Strength and deformation properties for structural analysis:

$$X_{fi,d} = k_\theta X_k / \gamma_{M,fi} \tag{3.3}$$

where;

$X_{fi,d}$ is the characteristic value of a material property in fire design, generally dependent on the material temperature,

X_k is the characteristic value of a strength or deformation property (generally f_k or E_k) for normal temperature design,

k_θ is the reduction factor for a strength or deformation property, ($X_{k,\theta}/X_k$), dependent on the material temperature,

$\gamma_{M,fi}$ is the partial safety factor for the relevant material property, for the fire situation

Proposals for partial safety factors for various materials (according to Structural Eurocodes 2-6 and 9) are assumed to be 1.0 for both the thermal and mechanical properties for all materials.

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4 Fire models

Several models can be used to describe the thermal actions upon a structure. A number of examples are illustrated in Figure 6.

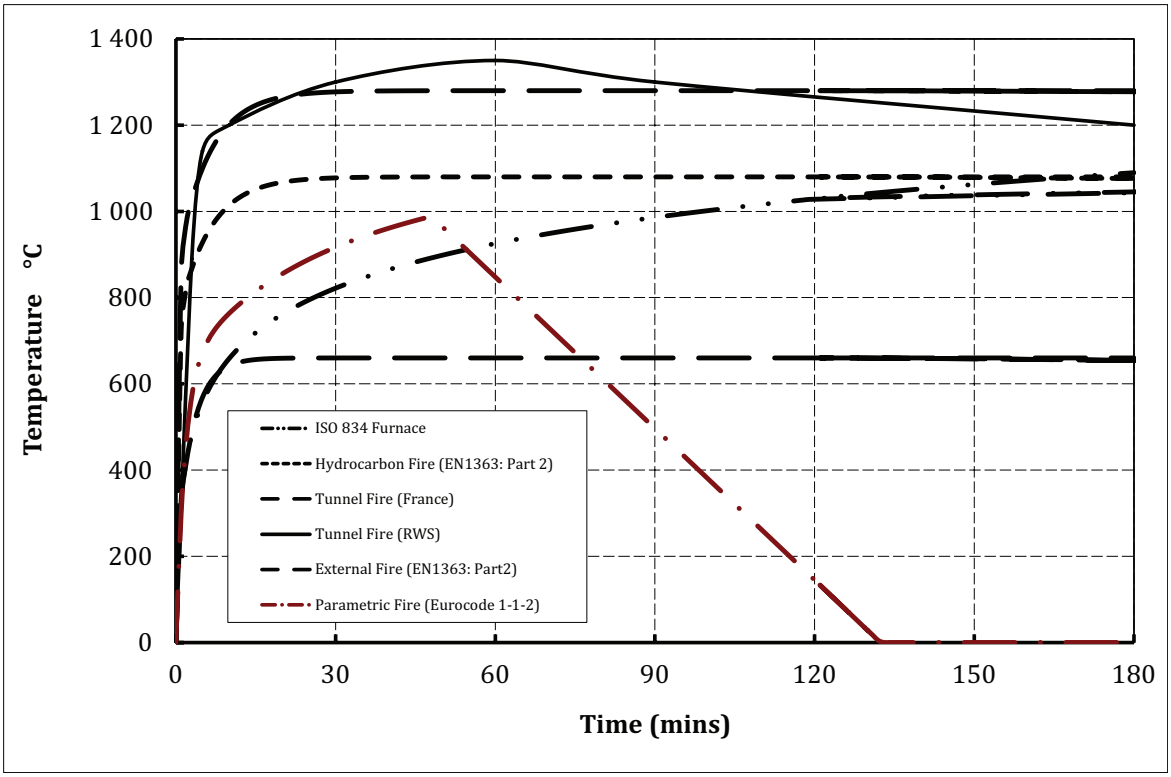

Figure 6 — Fire curves

The different types of fire generally fall within one of the following categories. These are:

— Standard Furnace (nominal) heating curves given, for example, in ISO 834

— Simplified formulae representing a natural fire or a set of temperature - time curves

— Steady-state fires

— Complex models that describe the spatial behaviour within a compartment that numerically describe the fire process

— Experimental fires

4.1 Standard (nominal) fires

There are four nominal temperatures - time furnace heating curves given as a function of time (t) and temperature (θ_g):

Cellulosic curve (ISO 834-1)

The standard temperature-time curve often referred to as the cellulosic curve, is given by the relationship:

$$\theta_g = 20 + 345 \log_{10}(8t + 1) \qquad [°C] \tag{4.1}$$

External fire curve (currently EN 1363-2)

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To characterize less severe fires immediately outside enclosures or emanating from within the building e.g. the condition of flames issuing from adjacent windows, the temperature/time relationship is given by

$$\theta_g = 660(1 - 0.687e^{-0.32t} - 0.313e^{-3.8t})+20 \qquad [°C] \tag{4.2}$$

Hydrocarbon fire curve (Currently EN 1363-2)

The hydrocarbon temperature - time curve which, realistically represents a hydrocarbon fire is given by:

$$\theta_g = 1080(1 - 0.325e^{-0.167t} - 0.675e^{-2.5t})+20 \qquad [°C] \tag{4.3}$$

Tunnel fire curves

In 1979 the RWS-curve originated from tests carried out in a model tunnel in which the temperatures attained 1350 °C after 60 minutes. The RWS-curve was developed by the Rijkswaterstaat, Ministry of Transport in the Netherlands and was based on the assumption that in a worst case scenario, a fuel, oil or petrol tanker fire with a heat release of 300 MW could occur and last for up to 120 minutes.

The primary difference between the RWS and the Hydrocarbon heating conditions is that the hydrocarbon curve is based on the temperatures that would be expected from a fire occurring within a relatively open space, where some dissipation of the heat would occur. In contrast, the RWS curve is based upon the conditions experienced by a fire occurring in an enclosed area, such as a tunnel, where there is little or no opportunity of heat dissipating into the surrounding atmosphere.

The RWS curve simulates the initial rapid growth of a fire using a petroleum tanker as the source, and the gradual drop in temperature reflects the reduction in fire load as it is burnt off. It has been used as a Standard for the protection of tunnels in the Netherlands since the 1980s.

The heating portion of the RWStunnel curve can be obtained by replacing 1080 °C in the hydrocarbon curve by 1350 °C.

France (HCM) and Germany (RABT-ZTV for trains and cars) also have tunnel fire curves which are illustratedin Figure 6.

Smouldering Fire:

In addition, a slow heating curve is also described in which the temperature within the furnace attains 345 °C after 20 minutes and then joins the cellulosic curve. This is not used as a thermal action for design purposes, but may be called upon for certain reactive fire protection materials, which rely upon a chemical/physical change in order to function as an insulator.

However, where fire safety devices rely upon only the action of hot smoke to function it is recommended until such time when there is an internationally agreed temperature/time curve the performance of devices are evaluated using the smouldering fire curve described in EN 1363-2 by the following equation:

For $0 < t \leq 21$

$$T = 20 + 154t^{0.25} \qquad [°C] \tag{4.4}$$

For $t > 21$

$$\theta_g = 20 + 345 \log_{10} \{8(t - 20)+ 1\} \qquad [°C] \tag{4.5}$$

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4.2 Natural fires

The parametric fire can be used for simulating the behaviour of post flash-over fires and can be used to represent characteristic occupancy related fires. This is an area of current research in which characteristic fires are being considered for standardization.

Since the fire consider the whole compartment has reached post-flashover and that there is no variation in temperature across the compartment in any direction, it is referred to as a Single Zone fire.

For compartment fires the temperature - time history of the entire fire process is given by the relationship:

$$\theta_g = 20 + 1325(1 - 0.324e^{-0.2t^*} - 0.204e^{-1.7t^*} - 0.472e^{-19t^*}) \qquad [°C] \tag{4.6}$$

where:

θ_g is the gas temperature in the fire compartment, °C

$$t^* = t \cdot \Gamma \qquad [h] \tag{4.7}$$

with;

t = time [h]

$$\Gamma = [O/b]^2/(0.04/1160)^2 \qquad [-] \tag{4.8}$$

O is the opening factor and is given by:

$$A_v h^{1/2}/A_t \qquad [m^{1/2}] \tag{4.9}$$

where:

A_v	is the area of vertical openings	[m^2]
h	is the weighted mean height of the vertical openings	[m]
A_t	is the total area of the enclosure (walls, floor and ceiling including the openings)	[m^2]

Using Γ = 1 in Formula (5.7) gives the standard (ISO) time-temperature curve, and using Γ = 50 and replacing 1325 by 1080, approximates to the Hydrocarbon fire.

In the Code, the limits of 0.02[O[0.20 are observed. However, the UK considers the opening factor can been extended down to 0.01 m$^{1/2}$ and can be applied to buildings with compartment floor areas greater than 500 m^2.

In the above equation, $b = \sqrt{(\rho c \lambda)}$.

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In which b is the thermal absoptivity of the total enclosure and has now been extended to cover a wider range of compartment types with:

$$100 \leq b \leq 2200 \qquad [\mathrm{J/m^2s^{1/2}K}] \tag{4.10}$$

The lower value would be representative of a compartment or building with a controlled environment and clad with lightweight insulation typically 6" (150 mm) thick whereas the upper value is representative of a very poorly insulated structure such as a dense concrete and un-insulated steel sheeting, e.g. unheated storage facility.

The Code recognizes the importance of the thermal properties of the compartment walls /floor/ceiling and is represented together with consideration of walls, which comprise two or more layers

The maximum temperature within the compartment is given by:

$$t_{\max} = \max[(0.2 \times 10^{-3} \times q_{\mathrm{t,d}}/O); t_{\mathrm{lim}}] \qquad [\mathrm{h}] \tag{4.11}$$

where:

$q_{\mathrm{t,d}}$ is the design fire load density and should obey the following limits: $50 \leq q_{\mathrm{t,d}} \leq 1\,000$ MJ/m^2

t_{lim} is given in hours.

The fire growth rate is taken into account in which t_{lim} = 15 min, 20 min, and 25 min is applied for fast, medium and slow growth rates respectively.

To account for different values of b representing the walls, ceiling and floor, $b = \sqrt{(\rho c \lambda)}$ is introduced as:

$$b = \left(\sum\left(b_j A_j\right)\right) / \left(A_t - A_v\right) \qquad [\mathrm{J/m^2s^{1/2}K}] \tag{4.12}$$

where:

A_j is the area of enclosure surface *j*, openings not included

b_j is the thermal property of enclosure surface *j*.

The temperature-time curves in the cooling phase are given by;

$$\theta_g = \theta_{\max} - 625(t^* - t^*_{\max} \cdot x) \text{ for } t^*_{\max} \leq 0.5 \qquad [°\mathrm{C}] \tag{4.13}$$

$$\theta_g = \theta_{\max} - 250(3 - t^*_{\max})(t^* - t^*_{\max} \cdot x) \text{ for } 0.5 < t^*_{\max} < 2 \qquad [°\mathrm{C}] \tag{4.14}$$

$$\theta_g = \theta_{\max} - 250(t^* - t^*_{\max} \cdot x) \text{ for } t^*_{\max} \geq 2 \qquad [°\mathrm{C}] \tag{4.15}$$

where:

$x =$ 1.0 if $t_{\max} > t_{\mathrm{lim}}$, or $x = t\,\mathrm{lim} \cdot \Gamma / t^*_{\max}$ if $t_{\max} = t_{\mathrm{lim}}$

A series of parametric fires is given in Figure 7 (fire load = 140 MJ/m^2, b = 1160, opening factor O from 0.04 m$^{1/2}$ to 0.30 m$^{1/2}$).

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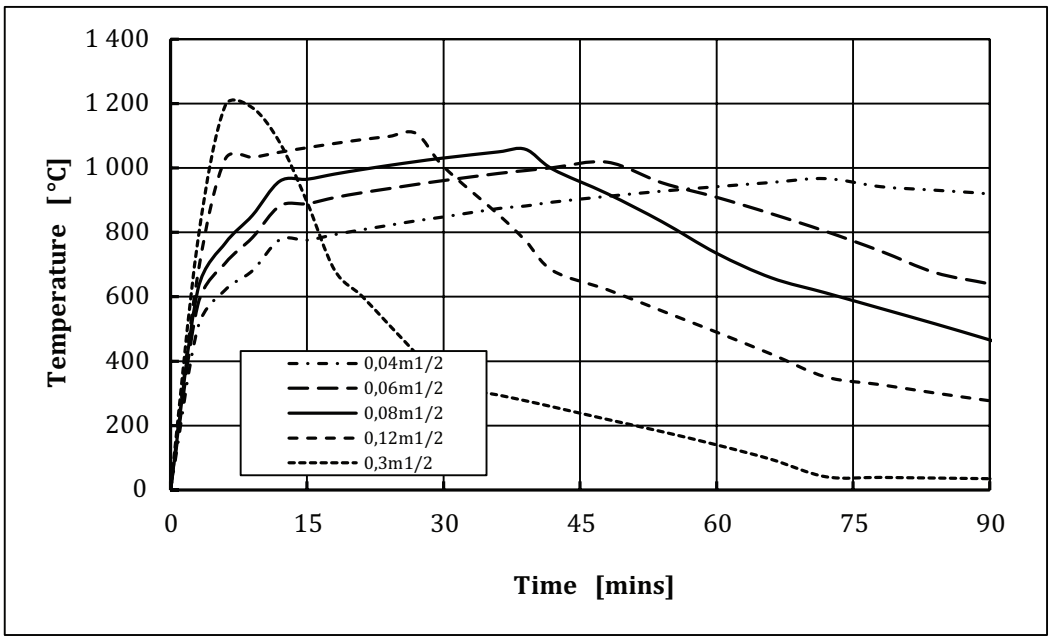

Figure 7 — Set of parametric fires

4.3 Numerical simulation of natural fires - Zone models

Zone models and field models generally are deterministic models. They can be used to solve problems in a number of categories, i.e. smoke and heat transport in enclosures, detector/sprinkler activation and evacuation of humans. They can provide very detailed simulations of complex fire scenarios and for this reason require considerable CPU.

The simplest representation of a compartment fire is a **Single Zone** model, which is generally applied to post flashover conditions. Homogeneous properties of the gas are assumed in the compartment such as the temperature, optical properties, chemical composition.

The temperature may be calculated by a heat balance approach considering the resolution of mass and energy conservation equation:

$$I_C = I_L + I_W + I_R + I_B \qquad [\text{kW}] \tag{4.16}$$

where:

I_C is the heat released during combustion

I_L is the heat removed due to replacement of hot gases by cold air

I_W is the heat loss to boundary surfaces

I_R is the heat dissipated by radiation through the openings

I_B is the heat stored in the gas volume (usually ignored)

The exchange of mass with the internal gas comes from the external gas (by openings) and the fire (pyrolysis rate), whereas the exchange of energy with the internal gas is calculated with respect to the surrounding surfaces, the fire and the openings.

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The quick response of this model and its simple equations give an advantage to the one-zone model and it is a helpful tool to estimate the temperature in a compartment after flashover has been achieved. Examples have already been given in Figure 7.

The **two-zone model** is based on the assumptions of accumulation of combustion products in a layer beneath the ceiling, with a horizontal interface. In this upper layer, one assumes uniform characteristics of the gas. Different zones are defined: the upper layer, the lower layer, the fire and its plume, the external gas and walls. The exchanges of mass, energy (and chemical species) are calculated between these different zones.

Zone models contain usually sub-models referring to processes in the gas zones and various transport and combustion processes. Therefore, the computer code contains subroutines dealing with:

— conservation equations for the gas zones

— source term sub-models

— mass transfer sub-models

— heat transfer sub-models

— embedded sub-model

The application of this type of model is mainly in pre-flashover conditions, and is used to evaluate the propagation of smoke in buildings, and estimate the life safety in terms of tenability criteria as a function of temperature, radiative flux, optical density and toxic gas concentration.

The general criteria for assuming the occurrence of flashover are:

— 500 °C to 600 °C in the upper layer,

— 25 kW/m^2 for radiation to the floor,

— flames emerging from window.

Field models or CFD models (computational fluid dynamics models) are the most sophisticated deterministic models for simulating enclosure fires. Field models incorporate sub-models for turbulence, heat transfer and combustion.

The CFD modelling technique is based on a complete, time-dependent, three dimensional solution of the fundamental conservation laws. The volume under consideration is therefore divided into a very large number of sub-volumes. The basic laws of mass, momentum, and energy conservation are applied to each of the sub-volumes.

The governing conservation equations for mass, energy, and momentum contain as further unknowns the viscous stress components in the fluid flow. Substitution of the viscous stress components into the momentum equation and solving them is central to any CFD code (so called Navier-Stokes equations).

Two cases of field models exist:

Direct numerical simulations (DNS)

The basic equations are solved without averaging, but such codes need a very short time and spatial step in order to simulate all time and spatial scale coming from the turbulent and the chemical processes. DNS require particularly powerful computers and are used for academic studies or confined to simple applications. The large eddy simulation (LES) technique is an example where the most realistic simulation of fire-induced flows can be performed.

Reynolds-averaged Navier Stokes (RANS)

The basic equations are pre-averaging on very short time scale, and use a turbulent model to take into account the short spatial scales. The most frequently model used is a second order closed $k - \varepsilon$ model.

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