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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*.

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 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.

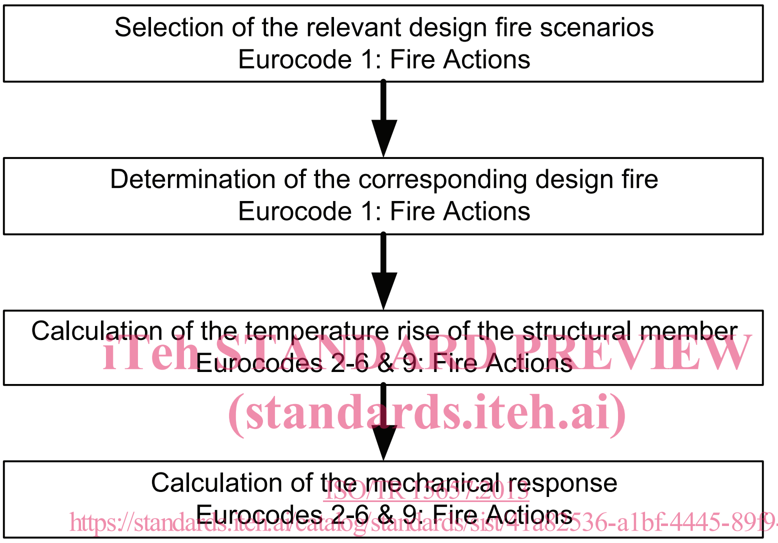


Figure 1 — Interaction of the Structural Eurocodes

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:

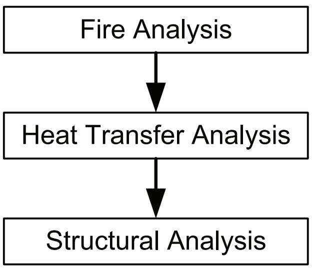


Figure 2 — Three stages to structural fire design

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.

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*.

1) Withdrawn.

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.

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.

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.			

Table 3 *(continued)*

Material	Typical Examples	Damage Conditions	Approximate Temperature °C
Polymethyl meth-acrylate	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- resin-ous or oil based	-	Deteriorates Destroyed	100 250
Annealed soda-lime-silica glass	Window glass, doors and internal glazing	Cracking due to thermal gradi-ents 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 tem-pered) soda-lime-silica glass	Impact safety glazing	Subject to unpredictable cata-strophic thermal shock failure If integrity retained, softening as above	Thermal gradient typi-cally 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, 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

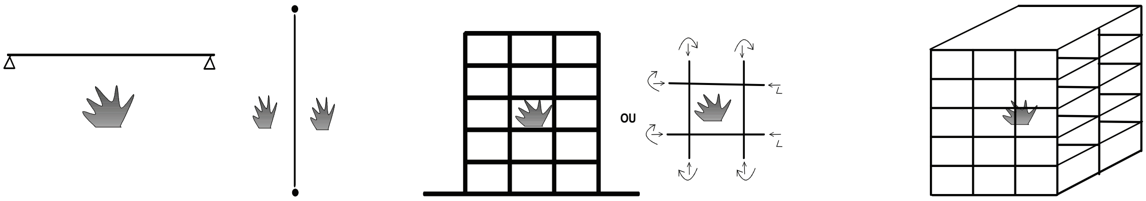
$$\sum \dot{Q} + G_{element} = \Delta E_{element} / \Delta t$$

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.

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

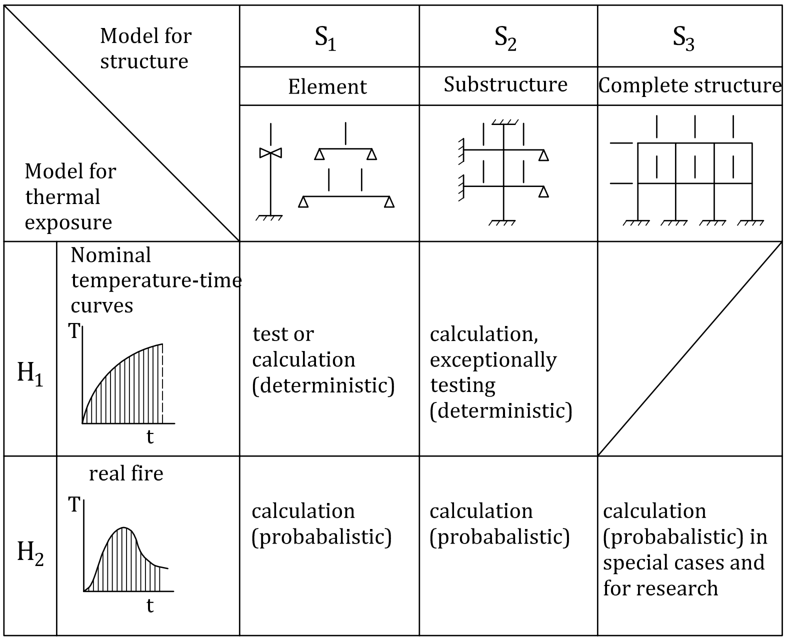


Figure 4 — Combination of thermal and structural analysis

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

