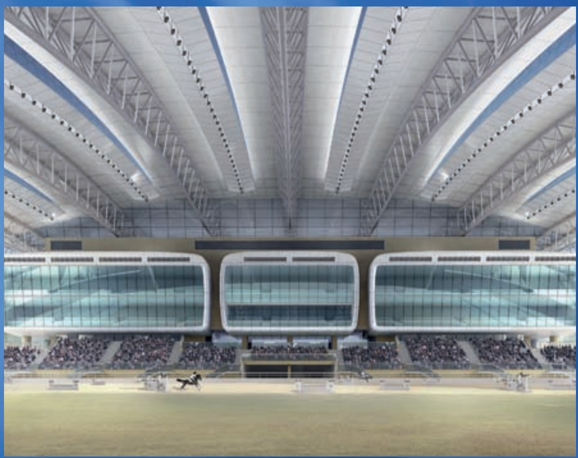
IStructE

Guide to the advanced fire safety engineering of structures



August 2007

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Guide to the advanced fire safety engineering of structures

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Acknowledgements
The Institution gratefully acknowledges the sponsorship provided for this *Guide* by Arup, British Constructional Steelwork Association, The Concrete Centre, Corus, and FEDRA.

Published by The Institution of Structural Engineers, International HQ, 11 Upper Belgrave Street, London SW1X 8BH
ISBN 978-0-901297-46-4

Front cover images: See Figures 6.1, 6.3, 6.4 and 6.7 for details.

CONTENTS

CFD: Computational fluid dynamics (CFD) models are used to solve the fluid movement within a compartment to predict smoke and fire development.

Emissivity: Indicates the efficiency of an emitting surface as a radiator, with a range between zero and 1.0. An ideal 'black-body' radiator has an emissivity value of 1.0.

Fire compartment: A space within a building enclosed by separating members (e.g. wall, floor) tested to the required fire resistance. The space may extend over one or more storeys.

Fire load: The energy released by combustion of materials in a space.

Flashover: A relatively rapid transition between the fire which is essentially localised around the items first ignited and the general conflagration when all surfaces within the compartment are burning.

Fully developed fire: A fire stage after flashover where all combustibles within the compartment are burning.

Localised fire: Fire involving only a limited area of the fire load in the compartment and where flashover has not occurred.

Natural fire curves: Temperature-time relationship of fire gases in a compartment determined on the basis of the physical properties of compartment, fire load and ventilation conditions.

Plume models: Mathematical model for representing the rising column of fire and smoke of a localised fire.

Standard fire test curves: A well-defined fire exposure curve used in standard fire tests for verification of fire resistance.

Time equivalence: Defined as the exposure time in a standard fire resistance test which gives the same heating effect on a structure in a given compartment.

Zone models: Mathematical model that divides the fire compartment into different control volumes or zones and defines the temperature in each zone based on the conservation of mass and energy.

FOREWORD

This *Guide* is at the forefront of the advanced analysis of structures and has come from a compelling need to better predict the performance of real structures in real fires and follows on progressively and logically from the earlier *Guide*, *Introduction to the fire safety engineering of structures*. It has been designed to help the engineer to deliver a level of finesse and flexibility for problem solving and value that is not available via the traditional prescriptive route embodied in the majority of building regulations.

One of our most important messages concerns the effectiveness of the process, which is essential for controlling the quality for both the designer and approving authority. It supports and borrows from the IStructE report *Guidelines for the use of computers for engineering calculations*, which emphasises the need for clear responsibility and an effective review process. The approach also exemplifies the methodology that would be necessary to logically increase levels of safety to meet business needs and to respond to natural extreme events or other unusual scenarios.

The Task Group has benefited from excellent comments from engineers and academics from around the world. This has greatly enhanced the breadth and the depth of this publication ensuring that the *Guide* has applicability in many countries because it relies on the basics of science and engineering.

I would like to thank all members of the Task Group and its Secretary, Berenice Chan, for their help in producing this *Guide*. In addition, I would like to recognise the significant contribution of Professor Colin Bailey of University of Manchester who drafted the *Guide*, under the direction of the Task Group. This has been a challenging document to develop and Colin's hard work and effective response to the requirements of the Task Group, in a timely manner, is much appreciated.

M Green
Task Group Chairman

1 INTRODUCTION

1.1 Background

This *Guide* provides an overview of the available advanced methods for designing structures for fire resistance and should be read in conjunction with the previous publication *Introduction to the fire safety engineering of structures*[1], which presented a range of simple design approaches and useful background information. Each stage of the advanced design process (modelling the fire, determining the heat transfer to the structure and high temperature structural analysis) is discussed, with guidance on the various approaches which can be adopted.

Traditionally, structural engineers did not venture into fire design, due to their lack of knowledge of fire behaviour, relying instead on simple prescriptive rules and guidance, which ensured sufficient passive fire protection to structural members, based on standard fire tests. Likewise, fire engineers also relied on simple prescriptive rules mainly due to their lack of knowledge of structural engineering and understanding of how structures behave under fire load. Structural fire design brings together the disciplines of structural engineering and fire engineering, to allow a performance-based design approach to be carried out which can allow more economic, robust, innovative and complex buildings to be constructed.

Currently the use of advanced structural fire design is not common, with most buildings being designed using the simple prescriptive approaches discussed in the previous publication. However, the benefits of using advanced design approaches are becoming more apparent, leading to an increased interest in their application.

The advantages of adopting advanced design approaches are[2]:

- Generally more economical designs, compared to the simple prescriptive approaches, whilst still maintaining acceptable levels of life safety.
- The construction of more innovative and complex buildings which were not possible due to the restrictive nature of the simple prescriptive rules.
- A better understanding of the actual structural behaviour of the building during a possible fire.
- The construction of more robust buildings due to the advanced design approach allowing identification, and strengthening, of any 'weak' links within the structure.
- An increase in the levels of safety offered by the simple prescriptive design approaches, by incorporating advanced structural fire design within a global fire strategy.

This *Guide* is aimed at the structural engineer and approving bodies. For the structural engineer, guidance is presented enabling the selection of a suitable advanced design approach, together with identifying the detailed procedures and corresponding tools, which can be used at each stage of the design. An understanding of the important characteristics and parameters, which need to be included within the chosen design approach, is also discussed. By providing guidance on a suitable framework for the design process, together with a simple design checklist, the *Guide* is also of benefit to approving bodies enabling the right questions to be asked, and informed decisions to be made.

Although the codes referenced in this *Guide* are generally those that are applicable in the UK and Europe, because the methodology used relies on the basics of science and engineering, the *Guide* will also have international applicability and will be able to be used with the relevant local codes.

1.2 Status of the *Guide*

The Institution of Structural Engineers has produced this *Guide* as guidance and it is only intended for use as such. It is not intended to provide the definitive approach in any situation, as in all circumstances the party best placed to decide on the appropriate course of action will be the engineer undertaking the particular project.

2 DESIGN METHODOLOGY

2.1 Introduction

The minimum legislative level of safety for structural fire design provides an acceptable risk associated with the safety of the building occupants, fire fighters and people in the proximity of the building.

Structural fire engineering involves the consideration of the likely fire severity, the heat transfer to the structure and high temperature structural analysis. In most cases designers will not implicitly consider these three components and will follow simple prescriptive rules or guidance based on fire resistance periods. Typical examples of prescriptive approaches consist of specifying a thickness of applied fire protection to steel members or specifying minimum sizes and cover to reinforcement for concrete members. Typical rules relating to the structural fire response of concrete, steel, timber and masonry are described in the previous publication[1] *Introduction to the fire safety engineering of structures*, on the *One-stop-shop in structural fire engineering* website[2] (www.structuralfiresafety.org) and in References 3 to 8.

Although, to-date, the well-known prescriptive rules have been shown to be generally adequate for the minimum life-safety requirement, they can be uneconomical, restrictive and do not provide an understanding of how buildings actually behave in fire. If the prescriptive rules are followed they are expected to satisfy the regulations. By adopting a performance-based approach to structural fire engineering, where the fire severity, heat transfer and structural response are considered, more economical designs can be achieved and more innovative and complex buildings can be constructed. The performance-based approach also allows an appreciation of how buildings will actually behave in a fire, with the option of designing more robust buildings. If a performance-based approach is adopted then the onus is on the designer to demonstrate that the regulations have been met.

If, following discussions with the client, there is a need to increase levels of safety to protect the building contents, the building superstructure, heritage, business continuity, corporate image of the occupants or owner, and/or the environmental impact then a performance-based approach should be considered, within an overall risk-based design, which incorporates fire safety management and active measures.

There are different approaches[2], of varying complexities, for a performance-based structural fire engineering design. The overall complexity of the design depends on the assumptions and methods adopted to predict each of the three design components relating to the fire severity, heat transfer and structural response. Figure 2.1 shows various methods for predicting each of the three design components. It is acceptable to use any permutation of the design components shown in Figure 2.1, with some general guidance on using different permutations given in Section 2.2.3.

Increasing the complexity of the structural fire design will lead to increased design costs, but with the benefit of a greater reduction in the uncertainty of the building response in a fire and typically a resulting economy in overall building costs.

2.2 Overview of design process

A reasonable design process[2] is shown schematically in Figure 2.2. Each step is described in detail in Sections 2.2.1 to 2.2.9.

2.2.1 Determine requirements and objectives

Life safety is the fundamental minimum legislative requirement for the structural fire design of buildings. The life safety requirements comprise reasonable:

- Safe egress of the occupants from the building or reasonable safe movement of occupants to designated refuge areas within the building.
- Safe operating conditions for fire fighters.
- Safety of people within or in the proximity of the building (including fire-fighters) from the threat of possible collapse of the building.

Life safety requirements are covered by regulations which may be functional or prescriptive. For example, the Building Regulations in England and Wales[9] provide the following functional objectives relating to structural aspects of fire safety:

- The building shall be designed and constructed so that in the event of fire its stability will be maintained for a reasonable period.
- To inhibit the spread of fire within the building it shall be divided with fire resisting construction to an extent appropriate to the size and intended use of the building.

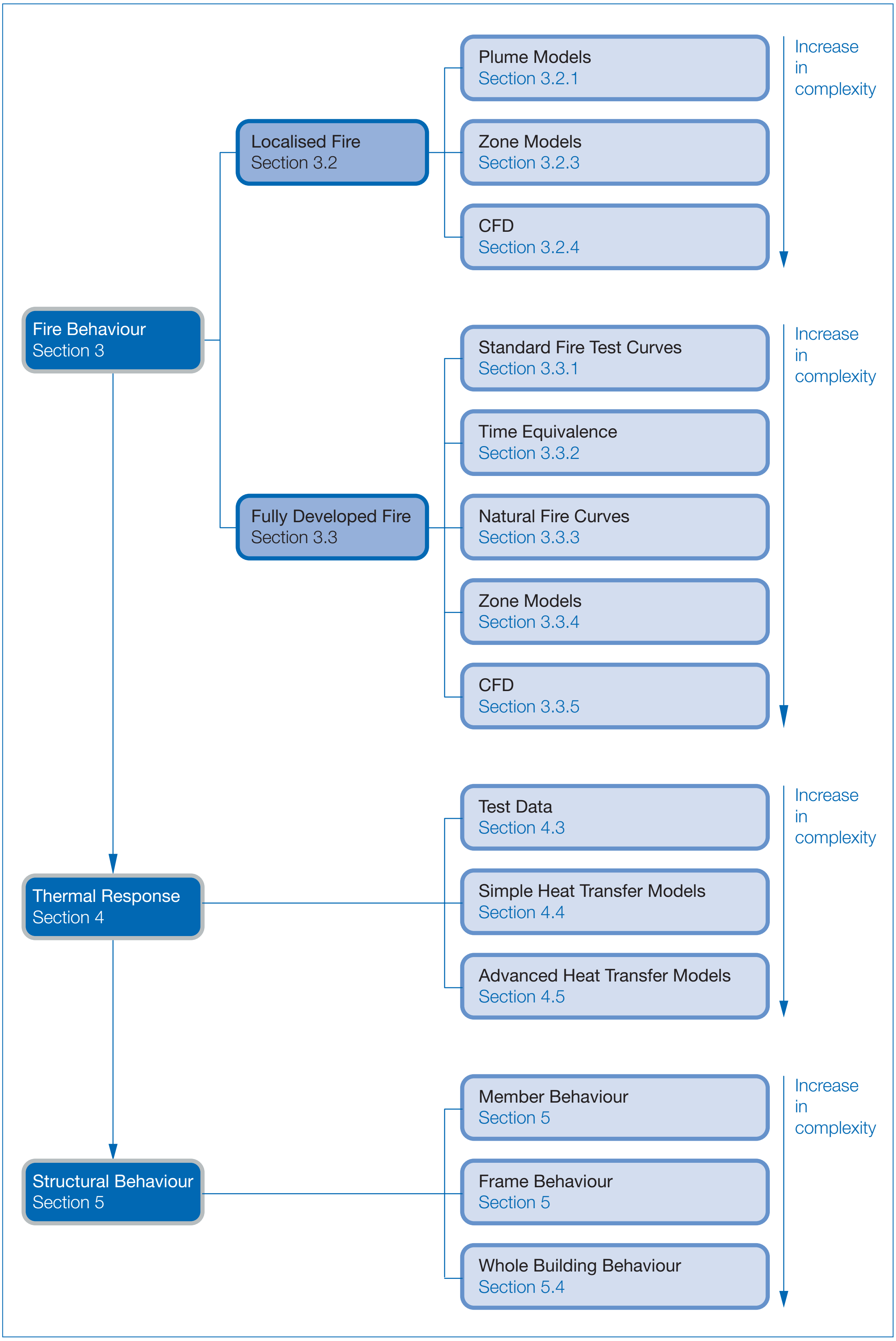


Figure 2.1 Available approaches for the three components of structural fire engineering design[2]

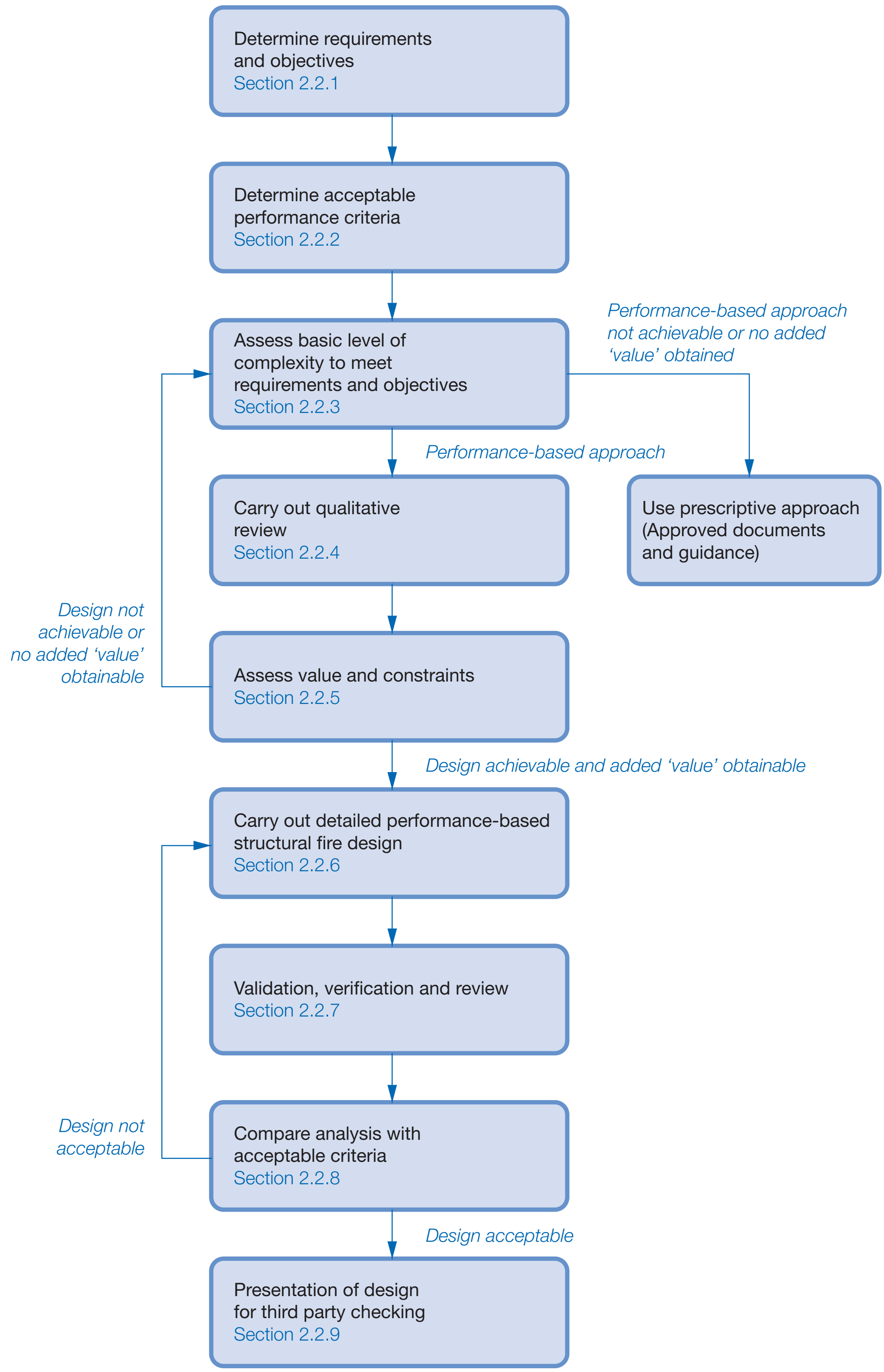


Figure 2.2 Design process[2]

To meet these life safety requirements either a performance-based approach or the simple prescriptive rules, as outlined in the approved documents[10] or guidance[1-8,11], could be adopted.

Should the client require it, the fire safety design could also deliver a higher standard than the legislative requirement for fire safety, to increase the protection to the building and its contents. To assess the 'value' of extending the fire design beyond the fundamental life safety requirements a risk assessment is generally required to assess acceptable risks taking into account the direct and indirect losses from any possible fire.

Any increase in safety above the fundamental life safety requirements can result in the need to provide additional measures, which could result in higher initial costs. It is important that the requirements and objectives are discussed with the client (and possibly insurance companies) at the start of the project and are clearly defined.

The requirements, objectives and the performance criteria for each building are particular to that building. The Qualitative Design Review (QDR) process as described in BS 7974[12] is the most appropriate method for drawing from the experience and knowledge of the team members in order to define the input to the quantitative analysis, define acceptance criteria and define a reasonable worst case fire scenario. The approach, the timing and the check lists that are provided in BS 7974, when reviewed in combination with the guidance in this document, form a useful basis for managing the overall approach.

2.2.2 Determine acceptable performance criteria

The acceptable criteria within a performance-based structural fire design should be based on the global fire strategy for the building.

A comparative, deterministic or probabilistic approach, as outlined in BS 7974[12], can be adopted to determine the acceptance criteria. For a comparative approach the levels of safety obtained from a performance-based design are compared to the levels obtained from a simple prescriptive approach to ensure equivalent safety levels are achieved. For a deterministic approach, set objectives are defined and these must not be exceeded. A probabilistic approach requires expert knowledge and is out of the scope of the *Guide*. For details of a probabilistic approach reference should be made to BS 7974[12].

To meet the life-safety requirements given in Section 2.2.1 the following points[2], if relevant to the considered building and adopted design approach, need to be addressed. Either a comparative or deterministic approach should be used when considering the acceptable structural response.

- The structure should remain stable for a reasonable worst case fire scenario considering cooling when appropriate. If natural fire curves are used the effect of the cooling stage of the fire on the behaviour of the structure should be considered. For example, for steel framed structures a significant proportion of the connections should be able to reasonably accommodate large tensile forces without loss of vertical shear capacity.
- Both vertical and horizontal compartmentation should be maintained for the duration of the reasonable worst case fire scenario. Vertical displacement of the floor slabs and beams in the proximity of the compartment walls should be considered, particularly when more advanced methods are being adopted. These displacements can be an order higher than those experienced at ambient temperature.
- All escape routes, especially for phased evacuation, should remain tenable for a reasonable period of time.
- Fire-fighting shafts should not be compromised for the duration of the reasonable worst case fire scenario.
- By consultation with specialist suppliers, the effect of large structural movements on any applied fire protection, fire stopping, penetration seals, and the integrity of ducts and dampers should be considered for the reasonable worst case fire scenario.
- If identified as a critical fire scenario, the risk and consequence of fire spread up the building, through windows, should be considered within the structural fire design strategy.

To reduce the loss of business associated with fire risk, satisfactory active measures and fire safety management are generally required to reduce the risk of fire ignition and subsequent development. It is important that any active measures and management systems are designed and installed correctly and adequately maintained. Fire safety management is a process which reduces the risk of fire ignition and ensures that if a fire does start that all the fire safety systems are in place and fully functional. More guidance on fire safety management is given in BS 5588-12[13].

If fire ignition does occur then it is important to ensure that the fire remains within the room of origin, or within the defined fire compartment, thus keeping the structural and building contents damage to a minimum.

It is worth mentioning that, provided any vertical and horizontal compartmentation is maintained, the magnitude of the displacement of the structure is relativity unimportant when considering reinstatement. For example the cost and time of replacing a floor slab with 100mm displacement is similar to the cost and time of replacing a floor slab with 400mm displacement.

2.2.3 Assess basic level of complexity to meet requirements/objectives

Either a prescriptive approach, with well-defined guidance, or a performance-based approach, based on the various methods in Figure 2.1, should be identified to meet the requirements/objectives.

A prescriptive approach is assumed to meet the minimum legislative requirements of life-safety, although it will also provide an unknown level of property and environmental protection. The restrictive nature of the prescriptive rules makes them impossible to use for some buildings. For example where exposed steelwork is a 'feature' or in buildings such as shopping centres, airports, etc. where it is not possible to apply the simple prescriptive rules. If this is the case then a performance-based approach should be adopted.

A performance-based structural fire design consists of defining the fire behaviour, the transfer of heat to the structure and high temperature structural analysis. Figure 2.1 shows the available methods covering these three aspects of the design.

The choice of the design approach will depend on[2]:

- the defined requirements and objectives
- the experience of the designer
- the potential economical return
- the need to consider higher levels of safety above the regulatory requirement
- the need to design complex and innovative buildings.

Considering life safety only, significant cost savings may be achieved by using a performance-based approach. For example:

- Steel-framed buildings that would require applied fire protection using the prescriptive approach.
- Concrete buildings where the member size is governed by the minimum dimensions given by the prescriptive approach.

It is possible to use any permutation of the methods shown in Figure 2.1 to define the fire behaviour, heat transfer and structural response. The following, general guidance[2] is provided when considering different permutations:

- The accuracy of the design as a whole should be considered. For example the designer would need to consider the effect, and validity, of using the simple standard temperature-time relationships with advanced heat transfer and structural response models, when carrying out a deterministic approach. The Eurocodes[14-19] do allow such a design approach but it must be noted that there is little to be gained in predicting the heat transfer and structural response to a high level of accuracy when the prediction of the fire is crude and bears little resemblance to reality. However, this combination may be appropriate when carrying out a comparative approach. An example would be the case where a standard fire is used and advanced analysis is used to compare the relative performance of a simple compliant structure with that of a more complex structure when test or prescriptive design data is not available.
- The comparative approach should be carefully reviewed to make sure that a true like for like comparison is being made. In particular it is important to make sure that using the standard fire curve does not mask any detrimental effects resulting from a more rapid rise in temperature that can occur in some real fires. Detrimental effects such as higher temperatures or larger differential temperatures across the structure can result in earlier strength loss or higher forces in connections. However the temperatures of structures with beneficial insulation properties tend to lag significantly behind the gas temperature and are less likely to suffer from these detrimental effects. An inspection of the natural and standard fire curves showing the temperature lag for the structure will enable an informed decision on whether the comparative approach is reasonable.
- If there is reliable thermal test data, relevant to the assumed fire behaviour, then this may be sufficient to replace the need for a thermal analysis for input into structural finite element analysis.
- The knowledge and experience of the designer. The use of zone models, CFD and finite-element heat-transfer and structural models requires specialist knowledge and should only be used by suitably experienced personnel.

- The accuracy and availability of the data representing the fire load, ventilation, and thermal properties of the compartment boundaries, heat release rates, material properties and applied static loads.
- Availability of software for zone, CFD and finite-element models.
- Available time to carry out the design.
- Capital cost of the project. For a low cost project the use of advanced fire models may not be justified.
- The importance of considering the structural behaviour during the cooling phase of the fire. If the structural behaviour during the cooling stage is considered to be important then standard fires cannot be used.

2.2.4 Carry out qualitative review

As is common with any design process, a qualitative review of how the structure will behave should be conducted. In most cases the structural engineer will rely extensively on experience and engineering judgment to obtain a 'feel' for how the structure will behave under fire conditions. The qualitative review may be enhanced by carrying out a scoping study.

The extent and need to carry out a scoping study will depend on the complexity of the final design approach adopted. Basically, the scoping study should be a more simplified approach compared to the final design. The scoping study will allow the designer to assess whether the final, more complex, design provides reasonable results, and in some cases will allow an early assessment of whether a complex design will result in cost savings.

For example[2], considering the available approaches in Figure 2.1, if the designer decides to carry out a time equivalence calculation to define the fire behaviour, use simple tables (test data) to define the thermal response and member design to define the structural behaviour, then as a scoping study the prescriptive rules (based on standard fire curves) could be considered to verify that the final results are reasonable.

At the other extreme of design complexity, if the designer decides to use CFD to model the fire behaviour, advanced heat transfer models to predict the heat transfer and whole building structural behaviour, then the scoping study should consider a more simplified approach. This simplified approach could consist of using parametric curves or zone models, simple heat transfer models and member or frame response. This scoping study will allow the designer to assess whether it is worth carrying out the more complex, and time consuming, design and will also allow an assessment of whether the final results from the complex analysis are reasonable.

In some complex designs, especially for structural finite element modelling of complicated structures under non-uniform heating, it will not be possible for the scoping study to provide the required information to assess whether the final results are reasonable. In this case the designer will have to rely on experience and engineering judgment.

2.2.5 Assess value and constraints

Based on the qualitative review, the proposed design should be assessed to ensure it delivers added 'value' above a more simplified approach. The assessment in terms of value will depend on the stated requirements and objectives. If the minimum requirement is life safety, then the added value may be defined in terms of initial savings. For example[2], the assessment may consider whether it is possible to reduce the applied fire protection on steel members or have smaller member sizes for concrete buildings, whilst still maintaining acceptable levels of life safety. Added value may also be defined in terms of a reduction in the uncertainty of the building response in a fire, which can lead to the design of more robust buildings.

If the requirements and objectives consider the risk relating to financial loss then the added 'value' will need to be based on both direct and indirect costs, within a risk-based approach.

As well as assessing the 'value', the designer also needs to assess the practicality of the proposed approach. For example[2]:

- Are qualified and experienced designers available to carry out the design?
- Is there sufficient scientific knowledge available? (For example material properties at elevated temperatures.)
- If required, is there sufficient validated software available which can be used efficiently and within any time constraints?

2.2.6 Carry out detailed performance-based structural fire design

The design should consider the severity of any reasonable worst case fire, the transfer of heat to the structure and the response of the structure. There are a number of methods, of varying complexity, as shown in Figure 2.1. These methods range from simple hand calculations to the use of sophisticated computer models.

Irrespective of the approach used, the proposed design should include[2]:

- a clear statement of the adopted approach and type of design model used
- a clear statement of the assumptions adopted and an assessment of the consequence of each assumption
- a consideration of the cumulative effect of assumptions
- identification of any uncertainties within the design and how these are addressed
- sensitivity analyses of the design, which may be based on experience
- identification of any 'weak' points within the structure and how these may be overcome.

In some cases the design may be limited to considering the likely severity of the fire, with the aim of ensuring that the atmosphere temperatures, from any possible fire, will remain sufficiently low as to not affect the structure. In this case the above points relating specifically to the structural response are ignored.

The use of sophisticated computer models can be time-consuming. It is advisable that the concept model (see Section 5.4.2), especially on the issues relating to boundary conditions, mesh density and connectivity (see Section 5.4.1), is agreed with the checking bodies before the analysis is carried out.

2.2.7 Validation, verification and review

The extent of validation, verification and review of the design should be proportional to the complexity of the design adopted.

Validation

In its general form validation is the process of demonstrating that the design approach (model) is suitable for its intended purpose. The appropriateness of the design approach covering the prediction of fire severity, heat transfer and structural response should be considered separately and also in combination with each other.

Within all design models a number of assumptions are adopted and these should be understood and systematically reviewed and assessed during the design process. This is particularly important when using computer software. Designers should not use any software without an appreciation of its capabilities and limitations. Any computer modelling should address the following[2] (with more details given in Section 5.4.1):

- boundary conditions
- non-linear material behaviour
- structural connections and localised behaviour
- mesh density
- connectivity
- large displacements and geometric non-linearity.

A clear statement explaining the effect of these assumptions and approximations should be included within the design.

Verification

Verification is an assessment of whether the design model has produced correct results and should include[2]:

- a check of input data
- an assessment of whether the results correspond to what was anticipated in the qualitative review
- a constant watch for errors and anomalies and an appreciation of why they might occur
- a sensitivity analysis, which may be based on experience. A sensitivity analysis would be of particular relevance if the results do not correspond to what was anticipated in the qualitative review
- an assessment of the degree of risk associated with possible errors. For example, has the software been validated against available test results or alternative software?

Review

A review of the design should be documented and checked, which should include information about how the design approach has been validated and verified.

2.2.8 Compare analysis with acceptable criteria

The results from the design are compared against the acceptable performance criteria defined in Section 2.2.2.

2.2.9 Presentation of design for third party checking

The design should be presented in a form that could readily be checked by a third party. Each step in the design process (see Figure 2.2) should be clearly documented including any assumptions and approximations.

The following general checklist[2] is presented as a guide. Consideration is given to the overall design approach adopted together with the choice of approach used to define the fire severity, heat transfer and structural response.

Overall design

- Has the design process (see Figure 2.2) been clearly described?
- Has each stage of the design process (see Figure 2.2) been clearly stated?
- Have the requirements/objectives (see Section 2.2.1) been clearly stated?
- Have the acceptable performance criteria (see Section 2.2.2) been defined, based on the overall fire strategy?
- Has the design been adequately validated, verified and reviewed (see Section 2.2.7)?
- Are the assumptions, approximations and accuracy consistent for the fire, heat transfer and structural model?
- Are the adopted assumptions clearly stated, with an assessment of the consequence of each assumption?
- Has the cumulative effect of any assumptions and approximations within the fire, heat transfer and structural model been considered?
- Have any uncertainties, or possible errors, with the design been addressed?
- Do the final results correspond with what was expected, based on the qualitative review (see Section 2.2.4)?

Fire model

- Has the fire model (see Figure 2.1) and the reasons for its choice been explained?
- If the standard temperature-time relationship has been adopted:
  - Has the effect of adopting such a simplistic representation when considering the thermal and structural response been assessed?
  - Have any possible detrimental effects of cooling been considered and addressed in the structural design?
- Has the accuracy of the input data for the ventilation, fire load, heat release rate, compartment geometry and thermal characteristics of the compartment boundaries been assessed?
- How has the reasonable worst case fire scenario been defined?
- Has a sensitivity analysis been considered by varying the ventilation and thermal characteristics of the compartment boundaries?
- If time-equivalence (see Section 3.3.2) is used, is it valid for the type of construction adopted?
- If CFD modelling (see Sections 3.2.4 and 3.3.5) is used, how has it been validated?

Heat transfer

- If charts, analytical methods or test data are used (see Section 4.4), to define the thermal distribution through members, are they valid for the fire model used?
- If simple or advanced heat transfer models (see Section 4.4 and 4.5) are used, do the heat flux and emissivity values correspond to the fire model adopted?
- If advanced heat transfer models are used (see Section 4.5), how is the modelling of moisture movement validated (although ignoring moisture movement will result in conservative temperature estimates, provided spalling does not occur)?

Structural response

- If simple models are used (see Section 5.3), are they valid for the chosen fire model?
- If detrimental, how has the possible effects of concrete spalling (see Section 5.2.3) been taken into account?
- If finite element models are used, the following points should be considered:
  - Has the input data been checked carefully?
  - Compared to the scoping study, experience or engineering judgement, are the results as expected?
  - Has the software been validated against available test results or alternative software?
  - Are the assumptions and approximations embedded within the software fully understood?
  - Has numerical failure (i.e. model instability) instead of actual structural failure occurred?
  - Has the mode of failure (see Section 5.4.3) been identified?
  - Has localised failure (see Section 5.4.1) been considered?
  - Are boundary conditions (see Section 5.4.1) realistic?
  - Has the mesh density adopted (see Section 5.4.1) been verified?
  - Has the correct material stress-strain-temperature relationships (see Section 5.4.1) been used?
  - Where appropriate, has strain reversal been included?
  - Where appropriate, have various fire scenarios been considered to define the worst case structurally?

3.1 Introduction

Fire severity needs to be defined to carry out a structural fire engineering design. The available approaches to defining fire severity are explained in this chapter and shown in Figure 3.1.

The basic development of an enclosed uncontrolled compartment fire can be divided into a number of stages, as shown in Figure 3.2, with each stage described in Table 3.1.

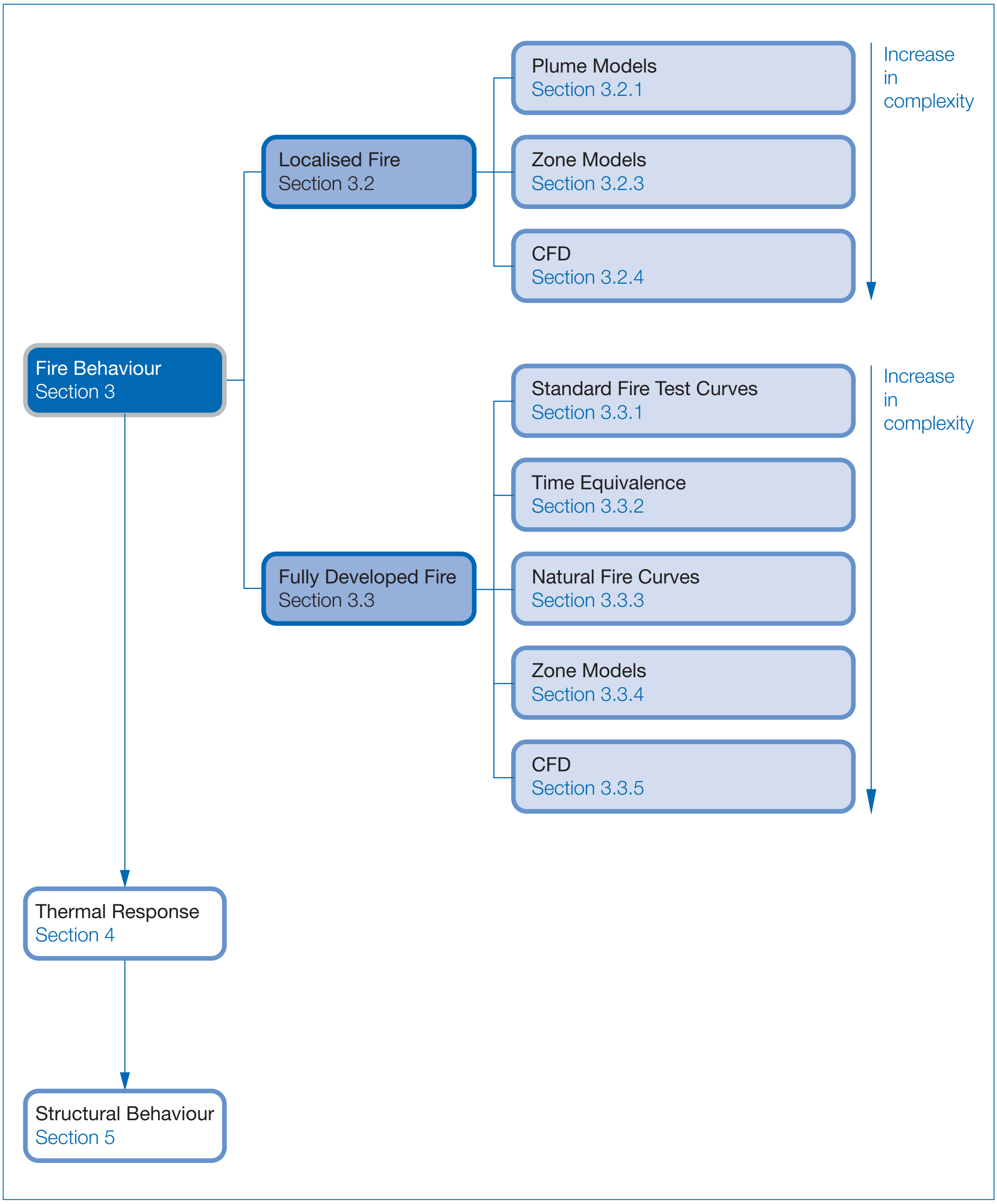


Figure 3.1 Available methods to define the fire severity

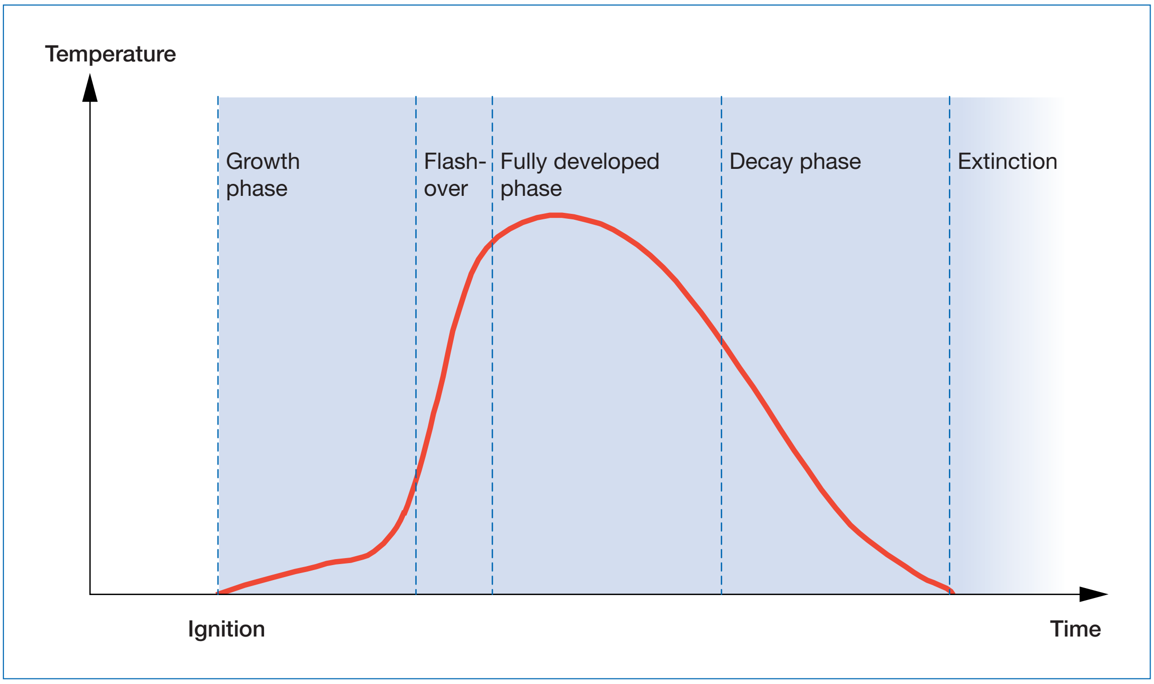


Figure 3.2 Temperature-time curve for an enclosed fire

Table 3.1 Stages of an enclosed compartment fire[2]

Fire Stage	Description
Growth phase (pre-flashover)	Ignition defines the beginning of the fire development. At the initial growth phase, the fire will normally be small and localised within the compartment and may stop at this stage. Smoke and combustion products (pyrolysis) will accumulate beneath the ceiling gradually forming a hotter upper layer in the compartment, with a relatively cooler and cleaner layer at the bottom. With sufficient supply of fuel and oxygen, and without the interruption of fire fighting or other active measures, the fire will continue to grow with the release of more hot gases and pyrolysis to the smoke layer. The smoke layer will descend as it becomes thicker. If the growth of the fire is slow due to lack of oxygen or combustible material in the proximity of the fire then the fire remains localised.
Flashover	If the development of the fire causes the gases in the compartment to become sufficiently hot (approximately 550-600ºC) sudden ignition of all combustible objects within the compartment will occur. This phenomenon is known as flashover with the whole compartment engulfed in fire.
Fully developed phase (post-flashover)	After flashover, the fire enters a fully developed stage with the rate of heat release reaching a maximum and the burning rate remaining substantially steady. The burning rate may be limited by availability of ventilation or fuel. Normally this is the most critical stage which, unless controlled, can lead to possible wide spread structural damage and fire spread to other compartments.
Decay phase	After a period of sustained burning, the rate of burning decreases as the combustible materials are consumed and the fire enters the decay phase.
Extinction	The fire will eventually cease when all combustible materials have been consumed and there is no more energy being released.

The factors influencing the severity of a fire in a compartment are:

- fire load type, density and distribution
- combustion behaviour of the fire load
- compartment size and geometry
- ventilation conditions of the compartment
- thermal properties of the compartment boundary.

The occurrence of flashover in a compartment fire defines a transition in the fire development process. Therefore, many fire models are classified as pre- or post-flashover models, except for computational fluid dynamic (CFD) models which attempt to model all stages of the fire.

As shown in Figure 3.1, there are a number of options[2] available to calculate the fire severity. The level of complexity increases from simple fire models to CFD models. The input parameters for each of these models varies, with the advanced models requiring very detailed and accurate input data and simple models requiring nominal input.

The standard fire curves are defined time-temperature relationships used in standard fire tests and are not based on any physical parameters. The time equivalence, natural fire curves, localised fires, zone models and CFD models include (to varying degrees) the physical parameters listed above. Pre-flashover fires can be modelled using localised fires, two-zone models and CFD models. Post-flashover fires are modelled using natural fire curves, one-zone models, and CFD models with time equivalence providing a simple approach of relating a post-flashover fire to the time-temperature relationship used in a standard fire test. The major assumption of these post-flashover models is that the atmosphere temperature throughout the compartment is assumed to be uniform. CFD models attempt to predict the complete fire growth from pre to post-flashover behaviour, incorporating varying temperature distributions through the compartment.

A summary of the fire models[2], their complexity, predicted fire behaviour, input parameters and design tools are shown in Table 3.2.

Table 3.2 Options for modelling compartment fires[2]

Fire model	Nominal fires	Time equivalence	Natural fire curves	Localised fires	Zone models		CFD/field models
					One-zone	Two-zone	
Complexity	Simple	Intermediate			Advanced		
Fire behaviour	Post-flashover fires			Pre-flashover fires	Post-flashover fires	Pre-flashover/ localised fires	Complete temperature-time relationships
Temperature distribution	Uniform in whole compartment			Non-uniform along plume	Uniform	Uniform in each layer	Time and space dependent
Input parameters	• Constant time-temp. relationship • No physical parameters	• Fire load • Ventilation conditions • Thermal properties of boundary • Compartment size		• Fire load and size • Height of ceiling	• Fire load • Ventilation conditions • Thermal properties of boundary • Compartment size • Detailed input for heat and mass balance of the system		Detailed input for solving the fundamental equations of the fluid flow
Design tools	Simple equations for hand calculations		Spread-sheet	Simple equations	Computer models		

When considering the fire behaviour, the designer needs to define whether the fire remains localised or flashover occurs resulting in a fully developed fire. A localised fire will occur when there is no spread of fire to the whole compartment due to the propagation being so slow that the temperature rise is not sufficient to cause flashover, or there is insufficient combustible material in close proximity to the source of the fire. It is generally accepted[20,21] that flashover transition occurs when the upper smoke layer reaches temperatures of about 550°C to 600°C or the radiation to the floor exceeds about 20kW/m².

Scenarios where localised fires are most likely to occur include:

- large high spaces with relatively limited fire load, such as atria, circulation areas in airports, shopping malls, etc.
- areas where there are high levels of ventilation such as in open canopies, typically at hotel entrances, under link bridges at airports, etc.
- areas where fire load can be reliably controlled to relatively low levels or spaced such that fire cannot readily spread from one area of fire load to another.

The only feasible design method to stop flashover in a compartment, where there is sufficient ventilation, is to limit the fuel and distance between fuel items or to use a suppression system. Design methods for determining flashover are presented in the CIBSE Guide[22] on Fire Engineering or PD 7974-1[21].

3.2 Localised fire

Pre-flashover or localised fires are useful when flashover is unlikely to occur, or information on the pre-flashover stage is required. The available models[2], in order of complexity, to estimate pre-flashover fires are:

- design equations given in BS EN 1991-1-2[14] (see Section 3.2.1)
- design equation given in PD 7974-1[21]
- two zone models (see Section 3.2.2)
- CFD models (see Section 3.2.3).

3.2.1 Fire plume models

BS EN 1991-1-2[14] (EC1) provides a simple approach for determining the thermal action of localised fires. The temperatures are dependent on whether or not the flame is impacting on the ceiling of the compartment (see Figure 3.3). For the case where the flame remains below the ceiling, EC1[14] provides guidance on calculating the temperatures in the plume along its vertical axis. For the case where the flame impacts on the ceiling EC1[14] provides guidance on calculating the heat flux at the level of the ceiling together with the flame length (L_h) as shown in Figure 3.3.

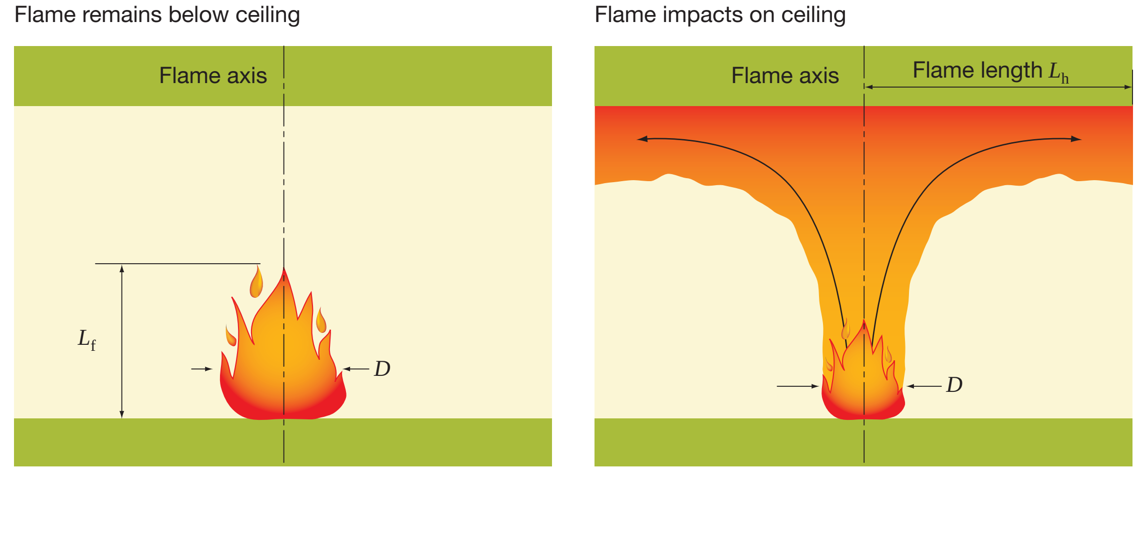


Figure 3.3 Definition of localised fire[2]

The UK National Annex to EC1[14] does not allow the use of the method presented in the code for localised fires. Designers are directed instead towards the method in PD 7974-1[21].

3.2.2 Simplified method given in PD 7974-1

PD 7974-1[21] (cl. 8.2.1.10) provides a simple expression to predict temperatures within an enclosure prior to flashover. The temperatures in the hot layer are assumed to remain below approximately 550°C. Above this temperature flashover is assumed to occur and post flashover models should be used. It should be noted that there is a typographical error in Equation 7 of PD 7974-1. The correct equation[23] is:

$$\theta = 6.85\left(\frac{Q^2}{A_w h^{1/2} h_k A_t}\right)^{1/3}$$

Where:

- θ is the temperature rise above ambient in the upper gas layer in °C
- Q is the total rate of heat release in kW
- A_w is the area of the ventilation opening in m²
- h is the height of the ventilation opening in m
- h_k is the effective heat transfer coefficient, as defined in PD 7974-1[21] in kW/m²K
- A_t is the total surface area of the enclosure in m²

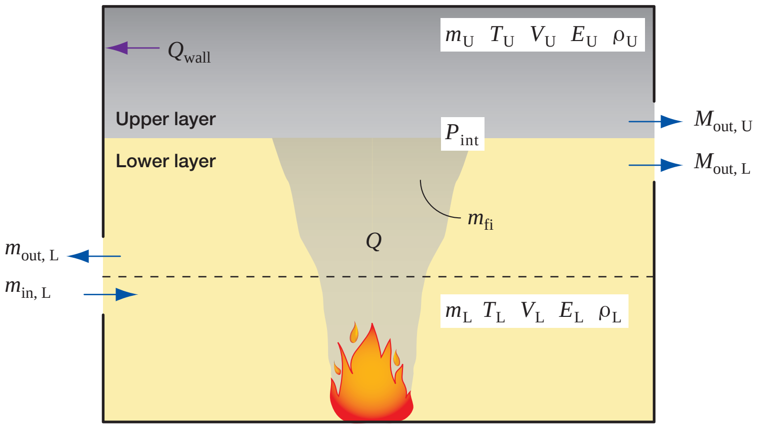
3.2.3 Two zone models

Zone models are simple computer models that divide the considered fire compartment into separate zones, where the condition in each zone is assumed to be uniform. The models define the temperature of the gases as a function of time by considering the conservation of mass and energy in the fire compartment.

Two-zone models are used for pre-flashover fires whereas one zone models are used for post-flashover fires. For two-zone models the compartment is divided into different areas including the upper layer, lower layer, fire and plume. The main features include[2]:

- The upper layer represents the accumulation of smoke and products of pyrolysis beneath the ceiling.
- In each layer, the gas temperature is assumed to be uniform with the upper layer being hotter.
- There is horizontal interface between the upper and lower layers.
- The air entrained by the fire plume from the lower layer into the upper layer is taken into account.

Figure 3.4 shows, schematically, how a compartment is modelled using a two-zone model. Similar to the one-zone models, the two-zone models are based on solving the ordinary differential equations for the conservation of mass and energy in the compartment, but at a higher degree of complexity. The conservation



Note

Physical properties of gas inside the fire compartment:

- E is the internal energy of gas
- m is the mass terms
- P_{int} is the gas pressure
- Q is the energy terms
- T is the gas temperature
- V is the volume
- ρ is the gas density

Figure 3.4 Schematic diagram for typical two-zone model[2] of mass and energy needs to be considered for individual zones, as well as the exchange of mass and energy between these different zones.

In real enclosure fires, a pre-flashover fire may develop into a post-flashover fire under certain circumstances. Annex D of BS EN 1991-1-2[14] (EC1) lists two situations when a two-zone fire model may develop into a one-zone fire model. They are:

- If the gas temperature of the upper layer is higher than 500°C.
- If the upper layer covers 80% of the compartment height.

3.2.4 Computational fluid dynamics

The use of Computational Fluid Dynamics (CFD) models to predict fire growth and compartment temperatures is becoming more popular. CFD models have been shown to be successful in the modelling of smoke movement, and have recently been applied to the modelling of fires.

According to Annex D of EC1[14], typical CFD models analyse systems involving fluid flow, heat transfer and associated phenomena by solving the fundamental equations of fluid flow. These equations represent the mathematical statements of the conservation laws of physics:

- The mass of a fluid is conserved.
- The rate of change of momentum equals the sum of the forces on a fluid particle (Newton's second law).
- The rate of change of energy is equal to the sum of the rate of heat increase and the rate of work done on a fluid particle (first law of thermodynamics).

In simplistic terms, the partial differential equations of the thermodynamic and aerodynamic variables are solved at numerous points within the considered compartment. The input requirement for CFD models is very demanding and requires expertise in defining the correct input parameters and assessing the feasibility of the calculated results. The model can provide information at numerous points within the compartment relating to temperature, velocity, toxic content and visibility.

3.3 Fully developed fire

A fully developed fire is defined as the stage at which all the available fuel within the compartment is burning. Either the available ventilation, or the quantity and nature of the fuel, will control the maximum heat release of the fully developed fire.

3.3.1 Standard temperature-time relationships

The nominal or standard fire curves are the simplest way to represent the behaviour of a fire within a design approach. The standard temperature-time relationships were developed to allow classification of building materials and elements in standard fire resistance furnace tests[24-26]. The temperature-time relationships do not represent real fire scenarios and do not explicitly take into account ventilation, fire load, compartment size and thermal characteristics of the compartment boundaries.

Although the standard fire curves do not represent actual fires they are typically used in the performance-based structural fire engineering design of members and whole structures, as endorsed by the Eurocodes[14-19]. For example it is possible to design members, frames and whole buildings using nominal fire curves. If the structural behaviour during cooling is considered to be important then the standard fire curves should not be used.

Figure 3.5 shows the standard temperature-time curves given in EC1[14] and PD 7974-1[21], which are summarised in Table 3.3.

Table 3.3 Nominal fire curves

Code	Fire type	Application
BS EN 1991-1-2[14]	External fire	For the outside of external walls which can be exposed to fire from different parts of the façade.
BS EN 1991-1-2[14]; PD 7974-1[21]	Standard fire	Defined in BS EN 1363-1[25] or BS 476-20[26], for representing a fully developed compartment fire.
BS EN 1991-1-2[14]; PD 7974-1[21]	Hydrocarbon	Representing a fire with hydrocarbon or liquid type fuel.
PD 7974-1[21]	Slow heating fire	Representing slowly growing fire for products that are reactive under the influence of fire.

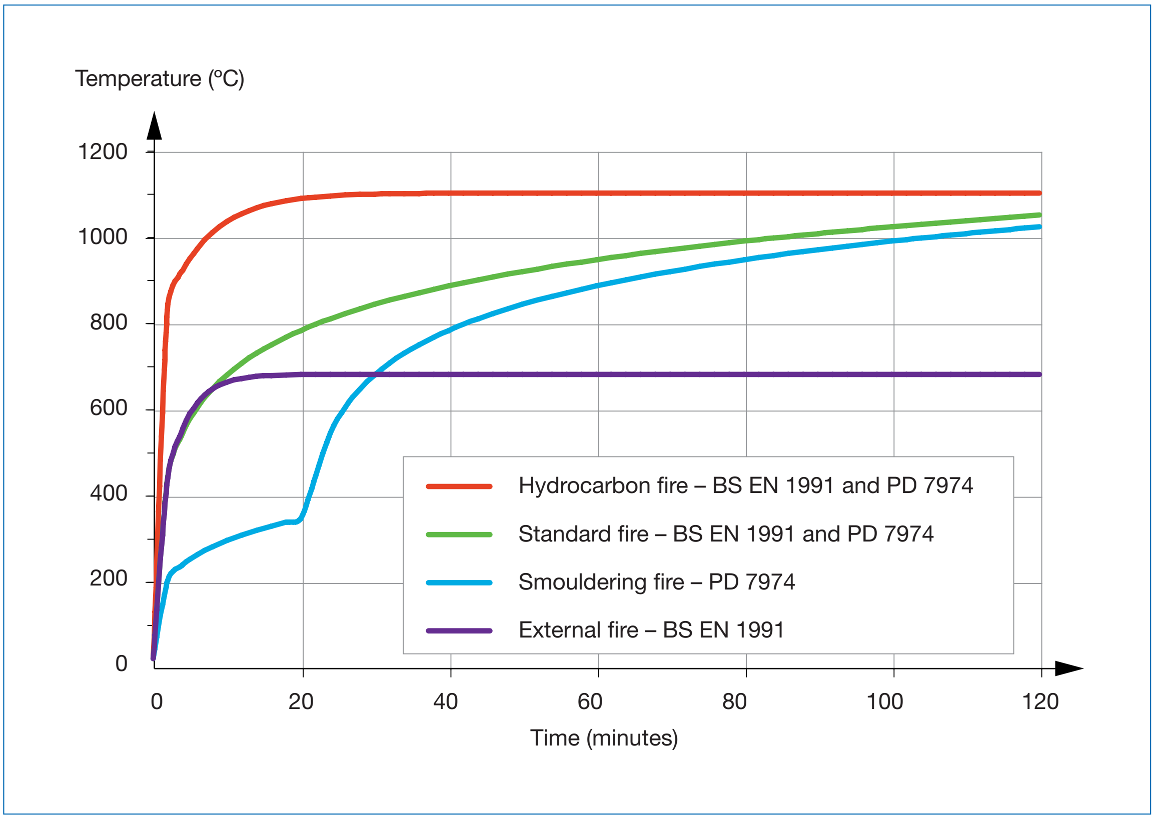


Figure 3.5 Standard/nominal fire curves

3.3.2 Time equivalence

The time-equivalence method is a simple approach that attempts to relate the severity of real fires to the standard temperature-time relationship. The definition of time-equivalence is the exposure time in a fire resistance test which gives the same heating effect on a structure as a given compartment fire. The most common 'heating effect' to be compared is the maximum temperature in structural members. Figure 3.6 illustrates the concept of time-equivalence, relating the actual maximum temperature of a structural member from an anticipated fire severity, to the time taken for the same member to attain the same temperature when subjected to the standard fire.

There are a number of time-equivalence methods which can take into account the amount of fire load, compartment size, thermal characteristics of the compartment boundaries and ventilation conditions, including:

- Law[27]
- Pettersson[28]
- CIB W14[29]
- Harmathy[30]
- BS EN 1991-1-2[14] (EC1).

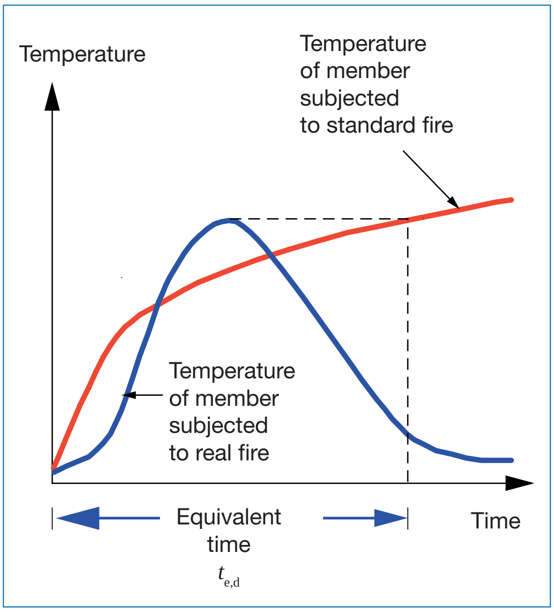


Figure 3.6 Concept of time-equivalence

Time-equivalence can either be determined by using a simple equation or taken from experimental data from natural and standard fire tests. Although simple to use, the time-equivalence is a crude approximate method of modelling real fire behaviour. If used the limitations of the method should be fully understood. For example, the method in EC1[14] is only valid for the members comprising:

- reinforced concrete
- protected steel
- unprotected steel.

It is not applicable for members comprising:

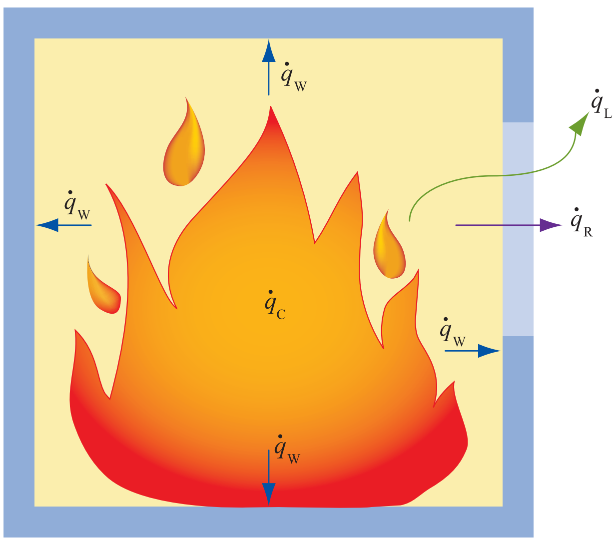
- composite steel and concrete
- timber.

PD 7974-3[31] and DD 9999[32] also provide additional information on the use of the time equivalence method and introduce factors to take into account the height of and occupancy profile of the building, together with any beneficial effects from suppression systems.

3.3.3 Natural fire curves

For natural fire models a heat balance energy equation is used to determine the temperature-time history of the fully developed fire. The main components considered within the heat balance equation are shown in Figure 3.7, where the heat produced by the combustion of the fuel is balanced by the heat losses. For heat losses the main terms comprise loss of heat by convection and radiation through openings together with the loss of heat by radiation and conduction through the boundaries of the compartment. Further details relating to the heat balance equation are given in References 23 and 33.

The concept of natural fire curves provides a simple approach to estimate post-flashover compartment fires. It is assumed that the temperature is uniform within the fire compartment and takes into account compartment size, fire load, ventilation conditions and the thermal properties of compartment walls and ceilings. Natural fire curves have been developed using a number of different approaches; the main methods are Magnusson and Thelandersson's[34] and the Eurocode[14] approach.



The heat balance of a compartment:

$$\dot{q}_C = \dot{q}_L + \dot{q}_R + \dot{q}_W$$

where

$\dot{q}_C$ is the heat released by combustion

$\dot{q}_L$ is the convective heat loss of hot gases and smoke through openings

$\dot{q}_R$ is the radiative heat loss through openings

$\dot{q}_W$ is the conductive heat loss to the walls

Figure 3.7 Heat Balance[2]

Magnusson and Thelandersson's method

Magnusson and Thelandersson[34] proposed a method for calculating the energy release rates for ventilation controlled fires in an enclosure, allowing the complete temperature-time curves for the fires to be derived.

Based on the energy balance equation by Kawagoe[35], the energy release rate is expressed as a function of time, in terms of fire load density, opening factor, and thermal properties of the enclosure boundary materials. The energy release rate curve comprises a polynomial increasing from zero to a maximum in the growth phase, followed by a constant during the fully developed phase and a polynomial decreasing from the maximum to zero in the decay phase. The maximum energy release rate is determined from the opening factor.

The main assumptions within the method included:

- the energy release rate is ventilation-controlled during the fully developed stage
- the temperature within the enclosure is uniform
- the heat transfer coefficient for the entire enclosure boundaries is assumed to be a single value
- the heat flow to, and through, the enclosure boundaries is one-dimensional.

The method has been calibrated against the experimental data from a series of fire tests.

In order to present the temperature-time curves in a simple and systematic way, Magnusson and Thelandersson defined a set of eight types of fire compartment according to the boundary material properties, defined as types A to H. A set of time-temperature curves was produced for Type A compartments and they are widely known as the 'Swedish' fire curves. A multiplying factor was presented to determine the temperature-time curves for the other types of compartments.

Petterson[28] and his co-workers used the fire curves, developed by Magnusson and Thelandersson, to develop design methods to predict the fire response of steel structures under fire conditions.

Eurocode approach

BS EN 1991-1-2[14] (EC1) provides an approach for determining empirical parametric (natural) fire curves of compartments. The method was developed through the research programme[36] 'Natural Fire Safety Concept' funded by the European Coal and Steel Community. The method was calibrated against a database of over 100 natural fires. It is therefore important that the designer is aware of the range of test parameters used to calibrate the curves and this is covered by the following limitations of the method, as specified in the code:

- maximum compartment floor area of $500m^2$
- maximum compartment height of 4m
- roof without openings
- compartments with mainly cellulosic type fire loads
- compartment linings with thermal inertia between 100 and 2200 $J/m^2s^{1/2}K$.

The limitations on floor area and compartment height have been removed in the UK National Annex.

Following the approach given in EC1[14], the complete parametric fire curve comprises a heating phase represented by an exponential curve up to a maximum temperature followed by a linearly decreasing cooling phase until a residual temperature is reached, which is usually assumed to be ambient temperature.

There are three stages, as shown in Figure 3.8, in the procedure for defining the design fire curves. The first stage consists of calculating the exponential curve representing the heating phase. This phase is governed by the ventilation conditions and the properties of the compartment boundaries. The second stage consists of defining the duration of heating and thus maximum temperature. The time to maximum temperature is dependent on the fire load density and ventilation conditions. Guidance is given in the code for the fire growth rate (i.e. slow, medium or fast) based on different types of buildings. The cooling phase of the fire curve is defined simplistically as a linear curve which is dependent on the maximum temperature reached and the corresponding time to reach this temperature.

As with all design methods, the accuracy of the estimated solution is dependent on the accuracy of the input. For the parametric fire curves given in EC1[14] the following data is required:

- fire load
- compartment size and geometry
- ventilation conditions
- specific heat capacity, density and thermal conductivity of the compartment boundaries.

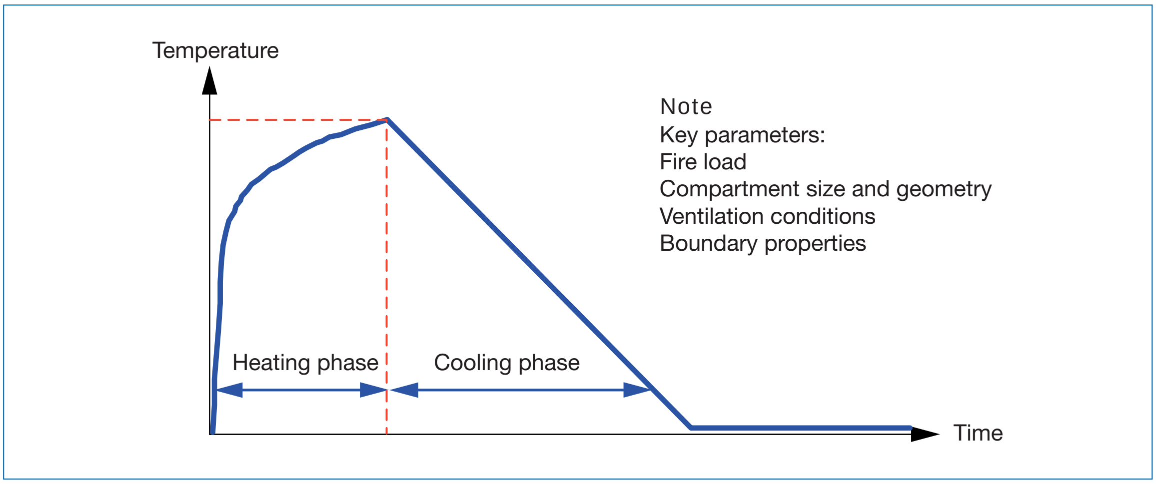


Figure 3.8 Typical natural (parametric) fire curve

3.3.4 Zone models

As explained in Section 3.2.2, zone models divide the fire compartment into separate zones, where the temperature of each zone is estimated based on the conservation of mass and energy. Two-zone models are used for pre-flashover fires whereas one zone models are used for post-flashover fires.

The underlying assumption of a one-zone model is that the gas temperature, gas density, internal energy and pressure are assumed to be uniform throughout the fire compartment. The fundamental aim consists of solving ordinary differential equations for the conservation of mass and energy in the compartment comprising:

- The energy balance between the heat released by the fire, the gas in the compartment, the compartment boundaries, and the external atmosphere through openings.
- The mass balance between the pyrolysis released by the fire, and the incoming and outgoing air through the openings.

By solving the equations for the conservation of mass and energy information for the temperatures of the gases in the compartment, the temperature of the compartment boundaries and the velocity of the gases through the openings can be obtained.

Annex D of EC1[14] provides basic equations for the conservation of mass and energy for the use in one-zone models. Figure 3.9 shows, schematically, how a compartment is modelled using a one-zone model.

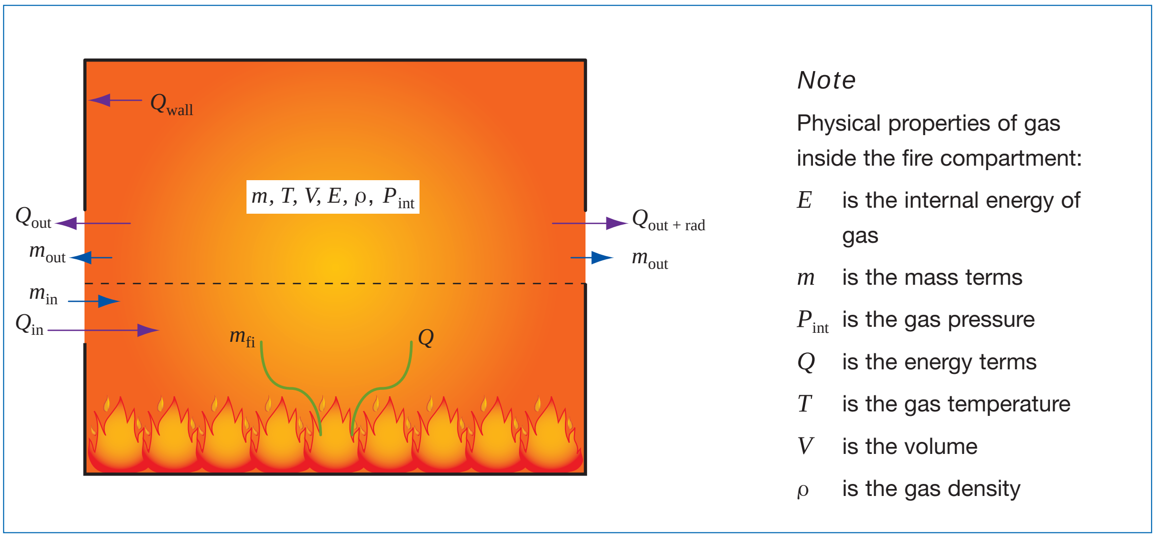


Figure 3.9 Schematic diagram for typical one-zone model[2]

3.3.5 Computational fluid dynamics

CFD models can be used to model post-flashover fires, provided they have been previously validated against test results of post-flashover fires. The general use of CFD models is discussed in Section 3.2.4.

3.3.6 External flame models

External structural members can be exposed to fire through the windows of the compartment (see Figure 3.10). The direction of the fire flame from the window can be deflected by wind which will affect the thermal actions on external members. External flame models have been successfully used to show that it is possible to design external steel columns so that they do not require applied fire protection.

BS EN 1991-1-2[14] provides a simple calculation approach for determining thermal actions for external members, based on the original derivation by Law and O'Brien[37]. The method provides the following information:

- The maximum compartment temperatures.
- The size and temperature of flame from openings.
- The heat transfer parameters of radiation and convection.

The conditions of application and assumptions made in the simple method of EC1[14] are summarised as follows:

- The maximum size of the fire compartment does not exceed 70m in length, 18m in width and 5m in height.
- Fire loads $q_{r,d}$ must be higher than 200MJ/m^2.
- The flame temperature is uniform across the width and the thickness of the flame.
- The forced draught conditions are defined by the conditions when there are windows on opposite sides of the fire compartment and when additional air is being fed to the fire from another source other than through the windows.
- The flame direction from an opening is assumed to be perpendicular to the façade when there is no wind and at a deflection of 45º when wind is considered.

Figure 3.10 Flame behaviour through external openings © Building Research Establishment Ltd

3.3.7 Use of test data

Subject to available resources it is possible to commission experimental tests to model the fire behaviour in actual enclosures. The test set-up should be identical to the proposed actual compartment following guidance given in BS 6336[38] or BS 476-32[39]. Only recognised research institutions or test laboratories should carry out any proposed test, with the assessment of the results being undertaken by suitably qualified staff.

A large number of full-scale fire tests, using either timber cribs or actual furniture for the fire load, have been conducted within realistic compartments throughout the world. A large number of the fire tests are in the public domain and the results can be used to supplement the fire design process. However, careful evaluation of the results is needed before they are integrated within the design. In particular the following issues should be recognised:

- A number of tests only use timber cribs whereas in most buildings a significant proportion of the overall fire load will consist of plastics, which increases the heat release rate of the fire.
- In some tests the cribs (fire load) were ignited simultaneously, ignoring a significant proportion of the pre-flashover phase.
- The ventilation, thermal boundary characteristics and compartment geometry used in the test may be significantly different to the proposed building, making the assessment of the likely fire behaviour difficult, if not impossible.

3.3.8 Key parametric studies to determine design fires for structural assessment

The severity of the fire will depend on the ventilation, fire load, heat release rate, compartment geometry and the thermal characteristics of the compartment boundaries. The sensitivity of these parameters should be assessed, when using the fire models, to define the reasonable worst case.

The definition of the reasonable worst fire severity will depend on the thermal conductivity of the structural material being assessed. For materials with high thermal conductivity, such as steel, the maximum temperature is generally the most important parameter. For materials with low thermal conductivity, such as concrete and masonry, the maximum temperature and duration of the fire are both important parameters.

For materials with low thermal conductivity it is impossible to define the worst reasonable design fire scenario without carrying out the structural analysis. Therefore, a range of design fires, encompassing low temperature maximum duration and high temperature minimum duration should be considered when defining the structural response.

The required parametric studies that should be conducted, to investigate the sensitivity of the parameters affecting the fire severity, are described below.

Ventilation

The ventilation will be due to general leakage, open doors and windows and breakage of glazing as the fire grows. A parametric study should be conducted varying the ventilation conditions between the minimum and maximum reasonable values to identify the worst credible fire severity. The maximum ventilation value is based on the assumption that all the glazing breaks during the fire, which may not result in the worst-case fire severity.

The size and distribution of the ventilation openings will depend on the model adopted. For the parametric fire curves and time-equivalence methods only the total area and weighted height of the vertical openings is considered. It is therefore fairly easy to vary these parameters to identify the worst credible case. For zone and CFD models the actual dimensions of the ventilation openings need to be defined. Using these models to conduct a parametric study, by varying the ventilation openings, can be an extensive task.

Fire load

Fire load densities for different types of buildings are given in various codes[14,21]. The designer should consider the accuracy of these values. The contribution to the fire load from construction elements and linings should also be considered. Parametric studies can be carried out to investigate the influence of varying the fire load. For certain risk categories the choice of a higher fractile than the 80% usually assumed for design should be considered.

Heat release rate

Basic values for heat release rates are given in codes[14,21] and design guides[22]. The possible influence of varying the heat release rate on the structural performance should be considered.

Thermal characteristics of the compartment boundaries

General guidelines for thermal properties of generic materials forming compartment boundaries are given in BS EN 1991-1-2[14] (EC1). It should be noted that the values given in EC1[14] are ambient properties and if elevated temperature properties are known then these should be used in preference.

3.3.9 Automatic suppression

Automatic suppression systems (gas or sprinklers) can be used to either control or extinguish the fire (see Figure 3.11). Guidance on the quantitative effect of suppression systems is given in PD 7974-1[21] and PD 7974-4[40].

EC1[14] applies a reduction factor to the design fire load to take into account the beneficial effect of an automatic suppression system. However, it is advisable that the probability of failure of the installed system should be considered within the overall design.

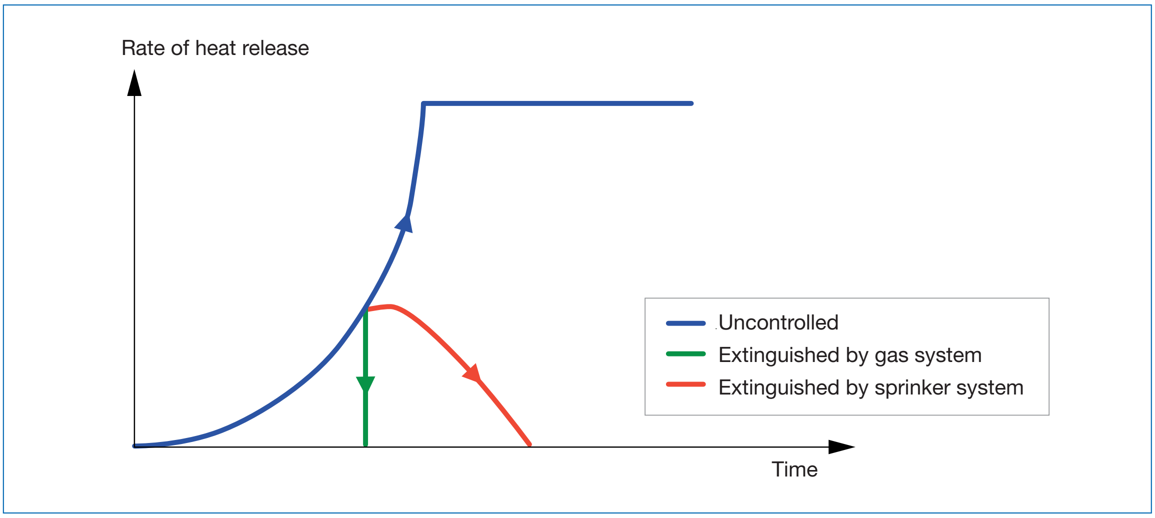


Figure 3.11 Effect of automatic suppression systems on the heat release rate

4.1 Introduction

The temperature distribution through a structural member is dependent on the radiation and convective heat transfer coefficients at the member's surface and conduction of heat within the member. The available design approaches are shown in Figure 4.1.

For materials with a high thermal conductivity, such as steel, it may be sufficiently accurate to ignore thermal gradients within members and assume a uniform temperature. This assumption is valid provided the member is not in contact with a material of low thermal conductivity, which will act as a heat-sink and thus create a thermal gradient through the member. Simple design equations[16-17] exist to predict the temperatures of steel members which are fully exposed to fire or steel members that support a concrete floor slab and are exposed on three sides.

Estimating the heat transfer in materials with a low thermal conductivity and/or high moisture content, such as concrete and masonry, becomes extremely complex due to the high thermal gradients. To carry out a performance-based approach, which investigates the structural response of the building, it is extremely important to obtain an accurate estimate of the temperature gradient through the structural members. Simple design charts are given in codes[15-19] defining the temperature distribution through members, which have been derived from standard fire tests. These charts can only be used if the standard fire curve is assumed to define the fire behaviour.

If parametric curves, zone models or CFD models are adopted to estimate the fire behaviour then either simple or advanced heat transfer models should be used. The use of simple or advanced heat transfer models requires knowledge of:

- the geometry of the member
- thermal properties of the materials, including the effects of moisture
- heat transfer coefficients at the member's boundaries.

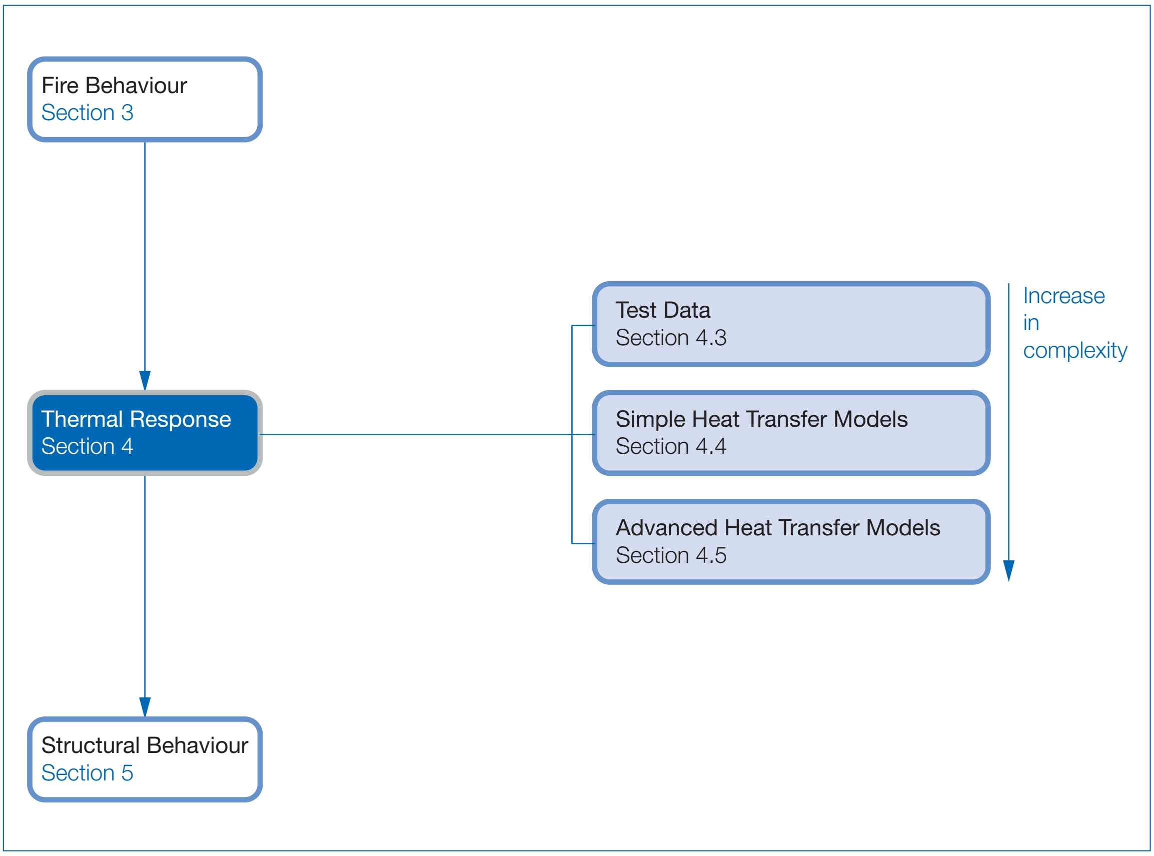


Figure 4.1 Available methods to define the thermal response

Table 4.1 Options for estimating the heat transfer[2]

Model	Design charts/Test data	Simple formulae	Advanced models
Complexity	Simple	Intermediate	Advanced
Analysis ability	• Exact solutions • Standard fire conditions	• Empirical solutions • Standard fire conditions	• Accurate solutions • Any fire conditions
Member types	• Dependent on available test data	• Mainly steel members	• Any material and construction methods
Input parameters	• Construction type • Member geometry	• Heat flux or fire curves • Boundary conditions • Member geometry • Material thermal properties	
Solutions	• Cross-sectional temperature charts • Tabulated thermal data	• Simple cross-sectional temperature profile	• One to three-dimensional time and space dependent temperature profile
Design tools	• Fire part of Eurocodes • Test/Research reports	• Fire part of Eurocodes • Design guides	• Finite element package
	Design charts/tables	Spreadsheet	Computer models

It is generally assumed that ignoring the effects of moisture will result in conservative estimates of the temperature distribution.

The available methods[2] are summarised in Table 4.1.

4.2 Basic principles of heat transfer

Heat transfer is the science to evaluate the energy transfer that takes place between material bodies as a result of a temperature difference. The three modes of heat transfer are conduction, convection and radiation. The thermal analysis can be divided into two parts:

- The transfer of heat by convection and radiation across the boundary from a fire to a member.
- The transfer of heat by conduction within a member.

The surface of a structural member exposed to a fire is subject to heat transfer by convection and radiation. Typically, the radiation is more dominant than the convection except for the very early stages of the fire. The thermal actions can be represented by the net heat flux $\dot{h}_{net}$ given by:

$$\dot{h}_{net} = \dot{h}_{net,c} + \dot{h}_{net,r} \qquad [1]$$

Where:

$\dot{h}_{net,c}$ is the net convective heat flux component as given by [2] below

$\dot{h}_{net,r}$ is the net radiative heat flux component as given by [3] below

For unexposed surfaces of members subjected to partial heating conditions, such as the unexposed side of walls and slabs, heat will transfer from the hot members to the boundary.

The heat transfer analysis according to [1] can be applied considering different boundary conditions. The following simplifications in the heat transfer can be considered[3]:

- For a surface exposed to ambient conditions, the gas temperature is taken to be equal to ambient temperature with both radiation and convection transfer considered.
- Alternatively, for a surface exposed to ambient conditions a fixed temperature equal to ambient temperature can be imposed on the boundary nodes of the surface.
- For a surface with insulation, the boundary can be treated as a non heat-flow condition.

It should be noted that the heat transfer to the boundary from a heated member has an important effect on the thermal response of the member within the region close to the unexposed surface, whereas the effect is relatively smaller in the region of the member close to the fire exposed surface.

The net heat flux $\dot{h}_{net,c}$ in W/m^2 due to convection is given by:

$$\dot{h}_{net,c} = \alpha_c\,(\Theta_g - \Theta_m) \qquad [2]$$

Where:

- α_c is the coefficient of heat transfer by convection in W/m^{2}K as given in Table 4.2
- Θ_g is the gas temperature in the vicinity of the fire exposed member in °C
- Θ_m is the surface temperature of the member in °C

The exact formula to define the heat flux due to radiation is complicated, as the parameters involved depend on the type of surface, the type of flame and the temperature.

For simplicity, BS EN 1991-1-2[14] (EC1) provides the following approximation for the net heat flux $\dot{h}_{net,r}$ (W/m^2) due to radiation:

$$\dot{h}_{net,r} = \Phi\,\varepsilon_m\,\varepsilon_f\,\sigma\left[(\Theta_r + 273)^4 - (\Theta_m + 273)^4\right] \qquad [3]$$

Where:

- ε_f is the emissivity of the fire (= 1.0)
- ε_m is the surface emissivity of the member (see Table 4.3)
- Φ is the configuration factor ($\leqslant 1.0$)
- Θ_r is the effective radiation temperature of the fire environment in °C
- Θ_m is the surface temperature of the member in °C
- σ is the Stephan Boltzmann constant (= 5.67×10^{-8} W/m^{2}K^4)

The configuration factor Φ takes into account varying radiative heat flux levels on the fire exposed surface of the members depending on the position and shadow effects. Annex G of EC1[14] provides guidance for calculating the value of Φ. Conservatively the configuration factor can be taken as 1.0.

Table 4.2 Typical values of convection coefficient α_c

Fire model or exposed condition	α_c (W/m^{2}K)
Standard fires	25
External fires	25
Hydrocarbon fires	50
Parametric fires	35
Unexposed side of separating members:	
• without radiation	4
• with radiation	9

Table 4.3 Typical emissivity values for materials

Material	Emissivity (ε_m)
Carbon steel	0.7
Stainless steel	0.4
Concrete	0.7
Others	0.8

Heat transfer by conduction in solids is governed by the Fourier's equation which states that the quantity of heat transferred per unit time across an area A is proportional to the temperature gradient $\partial T/\partial x$ as follows:

$$q = -kA\frac{\partial T}{\partial x}$$

Where:

A	is the area across which heat is transferred in m^2
k	is the thermal conductivity of the material in W/mK
q	is the heat transfer rate across the area A in W
T	is the temperature in K
x	is the distance normal to the area A in m

4.3 Test data

Test data giving the thermal distribution for generic forms of construction when subjected to the standard temperature-time relationship have been published. The sources of reference are given in Appendix A. A large proportion of the test data listed in Appendix A can be obtained from the one-stop-shop in structural fire engineering web-site[2] (www.structuralfiresafety.org).

Test data for some forms of construction and protection materials may be commercially confidential. However, designers should obtain the required data from manufacturers to ensure any assumptions taken in defining the temperature profile through the members are consistent with the assumptions and approximations within the global fire design of the structure.

In some cases manufacturers have extended limited test data, using simple models and techniques, to cover varying geometries and material characteristics. Once again designers should assess the assumptions and approximations adopted in extending available test data to ensure they are acceptable within the overall design strategy.

4.4 Simplified calculation models

4.4.1 Steel members

An empirical calculation method to estimate the temperature response of bare steel is presented in codes and design guides. The method is based on a lumped mass model where it is assumed that the temperature is uniform within the cross-section.

The rise in temperature is given by:

$$\Delta\theta_s = \frac{\dot{h}_{net,c} + \dot{h}_{net,r}}{c_s\rho_s}\frac{A_m}{V}\Delta t$$

Where:

$\Delta\theta_s$	is the incremental increase in temperature in °C
$\dot{h}_{net,c}$	is the net convective heat flux component in W/m^2
$\dot{h}_{net,r}$	is the net radiative heat flux component in W/m^2
$\frac{A_m}{V}$	is the section factor for the unprotected steel member
c_s	is the specific heat of steel in J/kgK
ρ_s	is the density of steel in kg/m^3
Δt	is the time interval in seconds

Various forms of the equation are given in codes and design guides. For example BS EN 1993-1-2[16] (EC3) introduces a shadow factor and PD 7974-3[31] replaces the Section Factor (A_m/V) with an Element Factor (EF).

As with all empirical equations the calculation method should only be used within the bounds of the test parameters used to derive the equation. The following points should be considered:

- The coefficient of heat transfer by convection (used to calculate the net convective heat flux) will be dependent on the fire model adopted.
- Emissivity values will vary depending on the fire model adopted.
- The shadow factor introduced in EC3[16] has only been calibrated against standard fires and is only valid for 'I' or 'H' sections.

Similar to unprotected steel, an empirical calculation method is presented in EC3[16] to calculate the incremental increase in temperature for a steel element protected with a spray or board material. However, the specific heat, thermal conductivity, density and moisture content of the protection material are required, which are properties not readily available in the public domain.

The empirical calculation method should only be applied to situations that are similar to the tests used to derive the equation, and should not be used for intumescent coatings, where reference should be made to the manufacturer's recommendations.

4.4.2 Concrete members

Due to the low thermal conductivity, high thermal gradients will occur through concrete members, which together with the effects of the mass transport of water or water vapour, makes estimating the temperature distribution through the members very difficult. Ignoring the effects of moisture will result in conservative estimates of temperature, providing spalling does not occur.

It is difficult to define the credible worst-case fire scenario for concrete members since a high temperature short duration fire could cause spalling due to thermal shock and a low temperature long duration fire will result in a high average temperature within the member, reducing its strength and stiffness.

Wickström[41] derived a simple calculation method based on results from computer-based thermal analyses. The method can be used with standard fire curves or parametric fires. Guidance is given in PD 7974-3[31] on the use of Wickström's method.

Hertz[42] derived a calculation method to estimate the uni-dimensional time-dependent temperature distribution through the concrete member. The method can be used with both standard and parametric fire curves by defining relevant parameters given by Hertz.

Temperature distributions, based on the standard fire curve, can be obtained from Annex A of BS EN 1992-1-2[15].

4.4.3 Composite members

Based on the lumped mass model, an empirical calculation method is presented in BS EN 1994-1-2[17] (EC4) for defining the temperature within a steel beam supporting a concrete floor slab.

Similar to concrete members, defining the temperature distribution through composite steel and concrete members, such as web in-filled beams and columns and concrete filled hollow sections, can be complicated. The design methods in EC4[17] and design guides[43] are linked to temperature distributions defined in standard fire tests and cannot be used for natural fires.

Advanced analytical methods need to be used to define the temperature distribution through members when parametric curves, zone models or CFD models are used.

4.4.4 Masonry members

The temperature distribution through common forms of masonry walls is given in BS EN 1996-1-2[19]. Although these curves are based on the standard fire curve there is some debate over the accuracy of the temperatures.

For natural fires, advanced analytical models are required to define the temperature distribution through the masonry wall.

Table 4.4 Aspects of modelling heat transfer

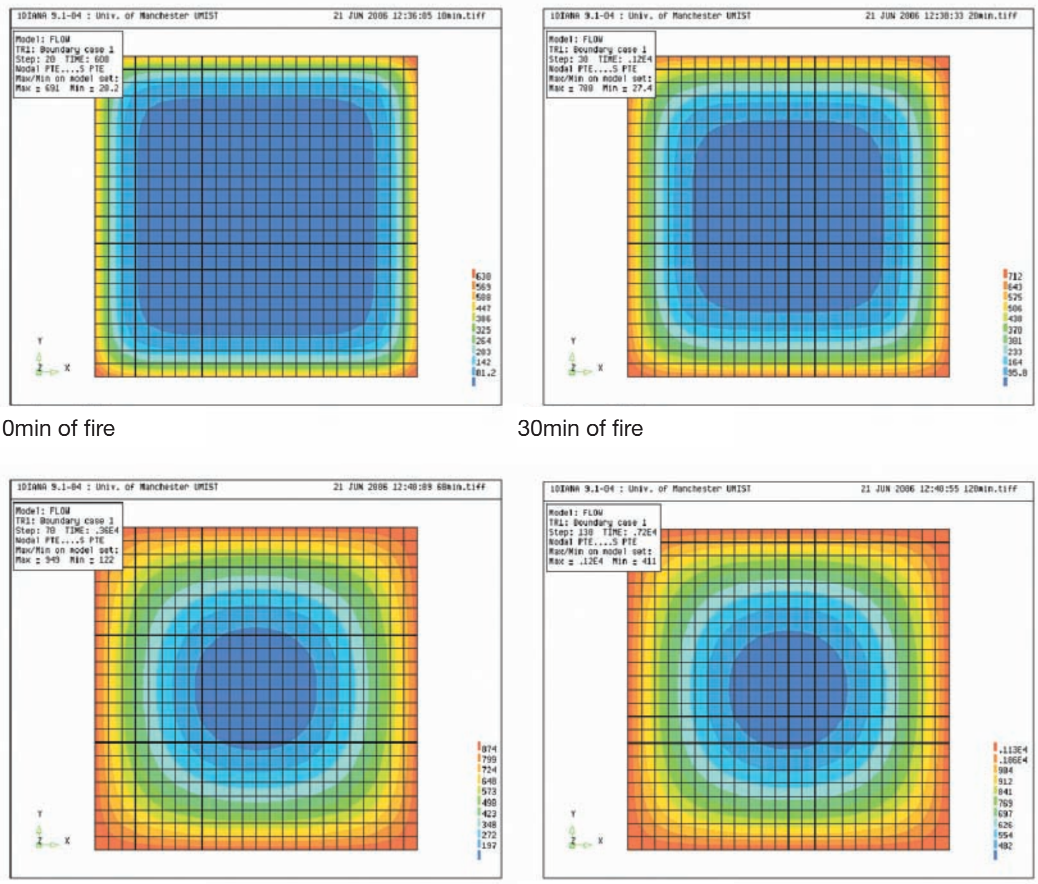
Meshing	• The shape and dimensions of the structural model are modelled by a finite element mesh of general flow continuum elements, in the form of triangles, quadrilaterals, wedges, or bricks. • The boundary elements or interface elements can be line shaped elements for a 2-D model, and triangular or quadrilateral elements for a 3-D model.
Boundary Conditions	• Heat sources can be represented by either temperature-time functions or heat flux in boundary elements. • Convection and/or radiation at boundaries of the structural model can be modelled by the heat transfer coefficient of boundary elements.
Material properties	• The material can be isotropic, orthotropic or anisotropic. • The material thermal properties of conductivity, specific heat and emissivity can be temperature-dependent.
Special features	• Hydration heat, moisture evaporation/movement, and change in contact conditions, may be modelled.

4.5 Advanced analytical methods

Advanced models for heat transfer problems require computer software. Heat transfer is a transient-state condition, coupled with time-dependent boundary conditions and temperature-dependent material properties. Consequently, most advanced models can only be developed based on finite difference or finite element techniques. The heat transfer analysis can be performed using a two-dimensional (2-D) or a three-dimensional (3-D) model.

The general aspects[2] for the modelling of heat transfer analysis are shown in Table 4.4.

The heat transfer analysis can be performed using commercial computer packages for general finite element modelling. However, the main problem with these packages is that they do not consider the mass transport of water or water vapour in permeable materials. It is possible to allow for these effects by varying the temperature-dependent thermal properties as shown in the Eurocodes. Alternatively, the effects of moisture can be ignored which will lead to conservative estimates of temperature, provided spalling does not occur. An example of using a finite element model to predict the temperatures through a concrete column is shown in Figure 4.2.



10min of fire

30min of fire

60min of fire

120min of fire

Figure 4.2 Temperature distribution through a concrete column

5.1 Introduction

The simplest method for predicting the structural behaviour of buildings in fire (see Figure 5.1) is to analyse individual members at the fire limit state using partial load and material safety factors, which take into account realistic loads at the time of the fire and actual material strengths. These methods are given in the codes[15-19] and design guides[1-8] and take into account the reduction in strength and stiffness of materials during a fire. Simple design methods, which are based on fundamental engineering principles, can be used irrespective of the fire model used. However, some empirical structural design methods are only valid for use with the standard time-temperature fire model, which was used in their derivation.

Simple plastic design methods exist to consider frame behaviour in a fire. In the Eurocodes, frame behaviour is utilised to allow the effective lengths of continuous steel, composite and concrete columns to be reduced from ambient temperature values.

Following the Cardington full-scale fire tests a simple sub-structure design model[44-47] for steel framed buildings with a composite floor slab was developed. The model is based on membrane action of floor slabs and allows the beneficial effect of the grillage of beams and floor slab, acting as a unit, to be included within the structural design. The approach can be used with any fire model.

The simple design models for individual members and sub-frames are assumed to be conservative but do

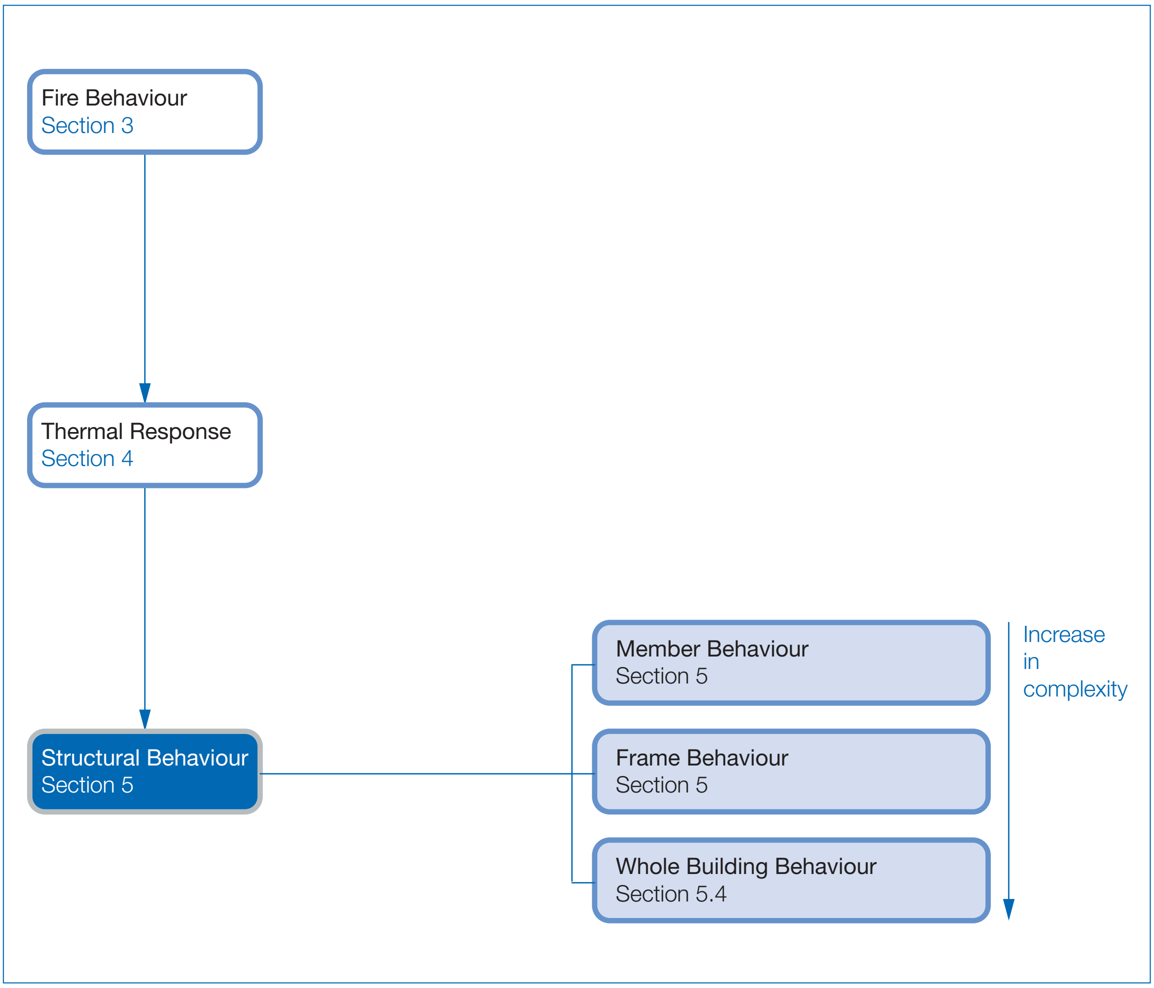


Figure 5.1 Available methods to define the structural behaviour

ignore some aspects of the actual behaviour of real buildings. A possible design approach to predict more accurately the behaviour of buildings in fire is to use finite element modelling. The approach incorporates the stress-strain-temperature relationship of materials and can predict stresses and deformations throughout the whole structure. Expertise is required to use these advanced models and special care is required in defining the types of elements used, boundary conditions, localised behaviour and interpretation of the results. The detailed aspects of finite-element modelling are discussed in Section 5.4.

Finite element modelling of whole building behaviour can provide a more accurate estimation and understanding of the structural response, over the full duration of the defined fire, compared to other methods. However, due to the need to use large elements to model the whole building, localised behaviour, such as reinforcement fracture or connection fracture may not be adequately modelled. If the consequence of localised behaviour is considered to be important then detailed finite element modelling of these areas is required or, alternatively, careful detailing in terms of additional reinforcement or ductile connections could be specified.

The overall frame stability in a fire should be considered. For braced frames no additional checks are normally required provided a sufficient number of cores or bracing, that provide the lateral resistance, have adequate fire resistance, shielding or containment within fire resisting cores. For sway frames, a frame analysis at elevated temperatures is required to ensure sufficient overall stability during a fire.

The available structural design methods[2] are summarised in Table 5.1.

It is worth emphasising that the analysis of the structure will only be as accurate as the fire modelling and thermal analysis. Therefore the accuracy of all three components of the design should be considered when assessing the final analysis.

Table 5.1 Options for structural analysis[2]

Model	Simple element	Sub-models	Advanced computer finite-element models
Complexity	Simple	Intermediate	Advanced
Input parameters	• Temperature through the cross-section • Material strength and stiffness reduction • Applied static load • Simplified boundary conditions	• Temperature through the cross-section and along the member • Material strength and stiffness reduction • Applied static load • Boundary conditions	• Temperature through and along the cross-section • Full material stress-strain-temperature relationship • Applied static load • Boundary conditions • Element type and density
Accuracy	• Ignores real behaviour but assumed to be conservative • Ultimate strength calculation	• Begins to consider actual load paths and restraint • Ultimate strength calculation	• Predicts internal stresses, displacements, and rotations for all members throughout the duration of the fire • Localised behaviour is not modelled accurately in whole building modelling
Design tools	• Simple equations for hand calculations	• Simple equations for hand calculations • Plastic design, redistribution of moments • Simple computer models	• Commercially available or purpose written computer software

5.2 Basic principles

All materials lose strength and stiffness at elevated temperatures. Based on test results, design codes[15-19] present simplified values of strength and initial stiffness for various materials at different temperatures.

The codes also provide simplified stress-strain-temperature relationships for steel and concrete, which can be used within advanced models.

5.2.1 Thermal expansion and thermal curvature

All materials will expand, to some extent, when heated. If a non-uniform temperature distribution forms through the section, thermal curvature will occur with the element generally deflecting towards the heat source. Any resistance to the free movement of axial thermal expansion or thermal curvature will induce internal stresses within the member. In addition, due to assuming plane sections remain plane, any non-linear temperature distribution through an element will induce internal thermal stresses.

Figure 5.2 Spalling of concrete[48]

5.2.2 Creep and transient strains

There are two types of tests to determine the material stress-strain-temperature relationship. These are steady-state tests and transient tests. For steady state tests the specimen is heated to a defined temperature and then loaded to failure. In transient tests the load remains constant and the specimen is heated to failure. Transient tests give lower stress values for a given strain but are considered to be more realistic. The heating rate will also influence the stress-strain relationship since there is a component of deformation arising from creep. For steel and concrete, the stress-strain-temperature relationship given in the Eurocodes takes into account classical creep, provided the heating rate remains between 2 and 50°C/minute.

Transient strains experienced by concrete on first heating can be important when the concrete is subjected to high compressive forces. Transient strains should be included in the modelling of structural concrete unless there is evidence/justification for ignoring their effect.

5.2.3 Spalling

Spalling of concrete in fire involves the breaking off of layers or pieces of concrete from the surface of the structure, as it is heated (see Figure 5.2). Although a large amount of research has been conducted into spalling, the behaviour is difficult to predict and no definitive design guidance is currently available to estimate the extent and consequence of spalling during a fire. For normal strength concrete, Reference 49 implies that the code provisions have sufficient conservatism to allow for spalling and practical guidance on spalling is provided in BS 8110-2[50] and BS EN 1992-1-2[15]. For concrete tunnel linings special consideration to spalling is required.

The main causes of spalling have been attributed to:

- heating rate
- moisture content
- permeability
- mechanical stress levels
- presence of reinforcement
- aggregate type.

For concretes that are susceptible to spalling, one or more of the following methods should be considered:

- thermal barrier
- polypropylene fibres
- moisture content control
- choice of aggregate
- air-entraining agent
- compressive stress control
- reinforcement (including the use of supplementary reinforcement).

5.3 Simple calculation methods

The simplest calculation methods are based on the behaviour of individual members. These members could be in the form of a column, beam, wall or floor slab. Guidance on the design of structural members is presented in codes and design guides. With member design, the effects of restraint to axial thermal expansion are ignored. However, the effects of thermal gradients through the cross section are generally considered.

The simple member calculation methods are typically based on strength and provide no detail on the displacement history, or maximum displacement, of the member during the fire.

If the design approaches are based on fundamental engineering principles, with the strength of materials within the member being reduced with increase in temperature, then they are valid for any fire scenario. However, there are some cases where the design procedures given in the codes (particularly relating to composite construction and timber members) are only valid for the standard time-temperature fire scenario, since they have been derived from, and validated against, standard fire test results. The designer should check that the calculation approach adopted for estimating the structural response is valid for the fire scenario considered.

It is generally accepted that the available calculation methods for the design of individual members will provide acceptable conservative answers. However, the design approach ignores the true structural response of the building, which can be either detrimental or beneficial to the survival of the building as a whole. The important modes of behaviour that are generally ignored in member design are described below[2]:

- The effects of thermal expansion of the beams laterally displacing external columns.
- Any induced forces acting on a wall due to the movement of the heated structure in the proximity of the wall.
- The effect of induced compressive forces due to restrained thermal expansion. These induced compressive forces could cause buckling of vertical elements, local buckling of beams, increase the susceptibility of concrete spalling, or increase the beneficial effect of compressive membrane action.
- Re-distribution of moments with frame action.
- Any pulling in of external columns from catenary action of beams.
- Any beneficial effect of alternative load paths, catenary action or membrane action.

Consideration should be given to these modes of behaviour when detailing members and connections.

5.3.1 Steel members

Simple design methods[16] to determine load-bearing capacity are available for steel tension, compression and beam members. If a uniform temperature distribution is assumed through the member then the calculation is simply based on a reduction in yield strength. Simple calculation methods are available to take into account varying temperature distribution through the member and along the member's length.

The design of steel members is based on the engineering principles applied in the normal cold design except that the effects of reduction in material strength and stiffness are taken into account, together with partial safety factors that relate to the fire limit state.

5.3.2 Composite members

Simple design methods[17] are available for the design of composite beams, columns, and floor slabs. Due to the need to define the high thermal gradients through the concrete, the induced thermal stresses within the concrete, and the interface behaviour between the steel and concrete, most methods are only applicable for the standard time-temperature fire scenario.

Simple tables are presented in codes and design guides for various forms of composite members. In some cases these tables take into account varying structural performance by including the actual estimated load on the member at the fire limit state. However, irrespective of whether actual load levels are considered or ignored, the tables are only applicable if the standard time-temperature relationship is used.

A simple design method[44,45,46,47] for steel beams supporting a composite floor slab has been developed following the Cardington fire tests. The method is based on fundamental engineering principles and is valid for any fire scenario.

5.3.3 Concrete members

The simplest approach for the design of concrete members is to use prescriptive tables which provide minimum geometric dimensions and cover to reinforcement. These tables, and their use, have been described in the previous IStructE publication *Introduction to the fire safety engineering of structures*[1].

Simple design methods[15] are available for concrete members based on the fundamental engineering principles used for cold design. Reduction in the strength of the concrete and reinforcing bars is included, together with partial safety factors that apply at the fire limit state.

For simply supported horizontal members the calculation of the design resistance is simply calculated using the normal stress-blocks adopted in normal cold design except the tensile strength of the reinforcement is reduced based on its temperature. In addition the partial material safety factors for both concrete and steel reinforcement are taken as unity. Provided the insulation criterion[1] is met, the concrete in compression will remain at a low temperature and is therefore assumed to retain its full strength.

For continuous horizontal members plastic design and normal redistribution can be used. In hogging regions the concrete strength in compression is reduced due to the effects of fire.

For concrete columns, the simplest design method is to ignore the strength of concrete above 500°C and define the actual temperature of the reinforcement. The calculation of the load-carrying capacity is based on the reduced area of concrete and reduced strength of the reinforcing bars using the same design approach for cold design but with material safety factors for the fire limit state. Alternately, the column can be divided into a number of zones and the column's capacity calculated using the actual strength of the concrete, based on the temperature, together with the reduced strength of the reinforcing bars. Both these methods are given in BS EN 1992-1-2[15]. The main limitation of the simple design methods, for column members, is that they ignore the redistribution of moments within the structure that occurs during a fire and they ignore the effects of transient creep.

5.3.4 Timber members

The simple design of timber members consists of the effective cross-section method and the reduced strength and stiffness method. These design approaches are described in the previous publication *Introduction to the fire safety engineering of structures*[1]. The methods are based on charring depths and temperature profiles, which need to be calculated. At present the only reliable temperature information is limited to the standard time-temperature response.

For small section timber members, protection from linings is required. In the case of walls and floors, tables are provided in codes and guides that allow the designer to assess the stability, insulation and integrity of the system. These tables are only valid for use with the standard time-temperature relationship.

5.3.5 Masonry members

Very limited research work has been conducted on the thermal and structural properties of masonry. Due to limited knowledge there is currently no reliable simple calculation method available for the design of masonry walls or columns.

The fire design of masonry walls is typically carried out using simple prescriptive rules given in the codes, as described in the previous publication *Introduction to the fire safety engineering of structures*[1].

5.4 Whole building behaviour and the use of finite element models

Purpose-written or commercially available finite element or finite difference software can be used to assess the structural response under fire conditions. This provides the potentially closest representation of real behaviour (see Figure 5.3). It should however be remembered that, as with all design methods, the use of the finite element and finite difference method is still an approximation of the real behaviour. Before such software is used the designer should be adequately experienced to identify the assumptions and approximations embedded within the software and in its use. Any software used must be able to model geometric and material non-linearity.

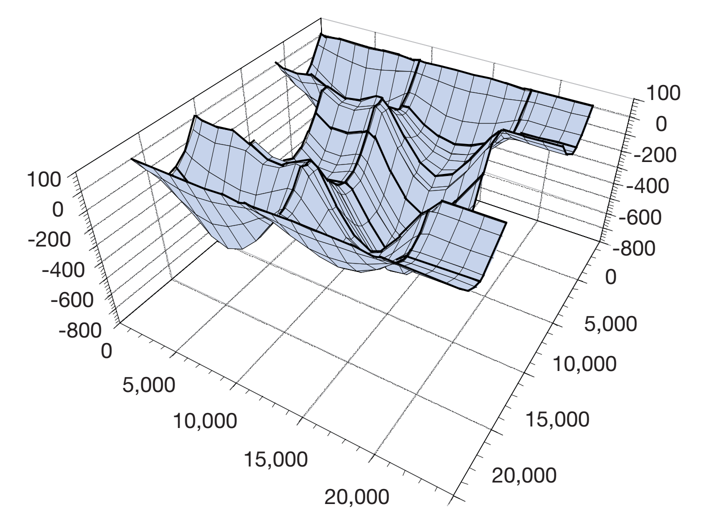


Figure 5.3 Use of finite element model to predict the response of a floor plate

5.4.1 General principles

The general principles of using finite element models are described below[2]:

- The structure is transferred into a discrete system by dividing (meshing) the structure into finite elements. Generally, the larger the number of finite elements the more accurate the estimate of the structural response, but the analysis time will increase. A balance needs to be made between the number of elements used and the required accuracy. This can only be assessed by carrying out a sensitivity analysis which involves conducting the same structural analysis but increasing the number of finite elements used.
- The type of finite element used to model the structure needs to be defined. The following guidance is offered:
  - Beam-column elements are line elements, modelling one-dimensional stress state, which include axial and flexural terms. They can be used effectively to model columns and beams. Integrating across the cross-section at several points along the element allows any cross-sectional variation to be included. It is important to ensure that the numerical integration across the cross-section accurately models any variation in material and temperature.
  - Spring elements are elements used to represent the variation of stiffness and strength between two nodal points that are in close proximity. These elements can be used to model connections.
  - Shell elements are planar elements, modelling two-dimensional stress state, which include both membrane and flexural terms. Integrating through the thickness of the element allows the variation of the properties to be included. These elements are typically used to model floor slabs.
- Connecting the finite elements together at nodal points needs careful consideration. It has been shown that the behaviour of structures during fire is predominantly governed by restraint to thermal expansion. It is therefore important that the elements are connected at the correct points to ensure accurate representation of thermal restraint.
- Material constitutive models need to be defined. For the one-dimensional stress state, the stress-strain-temperature relationship given in the codes can be used for steel and concrete. Creep is explicitly included in these models provided the heating rate remains between 2 and 50ºC. Thermal strains for all materials and transient strains for concrete should be included. For the two-dimensional stress state a biaxial stress-

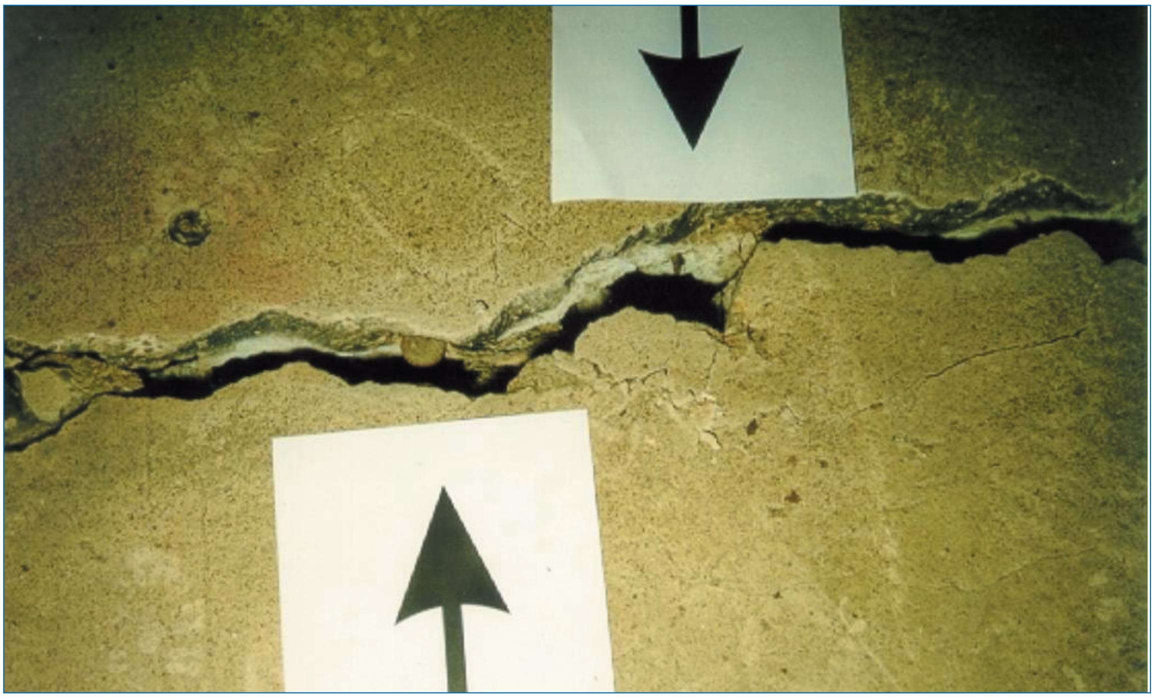


Figure 5.4 Reinforcement fracture following large scale tests[46]

strain-temperature relationship should be used. Strain reversal during both the heating and cooling stage of the fire should be considered, if it is detrimental to the structural behaviour.

- The boundary conditions should be defined. Due to the effects of restrained thermal expansion, the definition of boundary conditions can be important. It may be found that the slightest variation in boundary conditions results in significant changes in the estimated response. Boundary conditions can fall into two categories. The first relates to actual boundaries of the structure, which are fairly easy to define. The second relates to boundaries of a sub-model where the fixity at the boundary represents the rest of the structure which is not actually modelled. If it is found that variations of fixity have a significant effect on the predicted behaviour using a sub-model then the modelled area should increase and the boundary be moved away from the modelled area of interest.
- Localised behaviour cannot easily be modelled when considering whole or even sub-structure building behaviour, due to the need to refine the mesh density to adequately model localised behaviour. Areas of particular concern are:
  - Reinforcement fracture (see Figure 5.4) especially when a smeared cracking model[51] is adopted which is unable to predict localised fracture of reinforcement.
  - Connection fracture (see Figure 5.5). The forces on the connection will be totally different in a fire condition compared to those used to design the connection cold. The behaviour of the connections during both the heating and cooling stages of the fire should be considered.

  The designer should consider the possibility, and consequence on the overall design strategy, of localised failure.
- The applied static load should comply with the codes assuming fire limit state design. The rise in temperature, together with accurate thermal gradients should be applied in discrete steps to avoid numerical instability. The range of design fires encompassing low temperature maximum duration and high temperature minimum duration should be considered to identify the worst case in terms of structural response.
- If detrimental to the overall structural behaviour, the effect of possible spalling of concrete should be considered.
- Initial geometric imperfections should be applied to the columns and any laterally unrestrained beams. An initial imperfection of span/1000 is generally adequate. There is no need to provide imperfections if the model provides movement of the members as the temperature is increased.

Figure 5.5 Shear failure of bolts in a steel connection

5.4.2 Conceptual model

Based on the general principles of finite element modelling, described above, a conceptual model is defined taking into account the choice and number of finite elements, material constitutive models, boundary conditions, connectivity, and localised behaviour. Before the model is analysed it would be prudent to discuss and agree the conceptual model with the checking body. More general guidance on conceptual models is given in Reference 52.

5.4.3 Assessment of failure

The first level of assessment of failure is to compare the analysis with the defined acceptable performance criteria. This could include:

- A limit on the maximum displacement, or maximum rate of displacement, to ensure compartmentation is maintained, protection of fire-fighting shafts and protection of escape routes.
- Stability of the structure.
- A limit on the maximum strains in the reinforcement.

The above limits are easily defined within the analysis. However, localised behaviour such as fracture of the reinforcement (if a smeared cracking model is adopted) or connection failure can be more difficult to quantify. If large displacements are acceptable, an assessment on the likely fracture of reinforcement or connection failure due to high tensile/catenary forces should be conducted and if necessary more robust details should be adopted to ensure localised failure does not occur.

5.4.4 Sensitivity assessment

Finite-element analysis is a design tool to estimate the structural response. Similar to other design methods, assumptions and approximations are embedded within the method.

When using finite element models to predict the structural response of a building to a given defined temperature distribution, a sensitivity assessment may be required to assess the effect of mesh density, connection behaviour and boundary conditions adopted for sub-models.

6 CASE STUDIES

6.1 Introduction

The following four case studies, presented by Arup Fire, WSP, FEDRA and SAFE, highlight how the design methods presented within this *Guide* can be applied to obtain a better understanding of the structural behaviour during a fire, resulting in economical and robust buildings.

6.2 Kings Place

The Kings Place building in London (see Figure 6.1), designed by Arup, is a composite steel-framed structure with eight-storeys above ground level and three basement levels. The composite floors are constructed using 130mm deep composite slabs with profiled steel decking attached by shear connectors to steel beams with circular web openings.

Arup Fire calculated the structural fire response above ground level to a set of design fires. The design fires were based on natural fire curves (see Section 3.3.3) using realistic fuel and ventilation conditions. Based on the reasonable worst case design fire, the thermal distribution through the structural members could be calculated for the duration of the design fire scenario.

Figure 6.1 Artist Impression of Kings Place © Miller Hare

Three 3-D models were constructed and a non-linear structural fire analysis performed (see Figure 6.2) to encompass the effect of thermal actions and realistic static design loads on the structure. The results from these models allowed the stability and compartmentation under specific fire events to be improved by optimizing the structural design. By relying on secondary load-bearing mechanisms in the fire state, fire protection to most secondary steelwork was not necessary to satisfy fire safety requirements.

Working closely with the design team, main build contractor, and sub-contractor, resulted in a cost efficient and robust fire protection layout, integrated with an optimised steel superstructure design.

The overall aim of the work was to meet the life safety requirement of the building regulations through robust structural design and compartmentation provision. Based on the design detailing described above, the work was approved by building control, and the building insurers, whilst bringing a substantial cost saving to the project.

By carrying out an advanced structural fire engineering design the following added value was achieved:

- Overall improved robustness of the structure in fire events through a realistic understanding of the structural fire response and consequent detailing.
- Cost savings due to a reduction for the fire protection throughout the structure, by considering realistic fire scenarios, thermal distribution and structural response.
- Cost savings due to secondary beams not requiring fire protection.

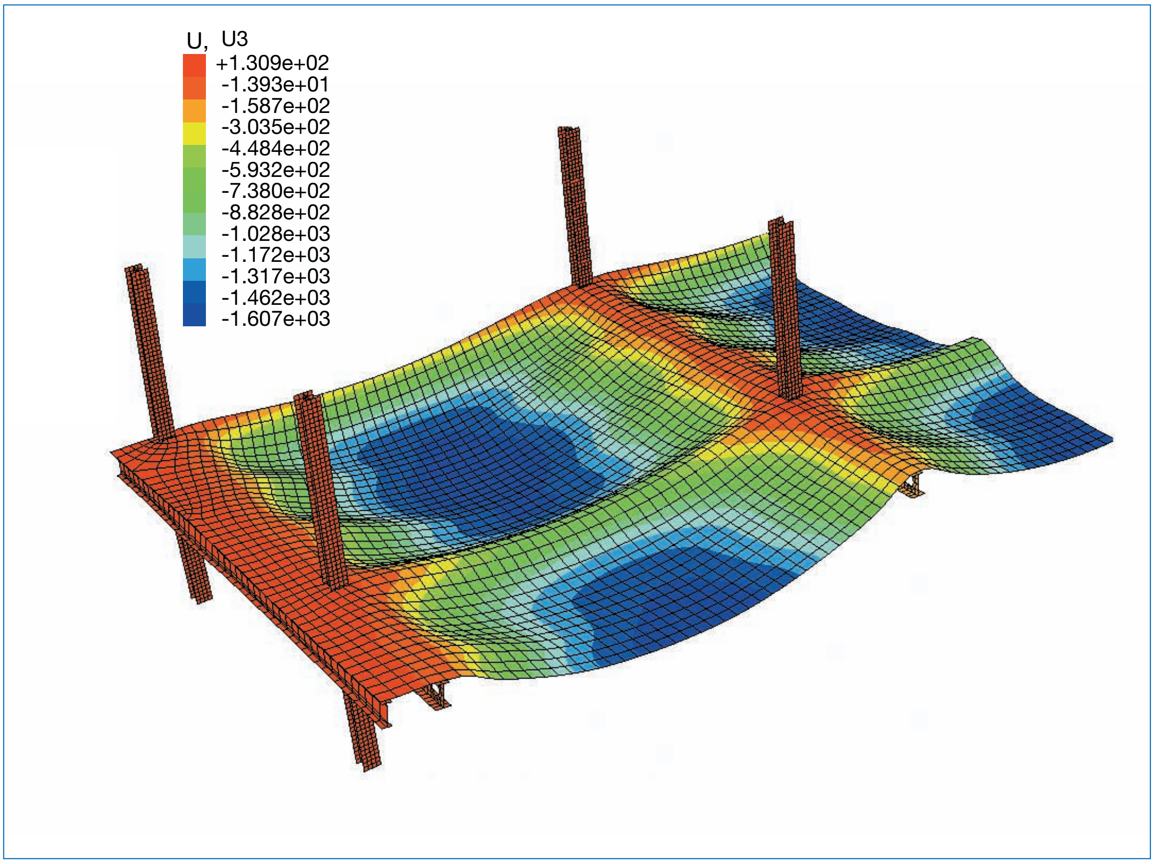


Figure 6.2 Deflection contour of the North-West portion of the building

6.3 Al Shaqab Academy and Equestrian Centre

The Al Shaqab Academy and Equestrian Centre is one of the earliest fire engineered building designs in Doha, Qatar. The equestrian centre provides Olympic standard facilities. WSP Fire Engineering carried out a full fire engineering analysis for the fully enclosed 5000 plus seats main performance arena (see Figure 6.3). Fire engineering permitted a unique, robust, and highly cost effective design that included the complete removal of the requirement for fire protection to the roof structure.

The proposed centre consists of an indoor arena, an outside arena, and a covered warm-up area, all enclosed within a single roof structure. The roof structure is approximately 350m long by 150m wide and rises to a maximum height of 36m above ground level. The main structure consists of a curved, aluminium standing seam roof over the indoor arena and covered warm up area. The standing seam roof is supported by a secondary structure of castellated beam sections and purlins. These are supported by a primary structure of longitudinal and transverse triangular trusses constructed mainly from hot rolled circular hollow sections. These primary trusses are supported by an arrangement of large concrete thrust blocks – at ground level and on the roof of the concrete main grandstand structure – and a number of raked columns.

The overall fire strategy was developed in accordance with the performance-based requirements of the *NFPA 101 - Life Safety Code*[53]. The primary goal of the design approach was 'protection of occupants not intimate with the initial fire development'.

The structural fire design comprised:

- A preliminary assessment of all compartments likely to pose a fire threat to the primary elements of structure and supports.
- Characterisation of those compartments in terms of layout, size, openings, fire loading and construction.
- Determination of the worst case fire conditions in each compartment which could possibly pose a threat to primary elements of structure and supports.
- An assessment of structural failure based on the concept of limiting temperature for the structural member concerned (see Section 5.3.1).

By obtaining a realistic estimation of the fire severity and structural response it was possible to justify that there was no need to apply fire protection to the roof structure. This will result in the construction of a more economical building.

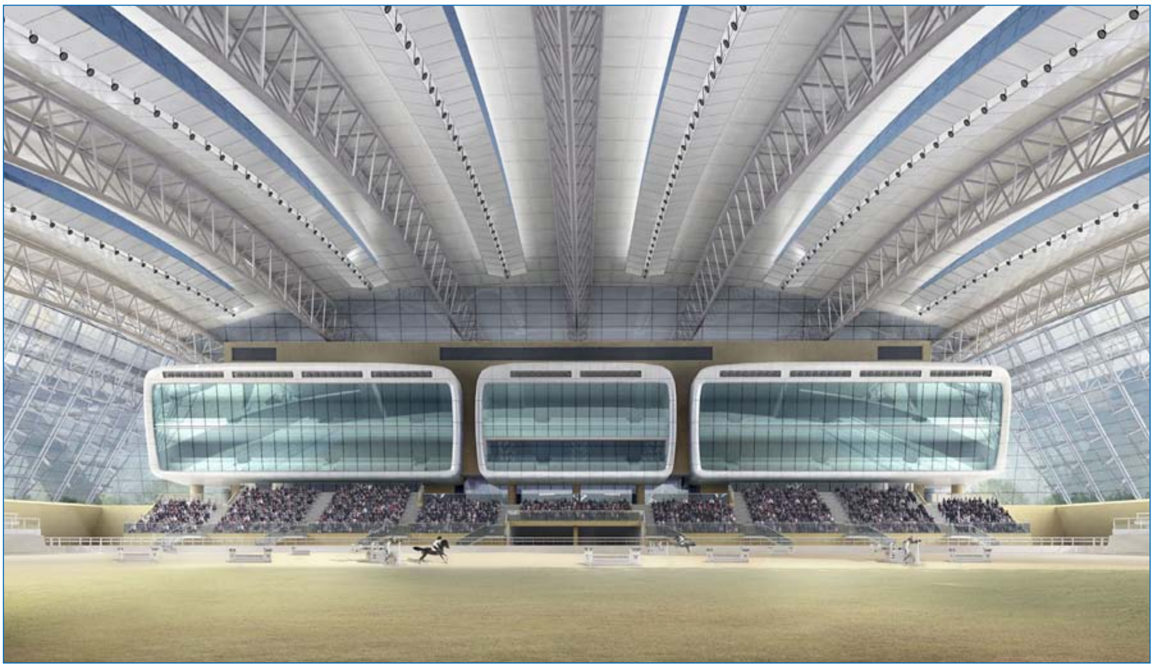


Figure 6.3 The Al Shaqab equestrian centre

6.4 Heathrow Airport Pier 6

London's Heathrow Airport is the world's busiest international airport and will be one of the first in the world ready for the A380 aircraft. Due to the increase in passenger numbers, generated by the new aircraft, larger airport facilities such as gate rooms, seating, etc. were required.

Although the accommodation of the new A380 was an important factor in the building of the new pier (see Figure 6.4), other factors such as ensuring that it complied with the new Part L regulations[54], creating a more energy efficient building, were just as important. The Pier 6 building has a high level of natural daylight and an energy efficient heating and cooling system which all combined to help with the sustainable approach.

The fire safety engineering of the structure, carried out by Buro Happold FEDRA, was part of the overall approach that required attention to detail and to value.

The structure comprises a new three-storey steel-framed structure approximately 280m long which supports a profile metal decking concrete floor and a flat composite panel roof. The south elevation of the building is predominately glazed with a curtain wall system and the remaining elevations are covered in a lightweight composite cladding panel. There are four standard vertical circulation cores (VCCs) south of the Pier. The VCCs are three-storeys high and have a complete steel frame structure with a profile metal deck concrete floor at departures and arrivals level.

One hour fire resistance was specified for both floors and columns and span/20 was considered to be sufficient as a deflection limitation for defining failure at the end of the 60 minute period when considering the stability performance requirements.

A comparative approach to BS 7974[12] (see Section 2.2.2) was adopted. With reference to Figure 2.1 (see Chapter 2) the following levels of complexity were adopted:

- Fire behaviour was defined using the standard fire.
- Thermal response was defined using test data.
- Structural behaviour was calculated by considering whole frame behaviour.

Figure 6.4 Heathrow Pier 6 © BAA Limited www.baa.com/photolibrary

The use of finite element software to model the whole frame behaviour enabled steps in the slab, consideration of column behaviour, and various grid spacing, to be considered which were outside the scope of the simplified SCI guidance document SCI 288[45]. The FBE Report 5[55] was used to benchmark the answers given by the finite element analysis. The rise in temperature and the corresponding reduction in performance of the steel and the concrete gradually lead to increased deflections (Figure 6.5).

Investigations and sensitivity studies were made into the feasibility of adopting an 18m × 14m, 9m × 14m, and a 9m × 9m grid. Account was taken of expansion effects at high temperatures, catenary action of the slab, column behaviour and the impact of cooling.

The output from the analyses allowed the correct mesh reinforcement to be provided, connections to be detailed to withstand likely forces, and other construction details to be specified to ensure an overall robust structure. In particular, the principal output was the identification of beams which needed fire protection to enable the whole frame to achieve the specified 60 minutes fire resistance. Figure 6.6 shows a plan of the building where secondary beams within a 9m × 9m grid can be left unprotected.

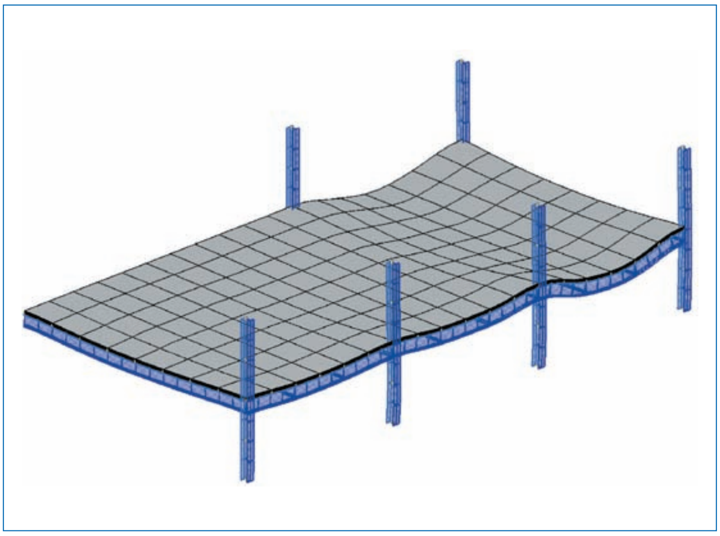


Figure 6.5 Modelling of the floor plate using finite-element software

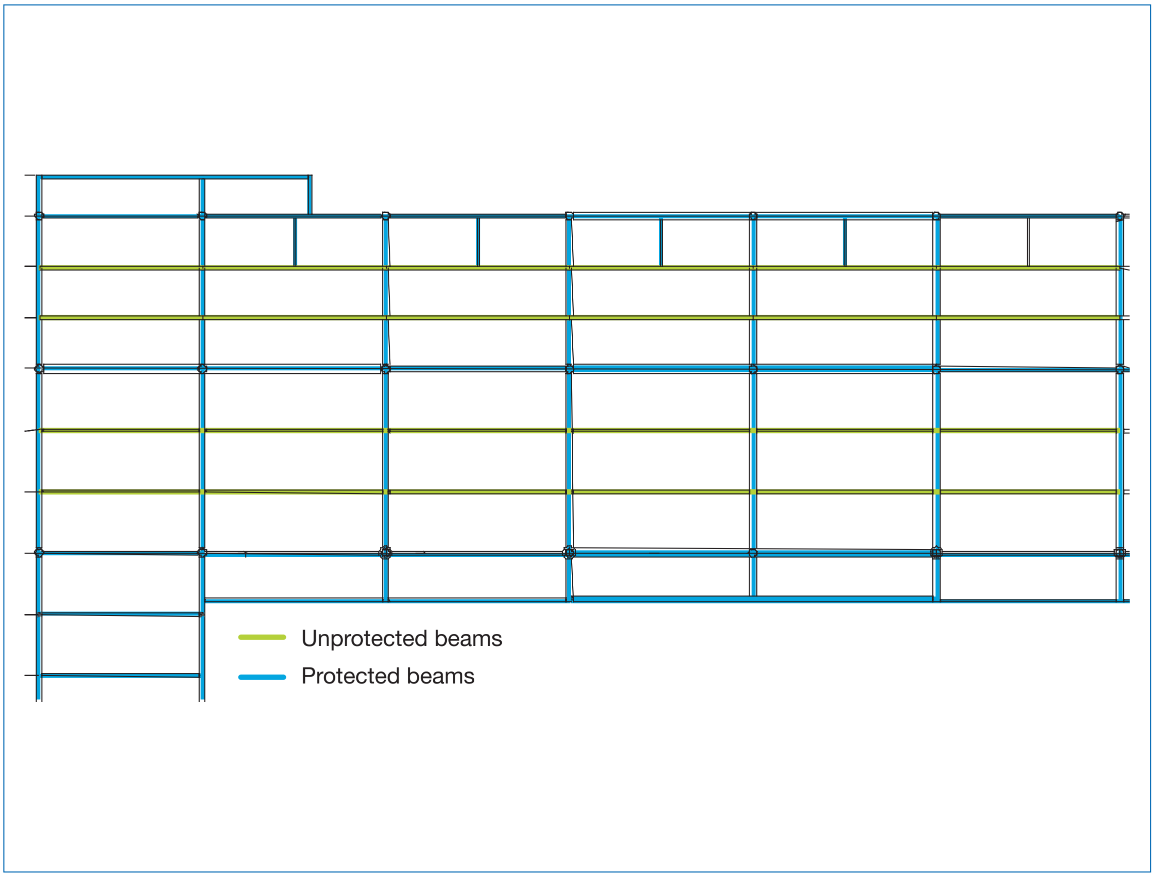


Figure 6.6 Plan showing typical 9m × 9m bay where secondary steel beams are left unprotected

6.5 Abbey Mill House

Abbey Mill House is a new land-mark building in the heart of Reading, UK (see Figure 6.7). The sixteen storey scheme consists of 140,000 sq ft (13,006m^2) of office space together with a separate block of affordable housing. The structural design of the office block uses a steel frame and composite floor slab with a maximum grid of 13.5 × 9 metres.

By considering the likely realistic fire and structural behaviour of the proposed office building, SAFE Consulting Ltd proved that the typically assumed fire rating of 120 minutes recommended in Approved Document B[10] could be reduced to 60 minutes. This significant reduction was achieved by adopting the time equivalence method (Section 3.3.2) and through negotiations and liaison with Reading Building Control.

Figure 6.7 Abbey Mill House © Lighthouse/Sheppard Robson

Recommendations by Kirby[56] were implemented in the analysis including:

- 80% fractile design fire load of 570MJ/m^2
- a factor for the thermal properties of the enclosure k_b of 0.09 min.m^2/MJ
- the assumption that a 100% ignition of all combustible materials occurs in the fire compartment
- the provision of the sprinkler reduction factor reducing the total fire load by 61%. Further reduction factors of the active fire fighting measures were not considered (fire fighting and automatic fire detection systems) as this would reduce the fire load to unrealistically low levels
- a reduction in the ventilation available, as parts of the glazing of the compartment could potentially remain intact post-flashover.

The assumptions, in the structural fire analysis, were made in parallel with the provisions made in the fire strategy, which included compartment floors and sprinklers provided throughout.

Approval from Reading Building Control was also granted to omit the structural fire protection on many of the secondary beams of the structure. This was achieved by implementing the method developed by Bailey et al[44,45,46], assessing the capacity of the composite slab engaging tensile membrane action when subjected to large deflections at elevated temperatures.

The maximum deflections, approximately span/17, proved to be within the maximum deflections experienced during the Cardington tests where the compartmentation of the composite floor was maintained throughout.

Figure 6.8 indicates the position of unprotected secondary beams and the protected beams subject to the additional load forming the perimeter of the slab panels.

By reducing the fire rating, intumescent paint can be applied (as opposed to board or spray fire protection) allowing services to pass through the cellular beams resulting in reduced floor to floor heights.

The total cost savings due to the reduction in fire rating and the omission of fire protection on most of the secondary beams amounted to significant project cost savings.

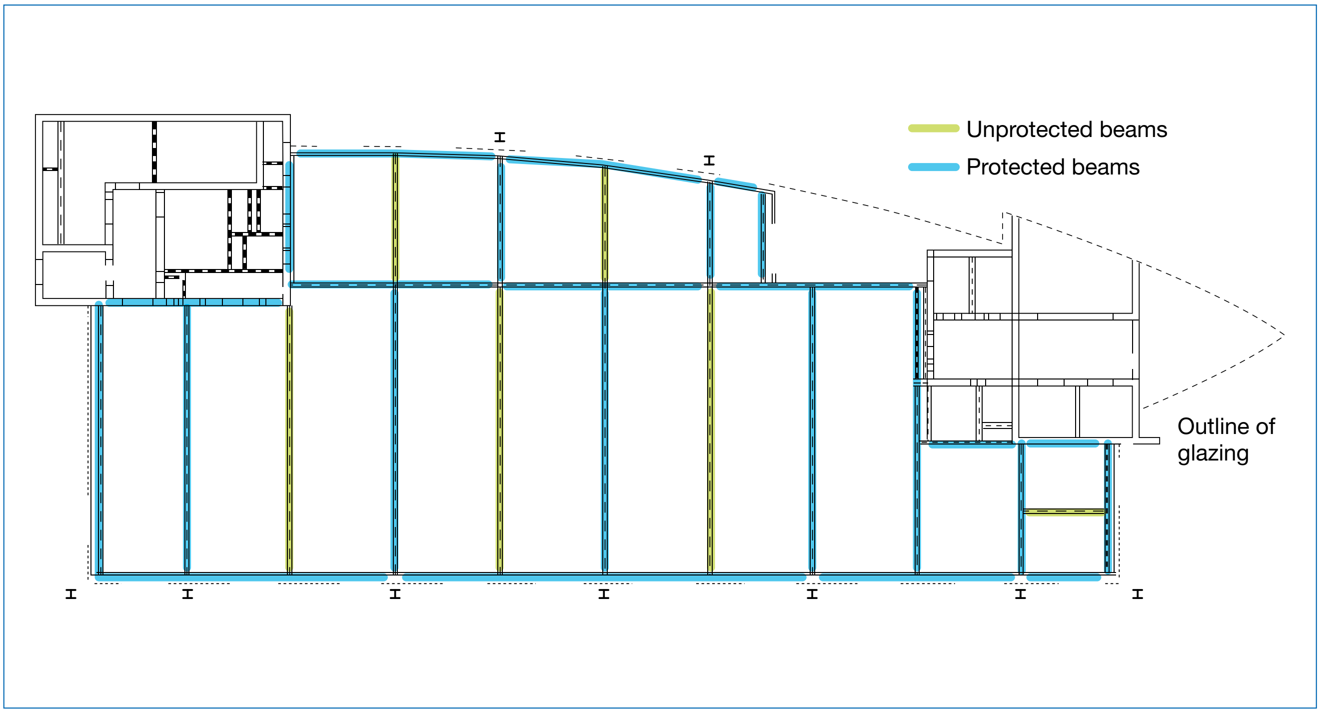


Figure 6.8 Plan view showing unprotected beams

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Material	Member	Reference	Descriptions
Steel and composite	Beams	National Building Research Studies Paper 12 (1953)*	• Steel joists in concrete encasement • 'Tee' beam with steel joists in concrete encasement
		Compendium of UK Standard Fire Test Data - 1, 2 and 3 (1988 to 1990)*	• Floor beams • Shelf angle floor beams • Slim floor beams
		British Steel Report No. SL/HED/R/S1199/18/92/C*	• 2 protected floor beams
		SL/HED/R/S2298/2/93/C*	• Flange plated slim floor beams
		SL/HED/R/S2442/3/96/C*	• An arched metal deck floor beam
		SL/HED/R/S2442/4/96/C*	• A composite slim floor beam
		SL/HED/TN/S2440/4/96/D*	• A composite slim floor beam
		SL/PDE/R/S2442/5/96/C*	• A shelf angle floor beam
		SL/PDE/R/S2442/6/96/C*	• 3 metal deck shelf angle floor beams
	Columns	National Building Research Studies Paper 12 (1953)*	4x3 inch to 12x3 inch steel joists with • Concrete encasement • Brick and block encasement • Plaster encasement • Other encasement
		Compendium of UK Standard Fire Test Data - 1 and 2 (1988 and 1989)*	• Unprotected columns • Web-encased columns • Columns in wall
		British Steel Report No. RS/R/S1199/5/86/B*	• Columns protected with AAC blocks
		SL/HED/R/S2070/1/94/R*	• Cold formed SHS columns protected with spray applied vermiculite cement
		SL/HED/R/S2139/1/92/D*	• 3 concrete-filled CHS columns
		SL/LP/R/S2348/1/93/D*	• 2 concrete-filled CHS columns
		SL/HED/R/S2442/1/94/C*	• Web-encased columns
	Connections	British Steel Report No. SL/HED/R/S2442/2/95/C*	• Bolted beam/column and beam/beam connections
	Floors	CIRIA Report 107 (1985)	• 1 trapezoidal profile LWC slab
		British Steel Report No. RS/RSC/S10244/1/87/D*	• Composite concrete/steel deck floor system
	Others	HMSO Symposium No. 2 (1968)	• 6 steel plate floor assemblies and 14 protected steel girders

Material	Member	Reference	Descriptions
Concrete	Beams	National Building Research Studies Paper 12 (1953)*	• 'Tee' beams
	Columns	National Building Research Studies Paper 12 (1953)*	• 6 to 20 inch and over, square columns • 12 to 20 inch, octagonal columns
		National Building Research Studies Paper 18 (1953)*	• Reinforced concrete square columns
	Floors	National Building Research Studies Paper 12 (1953)*	• Filler joist slabs • Reinforced concrete slabs • Hollow clay tile in concrete slabs
		CIRIA Report 107 (1985)	• 3 ribbed concrete floors
	Walls	National Building Research Studies Paper 12 (1953)*	• Reinforced concrete walls
Timber	Beams and columns	HMSO Symposium No. 3 (1970)	• Laminated timber beams and columns
	Floors	National Building Research Bulletin 13 (1951)*	• Timber floors on two Douglas fir joists
		National Building Research Studies Paper 12 (1953)*	• Boards on wood joists
	Partitions	National Building Research Studies Paper 12 (1953)*	• Solid wood-wool slabs • Solid plaster • Plasterboard supported in steel channels • Timber studding with plasterboard
Masonry	Walls	National Building Research Studies Paper 12 (1953)*	• Solid bricks of clay, concrete or sandlime • Solid concrete blocks
*Available for download at the one-stop-shop for structural fire engineering website (www.structuralfiresafety.org).			