

Structural fire design: Core or specialist subject?

Synopsis

The role and required skills of the structural engineer within the Built Environment is continually changing and expanding. With the ever-increasing supply of reliable computer software to aid in the production of design calculations, clients are beginning to look for 'extra' value from the structural engineer. To meet this demand structural engineers are beginning to incorporate additional facets into structural design which includes aesthetic, environmental, economical and sustainability issues, to name just a few. One area where additional 'value' can be offered is in performance-based fire design. However, at present, this seems to be only offered by specialist firms, with most structural engineers using simple prescriptive design rules that have not changed significantly over the past 50 years. The question arises as to whether the structural aspects of a performance-based fire design should be offered as a holistic structural design package on all projects. This paper presents the background to the existing prescriptive design approaches to fire design and explores the feasibility of whether performance-based structural fire design should be introduced within the design package offered by structural engineers.

Introduction

The aim of fire safety in buildings is to limit, to acceptable levels, the probability of death and injury to people, property loss, and damage to the environment. With respect to people, consideration needs to be given to the occupants who should be able to leave the building (or seek refuge within the building) in reasonable safety, firefighters who should be able to operate in reasonable safety and people in the proximity of the building who should, within acceptable levels of probability, not be exposed to the threat of possible collapse of the building. These life safety objectives for the fire design of buildings are covered by legislation¹. Property loss is not covered directly by legislation and higher levels of fire safety may be required to minimise the damage to the structure, fabric and contents of the building; to minimise any possible loss of business and, if necessary, protect the corporate image. Environmental issues should be considered, particularly for the possibility of fires occurring in buildings storing hazardous materials, where pollutants in the smoke and the run-off of water used to fight the fire can cause disproportionate damage to the environment.

The Building Regulations¹, which are concerned with life safety, provide the minimum legislative level of safety required in the design of buildings. For fire safety, the Building Regulations for England and Wales cover means of escape, internal fire spread (linings and structure), external fire spread and access and facilities for the fire service. One approach for meeting the requirements of the Building Regulations for England and Wales is to follow the guidance given in the Approved Document B (ADB)². The ADB is not mandatory and there is no obligation to adopt any particular solution contained in the document if the requirements can be met in any other way, which can readily be assessed by checking authorities. The document is based on prescriptive rules which state how the building should be constructed to meet the requirements. The document also allows a fire safety engineering (performance-based) approach to be adopted where the probability of a fire occurring, the likely fire severity, the ability of a structure to resist the spread of fire and smoke and the consequential danger to people in and around the building, are considered. It is possible to use a performance-based approach to solve a particular problem with an aspect of building design, with the rest of the design following the prescriptive rules given in ADB.

Although structural engineers should be aware of all the requirements relating to fire safety in the Building Regulations¹, the one requirement that impinges directly on structural design is Requirement B3(1) which states 'The building shall be designed and constructed so that, in the event of fire, its stability will be maintained for a reasonable period'. The ADB addresses this requirement by specifying fire resistance (measured in terms of time) to elements of the building, which is the approach adopted by most designers.

Various codes of practice³⁻⁸ and design guides⁹ provide simple prescriptive rules to ensure the elements of a structure achieve the required fire resistance given in the ADB. These approaches fit easily within the current design process and most structural engineers give them only a momentary thought. For example in the general case of designing concrete structures the prescriptive (tabular) rules, which are based on fire resistance, are used for initial sizing and governing cover distances to reinforcement (together with a consideration of durability) and provided these values are adhered to, no further thought is typically given to the fire design of the structure. Another example is the general design of steel structures, where the typical approach of achieving fire resistance to structural elements is to apply some form of fire protection. If the method of applying fire protection is adopted, the structural engineer typically completes his design of the steel structure concentrating on ultimate, serviceability and buildability issues, giving no thought to fire resistance, and then applying fire protection as an 'add-on'. The designs of masonry and timber structures follow similar prescriptive approaches to fire design.

The prescriptive rules embodied within the structural engineer's design process seem to have served us well, with no major problems highlighted from the existing building stock following experience of actual fires in real buildings. So is there a need for a change? Should the structural engineer venture beyond the bounds of the prescriptive approaches and understand the true behaviour of buildings when subjected to real fires? Many will argue against change, stating that performance-based fire safety engineering is a multi-disciplinary area of design application involving the integration of many different fields of science and engineering. Therefore the need to re-train existing structural engineers and the time and effort to produce 'full' fire engineering design calculations are not justified on typical small to medium sized buildings, which form the major work-load for most structural engineers. These are strong and justified arguments. However, it is the author's view that although 'full' performance-based fire safety calculations should not be carried out in the general structural design process, a more realistic prediction of the performance of the structure in a fire should be incorporated, enabling the structural engineer to produce more economical and safer buildings. This is a view shared by the authors of the Federal Emergency Management Agency's report¹⁰ following the World Trade Center disaster who state in their conclusions that 'The behaviour of the structural system under fire conditions should be considered as an integral part of structural design'. The forthcoming Eurocodes are beginning to produce the design tools to allow the performance of structures to be incorporated within the main design process. The structural engineer will then be able to produce more economical and safer buildings based on all design scenarios instead of being constrained by the existing prescriptive rules.

This paper discusses the background to the existing prescriptive approaches of structural fire design together with an introduction to the various performance-based approaches. The feasibility of including a performance-based approach into the structural design process is then discussed.

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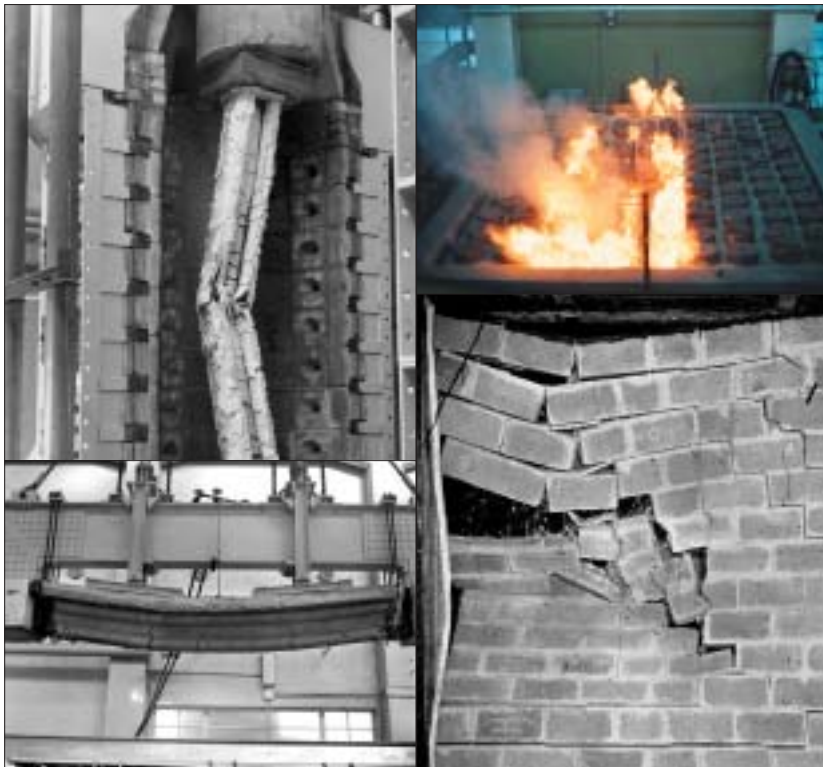


Fig 1. Standard fire tests for columns, floors, walls and beams

Prescriptive approach

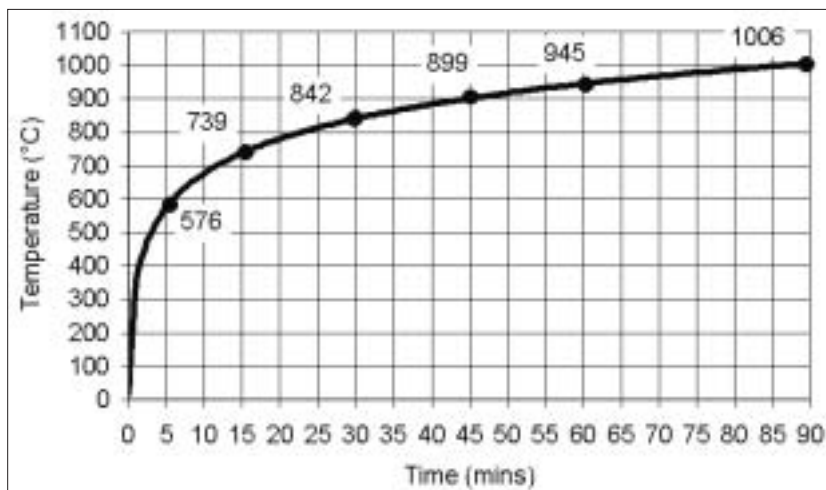
Prescriptive approaches are based solely on fire resistance. The definition of fire resistance will be explained first, followed by the typical prescriptive approaches adopted in the design of steel, concrete, masonry and timber structures.

Fire resistance

It is important to emphasise that buildings do not require fire resistance, it is only elements of the structure that require fire resistance. The fire resistance of the elements, given in the ADB, depends on the function and height of the building. The definition of fire resistance should be clearly understood by designers, since there is often a misconception that the stated fire resistance of elements (i.e. 30, 60, 90 or 120min) is directly related to the time that the building will withstand the effects of fire without collapse. Fire resistance of elements is the measure of time that an element, whether it is a structural element, a fire door, or a non-structural compartment wall, will survive in a standard fire test¹¹.

The history of the standard fire test can be traced back to the 1890s¹² when early attempts at establishing the fire behaviour of structural elements were made at the behest of insurance companies building authorities in the USA. In 1917 the first Standard¹³, for the fire tests on floors and partitions, was issued by the American Society for Testing and Materials (ASTM). In 1933 a more comprehensive Standard (E119)¹⁴, dealing with all

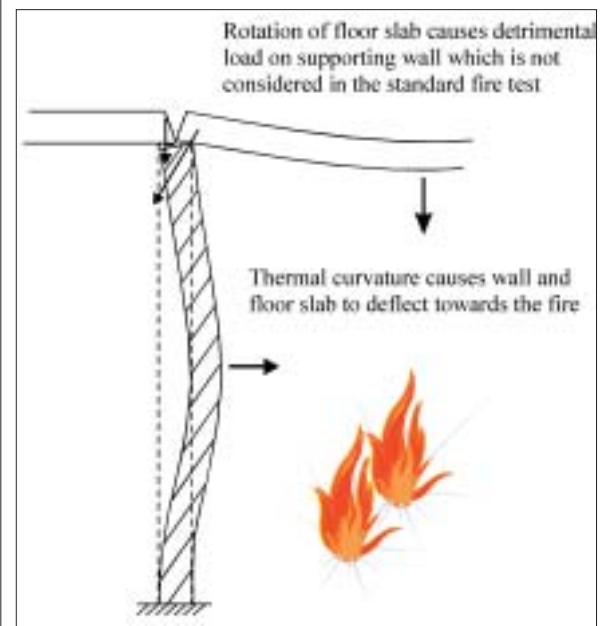
**Fig 2. (Below) Time-temperature relationship used in a standard fire test
Fig 3. (Right) Deflection of structure around supporting masonry wall causing detrimental effects that are not considered in the standard fire test**



types of building elements, was produced which superseded the ASTM Standard. In the UK the first edition¹⁵ of BS 476, dealing with fire resisting testing, was published in 1932. Subsequent revisions of the Standard have attempted to harmonise the heating curve on an international basis leading to the international Standard ISO 834¹⁶. The latest Eurocode EN 1363-1¹⁷ has revised the method of measuring the heating curve, by replacing the bead thermocouple with the plate thermocouple, in an attempt to standardise furnaces across Europe. At first sight the effect of changing the type of thermocouple used to measure the heat input would appear to be insignificant. However, using the plate thermocouple results in the tested members being subjected to more heat during the early stages of the test. This may result in some members failing the test to EN 1363-1 despite having passed the BS 476 test.

For structural elements, there are approved furnaces where a standard configuration of a wall, beam, floor or column can be constructed and tested. The dimensions of the elements are 3m x 3m for walls, 4.5m span for beams, 4m x 4m (typically) for floors and 3m height for columns. Fig 1 shows fire resistance tests conducted on various structural elements. The test follows the standard heating curve shown in Fig 2, where the temperature continues to rise. The failure criteria depend on the type of member tested and are defined in terms of stability, insulation and integrity. Stability is a measure of the ability of the member to support the applied load, with limits given on the maximum displacement and rate of displacement. These limits have primarily been set to reduce the probability of damage to the furnace. Insulation and integrity are generally associated with compartment/separating walls and floors. For insulation, the maximum temperature on the non-fire side must not exceed a maximum of 180°C or an average of 140°C. To maintain integrity no significant sized holes must form in the element, which will allow the transmission of hot gases. Failure by integrity is defined by ignition of a cotton pad held close to an opening.

The concept of fire resistance, and the standard fire test, has the considerable advantage of being easily understood by designers and checking authorities. To date it has been shown to be an adequate approach for ensuring a minimum level of fire safety to buildings. However, the development of the fire resistance test, although commendable in the 1890s has generally been considered to stifle the structural engineer's understanding of how buildings behave in fire. The question of how 'robust' the designed structure is, should a fire occur, cannot be answered if a prescriptive approach is adopted. This is because the building does not represent a collection of individual elements working independently of each other as tested in a standard furnace. The interaction between structural elements in a fire has both a possible beneficial and detrimental effect on



the survival of the building as a whole. Beneficial effects are generally due to the formation of alternative load-path mechanisms such as compressive and tensile membrane action, catenary action and possible rotational restraint from connections. Evidence of compressive and tensile membrane action has been provided by the fire tests^{18,19} on the full-scale buildings at the Building Research Establishment Laboratories in Cardington. The detrimental effect of a collection of structural elements acting as a unit can be due to restraint of thermal expansion resulting in large compressive forces being induced into elements (particularly vertical elements) which then causes instability. Another detrimental effect can be the behaviour of walls, which in a standard fire test may be shown to perform adequately but in a real building the movement of the heated structure around the wall may result in premature collapse (Fig 3). This effect was shown²⁰ for a non-loadbearing compartment wall in one of the fire tests on the steel-framed building at Cardington (Fig 4). In this test the wall was placed off-grid and the deflection of the unprotected beams caused significant deformation of the wall.

Another significant disadvantage of the standard fire test is that the standard time-temperature curve does not represent a real fire. There are generally three distinct phases to a real fire comprising a growth, steady burning and cooling phase. The severity of the fire is governed by the geometry of the compartment, the amount of combustible material, the ventilation conditions and the thermal characteristics of the compartment boundary. Different types of fire can result in different structural behaviour. For example a short duration high temperature fire can result in spalling of concrete exposing steel reinforcement due to the thermal shock. Whereas a long duration low temperature fire can result in a higher average temperature in the concrete members resulting in greater thermal expansion and a greater overall reduction in concrete strength.

The last, and probably the least acknowledged, disadvantage of the prescriptive rules developed from the standard fire resistance test is that the simple rules for steel, concrete, masonry and timber have been developed based on a range of tests, some of which are over 50 years old, using methods of construction and design loads that were relevant at the time of testing, but are now clearly outdated. Extensive research has been conducted, and is on-going, into increasing the economy of buildings by generally concentrating on optimising the performance of the structure at the ultimate and serviceability conditions and optimising the process of construction. The assumption is then taken that the current prescriptive rules developed from outdated tests on different forms of construction and subject to different loads can be applied to these new forms of construction. Of course, one way to avoid this problem is to re-test members that represent new forms of construction (or construction process), but this is expensive and necessitates the continual testing of structural elements that bear very little resemblance to the behaviour of elements in real buildings.

General prescriptive rules for steel structures

With the common perception that steel members perform badly in fire, most designers will blindly protect all exposed steel to achieve the required fire resistance. It is worth emphasising (since it is an often a misconception) that steel members do not require fire protection in order to conform to the guidance in the ADB, they require fire resistance. Of course one way of achieving this is to apply fire protection. The use of fire protection can be in the form of proprietary materials comprising sprays, boards or intumescent coatings or generic materials comprising concrete, brick, block, gypsum plaster and certain types of plasterboard. Guidance on the use of proprietary materials can be obtained from the 'Yellow Book'²¹ and guidance on generic materials can be obtained from the BRE publication⁹ *Guidelines for the construction of fire resisting structural elements*.

The typical prescriptive approach of specifying thickness of fire protection to steel elements has been based on ensuring that the steel does not exceed a maximum temperature of 550°C for columns and a maximum temperature of 620°C for beams

Fig 4.
Deformation of
structure causing
failure of
compartment wall



supporting concrete floors for a given fire resistance period. These temperatures are based on the assumption that a fully-stressed member at ambient conditions (designed to BS 5950-1 or BS 449) will lose its design safety margin when it reaches 550°C. The maximum temperature for beams supporting concrete floors is increased to 620°C since the top flange is at a lower temperature compared to the web and bottom flange, due to the concrete floor acting as a heat sink.

Generally the 550/620°C maximum temperatures are considered conservative since the members are not fully stressed at ambient temperature, the behaviour of steel at elevated temperatures used to derive the 550/620°C values is simplistic and, as explained previously, the structural elements do not behave in isolation.

General prescriptive rules for concrete structures

Most designers do not venture beyond BS 8110-1⁴ when checking the fire resistance of concrete members. Tabular data is given in BS 8110-1 specifying minimum geometric sizes and cover to all reinforcement, with some warning of spalling when covers exceed 40mm. Initial sizing of elements in concrete design will incorporate the guidance given in the prescriptive tables and provided the minimum element size and cover is maintained, designers will generally give no further thought to the fire design. In the author's experience BS 8110-2⁵, which provides more guidance on achieving the required fire resistance, is only used when either an error is made during construction relating to the cover, or when lightweight concrete is used.

BS 8110-2 presents three possible design methods to determine the fire resistance of concrete members, comprising tabulated data, application of test data and fire engineering calculations. In the case of tabulated data, BS 8110-2 removes the conservatism in the prescriptive rules given in Part 1 by specifying cover to the main flexural bars. Some warnings are given in relation to spalling, where it is stated that rapid rates of heating, large compressive stresses or high moisture content can lead to spalling, particularly for covers exceeding 40 to 50mm. The standard also highlights the fact that limestone aggregates are less susceptible to spalling, compared to concrete made from aggregates containing a high proportion of silica (i.e. flints, quartzites and granites). Some guidance is given on the protection of elements against spalling and also additional protection to remedy deficiencies in cover thickness.

The specified covers and geometric size of the elements are based on standard fire resistance test data²² mainly conducted in the 1950s. The tabulated data given in BS 8110-1 and BS 8110-2 are based on the conservative assumption that the structural elements considered are fully stressed at ambient temperature, that the reinforcing steel does not exceed 550°C and that the prestressing tendons do not exceed 450°C.

General prescriptive rules for masonry structures

Prescriptive rules for masonry structures are given in BS 5628-3⁶, which provides tabulated data for loadbearing and non-loadbearing single-leaf and cavity walls. Different types of clay and

concrete material used to construct the masonry unit are also considered.

The prescriptive rules are based on standard fire resistance test data²² extending over 50 years. The main disadvantage of the prescriptive rules is that no guidance exists for walls that are greater than the 3m high walls tested in the standard furnace. As the wall increases in height, the lateral displacement at the wall's mid-height will increase due to thermal curvature, with walls greater than 3m in height collapsing earlier than the 3m high tested walls. Other forms of masonry construction are permitted provided evidence of satisfactory performance is produced based on results from standard fire resistance tests. Therefore if a designer uses a form of masonry construction not covered by BS 5628-3, a standard fire test would need to be carried out.

It is worth mentioning that experience from real fires shows that masonry walls perform extremely well and failure, if it occurs, is generally due to the surrounding structure placing eccentric or lateral loads on the wall resulting in collapse.

General prescriptive rules for timber structures

Simple prescriptive rules for timber members, timber stud walls and timber joisted floor construction are given in BS 5268^{7,8}. In the case of members, the rules are based on charring depths, which are specified based on fire resistance periods. The predictable nature of charring provides a good insulator to the timber member, with the timber beneath the charred layer generally being unaffected by the fire. The stability and deflection of the member can easily be calculated based on an effective cross-section assumed to be the residual non-charred section. The use of charring depths is suitable for large section timber which will perform well in a fire. For smaller section timber, protection from linings is required. In the case of walls and floors, tables are provided that allow the designer to assess the stability, insulation and integrity of the system. However, care is required in ensuring the quality of fixings of the protecting lining to the supporting timber on site, which must be the same quality as the fixings used in the standard fire tests, from which the tables were derived.

Performance based approach

A comprehensive 'full' performance-based approach to fire safety engineering in buildings is an extremely complex multi-disciplinary design procedure and should be left to the trained specialist. The 'full' approach will involve consideration of active and passive measures, movement of smoke and fire, detection systems, fire safety management, structural response and risk analysis. BS 7974²³ presents a formalised, but flexible, framework within which to carry out a full fire safety engineering approach, augmented by a series of comprehensive Published Documents.

Although most structural engineers will generally not carry out a 'full' performance-based approach to fire safety, it is possible to carry out a structural fire performance-based approach, which will allow the engineer to understand and explain how buildings perform should they be subjected to severe fires. The process of structural fire engineering is analogous to the process of designing structures to withstand wind (Fig 5). As most readers will know, to check buildings for wind loads there are three basic steps comprising, an estimate of the site wind speed, an estimate of the wind pressures over the building and an estimate of the structural response. For a structural fire engineering performance-based approach the three basic steps comprise, an estimate of the severity of a fire, an estimate of the temperature distribution through the structure (thermal response) and an estimate of the structural response.

There are a number of options available to calculate the severity of the fire and the thermal and structural response, as shown in Fig 6. Each of the options will be discussed briefly below. However, the simplest and most common approach is to assume the fire behaviour is represented by the standard fire curve, define the thermal response from test data and estimate the response of the building assuming member behaviour. This approach forms the bases of the design methods in the fire

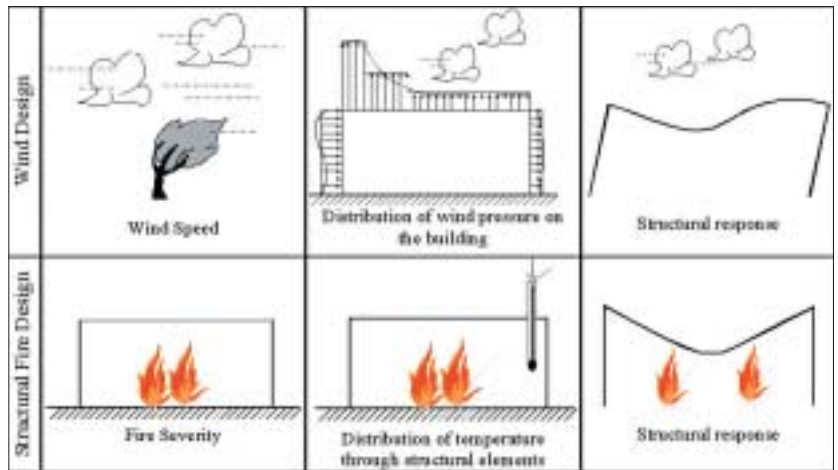


Fig 5. Process of wind design and structural fire design

parts of the Eurocodes. Although the disadvantages of assuming the standard fire curve and member design have been discussed, this 'simple' performance-based approach will generally allow more economical buildings to be designed and constructed compared to those designed using the prescriptive approach.

Fire behaviour

As explained, the simplest approach available to the structural engineer is to use the standard fire curve. The time-equivalence is a simple approach that tries to relate the actual 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 curve. There are a number of time-equivalence methods which take into account the amount of fuel load, compartment size, thermal characteristics of the compartment boundaries and ventilation conditions. Although simple to use, the time-equivalence is a crude approximate method of modelling real fire behaviour and the limitations of the method should be fully understood. The main limitation is that the method is only applicable to the types of members used in the derivation of the adopted formulae. For example the time-equivalence method present in EN 1991-1-2²⁴ is only valid for reinforced concrete, protected steel and unprotected steel.

Parametric fire curves allow the time-temperature relationship to be estimated over the duration of the anticipated fire. Compartment size, boundary characteristics, fuel load and ventilation are considered, with the most validated approach given in EN 1991-1-2. The approach is simple to use and, with

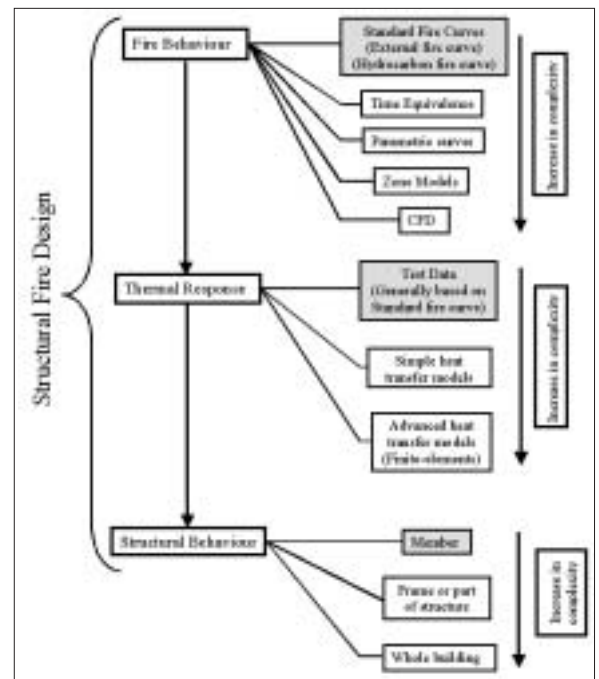


Fig 6. Options for a performance-based approach

the aid of simple spreadsheets, fire predictions can be easily derived. Once again the limitations of the method should be understood and in the case of the approach given in the Eurocode limitations on the maximum compartment floor area of 500m² and compartment height of 4m are stated. In addition the method is limited to fire compartments with mainly cellulosic type fire loads and compartments with linings that have a value of thermal inertia between 100 and 2200J/m²s^{1/2}K. The limitations are generally governed by the available test data used to derive the design method.

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 simplest model is a one zone model in which the conditions within the compartment are assumed to be uniform and represented by a single temperature. A more sophisticated modelling technique is the use of Computational Fluid Dynamics (CFD) to predict fire growth and compartment temperatures. CFD has been shown to be successful in the modelling of smoke movement and has recently been applied to the modelling of fires. Similar to the use of any computer model, both the zone and CFD models require expertise in defining the correct input data and assessing the feasibility of the calculated results.

Thermal response

Once the compartment atmosphere temperature is predicted, the temperature of the structure needs to be estimated to allow the structural response to be calculated. Calculation of temperatures in structural members can be extremely complex, especially for materials that retain moisture and have a low thermal conductivity. The simplest method of defining the temperature profile through the cross-section is to use test data presented in tables or charts which are published in codes or design guides. This test data is generally based on the standard fire curve. Simple design equations are presented in codes^{25,26} (and design guides^{27,28}) to predict the temperature development of bare steel. The approach considers both radiative and convective heat transfer and although a spreadsheet is required to solve the equation over the fire duration, it is simple to use. Similar equations exist for protected steel sections, however the thermal properties of the proposed protection material are needed, which generally are difficult to obtain from manufacturers.

It is possible to use simple heat transfer models based on one-dimensional heat flow. However, simple computer programs are needed to solve the heat transfer equations. Alternatively, advance finite-element heat transfer models can be used, but this requires the relevant expertise to ensure the models are applied correctly and used within their limitations.

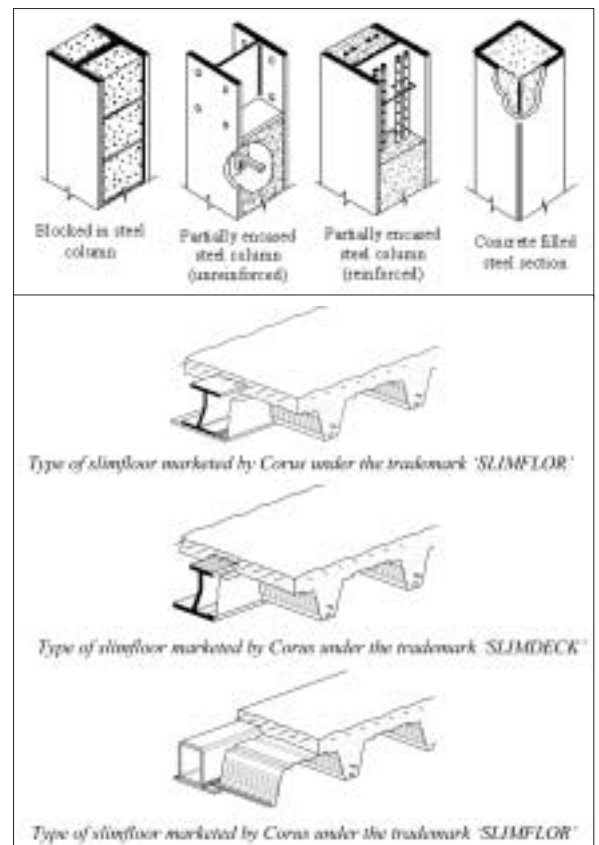
Structural response

The simplest method of predicting the structural response of buildings in fire is to analyse individual members at what is termed the Fire Limit State (FLS). The design adopts relevant partial safety factors^{3,25,26} which provide realistic estimates of the likely applied load at the time of the fire and the likely material resistance of the member. The approach of designing individual members has evolved from results and observations of standard fire tests.

The use of member fire design at the FLS, as covered by current codes of practice, will be familiar to practising structural engineers, since the principles closely follow the approach used to check members at the Ultimate Limit State (ULS). The main differences between ULS and FLS is that for fire design different partial safety factors for load and material resistance are used (to represent an accidental limit state) and the strength and stiffness of the member reduced based on the temperature distribution through the cross-section.

The prescriptive methods discussed earlier have been derived from standard fire test data assuming the members are fully stressed at ambient temperature. Member design at FLS has the advantage of allowing designers to predict the response of the structure under the actual likely load on the member at the time of the fire. Possible savings can be obtained since it is

Fig 7. Forms of steel construction that do not require passive fire protection²⁹



unlikely that members are fully stressed at ambient temperature. This is because serviceability and buildability issues typically result in the specification of member sizes and strength greater than that required to fulfil ULS. The steel industry has utilised the fire design methods for individual members in the development of forms of construction^{29,30} that generally do not require applied fire protection, which is costly in terms of material and application time. The typically forms of construction are shown in Fig 7 and comprise slimfloor beams, shelf angle beams, partially encased beams and columns, and concrete filled columns.

Design methods exist to consider frame behaviour or parts of a structure in fire. In the Eurocodes^{25,26} frame behaviour is utilised to allow the effective lengths of continuous steel, composite and concrete columns to be reduced from ambient temperature values. To conduct a frame analysis at elevated temperatures simple computer models are required, which include the effects of thermal expansion of the heated structure and correct boundary conditions.

Although member and frame design at FLS is a significant improvement on the prescriptive approaches, allowing designers to obtain some indication (although limited) of the actual behaviour of buildings in fire, recent fire tests^{31,32,33} on full-scale buildings have shown that member design is not, in some cases, realistic. To most designers this will come as no surprise since member design methods at ULS and SLS are only an approximation of the real behaviour of buildings. However, provided this approximation is conservative, resulting in safe, usable and economic buildings then the design approach is acceptable.

The results from full-scale fire tests revealed both detrimental and beneficial effects compared to the assumptions adopted for member design. For example, restraint to thermal expansion of heated members within a fire compartment, provided by the cold structure outside the compartment, can induce large compressive stresses in the heated members. These high compressive stresses can cause buckling failure of columns (or beams with inadequate lateral restraint) and in the case of concrete members can increase its susceptibility to spalling. However, in floor slabs the restraint to thermal expansion can be beneficial, inducing high compressive forces³³, resulting in an increase in load-carrying capacity due to

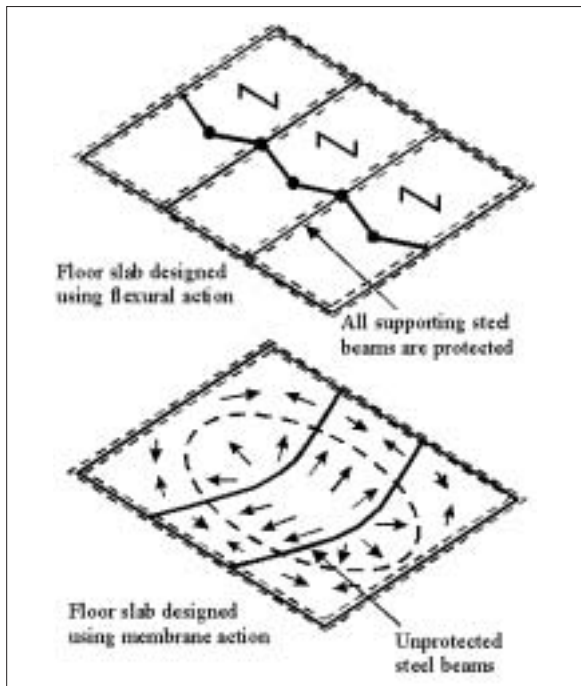


Fig 8. (Left) Design of composite floor using flexural and membrane action

Fig 9. (Above) Photographs showing fracture of plate (end-plate) and shear failure of bolts (fin plate)

Fig 10. (Right) Fracture of end-plate connection on a slim-floor edge beam



Fig 11. Picture showing lateral movement of external columns following a fire test on the Cardington Concrete Building

compressive membrane action.

A significant beneficial effect of whole-building behaviour for composite floor slabs was observed during the fire tests on the steel-framed building at Cardington. It was shown that the traditional design method for composite floor slabs, which is based on flexural behaviour (Fig 8), was conservative when the floor plate (comprising the floor and supporting beams) was considered in its entirety. Based on the test results and observations, a simple design method was derived^{8,34,35,36} that utilised the tensile membrane action of the floor plate (Fig 8) which was shown to occur during the tests. The approach is a significant advancement in useable design tools, allowing designers to utilise load-path mechanisms different from those assumed for normal design. The design method allows up to 50% of the steel beams within a given floor plate to be unprotected, compared to designs that follow the prescriptive approach. This can result in significant cost savings. Beneficial effects of compressive membrane action observed in the fire-test³³ on the full-scale concrete building are currently being investigated and new design guidance is anticipated in the near future.

There were other modes of detrimental behaviour observed during the full-scale fire tests that are not considered in member design. In the case of the steel-framed building, which incorporated a composite floor slab, it was observed³¹ that the connections were under high tensile force during the cooling phase. These high tensile forces lead to fracture of the welds and bolts forming the connection (Fig 9). It was shown that end-plate connections performed adequately, maintaining vertical shear under high tensile forces, even though fracture of the end-plate occurred. However, in the fin-plate type of connection the vertical shear was lost following shear failure of the bolts. The connections were also shown to be a possible 'weak-link' in a large-scale fire test³⁷ on a slim-floor system. In the test an end-plate connection fractured during the heating stage of the fire due to insufficient ductility (Fig 10). Although vertical shear remained, any beneficial rotational restraint from the connection was lost.

In the case of the concrete framed building, test observations³³ showed the detrimental effect of thermal expansion causing significant lateral movement (Fig 11) of the external columns, resulting in additional stresses in the column due to the P- Δ effect.

Although most designers will keep to member design at the FLS, following the guidance provided in the codes of practice, it is important that detrimental behaviour observed from full-scale tests are appreciated. An understanding of the true response of buildings in fire can allow the designer to easily reduce any detrimental effects by careful detailing and design.

At present, research^{32,38} is on-going looking at the modelling of whole building behaviour in fire with specialist companies using commercially available or purpose-written software. The main use of such software is in the modelling of steel-framed structures where significant savings in fire protection can be obtained. The main disadvantage of using sophisticated models is that they are seen as a 'black-box' which makes checking of designs difficult. In addition the main disadvantage currently facing these models is that they are not able to model localised failure to a sufficient level of accuracy (particularly reinforcement fracture in the slab). The application of these models is complex and should only be used by competent designers who fully understand both the limitations and capabilities of the model.

Conclusions

This paper has introduced the current methods for structural engineering. These methods range from the simple 'deemed-to-satisfy' prescriptive rules through to sophisticated structural performance-based approaches, where models exist to predict the likely fire severity, thermal distribution and structural response of members and the building as a whole. Without

doubt, the most sophisticated models (CFD and finite-element) require designers with multi-discipline skills to correctly define the input data and interpret the viability of the output. There is a strong argument that the use of such models should be left to the trained expert.

Training existing structural engineers to carry out 'full' performance-based structural fire designs will not be cost-effective for most of the buildings being constructed. However, it is the author's opinion that as a minimum, structural engineers should understand the philosophy behind the prescriptive approaches and have an understanding of the simplest performance-based approach of member design based on fire resistance. This simple design approach is presented in the structural Eurocodes and can easily be understood by existing structural engineers without the need for extensive re-training.

By using even the simplest performance-based approach, instead of prescriptive rules, the design and construction of more economical buildings are possible. Perhaps even more significant, is the fact that a performance-based design allows the designer to estimate the likely response of the building during a fire and assess its robustness, which is impossible if the prescriptive rules are followed.

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