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Author:	Colin Bailey, Professor, University of Manchester
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A Simplistic or Holistic Approach to Structural Fire Engineering?

Colin Bailey

Professor of Structural Engineering, The University of Manchester

Abstract

An elemental prescriptive approach, which is simplistic in nature, can be used to design buildings for structural fire safety. However, the simplicity of the approach means that realistic structural and fire behaviour are ignored and optimum design solutions in terms of safety and economy are impossible to obtain. The approach also holds the underlying assumption that any ignored beneficial effects outweigh any ignored detrimental effects of whole building behaviour and realistic fire scenarios. This paper presents the background to the prescriptive approach, its limitations, and introduces the benefits of using an holistic performance based approach. By considering the actual fire and structural behaviour, through a performance based approach, any 'weak-links' within the design can be identified, and rectified, allowing safer, more robust, and possibly more economical buildings to be constructed.

Keywords: Fire safety, prescriptive, performance-based, whole building behaviour.

1. Introduction

The minimum level of fire safety aims to limit, to acceptable levels, the probability of death and injury of building occupants, fire fighters and people in the proximity of the building. Levels of safety can be increased to protect the building contents, the building superstructure, heritage, business continuity, corporate image of the occupants or owner, and the environmental impact.

There are a number of different approaches to ensure fire safety within buildings, which include:

- A simplistic prescriptive approach (deemed-to-satisfy rules).
- A performance based approach to address a particular part of the design, with the rest of the design following a prescriptive based approach.
- An holistic performance based approach.

The simple prescriptive design approach, which states how individual elements of a structure should be constructed, is generally assumed to provide sufficient levels of life safety. Although simple to apply, the designer cannot assess the actual levels of safety embedded within a design which follows the prescriptive rules, since the design procedure does not consider the actual behaviour of the building or realistic fire behaviour. In addition, an assessment of the robustness of the building, or identification of any 'weak-links' within the design, is impossible. For some aspects of building design the restrictive nature of the prescriptive rules make them impossible to use. In this case a performance based approach could be used to design a particular aspect of the building with the rest of the building following a prescriptive design.

To assess actual levels of fire safety relating to life safety, property protection, business continuity and environmental impact, an holistic performance based approach should be carried out. A performance based approach must also be followed if the optimum economical design solution (considering initial and whole-life costs) is sought, or multiple accidental loads (such as earthquakes and fire or explosion and fire) are considered.

For structural fire engineering, the performance based approach involves the assessment of three basic components comprising the likely fire behaviour, heat transfer to the building's components and the structural response. The overall complexity of the design depends on the assumptions and methods adopted to predict each of the three design components as well as the willingness and experience of the designer.

This paper describes the limitations of the prescriptive approach and discusses the advantages of adopting a performance based approach to ensure safe

Contact Author: C. G. Bailey, Professor of Structural Engineering, University of Manchester, MACE, Pariser Building, PO Box 88, Manchester, M60 1QD
Tel: ++44(0)161-200-5795 Fax: ++44(0)161-200-4601
e-mail: Colin.Bailey@umist.ac.uk

and economical building designs.

2. Prescriptive approach

Prescriptive approaches are based solely on fire resistance. Fire resistance periods are typically specified depending on the building's function and height above ground and can vary throughout the world. It is important to emphasise that if a prescriptive approach is followed it is only the elements of the building that require fire resistance and not the building as a whole. 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 120 minutes) 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 test[1,2].

Figure 1 Standard fire resistance tests.

The history of the standard fire test can be traced back to the 1890's[3] when early attempts at establishing the fire behaviour of structural elements were made at the behest of insurance companies or building authorities in the USA. In 1917 the first Standard[4], 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)[5], dealing with all types of building elements, was produced which superseded the ASTM Standard. In the UK, the first edition[6] of BS476, 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 ISO834[2]. The latest Eurocode EN1363-1[7] 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.

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 × 3m for walls, 4.5m span for beams, 4m × 4m (typically) for floors and 3m height for columns. Figure 1 shows fire resistance tests conducted on various structural elements. The tests follow the standard heating curve[1,2] where the temperature continues to rise continuously. The failure criteria depends on the type of member tested and are defined in terms of stability, insulation and integrity. Stability is a measure of the member's ability to support the applied load, with limits given on the maximum and rate of displacement. These limits have primarily been set to reduce the probability of damage to the furnace and do not relate to true structural behaviour. 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 simply defined by ignition of a cotton pad held close to an opening.

3. Typical prescriptive rules for structural elements

With the common perception that steel members perform badly in fire, most designers will follow simple prescriptive rules, relating to fire protection thicknesses, and blindly protect all exposed steel to achieve the required fire resistance. It is worth emphasising (since it is often a misconception) that steel members do not require fire protection, 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.

Typically the prescriptive specification of fire protection thicknesses 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 supporting concrete floors, for a given fire resistance period. These temperatures are based on the assumption that a fully-stressed member at ambient conditions 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 stress-strain-temperature relationship of steel at elevated temperatures (used to derive the 550/620°C values) is too simplistic, and the structural elements do not behave in isolation.

For concrete members tabular data is presented in codes and design guides specifying minimum geometric sizes and cover to reinforcement. It is common for initial sizing of elements in concrete design to 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.

The tabulated data given in codes are typically based on the conservative assumption that the structural elements are fully stressed at ambient temperature, that the reinforcing steel does not exceed 550°C and the prestressing tendons do not exceed 450°C.

Prescriptive rules for masonry structures are given in codes, which provide 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 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.

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. This is a mode of failure that is totally ignored in a standard fire test.

Simple prescriptive rules for timber members, timber stud walls and timber joisted floor construction are given in codes. 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.

4. Limitations of the prescriptive approach

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 generally been shown to be an adequate approach for ensuring a minimum level of fire safety in buildings. However, the development of the fire resistance test, although commendable in the 1890's has generally been considered to stifle the 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[8,9] 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) leading to 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. This effect was shown[8] for a non-loadbearing compartment wall in one of the fire tests on the steel-framed building at Cardington (Figure 2). In this test the wall was placed off-grid and the deflection of the unprotected beams caused significant deformation of the wall.

Figure 2 Failure of non-loadbearing compartment wall due to deformation of the structure.

Another significant disadvantage of the standard fire test is that the time-temperature relationship 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[10] 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). However, this is expensive and necessitates the continual testing of structural elements that bear very little resemblance to the behaviour of elements in real buildings.

5. Performance-based approach

A comprehensive 'full' performance-based approach to fire safety engineering in buildings is an extremely complex multi-disciplinary design procedure. 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.

It is possible to carry out a *structural* fire performance-based approach, which will allow the designer to understand and explain how buildings perform should they be subjected to severe fires. The main advantage of a performance based approach is that actual actable performance criteria can be defined and the level of safety for each part of the design can be assessed. This is a significant improvement on the acceptance criteria underlying the prescriptive approach which relate to stability, insulation and integrity defined in a small-scale standard fire test.

The acceptable criteria within a performance based fire design should be based on the global fire strategy for the building. The following points should be considered when considering the acceptable structural response.

- The structure should remain stable for the full duration of the defined worst case fire scenario, including the cooling stage of the fire.
- Compartmentation should be maintained for the duration of the fire scenario, considering both the performance of the compartment wall and any movement of the structure in the proximity of the wall.
- All escape routes, especially for phased evacuation, should not be compromised for a reasonable period of time.
- Fire-fighting shafts should not be compromised for the duration of the fire.
- Fire stopping and dampeners should not be compromised for the duration of the fire.
- Any protection system should not exceed the displacements experienced in their validation tests.
- The consequence of fire spread up the building, through the windows, should be considered.

In some cases it is argued that the prescribed approach does address most of the above criteria, since elements, fire stopping, dampeners and protection systems are tested in standard fire resistance tests. However, as explained previously, the standard fire test does not consider actual structural and fire behaviour. A fire stopping system or compartment wall, or elements of a fire-fighting lift, may perform adequately in a standard fire test, yet in a real building the movement of the whole structure may cause premature failure of these components allowing the fire to spread throughout the building. In addition the prescribed approach does not consider the cooling stage of the fire where high tensile forces can occur within the structure leading to fracture of connections or reinforcement(8,11).

Within a performance based approach there are a number of options available with which to calculate the severity of the fire and the thermal and structural response, as shown in Figure 3. Each of the options will be discussed briefly below.

Fire Behaviour

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 boundaries.

The occurrence of flashover, in a compartment fire, defines a transition in the fire development. Therefore, many fire models are classified as pre- or post-flashover models, except for computational fluid dynamic (CFD) models, which can model all stages of the fire. There are a number of options available to calculate the fire severity. These comprise:

- Standard/Nominal Fire Models.
- Time Equivalence.
- Parametric Fire Models.
- Localised fires.
- External window fires.
- Zone Models.
- CFD or Field Models.
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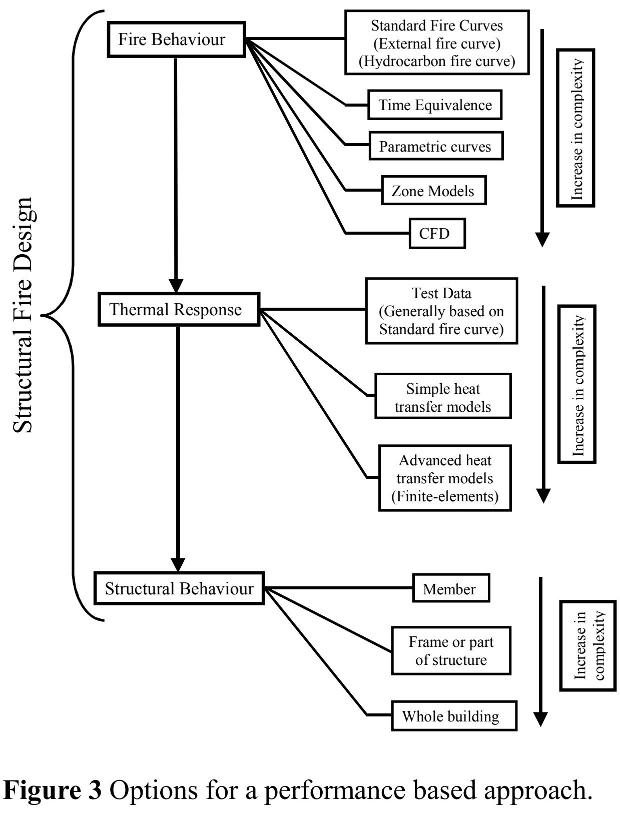

Figure 3 Options for a performance based approach.

The simplest approach is to use the standard fire curves but, as explained previously, these time-temperature relationships are not based on any physical parameters and do not consider the cooling stages of a fire, which can be extremely important when considering the structural behaviour. 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 time-equivalence method presented in the ENV version(12) of the Eurocode was used by ArupFire(13) on the 40 storey Swiss-Re building, St Mary Axe, London (Figure 4). By considering realistic fire loads and ventilation conditions it was shown that the fire-resistance could be reduced compared to the prescribed values. A number of conservative assumptions relating to ventilation conditions, fire load and heating of structural elements were also included.

Figure 4 Swiss Re, St Mary Axe, London

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. The approach is simple to use and, with the aid of simple spreadsheets, fire predictions can be easily derived.

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 where 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 in assessing the feasibility of the calculated results.

Heat transfer to the structure

The temperature distribution through structural members is dependent on the radiation and convective heat transfer coefficients at the member's surface and conduction of heat within the member.

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 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 moisture retention, 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 and design guides 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 are used to model the fire behaviour then either simple or advanced heat transfer models should be used. Careful attention should be given to the modelling of moisture if simple heat transfer models are adopted.

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[14,15,16] 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 from standard fire tests.

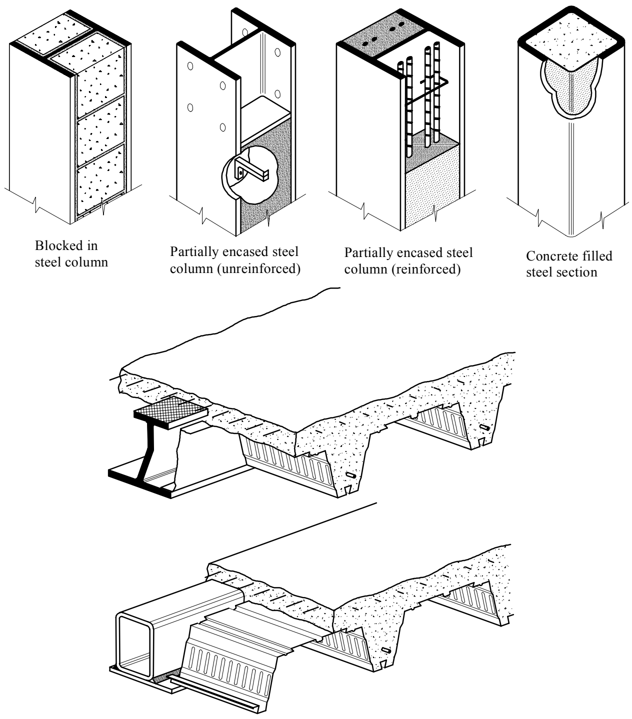

Figure 5 Forms of steel construction with partial protection.

The use of member fire design at the FLS, as covered by current codes of practice, utilises principles which 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 is 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 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 which are 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[17] that generally do not require applied fire protection, which is costly in terms of material and application time. The common forms of construction comprise slimfloor beams, shelf angle beams, partially encased beams and columns, and concrete filled columns. Typical forms of columns and slimfloor beams are shown in Figure 5.

Figure 6 Full-scale fire tests on the Cardington concrete and steel buildings.

Design methods also exist to consider frame behaviour or parts of a structure in fire. 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[8,9,18] on full-scale buildings (Figure 6) 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 forces[9], resulting in an increase in load-carrying capacity due to compressive membrane action.

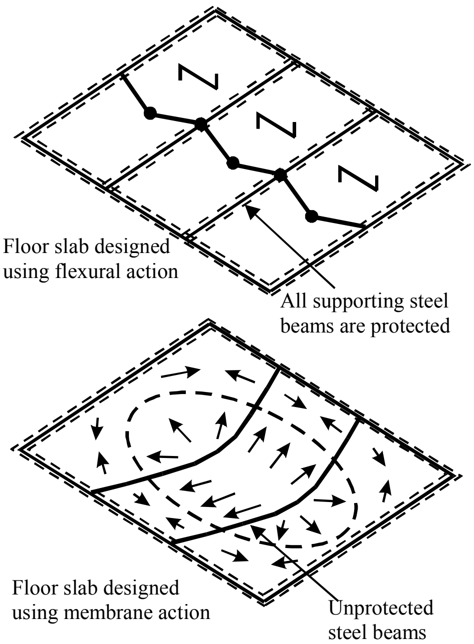

Figure 7 Flexural and membrane behaviour of floor slabs.

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 (Figure 7), 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[19,20,21] that utilised the tensile membrane action of the floor plate (Figure 7) which was shown to occur during the tests. This approach is a significant advancement in useable design tools, allowing designers to utilise load-path mechanisms which differ 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 (Figure 8), compared to designs that follow the prescriptive approach. This can result in significant cost savings. Alternatively, a more robust protection system, which is typically more costly, (such as encasing the beams in concrete) can be applied to only those beams that are required to retain their strength to ensure overall stability.

Figure 8 Example of using membrane action in the floor slab.

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 observed[8] that the connections were under high tensile force during the cooling phase. These high tensile forces led to fracture of the welds and bolts forming the connection (Figure 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 failure of the bolts.

Figure 9 Fracture of end-plates and shear failure of bolts in various connection types following a fire.

The connections were also shown to be a possible 'weak-link' in a large-scale fire test[22] on a slimfloor system. In this test an end-plate connection fractured during the heating stage of the fire due to insufficient ductility (Figure 9). Although vertical shear remained, any beneficial rotational restraint from the connection was lost.

Figure 10 Lateral movement of external columns following a fire test.

In the case of the concrete framed building, test observations[9] showed the detrimental effect of thermal expansion causing significant lateral movement (Figure 10) of the external columns, resulting in additional stresses in the column due to the P-Δ effect. Compressive membrane action in the floor slab was also observed, which was detrimental in that it increased the concrete's susceptibility to spalling (Figure 11), but was also beneficial in forming a load-carrying mechanism, in the form of compressive membrane action, which is far stronger than pure flexural action.

It is important that detrimental behaviour observed from full-scale tests is 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.

Figure 11 Spalling of concrete floor slab following the Cardington fire test.

At present, research[23,24] 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 models are not able to simulate localised failure to a sufficient level of accuracy, particularly reinforcement fracture in the slab and connection failure when considering whole building behaviour. At present designers take conservative assumptions by restricting the maximum allowable strains in the reinforcement and specifying ductile connections that have been shown to retain their vertical shear capacity following a fire.

6. Conclusions

There are a number of design approaches available to ensure structural fire safety of buildings. The simplistic elementary prescriptive approach of specifying forms of construction, which will achieve the required fire resistance periods, are commonly used. However, by adopting a prescriptive approach the designer cannot assess the actual levels of fire safety, robustness of the building and whether the optimum economical design solution has been achieved. The elemental prescriptive approach also ignores any detrimental effects observed from full-scale fire tests due to the building acting in its entirety.

By carrying out an holistic performance based approach the actual structural behaviour and realistic fire scenarios are considered and any 'weak-points', identified within the design. Any identified 'weak-points' can be easily, and typically cheaply, rectified to obtain a more overall robust building.

The performance based approach can also form a part of a risk analysis to consider multiple extreme loading events, such as earthquakes and fire, or expositions and fire, with the aim of reducing the overall probability of loss of life and financial loss.

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