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Performance Based Fire Engineering in the UK

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Abstract

This paper reviews the recent developments in fire engineering and the design approaches which are being used in the UK, compared with traditional prescriptive solutions. The research background which has underpinned this is briefly summarised, and the benefits of these more advanced methods are discussed. The focus is on structural fire engineering, but some consideration of modelling fires is also included. Some of the more commonly used design tools are discussed, together with the relative benefits they offer. The use of these more advanced approaches is then outlined in the context of which building types might be most suitable, and a number of case studies are included to illustrate this. Likely future developments are also discussed.

Keywords: Fire engineering, Performance based design, Steel structures, Composite construction

1. Introduction

Design for fire safety is clearly an essential element for all new buildings, and typically takes the form of compliance with national regulations, most commonly by following prescriptive rules. A wide range of issues need to be considered including detection, alarms, escape and stability of the structure. When using prescriptive methods these are largely treated independently, but in a performance based approach, there may be significant interactions, requiring an integrated approach. In this paper the focus will be principally on the structural engineering aspects of fire engineering and the need to maintain stability for a specified period, referred to as the fire resistance time, but there is clearly a strong interaction with how the fire itself is represented.

Minimum periods of fire resistance are specified in national regulations, typically accounting for building height and occupancy. These periods refer to the duration of exposure under standard fire conditions for which certain performance criteria are satisfied. In the context of structure, the requirement is that stability should be maintained for the designated fire resistance time. In a prescriptive approach this provision is deemed to be satisfied if, for steel framed structures, minimum levels of fire protection are applied, or in the case of reinforced concrete, minimum section sizes and reinforcement cover are specified. The latter is generally easy to achieve through normal detailing, but for steel structures it has been necessary to fit insulating materials around the steelwork. The traditional use of concrete, masonry or plaster for this purpose was superseded by lightweight specialist systems including sprays, boards and blankets, but over the past decade thin film intumescent coatings, which can be applied on-site or prior to delivery, have come to dominate the passive structural fire protection market in the UK.

Such prescriptive methods may ensure compliance but they do not necessarily ensure satisfactory performance, and they do add to construction costs, although in recent years prices in the UK have fallen significantly. The development of more rational, scientific methods of achieving satisfactory fire resistance, particularly for steel framed structures, was initially driven by the incentive of possible cost savings, and was prompted by evidence from real fires suggesting that reduced levels of protection may be sufficient. Recently, however, clients are beginning to recognise the value of a thorough assessment of fire safety and the possible consequences of a major fire, and in the case of unusual structural forms this approach may be the only way of ensuring satisfactory performance. These more advanced approaches, which may broadly be described as performance based design, vary in complexity and may comprise elements of how the fire develops, its effect on the temperature of the structure and how this then responds physically. The simplest approaches may only consider one of these aspects, but the most advanced will look at them all in an integrated manner.

2. UK Regulatory Requirements

Regulations covering fire safety requirements for buildings in the UK are set out in Approved Document B of the Building Regulations (DCLG, 2006), and provide prescriptive rules for a variety of measures in relation to building characteristics. A new standard, BS 9999 (BSI,

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2008), has recently been published, providing an alternative approach based on risk factors associated with the nature of the occupants, the building itself, and the factors likely to influence the severity of a fire, including allowance for sprinklers where appropriate. In general this leads to a reduction in the structural fire resistance requirements compared with Approved Document B, and in particular 2-storey offices less than 1000 square metres per floor, require only 15 minutes fire resistance.

The standard is based on fire engineering principles and allows more flexibility than is possible using conventional prescriptive guidance. Guidance is also provided for aspects not previously covered such as atria, fire service access, and post occupancy safety management. It therefore represents a significant advance, but compliance does not, in itself, represent performance based design.

3. The Development of Simple Performance Based Approaches for Steel Framed Buildings

The fire resistance of a steel member is typically expressed as a single limiting (critical) temperature – namely the temperature at which the element is expected to fail – and the purpose of the applied fire protection is to maintain the steel at a temperature below this level for the required fire resistance period. Prescriptive approaches adopt a single limiting temperature, regardless of the context, but research on individual beams and columns in the standard fire test have shown that this is inappropriate and that loading, 'massivity' of the cross-section, and any implicit protection or shielding, for example that provided by a concrete slab supported on the top flange of a steel beam, are important factors which can affect failure temperatures. This has led to the development of simple design methods such as the limiting temperature method. This is an empirical approach based on test data for both predicting the temperature which the steel will reach after the specified length of exposure under standard fire conditions, and determining the temperature at which the structure will 'fail'. In this context, failure is defined in the same way as the standard test, namely a maximum deflection in the case of beams, and for columns the point at which thermal expansion is exactly balanced by axial shortening.

The moment capacity method provides an alternative simple performance based approach for beams and is rooted in more fundamental structural principles, involving calculation of the reduced moment of resistance taking account of the effect of temperatures over different parts of the cross-section on material strength. This is then compared with the applied bending moment at the fire limit state. This is the equivalent of using plastic design for a single beam, but accounting for material softening.

These approaches were formally adopted in the world's first design code for steel in fire, BS5950 Part 8, first published in 1990 (BSI, 2003). Similar methods were subsequently included in the Eurocodes (BSI, 2005a, 2005b) which also provided methods for a more comprehensive range of structural systems, for example cellular beams, and covered additional aspects of fire engineering design, notably for modelling real fires.

In practice, for the majority of projects, these simple design approaches offer only modest savings compared with conventional prescriptive methods, and they provide no useful intelligence about how a structure might really behave in a fire. But they are significant in being the first formal recognition within design regulations of alternatives to basic prescription.

4. More Advanced Methods of Performance Based Design

The traditional prescriptive rules and indeed the simple calculation based design methods such as the limiting temperature approach are all based on test results for isolated elements under idealised conditions for both the structure and the fire. Observations from real fires have provided some evidence that elements of structure forming part of complete buildings perform significantly better than those tested in isolation under idealised conditions unrepresentative of most structures. One of the most convincing examples was the fire which broke out in the late stages of the construction of the 14-storey steel framed Broadgate Phase 8 development in London in 1990 (SCI, 1991). The fire started in a contractor's hut on the first floor, and although smoke spread rapidly throughout the building, the automatic detection, alarm and sprinkler systems were not yet operational. As a result the fire raged for over four hours with peak temperatures estimated at over 1000°C – well above what would be recognised as the critical temperature. However, despite the fact that most of the structure had not yet been fire protected, none of the structural elements – beams, columns, slabs – collapsed. There was some localised deformation, with large deflections in some beams and shortening of unprotected columns by about 100 mm, but otherwise the structure performed well and remained intact. The damaged members were replaced quickly and easily and there were no long term effects. This prompted research interest, both experimental and analytical, into whole structure behaviour.

5. Research on Whole Structures

Fire testing, even on isolated structural elements, is expensive and despite the limitations of the standard test, it would not be feasible to perform routine testing on more extensive structures. The objective of the experimental studies which have been conducted on complete structures has therefore been to provide data for the development and verification of computer models, and a basis for more advanced design guidance.

The results of ad hoc fire tests on complete structures are consistent with the observations from real fires such as the one at Broadgate outlined above. However, the most significant source of experimental data for steel structures in fire is the Cardington test programme (British Steel plc, 1999, Newman et al., 2006) led jointly by the Building Research Establishment (BRE) and British Steel (now Tata). Other tests have subsequently been conducted, supporting the findings of these tests, which provide quantitative evidence for new design approaches.

5.1. The Cardington tests

The experimental work was undertaken on an 8-storey composite building measuring 21 m × 45 m in plan with 3 bays (of 6 m, 9 m and 6 m) across the width, and five 9 m bays along the length (Fig. 1). It was constructed as a typical office development, using downstand beams supporting lightweight slabs cast in-situ onto ribbed steel decking. Composite action was achieved between both primary and secondary steel beams and the floor slabs using through-welded shear studs. Internal beams and most perimeter beams were unprotected but columns exposed to fire were generally protected. This was because preliminary studies had shown that they had little reserve of strength, and of course the consequences of column failure could be extremely serious.

The six fire tests were located in different types and sizes of fire compartments designed to test a variety of situations. The floors were loaded throughout the testing period using sand-bags, which contributed to an overall floor loading of 5.48 kN/m^2. For the secondary composite beams this represented a load ratio of 0.44.

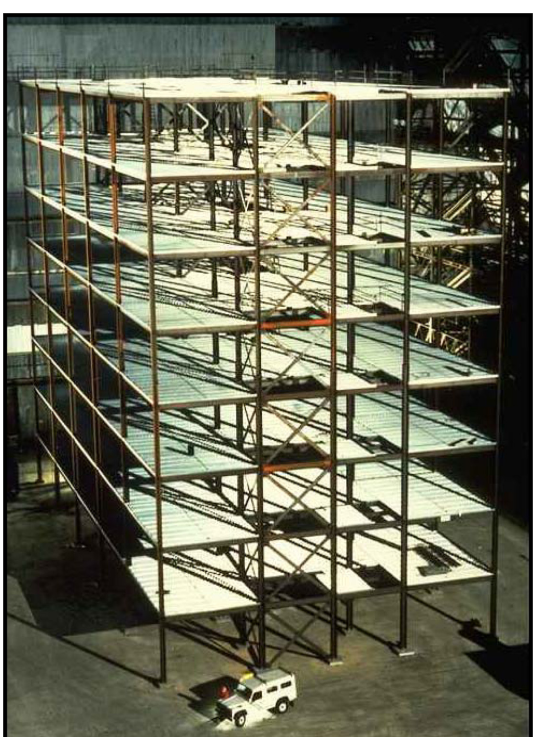

Figure 1. The Cardington test structure.

The tests had always been intended to enable the development of validated software, and the end result was *Vulcan*, a specialised computer model for simulating the behaviour of steel framed structures (Huang et al., 2003a, 2003b). This was gradually refined during the course of the Cardington tests, and the test data was also made freely available to enable benchmarking of other software.

The most significant qualitative observation from the tests was that in no case was there any indication of runaway failure, despite unprotected steel beam temperatures over 1000°C in some tests. Detailed analysis of the test data and the results of computer modelling revealed that tensile membrane action, a load-bearing mechanism which becomes significant in slabs under large vertical displacement, played a very important role in this respect. In this a radial membrane tension field is induced in the central area of the slab, balanced by a peripheral ring of compression. As a result of this mechanism the slab capacity increases with increasing deflection. In normal conditions it is not possible to allow sufficiently large deflections for this to make a significant contribution to structural performance, but in a fire, the essential requirement is that the structure maintains its integrity and doesn't collapse; and of course the failure criterion for the standard beam test is itself a large deflection – span/20. For fire conditions, tensile membrane action is therefore an important effect, providing opportunities for the use of unprotected steel beams.

Although the beams tested had generally been unprotected, the extent of the floor area exposed to fire in the tests was, in all but one case, limited, and in the largest test, which extended over the complete width of the building and two complete bays, the steel temperatures remained relatively low. Subsequent studies using *Vulcan*, which provided evidence for the development of tensile membrane action, showed that the conditions necessary for the development of this mechanism were two-way bending and vertical support along all four of the slab's edges. This has led to a new design approach in which primary grid-line beams are protected but intermediate, secondary beams are unprotected. In a typical framed structure, the composite slab is supported on secondary beams at about 3 m centres, and hence the potential savings can be significant.

6. Research on Fire Characteristics

The rise in atmosphere temperature in a fire has traditionally been represented by a standard time-temperature curve and this has been used as the basis for prescriptive methods of design. However, in a performance based design approach, it is logical that a more realistic fire model should be used, and this has also been the subject of major research studies across the world. Early work in this area resulted in a number of different 'time-equivalent' approaches in which the real fire was equated to an equivalent duration of exposure in the standard fire. However, perhaps the most important work led to the development of the so-called parametric fire curves which provide a full time-temperature history for the fire compartment, including both growth and decay phases, accounting for the fire load, ventilation conditions, and compartment characteristics. These have been incorporated into the Eurocodes (BSI, 2002) and provide a more realistic representation of how temperatures in a building fire might develop, but they have limitations – in particular they are sensitive to assumed ventilation characteristics, and as it is not normally possible to predict the degree of ventilation with any precision; it is therefore often necessary to consider a range of parametric curves.

A great deal of research has also been conducted using computational fluid dynamics (CFD). This has been used successfully to model temperature developments under a wide range of conditions, and some such studies have led to the development of simplified fire models for use in practice. A number of different finite element packages have been used for this purpose, but one of the most widely used is FDS, developed by the National Institute of Standards and Technology in the United States.

Traditionally fires have been considered as either uniform, in which case simplified models can be used, or localised, which may require a different approach. In most cases the fire is treated as static, which in the context of single elements of structure is clearly realistic. However, more recent studies have examined the effect of travelling fires, in which fire spreads as a function of time throughout a compartment (Flint et al., 2007). This gives a better representation of the exposure of the structure to heat as a function of time, and is particularly appropriate when considering whole structures, with different areas of the compartment at different temperatures depending on the progression of the fire. In a number of cases it has been found that such non-uniform conditions can lead to more onerous conditions than a uniform fire, and some designers are beginning to consider this as a matter of course.

7. Design Tools

7.1. Fire models

Much of the research outlined above has been directed towards developing useful practical design tools in the form of both structural and fire models. Practice varies depending on the nature and location of the project and the expertise available, but generally fire models are much more widely used than structural models. The simplest of these is the time-equivalent approach outlined above. In the UK, the National Annex to the Eurocode on actions (BSI, 2007) includes a particular time-equivalent method, and this is most commonly used simply to negotiate a reduction in fire resistance requirement, for example from 2 hours to 90 minutes.

Some designers also use a time equivalent approach to represent the fire when undertaking the structural analysis as part of a performance based design. In such cases the time-temperature relationship simply follows the standard fire curve for the duration indicated by the time equivalent analysis, rather than the standard prescribed time. Others adopt a similar approach but using the Eurocode parametric fire curves. Most rigorous approaches consider a range of fire scenarios, examining the effects of different levels of fire load and ventilation, selecting the worst case in terms of structural response. Different intensities of fire may be considered depending on the extent of the fire affected area – for example localised fires might use a very severe intensity, whilst a lower level would be adopted when considering fire engulfing the whole compartment. Lower fire intensities might also be used when considering fire over more than one floor, for example to take account of localised atrium conditions. And as mentioned above, some designers are beginning to adopt even more sophisticated approaches to model travelling fires rather than considering uniform heating throughout the affected area.

In the context of practical fire engineering CFD may be used to study smoke movements, but is not routinely used for fire models. Unfortunately, the computational demands of CFD are typically very high with very long analysis times. Hence its use in practice is generally limited to the study of localised conditions, or areas of particular interest, and the simpler time equivalent or parametric fire curves are currently used in the great majority of fire engineered buildings in the UK.

7.2. Structural models

As outlined earlier, the current Eurocodes provide simple calculation approaches for individual structural elements. However, these offer relatively little benefit over the conventional prescriptive approaches so are not widely used, and most structural fire engineering in practice considers the whole structure, or at least a part of the whole structure.

The most rigorous models are those based on finite element analysis. These can be general purposes packages such as *ABAQUS* or *ANSYS* which are set up with appropriate material and element characteristics to enable the overall structural behaviour under increasing temperatures to be simulated, or bespoke software such as *Vulcan* or *SAFIR* (Nwosu et al., 1999).

Large commercial packages have a well respected pedigree, and although they are very expensive, they can be used for purposes other than simply fire engineering studies. However, they do require an advanced level of proficiency on the part of the user, particularly in how the model is set up. Moreover, without the facility for defining those parameters essential for a fire engineering analysis in a simplified manner, the time required to create a model can be very long, and a considerable degree of judgement is required. Some organisations with very advanced levels of skill in-house have adapted packages to suit their specific needs and facilitate data definition, but even so the process can be very time consuming.

Alternative bespoke models such as *Vulcan* and *SAFIR* are much quicker and easier to use than general purpose finite element packages, certainly in terms of data definition and interpretation of results. This is a key advantage because it means they are not only suitable for use by non-specialists, making them ideal for structural engineers wishing to offer something more advanced than simple prescriptive solutions, but also the modelling is more consistent and less prone to being set up inappropriately. This is because certain parameters are predefined or generated automatically. Thus the user has little more to do than define the structure, the loading and the fire exposure conditions.

Because they are designed specifically for fire engineering analysis, the data input for such software is very efficient, and like general purpose packages, the output is comprehensive, most importantly providing details of deflections, member forces, and temperatures as a function of time. This can include behaviour during the cooling phase, which may be especially important when considering structural robustness and the performance of connections. Because they are designed for the specific purpose of analysing building structures in fire, they are not as general as standard commercial finite element software, but nevertheless offer a great deal of flexibility in the types of structure which can be studied.

It should be stressed that the requirements for a finite element model to be suitable for structural analysis in fire are rather specialised. In order to represent complete structures the analysis must of course be three-dimensional, including both the skeletal frame and floor slabs, and the formulation must account for both material and geometric non-linearity. Provision must be made for non-uniform temperature distributions across members (which can cause differential thermal expansion as well as a variation in material properties). Representation of the slab is particularly important – and challenging - if tensile membrane action is to be accurately modelled. Typically a layered orthotropic formulation is used, allowing for progressive cracking and material degradation separately in the two directions, with sophisticated failure criteria to account for the characteristics of both crushing in compression and cracking in tension.

Whilst the results of both general purpose packages and specialist fire engineering software are comprehensive, they do not explicitly state the point at which a structure is deemed to have failed so require some interpretation. Practice varies on this. Some take the view that the analysis will cease when it is no longer possible to achieve a convergent solution, regardless of the deformation. Others adopt a more conservative philosophy and limit the maximum deflection to that specified in prescriptive approaches – typically span/20. But even this is open to debate as the prescriptive rules were established for individual beams on rigid end supports. In the case of a slab, the total deflection is due not only to the deformation of the slab itself, but also the deflections of the secondary beams and the main beams supporting them. Arguably the deflection considered should therefore be the deflection relative to the supports, and not the absolute deflection. Until clearer guidance is available about what constitutes failure, these different interpretations are likely to prevail.

These finite element approaches, whether bespoke or general purpose, currently offer the most accurate representations of how a structure will behave when exposed to fire. They are therefore invaluable tools for designers seeking to exploit this area and achieve improved fire safety design for their clients. However, they do require long analysis times, and for general purpose packages the data definition is often also very labour intensive. A facility is available in *Vulcan* to allow a single structural bay to be studied. This is extremely quick to set up, and relatively quick to analyse, and such an approach may be suitable where a structure is very repetitive, or simply to provide an initial estimate of the likely design possibilities.

In all cases, of course, a specialist computer package is required. Accordingly there is some attraction in a simplified structural model suitable for rapid calculation without the need for sophisticated software. Bailey and Moore were the first to propose such an approach, considering a single structural bay with rigid vertical supports around the perimeter, and combining the strength of the slab with the residual strength of any intermediate secondary steel beams in fire (Bailey and Moore, 2000). Importantly the contribution from the slab included both flexural behaviour in the form of the yield line strength, and tensile membrane action, represented as an enhancement factor which is a function of the aspect ratio of the slab and the total vertical deflection. This approach does not attempt to provide any information other than an assessment of the failure point for the panel, and is based on a maximum deflection due to loading of span/20. Unlike the standard test criterion, additional deformations due to differential thermal expansion as a result of non uniform temperatures through the thickness of the slab are unlimited.

Others have taken a similar approach to Bailey and Moore, refining the model in particular ways, but the fundamental principles are the same. Two such examples are the Slab Panel Method developed (Clifton, 2006), and the FRACOF project (Vassart and Zhao, 2011).

These simplified models have the benefit of yielding immediate results, but offer neither the rigour nor the detailed information on structural response of the more sophisticated finite element based models. And of course they are limited to the geometry of a single, generally rectangular, bay with edge support in the form of protected grid beams supported on corner columns. Whilst they can be used in isolation, practice in the UK has generally been to explore initial design options using the simple approach, but then to perform more rigorous studies for the final design using a finite element model.

8. Performance Based Design in Practice

Even in the UK, where performance based fire engineering design is probably as well developed as anywhere in the world, a full fire engineering approach is still relatively rare, although it is becoming gradually more common. The term fire safety engineering is now generally taken to imply a performance based approach and is firmly established in the UK as an alternative to simple compliance with the prescriptive rules of Approved Document B. Indeed in some types of large or complex buildings such as airport terminals, it may be the only practical way to achieve an appropriate standard of fire safety. The value of a more fundamental approach is also beginning to be recognised by building developers and owners, who are seeking efficient, reliable and consistent levels of fire safety.

In the context of structural fire engineering, the most common approach is simply to use an alternative to the standard fire to justify a relaxation in the required fire resistance time. This might typically be based on the time equivalent method or the Eurocode parametric fire curves. In many cases the structure is then simply protected according to the requirements for this reduced fire resistance time. This is largely because the cost of more detailed studies on the response of the structure to fire is often not justified by the possible cost savings, since in the UK there has been a significant reduction of the cost of fire protection. With a very competitive and effective fire protection industry efficiency has been improved dramatically, and costs have consequently been driven down, with a fall of as much as 60% in some types of protection in the past decade or so.

For buildings higher than about 7 storeys, there is a clearer potential economic benefit from a detailed study of the structural response. In such cases designers will consider realistic fire scenarios using one of the approaches outlined above, and model the structure using a finite element model such as *Vulcan* or *ANSYS*. This not only enables a more precise specification of the fire protection requirements for individual members, but also allows close inspection of critical details to ensure that the desired overall performance for both structure and compartmentation can be achieved.

There are also signs that clients are demanding such an approach for a wider range of more modest buildings because they want a reliable level of fire safety, irrespective of whether cost savings are likely, and recognise that simple compliance with prescriptive rules does not necessarily ensure this.

9. Case Studies

Some examples of performance based fire engineering in practice are outlined in the following sections.

9.1. Heron Tower, London

Heron Tower is a 47-storey office building in the City of London, providing over 68,000 m^2 of floor space, based on ten 3-storey villages arranged around a central atrium. Each village is separated from the next by a 2-hour compartment floor and so is treated as a 3-storey building connected by an open void, requiring an assessment of multi-storey fires as part of the fire safety strategy. The main superstructure is an external vierendeel tube supporting long span steel beams acting compositely with a 130 mm deep concrete deck.

The response of the structure to fire was modelled by ARUP using *ABAQUS*, with two main purposes: to identify and mitigate any weaknesses in the fire performance and to optimise the structural design and fire protection as an integrated package (Fig. 2). Two types of fire scenario were considered – a post-flashover fire on a single level, and a multi-storey model with a less severe fire spreading to all floors – each based on the Eurocode parametric fire code approach.

Despite large deflections – as much as span/7.2 for the post-flashover case – the model demonstrated that stability and compartmentation were maintained, with no indication of column instability, despite columns being affected over a number of floors.

The single floor model was also analysed with all beams protected in accordance with prescriptive requirements. This showed considerable structural deformation, demonstrating that large deflections will occur in fully protected buildings in a post-flashover fire – a consideration which is often ignored. The finite element analysis also provided details of the forces/stresses and strains in the structure enabling the integrity of the structure to be demonstrated.

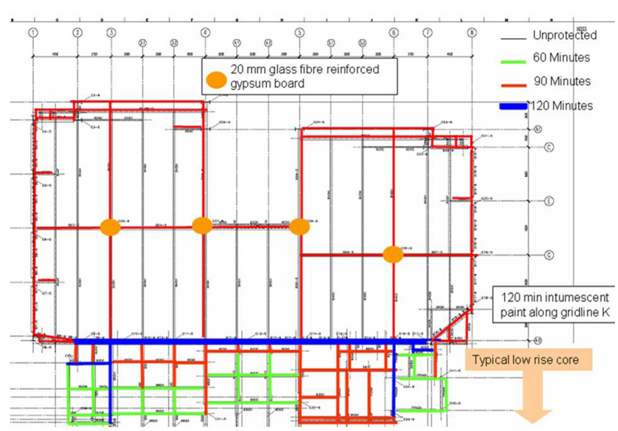

Figure 2. Reduced fire protection at Heron Tower as a result of a detailed analysis.

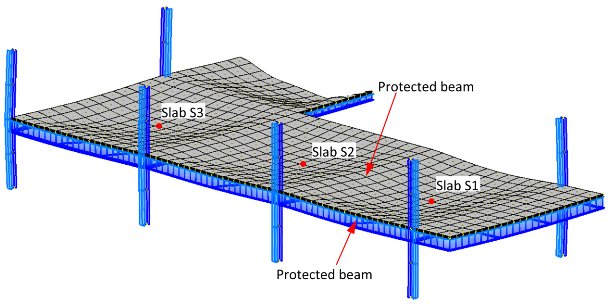

Figure 3. FE model of part of the floor plan at Kingdom Street, London.

In fact, it was shown that the final solution performed better than the originally proposed structure where all beams and columns were protected 120-minutes.

The result was an overall improvement on performance with significant savings for the client in terms of the cost and maintenance, and also a shorter project program, improved architectural finishes to exposed elements, reduced environmental impact, and less hazardous working conditions.

9.2. 4 Kingdom St., London

This 12-storey office block in central London is of conventional composite steel-framed construction with a central reinforced concrete core. The floor framing consists of primary and secondary long span cellular beams supporting a composite deck floor slab. The nominal fire rating for the building was 2 hours, but Ramboll demonstrated that this could be reduced to 60 minutes using the time-equivalent method detailed in PD 6688-1-2 (BSI, 2007), with appropriate allowance for the installation of a sprinkler system. Structural analyses were then conducted at a number of levels: the simplified Bailey method (Bailey and Moore, 2000) was used for single panels bounded by a perimeter of protected beams, with more extensive structural subframes modelled more precisely using the finite element software, *Vulcan* (Fig. 3). In addition, detailed studies were conducted for critical cellular beams, which are vulnerable to different modes of failure from solid web beams, to ensure the localised behaviour was satisfactory.

These studies enabled the structural fire protection to be reduced generally compared with traditional prescriptive requirements, and omitted from many of the secondary beams. As a result, significant cost savings were achieved without compromising safety.

9.3. The Shard, London

At 310 m, this 70 storey mixed use structure (Fig. 4) is presently the tallest building in Western Europe, and for a building of this size and nature a performance based approach is very important to achieve the required level of fire safety. The structure changes at different levels, but is steel-framed from levels two to 40, which accommodate retail and commercial floors.

Figure 4. The Shard, London.

The fire engineering study by WSP consisted of a consideration of worst case post-flashover fire scenarios using the parametric time temperature curve and taking account of a variety of realistic ventilation conditions corresponding to different degrees of glazing failure ranging from 25% to 100%. Thermal modelling was then used to determine member temperatures and whole frame modelling to determine overall performance. The fire rating of the concrete-filled steel box section external columns, fabricated from 100 to 125 mm-thick plate, was determined using external flaming calculations to BSEN 1991-1-2 (BSI, 2002), and partly because of their size, which provided a significant degree of inherent fire resistance, only a thin layer of intumescent protection was required.

Special consideration was given to the main transfer structures over the backpack/tower interface under the effects of severe and highly localised fires to determine a worst case limiting temperature. Additionally, a qualitative assessment of the likely performance of the concrete construction was undertaken by reference to historical performance and recent research.

As a result of these studies, considerable savings were achieved for the fire protection required for the steelwork, whilst achieving a clear and consistent level of safety.

9.4. Nuffield Hospital, Leeds

The structure of this 11 storey hospital uses long span cellular beams on an overall floor grid 18.6 m × 7.2 m, supporting a composite slab. The structural fire engineering by Buro Happold considered the 3-dimensional behaviour of the building, using a simplified approach initially for scoping calculations, followed by much more rigorous model of the whole frame using *Vulcan*. The approach adopted also accounted for the relatively low fire load and high level of compartmentation, demonstrating a reduction in the required fire resistance from 120 to 60 minutes.

This resulted in a solution where beams framing into columns were fire protected, but combinations of intermediate beams were unprotected.

Additional consideration was given to the interaction between the structural fire assessment and the fire strategy in relation to evacuation – a major consideration for hospitals, where a total evacuation is a last resort. A qualitative risk assessment was conducted to ensure that compartmentation would not be compromised by deflecting beams, and where necessary some beams were protected even if they did not need to be for stability reasons.

As a result of these performance-based studies, not only were fire protection costs reduced but also safety was improved.

9.5. 99 Bishopsgate, London

A structural fire engineering assessment was requested by the owners when work being undertaken during refurbishment revealed apparently substandard fire protection to some steel beams, with some areas damaged or missing. Whilst these were made good, the manufacturer would not warrant the overall standard of fire protection provisions throughout the building.

The 28-storey tower section of the building consists of a central concrete core and a steel frame supporting precast concrete planks with a concrete topping, with composite floor construction in areas of the 5-storey podium. AECOM used a structural fire engineering analysis to examine several areas (Fig. 5), each selected to represent a worst case scenario and thus considered to be representative of the whole building area. The areas considered included whole portions of the building to model the effect of the different forms of construction and the effect of the restraint of one area on another, as well as individual members to assess the performance of key elements. This was done using the specialist finite element software *Vulcan*, with exposure conditions defined according to the Eurocode parametric design fire, and the results were compared with the standard deflection limits. In addition, local checks were carried out via manual (spreadsheet) calculations to account for the significant and irregular web openings.

In order to account for the poor condition of the applied protection, various key beams and portions of beams were assumed to be unprotected, whilst the rest of the beams were assumed to have an effective protection of 30 minutes. Because of the form of floor construction it was not possible to take advantage of tensile membrane action in the tower section, and the analysis also had to consider the stability and bearing of the precast planks as well as the effect of any movements on the stability of the columns restrained by these beams.

Based on this performance-based fire engineering approach, it was shown that the structure is able to withstand a fire with significantly less protection than was originally specified and warranted in 1994 when the building was constructed, and hence that the existing fire protection provisions are sufficient.

10. Conclusions

Performance based fire engineering, typically considering both fire growth and structural response, is being used

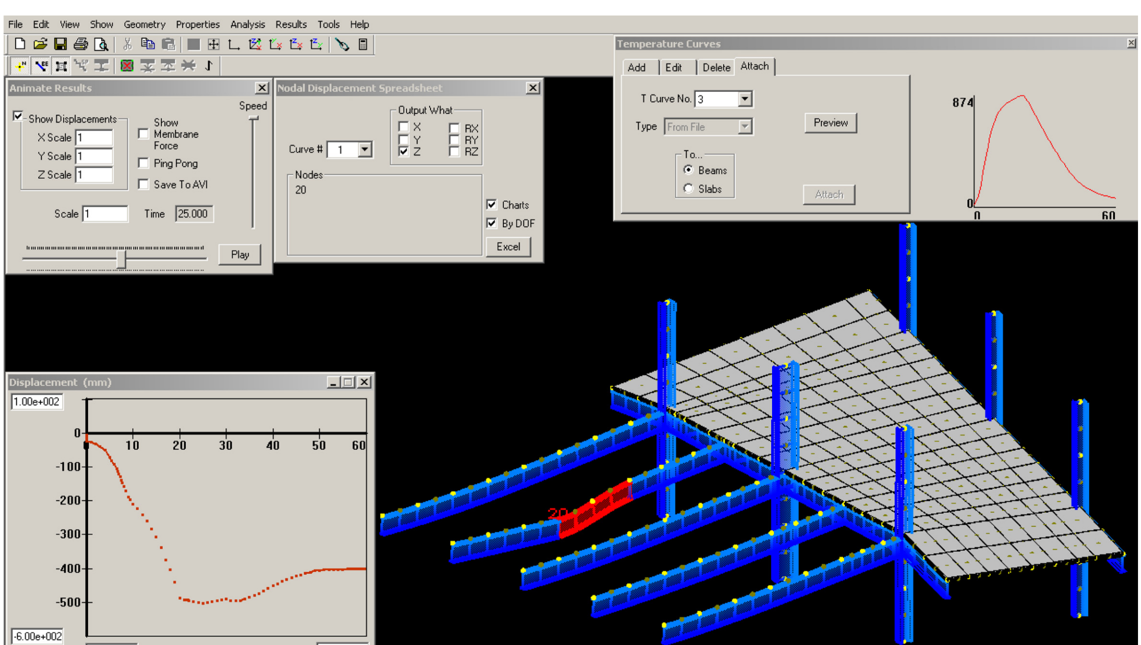

Figure 5. Vulcan analysis for part of the 2nd Floor at Bishopsgate.

in the UK principally on steel framed buildings above about six storeys. Ideally this is treated as an integral as part of ambient design, in which case significant savings in the cost of applied fire protection are possible. It is also recognised that a fundamental approach to fire safety engineering design may be the only practical approach for some large and complex buildings. However, there is also a growing recognition of the benefits of using these more advanced approaches on a wider variety of structures in order to provide greater confidence about the level of fire safety. Sophisticated tools are available to assist designers, and these are now widely accepted by regulatory authorities. Research continues with the aim of improving these, both in terms of fire models, with a growing interest in travelling fires, and structural response, where the principal outstanding issues are connection behaviour and failure criteria. In addition there is a growing sense that more rigorous approaches might usefully be applied to reinforced concrete structures, taking into account the potential for spalling. Ultimately it is likely that a structured approach will be developed for risk based design based on fire safety engineering.

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