PRACTICAL CASE STUDIES IN PERFORMANCE-BASED STRUCTURAL FIRE ENGINEERING DESIGN

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ABSTRACT

The specialist field of structural fire engineering is developing rapidly, along with the more general discipline of fire safety engineering. The results of international research and large-scale tests such as those conducted at Cardington in England during the 1990s are now starting to be used in practical fire-resistance design. Performance-based structural fire engineering guidance documents and standards have now been published in the United Kingdom and these are being used to realise more cost effective buildings. Furthermore, sophisticated finite element analysis software programs are being adopted by consulting engineers to predict the actual performance of structural frames in fire scenarios, and thus to enable robust yet cost-effective design solutions which optimise the extent and placement of fire protection. Such techniques are suitable for use as part of an integrated structural design process, treating the fire case as one of a series of limit states which contribute to both the conceptual and detailed design phases, rather than simply as a means of retrospectively calculating thicknesses of fire protection materials.

This paper uses the recently completed Leeds Nuffield Hospital in England, as an example of how such structural fire engineering techniques can be used by designers to optimise the inherent fire resistance of structures and the fire protection strategies which have been used to produce safe but economic solutions. It describes the use of *Vulcan*, a finite element program developed at the University of Sheffield, together with other levels of design calculation, and also outlines the rigorous sensitivity studies and checking procedures that were imposed to ensure flexible, robust solutions.

INTRODUCTION

The collapse of the World Trade Center (WTC) in New York on 11 September 2001 has forced designers and regulators to question our approach to the fire-safety design of buildings. While the event itself was extreme and hopefully unique, some important lessons have been learned. In May 2002, the Federal Emergency Management Agency (FEMA) published a report[1] outlining its study into the collapse of the WTC. Some of the report's main recommendations with respect to structural fire engineering (the prediction of the fire performance of structures and the design of structures for fire conditions) were:

- the behaviour of structural systems under fire conditions should be considered as an integral part of the design process,
- structural systems need redundancy and/or diversity,
- fire protection materials need to adhere under their design exposure conditions, and
- the performance of connections between beams and beams and columns under fire loads needs to be understood.

The way to ensure safety is to adopt a holistic solution that considers the interaction of the structural fire behaviour, fire safety systems, human response/evacuation and fire service intervention. The fire performance of the structure is determined by the combination of;

- the natural (inherent) fire resistance of the structure, and
- the fire protection (fireproofing) that is applied to the structural elements.

This allows designers the flexibility to balance the inherent fire resistance and the amount of fireproofing to achieve the performance goals. Performance and reliability can be increased without an increase in fireproofing. Furthermore, the building structure is less likely to be damaged through the life of the building than fireproofing and therefore designers may choose to enhance the inherent fire resistance to increase robustness, particularly where regular maintenance may be an issue.

DESIGN APPROACHES

Code Compliant / Traditional Design

The fire safety standard required by national codes is often achieved by designing in accordance with prescriptive guidance documents. These comprise generic guidance for typical buildings and usually cover evacuation, structural performance, fire containment and facilities for firefighting[2]. It is generally perceived that once prescriptive guidance is followed, the building is safe and that the fire safety risk associated with the design will be accepted by society. However, this is not necessarily true due to the generic nature of the guidance.

Building technology has advanced and designers today can deliver greater flexibility. Buildings are becoming taller, bigger and somewhat more complex and often necessitate a more rigorous approach to ensure safe solutions.

Engineered / Performance Based Designs

Prescriptive guidance has its place, but it constrains flexibility, leads to inconsistent levels of safety and is often inadequate for large buildings. The alternative is to use a performance-based approach. This concept is not new but in practice its use is often hampered by a lack of understanding (by the enforcers and/or the designers) and/or an absence of suitable technologies. Times are changing and new techniques, knowledge and guidance documents are enabling an increasing use of performance-based approaches, resulting in more flexible, cost-effective and safer buildings. This is no truer than in the field of structural fire engineering, where real fire and structural performance assessments are being applied to calculate fireproofing requirements. This is a valid exercise providing an appropriate margin of safety is demonstrated and the assumptions and impact on the overall fire strategy are checked thoroughly.

The conventional method for ensuring fire resistance period is to apply fireproofing to structural elements to prevent them reaching their critical temperatures. However, the critical temperatures are traditionally assumed to be between 550°C and 620°C[3] (1000°F and 1100°F in ASTM-E119[4]) and the fire performance is determined from a single element test in a furnace. This does not give a true representation of structures in fire because;

- the furnace temperature increases indefinitely with respect to time and therefore is not representative of real building fires which eventually burn out, and
- a single element does not represent the true fire performance of a structural frame.

Time equivalent and natural fire approaches now enable engineers to predict realistic compartment temperatures as a function of the compartment geometry and construction, the fire load and the ventilation conditions.

It is also possible to account for the real performance of structures in fire conditions. New design methods have been published by the Steel Construction Institute[5] and the Building Research Establishment[6] following the research and developments related to the full-scale testing conducted at Cardington[5]. Whilst representing a major step forward, these methods are unable to predict full three-dimensional (3D) interactions. Whole-frame behaviour is important for large buildings and generally requires numerical analysis. Some computer programs, such as *Vulcan*[7], can predict the 3D behaviour of structural frames, including the performance of columns and secondary effects such as membrane and catenary action. This allows engineers to investigate 3D robustness and to conduct integrated fire safety assessments. The benefits of this are that the global safety can be quantified and the inherent fire resistance of the structure can be improved.

An Integrated Approach

Time is the most appropriate measure against which fire performance can be measured[8,9]. It enables integration of the evacuation process, structural performance and fire service intervention etc. Every fire protection measure can have an effect, such as reducing the fire duration, extending the overall stability of the structure or decreasing the evacuation period.

LEEDS NUFFIELD HOSPITAL

Building Description

The case study presented in this paper is an 11-storey hospital that has recently been constructed on a congested, inner-city site in Leeds City Centre to meet the demand for high-quality operating theatre facilities. The building was conceived as a concrete-framed structure but when the design and build contractors were appointed, they elected to adopt a composite steel-frame solution to meet the tight, 90-week construction program.

The building is 60m long and 18.6m wide and just greater than 30m in height. Two bays of composite cell beams, 7.3m and 11.3m wide, span the 18.6m width. Lateral stability is provided by the central concrete core and the concrete shear walls at each end of the building.

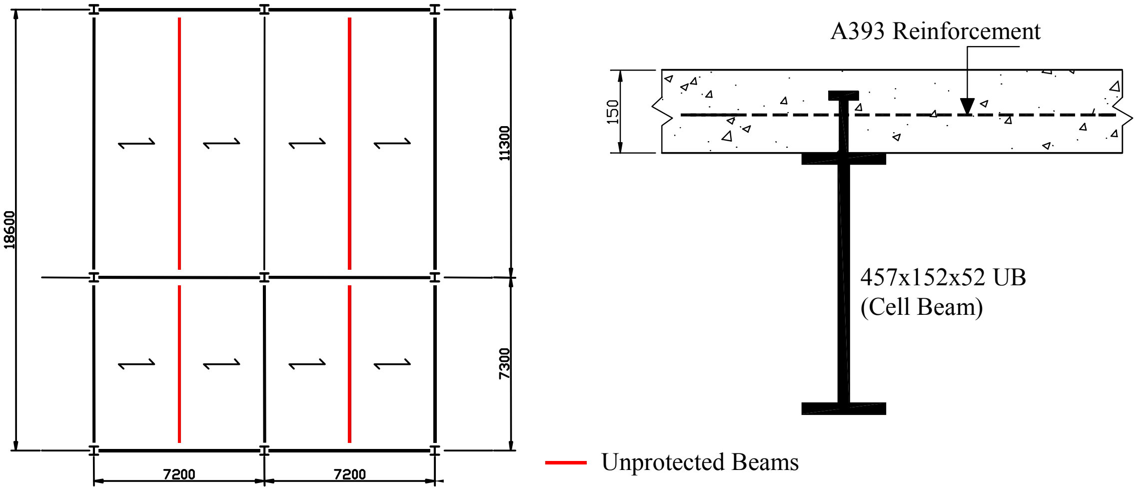

Fig. 1: Structural arrangement showing unprotected beams and a typical section

Importantly, the building had to satisfy strict criteria for floor vibrations, which controlled the design of the floor slabs and beams. Furthermore, hospital buildings have a well-managed, controlled fire load and contain a significant amount of natural compartmentation.

The internal columns are protected by fireboards. An intumescent system was used for the internal beams to minimise the construction period and to maximise the cell aperture available for service distribution.

Assessment Criteria

In any engineered solution, it is vital to define criteria against which the solution can be measured. For the hospital, it was agreed that the structure should survive the entire fire duration and that all compartmentation should retain its stability, integrity and insulation for this period. Columns should maintain their ability to support the vertical loads and the beams and floor system would be governed by the deflection criteria stipulated in BS476ref. Whilst, these deflection criteria do not necessarily represent real failure, it should be remembered that it they are used to assess the fire performance of structural systems and fireproofing materials. Therefore, the integrity of the slab and the performance of the fireproofing can only be ensured by adopting the furnace test failure criteria.

Fire Development

The first stage of the analyses is to determine the fire exposure and hence the temperature of each element with respect to time. There are several methods for doing this, including:

- Standard Fire Curves.
- Time-equivalent methods[10,11]. Simple equations relate the severity of a natural fire to an equivalent exposure period in a Standard Fire.
- Natural Fire Calculations[11]. Realistic atmosphere temperatures are calculated with respect to time based on the compartment geometry, ventilation characteristics and the fire load.

A ‘time equivalent’ period of less than 60 minutes was calculated for the hospital. Natural fire calculations (using parametric curves) were conducted to demonstrate that protected steel temperatures would not exceed that limiting temperatures[12] for the entire duration of a realistic, worst-case fire. This is a more rigorous assessment than the simple adoption of time-equivalent equations.

Structural Response - *Vulcan*

A representative portion of the structure was studied using the finite element analysis (FEA) program developed at the University of Sheffield, *Vulcan*. This is a non-linear program. that has been validated against large-scale fire tests[7]. Initial studies were conducted on a small subframe utilising symmetry. The objective was to investigate the optimum fireproofing profile to achieve the acceptance criteria. Sensitivity studies were also conducted varying the protection thickness, heating profile and sizes of structural elements (reinforcement mesh, concrete grade, beam sizes etc.).

Once the preferred solution was identified, a larger portion of the structure was analysed to demonstrate that the smaller models are representative of the real building. The displacements and forces were studied carefully to ensure the performance criteria were achieved. For example, the vertical displacements of the beam and slab were checked against their limit particularly where vertical compartmentation exists. Using this approach ensures the overall structural stability including the interactions between beams, columns and their connections. In all cases, the connections are fully protected even if one of the connecting members is an unprotected beam.

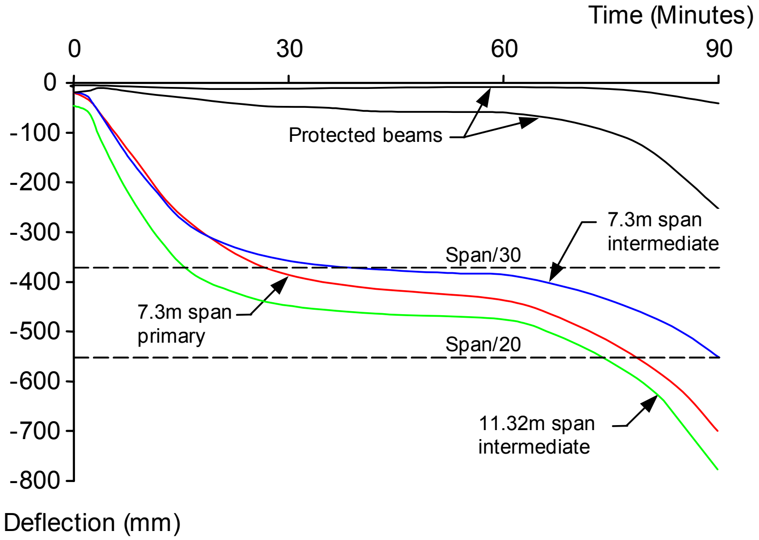

Fig. 2: Time-deflection graphs as predicted by *Vulcan*

The best value solution was reached by increasing the performance of the slab in exchange for the omission of fireproofing from intermediate beams (beams not connected to columns). Where fireproofing is required, the material and thicknesses were carefully selected to give the required performance. Since the inherent fire resistance was increased, the solution relies less on fireproofing and therefore is less susceptible to damage or failure. In other words, it is a more robust solution. The additional benefit is the saving generated from the omission of fireproofing and the associated reduction in the construction program.

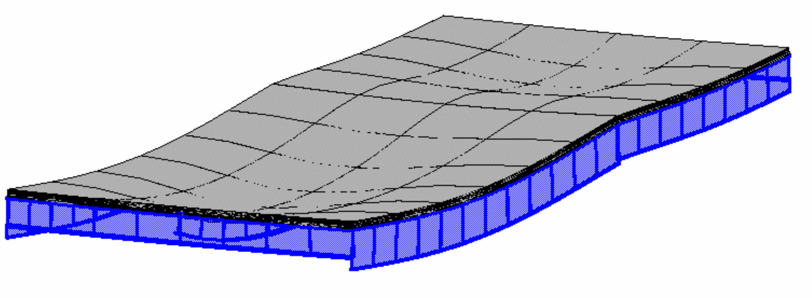

Fig. 3: Deflected shape at elevated temperature as predicted by *Vulcan*

COMPARISONS / BENEFITS

Table 1 shows approximate cost comparisons for a prescriptive code approach and the engineered solution that was adopted. As can be seen the engineered solution survives the entire fire duration and generates a net saving of approximately £250k. Figures are not provided for increased beam sizes because in this instance larger beams were required for deflection limitations as well as for the fire design.

	Code Approach		**Engineered Solution**	
	Requirement	**Cost/m^2**	**Requirement**	**Cost/m^2**
Column Fireproofing Primary Beam Fireproofing Intermediate Beam Fireproofing	120 minutes 120 minutes 120 minutes	£40	60 minutes 60 minutes Zero	£20
Slab reinforcement	A193	£3.00	A393	£4.20
Fire Resistance and Comparative Costs. Floor Area (8500m^2)	120 minutes in accordance with standard fire curve	£372k	Indefinite.	£123k
			Net Saving	**£249k**

Table 1: Cost comparison

IMPROVEMENTS

Although some of the latest technologies and research knowledge were used during the design process, there is room for future improvement. Some thoughts are discussed below.

- **Combined hazard** – In many buildings, it may be appropriate to consider the effect that compound events (such as a fire after an explosion) may have on the overall safety.
- **Risk based approach** – Quantified risk analyses represent the best method for determining appropriate fire safety measures. They can be used to appropriately balance cost, performance and safety. The technologies now exist that enable engineers to predict the consequences of a fire but the statistical data required to determine the likelihood of a particular fire developing is sparse.
- **Connections** – the fire performance of the beam-column connections details is vital for

the overall robustness of structures. Existing methods for modelling the performance of connection details are expensive computationally but research is underway that will enable *Vulcan* to effectively model connection performance is underway. This capability will be incorporated into the software in due course.

- **Local behaviour** – whilst the local performance of a beam does not necessarily effect the global performance of the structure, it is important with regards to local integrity failures. As with connections alternative modelling methods that are less computationally intensive are required.
- **Material properties at extreme temperatures** – Some fire types generated very high atmosphere temperatures very rapidly. There may be a need to investigate the performance of fireproofing material at these extreme temperatures even if they are only shortlived.

CONCLUSIONS

It is becoming increasingly clear to engineers that the traditional approach of simply fireproofing steel structures is not always acceptable. This approach is simplistic and does not directly consider the wider issues of whole-frame stability and building robustness. However, the technologies and understanding now exist that can enable the use of performance-based engineering studies. Correctly applied, structural fire engineering methods are more robust than prescriptive methods and they can address many of the issues raised by the FEMA Report.

Buro Happold have used the example of Leeds Nuffield Hospital to demonstrate how structural fire engineering can deliver significant cost savings without compromising safety. This is achieved by enhancing the inherent fire resistance of the structure and thereby placing less emphasis on the performance of fireproofing.

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