Finite Element Modelling of Structural Steel Frame in Fire

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Biography
Dr Ahmed Allam is a design manager and fire safety expert, with more than 15 years of wide and extensive experience in the different engineering fields and particularly the safety aspects on a wide range of projects. He is an expert at enhancing the structural response of buildings during fire and extreme conditions, and utilising the performance-based approach to meet the required fire safety level at optimum cost. In developing suitable fire safety engineered solutions and strategies to different type of buildings. He has employed complex analytical techniques, including structural finite element calculations and Computational Fluid Dynamics (CFD).

In addition to his contribution to develop different design techniques, he also has major contribution in developing the knowledge of the Fire Safety Engineering in the Middle East and has acted as the lead engineer on number of prestigious projects world wide amongst those are the £11bn Crossrail project in London and recently the $11bn Alraha Beach Development in Abu Dhabi and currently the $12bn Abu Dhabi International Airport.

Recently, Dr Ahmed Allam has been appointed to the prestigious title of visiting professor at University of Ulster for his unique technical contributions. With his research activities on fire safety, he has generated more than 30 publications and he is the author of several finite element codes. His latest technical achievement includes the publication of his innovative technical paper titled “Performance-based Structural Fire Safety Engineering Solutions Using Computer Modelling Techniques”.

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Abstract
Numerical modelling using Finite Element Analysis (FEA) has been utilised in the fire safety engineering design. The purpose of a study based on this method is to assess the effectiveness and the structural safety in fire condition. The paper demonstrates the capability of computer modelling in the structural fire engineering field. A new FEA-based technique to investigate the inherent fire resistance of composite cellular steel beams supporting concrete slabs in fire is introduced. The paper also discusses the possibility of using FEA to investigate the interaction between a fire compartment wall and a deflected heated steel beam. The benefits of using the computer modelling in identifying the optimum passive fire protection are highlighted. This type of modelling allows a fairly realistic representation of the behaviour of structures in fire conditions. It is intended that designs carried out in accordance with such computer models, as part of an overall structural fire engineering strategy, will achieve at least the level of safety required by regulations while allowing some economies in construction costs to be made. Finally, a suggested way forward in the field of structural fire engineering is discussed.

Keywords: Fire conditions, Finite element model, Thermal analysis, Computer modeling, Boundary conditions

Introduction
Considerable progress has been made in recent years in understanding how structures behave when heated in fires and in developing mathematical techniques to model this behaviour (Allam, 2003). Some of the methods developed are now contained in the design guidance. However, because of the requirement for the codes to contain simple checks that lend themselves to hand calculation, the range of structural types that could be considered is often limited. These simple checks should not be undervalued, as in the majority of building designs they will provide an economic and readily accessible method of design. In fire, the behaviour of a structure is much more complex than at ambient temperatures. Changes in the material properties and thermal movements will cause the structural behaviour to become nonlinear and inelastic. It is nonlinear in that doubling the load or temperature will normally cause the displacements to more than double. It is inelastic in that after the fire the structure will be permanently, or plastically, deformed. Fire safety engineering may be used as a means of fine tuning some aspects of the overall fire safety problem. Enhancements in certain measures may allow a change in another feature of the design. There are many examples of fire safety engineering factors that can be cited to justify an appropriate change in the design while maintaining acceptable standards of safety. Fire safety engineering enables the results of research and development to be applied to practical problems without having to go through the lengthy process of being formally recognised in an Approved Document. Statutory Authorities are not, however, obliged to accept fire engineering solutions, but will find them difficult to reject if a few simple principles are followed in their presentation. Not everything will be calculable, and any fire safety engineering solution inevitably has to include an element of judgment.

Computer modelling
Three-dimensional modelling is undoubtedly a useful tool, particularly in complex structures which cannot easily be resolved into simple two-dimensional frames. Three-dimensional modelling does, however, bring additional problems, with the potential to make mistakes within a large model, and with the complex analysis output which can frequently confuse, rather than elucidate.

The following factors can be identified as potential causes of unsafe design:
- Persons without adequate structural fire engineering knowledge or training may carry out structural fire analysis.
- There may be communication gaps between the design initiator and the computer program writer and user.
- A program may be used out of context.
- The checking process may not be sufficiently thorough.
- The limitations of the program may not be sufficiently apparent to the user.
• For unusual structures, even experienced engineers may not intuitively appreciate weaknesses in computer codes.

Numerical analysis of structures is built on an understanding of algebra, geometry and calculus. The key principles involved in developing a numerical model to understand structural behaviour are:
• Consideration of material property.
• Consideration of deformed shape of a structure.
• Reduction of complex structures into statically determinate, simple systems from which the true structure may be rebuilt

Structural Fire Engineering Strategy
The collapse of buildings in the World Trade Centre (WTC) complex on 11 September 2001 has given rise to significant implications for design, due to the following issues:
• Major structural damage, including collateral damage from collapsing structures
• Simultaneous fire on several floors, and non-functioning of the sprinklers system
• Five out of six escape stairs were blocked
• Ground floor lobbies endangered
• Simultaneous escape from all floors, non-phased evacuation and lifts used for escape

The probability of these features being combined in an extreme event in the future is generally agreed to be lower now than it was before the WTC collapses. However, it has highlighted some aspects of design which probably need to be considered differently.

Using simple static analyses techniques, the effect of removing key elements in a structure can be observed to reduce the risk of progressive collapse. This includes:
• Removal of key elements assessment combined with the fire effect
• Non-linear impact analysis and design
• Design of key elements for impact
• Analysis of flooring system for fire conditions
• Provision of collapse strengthening elements
• Enhanced passive fire protection of key elements. Fire bracing could be used as an equivalent terminology to wind bracing. These structural fire bracing should act to absorb the extra stress induced due to fire condition
• Detailing for ductility

This type of simple static analysis applied to a badly damaged structure, gives a good indication of how the building would perform with major elements damaged or unable to accommodate the applied load. The designer simply removes a variety of key elements to determine how the building elements need to be designed to redistribute the load in an extreme event. The elements removed represent the result of damage that is to be considered due to an extreme event or could cover a variety of scenarios, which the designer then has the option to examine. On special buildings, it may be appropriate to introduce key elements to inhibit progressive collapse. These elements, which could be reinforced against impact loads and fire-protected, could be designed as a robust spine whose purpose is to act as an alternative vertical load path in the event of impact and fire to prevent the progressive collapse. The dual combination of mixed structural systems with mixed fire protection systems provides an effective and redundant system, which may be appropriate for high-risk buildings in extreme events.

Cellular beams in fire
Cellular beams (e.g. see Figure 1) are currently being widely used in multi-storey buildings where, as well as reducing the total weight of the steelwork, they help decrease the depth of floors by accommodating pipes, conduits, and ducting. They are used in commercial and industrial buildings, as well as houses and portal frames (Nadjai, 2007). The literature reveals very few investigations of restrained steel beams in fire, apart from the notable series of full-scale tests carried out in the BRE testing facilities at Cardington, in which all the beams were laterally restrained. Another joint project conducted by the universities of Manchester and Sheffield investigated the effect of in-plane restraint and end connections on the behaviour of steel beams of normal rolled sections in fire (Allam, 2003). There are only limited research studies of the performance in fire of cellular beams. Assumptions for the behaviour of composite cellular beams in fire are still based on fire test data for solid-web beams. The fire resistance of isolated unprotected steel sections has now been well documented, and the performance-based design of these beams at the fire limit state has been widely applied. Consequently, the basis of the current design procedure comes from numerous full-scale tests on isolated steel
beams, the failure of which is usually due to loss of moment capacity as a result of the deterioration of steel strength as its temperature rises. BS5950 Part 8 only provides the moment capacity method for determination of the reduced strength of such beams in fire (BS 5950, 1990). There have been only a few fundamental studies of failure mechanisms related to composite floors. SCI P068 deals with the design of simply supported composite beams with rectangular openings (Lawson, 1987). Design is based on plastic analysis of the cross-section, and may also be used for non-composite and notched beams. A composite concrete floor-slab has the effect of significantly increasing the flexural resistance of a steel section. However, its effect on shear resistance is more complex. This work demonstrates an attempt to simulate composite flooring systems with cellular beams in fire conditions. This includes both thermal and structural fire analysis along with the necessary engineering assumptions.

**Thermal analysis**

Since analytical solutions of heat transfer problems are feasible only for linear applications with simple geometries and boundary conditions, a numerical method is used to solve the heat balance equation for temperature distribution in structural elements. A nonlinear heat flow equation must be solved to predict the distribution of temperature in a structure exposed to fire (Allam, 2002). Numerical schemes that incorporate either the finite element or finite difference method have generally been employed to approximate heat conduction. In this study, FEA is used to identify the temperature distribution in one or more materials. Heat transferred by convection and radiation at the boundaries are considered. The explicit forward difference time integration scheme is adopted and two-dimensional rectangular elements are used. Nonlinear boundary conditions and temperature dependence of material properties can be considered when FEA is used to analyse temperature distribution in fire-exposed structural element. This method can be applied in 1, 2 or 3 dimensions and, within the limitations of the input parameters, provides a complete general solution to the transient heat conduction problem. The temperature dependence of the material properties can be simply accommodated and the boundary conditions could also be generalised to functions of temperature if desired. It is recommended that a number of sensitivity checks are made for each calculation in order to ensure that the solution is sufficiently independent of numerical parameters, such as grid resolution and length of the numerical time-step.

**Computer model:**

The study includes different attempts to identify the temperature distribution in composite cellular steel beams using 2D thermal analysis. The main objective of these analyses is to try to understand the effect of the existing web-openings on the temperature distribution across the cross-section of the cellular steel beam.

The following cases are considered, see Figure 2:

1. Two cases where considered to analysis the I-section of the cellular steel beam:
   a. Section a-a through the web-opening
   b. Section b-b through the solid part of the web through the middle point between two openings.
2. Portion of the web-plate that covers the area between the centreline of a web-opening and the middle point between two web-openings. A comparison with a solid web-plate is considered.

In all the cases analysed, 2D thermal analysis technique using ISO834 temperature curve are utilised. The model takes into consideration the material properties and the effect of the boundary conditions. In all cases analysed for the web-plate, the fire boundary condition is assumed at all finite element nodes in an attempt to simulate the effect of the applied fire to the web-plate.

**Results**

Figure 3a shows the temperature-time curves for both cross-sections considered in Figure 1. The comparison shows slight difference between both cross-sections. The results suggest that the effect of the web-opening is relatively small on the temperature at point A and across the cross-section. Figure 3b shows temperature-time comparison for web-plate with and without openings. The results suggest that the effect of the web-opening in cellular steel beams is relatively low. However, the results show 3-6% increase in temperature at the middle point between two web-openings.
Figure 3. Temperature-time comparison

(a) Solid I-section and I-section at the web-opening of the cellular steel beam

(b) Solid web-plate and web-plate with opening of the cellular steel beam

Figure 4. Comparison of temperature distribution along a-a: solid web and cellular web

Figure 4 shows the temperature profile at both 30 and 60 minutes along the heated boundary for the portion of the web illustrated in Figure 3 in comparison with solid web-plate. The results suggest that the web-opening has relatively small effect on the temperature distribution along line a-a.

Figure 5 shows the temperature profiles for composite cellular steel beam at both 30 and 60 minutes. The results show a temperature drop starts at the bottom of the concrete slab.

Figure 5 shows the temperature distribution along line a-a for cellular beam with concrete topping.
Structural Fire Analysis

Using the finite element analysis provides an understanding of the true behaviour of the whole building and allows the displacement and stress of the structure to be predicted throughout the full duration of the fire. However, careful consideration should be given to:

- The adopted failure criteria and the consequences on the overall fire engineering strategy
- Consideration of the localised behaviour, especially the fracture of steel reinforcement and robustness of connections
- Boundary conditions and assumptions of lines of symmetry for sub-frames
- Interpretation of the results
- The adopted heating regime. If natural fires are considered then a range of feasible fire scenarios should be considered

![Central deflection](image)

![Bottom flange temperature](image)

![Axial force](image)

Figure 6. Comparisons between test and predicted central deflection and axial force (end-plate connection, axial stiffness K=8kN/mm) for different load ratios (LR).

It was important to check that the FE code can model this satisfactorily, before embarking on a more comprehensive analytical study. Typical comparisons for mid-span deflection and axial force of the heated steel I-beam, which were used in validating the FE code against test results, are shown in Figure 6. More details of the test results are discussed in previous papers [Allam, 2001 & BR, 1992].

Computer model

![Figure 7a](image)

![Figure 7b](image)

Figure 7a. Passive fire protection schemes

Figure 7b. Passive fire protection schemes
Different passive fire protection schemes are tested taking into consideration the structural arrangement shown in Figure 7. It is recommended that the structural fire engineer should consider running few pilot analyses for different parts of the structure to decide which structural portion will be simulated to identify the optimum passive fire protection scheme. Depending on the complexity of the structure, in some cases it is essential to consider different passive fire protection schemes in the building. The proposed passive fire protection schemes are shown in Figure 7a,b. The system could be considered as sufficient if the unprotected member(s) achieved the ultimate temperature that is associated with the fire resistance requirement. In this study, the web thickness of the different cellular beams was reduced as an approximate mean to take into account the effect of the web holes on the beam element during the overall structural analysis.

Results

Figure 8 shows the mid-span vertical deflections of steel beams plotted against the bottom flange temperature of the secondary steel beam. The results show that the secondary steel beams supporting the flooring system could withstand the induced large deflection at high temperature without any applied passive fire protection. The approach adopted in this study highlights the combined effect of the membrane action in the composite topping and the catenary action in the heated steel beam at large deflection which can be reduced in the later stages when steel temperatures are very high. The precise nature of this effect will depend on the support conditions and the effective ratio between membrane action in composite slab and catenary action in heated steel beam at large deflection.

Discussion and conclusions

- It is recognised that, due to the very little technical information available on the performance of cellular steel beams in fire, the treatment of these types of beams in composite floors is being considered in a simplistic approach and there is a definite need to improve engineering technology related to this particular subject.
- To achieve an optimum fire safety solution, a timeline-dependent approach enables a range of factors affecting fire hazard and escape time to be placed on a common framework so that the effects of altering various design features can be calculated. This enables the interacting effects of different features and different strategies to be evaluated in the overall design.
- Sophisticated finite element computer models can be used to predict the structural response of steel members, sub-frames, or entire buildings. The application of these models is complex and should only be used by competent designers who fully understand both the limitations and capabilities of the model. Due to the complex nature of the models, it is difficult for Checking Authorities to understand and approve designs which rely heavily on the results from such models.
- A probabilistic risk-based approach to safety issues could introduce reliable fire safety solutions, which is likely to influence the way in which those solutions should be presented. In addition, deterministic computer models can be used to assist in identifying the behaviour of different types of structures under fire. The performance of these models should be evaluated against large scale fire tests. New models may provide tools to define more effectively levels of fire performance for the whole assembly of structural components, in relation to the anticipated use of a building or specific parts of a building. When used in connection with risk and hazard analyses, these tools should offer a more economic approach to the safe design of both individual structural members and whole structural frameworks under fire conditions.

Risk-based solution

Although safety factors are utilised in engineering design, a risk-free system does not exist. Assumptions and conditions are of paramount importance in any design activity. Therefore, engineers and researchers should enhance design approaches by applying the latest acquired structural fire engineering knowledge as part of a risk-based approach. It is only by interactions amongst industry and academia that design approaches can be improved and predictions can be refined. Based on such highly precise deterministic analysis, it is important that the structural fire engineer produce a passive fire
protection that not only provides the structure with the required level of safety but also enhances the robustness of the structure. This requires the designer to be aware of all the factors that could affect the structural fire strategy.

Fire severity

In a standard fire resistance test, the gas temperature is increased to follow a predefined time-temperature curve. This heating regime is very different from that occurring in real fires. The maximum temperature attained in a real fire and the rate at which temperature increase depend on a number of factors relating to the fuel available, the geometric and thermal properties of the compartment and the availability of openings through which oxygen can be supplied to the fire. A parametric fire is a mathematical idealisation of a real fire in a compartment. The temperature increases to a maximum and then declines, as it would in a real fire. The fire temperature is a function of the ventilation factor, the fire load and the thermal properties of the wall linings.

The recommendations in Approved Document B (ADB, 1992), for structural fire resistance take no account of the ventilation of hot smoke and gases from a fire compartment. However, the Structural Eurocode 1 (Eurocode, 1995) provides methods for evaluating the effect of ventilation on the structural fire resistance. The approach is known as the “Equivalent Time of Fire Exposure” and is described in Annex E of the Eurocode. Depending on the configuration of the fire compartment, the parametric fire curve could take various shapes such as those shown in Cases 1 and 2, whilst the ISO834 curve still follows the standard shape. Case 1 in Figure 8 shows a comparison of parametric fire curve and the standard fire curve ISO834 according to BS476. For the same fire compartment, the same temperature is reached at two different times, depending on which curve is utilised. In Case 2, for the same comparison, for a given time, two different temperature values can be predicted according to the curve used. This could lead the designer to misleading results if a structural fire analysis is performed.

Effect of fire compartmentation

Any large structure will need to be divided into compartments vertically, horizontally or a combination of the two. This requirement is to limit the spread of the fire to the whole structure, and may also be imposed to allow the phased evacuation of any multi-storey structure, whereby only the floors contained within the fire-affected compartment are initially evacuated, and the remaining floors either above or below the fire-affected areas are evacuated at a later stage. The rules governing compartmentation are generally unclear on the reasons why the values, expressed either as a maximum floor area or volume, limiting compartment sizes have been selected. It is probable that most of the criteria are historically based on long past experience which may be no longer valid with improved fire-fighting methods. In addition to the material non-linearity that takes into consideration the material degradation due to elevated temperature and geometrical non-linearity that takes into consideration the change in the structure configuration, another type of non-linearity could be considered depending on the type of the compartment wall. This may be defined as boundary non-linearity, where the support condition of a particular member in the structure change during the fire as the structural member undergoes large deflection. This type of non-linearity can be demonstrated when a structural fire analysis is considered for a residential building with heavy partitions such as concrete block walls included to prevent fire spread, as shown in Figure 10. Another example of boundary non-linearity is the separation of connections during the heating or cooling phases. Although in a composite structure this may not cause much change as the steel beams are in composite action with the composite floor, it is to be expected that this type of discontinuity could affect the force distribution of the adjacent structure.
The beam does not deflect uniformly, which implies that the springs should have different characteristics. However, for simplification it can be considered as one curve as the distance between the wall and the beam is small. Nonlinear characteristic can be considered for the spring elements.

The way forward

Fire is recognised as a significant hazard in the service life of a structure. Therefore, there is a clear need to provide an improved understanding of the performance of materials and structures in fire and to provide clear design guidance in order to progress cost effective designs. Within the past 10 years sophisticated computer programs have been developed, which mathematically predict the anticipated worst case fire scenario, provide the optimum evacuation procedure and represent the behaviour of a steel frame in fire.

However, the use of these programs remains limited by the lack of relevant research data, requiring the designer to provide the necessary engineering assumptions to cover all the uncertainties, which further limits the modelling capabilities. Indeed, recent work has cast doubt on the notion of a standard time-temperature response, pointing to discrepancies in the construction and geometry of individual furnaces which have a significant impact on the temperature obtained by the element under test. These, together with observations from real building fires, have contributed to the general observation that whole structures exhibit a much different and better performance in fire than single elements. There are interactions and changes in load-carrying mechanisms in real structures that dominate the way they behave; it is entirely beyond the scope of the simple standard fire test to reproduce or assess such effects. As a result, the design of structures in fire is developing at a significant pace in line with fire safety engineering as a whole. It is certainly starting to have a growing impact on the way structures are designed and specified in many countries throughout the world. In addition to the new advanced deterministic analytical methods, improved probabilistic risk assessment techniques are now available to the experienced engineer to support performance-based design for the fire load case (Allam, 2002). Progress in structural fire safety can be integrated into the overall fire safety engineering approach pursued in the most recent generation of codes of practice. These new approaches should consider fire safety engineering as an integrated package of measures designed to achieve the maximum benefit from the available methods for preventing and controlling the consequences of fire. This new framework should be of benefit to the architect looking for better solutions; controlling authorities wishing to ask the right questions and engineers developing new avenues and skills in fire safety engineering.

Figure 11 summarises the current procedure for the involvement of the fire safety engineers in a project to identify the passive fire protection requirements and highlight the need for the participation of a structural fire specialist in the design team at the early stage of the design procedure. In many cases, it was not clear to the project team at what stage should the structural fire specialist be brought in. The importance of early involvement of the structural fire specialist has been demonstrated in a number of projects where the structure arrangement is optimised to enhance the performance in fire conditions (Alam, 2002-2003). Currently, it is very common that the structural fire engineer start to perform the expected role after the design team finish their final structural solution (blue dashed path, Figure 11). In the best case scenario s/he might be able to get involved just before the final structural solution takes place (yellow dotted path, Figure 11). In the optimum scenario, the structural fire specialist can provide the right advice.
based on previous experiences and research knowledge at a very early stage of the design procedure (Green solid path, Figure 11).

![Figure 11. The role of structural fire engineer](image)

**References**


