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INTEGRATED STRUCTURAL FIRE DESIGN FOR HIGH RISE BUILDINGS

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Abstract

The paper presents a fire safety design approach integrating evacuation, structural performance, fire fighting and fire safety management. An integrated performance based design with time as a basis of measurement is discussed. Such an approach allows increased design flexibility and enables engineers to predict the level of safety in each design and thereby derive the most cost effective and safe solution. A project example is also presented along with further improvements for the future. A high level of computer modelling was utilised during the design, which requires additional care and understanding by the designers and enforcers to ensure their validity.

Keywords: Fire Safety Engineering, Performance-based, Structural Performance, Evacuation, Finite Element Analysis

1. Introduction

This paper presents an integrated approach to structural fire safety design which can be adopted for high rise buildings.

Following the 9/11 incident in New York FEMA produced an assessment report. One of the recommendations is to consider the behaviour of structural systems under fires as an integral part of the design process. In fact, a holistic solution that considers the interaction of the structural fire behaviour, fire safety system provisions, human response/evacuation and fire service intervention is essential for the fire safety design of a high rise building.

Such a solution necessitates a performance-based design. This concept is not new but its use is rare due to expense, lack of understanding and the regulatory process. Performance-based approaches enable engineers to design buildings to meet a predefined performance criteria for a given design scenario. The performance requirements should be defined by the regulators and agreed with the owners and design team. The design scenarios should be building specific and defined by the enforcers, the client, and the design team in combination.

There were some immediate calls to change the regulations to ensure a higher level of fire protection in high rise buildings. However, the application of increased fire protection alone does not necessarily result in a higher level of overall fire performance of the building, but may result in an unnecessary cost burden.

The paper also presents a case study of a recent project where performance based design has been adopted to realise value to the client. The overall considerations during the project are discussed, along with further improvements that could be adopted.

2. The Current Design Approach

Fire safety in buildings is often achieved by designing in accordance with prescriptive guidance in order to achieve the national fire safety standard. These are usually a set of generic guidance for designers to follow and are tailored to be suitable to be used for typical building designs. The prescribed safety measures consider the following elements:

- Evacuation – ensure adequate means of escape by recommending the minimum number of escape routes, width and maximum travel distance. Means of detection and warning are sometimes recommended as part of the evacuation package.
- Structural performance – ensure adequate stability for a period of time when exposed to a prescribed fire temperature curve. The performance of structural elements is usually defined in terms of displacement when a single element is tested within a furnace.
- Fire size – minimise excessive fire spread by recommending maximum compartment sizes and/or the use of automatic sprinkler protection.
- Fire fighting access and facilities – ensure appropriate measures to aid firefighters.

These fire safety measures are provided almost independently of each other. Furthermore, they are often introduced near the end of the design process as an "after thought" to satisfy regulatory requirements. There is often little interaction between each element and at worst the fragmented approach does not offer a direct answer to how buildings would perform in a real fire.

It is generally perceived that once the recommendations within the guidance are followed, the building is safe and that the fire safety risk associated with the design will be accepted by society. However, the overall risk in specific buildings is not assessed since the guidance is generic.

Building technology has advanced since such guidance was first developed and designers today can have more flexibility in their design. Buildings are becoming taller, bigger and somewhat more complex and a better approach is required to ensure safety and that best value solutions are achieved.

3. An Integrated Approach

High rise buildings are required to have a high level of fire safety measures as they accommodate a large number of occupants and the total evacuation period will be long. A large uncontrolled fire is more likely to be detrimental to the occupants and the surrounding buildings. Tenable conditions within the evacuation routes must be maintained throughout the evacuation period. It is therefore necessary to have an integrated performance based approach that considers the hazards, consequences and corresponding fire protection measures as a holistic solution. For example, the evacuation period and the structural performance of the evacuation routes should be considered simultaneously. Increasing the fire protection measures without an understanding of the associated impact and benefits does not necessary result in increased safety, but may result in an unnecessary cost burden.

3.1 Measurable Performance and Fire Protection

The process of a real fire can be expressed in terms of time. This time can then be compared to the evacuation process, the fire performance of the structure, and fire service intervention etc. Every fire protection measure will have an impact in terms of time; such as reducing the fire duration, extending the overall stability of the structure or decreasing the evacuation period etc.

The use of time enables engineers to determine exactly which fire protection measures are required to achieve the performance standard. The impact of each fire safety measure can be quantified and therefore an integrated package can be provided for each individual building.

3.2 Design Process

It is recognised that not every tall building requires the same level of fire protection measures. Some of the defining factors are discussed later in this section. A typical design process is shown in Fig. 1. The entire process has to be coordinated between the designers (design team), the clients and the enforcers.

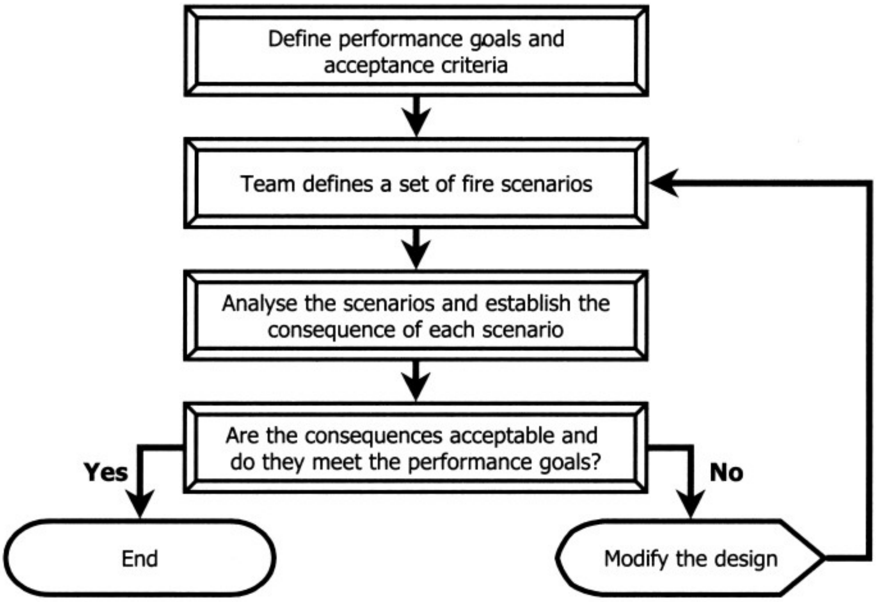


Fig. 1 Fire Safety Design Process

The design process shown in **Fig. 1** is deterministic but the element of risk (considering relative hazard, probability and consequences) can be introduced when defining the performance goals and acceptance criteria. A high factor of safety must be assigned for high risk scenarios, i.e. high probability of occurrence resulting is severe consequences. The safety factor can be reduced for lower risk events. The concept of risk is a large subject and therefore will not be discussed in details here, but has been presented previously [1,2].

It is also proposed that a threat analysis should be conducted as part of the design process. Such an analysis will determine whether additional design scenarios are required and enable the team to make an informed judgement if additional protection measures are required to safeguard against extreme hazards such as terrorist attack and arson. Other examples for consideration include the building location such as high rise buildings adjacent to airports, natural disaster sites etc. Such requirements are currently over and above most regulators' recommendations.

3.3 Evacuation

While defining the performance goal, an allowable maximum evacuation time will be determined. It is important to designate local and global (overall) evacuation periods. The local evacuation time must be relatively short to enable occupants to evacuate the fire compartment but the global period can be extended providing the tenability of the escape routes is maintained (stability, heat and smoke etc.). Where the solutions produced do not achieve the predefined performance goals, designers will have to decrease the evacuation time or increase the tenability period, e.g. by adding passive fire protection.

The use of computer models to study evacuation can provide a comprehensive analysis and predict the occupants' movement during a fire. However, it is important to understand the assumptions that are built into the software so that the designers and enforcers can accept the possible discrepancies between the model and reality. It is also the responsibility of the design team and enforcers to define the appropriate scenarios to be modelled.

3.4 Structural performance

The fire resistance period for high rise buildings is usually high. The conventional method of achieving the required fire resistance period is by applying passive fire protection to prevent structural steelwork (for steel structures) and steel reinforcement (for reinforced concrete and composite structure) from reaching their critical temperatures. However, the critical temperatures are traditionally assumed to be between 550°C and 620°C and the fire performance is determined from a single element test in furnace.

It is widely recognised that such an approach does not give a true representation of structures in fire because;

- the furnace temperatures do not represent real fire temperatures, and
- a single element does not represent the true fire performance of a structural frame.

Full-scale testing was conducted on an 8-storey steel composite building in the 1990's within the UK and the results are starting to influence the structural fire design [3]. From the fire tests and some extensive research, both the real fire temperatures and the corresponding overall structural performance were learned.

Engineers can now predict fire temperatures with respect to time more accurately. In addition the inherent fire resistance of steel composite frames can be estimated. It is possible to provide a solution considering the inherent fire resistance and passive and active fire protection to achieve the performance requirement. This can be a true performance based solution where the structure will fulfil its objectives under the scenarios set out at the beginning of the design process. Where necessary, it is possible to quantified the factor of safety achieved by specific design. This is not possible using prescriptive design approach.

Computer modelling (finite element) is a valuable tool to predict the structural fire performance, where the displacements and forces are calculated as part of the process. Some computer programs, such as Vulcan [4], can predict secondary behaviour (membrane action, catenary forces) of structures. Similarly to other computer modelling tools, the assumptions and scenarios adopted should be carefully studied and made clear to the design team and enforcers.

3.5 Fire Fighting Provisions and Fire Safety Management

The evacuation and structural performance in fire are two of the most important elements for life safety in a high rise building. However there are other elements within the fire safety design which complement the overall fire safety design. It is important that these elements are integrated as part of the "time line" approach and measurable performance.

Fire fighting operations can vary from region to region and fire fighting provisions such as protected shafts, lifts and vents are often installed. It is important for designers to understand fire fighting operations and the resultant effects so that they can be interpreted appropriately within the time line. Considerations should be given to interaction between the fire fighting operation, the structural performance in fire, and the evacuation time.

Fire safety designs rely on good fire safety management to a certain extent. A good management strategy will minimise the hazards, and the fire protection measures should only be required for events beyond management control. Reliable fire safety management should also permit a lower safety factor to be adopted in the fire safety design. For example, an appropriately maintained automatic sprinkler system will control most fires and therefore less reliance needs to be placed on passive systems. However passive systems may still be required to ensure robust and diverse solutions.

There are other active fire protection systems such as mechanical ventilation system, installed to extract smoke or provide pressurization to ensure tenable conditions are maintained, and automatic fire alarm and detection systems. These measures can have significant impact on the time line of the fire

4. Case Study

Buro Happold FEDRA recently produced a fire safety strategy for a medium-high rise building in London An integrated approach was adopted that considers the elements mentioned in Section 3. Some detailed studies on evacuation and structural fire performance were conducted, which is described in the following sections.

4.1 Defining Performance Goal

The building is primarily used as an office space and the tallest block consists of 20 storeys. Having considered the building occupancy profile, location and its significance in the city, the design team, together with the client agreed that the building does not need to perform to a higher standard than that indicated within the National Building Regulations. Extensive discussions with Building Control were held prior to the commencement of the design in order to ensure the correct checking capability and understanding of the design approach for the building.

When considering the fire scenarios, an onerous office fire load density of office was adopted as the base value. Even though an automatic sprinkler system would be installed, its operation was not account for when determining the maximum fire size. The design of all passive fire protection was based on this fire scenario.

4.2 Evacuation

The exits and stairs were sized on the assumption of a phased evacuation. The number and locations were carefully considered so that the local evacuation time is sufficiently low and the travel distances are comparable to prescriptive guidance. The stair locations are distributed diversely and apart from each other to prevent all escape routes being compromised by one incident. In term of global evacuation, the escape routes were carefully considered and an evacuation time of 58 minutes was calculated. This was introduced to the fire time line.

4.3 Structural Fire Performance

The superstructure would be constructed of a steel frame with composite floor slab. The building façade would be glazed with non-fire resistance glazing. Detailed studies were conducted to investigate the two separate parts of the design:

(i) The maximum fire temperatures and duration are mainly dependent upon fire load density, ventilation, compartment enclosure and its geometry. An initial study on the behaviour of the glazed façade under fire condition was conducted. It was demonstrated that the glazing would have failed much earlier than the structural steel elements and therefore additional ventilation can be introduced as a result. Further consideration was also given to possible inner rooms within the office which prevent substantial ventilation being introduced. The fire temperatures and duration can be calculated for the entire fire period for each ventilation cases. A typical time temperature history plot can be found in **Fig. 3**. A sensitivity study was also conducted varying parameters such as the fire load density, wall material and fire compartment geometry.

The adoption of real fire temperatures are departure from conventional design where Standard Fire Curve (ASTM E119, BS476) is usually followed but are considered more realistic in the performance based design compared to a furnace temperature curve. The real fire temperature curves also form the basis of the time line plot.

(ii) The 3-dimensional structural fire performance was studied using a finite element program Vulcan developed at the University of Sheffield [4]. It is a non-linear finite element program which has been validated against results from large scale fire tests. Initial studies were conducted on small subframe utilising symmetry. The objective was to investigate the optimum fire protection profile to achieve the performance criteria set out. 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 solutions were identified, a full-frame model was created comprising a quarter of the entire floor slab. The deflected shape of the model produced is shown in Fig. 2. 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 compartmentations exist. Using this approach ensures the overall structural stability including the interactions between beams, columns and their connections.

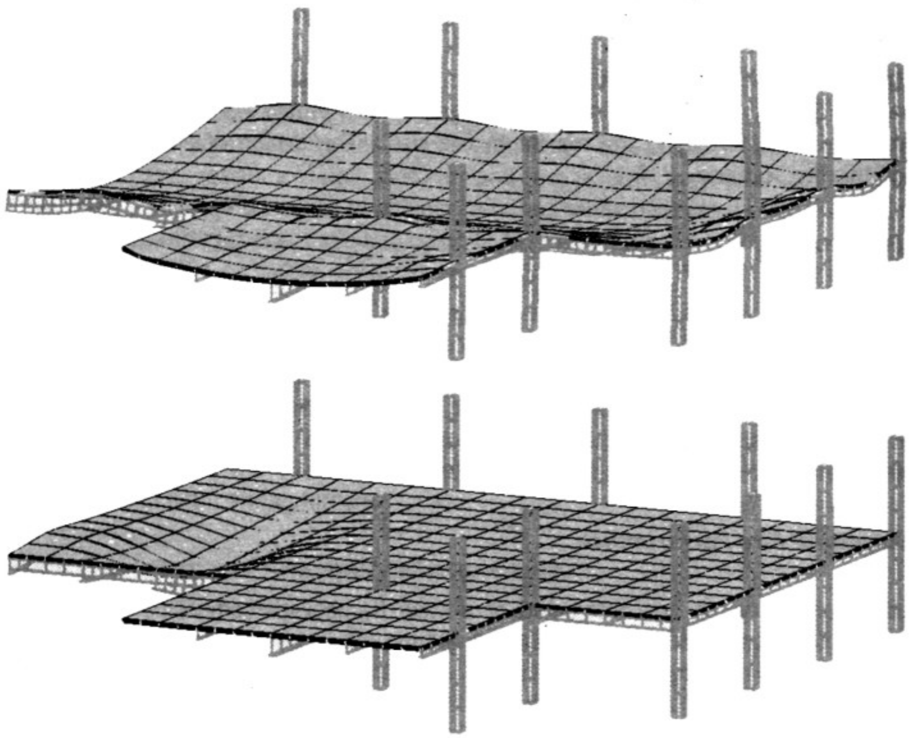


Fig. 2 Vulcan Model – (top) widespread fire across the entire floor, (bottom) small compartment fire

As a result of the studies, a best value solution was reached by increasing the performance of the slab in exchange for the omission of fire protection for the intermediate beams (beams not connected to columns). Where passive fire protection is required, the material and thicknesses were carefully selected to give the required performance.

The solution increases the inherent fire resistance of the superstructure, relies less on the passive fire protection, and therefore is less susceptible to damage or failure (due to less maintenance requirement). In other words, it is a more robust solution. The additional benefit is the saving generated from the omission of passive fire protection and the associated time savings in construction stage.

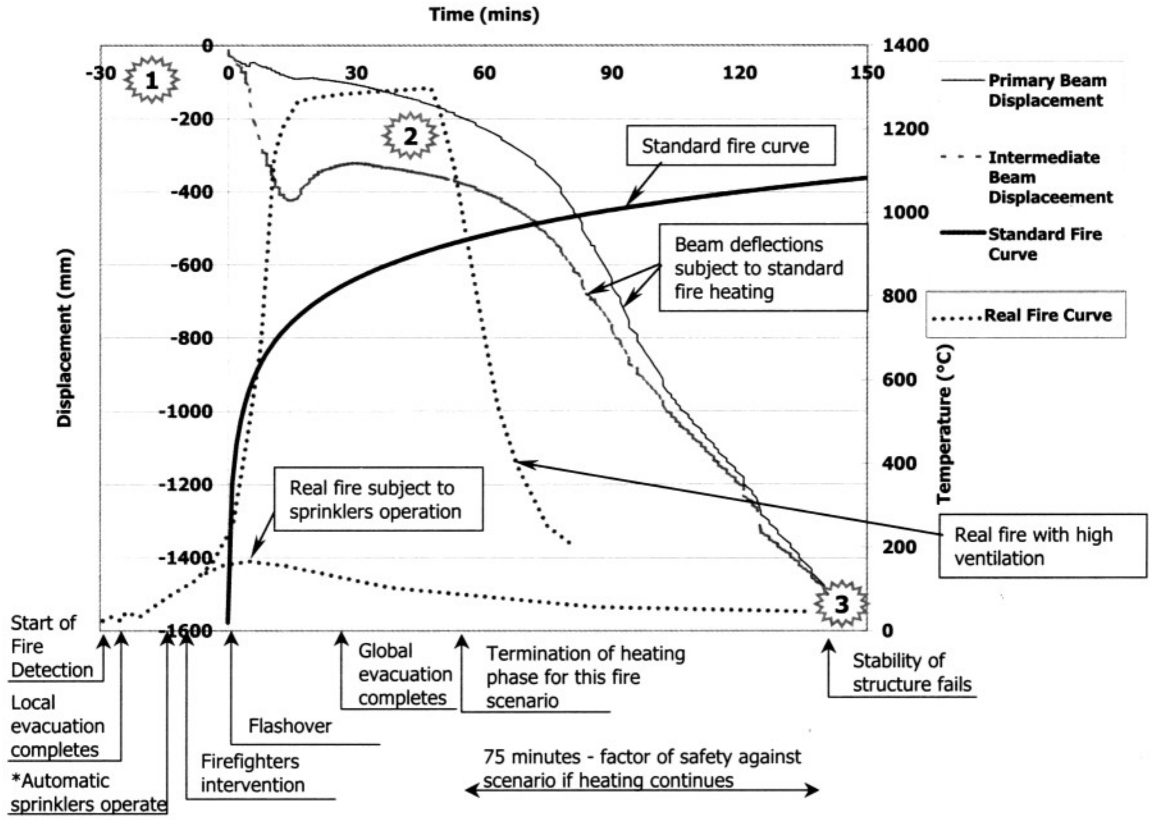
4.4 Other Considerations

Close communications between the designer and the controlling authorities were maintained throughout the design stages. The fire crew attendance time and fire fighting operations were added into the time line to ensure an integrated solution is achieved.

The time line also includes the operation of the general active fire protection installed throughout the building, i.e. automatic sprinkler protection and automatic fire detection and alarm system.

4.5 Results

Fig. 3 shows one of the integrated plots considering the elements discussed above. Three key events are identified that represent three different scenarios and their consequences.



* The effect of sprinklers are not included in order to consider the worst fire scenario.

Fig. 3 Performance based approach using time line

1 The first scenarios assumes the automatic sprinklers are fully operational and the fire size is successfully controlled. As a result, flashover does not take place and structural deformation is not incurred.

2 This scenario assumes the automatic sprinkler system fails and a fully developed fire takes place. The fire temperature curve shown in **Fig. 3** was calculated based on a typical ventilation condition. The maximum fire temperature achieved is approximately 1300°C and the heating phase lasts for 50 minutes. The fire will eventually burnout and the vertical displacement for the beams at the time would be approximately 350mm. These deflections are not shown in the plot.

3 Further analyses were also conducted using the BS476 Standard Fire Curve. This was to provide additional comfort in the design and so that comparisons could be drawn with a solution that would be derived using a more traditional prescriptive method. The predicted beam displacements shown in **Fig. 3** demonstrate a fire resistance period of 130 minutes. This can also be seen as a factor of safety against the unlikely event where the heating phase continues

4.6 Future Design Improvement

Although the design approach adopted for the building comprises a considerable amount of engineering assessment utlising some of the latest technology and research knowledge, there is room for future improvement. Some thoughts are discussed below.

- **Combined hazard** – In tall buildings, it may be appropriate to take into account of combined hazard such as the occurrence of fire after explosion.
- **Evacuation** - the modelling of evacuation assumes occupants behave rationally in the event of fire and follow the evacuation procedure designed for the building. A better understanding of human behaviour would benefit the model. The current strategy also disregards the use of elevators for means of escape.
- **Risk based approach** - Introduction of the approach in parallel may enable of engineers to produce better value solutions. For example, the effect of automatic sprinkler systems may be included in the structural fire assessment in future design.
- **Material properties at extreme temperatures** – From the calculation of fire temperatures, maximum atmosphere temperature can reach up to 1300°C. There may be a need to investigate the performance of material at the extreme temperatures.

Conclusions

The paper presents an integrated approach to achieve overall fire safety for tall buildings. Time is proposed as the basis for measuring performance and a time line plot can be produced that integrates the evacuation, structural performance, fire fighting and the effects of fire protection measures for the building. It prevents fire protection measures to be introduced as an "after thought" near the end of the design process. The resulting benefits (demonstrated from the case study) include:

- Flexibility in design for modern complex high rise building.
- Cost efficient solutions are reached.
- Knowledge on building performance in fires, which ensures adequate safety is achieved.

Computer modelling is often necessary in performance based design. However, care must be taken on the assumptions and scenarios adopted within the model and that these are acceptable to the design team and the enforcers. Appropriate checks should also be made to ensure validity of the model and that the input and output are interpreted correctly.

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