Fire engineering design and post fire assessment

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Synopsis

For some time the 'Fire Engineering Approach' or the 'Fire Safety Engineering Approach' has been adopted in Hong Kong for the design of new buildings or for the alteration and addition works in existing buildings. Such approaches enable the fire safety objectives and performance requirements of the Buildings Ordinance and its allied regulations to be met. As an alternative to the prescriptive requirements set out in the three codes of practice, namely 'Means of Escape in Case of Fire', 'Means of Access for Firefighting and Rescue Purposes' and 'Fire Resisting Construction', the Building Authority also accepts a fire safety engineering approach that takes into account means of escape, means of access, fire services installation, fire resisting construction, size, height, use, location, and fire safety management of the building together with suitable applications of applied science and engineering principles.

Fire engineering design offers a flexible alternative where it is impracticable to comply with prescriptive provisions in the three codes, especially when designing large and complex buildings or where significant alteration and addition works are required in existing buildings. The aim of fire safety design is to provide an overall level of safety equivalent to the one that was achieved by full compliance with the prescriptive provisions of the relevant codes of practice. It also provides a framework for engineers to demonstrate that the performance requirements of legislations are met, or in some cases bettered, to compensate for the deviation or shortfalls of the prescriptive codes.

This paper aims to provide an overview on fire engineering design and construction, post fire assessment and the role of structural engineers in fire engineering.

Introduction

Evolution of fire engineering

Within the last two decades, modern architecture has evolved dramatically in pursuit of spatial function and user needs. As one of the most prominent symbols of economic growth in a city, modern buildings are typically identified as large shopping complexes, high-rise or tall residential and office buildings, mammoth airports and 'big-box' warehouses. The interior space of these buildings has gradually become very complicated, with large open atrium spaces, multiple atriums and interconnecting floor spaces. The introduction of new construction materials and types of furnishings has great influences on fire safety. Instead of the wood furnishing used in the old days, high fuel loads from polyurethane furniture, plastics and other synthetic materials nowadays contribute to large and fast growing fires. These fast growing fires reduce the time that occupants have to evacuate safely and the time available for occupants to control or extinguish fires. Apparently, the traditional prescriptive building codes can no longer provide a suitable vehicle for design of these modern structures but the evolution of the fire engineering approach offers a unique and economical solution to engineers. With greater flexibility and more cost-effective engineering methodology, it allows more design options and choices of construction materials without compromising the primary goal of fire safety.

Fire engineering is a field which explores the various possibilities of preventing fires or reducing the risk and mitigating the damaging effects of fire. It can be defined as the art and science of designing buildings, structures and facilities for life safety and property protection in the event of an unwanted fire. This includes the application of scientific and engineering principles, based on an understanding of the phenomena and effects of fire, of reaction and behaviour of people, property and the environment as well as the impact of fire protection systems including detection, alarm, sprinkler and smoke control systems.

Fire Engineering is becoming one of the noblest professions by virtue of its growing role in saving life and property. To achieve the above objectives, the experiences and competences of fire engineering professionals fall within one of the six following domains: Fire Science; Psychology and Physiology; Active Fire Protection Systems Analysis; Passive Fire Protection Systems Analysis; Law, Regulation and Standards; and Fire Risk Management.

The role of structural engineer

Fire engineering is multidisciplinary in nature, having substantial relationships with building services, with mechanical, electrical and structural engineering and embraces an understanding of human behaviour. Therefore, structural engineers have a very important role in fire engineering, in particular the involvement in fire protection systems, laws, regulations and standards to fire risk management.

After the event of 9/11, understanding the real function of a structure and its response to fire has become a major topic within the building industry. New guidelines and design standards against such extreme events are being developed in various national codes and standards. Structural engineers must be aware that simply increasing the thickness of fire proofing materials without fully understanding structural response to tremendous heat provides no guarantee of better safety. It will be demonstrated in the later sections how the professional knowledge of structural engineers can contribute to the success of the fire engineering approach in the evaluation of actual structural response under fire and in post fire assessment.

Law, regulations and codes of practice

Fire safety requirements in Hong Kong

Legislation and codes of practice on fire safety in Hong Kong are basically prescriptive in nature. Two general ordinances, namely Buildings Ordinance and Fire Services Ordinance empower the Buildings Department (BD) and Fire Services Department (FSD) to oversee the passive and active fire protection systems in buildings. The statutory fire safety standards for compliance are laid down in the following codes of practice:

(A) Code of practice for fire resisting construction 1996

This code provides guidance on compliance with the requirements for fire resisting construction stipulated in Part XV of the Building (Construction) Regulations. It sets out the provisions on protection of buildings from effects of fire by inhibiting the spread of fire and by ensuring the integrity of structural elements and the overall stability of buildings. This is achieved by specifying a minimum fire resistance period in accordance with the type of use, the maximum compartmentation volume and requirements on protection of adjoining buildings and separation between different uses and occupancies.

(B) Code of practice for the provision of means of escape in case of fire 1996

This code sets out the Building Authority's requirements on the provisions for the protection of buildings from the effect of fire by providing adequate means of escape in the event of fire and other emergency. This is achieved by recommending the assessment of population density of floor, the type of usage, the minimum number of escape routes and their widths, the maximum travel distance, the construction of escape routes and appropriate signage etc.

(C) Code of practice for means of access for fighting and rescue purpose 1995

This code seeks to achieve the objective of assisting in firefighting and in saving life of people in buildings by ensuring adequate access for firefighting personnel in case of fire and other emergencies. This is achieved by recommending adequate emergency vehicle access (EVA), access staircases, fireman's lifts as well as fire fighting and rescue stairways according to the area, use and height of buildings.

(D) Codes of practice for minimum fire service installations and equipment and inspection, testing and maintenance of installations and equipment

These two codes are enforced by the FSD. The first Code of Practice provides the minimum fire protection systems required for different types of premises and the specifications for various fire service installations and equipment for meeting the statutory requirements. The second Code is written in accordance with Regulation 10 of the Fire Service (Installation and Equipment) Regulations of the Fire Services Ordinance, Cap. 95 to indicate the type and nature of inspections and tests which installations and equipment must normally pass in order to satisfy the Director of Fire Services. It gives guidance on administrative procedures for application and for inspection and testing and how these systems can be appropriately maintained and inspected throughout the building life.

It should be noted that the above safety provisions are prescriptive measures and are independent of each other. Adherence to the provisions may be taken to mean compliance with the Building Authority's (BA) requirements in fire safety of buildings.

Performance based fire safety code for buildings

Traditional prescriptive codes are simple and straightforward, and prescribe fire safety provisions for generic use or application. This target is achieved by specifying certain construction characteristics, limiting dimensions, or protection systems without referring to how these requirements could achieve a desired fire safety goal. These fire safety requirements are rigid. Design solutions that do not fully follow the prescriptive requirements will be treated as violation of the laws and would require application for a wavier. Prescriptive codes are easy for a third party to follow and use and relatively easy for building officials to enforce. They are generally suitable for simple or conventional building design.

To carry out performance based design properly in a standardised way, we must establish a code or engineering standard stating the fire safety objectives and acceptable methodologies that can be used to demonstrate compliance. Such document might be phrased as a method for quantifying equivalence to an existing prescriptive-based code that might identify one or more prescriptive measures as approved solutions or might specify performance criteria without referencing prescriptive requirements. The code should allow the use of any sound technical solution to demonstrate compliance with fire safety objectives. With the introduction of performance based codes, the concept of compliance will be based on verification of performance of the fire safety measures provided as a whole against the defined fire safety objectives instead of checking against the prescriptive requirements.

The form of a performance based design code varies amongst countries, tailored to suit their own societal needs, cultural characteristics, availability of qualified professionals, regulatory environment and public concerns. It is generally acknowledged that a performance based code should incorporate the following major characteristics: Be well defined scope; satisfy public expectations; clear intent; flexible in application; apply uniformly throughout the jurisdiction; ensure consistency of interpretation; easy to update; not hinder innovation; apply consistent approach to risk; minimise dispute; assure clear liability; ensure certainty and be cost effective for compliance.

Prescriptive code vs performance based approach

Whilst the application of a prescriptive code, in many cases, is straightforward it is not universally applicable to all cases unless amended quickly enough to meet with the fast changing technologiesin the building industry. Performance based code allow for more economical design and foster innovative building developments, with the market rather than the government determining the most efficient ways to meet safety standards.

The general advantages and disadvantages for the two types of codes are summarised below:

Prescriptive based code	
Advantages	**Disadvantages**
Simple, easy to follow and enforce	Subjective
Efficiency in checking for compliance	Inflexible for innovative design, usual situations and novel building features
Less arguments	Does not promote cost-effective design
Requires less engineering and scientific knowledge	Does not provide a direct answer to the performance of buildings under real fire

Performance based code	
Advantages	**Disadvantages**
Fire safety objectives and goals clearly defined	Requires high technology and knowledge based solutions
Allows different ways to achieve safety standards developed by engineers	Needs support from continuous research on fireengineering aspects (such astheories and tools)
Allows innovative design	Time consuming to seek solution between design engineer and regulator
Eliminates technical barriers to trades of new buildings and industrial products	Design has to be conducted by qualified engineers of the Fire discipline
Promotes use of new technologies and knowledge	
Allows cost-effectiveness and flexibility in design	
Reduces bureaucracy	

Development of performance based fire safety code in Hong Kong

The BA recognises the fire safety engineering approach as an alternative to the prevailing prescriptive codes. A practice note (Practice Note for Authorised Person and Registered Structural Engineers 204) was issued in 1998 to provide guidelines on design methodology and procedures of a fire engineering approach as well as compilation of a fire safety strategy report for building works. Meanwhile, a Fire Safety Committee (FSC) was established in the same year to consider fire engineering approach proposals in connection with the planning, design and construction of new building developments, addition and alteration proposals, enquiries and proposals to upgrade fire safety provisions in existing buildings.

Review of fire safety requirements

The Garley Building fire on 20 November 1996, Mei Foo Sun

Chuen fire on 8 April 1997 and some other major fire incidents prompted the Government to make a review of the fire safety situation of buildings in the late nineties. The following were called for:

- Reviewing and enhancing the fire safety provisions in the existing commercial premises and other buildings where the extant fire safety provisions are no longer sufficient to meet their current use;
- Reviewing the adequacy of current fire safety requirements stipulated in the present Building Regulations and codes of practice; and
- Reviewing the regulations governing and providing guidelines for the control, maintenance and management of fire safety measures in existing buildings.

Fire protection systems and fire safety management

Fire protection systems

The prime objectives of fire engineers are to prevent, delay or reduce the effects of flashover and provide adequate time for the occupants of the building to escape in case of fire, and to assess the reuse of the building after a fire event. The first goal is achieved by designing active fire protection systems such as early detection systems, alarm systems, sprinkler systems and smoke control systems which may require the calculation of activation times for sprinklers and detectors. The rate of fire growth leading to flashover can also be predicted based on the amount, type and arrangement of fuel, the compartmentation geometry and the available ventilation. Other calculations may compare evacuation times with the growth and temperature of the smoke layer in a compartment. The principle is to ensure that Available Safe Evacuation Time (ASET) (i.e. time to reach global and/or progressive collapse or time to untenability of the escape route) is always larger than the Required Safe Evacuation Time (RSET). ASET, which is most affected by smoke, depends on the tenability of the compartment and the escape route. Computational Fluid Dynamics (CFD) analysis can precisely predict the behaviour of fire and smoke in a fire and is a powerful tool to determine the ASET.

RSET = time to detect and alarm + time from alarm to response + travel time

On the other hand, passive fire protection systems are often vital to the stability and integrity of a building or structure in case of fire (albeit some structures can survive without them as Cardington tests showed). They also provide a certain degree of protection to building for survival from fire and enables reuse of the structures. These passive systems are built into the structures to provide the necessary stability and to separate the building into areas of manageable risk. They are designed to control the growth and spread of fire allowing the occupants to escape and the fire fighters to combat the fire. Such protection is either provided by the materials from which the building is constructed, or is provided by adding to the construction materials to enhance their fire resistance. Common passive protections are compartment walls, fire doors, ceiling systems, fire resisting walls and partitions, fire shutters, fire dampers, structural floors, water cooled hollow steel columns, walls and frames, fire protection and synthetic fire resistance materials.

Fire safety management

Fire safety management systems play a major role in fire safety engineering design. A good management strategy can minimise fire hazards and hence, the fire protection measures, i.e. active or passive protection systems should only be activated or utilised for events beyond management control. Theoretically, a reliable fire safety management system may warrant the use of a lower safety factor in fire safety design. It implies all elements in a fire safety engineering strategy are capable of being maintained and implemented effectively over the life of the building. However, the actual concern is mainly on the reliability of implementing and maintaining such a management system.

To increase the reliability of a fire safety management system, the following factors have to be considered:

- ownership of the building;
- number of fire safety personnel to be employed;
- level of staffing (i.e. staff-occupant ratio);
- level of fire safety training (e.g. frequency of fire-drill);
- level of security;
- effectiveness of communications procedures;
- frequency of maintenance and testing of fire safety systems;
- level of liaison with the fire brigade;
- contingency plan;
- planning for abnormal occupancies;
- level of independence of testing and auditing of management system.
- risk management level; and
- management of fire load.

The present fire safety management requirements are focused on the maintenance of fire services installations and ensuring that escape routes are free from obstruction. The maintenance of passive fire protection systems such as concrete cover, sprayed cementitious materials, gypsum based coatings and intumescent coatings are not mandatory. However, the maintenance of passive fire protection systems, which ensure the whole fire resisting design system functions properly when needed, forms an integral part of the fire safety management system. Actually, in the absence of a thorough fire safety management policy, fire safety cannot be assured irrespective of whether prescriptive or performance based approach is adopted.

Structural fire engineering design

What is structural fire engineering?

Traditionally, fire design of structures relies on the simple, single element tests and using either concrete cover protection or insulating materials in the form of board system, spray system and intumescent coating to protect the structures in accordance with the required fire resistance period (FRP). Thermal induced forces and change of mechanical properties at elevated temperatures are not calculated or designed for.

The evaluation of fire resisting performance of the enclosure boundaries can be carried out either on individual elements or on a more complex assembly. Until very recently, the structural fire assessment has been made mainly on individual elements under standard fire condition such as those recommended in BS 5950: Part 8: 1990.

The fire resistance of individual elements was obtained by test results or by simple capacity calculation taking into account the alteration of materials properties under elevated temperatures. Recently, it has been demonstrated by full scale test such as those carried out in Cardington, UK that element design underestimates the fire resistance of the whole structure. This is because structures often have inbuilt secondary load paths, which can be mobilised during fire when structural deflections become large. This inbuilt redundancy can provide an enhanced performance during fire in some structures.

Structural fire engineering design consists of the following activities:

- understand the mechanisms of fire growth and development (i.e. natural fire characteristics);
- establish the worst credible fire scenarios;
- determine the compartment time-temperature response;
- calculate the temperature distribution within structural elements (i.e. heat transfer); and
- evaluate structural response of the affected members and its subsequent effects on other active fire installations.

Comprehensive structural fire assessment should take into account the real fire loading, thermal and mechanical properties of members and their structural behaviour under fire. With the development of sophisticated modeling techniques and computer programs, a more efficient and reliable evaluation of whole structure response to real fire is possible. Hence, structural fire engineering can be defined as the analysis of the real structural response under credible fire scenarios.

Natural fire assessment

Fire resistance design of structural members is traditionally based on fire resistance testing using a standard time temperature curve. The standard curve is established by furnace tests conducted in accordance with the recommendations of ASTM-E119 or BS 476. The idea of standard fire approach was proposed in the International Fire Prevention Congress held in London in 1903. The ASTM-C19 (later changed to E119) was issued in 1917 and the first edition of BS 476 was published in 1932. The adoption of standard fire curve provides evidence to compliance of regulatory requirements in fire safety, and assists in fire resistance product development.

The temperatures in a standard furnace are relatively uniform when compared with those in a real fire compartment. Whilst the relevant test codes specify the same control temperature, the heat flux experienced by the test specimen is dependent on the form of construction of the furnace, the location of burners relative to the specimen and the type of fuel used. However, the form and shape of furnace is not standardised across the testing bodies. Furthermore, the physical limitations of standard furnaces inhibit the possibility to simulate complicated three-dimensional structural behaviour by a standard test. Hence, the influence of restraints or structural configuration, be it beneficial or detrimental, provided by the surrounding structure is thereby ignored. Obviously, the testing environments are not representative of the conditions of fire exposure in real conditions.

Natural fires are very different in peak temperatures and durations from the standard fire curve. The standard fire takes no account of the different thermal exposures resulting from different compartment geometries, ventilation conditions, fire load and compartment boundary materials. The behaviour and duration of a natural compartment fire is strongly dependent on the available ventilation and total fire load. If the supply air to a room is large, then the burning rate is dependent on the surface area and the burning characteristics of the fuel.

To assess the actual fire performance of a building, fire engineers are interested in the study of the temperature-time history of natural fire. The compartment fire process can be described by three distinct phases, namely the pre-flashover fire, the fully-developed fire and the decay period. There is a rapid transition stage called flashover between the pre-flashover and fully developed fire. Fully developed fire will only happen when there is no restriction to fire development and all combustibles within the compartment are burning. The heat energy release rate during this stage (i.e. design fire size) will be used for conducting fire engineering design.

Standard testing data of various fire loads can be obtained from testing data of world recognised engineering handbook (e.g. SFPE Handbook of Fire Protection Engineering) or research laboratories (e.g. Building and Fire Research laboratory of National Institute Standards and Technology).

Design fire scenario and fire size

The worst credible fire scenarios and design fire size of structures can be established by considering the possible fire hazard, uses and events, most probable fire load available (i.e. combustible materials or fuel) and the provision of active fire

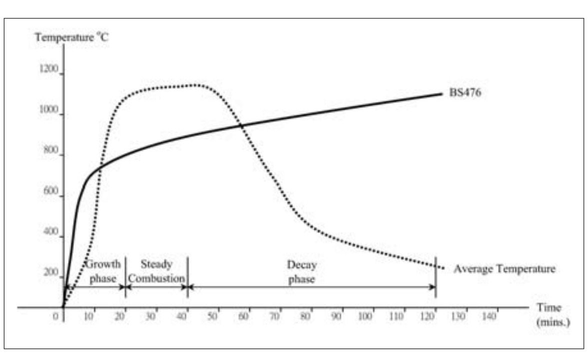


Fig 1. (left) Relationship between natural fires and standard fire curve

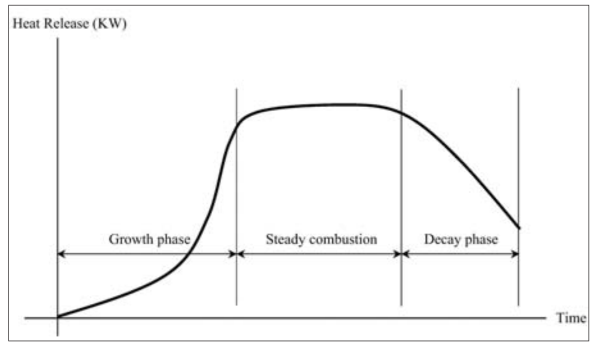


Fig 2. (right) History of a well-ventilated natural fire against rate of heat release

protection systems within the compartment area. Based on the potential uses, different worst scenarios are considered for estimation of the design fire size taking into account the active fire protection system provided.

Based on steady state fire conditions, the estimated heat release rate will then be utilised to calculate the heat transfer to the affected structural members by evaluating the heat energy transferred through convection and radiation from the credible fire.

The temperature of the affected members will then be used to assess the required fire protection provisions for meeting with the fire hazard.

Structural fire design approach

BS 5950: Part 8, Code of Practice for Fire Resistant Design was one of the first structural fire design codes for steel structures in the world. It provides design information and guidance for steel structures under standard fire loads. The code is based on the concept of limit state design. As the occurrence of a fire will render the structure to be under an accidental limit state, reduced partial load factors are adopted to simulate the actual loading condition during a fire incident. The structural capacity of members can be calculated by either the limiting temperature method or the moment capacity method. The limiting temperature method is mainly based on test data and is easy to apply. The structural capacity of a member under fire can be assessed by comparing its limiting temperature (i.e. maximum allowable temperature for a particular load) and the load ratio.

Load ratio = Load or moment at the fire limit site/ Load or moment resistance at 20°C

On the other hand, whole structural response under fire load can be analysed by using finite element or non-linear computer modeling with the proper use of the thermal and mechanical properties of the structures. Eurocodes 2, 3 and 4 allow consideration of natural fire in assessing the fire structural behaviour of concrete, steel as well as composite steel and concrete structures respectively.

Whilst it is generally accepted that deflections can be very large at the fire limit state as compared with the normal serviceability limit state, it may be necessary to use more stringent deflection limits for structural members that are supporting or above compartment walls to ensure the compartmentation functions throughout a fire.

Case study – Assessment of the fire resisting performance of steel structure of Langham Place Grand Atrium[20]

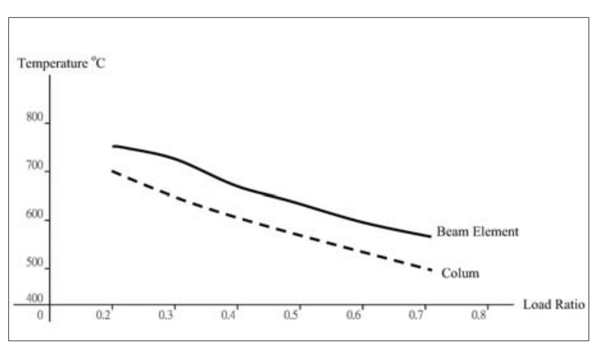


Fig 3. (right) Limiting temperature curve according BS 5950: Part 8

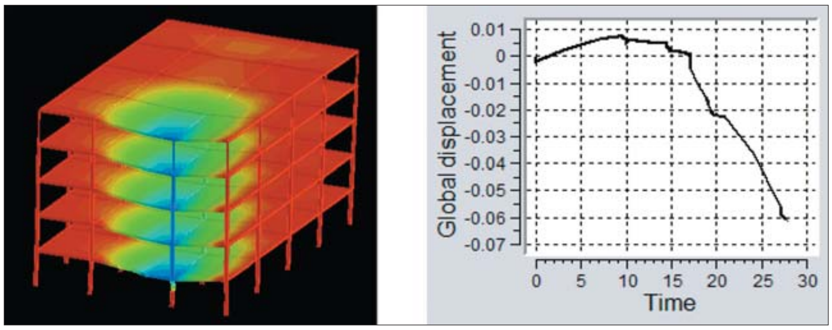


Fig 4. Structural response under fire from finite element analysis[19]

Project description: The Langham Place development is located at the corner of Argyle and Portland Streets, Mongkok. It comprises a 53-storey office tower, four levels of basements with carpark and retail and two retail atria, namely the Grand Atrium and Mini Atrium. The Grand Atrium has a ceiling height of about 50m. Main roof truss, glazing roof truss and 'Knife Blade' trusses/columns together act as the main structural support of the Grand Atrium. The roof structures are not fire-protected whereas the 'Knife Blade' trusses/columns are 2h fire protected at the lower 15m from ground level.

The Grand Atrium contains a Stage and Assembly areas as well as stationary food kiosks with seats both inside the atrium and on the east and west terraces. Note that the food kiosks (e.g. kitchen area) will be protected separately and are not considered a fire hazard to Grand Atrium. Fire engineering analysis has been conducted to evaluate the adequacy of the unprotected roof structure and partly protected columns in the event of a fire.

Fire scenario and design fire

The design fire size and fire locations were estimated for making heat transfer calculations of steel members in the Grand Atrium. A number of scenarios were considered based on possible events held in the Grand Atrium. The worst cases that have been considered are:

- Holiday decorations (large Christmas tree);
- Audio/visual display (televisions);
- Restaurant/café seating (sofa); and
- Communal exhibitions such as an automobile show and fashion show (assuming racks of clothing).

The most credible design fire load obtained from recognised fire protection handbooks and technical papers are tabulated as follows:

Fire	Peak heat release rate in MW	Remarks
Christmas tree	5.0	Based on a heat release of 325KW/m^2
Television	5.0	20in. and 26in. TV at 150MJ each
3 seat sofa	3.0	Upholstered chairs (2.0-3.0MW)
4 door car	2.0-5.0	–
Clothing	5.0	14kg of hanging garments at 27MJ/kg
Stage curtains	5.0	25m^2 of acrylic curtain

Design assumptions

The following assumptions are made so as to ensure the fire safety analysis is on the safe side:

- The fire growth has been conservatively assumed to be 'fast' in the calculations. In reality, a slower fire growth is more likely to occur.
- The design fire size is assumed to remain constant at its peak value output. Actually, the fire will burn out quickly due to lack of fuel.
- Heat loss to concrete and ambient air from the heated steel members has been ignored.
- Fire fighting activity by FSD has been ignored.
- Sprinkler has assumed to be inactive.
- To take into account the possible elevated fire location, a 5MW Christmas tree at 5m above the atrium base is assumed as the design fire.

Heat transfer calculation and structural assessment under fire

Based on the above fire scenarios, a design fire of 5MW was selected to assess the capacity of affected structural members. The assessment of the temperature variation in critical steel members can be conducted by adopting the thermal dynamic equations from CIBSE Technical Memoranda TM 19 and NFPA 92 B of National Fire Protection Association. The critical temperature of each member is then compared with the limiting temperature of unprotected steel under its load ratio (550°C in this case) to determine whether the proposed steel structures can maintain structural stability in the event of fire.

Assessment results

Members	***Temperature under 2h of design fire***	***Remark***
Main roof truss	37°C	Structurally stable
Glazing roof truss	47°C	Structurally stable
'Knife blade' truss/column	93°C	Structurally stable

The assessment results of the above fire engineering analysis concludes that a 5MW fast growth rate and maintaining a peak steady rate fire in the Grand Atrium will not result in structural instability for a period of 2h.

Post fire assessment

Aim and scope of post fire assessment

Post fire assessment is a different activity from design. It is aimed at assessing the real condition and adequacy of an existing building in respect of structural and fire safety after a fire incident. The adequacy of a fire damaged building is assessed by the exercise of professional engineering judgment based on the information obtained from a thorough investigation. This will include desktop study of the original design information, structural and building plans, design calculations and building history; site inspection and survey on the conditions of the building after fire; analysis of witness statements and fire brigade's report; and results of *in situ* tests on the affected structural elements, building materials and fire protection systems.

The scope of investigation encompasses the following items:

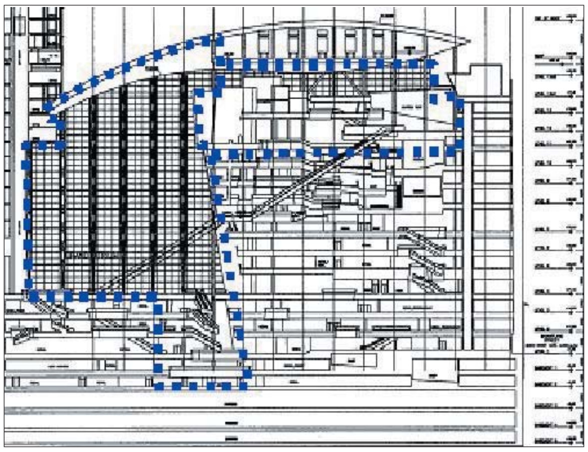
- possible cause and duration of the fire incident
- overall stability, strength and robustness of the structure
- defects and damage of the building
- fire safety provisions of the building after fire
- serviceability condition and durability of the building
- strengthening and repair proposals

When conducting a fire safety appraisal for a damaged building, it is important to establish the fundamental criteria such as the acceptable standards and codes of practice. Whilst there is no need for an existing building to comply with all the modern standards, it is necessary to assess the performance of the fire damaged building against the prevailing requirements and codes of practice in order to evaluate its safety margin and to carry out enhancement if found necessary. The post fire assessment can be carried out by either:

- ***Prescriptive approach*** – assess the present provisions directly in accordance with the relevant codes of practice and regulations; or

- ***Quantitative approach*** – commission detailed assessment based on site findings, model calculations and tests results.

Fig 5. Langham Place



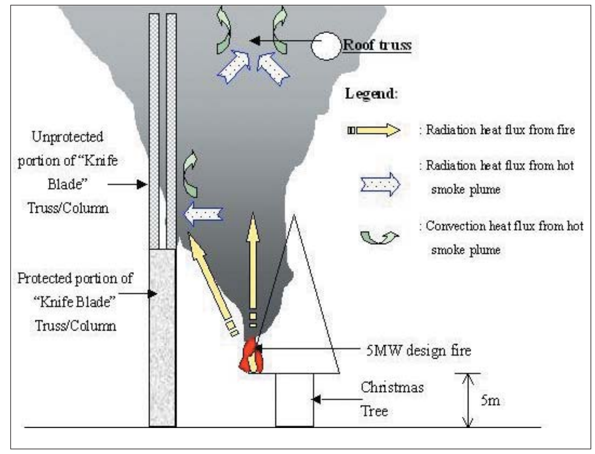


Fig 6. (left) Sketch of the Grand Atrium
Fig 7. (right) Illustration of fire scenario of Christmas tree fire in the Grand Atrium

Arson investigation and fire damage assessment

Arson investigation is one of the main duties of a fire engineer. Investigation is conducted by studying the witness statements and fire brigade's incident report, damages of the building and construction materials, results of test on structure, building materials and fire protection systems, and traces of chemicals found on site. The investigation report would form the basis for possible prosecutions or law suits and would also be of great help in formulating preventive and mitigating measures to reduce future fire risk.

Assessment of the effects of fire on building depends on the particular materials involved and whether the overall stability of the structures is in question. The general procedures should comprise items as listed below:

- Initial and detailed site inspections
- Desktop study
- Detailed collection of evidence
- Damage assessment
- Specification for repairs

Inspection of the damaged building will normally be in two phases, namely, the initial inspection to identify any damage requiring immediate shoring, demolition or other attention and to formulate the next course of action; and the detailed inspection to assess fully the damage with a view to developing remedial/repair measures and making recommendations on fire safety design requirements. An initial overview examining the most conspicuous damaged elements is necessary to give an early indication of the likely scale of the damage. It is also important to know the pre-fire condition of the structure before the performance of the structure can be established for its post-fire condition.

Instructions may have to be given by professional structural engineer for partial demolition, removal of debris, installing shoring and carrying out temporary support works to render structural safety. However, evidence should be carefully recorded prior to removal of debris. The positions, conditions, melting and charring of materials will provide good evidence for an estimate of time and temperature history of the fire. Fire performance of materials such as ignition temperature, colour and decomposition rate can be obtained from recognised literatures.

Damage assessment should consist of the following:

- An appraisal of the pre-fire conditions of the building, including its fire safety provisions and structural capacity.
- The time and temperature profile of the fire determined from the available evidences and a correlation with the standard fire test.
- Assessment of the temperature profile of the fire by examining and testing the elements of the structure and construction under consideration.
- Assessment of the structural capacity, overall stability and robustness of the damaged structure, fire safety provisions of the building and the need for repair based on the above temperature data and other evidences.

Behaviour of construction materials under fire

(A) Reinforced and prestressed concrete

Its properties after heating depend on a number of factors including rate of heating, duration of heating, loading regime and mix constituents. It is noted that normal concrete will lose most of its strength at 800°C. The colour of concrete will turn to pink and dirty yellowish-grey after it has been heated above 300°C and 450°C–500°C respectively.

The post-fire behaviour of prestressing steel is much more critical than that of normal reinforcing steel bar. The tensile properties of prestressing steels deteriorate markedly at elevated temperatures. The tensile strength of prestressing steel is reduced to 50% when it is heated to 370°C–420°C and is reduced to 7% of the original value when temperature reaches 700°C.

Consideration should be given to assess the following:

- reduction in compressive strengths of concrete
- creep due to large reduction of elastic modulus
- cracking around heavily reinforced areas
- deep cracking due to restrained cooling or thermal shock from water during fire fighting
- reduced bond between reinforcement and concrete
- spalling by explosion or sloughing
- reduction in strength of steel reinforcement and prestressing steel

(B) Structural steel

The yield strength at room temperature is reduced to about half at 550°C. Young's modulus decreases with temperature rise at a slightly higher rate than that does with yield strength. The original yield strength is almost completely recovered on cooling from temperatures of 500°C to 600°C for all sections. The yield strength is reduced by 30% for cold formed sections and 5% for hot rolled sections when cooling from 800°C.

(C) Timber

Timber is combustible and will easily burn out under fire. Timber shows brown colour at about 120°C–150°C, black colour around 200°C–250°C and evolves combustible vapours at about 300°C. At about 400°C to 450°C (or 300°C if a flame is present), the surface of timber will ignite and char at a steady rate. Only charred parts of a section lose all their strength whereas the remaining parts may assume to have no significant loss in strength.

Conclusions

Fire engineering is the science of formulating fire safety solutions for modern buildings and structures by quantifying hazards, assessing risks and defining an acceptable safety level. Performance based fire safety design has a distinct difference from that of traditional prescriptive based design in terms of specified requirements, knowledge of the designer and enforcement agent. It promulgates a shift from low technology design of simply comparing the prescriptive specifications against compliance to a high technology design approach of verifying the fire safety performance against objectives and acceptable criteria evaluated engineering tools.

To ensure successful implementation of a new performance based code, it is important that sufficient professional engineers are available to handle this technology orientated design approach. It is time for all related professional engineers to engage themselves in this challenging field with a view to promoting the advancement of fire engineering technology for the betterment of the Hong Kong society. With the support from the government and industry, we look forward to seeing a new era of fire safety as well as innovative designs for buildings and structures within the industry.

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