

Designing Against Fire

I. D. Bennetts

Noel Arnold and Associates, Melbourne Australia

I. R. Thomas

CESARE, Victoria University, Australia

ABSTRACT: This paper considers the design of buildings for fire safety. It is found that fire and the associated effects on buildings is significantly different to other forms of loading such as gravity live loads, wind and earthquakes and their respective effects on the building structure. Fire events are derived from the human activities within buildings or from the malfunction of mechanical and electrical equipment provided within buildings to achieve a serviceable environment. It is therefore possible to directly influence the rate of fire starts within buildings by changing human behaviour, improved maintenance and improved design of mechanical and electrical systems. Furthermore, should a fire develop, it is possible to directly influence the resulting fire severity by the incorporation of fire safety systems such as sprinklers and to provide measures within the building to enable safer egress from the building. The ability to influence the rate of fire starts and the resulting fire severity is unique to the consideration of fire within buildings since other loads such as wind and earthquakes are directly a function of nature. The possible approaches for designing a building for fire safety are presented using an example of a multi-storey building constructed over a railway line. The design of both the transfer structure supporting the building over the railway and the levels above the transfer structure are considered in the context of current regulatory requirements. The principles and assumptions associated with various approaches are discussed.

1 INTRODUCTION

Other papers presented in this series consider the design of buildings for gravity loads, wind and earthquakes. The design of buildings against such load effects is to a large extent covered by engineering based standards referenced by the building regulations. This is not the case, to nearly the same extent, in the case of fire. Rather, it is building regulations such as the Building Code of Australia (BCA) that directly specify most of the requirements for fire safety of buildings with reference being made to Standards such as AS3600 or AS4100 for methods for determining the fire resistance of structural elements.

The purpose of this paper is to consider the design of buildings for fire safety from an engineering perspective (as is currently done for other loads such as wind or earthquakes), whilst at the same time, putting such approaches in the context of the current regulatory requirements. At the outset, it needs to be noted that designing a building for fire safety is far more than simply considering the building structure and whether it has sufficient structural

adequacy. This is because fires can have a direct influence on occupants via smoke and heat and can grow in size and severity unlike other effects imposed on the building. Notwithstanding these comments, the focus of this paper will be largely on design issues associated with the building structure.

Two situations associated with a building are used for the purpose of discussion. The multi-storey office building shown in Figure 1 is supported by a transfer structure that spans over a set of railway tracks. It is assumed that a wide range of rail traffic utilises these tracks including freight and diesel locomotives. The first situation to be considered from a fire safety perspective is the transfer structure. This is termed Situation 1 and the key questions are: what level of fire resistance is required for this transfer structure and how can this be determined? This situation has been chosen since it clearly falls outside the normal regulatory scope of most building regulations. An engineering solution, rather than a prescriptive one is required. The second fire situation (termed Situation 2) corresponds to a fire

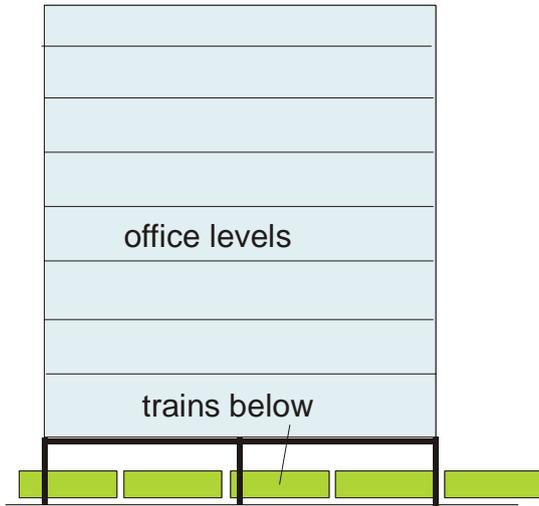


Figure 1 A Multi-storey office building

within the office levels of the building and is covered by building regulations. This situation is chosen because it will enable a discussion of engineering approaches and how these interface with the building regulations – since both engineering and prescriptive solutions are possible.

2 UNIQUENESS OF FIRE

2.1 Introduction

Wind and earthquakes can be considered to be “natural” phenomena over which designers have no control except perhaps to choose the location of buildings more carefully on the basis of historical records and to design building to resist sufficiently high loads or accelerations for the particular location. Dead and live loads in buildings are the result of gravity. All of these loads are variable and it is possible (although generally unlikely) that the loads may exceed the resistance of the critical structural members resulting in structural failure.

The nature and influence of fires in buildings are quite different to those associated with other “loads” to which a building may be subjected to. The essential differences are described in the following sections.

2.2 Origin of Fire

In most situations (ignoring bush fires), fire originates from human activities within the building or the malfunction of equipment placed within the building to provide a serviceable environment. It follows therefore that it is possible to influence the rate of fire starts by influencing human behaviour, limiting and monitoring human behaviour and improving the design of equipment and its maintenance.

This is not the case for the usual loads applied to a building.

2.3 Ability to Influence

Since wind and earthquake are directly functions of nature, it is not possible to influence such events to any extent. One has to anticipate them and design accordingly. It may be possible to influence the level of live load in a building by conducting audits and placing restrictions on contents. However, in the case of a fire start, there are many factors that can be brought to bear to influence the ultimate size of the fire and its effect within the building. It is known that occupants within a building will often detect a fire and deal with it before it reaches a significant size. It is estimated that less than one fire in five (Favre, 1996) results in a call to the fire brigade and for fires reported to the fire brigade, the majority will be limited to the room of fire origin. In occupied spaces, olfactory cues (smell) provide powerful evidence of the presence of even a small fire. The addition of a functional smoke detection system will further improve the likelihood of detection and of action being taken by the occupants.

Fire fighting equipment, such as extinguishers and hose reels, is generally provided within buildings for the use of occupants and many organisations provide training for staff in respect of the use of such equipment.

The growth of a fire can also be limited by automatic extinguishing systems such as sprinklers, which can be designed to have high levels of effectiveness. Fires can also be limited by the fire brigade depending on the size and location of the fire at the time of arrival.

2.4 Effects of Fire

The structural elements in the vicinity of the fire will experience the effects of heat. The temperatures within the structural elements will increase with time of exposure to the fire, the rate of temperature rise being dictated by the thermal resistance of the structural element and the severity of the fire. The increase in temperatures within a member will result in both thermal expansion and, eventually, a reduction in the structural resistance of the member. Differential thermal expansion will lead to bowing of a member. Significant axial expansion will be accommodated in steel members by either overall or local buckling or yielding of localised regions. These effects will be detrimental for columns but for beams forming part of a floor system.

tem may assist in the development of other load resisting mechanisms (see Section 4.3.5).

With the exception of the development of forces due to restraint of thermal expansion, fire does not impose loads on the structure but rather reduces stiffness and strength. Such effects are not instantaneous but are a function of *time* and this is different to the effects of loads such as earthquake and wind that are more or less instantaneous.

Heating effects associated with a fire will not be significant or the rate of loss of capacity will be slowed if:

- (a) the fire is extinguished (e.g. an effective sprinkler system)
- (b) the fire is of insufficient severity – insufficient fuel, and/or
- (c) the structural elements have sufficient thermal mass and/or insulation to slow the rise in internal temperature

Fire protection measures such as providing sufficient axis distance and dimensions for concrete elements, and sufficient insulation thickness for steel elements are examples of (c). These are illustrated in Figure 2.

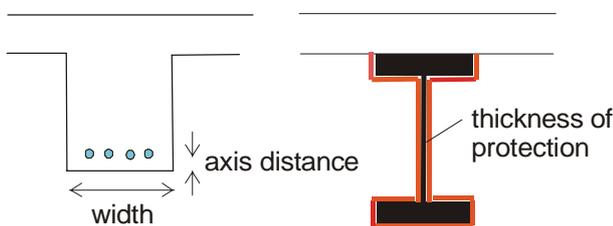


Figure 2 Concrete and Steel Elements

The two situations described in the introduction are now considered.

3 FIRES DUE TO TRAINS BELOW BUILDING

3.1 Possible Approaches

What level of fire resistance is required for the transfer structure shown in Figure 1?

One approach to answering this question could be to design the transfer structure to resist the most severe possible fire until that fire has burnt out. However, if the trains traveling below the building include a range of diesel locomotives and freight cars, it may not be economically feasible to design against the worst possible fire.

Another more rational approach would be to design the transfer structural elements against fire such that the probability of failure of the members in the event of fire (many different fires with different probabilities of occurrence) is no greater than that associated with the normal temperature loading conditions. In this approach account must be taken of:

- (a) the variability associated with loads applied to the building,
- (b) the possible fire train scenarios as characterised by their probability and heating characteristics, and
- (c) the effect of such fires on the resistance of the transfer members

This approach is now further described. As the resistance of the structural members is reduced, the probability of structural failure is increased. For a particular fire event *i*, this probability may be denoted as p_{ffi} given the variability associated with the loading and resistance. If the fire events are considered to be independent and the probability of occurrence of fire *event i* is denoted as p_i , then the overall probability of failure for a *given* structural element when subject to all possible fire events is:

$$p_{tf} = \sum_i p_i \times p_{ffi} \quad [1]$$

It can be argued that the fire design is satisfactory if this probability is less than some acceptably small value p_{acc} – for example, the value adopted for normal temperature design. It is generally accepted that the notional probability of failure of a key structural member subject to gravity loads and designed in accordance with Australian structural and loading standards is about 2×10^{-4} over the life of the building. The adoption of such a value would be appropriate on the basis that it is difficult to see why the structure should be safer in fire than under normal temperature conditions.

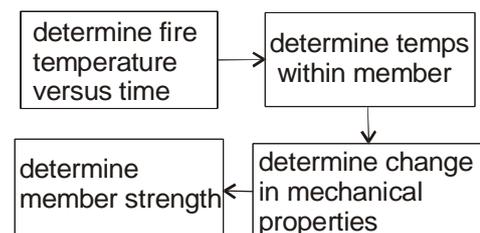


Figure 3 Effect of Fire on Member

How should p_{ffi} be determined?

Section 3.5 presents a simplified approach for determining these probabilities. The determination of the effect of a fire on the strength of a transfer member requires several steps that are illustrated in Figure 3.

3.2 Fire Characteristics

First, it is necessary to characterise the likely gas temperatures associated with the fire in the vicinity of a structural member. The sustained gas temperatures can be determined from experimental data from specific fire tests or other data (FRA, 2006) that can be related to the particular fire scenario being considered. For Situation 1, experimental data relating to train fires (White et al. 2005) and pool fires involving hydrocarbons (SFPE, 2002) would be relevant. As a general rule sustained gas temperatures of 900–1000°C would be expected for well-ventilated fires not involving hydrocarbons and up to 1100°C would be expected for pool fires. It is also important to determine the duration of severe heating. For fires involving trains this might be based on reported evidence of the duration of burning for similar train situations, or by determining the heat energy that could be released by the available fuel (Q_{tot}) (expressed in megajoules (MJ)), estimating the rate at which heat is released by the fire (called the heat release rate HRR) and calculating the duration of the fire from Q_{tot} / HRR (Figure 4). The total heat energy that could be released (Q_{tot}) can be determined from knowledge of the mass of combustible materials potentially involved in a burning

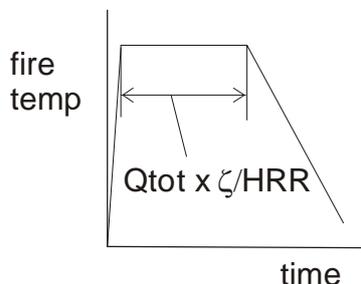


Figure 4 Simplified fire characteristics time

carriage and the heats of combustion for the various materials (heat released per unit mass of combustible). Also, the proportion of total fire load likely to be released during the peak burning period ζ can be estimated. The same is true for potential pool fires

involving flammable liquids such as diesel fuel. The heat release rate can be determined from empirical correlations such as those for pool fires (SFPE, 2002) or those associated with fires in enclosures (see Section 4.2). Clearly there is some uncertainty associated with the estimated fire characteristics and unless this uncertainty is modeled (which can be difficult) upper estimates of fire characteristics should be adopted for the various fire situations.

3.3 Member Temperatures

Once the gas temperature versus time relationships have been determined, it is then necessary to calculate the effect of these gas temperatures (via radiation and convective heating of the member surfaces) on the temperatures within the structural member. This is important since the strength of materials reduces with increased temperature. The calculation of temperatures within the member must take account of the thermal properties (specific heat capacity and thermal conductivity) and those of any insulation materials applied to the member surfaces. These calculations can be quite complex and will often require transient two-dimensional heat transfer analysis to be undertaken. Although the thermal properties are sufficiently well known for steel and concrete, they are often not explicitly known for some fire protective insulation materials that could be applied to the transfer members. Nevertheless, members protected with these insulation materials will have been tested under standard fire conditions (see Section 4.4) and the corresponding test data will give the recorded member temperatures for varying fire exposure periods. Using a trial and error process, the thermal properties could be derived from this data and then used to determine the temperatures of protected members when subject to the anticipated train fires.

3.4 Effect of Temperature on Member Strength

Once the temperatures within a transfer member are determined, the effects of temperature on the mechanical properties can be taken into account. Increased temperature will result in thermal expansion and reduction in strength and stiffness. Many studies have been undertaken on the effect of temperature on the mechanical properties of steel and concrete (CEN, 2003; Poh, 1996) Having established this, it is then necessary to determine the effect of the reduced strength and stiffness on the cross-sectional strengths of the member at critical cross-sections. It is generally assumed that the same models for cross-sectional capacity apply for elevated

temperature conditions as for normal temperature conditions, except for the reduction in strength and stiffness. This is found to be an acceptable assumption giving similar levels of uncertainty as for normal temperature calculations of capacity.

It is then necessary, using the equations of equilibrium, to determine the load capacity of the transfer members.

3.5 Measures to Limit Severity

Fire events will range from short duration fires that have little potential effect on the transfer structure (i.e. have a very low p_{ffi}) to less likely more severe fires that are much more likely to result in member failure (i.e. low p_i but higher p_{ffi}). The incorporation of a system, such as a drencher system, to directly impact the severity of potentially serious fires would greatly reduce the probability of failure p_{ffi} given a fire. If the system was sufficiently reliable and effective it could reduce p_{ff} to around p_{acc} . No further measures would be required. If the failure rate of the system is p_{fs} , then $(1 - p_{fs}) \times 100$ percent of the full range of potential fire events must be considered without the impact of the system.

3.6 Measures to Improve Thermal Resistance

Providing greater cover to reinforcement, or the application of a greater thickness of thermal insulation can increase the thermal resistance of a transfer member. If the failure probability of such systems is p_{fi} (e.g. due to unexpected and extensive spalling of concrete or insulation material) then $(1 - p_{fi}) \times 100$ percent of the full range of potential fire events must be considered with little or no benefit from these measures.

As noted above, the effect of a fire on a structural member is not instantaneous but takes time. Thus the longer a fire burns, the greater the probability of failure for a given level of thermal resistance. In the case of long duration fires, it may be appropriate to design the transfer structure to achieve p_{acc} up to a certain time of exposure where this time of exposure is dictated by the time for the achievement of effective fire brigade fire fighting on the basis that the sufficient equipment and access are available.

3.7 Simplified Approach – Failure Probability

The first order, second moment theory (FOSM) is used to determine the load and capacity reduction factors nominated in the loading and structural design standards for normal temperature design so as to ensure that there is a sufficiently high level of safety (and sufficiently low probability of failure).

It is found that the member resistance can be represented by a log normal distribution, whilst the gravity and live loads are normal and Gumbel (Type 1 Extreme Value) probability distributions, respectively. Given these distributions, approximate relationships giving member strength and loads as a function of a nominated probability of failure can be obtained (Melchers, 1987; Schleich et al, 1999)

The probabilistic representation of loads and resistances is illustrated in Figure 5 where schematic probability distributions for applied load and member strength (resistance) are shown. It should be observed that the strength is mostly greater than the applied loads. Failure occurs for situations where the two distributions intersect.

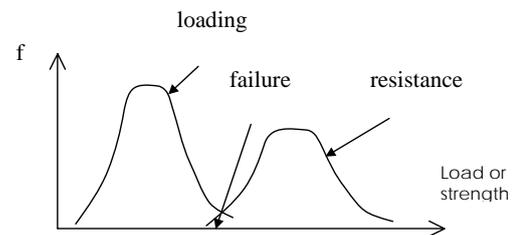


Figure 5 Probability of Member Failure

This area representing failure may be taken as being normally distributed (i.e. a ϕ function having a mean of 0 and a standard deviation of 1) such that:

$$p_f = \phi(\beta)$$

$$\beta = \phi^{-1}(p_f)$$

β is called the safety index and is 3.5 for a failure probability of 2.3×10^{-4} .

The probability distribution associated with gravity dead load is usually taken as a normal distribution. Using a FOSM approach, this can be represented by an expression of the form:

$$G_d = G_k (1 - \alpha_p \times \beta \times V_G) = g(\beta) \times G_k$$

where G_k is the characteristic load (in this case the mean load), α_p is the weighting factor for primary actions and V_G is the coefficient of variation (ratio

of standard deviation to mean load) and β is the safety index.

In the case of live load, this is distributed according to the Gumbel distribution and the design live load can be given by an expression of the following form (Schleich et al, 1999):

$$Q_d = m_Q \left\{ 1 - \frac{\sqrt{6}}{\pi} \times V_Q (0.577 + \ln[-\ln \phi(-\alpha_p \times \beta)]) \right\}$$

where m_Q is the mean live load, V_Q is the coefficient of variation of the live load and ϕ is the distribution function of the unit normal distribution. The characteristic live load Q_k (95 percentile) (3kPa for offices) is given by:

$$Q_k = m_Q \left\{ 1 - \frac{\sqrt{6}}{\pi} \times V_Q (0.577 + \ln[-\ln(0.95)]) \right\}$$

$$Q_d = q(\beta) \times Q_k$$

where

$$q(\beta) = \frac{\left(1 - \frac{\sqrt{6}}{\pi} \times V_Q (0.577 + \ln[-\ln \phi(-\alpha_p \times \beta)]) \right)}{\left(1 - \frac{\sqrt{6}}{\pi} \times V_Q (0.577 + \ln[-\ln(0.95)]) \right)}$$

The resistance of a structural member is often taken as having a lognormal distribution and the expression for design strength $\phi(\beta) \times R_k$ has the following form:

$$\frac{e^{-\alpha_R \times \beta \times V_R}}{e^{-1.645 \times V_f}} \times R_k$$

where V_R is the resultant coefficient of variation for design and V_f is the coefficient of variation associated with the dominant material strength and α_R is the adopted weighting factor for the resistance.

The load factors for normal temperature design can be derived from the above expressions. Once the coefficients of variation of the loads and resistance are known and weighting factors chosen, expressions for design dead load G_d , live load Q_d and resistance can be derived as functions of the safety index β and the characteristic values of dead load, live load and resistance. If the resistance is chosen such that:

$$\phi(\beta) \times R_k = g(\beta)G_k + q(\beta)Q_k$$

and a probability that the loads exceed the resistance over the life of the building of 2.3×10^{-4} (this corresponds to a β value of 3.5), it will be necessary for $g(\beta)$ to be about 1.20, $q(\beta)$ to be about 1.5 and $\phi(\beta)$ to be 0.8 for reinforced concrete flexural members. That is:

$$0.8R_k = 1.2G_k + 1.5Q_k \quad [2]$$

Under fire conditions, the resistance will reduce and the probability that the loads will exceed the resistance increases – assuming that the reduced resistance is present over the life of the building. The β value at which the following equation is satisfied corresponds to the probability of failure.

$$\phi(\beta) \times R_k(T) = g(\beta)G_k + q(\beta)Q_k \quad [3]$$

where $R_k(T)$ is the characteristic resistance under fire conditions. Dividing equation [3] by [2] gives an expression:

$$\frac{\phi(\beta)}{0.80} \times \frac{R_k(T)}{R_k} = \frac{G_k g(\beta) + Q_k q(\beta)}{1.20G_k + 1.5Q_k}$$

Rearranging to give an expression for the proportional reduction in characteristic strength gives:

$$\frac{R_k(T)}{R_k} = \frac{0.80}{\phi(\beta)} \times \frac{G_k g(\beta) + Q_k q(\beta)}{1.20G_k + 1.5Q_k} \quad [4]$$

For the particular reduction in resistance due to fire, it is possible to determine, by trial and error, the corresponding value of β at which the right side just equals the left side of Eq [4]. This corresponds to the probability of failure. As the characteristic resistance in fire is reduced, the value of β is reduced and the probability of failure increased. For example, if the ratio of characteristic live load to dead load (Q_k / G_k) for the transfer member is taken as 0.35, and if $R_k(T) / R_k$ is reduced to 0.83, then the probability of failure is about 0.006 over the life of the building – based on representative weighting factors and coefficients of variation. If $R_k(T) / R_k$ is 0.58, then the corresponding probability of failure over the life of the building of 0.50 (β value of 0). The corresponding load combination is $G_k + 0.7Q_k$ and is slightly greater than the “arbitrary point in time load” ($G_k + 0.4Q_k$) - a value that recognises that extreme incidents such as fire are transient events

and nominated in standards such as AS1170.0 for the loads to be adopted for the fire limit state. As will be noted in Section 4.4, this is only a reasonable load to adopt if the fire event is sufficiently improbable over the life of the building.

3.8 Implications for Design

It follows from Equation 1, that for situations where a fire event results in substantial reduction of resistance (e.g. $R_k(T)/R_k$ of 0.58), an acceptably low probability of failure in fire can only be achieved if the probability of occurrence over the life of the building of the particular fire event is very small (e.g. less than 2×10^{-4}). If, from statistical analysis of train incidents, it appears certain that a particular fire event will occur over the life of the building (i.e. $p_i = 1.0$), then it will be necessary to prevent any reduction in resistance for this fire event. This can be done by providing sufficient thermal insulation or by giving the member excess capacity.

The use of Equation [4] to estimate a probability of failure given a particular fire effect (i.e. $R_k(T)/R_k$) will lead to a higher than actual probability of failure for members subject to fire due to the fact no account is taken of the transient nature of the fire event. Nevertheless, this approach combined with Equation [1] provides a simplified approach for assessing the effect of a range of fire situations on the transfer structure.

As noted previously, since the reduction in resistance is a function of time and finite levels of protection are applied to a member, member failure will occur if the fire continues for an unlimited period of time. Is it reasonable to set an upper limit of time beyond which the effects of fire exposure are not considered? This answer to this question depends on what are the design objectives (e.g. life safety, property protection) and the response to the following additional questions:

What is the evacuation time for the supported building? From a life safety point of view there should be an acceptably low probability of structural failure at this time, taking into account all of the possible fire events.

What durations of (severe) fire are possible if there is no fire suppression or fire fighting intervention? If all fires are of short duration and have little effect then there is no concern. If however, fires may burn for a long time then this may need to be considered from the point of view of property and

asset protection, particularly in relation to future viability of the building and interference with railway operations.

Is it possible to have an effective fire-fighting intervention strategy, and if so, what is likely to be the maximum duration of heating before it can be assumed that the fire severity will be significantly reduced via fire fighting operations?

4 FIRE WITHIN BUILDINGS

4.1 Fire Safety Considerations

The implications of fire within the occupied parts of the office building (Figure 1) (Situation 2) are now considered. Fire statistics for office buildings show that about one fatality is expected in an office building for every 1000 fires reported to the fire brigade. This is an order of magnitude less than the fatality rate associated with apartment buildings. More than two thirds of fires occur during occupied hours and this is due to the greater human activity and the greater use of services within the building. It is twice as likely that a fire that commences out of normal working hours will extend beyond the enclosure of fire origin.

A relatively small fire can generate large quantities of smoke within the floor of fire origin. If the floor is of open-plan construction with few partitions, the presence of a fire during normal occupied hours is almost certain to be detected through the observation of smoke on the floor. The presence of full height partitions across the floor will slow the spread of smoke and possibly also the speed at which the occupants detect the fire. Any measures aimed at improving housekeeping, fire awareness and fire response will be beneficial in reducing the likelihood of major fires during occupied hours.

For multi-storey buildings, smoke detection systems and alarms are often provided to give “automatic” detection and warning to the occupants. An alarm signal is also transmitted to the fire brigade.

Should the fire not be able to be controlled by the occupants on the fire floor, they will need to leave the floor of fire origin via the stairs. Stair enclosures may be designed to be fire-resistant but this may not be sufficient to keep the smoke out of the stairs. Many buildings incorporate stair pressurisation systems whereby positive airflow is introduced into the stairs upon detection of smoke within the building. However, this increases the forces required to open the stair doors and makes it increasingly difficult to access the stairs. It is quite

likely that excessive door opening forces will exist (Fazio et al, 2006)

From a fire perspective, it is common to consider that a building consists of enclosures formed by the presence of walls and floors. An enclosure that has sufficiently fire-resistant boundaries (i.e. walls and floors) is considered to constitute a fire compartment and to be capable of limiting the spread of fire to an adjacent compartment. However, the ability of such boundaries to restrict the spread of fire can be severely limited by the need to provide natural lighting (windows) and access openings between the adjacent compartments (doors and stairs). Fire spread via the external openings (windows) is a distinct possibility given a fully developed fire. Limiting the window sizes and geometry can reduce but not eliminate the possibility of vertical fire spread.

By far the most effective measure in limiting fire spread, other than the presence of occupants, is an effective sprinkler system that delivers water to a growing fire rapidly reducing the heat being generated and virtually extinguishing it.

4.2 Estimating Fire Severity

In the absence of measures to extinguish developing fires, or should such systems fail; severe fires can develop within buildings.

In fire engineering literature, the term “fire load” refers to the quantity of combustibles within an enclosure and not the loads (forces) applied to the structure during a fire. Similarly, fire load density refers to the quantity of fuel per unit area. It is normally expressed in terms of MJ/m² or kg/m² of wood equivalent. Surveys of combustibles for various occupancies (i.e offices, retail, hospitals, warehouses, etc) have been undertaken and a good summary of the available data is given in FCRC (1999). As would be expected, the fire load density is highly variable. Publications such as the International Fire Engineering Guidelines (2005) give fire load data in terms of the mean and 80th percentile. The latter level of fire load density is sometimes taken as the characteristic fire load density and is sometimes taken as being distributed according to a Gumbel distribution (Schleich et al, 1999).

The rate at which heat is released within an enclosure is termed the heat release rate (HRR) and normally expressed in megawatts (MW). The application of sufficient heat to a combustible material results in the generation of gases some of which are combustible. This process is called pyrolysis.

Upon coming into contact with sufficient oxygen these gases ignite generating heat. The rate of burning (and therefore of heat generation) is therefore dependent on the flow of air to the gases generated by the pyrolysing fuel. This flow is influenced by the shape of the enclosure (aspect ratio), and the position and size of any potential openings. It is found from experiments with single openings in approximately cubic enclosures that the rate of burning is directly proportional to $A\sqrt{h}$ where A is the area of the opening and h is the opening height. It is known that for deep enclosures with single openings that burning will occur initially closest to the opening moving back into the enclosure once the fuel closest to the opening is consumed (Thomas et al, 2005). Significant temperature variations throughout such enclosures can be expected.

The use of the word ‘opening’ in relation to real building enclosures refers to any openings present around the walls including doors that are left open and any windows containing non fire-resistant glass. It is presumed that such glass breaks in the event of development of a significant fire. If the windows could be prevented from breaking and other sources of air to the enclosure limited, then the fire would be prevented from becoming a severe fire.

Various methods have been developed for determining the potential severity of a fire within an enclosure. These are described in SFPE (2004). The predictions of these methods are variable and are mostly based on estimating a representative heat release rate (HRR) and the proportion of total fuel ζ likely to be consumed during the primary burning stage (Figure 4). Further studies of enclosure fires are required to assist with the development of improved models, as the behaviour is very complex.

4.3 Role of the Building Structure

If the design objectives are to provide an adequate level of safety for the occupants and protection of adjacent properties from damage, then the structural adequacy of the building in fire need only be sufficient to allow the occupants to exit the building and for the building to ultimately deform in a way that does not lead to damage or fire spread to a building located on an adjacent site. These objectives are those associated with most building regulations including the Building Code of Australia (BCA). There could be other objectives including protection of the building against significant damage. In considering these various objectives, the following

should be taken into account when considering the fire resistance of the building structure.

4.3.1 *Non-Structural Consequences*

Since fire can produce smoke and flame, it is important to ask whether these outcomes will threaten life safety within other parts of the building before the building is compromised by a loss of structural adequacy? Is search and rescue by the fire brigade not feasible given the likely extent of smoke? Will the loss of use of the building due to a severe fire result in major property and income loss? If the answer to these questions is in the affirmative, then it may be necessary to minimise the occurrence of a significant fire rather than simply assuming that the building structure needs to be designed for high levels of fire resistance. A low-rise shopping centre with levels interconnected by large voids is an example of such a situation.

4.3.2 *Other Fire Safety Systems*

The presence of other systems (e.g. sprinklers) within the building to minimise the occurrence of a serious fire can greatly reduce the need for the structural elements to have high levels of fire resistance. In this regard, the uncertainties of *all* fire-safety systems need to be considered. Irrespective of whether the fire safety system is the sprinkler system, stair pressurisation, compartmentation or the system giving the structure a fire-resistance level (e.g. concrete cover), there is an uncertainty of performance. Uncertainty data is available for sprinkler systems (because it is relatively easy to collect) but is not readily available for the other fire safety systems. This sometimes results in the designers and building regulators considering that only sprinkler systems are subject to uncertainty. In reality, it would appear that sprinkler systems have a high level of performance and can be designed to have very high levels of reliability.

4.3.3 *Height of Building*

It takes longer for a tall building to be evacuated than a short building and therefore the structure of a tall building may need to have a higher level of fire resistance. The implications of collapse of tall buildings on adjacent properties are also greater than for buildings of only several storeys.

4.3.4 *Limited Extent of Burning*

If the likely extent of burning is small in comparison with the plan area of the building, then the fire cannot have a significant impact on the overall stability of the building structure. Examples of situations where this is the case are open-deck carparks

and very large area building such as shopping complexes where the fire-affected part is likely to be small in relation to area of the building floor plan.

4.3.5 *Behaviour of Floor Elements*

The effect of real fires on composite and concrete floors continues to be a subject of much research. Experimental testing at Cardington demonstrated that when parts of a composite floor are subject to heating, large displacement behaviour can develop that greatly assists the load carrying capacity of the floor beyond that which would be predicted by considering only the behaviour of the beams and slabs in isolation. These situations have been analysed by both yield line methods that take into account the effects of membrane forces (Bailey, 2004) and finite element techniques. In essence, the methods illustrate that it is not necessary to insulate all structural steel elements in a composite floor to achieve high levels of fire resistance. This work also demonstrated that exposure of a composite floor having unprotected steel beams, to a localised fire, will not result in failure of the floor. A similar real fire test on a multistorey reinforced concrete building demonstrated that the real structural behaviour in fire was significantly different to that expected using small displacement theory as for normal temperature design (Bailey, 2002) with the performance being superior than that predicted by considering isolated member behaviour.

4.4 *Prescriptive Approach to Design*

The building regulations of most countries provide prescriptive requirements for the design of buildings for fire. These requirements are generally not subject to interpretation and compliance with them makes for simpler design approval – although not necessarily the most cost-effective designs. These provisions are often termed deemed-to-satisfy (DTS) provisions. All aspects of designing buildings for fire safety are covered – the provision of emergency exits, spacings between buildings, occupant fire fighting measures, detection and alarms, measures for automatic fire suppression, air and smoke handling requirements and last, but not least, requirements for compartmentation and fire resistance levels for structural members. However, there is little evidence that the requirements have been developed from a systematic evaluation of fire safety. Rather it would appear that many of the requirements have been added one to another to deal with another fire incident or to incorporate a new form of technology. There does not appear to have been any real attempt to determine which provisions

have the most significant influence on fire safety and whether some of the former provisions could be modified.

Building codes such as the BCA not only specify the fire-resistance levels (FRL) required for structural elements within various classes of buildings but also how these requirements are to be assessed. Thus for an office building of greater than two levels, most loadbearing members will be required to have an FRL of 120 minutes assuming exposure to the standard fire test (SA, 2005). The standard time temperature curve bears little relationship to the fire temperature versus time relationships associated with real fires. The DTS provisions also specify the means by which the fire resistance is to be assessed. This can be via a fire test but is mostly done by assessing the resistance using Australian Standards such as the AS3600 (SA, 2001) for concrete structures, AS4100 (SA, 1998) for steel structures and AS3700 (SA, 2001) for masonry structures. Loading standards such as AS1170.0, referenced by the building codes, specify the level of load to be applied to a member in the event of fire. This is assumed to be the arbitrary point in time load (see Section), which is the load likely to be present in the event of fire. The floor load for office buildings is taken as the following combination of the characteristic loads $G_k + 0.4Q_k$. In the Australian codes the capacity reduction factor is taken as the same as for normal temperature design. It probably should be taken as 1.0. The above load combination approximately corresponds to the estimated “working load” that would be applied to an element of construction if it were tested under standard fire test conditions.

The FRL requirements specified in the DTS provisions are traditionally considered to result in member resistances that will only rarely experience failure in the event of a fire. This is why it is acceptable to use the above arbitrary point in time load combination for assessing members in fire. There have been attempts to evaluate the various deemed-to-satisfy provisions (particularly the fire-resistance requirements) from a fire-engineering perspective taking into account the possible variations in enclosure geometry, opening sizes and fire load (see FCRC, 1999). One of the outcomes of this evaluation was the recognition that deemed-to-satisfy provisions necessarily cover the broad range of buildings and thus must, on average, be quite onerous because of the magnitude of the above variations.

It should be noted that the DTS provisions assume that compartmentation works and that fire is limited to a single compartment. This means that fire is normally only considered to exist at one level. Thus floors are assumed to be heated from below and columns only over one storey height.

4.5 Performance-Based Design

An approach that offers substantial benefits for individual buildings is the move towards *performance-based* regulations. This is permitted by regulations such as the BCA which state that a designer must demonstrate that the *particular* building will achieve the relevant performance requirements. The prescriptive provisions (i.e. the DTS provisions) are presumed to achieve these requirements. It is necessary to show that any building that does not conform to the DTS provisions will achieve the performance requirements.

But what are the performance requirements? Most often the specified performance is simply a set of performance statements (such as with the Building Code of Australia) with no *quantitative* level given. Therefore, although these statements remind the designer of the key elements of design, they do not, in themselves, provide any measure against which to determine whether the design is adequately safe. Possible acceptance criteria are now considered.

4.5.1 Acceptance Criteria

Some guidance as to the basis for acceptable designs is given in regulations such as the BCA. These and other possible bases are now considered in principle.

- (i) compare the levels of safety (with respect to achieving each of the design objectives) of the proposed alternative solution with those associated with a corresponding DTS solution for the building.

This comparison may be done on either a qualitative or quantitative risk basis or perhaps a combination. In this case, the basis for comparison is an acceptable DTS solution. Such an approach requires a “holistic” approach to safety whereby all aspects relevant to safety, including the structure, are considered. This is, by far, the most common basis for acceptance.

- (ii) undertake a probabilistic risk assessment and show that the risk associated with the proposed design is less than that associated with

common societal activities such as using public transport.

Undertaking a full probabilistic risk assessment can be very difficult for all but the simplest situations. Assuming that such an assessment is undertaken it will be necessary for the stakeholders to accept the nominated level of acceptable risk. Again, this requires a “holistic” approach to fire safety.

- (iii) a design is presented where it is demonstrated that all reasonable measures have been adopted to manage the risks and that any possible measures that have not been adopted will have negligible effect on the risk of not achieving the design objectives.
- (iv) as far as the building structure is concerned, benchmark the acceptable probability of failure in fire against that for normal temperature design. This is similar to the approach used when considering Building Situation 1 but only considers the building structure and not the effects of flame or smoke spread. It is not a holistic approach to fire safety.

Performance-based design of a building strictly requires a holistic approach to be taken where all factors affecting fire safety are considered – not just the performance of the structure since this might be secondary to the safety of the occupants and the achievement of the design objectives (Acceptance Criteria (i)-(iii)). The authors are not aware of any well-documented methodology to demonstrate that a particular design will meet acceptance criteria (i), (ii) or (iii). Methods adopted tend to be developed for particular building situations and simplified sufficiently (sometimes grossly oversimplified) to enable evaluation of the design in a reasonable time frame and to achieve acceptance from the stakeholders (building certifier, peer reviewer, fire brigade, etc). A comprehensive risk model (Thomas et al. 2002) has been developed for apartment buildings and can be used to evaluate designs in accordance with Acceptance Criteria (i) – (iii). A similar model is being developed for commercial buildings at the Centre for Environmental Safety and Risk Engineering at Victoria University, Australia.

Acceptance Criteria (iv) can be used where the structural performance is considered in isolation. In this case, it is common to adopt the arbitrary point-in-time load for a member and to ensure that the probability of failure of a member is not greater than that for normal temperature conditions. The “fire load density “ is taken as the “primary action”,

it being assumed that this is the dominant variable in determining the fire severity for a particular enclosure. Considering a fully developed fire within an enclosure and that this fire can be properly characterised, a design fire load density could be specified to correspond to a particular probability of exceedence:

$$\rho_d = fd(\beta) \times \rho_k \quad [5]$$

where ρ_k is the characteristic fire load density (taken to be the 80 percentile), and

$$fd(\beta) = \frac{\left\{ 1 - \frac{\sqrt{6}}{\pi} \times V_{fd} (0.577 + \ln[-\ln \phi(-\alpha_p \times \beta)]) \right\}}{\left\{ 1 - \frac{\sqrt{6}}{\pi} \times V_{fd} (0.577 + \ln[-\ln(0.80)]) \right\}} \quad [6]$$

where V_{fd} is the coefficient of variation for the fire load density being considered and α_p is the weighting factor for primary actions (typically -0.7--0.9). If the acceptable probability of failure is p_{acc} , and since only significant fires will result in potential failure of a member, it is first necessary to determine the probability of having such a fire over the life of the building (p_{sf}) where this probability is given by:

$$p_{sf} = p_1 \times p_2 \times \dots \times p_j$$

where p_1 is the probability of having a fire start over the life of the building within the enclosure being considered and $p_2 \dots p_j$ are the probabilities that various measures employed to limit the fire do not operate. Such measures include occupant intervention, sprinklers or other suppression measures, and possibly extinguishment by the fire brigade.

$$\text{Let } p_{ffd} = \frac{p_{acc}}{p_{sf}}$$

If $p_{ffd} \geq 1$, it is not necessary for the member to have a fire resistance level. On the other hand, if $p_{ffd} < 1$, the corresponding value of β should be determined assuming a unit normal distribution (i.e. $\beta = \phi^{-1}(p_{ffd})$). This value should then be substituted into Equations [5] and [6] to give the required fire load density that can be used for assessing the total fire load within the enclosure. The structural members within the enclosure will need to survive a

fully developed fire arising from the presence of this fire load density.

(b) Other Issues

The design of reliable measures to greatly reduce the likelihood of a significant fire is of importance with respect to minimising the need for fire protective coatings for structural members. Further development of such measures (which are not associated with the building structure) is important and should be an ongoing development task.

In undertaking an assessment of a building structure under real fire conditions, it is important to consider the possibility of vertical fire spread and the implications for structural stability. Once again, it is possible to greatly limit the probability of this occurring by adopting particular design features for the sprinkler system.

Finally, the questions of arson and terrorism must be considered. Deliberate acts of fire initiation range from relatively minor incidents to acts of mass destruction. Acts of arson are well within the accepted range of fire events experienced by buildings (e.g. 8% of fire starts in offices are deemed "suspicious"). The simplest act is to use a small heat source to start a fire. The resulting fire will develop slowly in one location within the building and will most probably be controlled by the various fire-safety systems within the building. The outcome is likely to be the same even if an accelerant is used to assist fire spread. An important illustration of this occurred during the race riots in Los Angeles in 1992 (Hart 1992) when fires were started in many buildings often at multiple locations. In the case of buildings with sprinkler systems, the damage was limited and the fires significantly controlled. Although the intent was to destroy the buildings, the fire-safety systems were able to limit the resulting fires. Security measures are provided with systems such as sprinkler systems and include:

- locking of valves
- anti-tamper monitoring
- location of valves in secure locations

Furthermore, access to significant buildings is often restricted by security measures. The very fact that the above steps have been taken demonstrates that acts of destruction within buildings are considered—although most acts of arson do not involve any attempt to disable the fire-safety systems.

At the one end of the spectrum is "simple" arson and at the other end, *extremely rare* acts where at-

tempts are made to destroy the fire-safety systems along with substantial parts of the building. This can be only achieved through massive impact or the use of explosives. The latter may be achieved through explosives being introduced into the building or from outside by missile attack. The former could result from missile attack or from the collision of a large aircraft. The greater the destructiveness of the act, the greater the means and knowledge required. Conversely, the more extreme the act, the less confidence there can be in designing against such an act. This is because the more extreme the event, the harder it is to predict precisely and the less understood will be its effects. The important point to recognise is that if sufficient means can be assembled, then it will *always* be possible to overcome a particular building design. Thus these acts are completely different to the other loadings to which a building is subjected such as wind, earthquake and gravity loading. This is because such acts of destruction are the work of intelligent beings and take into account the characteristics of the target. Should high-rise buildings be designed for given terrorist activities, then terrorists will simply use greater means to achieve the end result. For example, if buildings were designed to resist the impact effects from a certain size aircraft, then the use of a larger aircraft or more than one aircraft could still achieve destruction of the building. An appropriate strategy is therefore to minimise the likelihood of means of mass destruction getting into the hands of persons intent on such acts. This is not an engineering solution associated with the building structure. It should not be assumed that structural solutions are always the most appropriate, or indeed, possible. In the same way, aircrafts are not designed to survive a major fire or a crash landing but steps are taken to minimise the likelihood of either occurrence.

The mobilization of large quantities of fire load (the normal combustibles on the floors) simultaneously on numerous levels throughout a building is well outside fire situations envisaged by current fire test standards and prescriptive regulations. Risk management measures to avoid such a possibility must be considered.

5 CONCLUSIONS

Fire differs significantly from other "loads" such as wind, live load and earthquakes in respect of its origin and its effects. Due to the fact that fire originates from human activities or equipment installed

within buildings, it is possible to directly influence the potential effects on the building by reducing the rate of fire starts and providing measures to directly limit fire severity.

The design of buildings for fire safety is mostly achieved by following the prescriptive requirements of building codes such as the BCA. For situations that fall outside of the scope of such regulations, or where proposed designs are not in accordance with the prescriptive requirements, it is possible to undertake performance-based fire engineering designs. However, there are no design codes or standards or detailed methodologies available for undertaking such designs. Building regulations require that such alternative designs satisfy performance requirements and give some guidance as to the basis for acceptance of these designs (i.e. acceptance criteria). This paper presents a number of possible acceptance criteria, all of which use the measure of risk level as the basis for comparison. Strictly, when considering the risks associated with fire a holistic approach that considers all of the aspects relevant to achieving the design objectives and the interrelationships between these aspects, should be adopted. In some situations, the performance of the building structure may well be secondary as far as life safety is concerned. In other situations, the performance of the structure may be of fundamental importance with respect to the design objectives.

For situations where the performance of the structure is critical or where it is considered in isolation to other fire safety aspects (i.e. direct effects of heat and smoke), it is possible to assess the required fire resistance by using FOSM or similar theory as used for normal temperature design. Such an approach is described in this paper.

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