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DESIGN OF STRUCTURES FOR FIRE IN THE AUSTRALIAN REGULATORY ENVIRONMENT AND THE IMPACT OF THE WTC COLLAPSE

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Abstract

This paper summarises the regulations and design methods applicable to the fire design of high-rise structures in Australia and discusses the effect of the WTC collapse on the building design and development community in Australia. In order to gauge the response of the general community to the disaster, data is presented on recent changes in share prices and rentals for high-rise offices in Australia. Recent increases in insurance premiums and reductions in the risks covered are discussed in terms of both global and local issues. The response of the Arup organisation is summarised, including the activities of a worldwide taskforce recently formed to provide technical advice on the response of tall buildings to fire and other threats.

The Australian performance-based regulatory system for structural fire design of tall buildings is summarised, including the general approach of the Building Code of Australia and the design methods included in the relevant Australian Standards. The emphasis on individual member design rather than whole building performance is described. Current developments in the design guidance are summarised.

Structural tools used in Australia for performance-based assessments are described. These tools allow a holistic approach to be taken to the design of structures for fire performance, with greater flexibility in accounting for the particular fire safety features of the project. Under a performance-based approach, the objectives of the design are clearly identified, in consultation with the stakeholders in the design. Following the WTC collapse, these objectives may on some buildings include consideration of a wider range of hazards and failure mechanisms than those traditionally included.

Keywords: Structures in fire, Fire design, Tall buildings, Performance-based, Risk-based, Robustness

1. Introduction

This paper summarises the regulations and design methods applicable to the fire design of high-rise structures in Australia and discusses the effect of the WTC collapse on the building design and development community in Australia.

2. Response to WTC Collapse in Australia

In order to gauge the response of the general community to the disaster with respect to building design, its effect on the demand for high-rise buildings has been investigated. The share prices of Australian property trusts have been used as an approximate indication of the demand for the properties held within their portfolios. It is recognised that there are many other forces at work affecting the price of any individual stock, but by looking at several stocks and comparing against the sector indices a general overview may be obtained. Figure 1 shows the share price of three Australian property trusts with assets which are predominantly high-rise CBD offices and one with assets which are predominantly high-rise hotels. Also plotted are the Australian Properties Index and the Australian Top 200 Index. It may be seen for the office trusts that there was little change in their share prices immediately after September 11, 2001, and that their price variation since that time has not been substantially different to that of the Property Trust Index or the Top 200 Index. In contrast, the price of the hotel trust (GHG) dropped substantially after September 11 and have not recovered since, a trend also observed in the business conditions for airlines around the world, and one would assume that this largely reflects the impact of the event on confidence in the tourist market.
Notes: CPA has 12 CBD office buildings located in Sydney (6), Melbourne (1), Adelaide (1), Perth (3) and Canberra (1) with a total valuation of $890m. Four of these buildings are over 20 stories in height, the tallest being 42 stories, representing 62% of the portfolio valuation. POF has 12 properties valued at $1800m, located in Sydney (9), Melbourne (2) and Perth (1). Five of these buildings are over 20 stories, the tallest being 50 stories, representing 68% of the portfolio. DOT has 16 properties valued at $2260m, with 13 in Sydney and one each in Melbourne, Perth and Canberra. The six largest buildings represent 71% of the portfolio and range in height between 22 and 42 stories. All prices are relative to that on Sept 10, 2001.

Fig. 1 Australian Property Trust Share Prices
Rental data also supports the view that the demand for high-rise buildings continues unabated. The Property Council of Australia (PCA) continues to define the highest level of office space, "premium", as "landmark office buildings located in major CBD office markets", with floor plate areas of at least 1000 m² and total areas of 30,000 m² in Sydney and Melbourne and 20,000 m² in other capital cities. These areas imply that these buildings are at least 20 to 30 stories in height. Median gross annual rental income for the year ended June 2001 and for the 6 months ended Dec 2001 reported by the PCA indicate that the relative values of Premium/A-Grade and the other grades have remained essentially unchanged before and after the September 11 event. Anecdotal evidence, including discussions with Jones Lang LaSalle, one of Melbourne's largest commercial property estate agents, confirms these conclusions. Property rental rates for high-rise have not been particularly volatile, and high-rise office space continues to command the highest prices.

Further evidence of the continued optimism in the high-rise sector is the continued construction of new high-rise buildings since September 11. A report just released by BIS Shrapnel, "Building Industry Prospects", predicts a 40% national increase in the annual rate of non-residential construction by 2006/07, with much of this increase being CBD office buildings. Melbourne has been experiencing boom conditions in high-rise construction over the last 3 years, and this has continued unabated since September 2001, with many new buildings currently being commenced or under construction, including the QV Centre (four 30-storey towers above a 12-level podium), numerous 20-level apartment towers at Docklands to the immediate west of the city centre, the new 18-level RACV tower, the new 18-level tower at 11 Exhibition Street and the refurbishment of the 20-storey Southern Cross building. Similar conditions have been experienced in Brisbane, Sydney and Perth over the same time period.

On the other hand, the detrimental effect on the insurance industry in Australia has been dramatic, in line with world-wide trends. Premium increases upon renewal of policies at the end of 2001 have been reported to range between 30% and 300% [Condon, 2002]. A recent survey by J P Morgan quotes a 51% increase in PJ/PL insurance premiums in 2002 and predicts a further 25% in 2003. Furthermore, the extent of cover has been reduced, with terrorism exclusions now becoming standard. These changes have been partly due to the WTC collapse but also due to insurance company collapses in Australia as a result of poor business practices. Other factors affecting premiums have been increasing insurance payouts and poor returns on funds invested by insurance companies. The Property Council of Australia [Larsen, 2001] is lobbying the government to form a funding pool to cover terrorism insurance, with the government picking up any shortfall in the event that the pool is exhausted. The emphasis is thus on spreading the financial risk of terrorism rather than penalizing high-rise buildings.

In addition, it appears that a greater emphasis on security of access to buildings has become evident since September 11, and this has undoubtedly been further heightened since the Bali bombing on October 12, 2002. A quote from the General Manager of SNP Security in December 2001 [Larsen, 2001] states that his company experienced an increase of between 10% and 20% in the demand for security in CBD areas immediately following September 11. Thus, rather than design a building to withstand a major offensive attack, the use of electronic surveillance equipment and security guards may be the more common defensive approach. Other defensive measures include the physical separation of "front office" and "back office" functions, including off-site location of computer record systems.

3. Arup Initiatives

The response of Arup, which is a multidisciplinary engineering company with over 6000 employees in over 50 countries around the world, to the WTC collapse has been to form a world-wide taskforce known as the Extreme Events Mitigation Task Force (EEMTF), drawing together specialists from all disciplines and localities within the organisation with expertise to address the building design issues arising from the WTC disaster. This expertise can then be applied on projects and used to assist clients in dealing with these issues.

Various major pieces of analytical work have now been conducted under the auspices of the EEMTF, including several demonstration finite element analysis models of airplane impact upon structure subframes and a review of a number of high-rise Australian buildings. A major analytical study has also been completed on the effect of fire on the WTC buildings for use in the court case which addressed whether the two airplane impacts should be treated for insurance purposes as one loss or two losses. The outcomes of this work are progressively being reported separately and used on major projects.
4. Overview Of Australian Performance-Based Regulations

4.1 Building Code of Australia

The Building Code of Australia (BCA) contains both Performance Requirements and Deemed-to-Satisfy (DTS) provisions. Only the Performance Requirements are required to be satisfied. The Deemed-to-Satisfy (DTS) provisions are given as acceptable means of satisfying the Performance Requirements, but they are not the only means. The aspects of fire design addressed by the Performance Requirements are: fire resistance of structural elements; the design of egress routes; and the provision of equipment for fire suppression, fire fighting, smoke management and occupant warning. The most commonly-used and general Performance Requirements affecting the fire resistance of structural elements are: CP1 (to ensure the structural stability of critical elements); and CP2 (to provide elements which will prevent the spread of fire within and between buildings).

The Performance Requirements are generally worded in terms of achieving the performance required "to the degree necessary", taking account of the particular hazard conditions of the building. The "degree necessary" is not defined, but acceptable methods of assessment include comparison against DTS and use of verification methods defined by the fire engineer in conjunction with the relevant authority. Further guidance is given in the form of BCA objectives. These objectives clarify the purpose of the Performance Requirements, and they include life safety, fire brigade safety and protection of adjacent occupancies. The objectives do not include property protection of the building being designed or consideration of the effects of business interruption, as these considerations are left to the judgement of the building owner.

4.2 Deemed-to-Satisfy Provisions for Fire Resistance

The DTS provisions define the fire resistance of the structure in terms of the Fire-Resistance Level (FRL) required for each building element. The FRL is the time to failure of the member when exposed to the furnace conditions as defined for the standard fire-resistance test. It has three components, being structural adequacy, integrity and insulation. The DTS provisions define also the means of demonstrating that a particular element design achieves the required FRL, generally by reference to an Australian Standard.

Typical FRLs are: apartments, hostels, hotels - 90 minutes; offices, public assembly buildings (theatres, schools, hospitals) – 120 minutes; shops – 180 minutes; industrial buildings – 240 minutes. In conjunction with the specification of different FRLs for different elements, there is a requirement that elements supporting other elements in the same fire compartment require at least the same FRL as the element they support.

The DTS provisions require sprinkler protection for all buildings with a height above ground exceeding 25 m. In addition, sprinklers are required for a number of specific cases, including: shops greater than 3500 m²; carparks with more than 40 cars; warehouses with storage over 4m high; isolated industrial buildings with very large area or volume; and residential aged care buildings (Victoria only). The DTS provisions do not give general reductions in FRL requirements for the provision of sprinklers, but concessions are given for specific cases such as: roofs and their supports; carparks; residential low-rise buildings (Victoria only); large isolated warehouses; and wall spandrels separating levels.

4.3 Australian Standards

The rules for fire design in the Australian Standards for structural design are generally oriented towards individual element performance and towards exposure to the standard fire-resistance test. In some cases, a brief comment is made in the Standard that recognised methods of more rigorous design may be used.

4.3.1 Loading
The Loading Code, AS1170, gives load combinations for fire. The multiplying factors of 1.1 for dead loads and 0.4 for live loads are lower than those used for normal-temperature design, being 1.25 for dead loads and 1.5 for live loads. This difference recognises that fire is an extreme event and therefore that it should be combined with reduced percentile values of the applied loads. For a typical case where the live load is approximately equal to the dead load, the design load in fire is thus 55% of the normal-temperature design load.
The Loading Code has recently been amended to include robustness requirements, which include issues for consideration such as alternate load paths, ductility and tie forces. These rules are currently written in a mainly qualitative manner (with some quantitative guidance on tie forces) and are not as comprehensive as those in the British Concrete Standard, BS8110.

4.3.3 Steel. The Steel Structures Code, AS4100, contains simplified calculation methods for individual elements. Structural response is treated separately to thermal response. The structural response is defined as the relationship between the applied load ratio and the limiting (maximum permissible) steel temperature. The applied load ratio is the ratio of the applied load under the fire load combination to the normal-temperature load capacity. For a steel beam at uniform temperature (four-sided exposure), the relationship between steel temperature and load ratio is the same as the material relationship between steel temperature and tensile yield stress obtained from testing of small-scale samples. As noted above, the load ratio is typically around 0.5 and the corresponding limiting steel temperature is typically around 550°C.

For a beam with a temperature gradient over its depth, such as one with a concrete slab on its top face (three-sided exposure), the steel temperature to be used is the average temperature measured by thermocouples located in accordance with the Australian fire testing standard, AS1530.4, i.e. two thermocouples on the bottom flange, one on the web and one on the top flange. Elevated-temperature ultimate strength analysis [Proe et al, 1986] has shown that this temperature, when used as an effective uniform temperature, gives a good measure of the load capacity of the member for a wide range of temperature gradients. The thermal response data used by the suppliers of fire protection material is generally based on this weighted average temperature. For columns with temperature gradients, the effective uniform temperature to be used is the maximum temperature over the cross-section. These simplified methods are thus applicable to both beams and columns, with and without temperature gradients across the section. They are applicable to both bare steel and protected members and to both standard fire exposure and real fire exposure.

The thermal response is defined as the combination of the exposed surface area to mass ratio of the steel section, the thickness of any applied fire protection material, the required time of exposure (FRL) and the limiting steel temperature. For protected steel members, a handbook of thermal data has been published in Australia for a wide range of commercially-available protection materials [Proe et al, 1990]. For bare steel members, AS4100 gives formulae for calculating thermal response for both four-sided exposure and three-sided exposure. These formulae are based on test data and generally give less conservative results (lower steel temperatures) than heat transfer calculations performed using the recommended heat transfer coefficients given in Eurocode 1, Part 2.2 and other European publications.

The influence of both axial restraint and catenary action are ignored in this Standard. It will often be the case that axial restraint applied at an early stage in the period of fire exposure will be followed by catenary action later in the fire. The location of the line of action of the axial restraint will determine whether its effect is detrimental or beneficial and this is difficult to determine. Catenary action developing later in the fire will generally be beneficial, transferring load to other cooler parts of the structure and ultimately preventing collapse in many cases.

4.3.3 Concrete. The Concrete Structures Code, AS3600, contains tabulated solutions for individual structural elements in fire. The fire resistance of both beams and columns is characterised in terms of the minimum cross-sectional width and the cover to reinforcement. The fire-resistance of slabs is given as a function of the overall slab thickness and the cover to bottom reinforcement, with smaller covers for continuous slabs than simply-supported slabs. Rules for wall design are given in terms of the ratio of applied load to squash load and the slenderess ratio. The tabulated solutions apply only to the response of these members in the standard fire test. As the thermal response is combined with the structural response, they are not directly applicable to other fire temperature regimes.

Spalling is noted as an issue for concrete but no rules are given for design to prevent spalling. The Code currently applies only to concrete strength grades up to 60 MPa. The Code is currently under revision with the aim of including concrete grades up to 120 MPa, and spalling will become a more significant issue for these concrete mixes.

4.3.4 Composite. Various composite cross-sections have been developed in Europe with the intention of providing protection to the steel components and enhancing the resistance to fire without the need
for external applied fire protection. These sections are in general not considered economic in Australia, particularly in view of the general reduction in FRL requirements in the performance-based environment.

The Composite Beam Code, AS2327.1, currently covers only simply-supported beams. For composite beams (acting compositely with a concrete slab), the method of calculation is the same as that for non-composite steel beams. In this case, the load ratio is the ratio of the applied load in fire to the load capacity of the composite member. The weighted average temperature of the steel section is used as an effective uniform steel temperature. Any heating of the concrete slab has a negligible effect on the member capacity. As for non-composite steel beams, the relationship between the effective uniform temperature and the load ratio of the composite beam is the same as the temperature versus yield stress relationship for steel. The accuracy of this simplified approach has been demonstrated using elevated-temperature ultimate strength analysis and comparison against test data [Proe, 1990].

5. Tools for Performance-Based Fire Engineering Assessments of Structures

5.1 Design Objectives

Obtaining explicit agreement on the fire design objectives between the stakeholders in the project is an important early step in the process of fire engineering as practiced in Australia and as documented in the Fire Engineering Guidelines [FCRC, 1996].

As noted above, the objectives of the BCA do not include property protection or business interruption, while consideration of malicious acts such as arson or terrorism is not explicitly recommended and is generally considered to be outside the requirements of the BCA. Thus, the decision to include or exclude consideration of terrorism is normally one to be made by the client in consultation with the potential insurers for the project and possibly a sample of the prospective tenants. Experience on recent high-rise projects indicates that cost competitiveness is still the governing factor and therefore consideration of rare high-impact events is excluded from the design. It is possible that a higher standard may be voluntarily adopted for certain prominent public buildings, but no examples are known to the authors at present.

5.2 Fire Growth Modelling

Where arson or terrorism is excluded from the analysis, a fire started at one location is assumed. Consideration of multiple fire starts at critical locations would substantially complicate the analysis, and no analysis of this type has been conducted by Arup Fire in Australia to date.

The selection of the fire to be used for the design forms one of the most important inputs to the analysis. Fire details required include its rate of growth, peak heat release rate and/or peak temperature, duration of peak burning and rate of decay. Also of great importance is the simultaneous spatial extent of the fire. In a large enclosure, the fire may not burn with equal intensity in all areas. In fact, recent work at Victoria University [Thomas and Bennetts, 2001] has demonstrated that fires tend to migrate towards the ventilation openings first and then progressively burn back into the parts of the enclosure further from these openings. Clifton's fire cell concept [Clifton, 1996] introduces a similar approach, with fire cells of defined area progressively moving around the enclosure. Hence, it may be unrealistic to assume that all parts of a large structure are exposed to the highest fire temperatures simultaneously.

For localised fires in large enclosures, Poon's method [Poon, 1995] may be useful in establishing a heat release rate. Under this method, the fire load and ventilation conditions are estimated and recognised empirical formulae are used to calculate rates of burning for both ventilation-controlled and fuel-controlled conditions, with the lower rate governing at any instant of time. The duration of burning is calculated based on the total fire load and its calorific content. The heat release rate thus obtained may be used for calculating fire temperatures. For this calculation, Alpert's ceiling jet equations are sometimes used. Alternatively, a two-zone heat balance model may be adopted, with the upper layer temperature used as a measure of the fire temperature to which the structure is exposed.

For small enclosures, fire conditions are typically assumed to be uniform throughout the enclosure and fire temperatures are based on a heat balance model for a well-stirred single-zone enclosure, such as
that first developed at the Swedish Institute of Steel Construction [Pettersson et al, 1976]. A slightly modified form of this method is documented in Eurocode 1, Part 2.2.

5.3 Heat Transfer

Once the fire temperature has been determined as a function of time and location, temperatures throughout the structure can be calculated. Methods of calculation are well established and software tools available. Heat transfer properties are a major unknown, however. These properties typically vary with temperature and are difficult to measure. Furthermore, they may be affected by physical changes, such as cracking, moisture migration and dislodgement of insulation materials. These changes may in turn be affected by the deformation of the structure as it heats up. Other unknowns include the effects of sooting of surfaces on their emissivities, which may depend on whether the combustion is predominantly smouldering or flaming. Commonly used software tools for heat transfer calculation include TASEF2, SAFIR and ABAQUS.

The removal of fire protection material on steelwork by an explosion which in turn causes a fire is a hazard not normally considered in building design. It was obviously a relevant factor in the WTC collapse, and consideration may in future be given to design for this hazard for critical elements in high-profile buildings which are deemed to be a target of terrorism. This design should include also assessment of redundant load paths, however, which may enable some loss of protection material to be tolerated.

5.4 Structural Response

Methods of analysis used in the determination of structural response at elevated temperature include: comparison with test data (identify important parameters, understand failure mechanisms); ultimate strength integration over cross-section (to calculate residual strength versus time); moment-curvature analysis over cross-section and length of member (to calculate deflections versus time); and finite element analysis using programs such as ABAQUS, STRAND and LS-DYNA (for more complex models).

Considerable progress has been made in the last two decades in extending the understanding of real buildings exposed to fire. Full-scale steel-frame buildings exposed to realistic fire scenarios have been conducted in many places around the world, including the office tests at BHP Melbourne Research Laboratories in Australia [Thomas et al, 1992] and at Cardington in the UK [Kirby, 1997]. In both cases no fire protection material was applied to the steel beams, while the columns were protected. These tests demonstrated that it is possible for a steel-frame building to withstand a major fire without collapse, despite heating of many steel beams to temperatures at which they would collapse if they were isolated elements. Extensive finite element analysis of the Cardington tests has been conducted [Huang et al, 2002; Usmani and Cameron, 2002], along with modelling of individual elements having axial and rotational restraint / support resulting from the interconnection of elements [Wang, 2002]. The purpose of this analysis is to develop simplified methods to allow the interconnection of the structural elements to be rationally taken into account in the design for fire.

Further whole-structure fire testing has recently been conducted at Cardington on a concrete frame building [Bailey, 2002]. This testing resulted in extensive spalling of the concrete slab, despite the fact that the fire was not particularly intense and the concrete characteristics were not in the high risk category for spalling. Substantial deflections of the slab occurred, but no part of the structure collapsed. Concrete is typically assumed to have substantial inherent fire resistance, but its vulnerability to spalling is difficult to predict. For high-rise buildings, the use of high-strength concrete can increase the risk of spalling.

The tools now becoming available for the performance-based design of structures make it possible to explicitly consider the risk of structural failure. One strategy employed is to establish a hierarchy of importance of structural elements, with elements contributing to global stability given higher priority than those whose failure would have only local effects. Members affecting egress paths or potential refuge areas may also be assigned greater significance. If lifts are to be used for evacuation, structural and reliability issues affecting their performance may need to be addressed. Redundancy in the package of fire safety measures, including both structural and non-structural aspects, may be taken into account. The structural design may also take account of the provision of sprinklers, with sprinkler reliability being increased by various enhancements where necessary.
While the circumstances leading to the collapse of the WTC buildings may be outside the realm of assaults for which buildings will be designed, the mode of collapse is important in that it demonstrated a mechanism of progressive failure which should now be considered in relevant cases. The total collapse of all columns over one level resulted in a dynamic impact on the floor below which could not be sustained, resulting in progressive collapse. This mode of failure demonstrates the importance of the robustness of the building core in combination with that of the columns.

Consideration of progressive collapse has been included in UK building codes since the famous partial collapse of the Ronan Point apartment tower in 1968. The general approach adopted in the UK and other codes to design for terrorism and avoiding progressive collapse is that, as there is no limit to the extent of the assault and its possible consequences, the objective should be to ensure that the consequences of an attack are not disproportionate to the cause. However, the quantification of this objective requires considerable judgement.

As shown by the full-scale fire testing conducted, the interconnection between structural elements can contribute substantially to the ability of a building to survive a high-impact event. The existence of alternative load paths and the use of members and their connections with substantial ductility and rotation capacity will considerably enhance building performance under these conditions. Buildings designed for earthquakes will have a natural advantage with regard to performance in fire. Steel-frame buildings in which the slab is well connected to the steel beams are likely to have improved ability to transfer load around the structure and mobilise catenary action in the slab and the beams to avoid collapse.

Conclusions

The level of debate on high-rise construction has increased since the WTC collapse. The general impression in Australia is that the approach by owners and regulators has not changed significantly, although issues of insurance and security are now more prominent.

The decision to include or ignore the risk of terrorism is one for clients in consultation with insurers. Generally cost competitiveness governs, but a higher standard may be voluntarily adopted for prominent public buildings.

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