APPLICATION OF FIRE RESEARCH TO BUILDING FIRE SAFETY DESIGN - CURRENT BENEFITS AND FUTURE NEEDS

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ABSTRACT

There is a strong international move towards performance based fire regulations for buildings with New Zealand and Australia at the forefront of research in this field. The reform of regulations is thought to offer more innovation and flexibility in building design and greater cost effectiveness in construction.

An important part of the research in this area is related to the development of agreed approaches to fire safety design, such as the Fire Code Reform Centre's "Fire Engineering Guidelines" or New Zealand's "Fire Engineering Design Guide".

Such design process documents have incorporated or referenced much of the latest research in areas such as:

- tenability criteria
- fire compartment models
- egress models
- risk assessment.

Use of such design guidelines or equivalents in major projects in countries such as Hong Kong and Australia have highlighted where fire engineering can offer real benefits to building designers and ultimately building owners and operators.

However, there is still much research to be done and use of a systematic, logical design approach clearly identifies where design data or modelling techniques are still urgently required. Such areas are:

- fire growth rates and peak heat release rates for non-residential occupancies

- pre-movement times related to egress

- experimental validation and limits of applicability of CFD and other compartment fire models

- probability/reliability data on fire protection systems for risk based analysis.

Examples from case studies will be shown where lack of such research and poor judgement can lead to inferior design solutions or where unnecessarily conservative designs can lead to cost excesses.

In summary, the link between fire engineering designers and the research community is very important to highlight areas of fire research that will have the most benefit to the building and construction industry.

1.0 INTRODUCTION

The international trend towards quantitative fire engineering and performance based fire safety regulations is creating new opportunities for design of buildings.

The move to performance based fire engineering design is based on the premise that it will lead to:

- better, more functional buildings
- greater innovation
- equal or better levels of safety
- more cost effective construction
- a more competitive building industry.

For steel structures, major research programs have been undertaken or are in progress that are providing the technical basis for advanced fire safety design. Major experimental studies and risk assessment techniques are being utilised to show how to design steel structures, in some cases, with bare steel providing adequate 'fire resistance'.

Another major research activity is that of the Fire Code Reform Centre which is conducting a comprehensive 5 year research program to support performance based design.

This paper looks at and summarises the trend towards performance based design. It highlights some of the important international research on fire engineering and illustrates through some case studies where further research is required.

2.0 PERFORMANCE BASED REGULATIONS

The introduction of performance based building regulations has been summarised in a number of papers by Meacham and Johnson(1,2). They show that:

- The UK has had performance based regulations since 1985 and also has a flexible Approved Document - B(3) with progressive 'deemed-to-satisfy' prescriptive solutions. There is also a British Standard draft for development available for fire engineering design(4).

- New Zealand adopted the UK framework for performance based regulations in 1991 and has a document of 'approved solutions' as well as the NZ Fire Engineering Design Guide(5) for performance based solutions.

- Australia has followed the UK and NZ approach and all states of Australia will adopt the new Performance Building Code of Australia (BCA96)(6) in July - August 1997. The BCA96 provides prescriptive 'Deemed-to-Satisfy' solutions but also provides for design to performance based requirements as an alternative. The 'Fire Engineering Guidelines' of the Fire Code Reform Centre(7) has been developed and published in 1996 as the preferred methodology for performance based design.

- The US and Canada are moving towards performance based building codes around 2001 and the National Fire Protection Association (NFPA), Society of Fire Protection Engineers (SFPE) and National Research Council of Canada (NRCC) are influential in this process.

- A number of other countries will allow performance based design to be utilised to establish equivalence to current prescriptive regulations for special structures or major projects. These countries include:
    - Hong Kong
    - Singapore
    - Japan
    - Israel

Other signs of the global interest in performance based fire engineering design include:

- the major activity of ISO/TC92/SC4 on fire engineering in which at least 10 countries are participating in international standards writing.
- the formation of the International Fire Safety Engineering Institute (IFSEI) linking professional fire engineering organisations from the UK, USA and Australia.

It is clear that research into fire science and engineering has provided a firm basis for countries to proceed to performance based fire safety design. This parallels earlier development for buildings in the fields of:

- structural engineering;
- seismic design; and
- wind engineering.

3.0 RESEARCH

3.1 Steel Structures

3.1.1 General

There has been a great deal of research into performance of steel structures in fire. In simple terms, what has been found is that a structural steel frame of a building performs much better than the individual elements that are tested in the laboratory furnace test using the standard time temperature curve.

Much of the research has been documented in the international literature(8,9) and the approach to quantitative fire engineering design of steel structures in contained in the SFPE Handbook(10).

In this paper it is only possible to touch on a limited number of major research efforts that are seen to have international significance in the move towards greater use of steel in building construction.

3.1.2 BHP - 140 William Street

The building known as 140 William Street is a 41 storey office building built in Melbourne in the 1970's. The building was the corporate headquarters of BHP, Australia's largest steel maker and featured steel strongly in its construction.

When first built, the castellated steel beams supporting the floors were required to be fire proofed to provide a 2 hour fire rating to the structure. This fire rating of the beams was provided by sprayed fire proofing using a material containing asbestos.

When the building was prepared to be substantially refurbished in the late 1980's, the question was asked by BHP and the owner, AMP Society, whether the asbestos material, being removed for health reasons, needed to be replaced.

BHP Research joined with Professor Vaughan Beck of Victoria University and Lincolne Scott, consulting engineers, to examine scientifically whether fire proofing of the beams was really necessary.

The research(11,12) undertaken involved large scale experimental work as well as theoretical analysis and fire risk assessment to establish that the fire proofing, once removed, did not need to be replaced.

The decision to leave the steel beams unprotected was based upon the fact that:

- the building was fully sprinkler protected
- smoke detectors, evacuation warning systems, sprinklers and protected fire stairs would ensure levels of life safety equal to or better than required by prescriptive building code
- the central core structure of the building remained protected
- office fire loads were relatively low and therefore the threat to the structure is not severe
- the steel beams and structure generally has an inherent fire resistance
- in the event of sprinklers failing and ceiling collapse, the effect of fire on the steel beams would be limited to localised deformation
- there was no likelihood of severe deformation or major building collapse even if sprinklers failed

Major full scale fire tests showed that the beams, when fully loaded, could survive a total compartment burnout with minimal deflection. Of particular interests in the tests was that fires in a typical office layout were difficult to sustain without deliberately breaking the glazed windows. This is consistent with more recent work in the UK(13) and Ireland(14) that suggests window breakage does not occur as frequently as expected, and without window breakage, flashover and fully developed compartment fires are unlikely.

While the results of the 140 William Street research cannot be immediately translated across to all other steel frame buildings, the principles of the fire and structural analysis have been applied by BHP Research to some 8 other office buildings around Australia. A full fire engineering evaluation has shown that unprotected steel beams, but protected columns, can meet the safety requirements of the Building Code of Australia when part of a complete package of fire safety measures including automatic sprinklers.

3.1.3 *Cardington Tests*

Following the success of the Australian BHP Research Program, British Steel (BS), the Steel Construction Institute (SCI) and the Fire Research Station (FRS) and others in the UK embarked on an even more ambitious research program(13). This research was directed towards the experimental study of a building subjected to some very high fire loads. An 8 storey steel frame building was built within the Large Building Test Facility (LBTF), UK which is a major research facility operated by the FRS as part of the UK Building Research Establishment (BRE)(14).

This steel building has been subjected to a series of major full scale fire tests coordinated test program sponsored by the European Coal and Steel Community (ECSC), British Steel Technical (BST), Building Research Establishment (BRE) and others.

Results of the various test programs can be found in regular issues of the LBTF News (15).

Robinson and Newman(19) has summarised the findings of the Cardington test program, although they have stressed the fact that a good deal of analysis is still required.

They have indicated that the design approach of BS5950: Part 8 and the Eurocodes on steel buildings is very conservative. The Cardington tests have shown that steel beams have remained in place, supporting their load, at temperatures as much as 330°C higher than BS5950: Part 8 would predict. Any deformations were very localised, with the structure totally undamaged away from the fire compartment.

The design implications appear to be:

- unprotected beams in composite frames can withstand 1100°C without collapse
- columns are more critical and will need protection in multi-storey buildings
- the floor slab gives stability in fire
- load transfer is not part of current design procedures but obviously occurs
- slab membrane action also occurs
- where double glazed windows do not break, fire development is often insignificant.

3.2 Fire Code Reform Centre

3.2.1 *General*

The FCRC commissioned a major fire research program(2) in 1994 that was designed to support the introduction of performance based building and fire safety regulations in Australia.

The ultimate aim of this program was to develop a risk based methodology for fire engineering design as ultimately the only tool properly able to evaluate rare events such as fires and support cost effective solutions.

3.2.2 *Prescriptive Code Improvements*

A number of the research programs have been directed at improving the science, logic and flexibility of the prescriptive "Deemed-to-Satisfy" solutions in the Building Code of Australia(6).

These programs are:

Project 1:	Fundamental analysis of the BCA provisions for fire safety
Project 2:	Role of material in fire safety and the regulations
Project 3:	The influence of non-combustibility and fire resistance concepts on fire safety
Project 4:	Development of a fundamental risk tool to analysis options and provide more flexibility in the BCA prescriptive provisions.

3.2.3 *Design Oriented Research*

A key objective of the FCRC research program is to improve the practice of fire engineering design in all sections of building and construction.

The remainder of the FCRC program is directed towards capturing the latest Australian and international fire science and engineering and producing it in a form suited to direct project application by practitioners.

Project 5A was the first fire research effort to produce tangible results with the production of the "Fire Engineering Guidelines" as an agreed methodology for fire safety design around Australia(7).

The second project to be completed has been Project 6, specifically aimed at fire safety in Shopping Centres(17). This project consisted of:

- a major statistical survey
- experimental fire testing
- risk assessment
- design advice and proposed code changes.

The significant findings are summarised as follows:

Hazard is defined by the Fire Engineering Guidelines as; "An event that in a particular set of circumstances has the potential to give rise to unwanted consequences".

The event is a fire and the unwanted consequences can be in the form of exposure of the occupants of a building to untenable conditions or damage to property. Accordingly, with respect to life safety, the circumstances will include any situation that has the potential to cause the occupants to be exposed to untenable conditions or increase the likelihood that they will be exposed. The hazards may therefore be created due to the fire load, the type of occupants, the general layout of the building, etc (Refer Chapter 4 of the Fire Engineering Guidelines[2]).

The fire hazards in retail stores are examined in detail in a recent report(2) arising from the research work of the Fire Code Reform Centre on Project 6.

Their findings may be summarised as follows:

- current levels of fire safety in retail centres are very high
- fires in retail areas are not uncommon, but are invariably small
- such events usually involve cooking fires, fires in rubbish bins and small electrical fires
- most small fires are extinguished by occupants
- the risk of large fires that would threaten lives is greatest at night when centres are unoccupied
- the greatest protection to life safety is to keep the fire small, and smoke detectors, sprinklers and fire fighter intervention all play an important role
- major problems with malicious damage and maintenance in retail areas suggest the possible elimination of:
    - fire shutters
    - break glass alarms
    - fire hose reels
    - complex smoke control systems.

The mean fire load density for retail areas was 41kg/m^{2}wood equivalent, although there was wide variation. Significantly higher values are likely in back of house storage areas, notably footwear shops and stationers. However, many other factors, including fuel orientation and available ventilation, need to be considered in assessing fire hazard.

The fire safety design of shopping centres is not based on arson fires. Rather a strategy of prevention should be adopted through appropriate security measures. Nevertheless, experience has shown that automatic sprinklers can be effective in many arson situations, depending upon the form of ignition and fuels involved.

With respect to a typical Centre the hazards would include:

1. The fuel load represented by the retail areas and the back of house areas.
2. The potential for smoke, in the form of an extensive line plume, to spill into the mall area from the specialty shops and the Safeway Supermarket or Big W store.
3. The egress provisions from the mall, Safeway Supermarket or Big W store and specialty shops.
4. The occupants are assumed include the elderly and handicapped, and slower than typical movement times must be considered.

3.2.4 *Future Research*

The most far reaching of the FCRC research has just commenced with Project 5B now underway.

This project is designed to capture all of the previous FCRC and other international research and produce an update "Fire Engineering Guidelines" that incorporates a truly risk based design code. It will provide a probabilistic risk assessment tool, together with comprehensive fire engineering methods and data, as well as a computer code and commentary material. It will allow engineers to "measure" the levels of fire safety:

- evaluate different levels of redundancy
- incorporate data on reliability of sub-systems into design analysis, and
- explicitly consider safety factors and margins of safety.

4.0 BENEFITS

4.1 General

Fire engineers around the world are starting to utilise the efforts of researchers in their fire safety design of buildings, transport and industrial facilities. Some examples are provided that illustrate a range of benefits to individual projects and whole process of fire safety design.

4.2 Steel Structures

4.2.1 *International Iron and Steel Institute (IISI)*

A recent state-of-the-art publication by the IISI(8) lists some 28 major buildings internationally that have been designed using unprotected steel or some other innovative approach to use of structural steel in building design.

Examples include:

- A 16 storey office building in Melbourne, Australia using unprotected steel beams and decking in an open car park below the office tower.
- A shopping complex, consisting of 5 levels below-ground and 6 levels above, using prefabricated composite steel concrete columns.
- A major new air terminal of Chicago's O'Hare Airport where an exposed steel barrel vault and roof truss system supported by clusters of exposed tubular steel columns was accepted, despite local regulations originally requiring a fire resistant structure.

4.2.2 HACTL, Hong Kong

At the new HACTL container terminal, Arup Fire(18) developed and tested a roof truss system consisting of waterfilled tubular roof trusses into which sprinklers were screwed to provide fire suppression and structural protection without the need for passive fire protection.

4.2.3 Columbia University

At the new Student Centre at Columbia University in New York, a large steel and glass facade covering one face of a new atrium required 2 hour fire resistance in accordance with local codes.

However, a fire engineering analysis by Lovell(19) for this sprinklered building showed that unprotected steel could be used in the facade without fear of structural failure.

4.2.4 Singapore Mega Exhibition Centre

An analysis by Lovell(20) established that steel columns could be left unprotected because of their inherent fire resistance and the relatively low combustible loads in the vicinity of the columns. The use of automatic sprinklers to provide a high degree of fire safety was an important part of the fire strategy for this important new exhibition centre in Singapore.

4.3 Fire Code Reform Centre

4.3.1 General

In Australia, the introduction of the performance based building regulations on 1 July 1997 has created great interest in fire engineering analysis and methodologies for fire safety design.

Along with education and training, professional indemnity insurance, private building certification and professional accreditation, a key factor in the transition to the performance era has been the introduction of the "Fire Engineering Guidelines"(7). This important methodology document was developed by the Fire Code Reform Centre in Australia and gained the endorsement of the building regulators, building surveyors and fire brigades.

The "Guidelines" were in part based on the earlier draft of the National Building Fire Safety System Code (NBFSSC) developed in Australia in 1991(21). Significant concepts, particularly the Qualitative Design Review (QDR) or as it is named in Australia, the Fire Engineering Design Brief (FEDB), were adopted from the draft British Standard on application of fire engineering to building fire safety design.

The first edition of the "Fire Engineering Guidelines" was published in 1996 and after one year of use by practitioners the advantages of its introduction can be identified. At the same time, there are a number of areas in the Guidelines that have been found unworkable or need further research effort.

4.3.2 Education & Training

A first advantage of the introduction of the "Guidelines" was that it was used as the basis of a series of short courses to teach a systematic approach to fire safety engineering of buildings. This has been a significant part of the"technology transfer" necessary to prepare many in the fire engineering community for the opportunities emerging performance based design.

The "Guidelines" have also formed the basis, at least in the state of Victoria, for a six month part time course for building surveyors who will certify and approve designs based on the performance option under the new Building Code of Australia(6).

This education and training is strongly supported by the Society of Fire Safety through seminars and newsletters and, at least in some areas, there is a "cultural change" as there was in New Zealand. Building and fire officials as well as design engineers are discussing egress times and fire spread instead of travel distances and compartmentation.

On the other hand, those states in Australia where the Guidelines have not been well introduced and courses have not been available, there seems far less enthusiasm for performance based design. In some cases, considerable apprehension amongst building and fire authorities is evident and performance based design is less likely to be encouraged.

4.3.3 Project Experience

The authors of this paper have been involved in a number of projects where the "Guidelines" have been utilised. The results have been mixed, depending on how and when the "Guidelines" have been implemented.

On a major art gallery project in Victoria, the performance BCA (BCA 96) and the "Fire Engineering Guidelines" were referenced in the client brief and have been used since the start of concept design for the project. The Fire Engineering Design Brief (FEDB) was established at an early stage and input to the FEDB report has been provided by:

- architects
- fire engineer
- building surveyor
- fire authority
- insurance broker
- client.

This team reached agreement on:

- fire safety objectives
- acceptance criteria
- hazard analysis
- fire scenarios
- form of analysis
- fire safety design options.

Only then did any detailed analysis commence.

The Guidelines are also proving to be a methodology that is assisting strongly with project coordination with respect to fire safety on this gallery project.

Another project involving design of fire safety showed how the Guidelines could have assisted the process if used from the beginning of the project. This project was a railway station with connecting tunnel for which the mechanical engineers had undertaken extensive computational fluid dynamics (CFD) analysis.

The problem was that no agreement or justification had been established for the design fires on which very lengthy and complex CFD analysis had been performed. The architect and mechanical engineers had not consulted with building/fire authorities, even when construction was underway. Our consulting advice as independent advisors to the client was that the architect should engage a competent qualified fire engineering consultant. Further, we recommended that the "Guidelines" be adopted as a methodology for the urgent development of a full fire safety strategy for the project.

The result on this rail station project was that the fire engineering consultants were able to successfully develop an integrated fire safety strategy quite quickly, and support it with fire engineering analysis in accordance with the scenario development and sub-system format provided in the "Guidelines".

5.0 FUTURE NEEDS

In Australia, use of the "Fire Engineering Guidelines" has revealed a number of issues and concerns that require further research. This was anticipated in the preparation of the first edition of the Guidelines due to fire science and engineering still being a young discipline.

A major area where fire research is needed is to provide more data and perhaps a design method for the selection of the design fire and rate of fire growth. Clearly a range of scenarios need to be considered by the fire engineers for any particular building, but regular disagreement occurs between fire engineers on the "worst credible" fire growth rate in any fire scenario.

The design fire has a major impact on the analysis and final design outcome. A less conservative approach tends towards "unsafe" buildings in many situations. On the other hand, constant use of "ultrafast" growth rates up to massive fire size without regard to fuel and ventilation control can make for highly conservative and very expensive building designs.

Part of the difficulty for fire engineers is the very limited data on fire growth rates for occupancies other than residential. Much greater data bases, experimental work and even a method for establishing design fires needs to be developed internationally.

Another area of the "Guidelines" that has encouraged what is probably overly conservative design is the chapter on the occupant avoidance sub-system. While it is generally agreed that the concepts on the factors affecting pre-movement and travel times for egress are reasonable, recent data from Proulx and Fahy, for example, suggest far shorter pre-movement times in some occupancies(22). The Fire Code Reform Centre is looking to commission further research on occupant factors and egress with a view to revising this sub-system of the Guidelines.

As indicated, the "Fire Engineering Guidelines" has proved to be a useful methodology for the introduction of performance based design of fire safety for buildings in Australia. The document has been useful for education and training as well as for real design of buildings and other facilities.

The next stage in Australia is the development of a full Fire Engineering Design Code and computer program for analysis that can encompass both purely time based analysis and full probabilistic risk based design. This is encompassed in the Project 5B of the Fire Code Reform Centre that is just commencing in Australia.

6.0 SUMMARY

The strong move towards performance based fire regulations for buildings has highlighted the benefits but demonstrated the need for further fire research if the maximum potential is to be realised.

Research into steel structures internationally and the work on the Fire Code Reform Centre in Australia are examples of work that have contributed to this shift to reform of the process of fire safety design.

There is, however, a need for further research in selected areas such as design fires, egress, reliability of sub-systems and safety factors that is required in order to support more cost effective designs based on risk based methodologies.

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