

Performance-based Fire Engineering Design and its Application in Australia

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ABSTRACT

In the international context there have been considerable advances recently towards the development of a performance-based approach for fire safety design. For the consideration of others involved in planning or implementing a performance-based approach, an examination is given of the experiences gained in Australia. This paper outlines those developments that have led to the implementation of a performance-based approach to fire safety design in Australia. It is noted that several factors must be in existence for there to be a successful implementation of a performance-based approach. Some important issues that need to be resolved are noted also. A brief description is given of some research which is currently in progress to further develop a risk-assessment model. Finally, some challenges and issues surrounding the future international application of a performance-based approach to fire safety design are presented.

KEYWORDS: design criteria, fire engineering, performance-based codes, risk assessment models

INTRODUCTION

The basic concept of a performance-based approach is not to prescribe solutions but rather demonstrate that the proposed design meets defined objectives. A comprehensive performance-based approach necessitates the ability to translate the objectives into quantifiable parameters, to set limits for these parameters and to have means of estimating

performance of a proposed design to validate compliance with the required performance parameters. As was recently observed [1], the movement toward performance-oriented fire safety codes and regulations, which began to develop momentum some 10-15 years ago now involves at least 13 nations worldwide and several international organisations.

The genesis for this movement coincides with the emergence of fire safety science as a research field in the 1950's and 1960's and the subsequent introduction of fire safety engineering tools. By the 1970's, a number of groups and individuals involved in fire safety design began to investigate engineering approaches to fire safety evaluation and design as an alternate to the prescribed approaches of the day. It is reasonable to ask why is there such a widespread movement towards the introduction of performance-based codes? It is advanced that there are three principal reasons for the introduction of such codes; namely:

- 1) to promote innovation
- 2) to implement cost-effective designs
- 3) to enhance international trade.

A prescriptive-based regulatory approach is based on prescribing unambiguous requirements that are assumed to achieve implicit objectives, which are frequently unstated. For a *performance-based system*, an alternate framework has been proposed [2] which comprises three separate components:

- Codes, which specify *societal goals*, *functional objectives* and *performance requirements* to reflect society's expectations of the level of health and safety provided in buildings; for example, items such as acceptable access, egress, ventilation, fire protection, electrical services, sanitary services and so on. Such codes do not specify how these requirements are to be met.
- Guidelines that are separate documents, adopted by reference, that describe *accepted methodologies* for complying with the requirements of the code(s).
- Evaluation and Design Tools, which provide *accepted methods* to assist in the development, review and *verification* of designs in accordance with *engineering standards* and guidelines.

At a minimum, the code will explicitly state *societal goals* (what we expect from the building), *functional objectives* (how a building or its systems function to meet a *societal goal*) and *performance requirements* (a statement of the level of performance that must be met in order for a building to meet the *societal goals* and *functional objectives*). *Acceptable methods* for meeting the requirements of the code may be included in, or referenced by the code. *Acceptable methods* may include deemed-to-satisfy provisions or engineering standards, practices, tools and methodologies that can be used in an accepted manner for both design and *verification of compliance*.

DEVELOPMENT OF THE PERFORMANCE-BASED APPROACH IN AUSTRALIA

Research into risk assessment modelling to consider the effects of fire in buildings were commenced in Australia by Beck in 1979. The aim of this research was to identify cost-effective design solutions that would achieve acceptable levels of fire safety for the

occupants of buildings. This resulted in the development of a risk assessment system model to predict the effects of fire in multi-storey, multi-compartment buildings [3,4]. After a four-month sabbatical period at the National Research Council of Canada (NRCC) the NRCC contracted the author to further develop his model and make it applicable to Canadian high-rise apartment buildings. Subsequently, research collaboration between Victoria University of Technology (VUT) and the NRCC resulted in several publications under joint authorship [5,6]. This research collaboration has been very beneficial in the sharing of ideas, concepts and results. As evidence of the evolutionary developments associated with the original risk-cost assessment model concept, the NRCC have published details of their FIRECAM™ risk-cost assessment model [7], whereas in Australia, related developments have led to the development of the CESARE-Risk model (described subsequently).

The Fire Safety and Engineering project (described subsequently) was conducted at the Warren Centre for Advanced Engineering at the University of Sydney in 1989 (under leadership of the author). This was followed by was the development of the draft National Building Fire Safety System Code (NBFSSC) [8]. The draft NBFSSC was the first performance-based engineering code for the design of fire safety systems in buildings that used a risk assessment framework. The draft NBFSSC adopted a risk-assessment methodology to identify cost-effective designs that achieve levels of life safety that are equivalent to prescriptive designs specified in the building regulations. The draft NBFSSC has been influential in the international context. For example, the conceptual framework of the draft NBFSSC was subsequently adopted as the framework for the draft British Standards Institute (BSI) Code of Practice [9] and the International Standards Organisation (ISO) document [10]. The Fire Code Reform Centre's Fire Engineering Guidelines document (described subsequently) can be seen as building on the draft NBFSSC and the more recent and related developments undertaken by BSI and ISO. More recently some important initiatives have been undertaken in support of a performance-based approach to fire safety design in buildings; these initiatives are described briefly below.

Performance-Based Building Code

The present building control system in Australia is one in which the individual six State and two Territory authorities administer a set of generally uniform technical provisions through individual State and Territory legislation. The individual State and Territory authorities are represented on the Australian Building Codes Board (ABCB). The ABCB is responsible for the development of a model code, namely the Building Code of Australia (BCA). The Building Code of Australia published in 1990 (BCA, 90) [11] is a prescriptive code and forms the technical basis of current State and Territory building regulations. In October 1996 the ABCB launched the new "performance-based" Building Code of Australia 1996 (BCA, 96) [12]. This will be the first set of performance-based building regulations in Australia (the existing BCA, 90 has about 20% of clauses with performance requirements). The BCA, 96 is a significant development and represents the introduction of a performance code via a hierarchy that includes performance requirements above the existing deemed to satisfy provisions (which have essentially not changed from the BCA, 90 and will remain). The BCA, 96 is based on a four level hierarchy; namely: objectives (societal goals),

functional statements (functional objectives), performance requirements, deemed-to-satisfy provisions (prescriptive methods to meet the performance requirements that are essentially the existing BCA, 90) and verification methods. These verification methods can be used to prove that an alternative solution complies with the performance requirements. Each State and Territory will progressively adopt the BCA, 96 via a legislative process. There are a number of serious deficiencies with the BCA, 96; for example:

- The BCA, 96 is the result of a direct conversion from the BCA, 90. This has resulted in a legacy of inconsistencies since no attempt has been made to evaluate whether a more logical arrangement of component and subsystems could be defined.
- Many of the functional statements are written in absolute qualitative terms. As such, no recognition is made for realistic (probabilistic) achievement of the objective.
- There are multiple functional statements associated with a particular element or component and often a number of the statements conflict with one another.
- Performance requirements, in the main, are not quantified. It is desirable for operational design purposes that such requirements are quantified.
- Only one accepted method has been specified which can be used to demonstrate compliance with the requirements of the code.

Using the accepted verification method for radiant heat exposure at boundaries, it can be shown that some deemed-to-satisfy boundary setbacks do not meet the criteria set out within the method; this in turn means these setbacks do not meet the performance requirements. In some cases the designer or approval authority is forced to deal with a non-quantified performance requirement and/or without an equivalent deemed-to-satisfy solution or reference to an accepted method. Obviously, defining code objectives and performance levels is not an easy task [13]. While the BCA, 96 has some serious limitations, nevertheless a foundation has been laid for a performance-based approach in Australia.

Fire Code Reform Centre Limited

The Fire Code Reform Centre Limited (FCRC) was established as an independent organisation by a co-joint initiative between the Australian Government, industry and research organisations. Its mission is to develop for approval and adoption by the Australian Building Codes Board (ABCB) a cost-effective, engineered approach to fire safety design and reform of aspects of the existing building code based on similar principles. Central to this reform is a 5 year, \$5M (AUD) program of defined fire research and experimentation that is being executed under contract by a research consortium comprising BHP, CSIRO, Scientific Services Laboratory and Victoria University of Technology (VUT is the major research provider to FCRC). The projects comprising the FCRC program of research are listed below:

- Project 1: Restructure the BCA Fire Provisions (Duration 9 Months - Complete)
- Project 2: Fire Performance Requirements for Lining Materials (Duration 2 years)
- Project 3: Fire Resistance and Non-Combustibility Requirements (Duration 3 years)
- Project 4: Alternative Fire Safety System Design Solutions for the BCA (Duration 5 years)
- Project 5A: Fire Engineering Guidelines (Duration 1 year - Complete)
- Project 5B: Fire Safety Design Code (Duration 4 years)
- Project 6: Fire Safety in Low-Rise Shopping Centres (Duration 15 months).

In FCRC Project 4 a risk-assessment model will be further developed to quantify the performance of fire-safety systems designs in each occupancy category. Progressive outputs from the project will specify alternative, cost-effective solutions, suitable for inclusion in deemed-to-satisfy provisions of the BCA. This will allow flexibility to be introduced into the BCA and will also provide the basis for the development of the Fire Safety Design Code in Project 5B. This latter project will develop a systematic, fully performance-based, Fire Safety Design Code. The Code is expected to become an Australian Standard, adopted by the BCA, to provide an acceptable methodology of achieving compliance with the requirements of BCA, 96 whenever the prescriptive design approach is not adopted or is not appropriate. The project includes also the development of a Commentary, Manual and “user-friendly” computer software for each category of building occupancy. These will provide accepted methods of complying with the Code. The Fire Safety Design Code will represent a further development of the Fire Engineering Guidelines document.

The output from FCRC Project 5A has been the publication of the Fire Engineering Guidelines document [14]. This document is an important Australian development that systematically describes procedures and methodologies for a performance-based approach to the design of fire safety in buildings. The Fire Engineering Guidelines document is concerned with the identification of an appropriate conceptual design for fire safety components, subsystems or the system depending on the objectives of the study. The document is relevant to the evaluation of fire safety and protection in buildings; detailed design and specification are outside the scope of the Guidelines. The Fire Engineering Guidelines is based on four fundamental principles, namely:

- When assessing fire safety and/or protection issues, it is necessary to consider the interactive performance of fire safety subsystems (normally, a minimum two, through to the complete fire safety system depending on the objectives of the study).
- That these interactive effects are represented by placing key events on a common timeline (since time is the common link between subsystems).
- That normally a multiple number of fire scenarios must be considered (otherwise, invalid results may be obtained for design purposes).
- That performance of the fire safety subsystem or system is evaluated by considering exposure to real fire conditions.

Consistent with these principles, the Fire Engineering Guidelines contain three levels of design. Design Levels 1 and 2 make use of single or multiple scenarios that are considered in isolation. Design Level 3 uses multiple scenarios that are combined using the probability of their occurrence; that is, a risk assessment approach which enables cost-effective designs to be identified. The Fire Engineering Guidelines document encourages professionals involved in fire engineering design to work together using a common design framework described in the document. The Guidelines document advocates the development of a Fire Engineering Design Brief (as contained also in the BSI document [9]) in which the design team (comprising the design engineer, building approval official, fire brigade officer and other relevant parties) meet at the commencement of the project and agree on important issues. Examples of such issues include: objectives, assessment criteria, level of design, fire scenarios to be investigated, models to be used, assumptions and data to be used. While the Fire Engineering Guidelines document is an important initiative, the document must be seen

as the first edition that will be further developed. Examples of areas requiring further consideration include:

- In the context of design Level 2 reference is made selection of the “worst case scenarios” and the attendant use of appropriate “safety factors”. However, little or no guidance is given for the selection of these terms and the values chosen will have a major impact on the design. Further guidance is required and the recent work by Magnusson and others [15] is relevant.
- Concern has been raised that the provisions for occupant response and evacuation durations may be very conservative and lead to the assessment that current prescriptive designs are unsafe in situations where this is believed not to be the case.
- The document attempts to concentrate on principles and not insert details (for example, on equations to be used). This is an acceptable approach when there is a considerable body of available knowledge (for example, plume equations). However, where information is less certain or available (for example, selection of both characteristic values from populations to define design scenarios and safety factors) then guidance is required.

Engineering Standard Documents

In the prescriptive regulations extensive reference is made to Australian Standards for the purposes of design, construction, installation and maintenance of fire safety and protection components and subsystems. These standards are, in the main, prescriptive in their content. To have an integrated approach to performance-based design it is important that these Australian Standards have provisions that define the performance of the appropriate components and subsystems; namely, the time of operation or failure and their effectiveness and reliability. This information can then be used when undertaking fire engineering design; for example, as outlined in the Fire Engineering Guidelines document. Following discussions within Standards Australia it has been decided, in principle, to develop a guide document for use by the appropriate committees regarding the inclusion of performance information in standards.

THE REQUIRED ENVIRONMENTAL SETTING

The successful implementation of a performance-based approach to fire safety design requires the convergence of a set of factors that collectively support the philosophy and application of such an approach. It is useful to reflect and examine how these factors have applied in Australia.

Consensus View and Fire Engineering Framework

In the 1980's a view emerged that the cost of fire-safety and protection regulations may be excessive and this was then translated into the need to develop more cost-effective designs. In 1989 the Fire Safety and Engineering project was conducted at the Warren Centre for Advanced Engineering at the University of Sydney [16]. While there were somewhat

disparate views in the beginning, during the project a general consensus view emerged that design should be conducted within an engineering framework based on clearly defined performance objectives. Another key recommendation to emerge from the project was that risk assessment models should be used as a basis for identifying cost-effective combinations of fire-safety subsystems for building designs. Following the project, participants became influential in assisting to gain a similar consensus in the broader technical community.

Since the Warren Centre project, two other initiatives have been or are being undertaken, which are influential in developing a framework in which to conduct fire engineering design. These were the project that prepared the draft National Building Fire Safety System Code [8] and more recently the formation of the Fire Code Reform Centre Ltd (FCRC). Both these projects are described previously in this paper.

Regulations

The Australian Building Codes Board (ABCB) released the Performance-based Building Code of Australia (BCA, 96) in October 1996. This code, described elsewhere in this paper, is planned to be progressively adopted as the basis for State and Territory regulations from July 1997. Despite the limitations of the BCA, 96, this is nevertheless a most important initiative since it mandates a performance-based approach that can be used in conjunction with a prescriptive-based approach. Equally important, the document is forcing a rapid cultural change within industry as individuals and organisations recognise the need to address the opportunities and challenges presented by such a change.

Guidelines

To support the introduction of the BCA, 96, the FCRC has recently published its interim Fire Engineering Guidelines document [14]; these Guidelines are described elsewhere in this paper. The objectives established for the design should be consistent with, but are not restricted to, the objectives identified in the BCA. The Guidelines document identifies the quantitative performance parameters that should be used to demonstrate compliance with the objectives. The document notes that the performance required for a new design should be equivalent to the performance achieved for a design that is in accordance with the prescriptive requirements of the BCA, 96. Alternatively, the opportunity exists to establish performance levels independently, and without reference to an equivalent design specified in the BCA, 96. It will be necessary to review and revise each document to ensure that there is harmonisation of the relationship between the objectives (BCA, 96) and the performance measures (Fire Engineering Guidelines) and to reference in the BCA, 96 the Fire Engineering Guidelines as providing an accepted methodology.

System Administration

The implementation of a performance-based design approach means there are new challenges associated with providing comprehensive documentation, approval and the need

to ensure the integrity of the design during the life of the building. Further, building approval officials will face demanding technical, professional ethics and competency issues when a performance-based design is submitted for approval, particularly when they are part of the design team. In the case of performance-based approvals the issue of documentation and approval, particularly post construction, has not yet been established. How will an approval authority or fire brigade authority assess an existing performance-based designed building for code compliance in, say, five years and what will be the reference level? Options being considered by the regulators include requirements for design parameters, methodologies, and limiting assumptions to be included on approval documents and for occupation certificates (permits) to include similar details and be displayed in a prominent location within a building after construction. An interesting ethical conflict for approval authorities and designers is where a performance assessment may highlight the inconsistencies of the prescriptive approach to the point of requiring more onerous and/or expensive requirements. There are problems in attempting to extract performance clauses from the existing deemed-to-satisfy provisions; this can then expose limitations associated with the prescriptive approach. In Australia these issues are being addressed by firstly providing the legal framework to ensure that if the existing deemed-to-satisfy provisions are used to meet the performance requirements then, regardless of the actual outcome, it is deemed that the performance requirements have been satisfied. This is being done as a matter of expediency to enable a transition to a fully performance-based approach without disturbing the existing status quo.

Education and Professional Societies

It is essential that educational programs are implemented to support the performance-based design approach. For example, at CESARE a Graduate Diploma and Master degree in Building Fire Safety and Risk Engineering were introduced in 1992 to focus on the need of professional engineers who have little or no training in this area. In 1996, with the active support of the Building Control Commission in Victoria, a Graduate Certificate in Performance-based Building and Fire Codes was introduced. This course is designed to develop appropriate skills in those professions which are actively involved in the process of performance-based design; namely, building approval officials, fire brigade personnel and technical personnel from the fire protection and insurance sectors of the industry. The Centre has some 70 students enrolled in these courses. Courses at sub-degree, degree and post-graduate level are available at a limited number of other universities and educational institutions in Australia.

It is essential that those professionals involved in performance-based design and approval of buildings take responsibility for their continuing professional development; this is intrinsic to a professional discipline. In the case of professional building officials, one state-based industry registration body now requires practitioners to practice within their area of expertise; the completion of the Graduate Certificate course is deemed to provide evidence of appropriate expertise in the performance-based arena.

There are several professional societies in Australia that support the continuing professional development of people involved in the fire safety and protection industry. An important

recent initiative has been the formation of the Society of Fire Safety (SFS) within The Institution of Engineers, Australia. The SFS, which has a national structure, has been formed with the aims of further developing and applying fire engineering techniques for the benefit of the Australian Community. The SFS is in the process of affiliating with the Society of Fire Protection Engineers and the Institute for Fire Safety (UK).

Other Factors

The introduction of a performance-based approach in Australia has been facilitated by a number of other factors. For example, the relatively small population has enabled the key stake holders to be actively involved in the process. Further, a small informal group of technical people from various organisations have developed shared goals for the future needs of fire engineering and have actively worked together over several years for the achievement of those goals.

CESARE-RISK MODEL

The CESARE-Risk model is a risk assessment model that is used to quantify the performance of a building fire safety system. The model has been developed consistent with the four fundamental principles adopted in the Fire Engineering Guidelines for fire safety and protection design (outlined previously) and adopts a comparative cost-effective decision criterion described previously by the author [3]. This criterion states that for an alternative design to be considered acceptable, the calculated expected risk-to-life and fire-cost expectation shall be equal to or less than the values for the same parameters for an equivalent design conforming with the prescriptive requirements in the regulations. Given subsequently is a brief description of aspects of the model that are the subject of current research; details of the research will be published shortly in the scientific literature.

Expected Value Model

The approach adopted in the CESARE-Risk model is based on the recognition that the modeling of fire growth and spread of fire in a building and its interaction with occupant egress can be split into two components. The first component of the modeling consists in setting up an event tree to describe the conditions of the building. This is a static event tree describing such things as whether or not the sprinklers (if there are any) are operational and effective. The event tree is described in some detail elsewhere [17] and represents fire scenarios that can run into several hundreds to thousands, each occurring with some probability. Given the occurrence of a particular scenario, the real difficulty lies with the second component, namely in the modeling of those conditions that can lead to significant loss of life. They consist of time-dependent, non-stationary stochastic growth processes of fire growth and spread and human behaviour, each of which having an infinite number of different realisations. Under such circumstances, the average (expected) outcome over all realisations corresponding to the particular scenario can be estimated. Having repeated the procedure with each of the scenarios defined by the event tree, the global expected outcome

can then be calculated by averaging over the various scenarios, using the appropriate probabilities from the event tree.

The most satisfactory way of calculating an expected loss (expected risk-to-life or fire-cost expectation) is an exact analytic one. There are some extremely simple situations where this is actually feasible [15]. However, in most realistic fire situations, recourse must be had to approximate methods. The next best approach appears to be Monte Carlo simulation. However, the Monte Carlo method itself can be extremely computationally intensive. The use of representative sampling instead of simple random sampling has been advocated by Magnusson and colleagues [15]. One possible compromise is the recognition that the average loss of life over all realisations (leading to the loss of life) for a particular scenario, could be taken to correspond to a limited number of representative realisations. Recourse could be made to a worst case condition; however, this is clearly inappropriate for an expected value model.

A simulation study was undertaken to compare the expected number of deaths when untenable conditions set in during an evacuation with (1) the number obtained by taking just one average realisation and (2) the average number of deaths obtained from just three appropriately chosen realisations for each of the key random variables. Here a realisation corresponds to a particular sample from the following random variables:

- the fire severity variable which will give rise to a unique time-dependent variation for fire signatures such as carbon monoxide, temperature and smoke density and times of occurrence for fire cues
- occupant response duration to cues,
- movement speed
- the variable representing the probability of incapacitation or fatality to a relevant fire signature (such as carbon monoxide or temperature).

In the three-realisation representation, the values chosen for each of the above random variables correspond to μ , $\mu \pm 1.2\sigma$, where μ and σ are respectively the mean and the standard deviation of the random variable. The coefficient 1.2 was selected to ensure that a random variable, taking the three chosen values with equal probability, would have a mean of μ and a standard deviation of approximately σ . The results of analyses (1) and (2) were compared with a Monte Carlo simulation for the same problem. Overall it was found that the three-realisation (2) approximation drastically reduced the error associated with the single realisation (1) to manageable proportions. Accordingly, it was decided to adopt the approximate three-realisation representation model as the basis for calculating expected risk-to-life values in the CESARE-Risk model, where the statistical parameters of the relevant random variables are determined a priori. For each of the three fire severity realisations for each fire type (smouldering and flaming and flashover), deterministic models are used to estimate the time-dependent variations for the fire signatures and the times of occurrence of the fire cues. The fire severity random variable was determined a priori using a Monte Carlo simulation by considering distributions for each of the input parameters. In the case of the other random variables: occupant response duration, movement speed and probability of incapacitation or fatality, use was made of experimental data and field observations to estimate their statistical parameters.

Modelling Considerations

The CESARE-Risk model is being developed by the Centre for Environmental Safety and Risk Engineering, with financial input from FCRC. Within the FCRC program, the CESARE-Risk Model will be used for both Projects 4 and 5B (described previously). These two applications have important implications for the development of the model. Namely, that ultimately CESARE-Risk will be used as a design tool by consulting engineers and building approval officials to assist to identify cost-effective design solutions for buildings. As such, it is essential that the computer program execution time is commensurate with the expectation of designers; namely that the execution time is limited to a matter of hours (not days). The principal factors that influence the computational time are the:

- Duration required to compute each deterministic submodel (in particular, the fire growth sub-model).
- Determination of the time-dependent distributions associated with each of the key variables that are inserted onto the time-line for each of the scenarios.
- Number of scenarios considered.
- Computational scheme invoked to represent the multiple interactions between fire growth and human behaviour for each of the scenarios.

To resolve the conflict between the desire for improved accuracy for the estimates obtained from each of the sub-models, recognising the uncertainties attached to each of the submodels (for example, human behaviour) and the time required to execute the risk assessment model, the following criteria were adopted:

- Use submodels that are computationally efficient and which produce robust and somewhat conservative estimates. It is not essential to have a submodel that produces a more accurate estimate of reality if this means that a substantially greater computational time is required.
- Where appropriate, time-dependent distributions (associated with the key variables that are inserted onto the time-line) are determined using Monte Carlo simulations that are conducted prior to running the risk assessment model.
- It is likely that the number of fire scenarios may be in the order of thousands; accordingly, and where appropriate, reduce the number of scenarios in the risk assessment model. The event tree used to define the number of fire scenarios is systematically assessed to evaluate under what circumstances certain scenarios can either be eliminated or combined with other similar scenarios.

The recommendation given above, that submodels should be selected which are computationally efficient and which produce robust and somewhat conservative estimates, must be considered in the context of risk assessment modelling. These issues can, and will be, investigated classically by conducting a sensitivity analysis. However, it is the author's view that if producing a slightly more accurate estimate for a single realisation involves a substantial increase in computational time then, in general, this cannot be justified. This is because of the deleterious effect this will have on the overall computational time (for multiple realisations and multiple scenarios) and because the uncertainties associated with defining multiple realisations and scenarios will tend to overwhelm minor improvements in accuracy elsewhere. Further, both conservative and "more accurate" estimates are only

approximations and both estimates should have (engineering) correction factors applied to produce estimates of “reality”.

As a consequence, the resultant performance parameters (for example, risk to life and fire-cost expectations) will tend to be conservative estimates. This should be of relatively little consequence (in terms of identifying an acceptable alternative design) since a comparative decision-making criterion is adopted. Accordingly, any conservative assumptions and estimates incorporated into the estimates for the performance parameters for the alternative design(s) will be reflected also in the performance estimates for the code-complying design.

Fire Growth and Smoke Spread Models

Computer modelling of fire development, smoke and fire spread are major components in risk assessment models. The concept of the zone model has the ability to reduce computational complexity of fire growth and smoke spread modeling without unduly sacrificing accuracy. This makes the zone model a powerful tool for risk-cost assessment. Following an evaluation of various fire growth models for possible inclusion within the CESARE-RISK model, it was decided to select the NRCC Fire Growth Model [18], based on its merits of simplicity, efficiency and robustness. Predictions from the NRCC Fire Growth Model have been compared with experimental results obtained for various fire conditions; namely, smouldering, flaming and flashover. Modifications to the NRCC Model have been undertaken to achieve closer agreement between the predicted and the measured results. The results obtained in the validation program have demonstrated the robustness of the Model to predict the fire growth and the average room (exhaust) conditions from the enclosure of fire origin for smouldering, flaming and flashover fire types under different ventilation conditions. It is recognised that further modifications are required.

The CESARE-SMOKE model, which uses the zone concept and network approach to model smoke spread in large residential buildings, was developed at the Centre [19,20]. The predictions obtained from the model for smoke spread in a tower agreed reasonably well with experimental results obtained by Hokugo et al [21]. The model is also being validated against recent experimental data obtained in the Experimental Building-Fire Facility at VUT. The CESARE-SMOKE model is coupled with the NRCC Fire Growth Model to predict smoke movement to each enclosure in a building. Research is in progress at the Centre to define stochastic models for fire growth [22], smoke spread and fire spread.

Human Behaviour Model

The aim of the CESARE-Human Behaviour model is to estimate the number of persons in different locations in an apartment building at different times during a fire incident. The Model consists of the Response Submodel that deals with behaviour up to the time when evacuation begins by occupants leaving an apartment and the Evacuation Submodel that deals with the movement of people in a building. The Human Behaviour Model, in conjunction with the Fire Growth and Smoke Spread Models, is used to estimate the cumulative time-dependent exposure of occupants to toxic and thermal effects.

Response Submodel: The structure of this submodel is based on a review of the literature and the responses obtained by CESARE researchers to both detailed interviews and questionnaires from people who have experienced fires in their apartment buildings [23]. The Response Submodel considers the probabilities of response and the duration between occupant recognition of a cue and the resulting action. The responses for occupants of the apartment of fire origin are assumed to be either evacuate or remain and reflect the dominance of fire and automatic cues. Whereas, the responses for occupants of apartments of non-fire origin to cues are assumed to be either evacuate, investigate (seek supportive information from the corridors before deciding to evacuate) or remain in the apartment. Currently, CESARE researchers are collecting additional data. For example, research is being conducted to estimate the probabilities and times of responses of sleeping subjects to alarms [24] and to estimate the duration required for awaking subjects to reach a stage where their responses will be similar to a fully awake person's responses.

Evacuation Submodel: This is a dynamic network model that is used to estimate the spatial distribution of the expected number of occupants as a function of time. It is assumed that once occupants leave an apartment they seek to exit the building. However, this movement strategy can be altered by smoke conditions which can force occupants to seek alternative exit routes. If these exits are not available, then occupants are assumed to attempt to return to their apartment.

Occupant Groupings: Since occupants can have different response parameters (probabilities, response durations and movement speeds), it was decided to define several occupant group categories. Census data was used to undertake a demographic analysis of the Australian population. This is used to provide an initial categorisation of the occupants. Also in recognition of the importance of the effect of age, drugs and alcohol and mobility-related handicaps on fire fatalities, further occupant groups were defined.

Incapacitation and Fatalities: The calculation of occupant incapacitation and fatality is based on the temporal accumulation of toxic and thermal effects associated with each occupant (group). For simplicity, it is assumed that the effects of toxic gases and heat are mutually exclusive; that is, death can be caused by either toxic gases or heat, but not both.

Fire Brigade Model

To quantify the effects of fire brigades, the Australasian Fire Authorities Council (the peak body representing fire brigades in Australia and New Zealand) has developed a Fire Brigade Intervention Model (FBIM). The FBIM is currently being revised in conjunction with the FCRC. The FBIM, which can be characterised as an event tree, is used to estimate the time of arrival of the fire brigade at the enclosure of fire origin, as a function of the time of notification and operational procedures, resource availability and capability. In addition, actions such as fire control and extinguishment and search and rescue are also modelled as a function of: the fire conditions, the number and distribution of occupants trapped and incapacitated and fire brigade operational procedures, resource availability and capability.

Barrier Performance

To estimate the time-dependent performance of barriers under real fire conditions, a CESARE-Fire Barrier model has been developed. For example, the model [25] is used to predict the time and probability of failure of a range of timber-framed assemblies. Deterministic time-dependent submodels for: fire severity, thermo-structural response and failure criteria, are used to predict the time of failure of a barrier to a realistic fire and load condition scenario. A Monte Carlo simulation is used to conduct multiple numerical simulation experiments to determine, for each experiment, whether failure of the barrier occurs (and if so, the time of failure). This information is then used to estimate the probability cumulative density function of the time to failure. CESARE-Fire Barrier provides input to CESARE-Risk; namely, the expected time of barrier failure and the overall probability of failure.

CHALLENGES AND ISSUES

While issues have been previously identified in this paper that describe suggested improvements to the BCA, 96, the Fire Engineering Guidelines and Australian Standards documents, given subsequently are some additional issues for consideration. Even before the BCA, 96 has come into use, potential challenges have been identified which will have to be eventually resolved. One issue will be the selection of acceptability criteria. The temptation will be that building approval officials will tend to adopt conservative estimates of acceptable values for fire safety design parameters (when adopting absolute criteria for design purposes). This may present the problem of revealing that the deemed-to-satisfy provisions do not meet the performance required. In such an instance, the questions which need to be raised are: is the performance objective wrong?, are the deemed-to-satisfy provisions wrong? or is the method of demonstrating acceptability wrong? In addition, the BCA, 96 does not list the Fire Engineering Guidelines as being an accepted document that complies with its performance provisions. While this is partly a reflection of similar publication deadlines for the documents, there are important issues to be addressed regarding the consistency between the documents in terms of the objectives, the parameters to be used for these objectives and the limit criteria for these parameters.

The selection of fire scenarios and assumptions regarding models and data to be used will have major influences on the results; accordingly, these are central to the application of a performance-based code. Scenarios and assumptions are an unavoidable mix of scientific, engineering and value judgments. Should designers make these issues their responsibility, or will building approval officials and code writers, once they understand the judgments involved, be unwilling to support such a proposition? The Fire Engineering Guidelines provides some guidance on these issues. For example, while the use of multiple scenarios is encouraged, few other details are provided. In addition, designers and authorities are encouraged to form a design team and develop an initial Fire Engineering Design Brief for a project. A further issue arises in the adoption of a comparative decision-making criteria (based on imputed performance for code specified designs) when, as will often be the case, conforming buildings do not present a single risk or cost value for comparison. There is the opportunity to reverse engineer the method and to use the least safe conforming-building

for reference. Further, the Fire Engineering Guidelines suggest, wisely, that building officials form part of the team setting the fire engineering design brief for a building. However, can these officials successfully distance themselves from the design process since the legal system assumes that they are so separated? While it is difficult, and indeed inappropriate, to be prescriptive in relation to each of these issues, it is expected that active educational programs, professional societies' activities and codes of ethics will be essential to the development and acceptance of a professional approach by all groups involved in the design process.

It is a relatively simple task to add complexity to a risk assessment model. However, perhaps a more challenging task is to ensure that such models are suitable for "routine" design purposes (particularly from a computer program execution perspective). This will require a balance to be achieved between "simplicity" and "accuracy" of the result and ultimately the ability to correctly discriminate between various design features. To advance the development and application of both fire engineering, in general, and risk assessment models, in particular, there is need for international collaboration. The real challenge is not the development of models but rather the collection of data for input to the models. It would appear that an imbalance currently exists in the scientific resource allocation, with too much scientific effort being devoted to the development of models that attempt to predict essentially the same parameters (consider the number of zone models that have been developed [26]). To redress this apparent imbalance we need to spend more of our resources in firstly characterising the discrepancies between the model predictions and controlled experiments. Secondly, it is important to realise that in reality fire can have many different realisations, that we must characterise these different realisations and incorporate this information into our analysis. Only by recognising that fire (and the responses to fire) is inherently a time-dependent, non-stationary stochastic growth processes, is it possible to appreciate that apparently significant issues, such as small discrepancies between different model predictions, are overwhelmed by differences caused by the underlying stochastic processes. In addition, to rationalise and clarify research directions, much more effort needs to be expended in analysing, in a rigorous and imaginative way, the substantial amount of data available in fire statistics.

CONCLUSIONS

Significant advances have been made in recent years in Australia to implement a number of important initiatives that are designed to mandate, facilitate and support the introduction of a performance-based approach to building and fire safety design. As a result of these initiatives, key factors are in place which will provide the foundation for the potential widespread application of a performance-based approach to design. While much has been achieved, much remains to be done and implemented. For example, the objective statements in the performance-based Building Code of Australia need to be revised in order to adopt a more consistent and less absolute terminology. Some operational difficulties can also be expected to arise with the BCA, 96; namely it will be necessary to investigate those situations when deemed-to-satisfy provisions do not meet the established performance requirements. Further, there is a need for a statement of compatibility between the objectives of the BCA, 96 and the performance parameters and criteria adopted in the

FCRC Fire Engineering Guidelines; this can be facilitated by having the Guidelines referenced in the BCA, 96 as providing an accepted method of demonstrating compliance with the objectives of the BCA, 96. While the Fire Engineering Guidelines document is an important initiative, the document must be seen as a first edition that will be further revised and developed. In addition, it is necessary that procedures be developed to demonstrate and to certify that the fire engineering design assumptions are maintained through the life of the building.

A variety of methodological approaches can be adopted to implement a performance-based approach. To identify cost-effective design solutions for building fire safety systems, it is advocated that a risk-cost methodology be adopted as providing a rational and systematic methodology to evaluate the multiplicity of possible outcomes from the effects of fire in buildings. The CESARE-Risk model (described in this paper) is a risk-cost assessment model which is based on the use of multiple fire scenarios, where the inherent stochastic nature of fire and response to fire are considered and where deterministic models are used to predict the time-dependent variation of the fire environment throughout a building. Because of rapid developments that are occurring in risk-cost assessment modelling, this field of research can only benefit from on-going debate and collaboration in relation to both technical and implementation issues. For example, there is a need to develop more of a focus on the collection of data for inclusion in models. However, the collection of appropriate data is very demanding of resources and an opportunity exists for the international fire science community to coordinate its efforts in this regard.

The desire to improve the accuracy of models and to use more comprehensive data sets are a self evident objective that is central to the scientific spirit of inquiry and rigour. However, in pursuit of this desirable objective it is important not to lose sight of another objective, namely to introduce a more rational approach to fire safety design. There is a view, in some countries, that it is preferable to defer the implementation of a performance-based approach pending the development of a fully validated methodology and methods. While recognising the logic of such an approach, there is a danger that such an objective may never be realised. As a consequence, the implementation of a more rational, performance-based approach may even be prevented while less desirable methods (heuristics) continue to be used. It may be a more reasonable approach to both develop and apply an "imperfect methodology", based on existing technology, and to have a commitment to further improve the methodology through experiences gained by its application and by research.

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