Advances in Fire Design for Reinforced Concrete Structures – Moving to More Rational Design Methods

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Synopsis: This paper examines research work and development of design methods for the fire performance of reinforced concrete structures in the past five years, relating it to:

- the effect of the change to performance-based codes on design of concrete buildings for fire;
- the implementation of this research into AS 3600 – Concrete Structures (1), including the implications of the introduction of high-strength (500Mpa) reinforcing steel. The effect of this research on concrete design and construction, including changes to construction types, member sizing, specification, ease of use, and performance is discussed;
- Current Australian and overseas research projects and their likely impact;
- overseas experience with fire performance, including legal and societal impacts on the building industry of such changes and the implications for designers and specifiers in Australia.

Keywords: fire design, performance-based codes, steel- reinforced concrete, AS3600

1 INTRODUCTION

Building construction technology is changing at breathtaking pace. Every year we see new methods and materials offered to the industry which provide many desirable benefits. Through the increased flexibility allowed by codes, designers and specifiers can now take advantage of these benefits by designing for performance.

This paper examines the specific advantages and disadvantages of the performance-based approach. Looking at recent research and its implementation into AS3600: 1994- Concrete Structures, as well as actual building fires, both in Australia and overseas, the implications of the new approach for designers and specifiers are discussed.

2 THE EFFECT OF THE CHANGE TO PERFORMANCE-BASED CODES ON DESIGN OF CONCRETE BUILDINGS FOR FIRE

a) What are Performance-Based Codes?

Performance-based codes of practice have meant a quantum change in the attitudes and understanding required by designers and specifiers. Gone are the relative certainties of set solutions laid out in the old codes and regulations. Now, assessment has to be made of a number of possible quite complicated criteria. For instance:

What is the type and layout of structure?
What are its fitments, its finishes and hence its fire load?
What is its intended function?
What are the means of escape and probable evacuation times?
What is the likely fire brigade response time?

The flow chart shown in Figure 1 indicates the typical sequence of designing structures for fire.

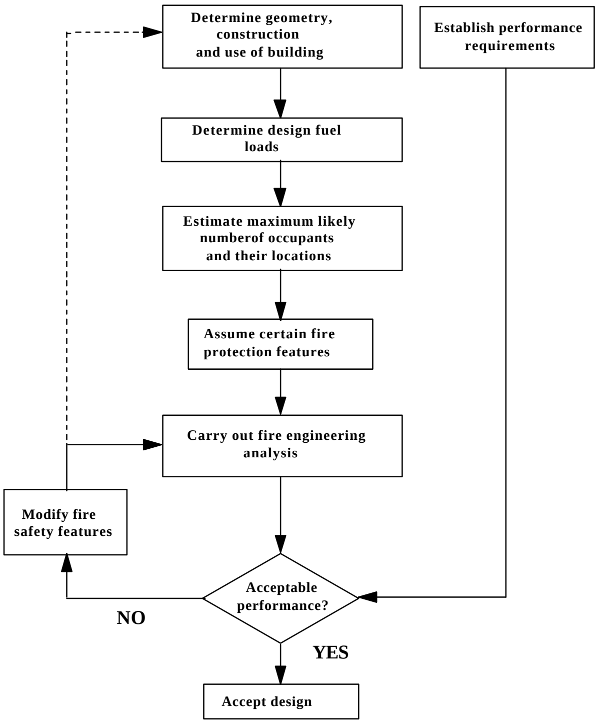


Figure 1 - Overview of Specific Fire Engineering Design [from (7)]

a) Current Provisions

The Building Code of Australia (BCA) (2) sets out the requirements for buildings in a five-level hierarchy:

1. Objectives (or societal goals);
2. Functional Statements
3. Performance Requirements
4. Deemed to Satisfy Provisions
5. Verification methods, used to provide an alternative design which meets stipulated performance requirements.

The five levels group into three components:

1. A code which specifies societal goals, functional objectives and performance requirements to reflect society's expectations of the level of health and safety provided in buildings, eg, acceptable access, fire protection, ventilation, etc. The code does not specify how these requirements are to be met.
2. Standards and practice as separate documents adopted by reference that describe accepted methodologies for complying with the code (eg, AS 3600).
3. Evaluation and design tools which provide accepted methods to assist on the development, review and verification of design in accordance with engineering standards and guidelines (eg, the "Fire Engineering Guidelines").

3 The Effect of Research on Concrete Design and Construction, Including Changes to Construction Types, Member Sizing, Specification, Ease of Use, and Performance

3.1 BCA Requirements

The BCA sets out the requirements for the design of a building in Australia against the effects of fire. There are several methods for doing this, but the one most frequently used by designers is the deemed-to-comply Fire Resistance Levels (FRL) and the complementary deemed-to-satisfy Fire Resistance Periods (FRP) specified in AS 3600.

The approach to design against fire in the BCA is in the process of rationalisation and amendment. Changes so far have resulted in the lowering of FRLs for various members, eg, columns in carparks.

For instance, requirements for FRPs for columns in AS 3600 are based largely on testing of members as reported and codified in overseas standards/codes. FRP is given as a function of only cover to reinforcing steel and the least dimension of the column. No account is taken of the other column design parameters that are now known to affect the FRP, including the concrete compressive strength, the effective length of the column, the applied load and the aspect ratio of the column.

When the rules for reinforced columns were first prepared only limited data were available and this related to only to columns with square or circular cross-section. These new rules meant that the concessions in the previous standard AS 1480 – Concrete Structures (5) which permitted blade columns to be designed as walls for fire purposes were negated. As a result reinforced concrete blade columns are disadvantaged vis a vis square columns in situations such as carparks, where narrow columns are required for optimum space utilisation. These rules have also created the anomalous situation where reinforced concrete blade columns are required to be a minimum of 300 mm wide whereas reinforced concrete masonry columns need only be 190 mm wide.

Since the formulation of the rules in AS 3600 further test data has become available. Further, computer simulation programs, based on heat transfer theory and engineering analysis have been developed to more accurately predict the behaviour of reinforced concrete columns under fire conditions. As a result of these advances the Cement and Concrete Association of Australia and the Steel Reinforcement Institute of Australia funded the Building Research Association of New Zealand (BRANZ) to carry out a research program to address these restrictions and resolve these anomalies (6).

3.2 Research Outcomes

The project utilised a computer model developed by the National Research Council of Canada (NRCC), and compared with fire tests undertaken at BRANZ. The results of both the fire tests and the model were analysed to fit a conservative equation to the computer simulation model using a multiple linear regression technique. The form of equation was intended to be suitable for inclusion in AS3600.

The equation developed was as follows:

$$R = \frac{k \times f'_c{}^{1.3} \times B^{3.3} \times D^{1.8}}{10^5 \times N*^{1.5} \times L_e^{0.9}} \quad \text{Equation 1}$$

where

R = fire resistance period of the column (minutes)
k = a constant dependent on the cover and amount of steel (Table 1a or 1b)
f'_c = the 28-day compressive strength of the concrete (MPa)
B = the least dimension of the column (mm)
D = the greatest dimension of the column (mm)
$N*$ = the design axial load for fire conditions (kN)
L_e = effective length (mm)

Steel Ratio	Cover to Reinforcing Steel	
	< 35 mm	≥ 35 mm
< 2.5%	1.47	1.48
≥ 2.5%	1.66	1.81

Table 1a – k-Values for Design Equation 1 (400Y Reinforcement)

Further, the research also provides results for 500 MPa reinforcing steel. This will enable a smooth transition in the existing codes of practice during the imminent move from the existing 400 MPa reinforcing steel in Australia, precluding a "lag" period during the introduction of the new material.

Steel Ratio	Cover to Reinforcing Steel	
	< 35 mm	≥ 35 mm
< 2.5%	1.49	1.50
≥ 2.5%	1.68	1.88

Table 1b – k-Values for Design Equation 1 (500N Reinforcement)

3.3 Comparison with AS 3600-1994

A brief illustration of the benefit obtained from using the computer model and Equation 1 (which are confirmed through testing) over the current AS 3600 fire resistance levels is given in Table 2. The data assumes a 28-day characteristic compressive strength of 35 MPa, concrete cover of 35 mm, slenderness ratio of 25, design load = $0.5N_{uo}$ and steel ratio of 2.5%. It can be seen that, for these examples, the period of structural adequacy assessed according to AS 3600 is overly conservative when compared with that obtained through the application of Equation 1.

Column Size (mm/mm)	Fire Resistance from Equation 1 (minutes)	Fire Resistance from AS 3600 (minutes)
150 x 600	68	30
150 x 1200	84	30
200 x 200	64	60
200 x 400	78	60
200 x 800	96	60
200 x 1600	119	60
300 x 300	103	90
300 x 600	127	90
300 x 1200	157	90
500 x 500	191	120
500 x 1000	235	120

Table 2 – Comparison Between Proposed Design Equation and AS 3600 Fire Resistance Values for 400 Y Reinforcement

4 IMPLEMENTING RECENT RESEARCH

Amendment 2 to AS 3600-1994, due in 1999, will include simplified versions of Equation 1 for both 400 MPa and 500 MPa reinforcing bar. These amendments, given in the following sections will enable designers to more accurately determine fire resistance periods for rectangular columns, and are based on the work of Wade et al discussed above (6):

The equations still use the design axial force, and hence will be most effective if used in refined designs.

4.1 Initial Assumed Column Dimensions

The initial column sizes assumed in the design are as follows. Other column profiles may be analysed by pro-rata.

1. 300 mm x 600 mm column; and
2. covers as determined by durability considerations.

4.2 FRP for 500 MPa Reinforcement

This equation will be contained within the main body of the Code:

FRP = $117\,[(k/k_o)(f'_c/f'_{co})^{1.3}(D_c/D_{co})^{3.3}(D_g/D_{go})^{1.8}]/[(N^*/N^*_o)^{1.5}(L_e/L_{eo})^{0.9}]$, Equation 2

where

k = a constant dependent on steel ratio
= 1.5 when $A_s/A_g < 0.025$; or
= 1.8 when A_s/A_g (0.025

where A_s is the cross-sectional area of steel in mm^2
and A_g is the cross-sectional area of concrete in mm^2

k_o = 1.8
f'_{co} = 35 MPa
D_c = the smaller cross-sectional dimension of a rectangular column
D_{co} = 300 mm
D_g = the larger cross-sectional dimension of a rectangular column
D_{go} = 600 mm
N^* = the design axial force for the fire limit state (kN) but not less than $0.4N_{uo}$
N^*_o = 2724 kN
L_e = the effective length of the column
L_{eo} = 2250 mm

For columns of circular or regular polygonal cross-section, D_c in the above equation shall be taken as equal to $(A_g$.

4.3 FRP for 400 MPa Reinforcement

This equation will be contained within the Code commentary, to enable designers to work on structures that used older material:

FRP = $120\,[(k/k_o)(f'_c/f'_{co})^{1.3}(D_c/D_{co})^{3.3}(D_g/D_{go})^{1.8}]/[(N^*/N^*_o)^{1.5}(L_e/L_{eo})^{0.9}]$, Equation 3

and where

k = 1.5 when $A_s/A_g < 0.025$; or
= 1.7 when A_s/A_g (0.025
k_o = 1.7
N^*_o = 3499 kN

All other values are as previously described for Equation 2.

4.4 Structural Adequacy

4.4.1 Prediction of FRP's

FRP's may now be predicted using BCA Clause 3 of Specification A2.3, and using the relevant elevated temperature properties of materials. Reinforcement ductility, recesses and chases

4.4.2 Low Ductility Reinforcement

Of particular note is the fact that, for the first time in AS3600, the attention of designers is drawn to the need for care when Class L (low ductility, hard drawn) reinforcement is used. This is due to the possibility of brittle failure during a fire situation when the member sags under the effects of heating, putting the reinforcement into significantly increased tension.

4.4.3 Recesses for Services in Walls

The maximum area allowed for service recesses, where the remaining wall thickness is not less than half the nominal wall thickness, is 10,000 mm^2 on one or both faces of a wall in any 5 m^2 of wall face. Otherwise, the thinner wall thickness is to be used for FRP calculation.

4.4.3 Chases

The effect of chases on the structural adequacy of walls is covered in detail. Chases spanning both parallel and perpendicular to the one and two-way spanning walls are considered.
The effect of chases on integrity and insulation is also described.

5 OVERSEAS EXPERIENCE WITH FIRE PERFORMANCE AND ITS RELEVANCE TO AUSTRALIA

5.1 General

North America (USA and Canada) and UK, have all enacted or are looking at performance-based codes.

The United States has suffered several serious fires that are well documented and have given an insight into both the strengths and weaknesses of a performance-based approach to fire design.

Major fires in high-rise structures overseas are well known in the engineering community. The 1988 First National Bank fire in Los Angeles (US$50 million damage), and, the fire at One Meridian Plaza in Philadelphia in 1991, which took the lives of three firefighters and cost affected businesses upwards of US$4 billion (1994 prices), including consequential costs, are well documented.

The lessons from fires such as these appear common across all the countries currently assessing performance-based codes:- The benefits of such codes to designers, developers and society as a whole can be considerable, but educated assessment of each individual case is essential by planners and engineering designers.

5.2 Performance-Based Codes for Fire – The Pros and Cons

Fire safety involves control of risk to life and possibly property. Performance-based codes and supporting risk-assessment methodologies attempt to quantify risk and compare alternative design solutions. In this sense fire can be equated with other risk events such as high winds or earthquakes.

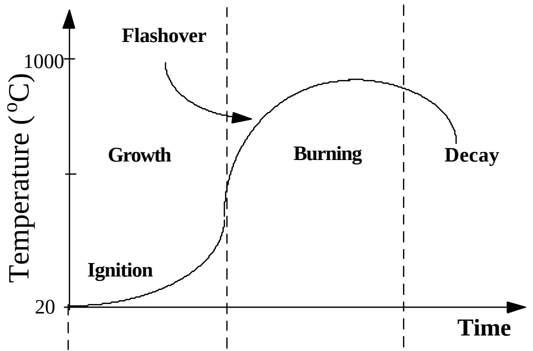
The Australian approach to fire differs somewhat from that overseas. In Australia, structural integrity in the post-fire condition has been significantly downgraded from the previous levels stipulated in the prescriptive codes and regulations hitherto in place. The balance between active and passive systems has shifted fundamentally. This is shown from Figure 2, which shows a typical fire curve for a fire for which no fire fighting intervention takes place. Previous practice took into account all three stages of the fire. Performance-based codes reliant fundamentally on life safety only, take into account only the first stage

This is one of the areas where education of designers and end-users is essential. Fire is the only area in our codes where significant structural damage is allowed or even expected in the design limit state condition, rather than in the ultimate limit state.

Societal cost is often the hidden or “forgotten” factor in Australian designs, as was seen for the Meridian Plaza fire. As an example, the Morley (now Morley Galleria) shopping centre in Perth was severely damaged by a fire in 1986. The centre was not rebuilt for *ten years* as enough customers switched to another local centre after the fire that redevelopment proved economically non-viable. The cost of structural damage was only about $2 million. The value of lost stock ran to approximately $10 million. However, lost revenue to both the retailers and centre management ran into several tens of millions of dollars. The cost to society and the economy of the lost jobs from these and other satellite businesses and amenities although never quantified, was significant. The opinion of the fire brigade is that better compartmentation would have enabled the fire to be contained and considerably less damage to have occurred. This would probably have resulted in the continued viability of the centre.

There is a widely accepted rule of thumb in the insurance industry that only one-third of businesses who claim on business interruption policies actually survive the trauma of rebuilding their business. Another one-third fold within one year of recommencing operations, after their insurance ceases payment and one-third never reopen for business.

As shown above, one of the primary reasons for this low success rate is that enough customers find alternative supply during the transition period that the business is no longer viable.



Stage	Growth	Burning	Decay
Fire behaviour	Fuel-Controlled	Ventilation-Controlled	Fuel-Controlled
Human behaviour	Escape	Death	
Detection	Smoke Detectors Heat Detectors	External Heat & Flame	
Active Control	Extinguish by hand, sprinklers or Fire Service	Control by Fire Service	
Passive Control	Smoke control, Flammability, surface spread of flame	Fire resistance, containment, collapse	

Figure 2 - Typical Fire Development Curve [from (7)]

5.3 Overseas experience

Overseas, particularly in the United States and Canada, post-fire function is recognised as having both a major public safety and a societal cost benefit.

For instance, sprinklers are now not always required in previously specified applications. However, 90% of all fires in sprinkled buildings are controlled by the activation of four or fewer (effective) sprinklers. In Australia our record speaks for itself. There have been no fatalities in building fires where sprinklers have operated properly.

Fire modelling gives us a probabilistic solution to the expected fire in a given structure for a given fire load. However, different models currently available give widely differing results. So too can two different designers modelling the same fire with the same software. As with many types of design, the input determines the result, which may not correlate with actual performance.

As an example, the recent fire in the Channel Tunnel between England and France, in November 1996, showed the potential flaws in relying solely on the results of theoretical modelling. The design indicated that fire proofing on the tunnel's inner roof could be omitted. However, during the fire, explosive spalling of the concrete lining reduced the tunnel's thickness to only 50 mm in some locations. This was an outcome not predicted by the designers based on their input to and the results from the fire model, and obviously presented a serious problem.

Designers need to appreciate that the "human factor" is often a significant one in the performance of structures in fire. NFPA reports on several recent fires in industrial, commercial, institutional and residential buildings highlight the possible shortcomings of inappropriate understanding of building performance. Among the most common have been:

- fire doors wedged open allowing fire spread;
- fire doors permanently locked preventing escape;
- inadequately fire-stopped penetrations through compartment walls allowing fire transmission;
- inadequately maintained sprinkler and hydrant systems failing to operate effectively;
- later modifications to internal layouts rendering sprinklers or detectors ineffective through shielding;

6 FUTURE DEVELOPMENTS IN RESEARCH

6.1 Cardington Fire Research Projects, UK

The first stage of this ambitious project involved the construction of a full-size seven-storey composite steel-framed office building which has been fire tested to determine the actual performance of structural elements in typical office fire conditions. Further full-scale buildings of differing materials types have been constructed or are planned. A cast in-situ reinforced concrete office building is about to undergo similar testing at the time of writing.

The photographs below (figures 3 & 4) were taken after the testing of the composite frame and show typical damage to major load-bearing elements. The degree of damage from a fire of typical office fire loading shows the need for adequate design of both the active and passive protection systems for modern building structures.

The next stage, the European Concrete Building Project's in-situ concrete frame has been completed. This is the UK concrete construction industry's most ambitious project to date and is being led by the British Cement Association, the Building Research Establishment, and the Reinforced Concrete Council.

The frame is seven storeys in height and based on a plan of three bays by four and designed using Eurocode2. The building incorporates high-strength, high-performance concretes that will be tested under a similar fire load to the composite-framed structure described above.

Figure 3 - Typical Post-Fire Damage to Composite Slab

Figure 4 - Typical Post-Fire Damage to Slab at Column Perimeter in Composite Frame

6.2 Monash University, Australia

Monash University researchers tested eighteen slender reinforced concrete walls in standard fire conditions. Some of the results are presented in a poster presentation at this conference (Crozier and Sanjayan, 1999). The results show that the thermal bowing contributes to a significant reduction to in-plane load capacity of walls subjected to one-sided fire exposure (see Figure 5). The results also are in good agreement with the theoretical model. The details of the theoretical model can be found in Crozier and Sanjayan (1997). Research work is also being carried out at Monash University on residual strength of high-strength concrete beams exposed to fire (Crozier, Sanjayan and Liew, 1998) and spalling of high-strength in fire (Sanjayan and Stocks, 1993).

Figure 5 - Typical Post-Fire Damage to Wall Panel

7 DISCUSSION

In structural design we have traditionally relied upon a balance between the performance of materials, the validity of our design assumptions and the quality of construction. Over the years these have reached a balance where empirical evidence shows us the validity, or otherwise of our assumptions.

As discussed, the ever increasing pace of change with new methods of design and construction and the appearance of new or radically modified materials leaves prescriptive codes lagging and severely penalises specifiers and designers. However, performance-based codes sweep away the traditional balance effectively contained within the old prescriptive codes.

The new performance-based codes rely on new assumptions regarding the design and performance of our building structures. These can now be gauged much more accurately than before. One potential danger however is the current lack of comprehension by designers, specifiers and end users of the new responsibilities that come with the vastly increased flexibility offered by the new codes.

For instance, the designer can assume one of three fire control mechanisms (10): uncontrolled, contained (ie the fire is held within a defined locality until the fire brigade responds to put the fire out) and suppressed (ie the active fire control system puts the fire out). Each is possible to design for, and obviously have significantly different cost implications for the project, but each puts significantly different responsibilities on the designer.

The new codes and design recommendations can appear to imply a certainty of material performance, a certainty of design assumption, a certainty of construction and a certainty of structural maintenance- in fact perfect performance

It appears that many designers and building owners do not conceive of situations where all the disparate elements - the human as well as the material- will not work together in perfect harmony, eg fire doors that should seal off compartments are wedged open by occupants to ease access, sprinkler systems are rendered locally ineffective by the placement of screens or shelving, hydrants are switched off for testing and not reactivated afterwards, refurbishment works can and do create unprotected penetrations through fire walls. These conditions are all common occurrences in our buildings

Under the understandable pressure to refine designs to the maximum permissible for cost and space savings, some designers appear not to consider the need for a measure of redundancy or “robustness” in the structure.

It is the responsibility of both designers and users to ensure that the undoubted opportunities afforded by performance-based codes are translated into workable designs that allow for the reality of day to day usage.

As a final consideration, One Meridian Plaza, described above eventually cost $US4 billion (or almost $AUD6.5 billion). Fire losses to commercial property in Australia in 1997 totalled $AUD631 million (source: Insurance Statistics of Australia “commercial property claim type reports”). The possible cost savings to the Australian building industry that might be derived from performance-based codes have been postulated as being in the order of $AUD200 million per year (source: Fire Code Reform Centre). This is not inconsiderable, yet is small by comparison to even a single significant loss.

An appreciation of the level of risk attendant with the undoubted gains possible from the adoption of more rational codes of practice must become a part of every designers' understanding and application of these new codes.

8 CONCLUSIONS

1) Performance-based codes offer designers and specifiers significantly enhanced flexibility and the opportunity to take advantage of new materials, methods and knowledge specific to the situation or structure being considered.
2) The BCA however currently specifies fire protection requirements only in terms of preserving life, not property – a significant departure from the traditional approach which contained both.
3) Designers especially therefore, need to understand the limitations of these new provisions and the potential risks of assuming perfect operation of all the disparate elements that are involved in the fire performance of a building, e.g.. active and passive protection, fire brigade response and building use and maintenance
4) Specifiers, designers and end-users need to learn to adopt risk analysis as part of every performance design. E.g. that a saving of $1 million on structural costs may lead to a risk exposure of $100's millions in business interruption costs. This may be acceptable both to the client and society at large. However, it may not.

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