# CONCRETE BLADE COLUMNS IN FIRE

**KEYWORDS:** reinforced concrete, columns, fire resistance, standards.

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# Concrete Blade Columns in Fire

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**SYNOPSIS**

*The Building Regulations of Australia governing the design of structures to resist fire are changing. A distinction is being made between life safety and property protection. As a result traditional requirements for high levels of passive fire resistance are being reduced. In the specific area of parking buildings and parking garages under residential developments this is very evident. Blade columns are widely used in these applications but there is little information available to enable a rational design for the fire resistance of the column to be carried out. Further, there are anomalies between the fire design for concrete blade columns and masonry columns as set out in the respective Australian standards. This paper describes research which has used a computer program developed by the National Research Council of Canada, correlated against previous fire tests, and modified to evaluate the fire resistance of this particular type of column. A range of geometric cross-sections, material properties, and reinforcement areas were studied. It is concluded that the existing requirements for fire resistance of reinforced concrete columns are overly conservative. The results of this research are presented, and an alternative method for fire design has been developed. Amendments to AS 3600 are suggested.*

## 1. INTRODUCTION

The Building Code of Australia (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[1].

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.

The requirements for FRPs 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 which 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 only to columns with square or circular cross-section. This meant that the concessions in the previous standard AS 1480[2], which permitted blade columns to be designed as walls for fire purposes were negated. This has meant that reinforced concrete blade columns in situations such as carparks have been disadvantaged vis a vis square columns. This has also created the anomalous situation where reinforced concrete blade columns are required to have a minimum width of 300 mm whereas reinforced concrete masonry columns can be 190 mm wide.

Since the formulation of the rules in AS 3600, further test data has become available and computer simulation programs, based on heat transfer theory and engineering analysis, have been developed to predict the behaviour of reinforced concrete columns under fire conditions. Therefore, the Cement and Concrete Association of Australia and the Steel Reinforcement Institute of Australia funded the Building Research Association of New Zealand to carry out a research program to address these restrictions and to try and resolve the anomaly. This paper presents the findings of this research.

## 2. PROJECT METHODOLOGY

The approach adopted for this project was to use a computer model to calculate the thermal and structural response of reinforced concrete columns under simulated standard fire conditions. A model[3] developed by the National Research Council of Canada (NRCC) was identified as being suitable for this purpose, with comparison with available experimental data showing reasonable agreement. The key design parameters for the columns were identified[4,5], and a parametric study was designed to cover different parameter values that might reasonably be expected in practice. This required many computer simulations to be carried out. The results were analysed by attempting to fit a conservative equation to the computer simulation results using a multiple linear regression technique. The form of the equation was intended to be suitable for inclusion in a building control document for determining the fire resistance of reinforced concrete columns.

## 3. MATERIAL PROPERTIES

The material properties required as input to the computer model included: thermal conductivity, heat capacity, moisture content, thermal expansion and stress-strain relationships for the concrete, and thermal expansion and stress-strain relationships for the reinforcing steel. The literature was reviewed and it was found that Lie[6] provided the most

comprehensive set of properties in a form that could be utilised in this study. The following material properties are taken from Lie except where otherwise noted.

### 3.1 Concrete

The following values for thermal conductivity, $k_c$, as a function of temperature, $T$, of a siliceous aggregate concrete were used in this study.

$$\text{For } 0 < T \le 800°\text{C}, \quad k_c = -0.000625T + 1.5 \text{ Wm}^{-1}°\text{C}^{-1}$$

$$\text{For } T > 800°\text{C}, \quad k_c = 1.0 \text{ Wm}^{-1}°\text{C}^{-1}$$

Similarly, the values for the heat capacity, $\rho_c c_c$, of a siliceous aggregate concrete were:

$$\text{For } 0 \le T \le 200°\text{C}, \quad \rho_c c_c = (0.005T + 1.7) \times 10^6 \text{ Jm}^{-3}°\text{C}^{-1}$$

$$\text{For } 200°\text{C} < T \le 400°\text{C}, \quad \rho_c c_c = 2.7 \times 10^6 \text{ Jm}^{-3}°\text{C}^{-1}$$

$$\text{For } 400°\text{C} < T \le 500°\text{C}, \quad \rho_c c_c = (0.013\text{T} - 2.5) \times 10^6 \text{ Jm}^{-3}°\text{C}^{-1}$$

$$\text{For } 500°\text{C} < T \le 600°\text{C}, \quad \rho_c c_c = (-0.013\text{T} + 10.5) \times 10^6 \text{ Jm}^{3}°\text{C}^{-1}$$

$$\text{For } T > 600°\text{C}, \quad \rho_c c_c = 2.7 \times 10^6 \text{ Jm}^{-3}°\text{C}^{-1}$$

The following elevated temperature values for the coefficient of thermal expansion, $\alpha_c$, of concrete were used.

$$\alpha_c = (0.008T + 6) \times 10^{-6} \text{ °C}^{-1}$$

The following stress-strain curves for concrete as a function of temperature were used in this study. Stress-strain data for concretes of differing initial compressive strength can be derived from these formulations.

$$\text{for } \varepsilon_c \le \varepsilon_{\max}, \quad f_c = f_c'\left[1 - \left(\frac{\varepsilon_{\max} - \varepsilon_c}{\varepsilon_{\max}}\right)^2\right]$$

$$\text{for } \varepsilon_c > \varepsilon_{\max}, \quad f_c = f_c'\left[1 - \left(\frac{\varepsilon_c - \varepsilon_{\max}}{3\varepsilon_{\max}}\right)^2\right]$$

$$\text{where: } \quad f_c' = f_{co}' \text{ if } T < 450°\text{C}$$

$$f_c' = f_{co}'\left[2.011 - 2.353\left(\frac{T - 20}{1000}\right)\right] \text{ if } T \ge 450°\text{C}$$

$$\varepsilon_{\max} = 0.0025 + (6.0T + 0.04T^2) \times 10^{-6}$$

Graphically, these equations are shown in Figure 1 for a siliceous aggregate concrete with a 28-day compressive strength of 35 MPa.

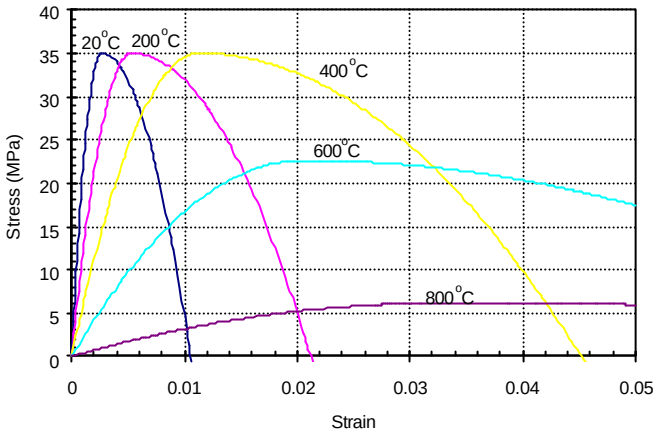


**Figure 1 : Stress-Strain Relationship for 35 MPa Concrete**

Moisture present in the concrete will also have an effect on the fire resistance, with some of the energy from the fire being absorbed during evaporation of that moisture. The value of moisture content assumed for this project is 5% by volume (or about 2.2% by mass). This is the same as used by Lie and Celikkol[7] in a study of fire resistance of circular concrete columns and is considered to be acceptable here.

### 3.2 Steel

The thermal expansion of steel can be related to its temperature by a coefficient of expansion, which is defined as the expansion of a unit length of the steel when it is raised 1°C in temperature. The following elevated temperature values for the coefficient of thermal expansion, $\alpha_s$, of steel were used in this study.

$$\text{for } T < 1000°\text{C}, \quad \alpha_s = (0.004T + 12) \times 10^{-6} \text{ °C}^{-1}$$

$$\text{for } T \ge 1000°\text{C}, \quad \alpha_s = 16 \times 10^{-6} \text{ °C}^{-1}$$

The yield strength of the reinforcing steel (Grade 400Y) was taken as 400 MPa. A 500 MPa steel was also investigated but is not reported or discussed here, other than to say it resulted in a small improvement in the fire resistance. The strength of steel at elevated temperatures decreases rapidly and at 600°C the strength has reduced to about one half of the original value.

The following stress-strain curves were used.

$$\varepsilon_p = 4 \times 10^{-6} f_{y0}$$

$$\text{For } \varepsilon_s \le \varepsilon_p, \quad f_y = \frac{f(T, 0.001)}{0.001}\varepsilon_s \quad \text{where:}$$

$$f(T,0.001) = (50 - 0.04T) \times \{1 - \exp[(-30 + 0.03T)\sqrt{(0.001)}]\} \times 6.9$$

For $e_s > e_p$,

$$f_y = \frac{f(T,0.001)}{0.001} e_p + f[T,(e_s - e_p + 0.001] - f(T,0.001)$$

where :

$$f[T,(e_s - e_p + 0.001)]$$
$$= (50 - 0.04T) \times \{1 - \exp[(-30 + 0.03T)\sqrt{e_s - e_p + 0.001}]\} \times 6.9$$

Graphically, these equations are shown in Figure 2 for Grade 400Y reinforcing steel.

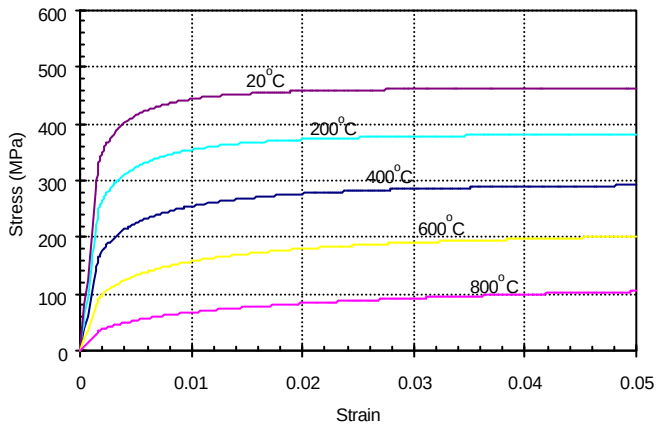


**Figure 2 : Stress-Strain Relationship for Grade 400Y Steel**

## 4. THE DESIGN FIRE

The design fire used was that specified in AS 1530 Part 4[8]. This fully-developed fire can be described by the following equation.

$$T - T_o = 345 \log_{10}(8t + 1)$$

where:

$T$ = furnace gas temperature (°C)

$T_o$ = initial temperature (taken as 20°C)

$t$ = time (minutes)

This fire is similar to, but not the same as, that used in published studies[3,7] of the fire resistance of concrete columns using the NRCC computer model. Other heat transfer properties (such as furnace wall emissivity, convective heat transfer coefficient and concrete emissivity), found to be acceptable for the NRCC column furnace, were used.

## 5. PARAMETRIC STUDY

Previous studies have identified design variables affecting fire resistance of rectangular reinforced concrete columns. They include: load level, percentage of longitudinal steel, effective length, concrete compressive strength, column cross-sectional area, and column shape or aspect ratio. Concrete aggregate type is also important but was not investigated as part of this study. Analysis was based upon a concrete using normal-weight siliceous aggregate which represents a reasonable worse case. Eleven different sized columns were considered, as shown in Table 1. Three values of concrete compressive strength and three values of slenderness ratio were considered, as shown in Table 2. The overall analysis allowed for concrete strength to be in the range 20-50 MPa.

Since effective length is used as an input to the NRCC model, rather than slenderness ratio, the relationship between effective length and slenderness ratio for columns of different least dimension was determined. Radius of gyration for a rectangular column is taken as 0.3 × least dimension from AS 3600 clause 10.5.2.

**Table 1 : Column Cross-Section Shapes**

| Aspect Ratio | Lesser Column Dimension (mm) | | | |
|---|---|---|---|---|
| | 150 | 200 | 300 | 500 |
| 1:1 (=1) | | ✓ | ✓ | ✓ |
| 1:2 (=2) | | ✓ | ✓ | ✓ |
| 1:4 (=4) | ✓ | ✓ | ✓ | |
| 1:8 (=8) | ✓ | ✓ | | |

**Table 2 : Concrete Strength / Slenderness Ratio**

| Concrete Compressive Strength (MPa) | Slenderness Ratio | | |
|---|---|---|---|
| | 22 | 25 | 40 |
| 25 | ✓ | ✓ | ✓ |
| 35 | ✓ | ✓ | ✓ |
| 40 | ✓ | ✓ | ✓ |

Two values of concrete cover to vertical reinforcing steel and two values of reinforcement ratio were considered, as shown in Table 3 .

**Table 3 : Cover / Steel Area**

| Cover to Face Vertical Steel | Steel Area / Gross Column Area |
|---|---|

| (mm) | 1% | 2.5% |
|---|---|---|
| 25 | ✓ | ✓ |
| 35 | ✓ | ✓ |

From AS 3600 Table 4.10.3.2, concrete cover to the face of reinforcing steel will typically be in the range 20 - 45 mm. However, the longitudinal steel is normally restrained with ties so the typical cover to the longitudinal steel will be slightly larger. AS 3600 clause 10.7.1 requires the area of longitudinal steel to typically be in the range 1 - 4% of the gross cross-sectional area of the column.

For each column size, two reinforcement amounts were selected (1% and 2.5%) and the corresponding (hypothetical) bar diameter was determined.

## 6. THE COMPUTER MODEL

The computer model was developed at NRCC and included the calculation of the temperatures in the column as well as its deformations and strength during the exposure to fire. The model was modified by NRCC to specifically incorporate the material properties and design fire identified in this study, but the underlying calculation technique used was unchanged. A detailed account of the model will not be given here as it has been published in several other places[3,7,9]. An overview of the model, based on Lie and Irwin[3] follows.

The cross-sectional area of the column is divided into a triangular network, with square elements within the column and triangular shaped elements at the surface. By symmetry, only one-quarter of the column cross-section needed to be analysed in the thermal model. The column was assumed to be exposed to a standard fire resistance time-temperature boundary condition on all sides. The temperature rise at the different points in the column is determined from an energy balance, using a finite difference technique.

The effect of moisture is considered by assuming the moisture starts to evaporate when the column element reaches 100°C. At this time the energy input is directed into evaporating the moisture instead of increasing the temperature of the element. This continues until all the moisture is evaporated, at which point the element starts to increase in temperature again. Moisture migration through the concrete is not modelled.

In order to determine the strength of the column during the exposure to fire, the triangular network is transformed into a rectangular network, and it is assumed that the stresses and deformations at the centre of an element are representative of those of the whole element. The strength of the column is determined from a load-deflection analysis, with the strength reducing with the duration of exposure. The columns are represented as pin-ended columns with an effective length of $L_e$. Given a small initial eccentricity, the curvature, $\chi$, of the column is assumed to vary from pin-end to mid-height according to a straight line relationship where the deflection, Y, at mid-height is given by:

$$Y = c\frac{(L_e)^2}{12}$$

Thus for any given deflection at mid-height and curvature, the axial strain is varied until the internal moment at the mid-section is in equilibrium with the applied moment at any point given by:

load × (deflection + eccentricity)

A load-deflection curve is then determined at specified times during the fire exposure. In determining the column strength the following assumptions were also made:

a) The properties of the concrete and steel are as described elsewhere in this report.

b) Concrete has no tensile strength.

c) Plane sections remain plane.

d) The reduction in column strength due to shrinkage, creep and shortening due to load prior to fire exposure is negligible.

The fire resistance of the column is determined by equating the strength of the column at any time to the applied axial load. When the strength of the column falls below the value of applied load, failure is assumed to occur under fire exposure and the time at which this occurs is the Fire Resistance Period of the column.

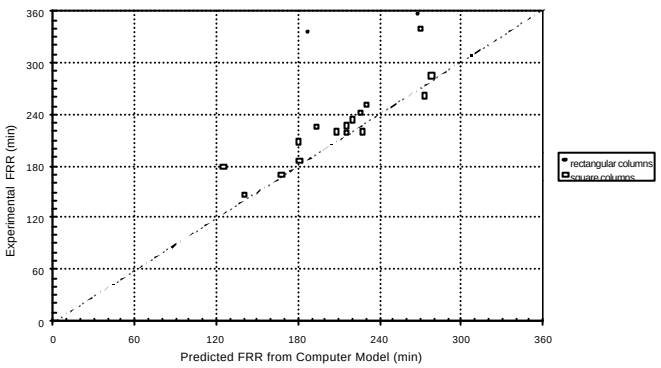


**Figure 3 : Comparison Between the Computer Model and Experiments**

## 7. COMPARISON WITH EXPERIMENTS

The modified NRCC computer model was used to predict the times to failure of a selected number of reinforced concrete columns previously tested by NRCC in Canada[10]. The comparison is shown in Figure 3. Of the 18 columns presented in Figure 3, all except two had a square cross-section. The column design parameters varied were concrete cover, applied load, effective length, concrete/steel strength, moisture content and the length of the column side. However, the fire exposure assumed in the model differed from that of the test. The test exposure followed the North American fire resistance time-temperature curve, ASTM E119[11], while the computer model used the AS 1530 Part 4 curve. The exposures are

sufficiently similar such that the effect on the time to failure is expected to be quite small.

## 8. RESULTS

A total of 792 computer simulations were carried out. The output of each computer simulation was a plot of the column strength as a function of time. It was then possible to identify the maximum (factored) design axial load for any fire resistance time of interest (eg 30, 60, 90, 120, 180 and 240 minutes or intermediate values) for each of the simulated cases.

The required simulations were divided into four different cases or categories for the 400 MPa reinforcement, as described in Table 4 below. (A further four cases were also developed for 500 MPa steel but are not presented here). In the analysis, steel yield strength, cover to steel reinforcement and the ratio of steel cross-section area to the gross column area were treated as non-continuous variables (ie. they had given fixed values). All the other relevant variables were permitted to vary continuously within defined limits.

**Table 4 : Summary of Cases for 400 MPa Reinforcement**

| Case | Cover to Steel Reinforcement (mm) | % Steel |
|---|---|---|
| 1 | 35 | 2.5 |
| 2 | 35 | 1.0 |
| 3 | 25 | 2.5 |
| 4 | 25 | 1.0 |

For each case, a multiple linear regression analysis using Microsoft Excel[12] was carried out to determine how well the fire resistance of a column could be represented by an equation of the following form.

$$R = \frac{k \times f_c'^{\mathrm{a}} \times B^{\mathrm{b}} \times D^{\mathrm{c}}}{C^{\mathrm{d}} \times L_e^{\mathrm{e}}}$$

where: $R$ = fire resistance period of the column (min)
$k$ = a constant dependent on the cover and amount of steel
$f_c'$ = the 28-day compressive strength of the concrete (MPa)
$B$ = least dimension of the column (mm)
$D$ = the greatest dimension (mm)
$C$ = the design axial load for fire conditions (kN)
$L_e$ = effective length (mm)
a,b,c,d,e = regression constants

The load specified will be according to AS 1170[13]. This allows, for the fire limit state, a design load taken from the following combination of factored loads.

$$1.1\,G + \psi_c\,Q$$

where : $G$ = dead load

$Q$ = live load

$\psi_c$ = live load combination factor from AS 1170.1 Table 2.2.

The five dependent variables were converted to base-10 logarithms to formulate the linear regression relationship as follows.

$$\log_{10} R = \log_{10} k + a \log_{10} f_c' + b \log_{10} B + c \log_{10} D - d \log_{10} C - e \log_{10} L_e$$

The results obtained for the power relationships (a,b,c,d,e) providing the best fit for each case were then averaged over all cases, giving the following relationship between fire resistance and the various design parameters. These values are given in the equation below. The value of $k$ given in Table 5 was determined such that approximately 95% of the data points provided a conservative estimate of fire resistance compared to the value determined directly from the computer model.

$$R = \frac{k \times f_c'^{1.3} \times B^{3.3} \times D^{1.8}}{10^5 \times C^{1.5} \times L_e^{0.9}} \quad \text{..... [equation 1]}$$

The above equation requires that a value for $C$ of no less than 40% of the initial ultimate strength in compression of the column be used in equation 1 ($\geq 0.4\,N_{uo}$ in AS 3600 terminology). A comparison between the fire resistance obtained using this equation and that obtained directly from the computer model for one of the four cases is shown in Figure 4. The comparisons for the other cases are similar in appearance.

**Table 5 : k-Values for Design Equation**

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

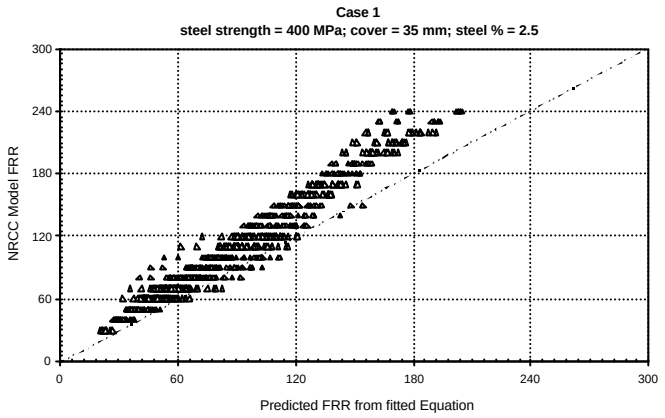


**Figure 4 : Comparison Between Equation and Model**

## 9. SENSITIVITY ANALYSIS

The main reason for carrying out this research project was to quantify the increase in fire resistance with an increase in the aspect ratio of the column. A sensitivity study was carried out using the computer model. Figure 5 compares columns of different aspect ratio, showing the maximum applied load permitted for different fire resistance periods. It can be seen that for a given load, increasing the aspect ratio results in a significant improvement in the fire resistance of the column. Other design parameters for the columns are as noted in the figure. The current AS 3600 assigns a fire resistance of 60 minutes to all four of these columns based on the cover and column least side dimension.

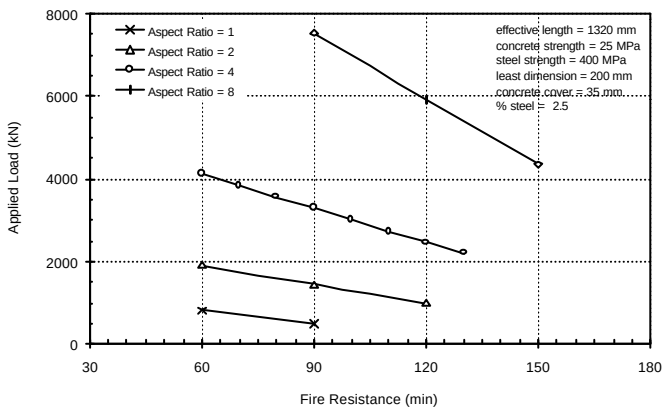


**Figure 5 : Effect of Changing Aspect Ratio**

The effect of changing the column least side dimension, and maintaining a constant aspect ratio of 2, is shown in Figure 6. As expected, the fire resistance achieved for a given load increases significantly as the least dimension is increased.

Varying the concrete compressive strength also increases the fire resistance for a given load, as shown in Figure 7.

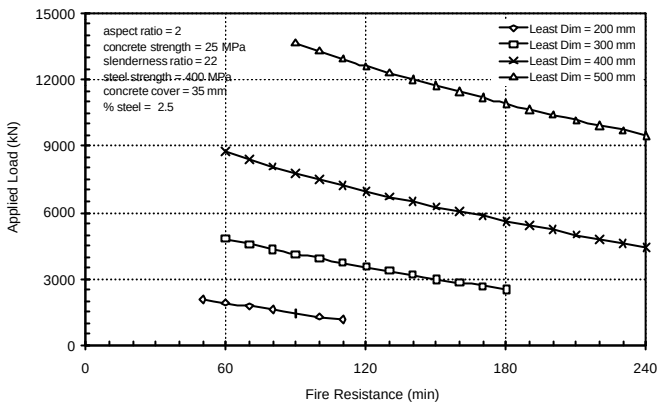


**Figure 6 : Effect of Changing Least Dimension**

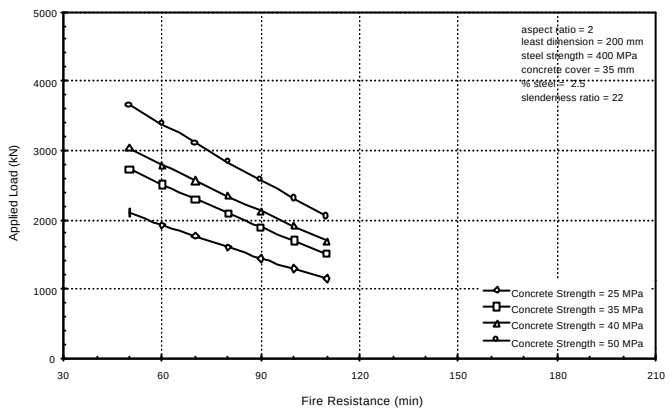


**Figure 7 : Effect of Changing Concrete Strength**

**Table 6 : Comparison Between Proposed Design Equation and AS 3600 Fire Resistance Values**

| Column Size (mm/mm) | Fire Resistance from Eqn 1 (min) | Fire Resistance from AS 3600 (min) |
|---|---|---|
| 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 |

## 10. COMPARISON WITH AS 3600

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 6, assuming a 28-day characteristic compressive strength of 35 MPa, concrete cover of 35 mm, slenderness ratio of 25, design load = 0.5 $N_{uo}$ 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.

## 11. CONCLUSIONS

Blade (rectangular) columns have an improved fire resistance compared to a square column of the same least dimension. An equation, based on multiple linear regression analysis, has been described for the fire resistance of normal-weight siliceous aggregate columns intended for future use in AS 3600, which will take this improved performance into account. It will also account for variations in the concrete compressive strength, the fire design axial load, the effective length or slenderness ratio of the column, cover to steel, amount of cross-sectional steel, and least column dimension, for both square and rectangular columns. This will allow more accurate and less conservative predictions of fire resistance to be made compared with existing AS 3600 requirements.

## 12. ACKNOWLEDGEMENTS

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## 13. NOMENCLATURE

a,b,c,d,e = constants
$c$ = specific heat (J kg-1°C-1)
$f_c$ = compressive strength of concrete at temperature $T$ (MPa)
$f_c'$ = cylinder strength of concrete at temperature $T$ (MPa)
$f_y$ = strength of steel at temperature $T$ (MPa)
$k$ = thermal conductivity ($Wm^{-1}°C^{-1}$)
$k$ = constant (in design equation)
$t$ = time (min)
$B$ = least dimension of column (mm)
$C$ = fire design limit state axial load (kN)
$D$ = greatest dimension of column (mm)
$G$ = dead load (kN)
$L_e$ = effective length (mm)
$N_{uo}$ = initial ultimate strength in compression (kN)
$Q$ = live load (kN)
$R$ = fire resistance (min)
$T$ = temperature (°C)
$Y$ = deflection at mid-height (mm)

### Greek Letters

$\alpha$ = coefficient of thermal expansion ($°C^{-1}$)
$\varepsilon$ = strain ($m^{-1}$)
$\rho$ = density ($kgm^{-3}$)
$y_c$ = live load combination factor
$\chi$ = column curvature

### Subscripts

c = concrete
max = maximum
o = room temperature value
p = plastic
s = steel

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