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SUMMARY REPORT ON A FINITE ELEMENT PROGRAM FOR MODELLING THE THERMAL RESPONSE OF BUILDING COMPONENTS EXPOSED TO FIRE

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PREFACE

This work completes the first stage of a project concerned with modelling the fire resistance of building elements using numerical methods. It focuses on the thermal response of simple concrete and steel members compared with results from standard fire resistance tests.

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KEYWORDS

Beams; Columns; Concrete; Design; Fire; Fire Resistance; Fire Properties; Floors; Mathematical Models; New Zealand; Steel.

ABSTRACT

This report summarises work carried out in a research project aimed at modelling, by computer, the performance of building components when exposed to fire. A finite element computer program (NISA) was used to predict temperatures on and within steel I-sections and concrete slab components. Useful results were obtained.

The study concludes that the finite element computer program (NISA) will be useful for analysing fire-resistance performance. Common building components made of concrete and steel have been modelled in this study, with relatively good agreement being achieved between calculated and measured values. In general, results tend to over-estimate temperatures (rather than under-estimate) and for practical purposes this enables the program to be used with confidence for the types of components and materials included in this study. Further work is required to establish the same level of confidence for other materials and types of components.

In further work it is intended to use the program to model the performance of concrete floors exposed to real (non-standard) fires, and to consider the effects of fire on structural behaviour by calculation of the resultant stresses and deformations in structural building elements.

Contents

Introduction

Aim

This report describes the use of a finite element program (NISA) for modelling the temperatures on and within building components exposed to fire. The components considered were: alluvial quartz concrete slabs and steel I-sections (exposed as a column and as a beam/floor slab). The work described in this report was carried out to:

- assess how useful the finite element program is likely to be for analysing fire-resisting performance of buildings; and
- assess the accuracy of results obtained from the program by comparison with data recorded in standard fire resistance tests; and
- thereby establish the utility of the program for further applications.

The Program

The computer program used is a commercial general-purpose finite element package capable of handling non-linearity and temperature-dependent material properties for problems of transient heat transfer. The program is called NISA II and is supplied and supported by the Engineering Mechanics Research Corporation[1]. In addition to the main module for heat transfer analysis (HEAT) there are pre- and post-processing modules for ease of model construction, finite element meshing and analysis of results.

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[1]Engineering Mechanics Research Corporation, PO Box 696, Troy, Michigan 48099 USA.

A Theoretical Overview

NISA II - Summary of Capabilities

With respect to problems concerning heat transfer at fire temperatures, NISA II is capable of taking the following factors into account.

- time-dependent fire/furnace gas temperatures
- material properties which are time- and/or temperature-dependent
- 1, 2, or 3 dimensional analysis
- emissivity and convective heat transfer coefficients which may vary with temperature
- phase changes e.g. evaporation of moisture
- automatic finite element meshing routines

Heat Transfer

There are many heat transfer texts available. Incropera and deWitt (1990) have been used for reference in this study.

Conduction

Materials are assumed to obey Fourier's Law of heat conduction such that:

$$q'' = -k\left(\mathbf{i}\frac{\partial T}{\partial x} + \mathbf{j}\frac{\partial T}{\partial y} + \mathbf{k}\frac{\partial T}{\partial z}\right)$$ (refer to page 30 for all nomenclature)

The heat diffusion equation is obtained by considering the heat flow within the body, and conservation of energy, and is given by:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{q}=\rho c_p\frac{\partial T}{\partial t}$$

Radiation

Consider grey bodies or surfaces for which the emissive power is independent of the radiation wavelength. Assume a body of surface temperature T_s, is enclosed within a space with wall temperature T_e. The radiant energy emitted from the surface of the body per unit time and area is given by q^r.

$$q^r = \varepsilon\sigma T_s^4$$

Radiant energy absorbed by the surface due to the wall temperature T_e is given by q^a.

$$q^a = \alpha\sigma T_e^4$$

From Kirchoff's Law : $\alpha \approx \varepsilon$

The net rate of radiation heat exchange between the surface and its surroundings, expressed per unit of surface area, is:

$$q'' = \varepsilon\sigma\left(T_e^4 - T_s^4\right)$$

Now considering a fire situation, and assuming a special case where the test specimen has been inserted into an isothermal black-body cavity (Mooney, 1992), the net rate of radiation exchange can be given as:

$$q'' = \varepsilon\sigma\left(T_f^4 - T_s^4\right)$$

(Where T_f = temperature of the fire gases, T_S = surface temperature of the test specimen, and ε = emissivity of the specimen surface.)

There is some debate in the literature with respect to the emissivity term and Mooney (1992) gives a good summary.

Convection

When part of the surface of the body is in contact with a fluid medium with temperature T_f, the rate of heat exchange between the body and the fluid is given by Newton's Law of cooling.

$$q'' = h\left(T_f - T_s\right)$$

Material Properties

Concrete

General

In this study, alluvial quartz concrete was selected for investigation as it was previously found (Wade, 1992) to be the least insulating of the concrete types currently used in New Zealand for which test data is available and therefore represents a worse case situation.

Thermal Conductivity

The molecular structure of the aggregate has an important influence, with crystalline materials having a higher thermal conductivity than amorphous materials. The thermal conductivity of dry quartz concrete as given by Lie and Williams-Leir (1979) is shown in Table 1.

Specific Heat

The specific heat of alluvial quartz concrete is also given in Table 1. In siliceous aggregates containing quartz, an "artificial" increase in the specific heat is observed due to an endothermic process ocurring when the α-quartz changes to β-quartz at about 500°C.

Density

Density of alluvial quartz concrete at elevated temperature was assumed to be constant at 2300 kg/m^3.

Temperature		Thermal Conductivity	Specific Heat
(°C)	(K)	(W/mK)	(J/kg K)
0	273	2.57	765
25	298	2.57	765
50	323	2.49	809
75	348	2.42	852
100	373	2.36	883
115	388	2.34	935
125	398	2.31	987
150	423	2.25	1061
175	448	2.19	1096
200	473	2.14	1113
225	498	2.09	1126
250	523	2.05	1139
275	548	2.02	1148
300	573	1.99	1157
325	598	1.96	1165
350	623	1.93	1174
375	648	1.90	1183
400	673	1.86	1196
425	698	1.81	1274
450	723	1.76	1478
475	748	1.70	1683
500	773	1.64	1796
525	798	1.57	1683
550	823	1.52	1509
575	848	1.49	1400
600	873	1.45	1287
625	898	1.43	1191
650	923	1.41	1178
675	948	1.38	1174
700	973	1.36	1183
750	1023	1.31	1170
800	1073	1.28	1135
850	1123	1.28	1117
900	1173	1.28	1122
1000	1273	1.28	1139
1100	1373	1.31	1148
1200	1473	1.34	1161
1275	1548	1.36	1170

Table 1 : Thermal Properties of Dry Quartz Concrete

Moisture

The effect of moisture in the concrete can be significant because the energy required to evaporate the water is not available to increase the temperature of the concrete. Typically, therefore, a plateau will be apparent in the time-temperature curve at about 100°C.

The effect of moisture is taken into account by specifying the volumetric enthalpy versus temperature curve for moist concrete. The product of specific heat and density (known as volumetric heat capacity) is determined from the slope of the enthalpy curve as follows:

$$\frac{dE}{dT} = c_p \rho$$

and by integrating over the temperature range T_0 to T –

$$E = \int_{T_0}^{T} c_p \rho \, dT + \sum \ell_i$$

where: E = volumetric enthalpy $\left(\mathrm{J/m^3}\right)$

c_p = specific heat $\left(\mathrm{J/kg \cdot K}\right)$

ρ = mass density $\left(\mathrm{kg/m^3}\right)$

ℓ_i = latent heat due to phase changes $\left(\mathrm{J/m^3}\right)$

Considering the concrete and water separately, and making a mathematical approximation by assuming the moisture evaporates between the temperatures of 100°C and 115°C as shown in Figure 1, the total volumetric enthalpy can be given as follows. (Volumetric enthalpy is represented by the area under the curve. The approximation made is that the area under the curve between 100°C and 115°C is equal to the latent heat of vaporisation of water taken as 2257 kJ/kg.)

$$E_{total} = E_{conc} + m_c E_{water} = \int_{T_0}^{T} c_p^c \rho^c \, dT + m_c \int_{T_0}^{T} c_p^w \rho^w \, dT \left(\mathrm{J/m^3}\right)$$

$$= \int_{T_0}^{T} c_p^c \rho^c \, dT + m_c \left[\int_{T_0}^{T_{100}} c_p^w \rho^w \, dT + \ell_i \right]$$

The finite element model assumes that once the moisture has been evaporated it is removed from the system. In reality it is not as simple as this, because of mass transport of moisture which can be driven through a slab, evaporating and condensing at various depths. Imagine a single point within the thickness of a concrete slab. Not only is energy required to drive off moisture associated with that element volume, but moisture associated with other elements closer to the fire-exposed face may have been driven through the slab to condense at the element in question. So to that element, in terms of the energy requirement to remove moisture, it may appear to have a higher "effective" moisture content than its original measured moisture content. For the same reason the "effective" thermal conductivity may also appear to be higher. This effect is likely to become more dominant the greater the distance from the fire-exposed face.

From a modelling viewpoint, assuming the actual or measured moisture content for calculation purposes is likely to yield a conservative solution.

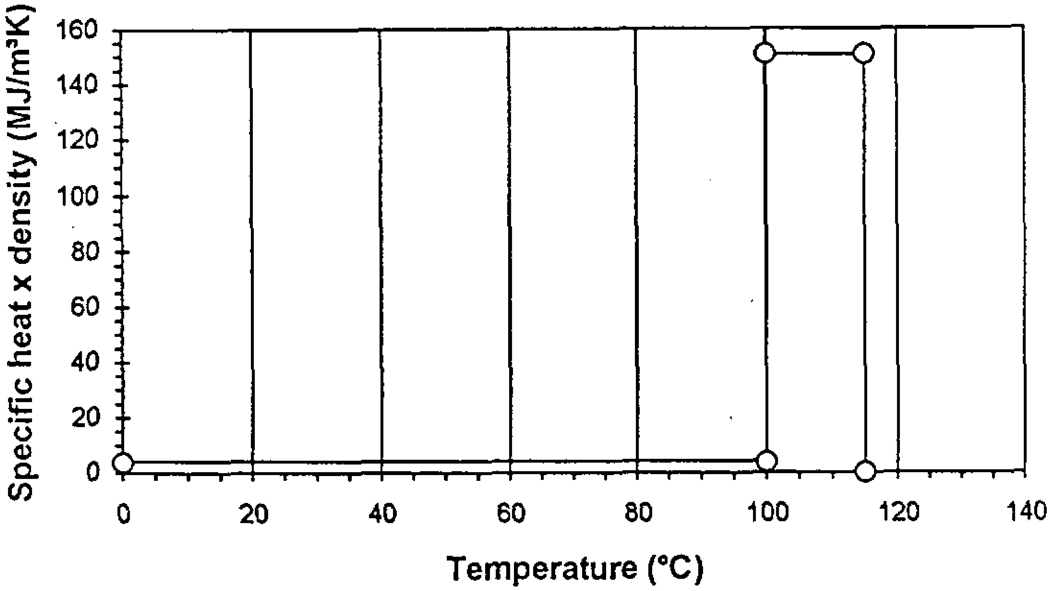


Figure 1 : Heat Capacity of Water

Steel

Thermal Conductivity

The thermal conductivity of steel as a function of temperature is given in Table 2 from Wainman et al. (1990).

Specific Heat

The specific heat of steel as a function of temperature is also given in Table 2 from Wainman et al. (1990). The properties can be considered to relate to Grade 43A structural steel (hot rolled sections). At around 730°C, steel undergoes a phase change to adopt a denser internal structure. This is characterised by a jump in the specific heat at that temperature as shown in Table 2.

Incropera and deWitt (1990) provide data for a carbon-manganese-silicon steel (1%<Mn<1.65%;0.1%<Si<0.6%) which is representative of Grade 50B steel, and this is shown in Table 3.

Density

The density of steel is approximately 7850 kg/m³. Table 2 also tabulates mass density as a function of temperature, again from Wainman et al. (1990).

Incropera and deWitt (1990) give the density of carbon-manganese-silicon steel (Grade 50B) as 8131 kg/m³ at 27°C.

Temperature (°C)	Thermal conductivity (W/m.K)	Specific heat (J/kg.K)	Density (kg/m³)
20	52.0	440	7850
50	51.7	450	7842
100	51.0	480	7827
150	50.0	505	7812
200	48.8	530	7797
250	47.5	550	7781
300	46.0	565	7765
350	44.5	585	7748
400	42.7	610	7731
450	41.0	640	7713
500	39.2	675	7695
550	37.5	715	7675
600	35.5	760	7655
650	33.8	820	7635
700	32.0	1010	7616
725	31.0	1600	7608
735	30.0	5000	7612
750	28.5	1300	7618
775	26.5	1010	7622
800	26.0	810	7626
825	25.8	730	7627
850	26.0	685	7622
875	26.2	660	7611
900	26.5	650	7599
950	27.0	650	7574
1000	27.5	650	7549
1050	28.0	650	7523
1100	28.5	650	7500
1150	29.0	655	7477
1200	29.5	655	7453

Table 2 : Thermal Properties of Steel (Grade 43A)

Temperature (°C)	Temperature (K)	Thermal conductivity (W/m.K)	Specific heat (J/kg.K)
27	300	41.0	434
127	400	42.2	487
327	600	39.7	559
527	800	35.0	685
727	1000	27.6	1090

Table 3 : Thermal Properties of Steel (Grade 50B)

Boundary Conditions

Standard Fire Resistance Test

This study is concerned with comparing the measured temperatures, from standard fire resistance tests, on and within building components with the results of analytical studies based on finite element modelling techniques. It is necessary to establish confidence in the model's prediction of standard fire test results before modelling alternative design fires. In standard fire resistance testing, the furnace temperature is driven to follow a prescribed time-temperature curve. For example, ISO 834 (ISO, 1975) and BS 476 Part 8[2] (BSI, 1972) specify the following:

$$T_{fire} = 345\log_{10}(8t+1) + T_0$$

where: T_{fire} = furnace gas temperature $(°C)$

T_0 = initial temperature $(°C)$

t = time interval (min)

The time-temperature curve specified in BS 476 Part 20 (BSI, 1987) is identical except that $T_0 = 20°C$. In the calibration studies which follow, the actual gas temperatures were used in specifying the analytical boundary conditions. In making practical use of the finite element model, the prescribed standard time-temperature curve would be specified, or any time-temperature curve which is appropriate to the fire, and which may depend on ventilation, fire load, rate of burning etc.

[2] Superseded by BS 476 Part 20 in 1987.

Radiation

The boundary conditions to be specified for radiation are the resultant emissivity and the ambient temperature. For fire-exposed surfaces, the ambient temperature is time-dependent and can be specified using actual measured gas temperatures or from the standard time-temperature curve given above. For non-exposed surfaces e.g., on the unexposed side of a wall or floor slab, the ambient temperature may be assumed to be constant.

The term resultant emissivity is commonly used to represent emissivity modified by surface properties and geometric configuration, although this approach has been disputed by Mooney (1992). The resultant emissivity of building materials exposed to fire is typically in the range 0.6 to 1.0 (Sterner and Wickström, 1990) and will vary with temperature and the characteristics of the test furnace.

For concrete, a resultant emissivity of 0.9 is commonly assumed. For steel, ECCS (1985) recommends a general value of 0.5, while guidance is given by Kirby (1986) for steel sections as follows:

Element location	**Resultant emissivity**
external column	0.3
internal columns	0.7
beam exposed to direct flame	0.5-0.7
beam protected from direct flame or beneath a very high ceiling	0.3-0.5

In this study radiation exchange between the different surfaces (e.g., between the web and flanges of an I-section) has not been taken into account. This effect is not likely to be significant for a conductive material such as steel, but would need to be considered for less conductive materials and would be particularly important in cavity wall construction.

Convection

Convection is generally not as important as radiation on the fire-exposed surfaces, but can be significant on the unexposed surfaces. Sterner and Wickström (1990) state that a value of approximately 25 $W/m^2.K$ for the heat transfer coefficient is commonly found in the fire literature. CEB (1987) propose a value of 25 $W/m^2.K$ for fire-exposed concrete surfaces and 15 $W/m^2.K$ for the unexposed surfaces.

A theoretical approach (Appendix A) assuming free convection heat exchange between a heated vertical plate and air shows $h \approx$ 6-8 W/m².K is reasonable for the unexposed surface.

A similar approach assuming forced air flow over a vertical plate shows that $h \approx$ 8-12 W/m².K is a reasonable value for the fire-exposed face, and therefore the 25 W/m².K commonly recommended seems rather high. The assumed theoretical flow characteristics may differ from the actual situation in a fire test furnace, and in a real fire compartment, and therefore variability in the convective heat transfer coefficient can be expected to some extent.

Another possible explanation for the difference between the theoretical estimate and commonly used or recommended values could also be that a higher heat transfer coefficient gives better correlation with test results by compensating for the fact that furnace thermocouples do not measure the actual gas temperature because of radiation and convective heat losses from the thermocouples, but rather the thermocouple temperatures lie somewhere between the actual gas temperature and the temperature of the bounding surfaces (Keltner and Moya, 1989).

Values of 7 W/m².K and 10 W/m².K will be used in this study for the unexposed and exposed surfaces respectively.

Calibration Studies

Alluvial Quartz Concrete Slab - 175 mm Thick

Test Data

A 175 mm thick alluvial quartz concrete slab was tested in a vertical orientation in the oil-fired BRANZ furnace (Wade, 1992). The moisture content at the time of test was determined to be 2.8% by mass. The time-temperature curve followed ISO 834 (ISO,1975) and the initial temperature was 12°C (285 K). Temperatures within the slab were recorded over a 4 hour period at depths of 35, 70, 105, and 140 mm and on the unexposed face.

The Finite Element Model

A three-dimensional 8-node solid element was selected to model a section through a concrete slab exposed to fire from one side. The analysis was essentially one-dimensional as all nodes at the same depth from the fire-exposed face were assumed to have the same temperature. The NISA input data file is given in Appendix B.

Material Properties

The material properties for quartz concrete (Table 1) were used and a moisture content (mass fraction) of 2.8% was assumed. The volumetric enthalpy curve versus temperature for the moist concrete is given in Figure 2 and tabulated in Appendix B.

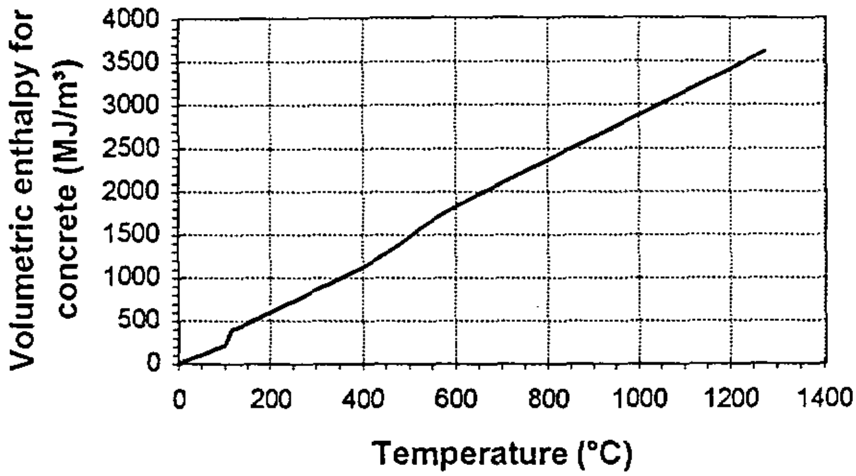


Figure 2 : Volumetric Enthalpy for Alluvial Quartz Concrete (Moisture Content 2.8%)

Boundary Conditions

The actual furnace gas temperatures, as measured by the furnace thermocouples, were used as the input to the analysis. On the fire-exposed side, the emissivity was taken as 0.9 and the convective heat transfer coefficient as 10 W/m².K. On the non fire-exposed surface, the emissivity was taken as 0.9 and the convective heat transfer coefficient as 7 W/m².K.

Results and Comparison with Test Data

The predicted and measured temperatures within the concrete slab are compared in Figure 3. General observations are as follows:

- After 60 minutes, the predicted temperatures are within about 40°C of the measured temperatures, except for the fire-exposed face where the predicted temperature exceeds the measured value by about 70°C.
- After 240 minutes, the predicted temperatures are within about 80°C of the measured temperatures.
- At temperatures of interest in a fire (above 400°C) the predicted values are conservative (i.e., they overestimate).

Better agreement can be achieved to within 40°C after 60 minutes (again excepting the fire-exposed face) and 50°C after 240 minutes by assuming a higher moisture content. As discussed previously this is probably due to migration of moisture through the concrete and condensation. Figure 4 shows this comparison for an assumed moisture content of 7% by mass.

Figure 3 : Comparison of Predicted and Measured Temperatures for 175 mm Thick Alluvial Quartz Concrete Slab with 2.8% Moisture Content

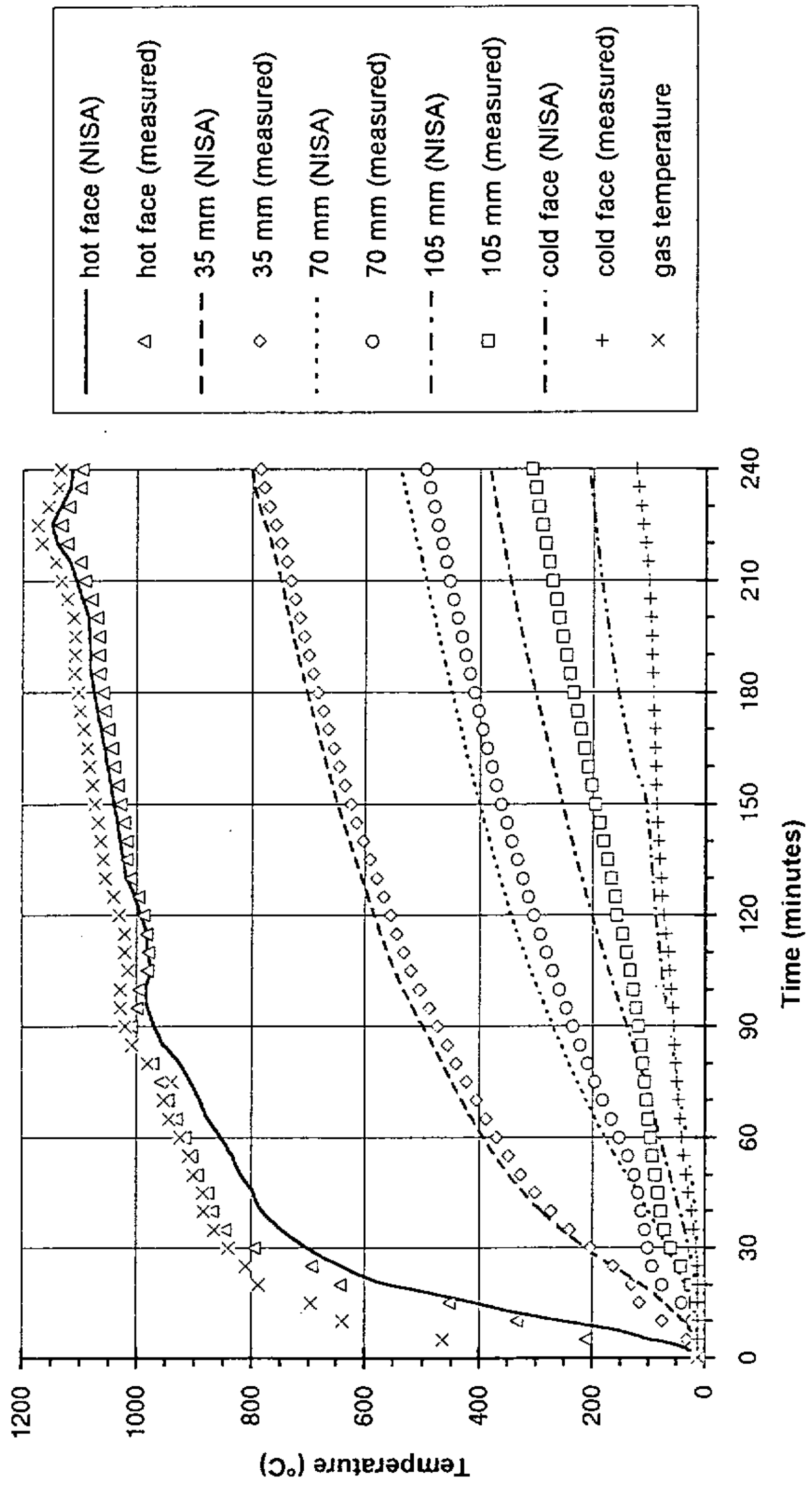
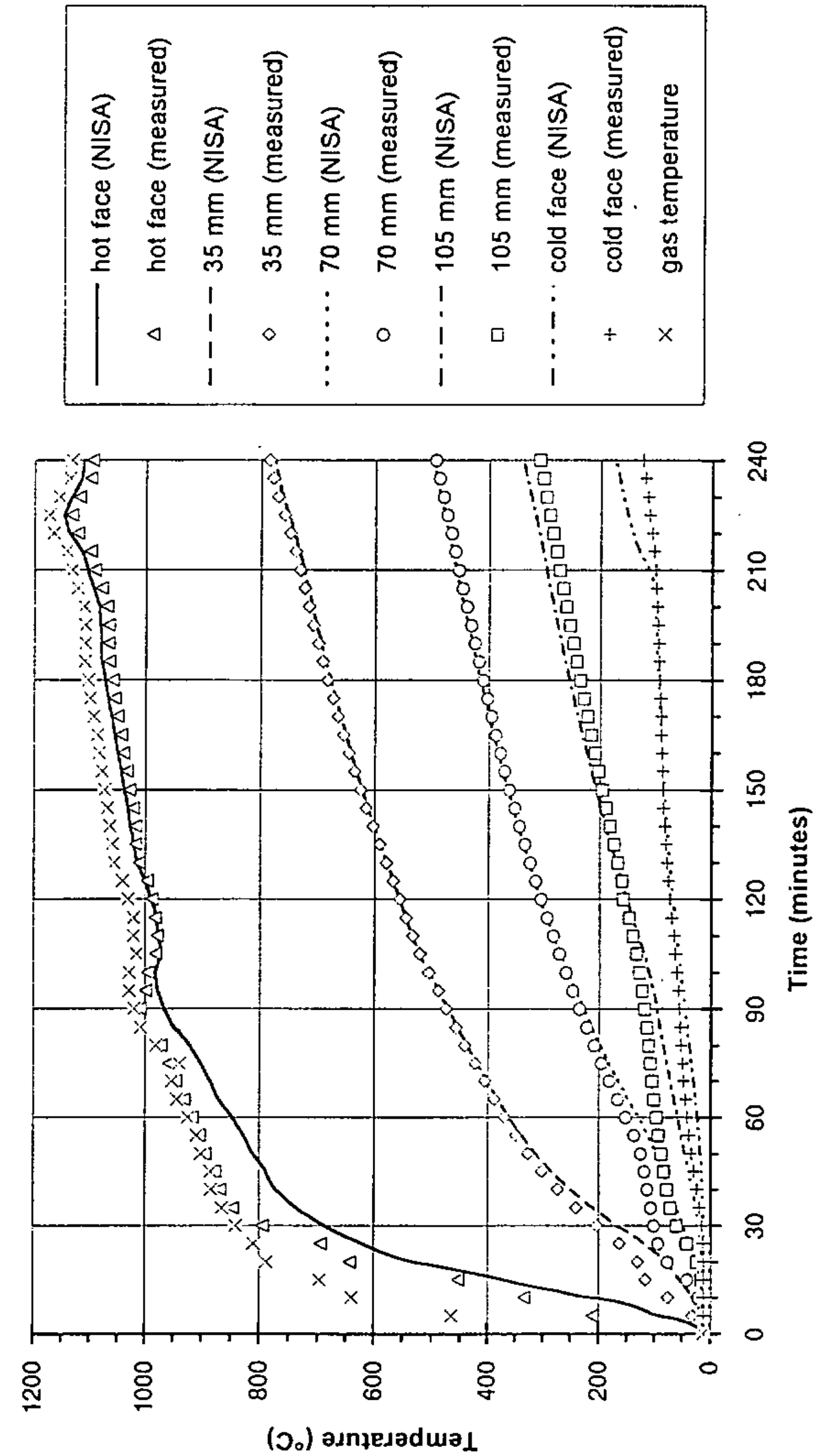


Figure 4 : Comparison of Predicted and Measured Temperatures for 175 mm Thick Alluvial Quartz Concrete Slab with 7% Moisture Content



Alluvial Quartz Concrete Slab - 64 mm Thick

Test Data

A 64 mm thick alluvial quartz concrete slab was tested in a vertical orientation in the oil-fired BRANZ furnace (Wade, 1992). The moisture content at the time of test was determined to be 3.3% by mass. The time-temperature curve followed ISO 834 (ISO, 1975), and the initial temperature was 12°C (285 K). Temperatures within the slab were recorded over a 1 hour period at depths of 20 and 40 mm and on the unexposed face.

The Finite Element Model

A three-dimensional 8-node solid element was selected to model a section through a concrete slab exposed to fire from one side. The analysis was essentially one-dimensional as all nodes at the same depth from the fire-exposed face were assumed to have the same temperature i.e., they were "coupled". The NISA input data file is given in Appendix C.

Material Properties

The material properties for quartz concrete (Table 1) were used, and a moisture content (mass fraction) of 3.3% was assumed. The volumetric enthalpy curve versus temperature for the moist concrete is given in Figure 5 and tabulated in Appendix C.

Boundary Conditions

The actual furnace gas temperatures measured in the BRANZ fire test (Wade, 1992) were used as input to the analysis. On the fire-exposed face the emissivity was taken as 0.9 and the convective heat transfer coefficient as 10 W/m^2.K. On the non fire-exposed surface, the emissivity was also taken as 0.9 and the convective heat transfer coefficient as 7 W/m^2.K.

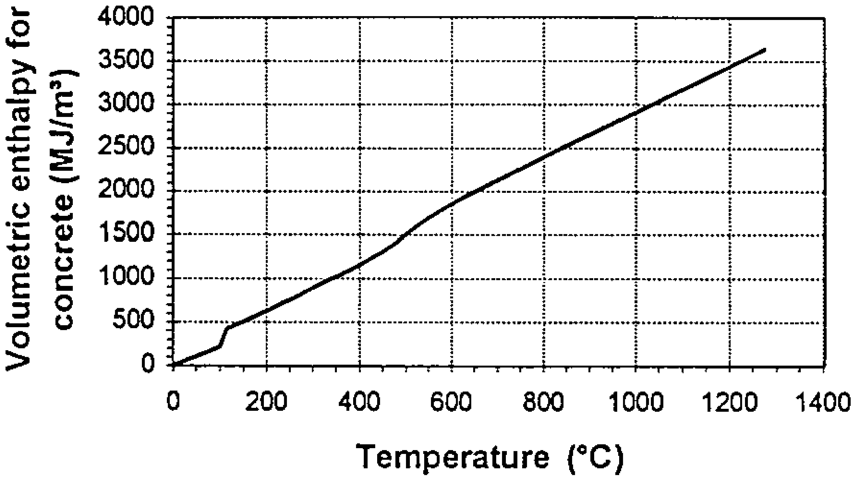


Figure 5 : Volumetric Enthalpy for Alluvial Quartz Concrete (Moisture Content 3.3%)

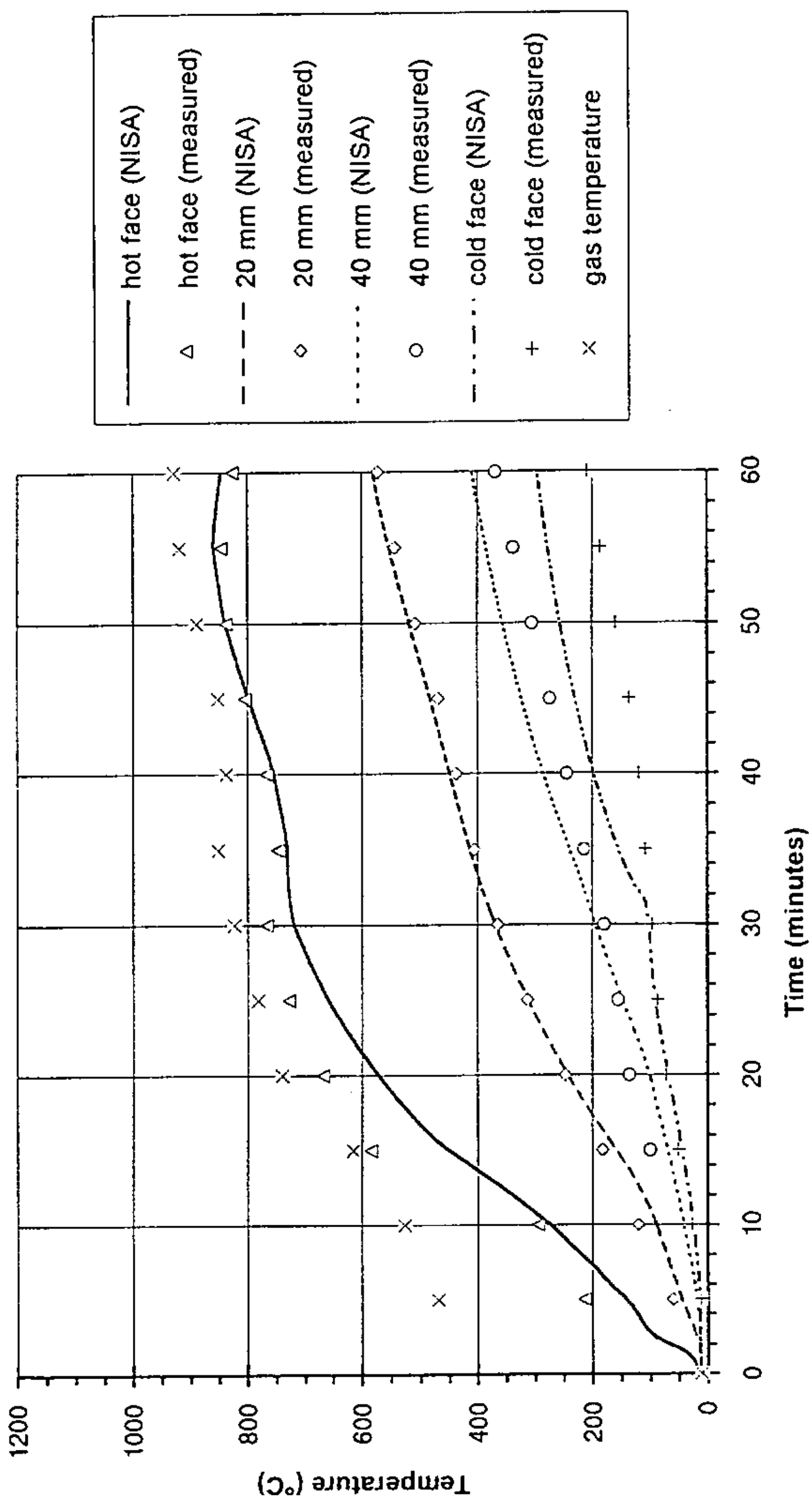
Results and Comparison with Test Data

The predicted and measured temperatures within the concrete are compared in Figure 6.

General observations are as follows:

- After 30 minutes, the predicted internal temperatures are within about 15°C of the measured temperatures.
- After 60 minutes, the predicted temperatures are within about 40°C of the measured temperatures, except for the unexposed face which is overestimated by about 80°C.

Figure 6 : Comparison of Predicted and Measured Temperatures for 64 mm Thick Alluvial Quartz Concrete Slab with 3.3% Moisture Content



203UC52 Steel Column Exposed to Fire on 4 Sides

Test Data

A 203UC52 unprotected steel column (grade 43A) was fire tested as described by Wainman and Kirby (1988) in Data Sheet 82. The time-temperature curve followed BS 476 Part 8 (BSI, 1972), and the initial temperature was 27°C (300 K). Temperatures on the column were recorded over a 4 hour period on the web and flanges.

The Finite Element Model

A two-dimensional 4-node planar element was selected to model a section through the steel column exposed to fire from all sides. Due to symmetry it is only necessary to model one-quarter of the column. The NISA input data file is given in Appendix D.

Material Properties

The material thermal properties for grade 43A hot rolled steel (Table 2) were used.

Boundary Conditions

The BS 476 Part 8 standard time-temperature curve was used as input to the analysis. On the fire-exposed surfaces, the emissivity was taken as 0.7 and the convective heat transfer coefficient as 10 $W/m^2.K$.

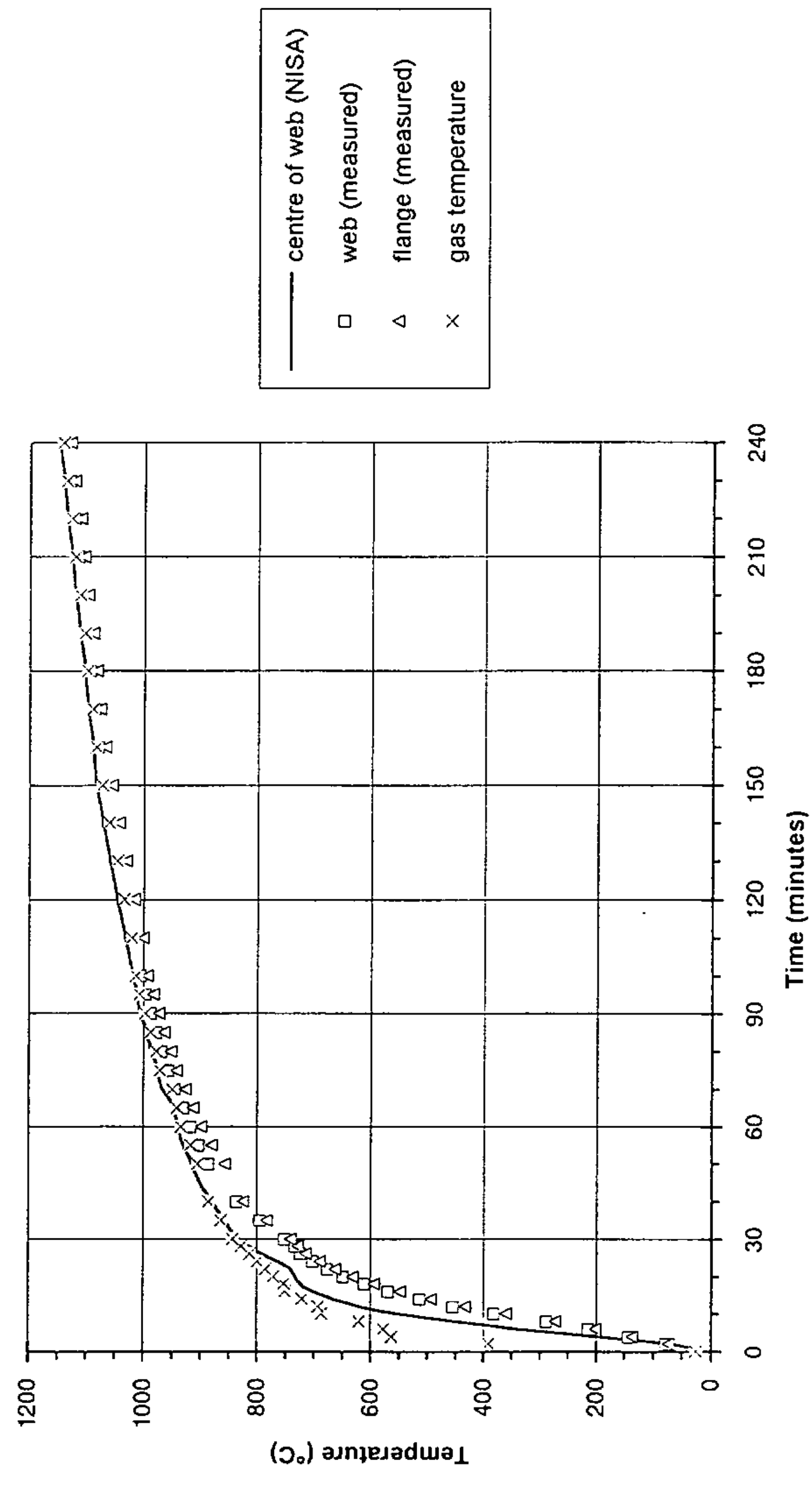
Results and Comparison with Test Data

The predicted and measured temperatures on the steel column are shown in Figure 7.

General observations are as follows:

- The measured web and flange temperatures are very similar.
- After 30 minutes, the predicted temperatures are within about 80°C of the measured temperatures.
- After 240 minutes, the predicted temperatures are within about 20°C of the measured temperatures.
- At temperatures of interest in a fire (above 400°C) the predicted values are conservative (i.e., overestimates).

Figure 7 : Comparison of Predicted and Measured Temperatures for 203UC52 Steel Section Exposed to Fire on 4 Sides



203UC52 Steel Beam Exposed to Fire on 3 Sides

Test Data

A 203UC52 unprotected steel beam (grade 50B) was fire tested as described by Wainman and Kirby (1988) in Data Sheet 27. The upper flange was covered by a dense concrete slab 130 mm thick. The time-temperature curve followed BS 476 Part 8 (BSI, 1972) and the initial temperature was 6°C (279 K). Temperatures on the beam were recorded over a 55 minute period on the web and flanges.

The Finite Element Model

A two-dimensional 4-node planar element was selected to model a section through the steel beam and concrete floor exposed to fire from the underside. Due to symmetry it is only necessary to model one-half of the construction. The situation is shown in Figure 8. The NISA input data file is given in Appendix E.

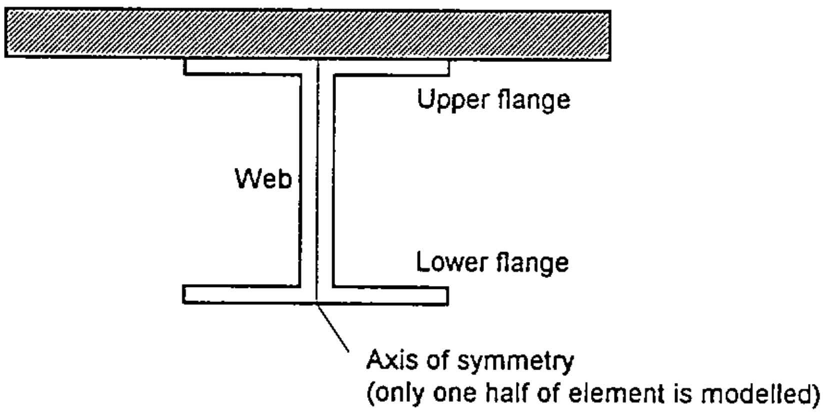


Figure 8 : Sketch of Steel Section and Floor Slab (not to scale)

Material Properties

The material thermal properties for grade 50B hot rolled steel (Table 3) were used.

Boundary Conditions

The actual or measured furnace gas time-temperature curve was used as input to the analysis (the furnace was in this case gas-fired). On the fire-exposed surfaces the emissivity was taken as 0.5 and 0.9 for the steel and concrete respectively, and the convective heat transfer coefficient as 10 W/m^2.K.

Results and Comparison with Test Data

The predicted and measured temperatures on the web, upper and lower flange of the steel beam are shown in Figure 9. The predicted temperature isotherms after 55 minutes fire exposure are shown in Figure 10.

General observations are as follows:

- The measured web and lower flange temperatures are very similar (within about 20°C).
- After 15 minutes the predicted temperatures are within about 70°C of the measured temperatures.
- After 55 minutes the predicted temperatures are within about 30°C of the measured temperatures.
- At temperatures of interest in a fire (above 400°C) the predicted values are conservative (i.e., overestimates).

Figure 9 : Comparison of Predicted and Measured Temperatures for 203UC52 Steel Section Exposed to Fire on 3 Sides

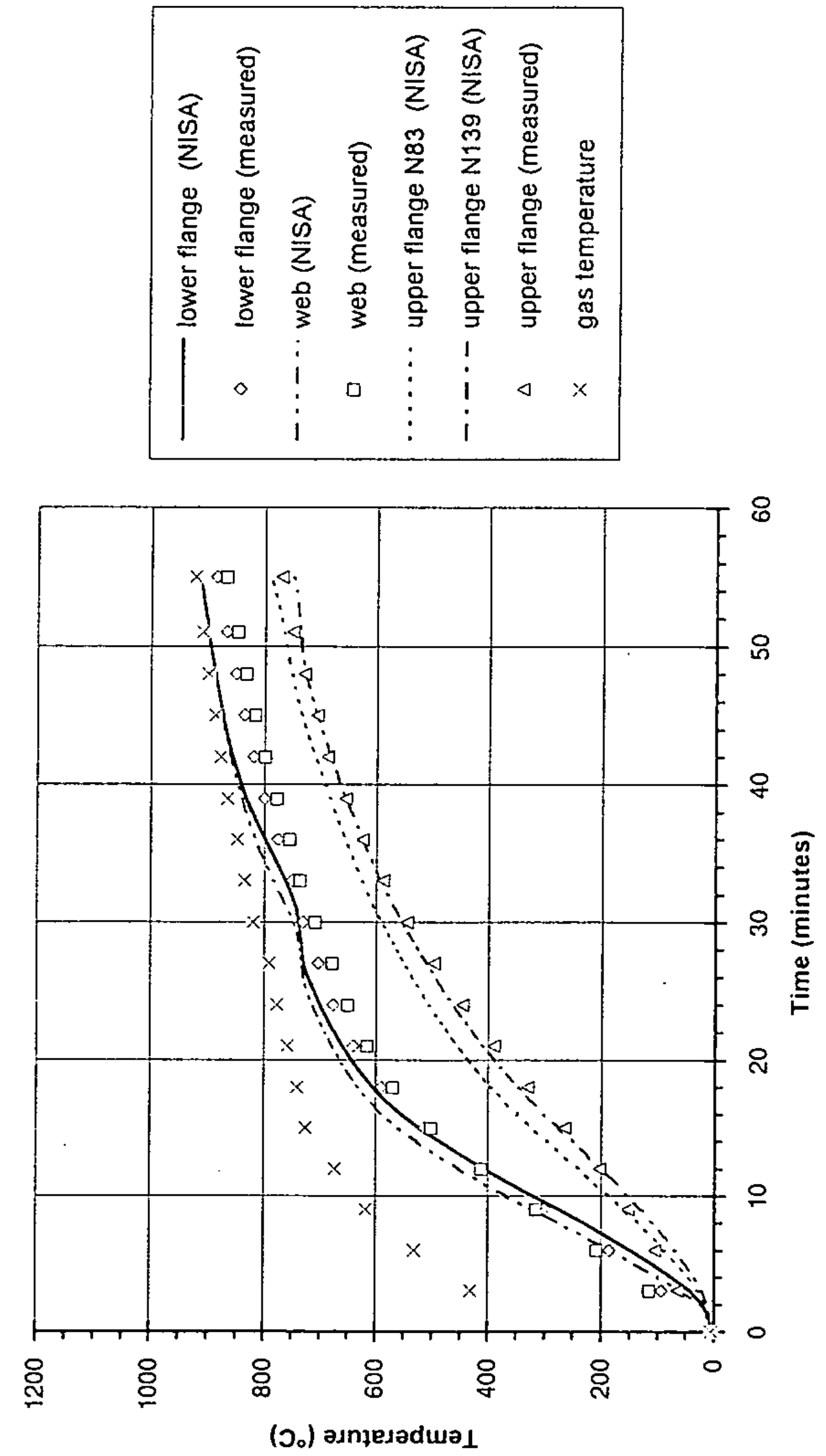
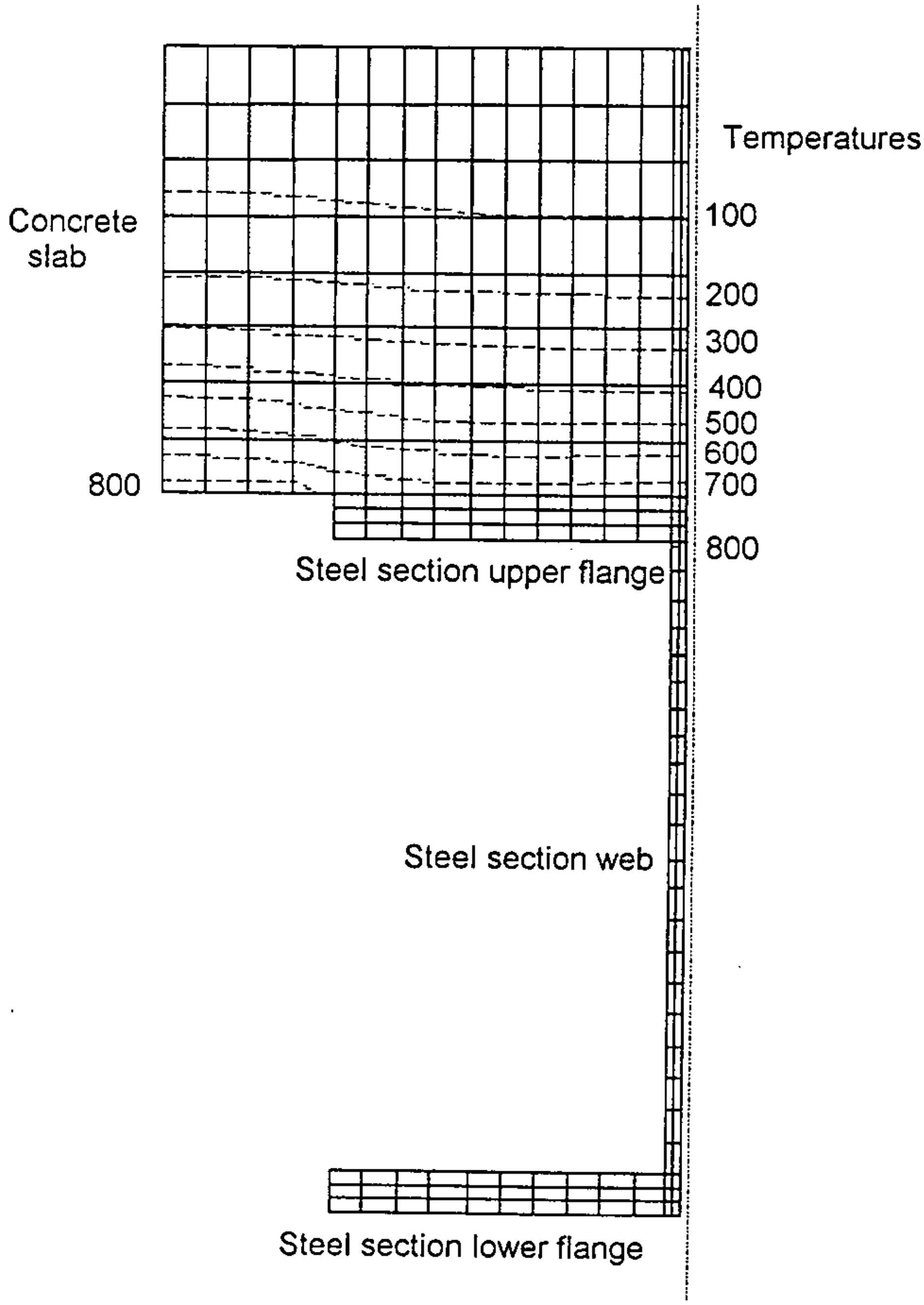


Figure 10 : Predicted Temperature Contour Plot after 55 Minutes Fire Exposure
(temperatures in °C)



Summary

The finite element model (NISA II) described in this report can be used for reasonably accurate analytical studies of the thermal response of building components exposed to fire.

The predicted temperatures of the fire-exposed components considered in the study were generally within about 80°C of the measured values and often much closer than this. The overall agreement between measured and calculated values is considered to be relatively good.

At temperatures of importance in fire engineering (above 400°C) the results achieved for concrete at its in-service moisture content will generally be conservative (i.e., they will tend to over-estimate the actual values) given the thermal properties described in this report. This means the results can be safely applied in many situations. For concrete, the mass transport of moisture complicates the analysis, and generally accuracy is reduced for lower temperatures and during the first 30 minutes of the fire test. For steel, again, the results are generally conservative at temperatures above 400°C.

The results of the analytical model described here can be used: by test laboratories to assist in the extrapolation of fire resistance test results; by consultants requiring the assessment of fire performance under non-standard fire conditions; and by manufacturers to assist in product development.

Further work is required to consider materials of construction and types of building element that differ from those considered in this study. Further work is also required to analyse real (non-standard) fire performance and for calculation of structural performance (stresses and deformations).

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Symbols

---

c_p = specific heat at constant pressure (J / kg · K)

E = volumetric enthalpy (J / m^3)

h = convection heat transfer coefficient (W / m^2 · K)

i, **j**, **k** = directional components of the heat flux vector

k = thermal conductivity (W / m · K)

ℓ_i = latent heat of evaporation of water (J / m^3)

m_c = moisture content (mass fraction %)

q'' = heat flux density (W / m^2)

q^a = radiant energy absorbed by surface (W / m^2)

q^r = radiant heat flux density (W / m^2)

$\dot{q}$ = rate of energy generation per unit volume (W / m^3)

T = temperature (K)

T_e = surface temperature of the wall (K)

T_f = temperature of fire gases (K)

T_s = surface temperature of a body (K)

t = time (s)

x, y, z = rectangular coordinates

α = absorptivity

ε = emissivity

ρ = mass density (kg / m^3)

σ = Stefan - Boltzmann constant (5.667×10^{-8} W / m^2 · K^4)

Appendices

Appendix A

Convective Heat Transfer Coefficient For the Unexposed Surface

Consider free convection heat exchange between a heated vertical plate surface and air (Incropera and deWitt, 1990). The Rayleigh Number is given as follows :

$$R_{a_L} = \frac{g\beta(T_s - T_\infty)L^3}{\alpha \upsilon}$$

The transition from laminar to turbulent flow occurs when $R_{a_L} > 10^9$.

For turbulent flow, $$\overline{Nu_L} = \left\{ 0.825 + \frac{0.387 R_{a_L}^{1/6}}{\left[1 + \left(\frac{0.492}{Pr}\right)^{9/16}\right]^{8/27}} \right\}^2$$

and the convection heat transfer coefficient, $\bar{h} = \frac{\overline{Nu_L}k}{L}$

where

$\overline{Nu_L}$ = Nusselt Number

Pr = Prandt Number

k = thermal conductivity $(\mathrm{W/m \cdot K})$

L = characteristic length (m)

υ = kinematic viscosity$(\mathrm{m^2/s})$

β = volumetric coefficient of expansion$(\mathrm{K^{-1}})$

g = gravitational constant $(\mathrm{m/s^2})$

For a heated surface at temperature $T_s = 373$ K and air at a temperature $T_\infty = 285$ K

$$g = 9.8 \text{ m/s}^2;\ T_f = \frac{T_s + T_\infty}{2} = 329 \text{ K};\ \alpha = 26.79\times10^{-6} \text{ m}^2/\text{s};\ \upsilon = 18.81\times10^{-6} \text{ m}^2/s;$$

$$k = 28.45\times10^{-3} \text{ W/m}\cdot\text{K};\ \beta = \frac{1}{T_f} = 0.00304;\ Pr = 0.703 \text{ (properties evaluated at } T_f\text{)}.$$

$$R_{a_L} = \frac{9.8\times0.00304\times(373-285)\times1^3}{26.79\times10^{-6}\times18.81\times10^{-6}} = 5.208\times10^9 \quad (>10^9 \Rightarrow \text{turbulent})$$

$$\overline{Nu_L} = \left\{0.825 + \frac{0.387\times(5.208\times10^9)^{1/6}}{\left[1+\left(\frac{0.492}{0.703}\right)^{9/16}\right]^{8/27}}\right\}^2 = 205.11$$

$$\bar{h} = \frac{\overline{Nu_L}\cdot k}{L} = \frac{205.11\times28.45\times10^{-3}}{1} = 5.8 \text{ W/m}^2\cdot\text{K}$$

Similarly, for a heated surface at temperature $T_s = 473$ K and air at a temperature $T_\infty = 285$ K

$$g = 9.8 \text{ m/s}^2;\ T_f = \frac{T_s + T_\infty}{2} = 379 \text{ K};\ \alpha = 34.77\times10^{-6} \text{ m}^2/\text{s};\ \upsilon = 24.10\times10^{-6} \text{ m}^2/s;$$

$$k = 32.2\times10^{-3} \text{ W/m}\cdot\text{K};\ \beta = \frac{1}{T_f} = 0.00264;\ Pr = 0.694 \text{ (properties evaluated at } T_f\text{)}.$$

$$R_{a_L} = \frac{9.8\times0.00264\times(473-285)\times1^3}{34.77\times10^{-6}\times24.1\times10^{-6}} = 5.81\times10^9 \quad (>10^9 \Rightarrow \text{turbulent})$$

$$\overline{Nu_L} = \left\{0.825 + \frac{0.387\times(5.81\times10^9)^{1/6}}{\left[1+\left(\frac{0.492}{0.694}\right)^{9/16}\right]^{8/27}}\right\}^2 = 211.9$$

$$\bar{h} = \frac{\overline{Nu_L}\cdot k}{L} = \frac{211.9\times32.2\times10^{-3}}{1} = 6.8 \text{ W/m}^2\cdot\text{K}$$

Convective Heat Transfer Coefficient For the Fire-Exposed Surface

Consider a forced flow of furnace gases over a vertical plate (Incropera and de Witt, 1990).

The Reynolds number is given by :

$$Re_L = \frac{u_\infty L}{\upsilon}$$

For laminar flow $(Re_L < 5 \times 10^5)$

$$\overline{Nu_L} = 0.664\, Re_L^{1/2}\, Pr^{1/3}$$

For turbulent flow $(5 \times 10^5 < Re_L \le 10^8)$

$$\overline{Nu_L} = \left(0.037 Re^{4/5} - 871\right) Pr^{1/3} \quad (0.6 < Pr < 60)$$

and $\bar{h} = \dfrac{\overline{Nu_L} k}{L}$

For a film temperature, $T_f = 1100$ K; $u_\infty = 10$ m/s; $L = 2.2$ m

$\upsilon = 141.8 \times 10^{-6}$ m²/s; $k = 71.5 \times 10^{-3}$ W/m·k; $Pr = 0.728$

$$Re_L = \frac{10 \times 2.2}{141.8 \times 10^{-6}} = 1.55 \times 10^5 \text{ (laminar flow)}$$

$$\overline{Nu_L} = 0.664 \times (1.55 \times 10^5)^{1/2} \times 0.728^{1/3} = 235.3$$

and $\bar{h} = \dfrac{235.3 \times 71.5 \times 10^{-3}}{2.2} = 7.6 \text{ W/m}^2 \cdot \text{K}$

Alternatively for $T_f = 900$ K; $u_\infty = 24$ m/s; $L = 2.2$ m

$\upsilon = 102.9 \times 10^{-6}$ m²/s; $k = 62 \times 10^{-3}$ W/m·k; $Pr = 0.720$

$$Re_L = \frac{24 \times 2.2}{102.9 \times 10^{-6}} = 5.1 \times 10^5 \text{ (turbulent flow)}$$

$$\overline{Nu_L} = \left(0.037 \times (5.1 \times 10^5)^{4/5} - 871\right) \times 0.72^{1/3} = 446.3$$

and $\bar{h} = \dfrac{446.3 \times 62 \times 10^{-3}}{2.2} = 12.6 \text{ W/m}^2 \cdot \text{K}$

Appendix B

Alluvial Quartz Concrete Slab - 175 mm Thick

NISA Data Input File

```
**EXECUTIVE
ANAL=THEAT
SAVE=26
FILE=A175G
INIT=285
RESTART=0
*TITLE
FIRE EXPOSURE OF INFINITE CONCRETE SLAB WITH THERMAL PROPERTIES AS FOR
QUARTZ FROM LIE AND WILLIAMS-LEIR WITH MOISTURE CONTENT OF 2.8% - ACTUAL
GAS TEMPS
*ELTYPE
 1, 104,     1
*NODES
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     2,,,, 1.75000E-01, 0.00000E+00, 1.00000E-02,      0
     3,,,, 1.75000E-01, 1.00000E-02, 1.00000E-02,      0
     4,,,, 1.75000E-01, 1.00000E-02, 0.00000E+00,      0
     5,,,, 1.68000E-01, 0.00000E+00, 0.00000E+00,      0


   100,,,, 7.00000E-03, 1.00000E-02, 0.00000E+00,      0
   101,,,, 0.00000E+00, 0.00000E+00, 0.00000E+00,      0
   102,,,, 0.00000E+00, 0.00000E+00, 1.00000E-02,      0
   103,,,, 0.00000E+00, 1.00000E-02, 1.00000E-02,      0
   104,,,, 0.00000E+00, 1.00000E-02, 0.00000E+00,      0
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     5,     6,     7,     8,     9,    10,    11,    12,

    24,     1,     1,     1,     0
    93,    94,    95,    96,    97,    98,    99,   100,
    25,     1,     1,     1,     0
    97,    98,    99,   100,   101,   102,   103,   104,
*MATHEAT
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KXX ,     1,0,     1,2.59,0,0,0,0,1
C   ,     1,0,     2,1796,0,0,0,0,1
*PCHANGE1
**2.8% moisture content - quartz concrete from Lie et al
273,0,298,51E+06,323,103E+06,348,157E+06
373,214E+06,388,391E+06,398,413E+06,423,471E+06,
448,533E+06,473,597E+06,498,661E+06,523,726E+06,
548,792E+06,573,858E+06,598,925E+06,623,992E+06,
648,1060E+06,673,1129E+06,698,1200E+06,723,1279E+06,
748,1370E+06,773,1470E+06,798,1570E+06,823,1661E+06,
848,1745E+06,873,1822E+06,898,1893E+06,923,1962E+06,
948,2029E+06,973,2097E+06,1023,2232E+06,1073,2365E+06,
1123,2494E+06,1173,2623E+06,1273,2883E+06,1373,3146E+06,
1473,3411E+06,1548,3612E+06
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2400,0.799,2700,0.800,3000,0.811,3300,0.816
3600,0.827,3900,0.840,4200,0.846,4500,0.855
4800,0.866,5100,0.885,5400,0.893,5700,0.899
6000,0.899,6300,0.890,6600,0.894,6900,0.894
7200,0.901,7500,0.908,7800,0.918,8100,0.920
8400,0.924,8700,0.926,9000,0.930,9300,0.933
9600,0.937,9900,0.940,10200,0.944,10500,0.948
10800,0.951,11100,0.955,11400,0.954,11700,0.955
12000,0.956,12300,0.964,12600,0.971,12900,0.978
13200,0.995,13500,1.000,13800,0.987,14100,0.974
14400,0.972,14700,0.972
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```

Volumetric Enthalpy as a Function of Temperature

THERMAL PROPERTIES OF CONCRETE

latent heat of vap = 2257 kJ/kg

Lie and Williams-Leir - dry quartz   moisture content = 2.80%

Temperature C	Temperature K	k W/mK	k ratio	c J/kg K	c ratio	density kg/m³	Δ e(conc) J/kg	c(water) J/kg K	Δ ew J/kg	Δ e(total) J/kg	enthalpy MJ/m³
0	273	2.57	1.000	765	0.426	2300		4184			0
25	298	2.57	1.000	765	0.426	2300	19128	4184	2929	22057	51
50	323	2.49	0.969	809	0.450	2300	19674	4184	2929	22603	103
75	348	2.42	0.942	852	0.475	2300	20761	4184	2929	23690	157
100	373	2.36	0.918	883	0.492	2300	21685	4184	2929	24614	214
115	388	2.34	0.909	935	0.521	2300	13630	150467	63196	76826	391
125	398	2.31	0.899	987	0.550	2300	9609	0	0	9609	413
150	423	2.25	0.875	1061	0.591	2300	25598	0	0	25598	471
175	448	2.19	0.852	1096	0.610	2300	26957	0	0	26957	533
200	473	2.14	0.833	1113	0.620	2300	27609	0	0	27609	597
225	498	2.09	0.813	1126	0.627	2300	27989	0	0	27989	661
250	523	2.05	0.798	1139	0.634	2300	28315	0	0	28315	726
275	548	2.02	0.786	1148	0.639	2300	28587	0	0	28587	792
300	573	1.99	0.774	1157	0.644	2300	28804	0	0	28804	858
325	598	1.96	0.763	1165	0.649	2300	29022	0	0	29022	925
350	623	1.93	0.751	1174	0.654	2300	29239	0	0	29239	992
375	648	1.90	0.739	1183	0.659	2300	29457	0	0	29457	1060
400	673	1.86	0.724	1196	0.666	2300	29728	0	0	29728	1129
425	698	1.81	0.704	1274	0.709	2300	30870	0	0	30870	1200
450	723	1.76	0.685	1478	0.823	2300	34402	0	0	34402	1279
475	748	1.70	0.661	1683	0.937	2300	39511	0	0	39511	1370
500	773	1.64	0.638	1796	1.000	2300	43478	0	0	43478	1470
525	798	1.57	0.611	1683	0.937	2300	43478	0	0	43478	1570
550	823	1.52	0.591	1509	0.840	2300	39891	0	0	39891	1661
575	848	1.49	0.580	1400	0.780	2300	36359	0	0	36359	1745
600	873	1.45	0.564	1287	0.717	2300	33587	0	0	33587	1822
625	898	1.43	0.556	1191	0.663	2300	30978	0	0	30978	1893
650	923	1.41	0.549	1178	0.656	2300	29620	0	0	29620	1962
675	948	1.38	0.537	1174	0.654	2300	29402	0	0	29402	2029
700	973	1.36	0.529	1183	0.659	2300	29457	0	0	29457	2097
750	1023	1.31	0.510	1170	0.651	2300	58804	0	0	58804	2232
800	1073	1.28	0.498	1135	0.632	2300	57609	0	0	57609	2365
850	1123	1.28	0.498	1117	0.622	2300	56304	0	0	56304	2494
900	1173	1.28	0.498	1122	0.625	2300	55978	0	0	55978	2623
1000	1273	1.28	0.498	1139	0.634	2300	113043	0	0	113043	2883
1100	1373	1.31	0.510	1148	0.639	2300	114348	0	0	114348	3146
1200	1473	1.34	0.521	1161	0.646	2300	115435	0	0	115435	3411
1275	1548	1.36	0.529	1170	0.651	2300	87391	0	0	87391	3612

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573,0.774,598,0.763,623,0.751,648,0.739
673,0.724,698,0.704,723,0.685,748,0.661
773,0.638,798,0.611,823,0.591,848,0.580
873,0.564,898,0.556,923,0.549,948,0.537
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1173,0.498,1273,0.498,1373,0.510,1473,0.521
1548,0.529
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373,0.492,398,0.550,423,0.591,448,0.610
473,0.620,498,0.627,523,0.634,548,0.639
573,0.644,598,0.649,623,0.654,648,0.659
673,0.666,698,0.709,723,0.823,748,0.937
773,1.000,798,0.937,823,0.840,848,0.780
873,0.717,898,0.663,923,0.656,948,0.654
973,0.659,1023,0.651,1073,0.632,1123,0.622
1173,0.625,1273,0.634,1373,0.639,1473,0.646
1548,0.651
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     $ 5,6,7,8
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*TIMEINTEG
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*STEPSIZE
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15,15,15,15,15,15,15,15,
15,7.5,7.5,3.75,3.75,7.5,7.5,7.5,
7.5,7.5,15,15,15,15,15,15,
30,30,30,30,30,30,30,30,
30,30,30,30,30,30,30,30,
30,30,30,30,60,
*CONVBC
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10.0,1447.5
*RADBC, SIGMA=5.667E-08
** RADBC SET =       1
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0.900E+00,0.285E+03
    1,,,1,-1,,,1
0.900E+00,1447.5
*TEMPHISTORY
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*TEMPOUT
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*PRINTCNTL
 TEMP,0
*ENDDATA
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Appendix C

Alluvial Quartz Concrete Slab - 64 mm Thick

NISA Data Input File

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SAVE=26
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FIRE EXPOSURE OF INFINITE CONCRETE SLAB (60MM) WITH THERMAL PROPERTIES AS
FOR QUARTZ FROM LIE AND WILLIAMS-LEIR WITH MOISTURE CONTENT OF 3.3%
*ELTYPE
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*NODES
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     3,,,, 0.00000E+00, 1.00000E-02, 1.00000E-02,     0
     4,,,, 0.00000E+00, 0.00000E+00, 1.00000E-02,     0
     5,,,, 5.00000E-03, 0.00000E+00, 0.00000E+00,     0

    53,,,, 6.40000E-02, 0.00000E+00, 0.00000E+00,     0
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     5,      6,      7,      8,      9,     10,     11,     12,
     3,      1,      1,      1,      0

    45,     46,     47,     48,     49,     50,     51,     52,
    13,      1,      1,      1,      0
    49,     50,     51,     52,     53,     54,     55,     56,
*CPTEMP
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TEMP $     9,     10,     11,     12,
TEMP $    13,     14,     15,     16,
TEMP $    17,     18,     19,     20,
TEMP $    21,     22,     23,     24,
TEMP $    25,     26,     27,     28,
TEMP $    29,     30,     31,     32,
TEMP $    33,     34,     35,     36,
TEMP $    37,     38,     39,     40,
TEMP $    41,     42,     43,     44,
TEMP $    45,     46,     47,     48,
TEMP $    49,     50,     51,     52,
TEMP $    53,     54,     55,     56,
*MATHEAT
DENS,      1,0,      0,2300,0,0,0,0,1
KXX ,      1,0,      1,2.57,0,0,0,0,1
C   ,      1,0,      2,1796,0,0,0,0,1
*PCHANGE1
**3.3% moisture content - quartz concrete from Lie et al
273,0,298,52E+06,323,105E+06,348,161E+06
373,219E+06,388,421E+06,398,443E+06,423,502E+06,
448,564E+06,473,628E+06,498,692E+06,523,757E+06,
548,823E+06,573,889E+06,598,956E+06,623,1023E+06,
648,1091E+06,673,1159E+06,698,1230E+06,723,1310E+06,
748,1400E+06,773,1500E+06,798,1600E+06,823,1692E+06,
848,1776E+06,873,1853E+06,898,1924E+06,923,1992E+06,
948,2060E+06,973,2128E+06,1023,2263E+06,1073,2396E+06,
1123,2525E+06,1173,2654E+06,1273,2914E+06,1373,3177E+06,
1473,3442E+06,1548,3643E+06
*TIMEAMP
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900,0.843,1200,0.878,1500,0.912,1800,0.936
2100,0.923,2400,0.936,2700,0.967,3000,0.992
3300,1.000,3600,0.979,
```

```
*TEMPFN
 1,37
0.0,1.000,298,1.000,323,0.969,348,0.942
373,0.918,398,0.899,423,0.875,448,0.852
473,0.833,498,0.813,523,0.798,548,0.786
573,0.774,598,0.763,623,0.751,648,0.739
673,0.724,698,0.704,723,0.685,748,0.661
773,0.638,798,0.611,823,0.591,848,0.580
873,0.564,898,0.556,923,0.549,948,0.537
973,0.529,1023,0.510,1073,0.498,1123,0.498
1173,0.498,1273,0.498,1373,0.510,1473,0.521
1548,0.529
 2,37
0.0,0.426,298,0.426,323,0.450,348,0.475
373,0.492,398,0.550,423,0.591,448,0.610
473,0.620,498,0.627,523,0.634,548,0.639
573,0.644,598,0.649,623,0.654,648,0.659
673,0.666,698,0.709,723,0.823,748,0.937
773,1.000,798,0.937,823,0.840,848,0.780
873,0.717,898,0.663,923,0.656,948,0.654
973,0.659,1023,0.651,1073,0.632,1123,0.622
1173,0.625,1273,0.634,1373,0.639,1473,0.646
1548,0.651
*HEATCNTL, ID=      1
15,15,5,0.001
*TIMEINTEG
0.5,60,3600,1,
*STEPSIZE
3.75,3.75,7.5,15,15,15,15,15
15,15,30,30,30,7.5,3.75,3.75,
3.75,3.75,7.5,15,15,30,30,30,
30,30,30,30,30,30,30,30,
30,30,60
*CONVBC
** CONVBC SET =      1
    13,,,2,-1
7.00,0.285E+03
    1,,,1,-1,,,1
10.00,1201.8
*RADBC, SIGMA=5.667E-08
** RADBC SET =      1
    13,,,2,-1,
0.900E+00,0.285E+03
    1,,,1,0,,,1
0.900E+00,1201.8,0.900E+00,1201.8,0.900E+00,1201.8,0.900E+00,1201.8,
*TEMPHISTORY
4,1,17,33,53
*TEMPOUT
0,3600,300
*PRINTCNTL
 TEMP,0
*ENDDATA
```

Volumetric Enthalpy as a Function of Temperature

THERMAL PROPERTIES OF CONCRETE

	latent heat of vap = 2257	kJ/kg
Lie and Williams-Leir - dry quartz	moisture content = 3.30%	

Temperature C	Temperature K	k W/mK	k ratio	c J/kg K	c ratio	density kg/m³	Δ e(conc) J/kg	c(water) J/kg K	Δ ew J/kg	Δ e(total) J/kg	enthalpy MJ/m³
0	273	2.57	1.000	765	0.426	2300		4184			0
25	298	2.57	1.000	765	0.426	2300	19128	4184	3452	22580	52
50	323	2.49	0.969	809	0.450	2300	19674	4184	3452	23126	105
75	348	2.42	0.942	852	0.475	2300	20761	4184	3452	24213	161
100	373	2.36	0.918	883	0.492	2300	21685	4184	3452	25137	219
115	388	2.34	0.909	935	0.521	2300	13630	150467	74481	88111	421
125	398	2.31	0.899	987	0.550	2300	9609	0	0	9609	443
150	423	2.25	0.875	1061	0.591	2300	25598	0	0	25598	502
175	448	2.19	0.852	1096	0.610	2300	26957	0	0	26957	564
200	473	2.14	0.833	1113	0.620	2300	27609	0	0	27609	628
225	498	2.09	0.813	1126	0.627	2300	27989	0	0	27989	692
250	523	2.05	0.798	1139	0.634	2300	28315	0	0	28315	757
275	548	2.02	0.786	1148	0.639	2300	28587	0	0	28587	823
300	573	1.99	0.774	1157	0.644	2300	28804	0	0	28804	889
325	598	1.96	0.763	1165	0.649	2300	29022	0	0	29022	956
350	623	1.93	0.751	1174	0.654	2300	29239	0	0	29239	1023
375	648	1.90	0.739	1183	0.659	2300	29457	0	0	29457	1091
400	673	1.86	0.724	1196	0.666	2300	29728	0	0	29728	1159
425	698	1.81	0.704	1274	0.709	2300	30870	0	0	30870	1230
450	723	1.76	0.685	1478	0.823	2300	34402	0	0	34402	1310
475	748	1.70	0.661	1683	0.937	2300	39511	0	0	39511	1400
500	773	1.64	0.638	1796	1.000	2300	43478	0	0	43478	1500
525	798	1.57	0.611	1683	0.937	2300	43478	0	0	43478	1600
550	823	1.52	0.591	1509	0.840	2300	39891	0	0	39891	1692
575	848	1.49	0.580	1400	0.780	2300	36359	0	0	36359	1776
600	873	1.45	0.564	1287	0.717	2300	33587	0	0	33587	1853
625	898	1.43	0.556	1191	0.663	2300	30978	0	0	30978	1924
650	923	1.41	0.549	1178	0.656	2300	29620	0	0	29620	1992
675	948	1.38	0.537	1174	0.654	2300	29402	0	0	29402	2060
700	973	1.36	0.529	1183	0.659	2300	29457	0	0	29457	2128
750	1023	1.31	0.510	1170	0.651	2300	58804	0	0	58804	2263
800	1073	1.28	0.498	1135	0.632	2300	57609	0	0	57609	2396
850	1123	1.28	0.498	1117	0.622	2300	56304	0	0	56304	2525
900	1173	1.28	0.498	1122	0.625	2300	55978	0	0	55978	2654
1000	1273	1.28	0.498	1139	0.634	2300	113043	0	0	113043	2914
1100	1373	1.31	0.510	1148	0.639	2300	114348	0	0	114348	3177
1200	1473	1.34	0.521	1161	0.646	2300	115435	0	0	115435	3442
1275	1548	1.36	0.529	1170	0.651	2300	87391	0	0	87391	3643

Appendix D

203UC52 Steel Column Exposed to Fire on 4 Sides

NISA Data Input File

```
**EXECUTIVE
ANAL=THEAT
SAVE=26
FILE=BS82C
INIT=300
*TITLE
STEEL COLUMN 4-SIDES EXPOSED TO FIRE - BRIT STEEL DATA SHEET 82b
*ELTYPE
 1, 102,     1
*NODES
     1,,,, 0.00000E+00, 4.00000E+00, 0.00000E+00,     0
     2,,,, 1.25000E+01, 4.00000E+00, 0.00000E+00,     0
     3,,,, 1.25000E+01, 1.02000E+02, 0.00000E+00,     0
     4,,,, 0.00000E+00, 1.02000E+02, 0.00000E+00,     0
     5,,,, 4.16667E+00, 4.00000E+00, 0.00000E+00,     0

    79,,,, 6.68000E+01, 2.00000E+00, 0.00000E+00,     0
    80,,,, 7.58500E+01, 2.00000E+00, 0.00000E+00,     0
    81,,,, 8.49000E+01, 2.00000E+00, 0.00000E+00,     0
    82,,,, 9.39500E+01, 2.00000E+00, 0.00000E+00,     0
*ELEMENTS
     1,      1,      1,      1,     0
    26,     27,     16,      4,
     2,      1,      1,      1,     0
    27,     28,     17,     16,
     3,      1,      1,      1,     0
    28,     15,      3,     17,

    61,     62,     81,     80,
    55,      1,      1,      1,     0
    62,     63,     82,     81,
    56,      1,      1,      1,     0
    63,     53,     64,     82,
*MATHEAT
DENS,      1,0,      3,7850E-09,0,
KXX ,      1,0,      1,52E-03,0,
C   ,      1,0,      2,5000,0,0
*TEMPFN
 1,30
293,1,323,0.994,373,0.981,423,0.962,
473,0.938,523,0.913,573,0.885,623,0.856
673,0.821,723,0.788,773,0.754,823,0.721
873,0.683,923,0.650,973,0.615,998,0.596
1008,0.577,1023,0.548,1048,0.510,1073,0.5
1098,0.496,1123,0.5,1148,0.504,1173,0.51
1223,0.519,1273,0.529,1323,0.538,1373,0.548
1423,0.558,1473,0.567
 2,30
293,0.088,323,0.09,373,0.096,423,0.101,
473,0.106,523,0.11,573,0.113,623,0.117
673,0.122,723,0.128,773,0.135,823,0.143
873,0.152,923,0.164,973,0.202,998,0.32
1008,1,1023,0.26,1048,0.202,1073,0.162
1098,0.146,1123,0.137,1148,0.132,1173,0.130
1223,0.130,1273,0.130,1323,0.13,1373,0.13
1423,0.131,1473,0.131
 3,30
293,1,323,0.999,373,0.997,423,0.995,
473,0.993,523,0.991,573,0.989,623,0.987
673,0.985,723,0.983,773,0.98,823,0.978
873,0.975,923,0.973,973,0.97,998,0.969
1008,0.97,1023,0.97,1048,0.971,1073,0.971
1098,0.972,1123,0.971,1148,0.97,1173,0.968
1223,0.965,1273,0.962,1323,0.958,1373,0.955
1423,0.952,1473,0.949
*TIMEAMP
**TIME TEMP CURVE - measured gas temps
**TEMP AT 14400 SEC = 1423 K
1,44,0
```

```
0,0.211,120,0.467,240,0.587,360,0.598
480,0.628,600,0.675,720,0.679,840,0.699
960,0.720,1080,0.721,1200,0.734,1320,0.746
1440,0.755,1560,0.766,1680,0.776,1800,0.785
2100,0.799,2400,0.814,2700,0.828,3000,0.837
3300,0.848,3600,0.853,3900,0.859,4200,0.874
4500,0.878,4800,0.886,5100,0.892,5400,0.900
5700,0.904,6000,0.909,6600,0.918,7200,0.928
7800,0.937,8400,0.946,9000,0.954,9600,0.958
10200,0.964,10800,0.968,11400,0.974,12000,0.980,
12600,0.984,13200,0.990,13800,0.994,14400,1,
*HEATCNTL, ID=     1
 15,15,4,1.0E-3
*TIMEINTEG
0.5,60,14400,1,
*STEPSIZE
1.875,1.875,3.75,7.5,15,30,60,60
60,60,60,60,60,60,60,60
60,60,60,60,60,60,30,30,
15,15,15,15,15,15,15,15,
15,15,15,15,30,30,30,30,
30,30,30,30,30,30,30,30,
60
*CONVBC
** CONVBC SET =      1
     1,,,3,-1,       ,       ,     1
0.100E-04,0.1423E+04
     1,,,4,-1,       ,       ,     1
0.100E-04,0.1423E+04
     2,,,3,-1,       ,       ,     1
0.100E-04,0.1423E+04
     3,,,2,-1,       ,       ,     1
0.100E-04,0.1423E+04

0.100E-04,0.1423E+04
    45,,,3,-1,       ,       ,     1
0.100E-04,0.1423E+04
    46,,,3,-1,       ,       ,     1
0.100E-04,0.1423E+04
*RADBC,SIGMA=5.67E-14
** RADBC SET =      1
     1,,,3,-1,       ,       ,     1
0.700E+00,0.1423E+04
     1,,,4,-1,       ,       ,     1
0.700E+00,0.1423E+04
     2,,,3,-1,       ,       ,     1

0.700E+00,0.1423E+04
    45,,,3,-1,       ,       ,     1
0.700E+00,0.1423E+04
    46,,,3,-1,       ,       ,     1
0.700E+00,0.1423E+04
*TEMPHISTORY
7,1,2,3,4,22,53,54
*TEMPOUT
0,14400,300
*PRINTCNTL
 TEMP,0
*ENDDATA
```

Appendix E

203UC52 Steel Beam Exposed to Fire on 3 Sides

NISA Data Input File

```
**EXECUTIVE
ANAL=THEAT
SAVE=26
FILE=BS27C
INIT=279
*TITLE
STEEL COLUMN 3-SIDES EXPOSED TO FIRE - BRIT STEEL DATA SHEET 27
*ELTYPE
 1, 102,     1
*NODES
     1,,,, 0.00000E+00, 4.00000E+00, 0.00000E+00,     0
     2,,,, 1.25000E+01, 4.00000E+00, 0.00000E+00,     0
     3,,,, 1.25000E+01, 1.02000E+02, 0.00000E+00,     0
     4,,,, 0.00000E+00, 1.02000E+02, 0.00000E+00,     0
     5,,,, 4.16667E+00, 4.00000E+00, 0.00000E+00,     0

   297,,,, 2.54750E+02, 1.14500E+02, 0.00000E+00,     0
   298,,,, 2.71000E+02, 1.14500E+02, 0.00000E+00,     0
   299,,,, 2.87250E+02, 1.14500E+02, 0.00000E+00,     0
   300,,,, 3.03500E+02, 1.14500E+02, 0.00000E+00,     0
   301,,,, 3.19750E+02, 1.14500E+02, 0.00000E+00,     0
*ELEMENTS
     1,     1,      1,      1,     0
    26,    27,     16,      4,
     2,     1,      1,      1,     0
    27,    28,     17,     16,
     3,     1,      1,      1,     0
    28,    15,      3,     17,

   238,     2,      1,      1,     0
   184,   185,    300,    299,
   239,     2,      1,      1,     0
   185,   186,    301,    300,
   240,     2,      1,      1,     0
   186,   163,    268,    301,
*MATHEAT
DENS,      1,0,      0,0.8131E-05,0
KXX ,      1,0,      1,0.0422,0
C   ,      1,0,      2,5000,0
DENS,      2,0,      0,0.23E-05,0
KXX ,      2,0,      0,0.0014,0
C   ,      2,0,      0,880,0
*TEMPFN
 1,7
273,0.972,300,0.972,400,1,600,0.941,
800,0.829,1000,0.654,1473,0.65
 2,20
273,0.087,300,0.087,400,0.097,600,0.112,
800,0.137,1000,0.218,1008,1,1023,0.26,
1048,0.202,1073,0.162,1098,0.146,1123,0.137,
1148,0.132,1173,0.130,1223,0.130,1273,0.130,
1323,0.13,1373,0.13,1423,0.131,1473,0.131
*TIMEAMP
**STD TIME TEMP CURVE - measured gas temps
**TEMP AT 3300 SEC = 1196 K
1,19,0
0,0.233,180,0.589,360,0.672,540,0.745
720,0.791,900,0.835,1080,0.845,1260,0.863
1440,0.878,1620,0.890,1800,0.914,1980,0.926
2160,0.937,2340,0.952,2520,0.962,2700,0.971
2880,0.981,3060,0.989,3300,1
*HEATCNTL, ID=     1
 15,15,4,1.0E-3
*TIMEINTEG
0.5,60,1800,1,
*STEPSIZE
1.875,1.875,3.75,7.5,15,30,60,60
60,60,60,60,60,60,60,60
60,60,60,60,60,60,30,30,
```

```
15,15,15,15,15,15,15,15,
15,15,15,15,15,15,15,15,
15,15,15,15,15,15,30,30,
30,30,30,30,30,30,30,60
*CONVBC
** CONVBC SET =       1
     1,,,3,-1,       ,       ,     1
0.100E-04,0.1196E+04
     1,,,4,-1,       ,       ,     1
0.100E-04,0.1196E+04
     2,,,3,-1,       ,       ,     1

   225,,,4,-1,       ,       ,     1
0.100E-04,0.1196E+04
   233,,,4,-1,       ,       ,     1
0.100E-04,0.1196E+04
*RADBC,SIGMA=5.67E-14
** RADBC SET =      1
     1,,,3,-1,       ,       ,     1
0.500E+00,0.1196E+04
     1,,,4,-1,       ,       ,     1
0.500E+00,0.1196E+04
     2,,,3,-1,       ,       ,     1
0.500E+00,0.1196E+04
     3,,,2,-1,       ,       ,     1
0.500E+00,0.1196E+04

   217,,,4,-1,       ,       ,     1
0.900E+00,0.1196E+04
   225,,,4,-1,       ,       ,     1
0.900E+00,0.1196E+04
   233,,,4,-1,       ,       ,     1
0.900E+00,0.1196E+04
*TEMPHISTORY
9,2,3,45,53,54,83,114,139,280
*TEMPOUT
0,1800,300
*PRINTCNTL
 TEMP,0
*ENDDATA
```

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