NO.93
(1989)

BUILDING RESEARCH ASSOCIATION OF NEW ZEALAND

REPRINT

CI/SfB | | Hy | (K43)
UDC 693.98:536.2

Modelling of Heat Transfer in Composite Structures at Fire Temperatures

A. J. Groom

Reprinted from *International Symposium on Fire Engineering for Building Structures and Safety, Melbourne,* 14 -15 November 1989

branz
BUILDING RESEARCH ASSOCIATION OF NEW ZEALAND

International Symposium on Fire Engineering
for Building Structures and Safety
Melbourne, 14-15 November 1989

Modelling of Heat Transfer in Composite Structures at Fire Temperatures

A.J. GROOM
Fire Scientist, Building Research Association of New Zealand

SUMMARY Computers are increasingly being used to model heat transfer in composite building structures at fire temperatures. A literature search was carried out to identify software packages available for this pupose. A review is presented of the mathematical techniques used in the various models, their requirements in terms of knowledge of material thermal properties and geometries, and their relative merits in terms of accuracy, scope of application and efficiency. It was found that while mathematical modelling of heat transfer in steel and concrete structures is well established, the modelling of heat transfer in timber and gypsum products has not yet gained wide acceptance due to the difficulty of modelling pyrolysis and mass transfer processes. It was concluded that it is the role of testing laboratories and research establishments to validate heat transfer modelling of these materials and educate the building industry in the use of such models.

1 INTRODUCTION

The purpose of this paper is to present an overview of the mathematical modelling of heat transfer in composite structures at temperatures around 1000° C. Examples of composite structures are door leaves with timber or mineral fibre cores and timber or metal facings, and timber or steel stud walls lined with gypsum plasterboard with fibreglass insulation filling the cavities.

The current methods of assessing heat flow through composite building structures at high temperatures are based on empirical assessments of tests carried out with similar materials in similar geometries. The extrapolation between these structures and those with, say, the same materials in a different geometry may not be valid if the complex interactions between mechanisms of heat transfer are not taken into account.

Research into heat transfer in composite structures at fire temperatures is currently neglected in favour of fire growth and development models where heat transfer is simply treated as a model parameter. This results in the need to adjust the parameters of heat transfer in order to obtain a best fit of the theoretical results to experimental data. This is a typically empirical approach and results thus obtained cannot, in general, be applied to other problems.

Many fire models claim to accurately model fire growth in a compartment without accurately modelling the heat transfer from the compartment. The heat transfer modelling part of the system will then be the weak link in the modelling chain, and the model will yield meaningless results from an engineering point of view.

Computer modelling of the heat flow through composite structures at fire temperatures has several advantages over the more traditional methods. First, the cost of computer modelling can be significantly lower than that of conventional fire resistance testing. Second, results can be obtained in far less time. Third, computer generated results are generally more representative than the results of a single fire resistance test. Fourth, computer modelling makes it possible to determine the performance of a component which may be difficult to measure in a physical test. Finally, changes in geometry and material types within a known design can be performed to optimise thermal performance and cost and perform sensitivity analyses.

Computer performance modelling has been used in the automobile, aerospace and electronics industries for many years. This process is well established in the areas of fire performance of steel and concrete constructions (Bazant and Panula, 1978). In the area of timber construction, however, the use of computer modelling is still largely confined to research organisations because of the limited knowledge of the physical and chemical processes involved in wood combustion.

Further, such methods of design and analysis are being accepted by many international building authorities as alternatives to the costly and time-consuming method of full-scale testing used to determine the heat transfer through a structure at fire temperatures (Pettersson, 1984).

The paper will discuss the basic principles of the different models, their advantages and disadvantages over traditional methods of determining fire resistance and how aspects of the physical system being modelled are taken into account. The factors involved in computer implementation of these models are described and the paper concludes with some examples of heat transfer software. Finally, supplemental bibliographical material appears in the Appendix.

This material is subdivided into sections covering the major factors in heat transfer analysis of composite structures at fire temperatures. Readers are invited to consult international software databases such as MENU (The Software Catalog, 1985) and FIREDOC (Jason, 1987), which are updated daily, for further information.

2 MATHEMATICAL MODELLING

2.1 Types of Models

Mathematical modelling involves the solution of a set of equations that describe the physical processes and boundary and initial conditions of heat flow in a particular structure, i.e. a mathematical, rather than physical, model of the structure.

2.1.1 Analytical modelling

The types of mathematical model commonly used are analytical and numerical. The analytical model produces explicit equations for the behaviour of a model (Delichatsios, 1983). This has the advantage of being able to easily demonstrate the change in performance as a result of a parameter change. The principal disadvantage of this technique is that it applies only to very simple problems. The mathematics become very unwieldy if one considers radiative and convective heat transfer, or two and three dimensional systems with complex geometries.

2.1.2 Numerical modelling

The second technique, the one discussed in this paper, is numerical modelling. This involves breaking the physical system into many small units and solving a simplified set of equations for each unit, taking into account the interactions between units (Gandhi, 1986).

This greatly reduces the mathematical complexity of the problem but increases the computational size of the problem to a point where it is no longer practical to generate solutions by hand. The problem must then be configured for a computer. With powerful personal computers and mainframes becoming increasingly accessible to the engineering profession, this is no longer an insurmountable problem. Numerical modelling software packages designed for use in research institutes are now being made generally available.

The two principal numerical modelling techniques are the finite element and finite difference techniques. The finite difference method involves solving the equations describing the system at one point within each element and describes heat flow between elements by an effective conduction. On the other hand, the finite element method takes into account the geometry of each element and its relative orientation in the structure. In general, the finite element technique yields more accurate results than the finite difference method and is capable of handling complex geometries. However, the finite difference method can more easily incorporate the more complex physical processes of pyrolysis and mass transfer. The method used, therefore, depends on the composition of the structure being modelled.

2.2 Model Requirements

This technique for predicting the fire performance of building structures is not without its disadvantages. In order to be able to model the performance of a composite structure accurately, one must know the detailed thermal properties of the materials being used. Without this knowledge, only a qualitative assessment of performance is obtainable. The determination of thermal properties of building materials at high temperatures will not be dealt with in this paper. The reader is referred below to articles describing the work in this area.

One must also be able to quantify the geometry of the structure that is being modelled, as this information is needed to generate the distribution of temperatures in the structure at different times and locations.

Finally, the boundary and initial conditions also must be well understood, both spatially and temporally.

2.2.1 Material properties

A range of experimental techniques have been developed to determine the thermal properties of non-combustible materials whose structural and thermal properties vary little over a wide range of temperatures. In these materials the dominant heat transfer mechanism is conduction, the simplest mechanism to model. Such materials include concrete, masonry and steel. Heat transfer in concrete is complicated by the porosity of the material and the amount of free and chemically combined water it contains. This gives rise to an increased contribution to the heat flow from convection and mass transfer at temperatures of 100 to 200°C.

It is fair to say that the major difficulty encountered in the measurement of these properties is the variation between specimens, especially for materials such as wood and concrete where, respectively, timber species and density, and type of aggregate used, can have a considerable effect. This highlights another advantage of the modelling technique over the fire resistance test in that the model will determine the properties of a representative specimen or many types of specimen as opposed to the statistically inaccurate results obtained from testing a single specimen.

The situation is complicated when considering materials that decompose at relatively low temperatures (300 to 500°C). The decomposition may produce an added source of heat or, alternatively, may remove heat from the structure through exothermic chemical reactions and latent heats of phase change. As well as conduction, the mechanism of convection then becomes important as decomposition products may carry heat between different areas of the structure. Also, at fire temperatures internal radiation in porous materials becomes an important factor.

Examples of such materials are wood and wood-based products (Fredlund, 1988) and gypsum products which undergo a loss of chemically combined water at 100 deg C (Abrams, 1980).

To some extent this decomposition can be taken into account as an effective change in thermal properties or structure geometry, retaining the simplicity of the problem and avoiding the problem of simultaneous heat and mass transfer (White and Schaffer, 1978).

In some situations, materials in the structure deteriorate to the extent that flames or hot gases can enter an otherwise unexposed area through a gap or fissure. This can drastically affect the heat flow within the structure but remains an extremely unpredictable occurrence. Some models endeavour to take this loss of integrity into account as effective changes in geometry or thermal properties at a prescribed temperature (Gandhi, 1986).

2.2.2 Structure geometry

As a first approximation one can ignore the geometry of materials in a structure and consider its fire resistance properties as a function only of the mass of material present. This is commonly used in fire design of steel members where the ratio of the mass of the member to its cross-sectional area is considered a good indication of fire resistance properties.

Mathematical modelling goes one step further in considering the geometry of the whole structure as an important factor in its fire performance.

All heat-transfer mechanisms depend on the geometry of the structure. The flow of heat through a solid body, a conduction process only, is nevertheless affected by the heat transfer mechanisms at the boundaries of the object. Convection is the most complex of heat flow mechanisms where the fluid flow around an object depends on the properties of the fluid (commonly air) and the particular geometry of the object. Much work has been done in this field for a very wide range of applications (Wickstrom, 1977). Radiation heat flow between two surfaces is determined by the emmissivities of the surfaces, their relative orientation and the opaqueness of the intervening gases (Yamizaki, 1985).

The symmetry of a structure is also important in determining the mathematical complexity of the problem. For example, a large plane object with an evenly distributed heat flux across its surface can be thought of as a one-dimensional heat transfer problem. On the other hand, an irregularly shaped structure or one with a localised heat source must be considered as a heat transfer problem in two or three dimensions with a resulting increase in complexity.

The accuracy obtainable from computer-generated results depends, to a large extent, on how accurately the geometry of the structure is specified. Dividing the structure into a greater number of small structures generally increases the accuracy of the results. However, this requires a much larger amount of time to quantify the geometry and feed these data into the computer, often the major component of the total modelling time. Some commercially available packages have graphics interfaces to facilitate this task.

Once the geometry of the structure has been specified, the model can be used relatively quickly to determine solutions for a range of material parameters.

2.3.3 Boundary and initial conditions

Generally, a range of boundary and initial conditions can be supplied to a given model to simulate a variety of fire situations. The heat source of the model can be specified as a constant external temperature, to simulate, for example, the steady-state conditions near a fireplace, or a time-dependent external temperature to simulate a standard fire resistance test.

The mechanisms by which heat is transferred to, and lost from, the structure must also be specified. These boundary heat transfer mechanisms will limit the total amount of heat transferred to and from the structure and thus are as important as the internal mechanisms in determining the heat flow through the structure.

By varying the boundary and initial conditions one can model heat transfer through, for example, internal and external walls where temperature and ventilation conditions may vary on the unexposed side of the structure. It can also simulate exposure to fires which have different fuel sources and, hence, differing radiative and convective heat contributions.

3 HEAT-TRANSFER MODELLING SOFTWARE

3.1 Introduction

Obtaining results from a computer implementation of a mathematical model requires some expertise on the part of the user but the program can be used to generate the design tables and graphs with which engineers are more familiar. Engineers are often interested in the point at which a structure reaches a certain structurally critical temperature, such as 500°C where a steel member has only fifty per cent of its strength (Kruppa, 1979). Another example is the charring temperature of timber which is commonly taken to be 300°C (White and Schaffer, 1978). At this point the timber has lost much of its strength.

Computer models can be used to generate graphs showing the time to reach these critical points as a function of various structural and material parameters. Because of the generally short times (tens of minutes to several days) required to obtain results it is possible to quickly determine the best design for a given structure by running the model with different parameters and observing the results. Detailed knowledge of the physical processes being modelled is not necessary. All that is taken care of by the program. However, a basic understanding of the process of heat transfer is necessary to provide input for the model and to interpret the results.

The size of computer facility necessary to run heat transfer modelling software depends on the complexity of the model and/or the accuracy required. As a general rule, solutions of increasing accuracy require faster computers (memory storage limitations generally become significant for the large and complex programs used by research organisations). Thus, in financial terms, there is a trade off between the benefits of more reliable data against the increased financial outlay needed to obtain those data. Costs of running heat transfer software packages range from a few cents on a personal computer to several thousand dollars per hour for the powerful super computers found in research organisations (New Scientist, 1988).

Happily, the packages of most use to engineers and designers are configured for personal computers and can generate useful results in a matter of a few hours for the cost of the power used and staff time involved.

3.2 Examples of Available Heat-Transfer Software

WOOD1

This program was developed to solve the heat and mass transfer problem of wood pyrolysis at high temperatures (Fredlund, 1985). The mathematical models developed for heat and mass transfer on which this program is based are very rigorous due to a large amount of background research into the physical and chemical processes occurring in wood at fire temperatures. Results from the program have been verified for a range of wood species and temperature and moisture conditions. The modelling technique used is a one-dimensional finite-element method for the coupled heat and mass transfer. The program running time is given as 129 minutes on an IBM-compatible personal computer and 26 seconds on an IBM 3090 mainframe computer.

WOOD2

A program identical to WOOD1 with a two-dimensional finite-element modelling approach. This program would be used to study more complex geometries or localised heat sources.

HEATMASS

This program was developed at the Building Research Association of New Zealand primarily to look at heat and moisture transfer in composite constructions at ambient temperatures. However it has since been applied to the study of heat transfer in the environment of a solid fuel burning stove (Cunningham, 1988). The modelling technique used is a finite difference scheme which can be applied to heat flow in up to three dimensions. Heat transfer modes are described by effective temperature-dependent thermal resistances and simple one dimensional fluid flow can be modelled. The program running time is of the order of several minutes on a VAX 11/750 computer.

FIRES-T3

FIRES-T3 is a general three-dimensional finite-element heat transfer modelling program used to evaluate the temperature distribution history in composite structures exposed to fire temperatures (Iding, Bresler, and Nizamuddin, 1977). The program can deal with an amount of free water within the structure as well as conductive heat transfer. The program is written in FORTRAN.

TOPAZ3D

TOPAZ3D is a general three-dimensional finite-element computer code for heat transfer analysis (National Energy Software Centre, 1988). Temperature dependent material properties may be specified. The program has a graphics facility for the input of geometrical data and mesh generation, and a graphics output routine for displaying results.

ANSYS

ANSYS is a general three-dimensional finite-element heat transfer and structural analysis program. The program is designed to run on a variety of systems with running times of 35 minutes on a VAX 11/780 to 3.5 hours on a desktop personal computer. The program is best suited to isolated solid structures, i.e., structures without cavities, and so is limited when dealing with building components such as cavity walls. However, it is well suited to problems such as insulated steel and reinforced concrete beams and columns, and solid, non-combustible, walls and doors (Scott, 1988).

STOVE

STOVE is a one-dimensional steady-state program designed for the study of heat transfer in the vicinity of solid-fuel heaters (Peacock and Dipert, 1986). The program was developed at the National Bureau of Standards (now the National Institute of Standards and Technology) and is written in FORTRAN. The structure is represented by a number of nodes with temperature dependent thermal resistances between each node. The program running time is of the order of seconds on any computer capable of running FORTRAN programs.

4 DISCUSSION

Current heat transfer models are capable of dealing with conduction through solid materials and solids of varying thermal conductivity and composition. They are also able to model convective and radiative heat transfer at boundaries, and heat transfer between a number of isolated but interacting structures. Additionally, some are capable of modelling air and moisture movement at fire temperatures, processes which are significant in materials such as concretes, timber and gypsum boards.

The addition of sophisticated graphics devices for the input and output of results is now available with many software packages. This greatly facilitates the modelling process by allowing the modeller to visualise the structure being modelled. Some packages can also provide graphs of temperature versus time for any location in the structure and produce contour plots of the temperature distribution throughout the structure at a given time.

Difficulties remain, however, in producing practical results for some structures and materials. Currently there are few models equipped to deal with combustion and pyrolysis phenomena, which effectively excludes timber structures. In addition, convective heat transfer in structural voids must be simplified to avoid the complex problem of air flow modelling. The thermal properties of the materials being used must be evaluated accurately for the model to produce quantitatively useful results. Finally, sudden structural deterioration has a large effect on the heat transfer through a composite structure but its occurrence and effect is highly unpredictable.

In New Zealand the use of heat transfer models to predict fire resistance of building structures is limited by design standards that render only a small number of prototype variations amenable to test by expert opinion. An example is NZS 4232:1988 which deals with the performance of fire resisting doorsets (NZS 4232, 1988). Research organisations and testing laboratories committed to helping the building industry have a responsibility to develop and promote heat transfer modelling techniques. This would enable the industry to reduce design and testing costs and provide an increased number of products that comply with the standards. The principal mechanism by which this can be achieved is through technical input to standards revision committees. The resulting standards would be more flexible due to their performance-based, rather than prescriptive, nature.

It is important to note that simple engineering design calculations and computer-based heat transfer models are both mathematical calculation methods, differing only in the degree of complexity. The validity of the computer modelling approach must be borne out by extensive research and testing, just as was the case for engineering design calculations.

5 CONCLUSIONS

A literature search was carried out to determine the state of heat transfer modelling in the research and design fields. It was found that heat transfer modelling of composite structures at fire temperatures has been developed to the extent that it is now possible to model a wide variety of composite structures.

Current legislation in New Zealand excludes results obtained from mathematical modelling of heat transfer from wider acceptance, with the exception of calculation methods for some simple steel constructions. This is understandable in light of the difficulties involved with the accurate determination of material thermal properties and the development of models for pyrolysis and combustion mechanisms. However, these models can be used very effectively at the design stage to minimise the amount of prototype testing required.

In view of the above, a greater amount of research is needed to provide data to validate the heat transfer modelling approach. Also, a more active promotion of this technique from testing laboratories and research establishments should speed its transition from a research tool to an acceptable method of performance evaluation.

6 REFERENCES

Abrams, M.S. (1980). Behaviour of inorganic materials in fire. Portland Cement Association, report RD067.01M.

Bazant, Z.P. and Panula, L. (1979). Practical prediction of time-dependent deformations of concrete. Materials and Structures, Vol.12 No.69.

Cunningham, M.J. (1988). Modelling of moisture transfer in structures - 1. A description of a finite difference nodal model. In press.

Delichatsios, M.A. and de Ris, J. (1983). An analytical model for the pyrolysis of charring materials. Factory Mutual Research Corporation, technical report J.I. OKOJ1.BU.

Fredlund, B. (1985). A computer model for the analysis of timber structures exposed to fire. Lund Institute of Technology, report LUTVDG/(TVBB-3020).

Fredlund, B. (1988). A model for heat and mass transfer in timber structures during fire: a theoretical, numerical and experimental study. Lund Institute of Technology, report LUTVDG/(TVBB-1003).

Gandhi, P.D. (1986). How a computer program can predict fire performance -FIRES-T3. Lab Data, Vol.19 No.2, p. 9.

Iding, R.H., Bresler, B. and Nizamuddin, Z. (1977). FIRES-T3 computer program for fire response of structures - thermal-3D version. Dept. Civil Eng. Berkeley, Report No. UCB-FRG-77-15.

Jason, N.H. (1987). Firedoc users manual. National Bureau of Standards, NBSIR 87-3562.

Kruppa, J. (1979). Collapse temperature of steel structures. American Society of Civil Engineers, Journal of the Structural Division, Vol.105 No.ST9, p.1769.

National Energy Software Centre. (1988). Argonne National Laboratory, Product literature.

New Scientist, (1988), Sept. p.45.

NZS 4232: 1988 - Performance criteria for fire resisting doorsets, New Zealand Standards Association, Wellington.

Peacock, R.D. and Dipert, R.A. (1986). STOVE: a predictive model for heat transfer from solid fuel appliances. National Bureau of Standards, NBSIR-86-3300.

Pettersson, O. (1984). Fire research today - influence of the mathematical model. Building Research and Practice, Vol.12 No.3, p. 150.

Scott, L. (1988). Swanson Analysis Systems (Houston, Texas), Product literature.

The Software Catalogue - Science and Engineering. (1985). Elsevier Science Publishing Co., New York.

White, R.H. and Schaffer, E.L. (1978). Application of CMA program to wood charring. Fire Technology, Vol.14 No.4., p. 279.

Wickstrom, U. (1977). A numerical procedure for calculating temperature in hollow structures exposed to fire. National Bureau of Standards, NBS-GCR-77-100.

Yamizaki, M. and Miyashita, T. et al. (1985). An analytical study on the thermal stress of mass concrete. Kajima Corporation, KICT Report no. 57.

Appendix

Thermal Properties:

Bresler, B. and Iding, R.H. (1983). Fire response of prestressed concrete members. American Concrete Institute, ACI SP-80.

Melinek, S.J. and Thomas, P.H. (1987). Heat flow to insulated steel, Fire Safety Journal, Vol.12 No.1., p. 1.

Numerical Heat Transfer Modelling:

Brown, D.K. (1984). An introduction to the finite element method using basic programs. Surrey Univ. Press, London.

Dho, M.H. and Springer, G.S. (1983). Mass loss of and temperature distribution in southern white pine and douglas fir in the range 100 to 800°C. Journal of Fire Sciences, Vol.1 No.4, Jul., p. 271.

Fung, F.C.W. (1977). A computer program for the thermal analysis of the fire endurance of construction walls. National Bureau of Standards, NBSIR 77-1260.

Iding, R.H. (1977). FIRES-RC II computer program for fire response of structures - reinforced concrete frames. Dept. Civil Eng. Berkeley, Report No. UCB-FRG 77-8.

Shih, T.M. (1984). Numerical properties and methodologies in heat transfer. Proc. of the 2nd National Symposium on Numerical Properties and Methodologies in Heat Transfer, Hemisphere, Washington.

Shih, T.M. (1984). Numerical heat transfer. Hemisphere, U.S.A.

Zienkiewicz, O.C. (1971). The finite element method in engineering science, McGraw-Hill.

Analytical Heat Transfer Modelling:

Andersson, L. and Jansson, B. (1987). Analytical fire design with gypsum. Institute of Fire Safety Design, report IFSD87-MG001.

Lefter, J. (1987). Fire safety of concrete slabs. Concrete International, Vol.9 No.8, p. 23.

Melinek, S.J. and Thomas, P.H. (1987). Heat flow to insulated steel, Fire Safety Journal, Vol.12 No.1., p. 1.

Thermal Properties of Timber:

Buchanan, A.H. (1987). Fire resistance of timber. NZ. J. Timber Construction, Vol.3 No.1, p. 14.

Dho, M.H. and Springer, G.S. (1983). Mass loss of and temperature distribution in southern white pine and douglas fir in the range 100 to 800°C. Journal of Fire Sciences, Vol.1 No.4, Jul., p. 271.

Dho, M.H. and Springer, G.S. (1983). Model for predicting changes in the strengths of timber exposed to elevated temperatures. Journal of Fire Sciences, Vol.1 No.4, Jul., p. 285.

Dho, M.H. and Springer, G.S. (1983). Failure time of loaded wooden beams during fire. Journal of Fire Sciences, Vol.1 No.4, Jul., p. 297.

Dho, M.H. and Springer, G.S. (1983). Degradation of mechanical properties of wood during fire. National Bureau of Standards, NBS-GCR-83-433.

Havens, J.A., Welker, J.R. and Sliepcevich, C.M. (1971) Pyrolysis of wood: A thermoanalytical study, J. Fire and Flammability, Vol.2, p. 321.

Jonsson, R. and Pettersson, O. (1985). Timber structures and fire. Swedish Council for Building Research, D3:1985.

Kanury, A.M. (1971). Burning of wood - A pure transient conduction model. Fire and Flammability, Vol.2, Jul., p. 191.

White, R.H., Schaffer, E.L. and Woeste, F.E. (1984). Replicate fire endurance tests of an unprotected wood joist floor assembly. Wood and Fiber Science, Vol.16 No.3, p. 374.

White, R.H. (1985). Design of fire-resistive coated wood members. Proc. 3rd Ann. Fire Eng. Conf., Riverdale, New York.

Thermal Properties of Gypsum:

Abrams, M.S. (1980). Behaviour of inorganic materials in fire. Portland Cement Association, report RD067.01M.

Andersson, L. and Jansson, B. (1987). Analytical fire design with gypsum. Institute of Fire Safety Design, report IFSD87-MG001.

Final report on the activity (1973-1980) of RILEM Committee 23-GP Gypsum Plaster (1982). Materials and Structures, Vol.15 No.85

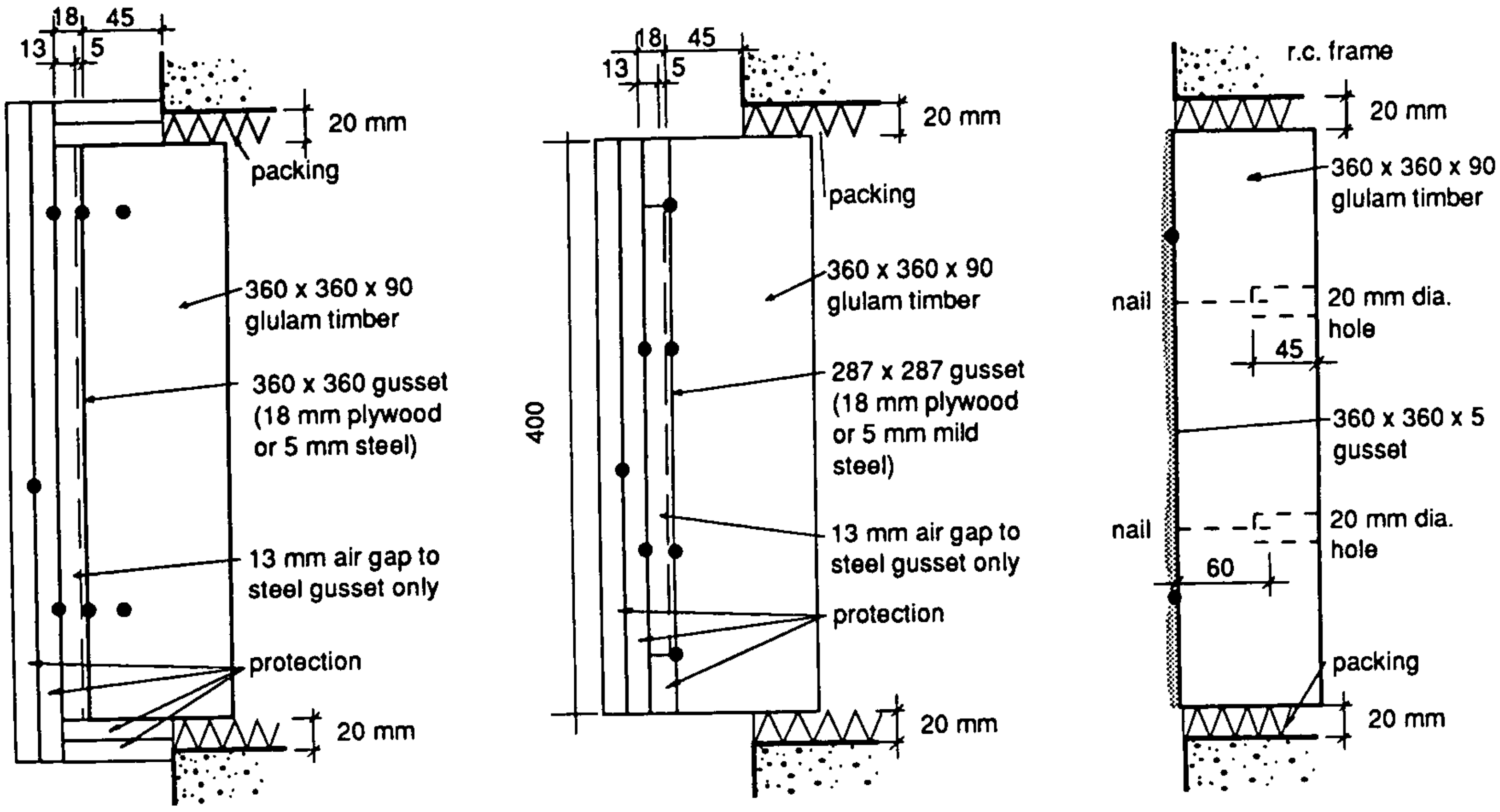
Heat Transfer Mechanisms:

Cooper, L.Y. (1984). Thermal response of unconfined ceilings above growing fires and the importance of convective heat transfer. National Bureau of Standards, NBSIR 84-2856.

Oziski, M.N. (1978). Radiative transfer and interaction with conduction and convection. Wiley Interscience, New York.

Paulsen, O. (1979). On heat transfer in fire test furnaces. Technical Univ. of Denmark, unnumbered report.

Romanenko, P.N., Koshmarov, Y.A., and Bashkirtsev, M.P. (1985). Thermodynamics and heat transfer in fire fighting. Oxonian Press, New Delhi



2 (a) : Arrangement A   2 (b) : Arrangement B   2 (c) : Arrangement C

Figure 2 : Protected gusset specimens

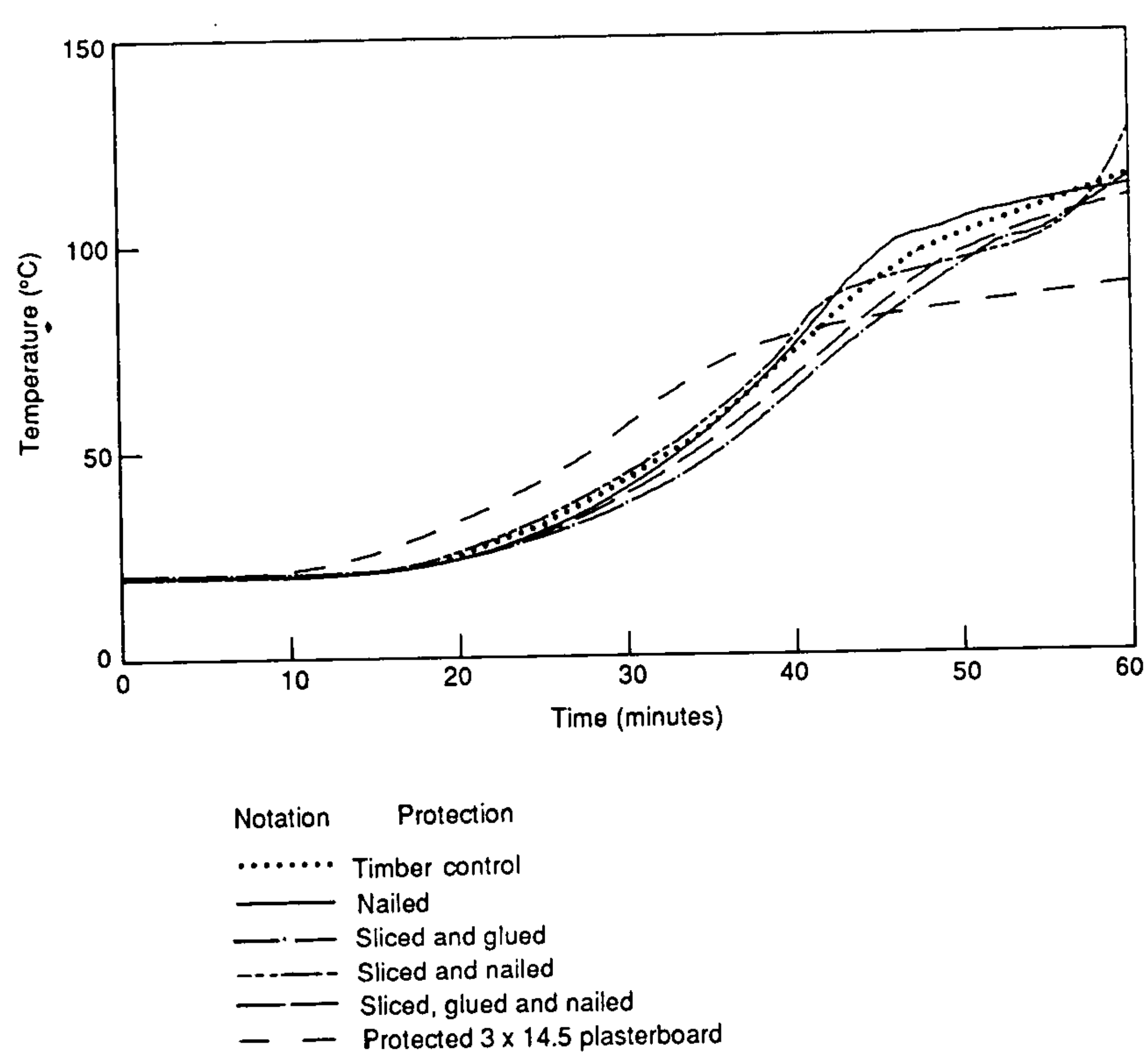
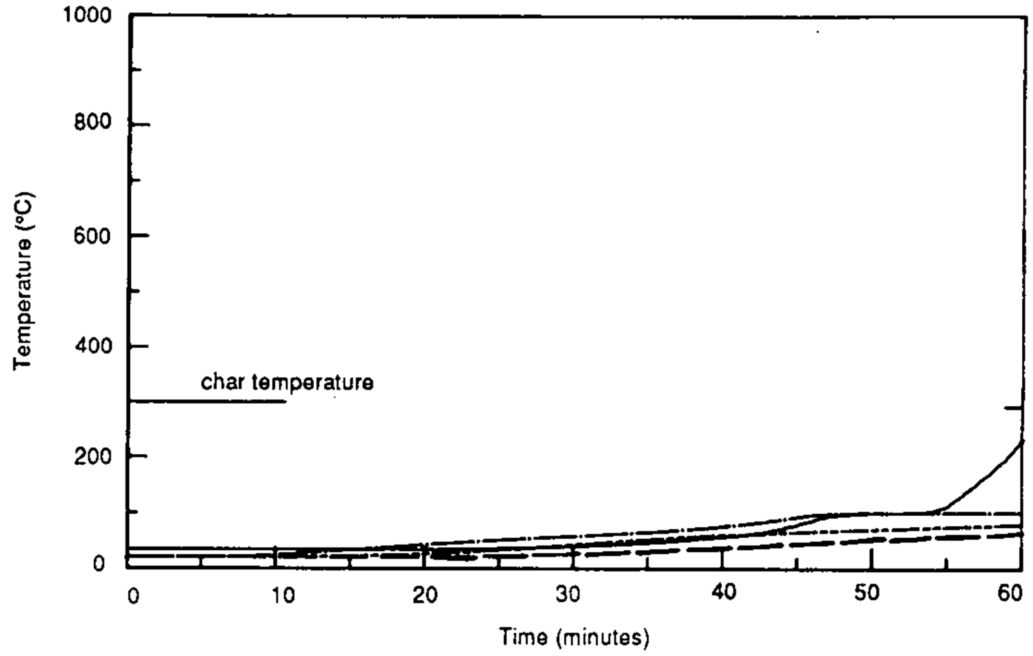
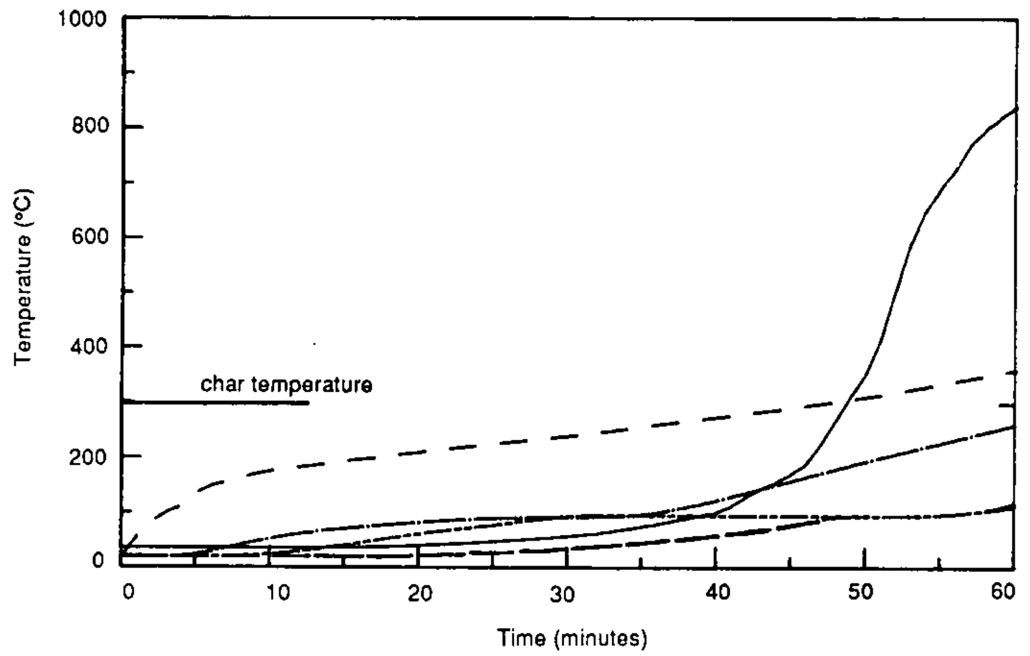


Figure 3: Block test temperatures
(at mid-depth of block)



Plywood Gusset



Steel Gusset

Notation	Protection
————————	2 layers of 18 mm thick plywood
——·——·——	19mm thick paper-faced gypsum plasterboard
——··——··——	2 layers of 14.5 mm thick paper-faced gypsum plasterboard
————————	40 mm thick solid timber
— — — — —	intumescent coatings

Figure 4 : Glulam timber surface temperatures, arrangement A

Modelling of heat transfer in composite structures at fire temperatures.
GROOM, A.J.
1989 34632

BUILDING RESEARCH ASSOCIATION OF NEW ZEALAND INC.
HEAD OFFICE AND LIBRARY, MOONSHINE ROAD, JUDGEFORD.

The Building Research Association of New Zealand is an industry-backed, independent research and testing organisation set up to acquire, apply and distribute knowledge about building which will benefit the industry and through it the community at large.

Postal Address BRANZ, Private Bag Porirua

ISSN 0111–7459