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MICRO TO MACRO ENGINEERING COMPUTATIONS

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MICRO TO MACRO ENGINEERING COMPUTATIONS

INAUGURAL LECTURE

Delivered at the College on December 4, 1984

by

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UNIVERSITY COLLEGE OF SWANSEA

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Introduction

The last decade or so has witnessed rapid progress in the development of electronic computers which in turn has stimulated the development of numerical methods for the solution of a wide range of significant problems in science and engineering. High speed computers now play an everyday role in most pure and applied science disciplines. They do not simply serve as a means of alleviating tedious repetitive computational tasks but in many cases have opened new horizons by providing solution capabilities on a scale until recently unimagined. This growth in computing power has occurred at a breathtaking pace over the last decade and promises to proceed at even greater speed during the next.

Nowhere has the impact of the computer been greater than in the field of engineering. The engineering profession, being a pragmatic one, was prepared to accept the practical benefits of the computer at an early stage so that by now computer methods play a leading role in both research and design. Of course improvements in computer performance would be useless without the parallel development of numerical techniques and the associated software generation. It is true to say that the most significant advance in this direction has been the development of the Finite Element Method in which the Department of Civil Engineering at University College, Swansea has been priviledged to play a leading role. The finite element method has, if not revolutionised, at least drastically influenced the analysis and design procedures used in most branches of engineering. The method, as well as facilitating the solution of some of the more traditional engineering problems, has provided the means of analysing complex situations which were previously considered insoluble.

The large amount of input information necessary for a finite element analysis requires that steps be taken to ensure that the generation of this data is made as automatic as possible. For many applications the commercial costs of preparing finite element input data can exceed the computer costs of the analysis itself. Therefore the development and use of pre-processing packages for automatic data generation is amply justified by savings in manpower and reduction in errors.

The ease with which computer studies can provide data also poses serious problems with regard to the presentation and assimilation of this information. This is particularly true of dynamic problems where information, such as displacements and stresses, at each point in the structure must be presented for each instant of time. The use of computer graphics has become invaluable for such purposes and the recent availability of colour graphic options has proved to be particularly beneficial. The investment of research effort into the development of pre- and post-processor techniques and software is considerable and work in this area is currently considered to be equally important as the development of further finite element techniques.

For the foregoing reasons this lecture will feature the applicability of the finite element method to a wide spectrum of engineering problems and will illustrate the use of pre- and post-processor techniques as an integral part of the design procedure. The contents will be divided into the following sections:-

*Historical background

*Basic principles of the finite element method

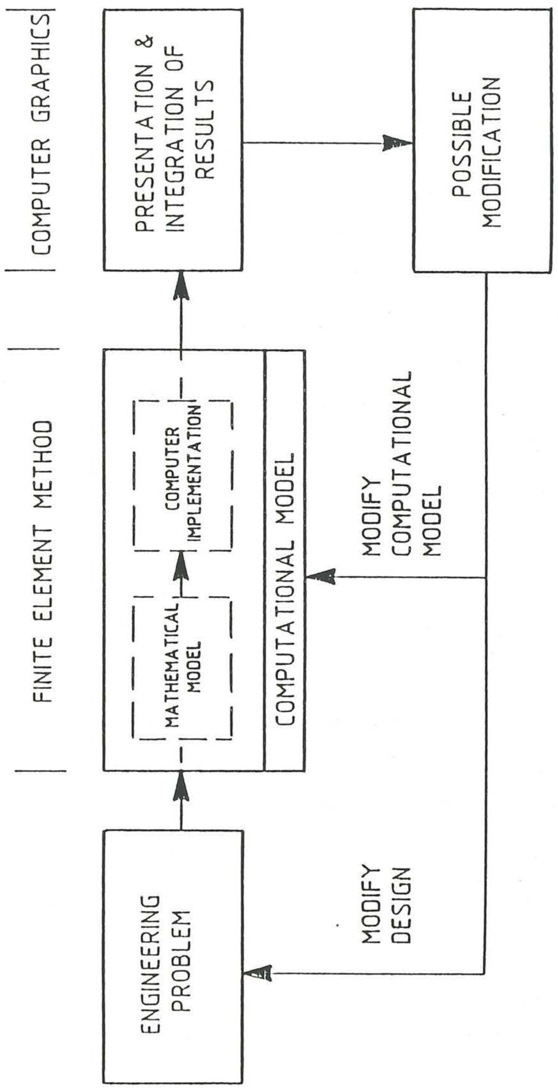
*Applications and computer-aided-design

*Computer graphics (Pre- and post-processors)

*Future trends in engineering computing

Before proceeding with a historical review of the finite element method let us begin by introducing the concept of a computational model as outlined in Fig. 1. This will help to put the finite element method into its proper perspective.

Let us assume that we have an engineering problem which might, for example, involve the selection of an economic design for a particular structure. After we have produced an initial trial structural design, the performance of the structure in its likely environment during and after construction must be predicted and assessed to check for its adequacy. We must therefore choose a suitable computational model to provide some insight into the structural behaviour. This model may vary from a simple 'back-of-the-envelope' hand calculation to a highly sophisticated nonlinear analysis requiring several hours of computing time. The choice of the



A TYPICAL ENGINEERING COMPUTATIONAL PROCESS

Fig. 1 Computational model

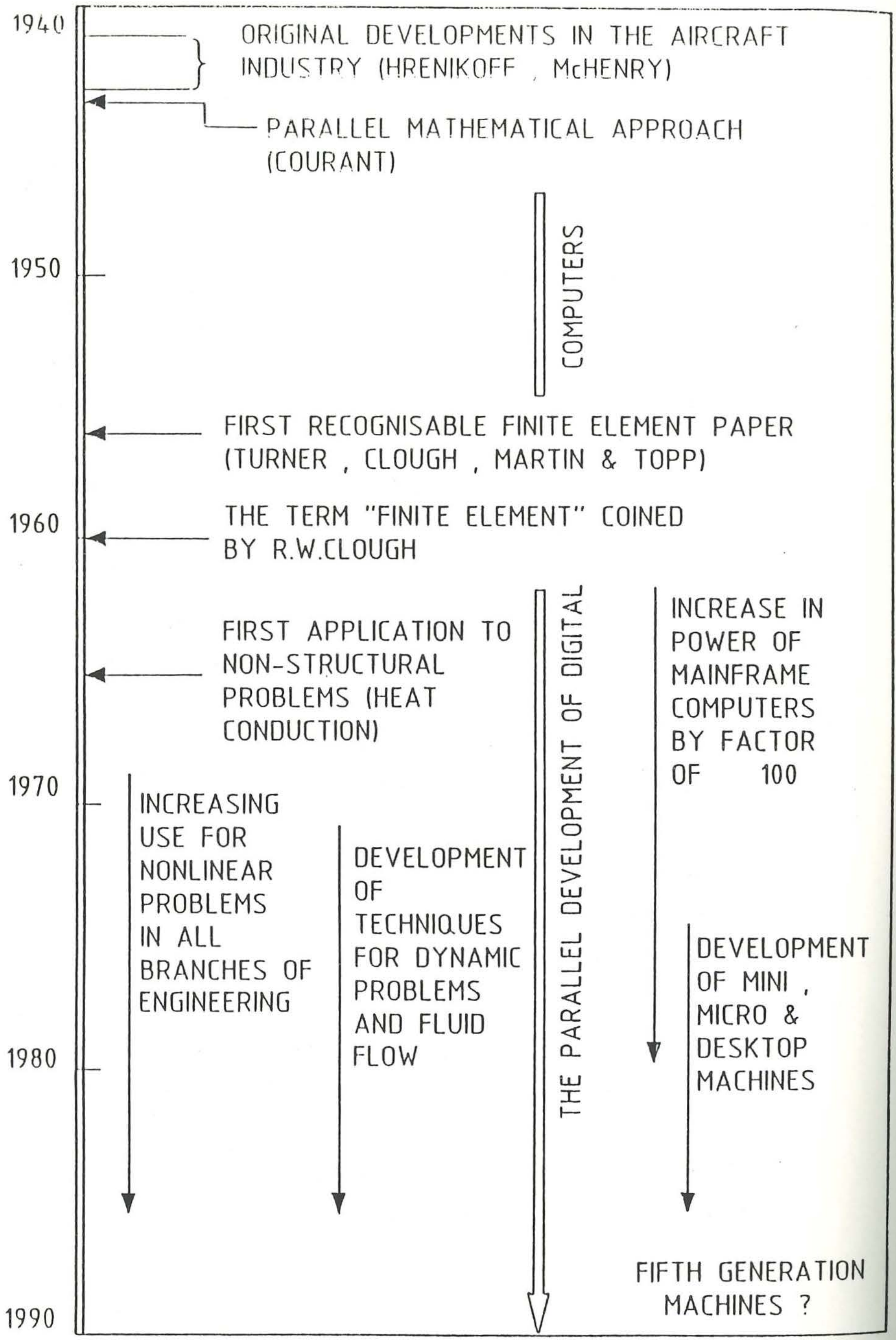
model will therefore depend on many factors including the time, money, expertise and software available and the degree of accuracy required. Having obtained a solution based on the model, the results must then be presented in some meaningful, usually graphic, form and checked. If the solution is inadequate then the model must be modified. Once a satisfactory model has been obtained then the performance of the design can be properly assessed.

Historical background

A brief historical summary of the finite element method is provided in Fig. 2. The finite element method originated from the aircraft industry in the early 1940's. With the advent of metal skinned aircraft it was quickly realised that the skin could act in a load carrying role but the means of analysing such a continuous structure was at that time unavailable. Using a large mesure of physical intuition Hrenikoff and later McHenry approximated the two dimensional metal sheets by an arrangement of simple elastic bars. At approximately the same time, but following a mathematical approach, Courant used piecewise continuous functions to approximate the true function in order to obtain the solution of a torsion problem. This approach was later formalised and the first recognisable finite element paper appeared in 1956. The term finite element was introduced by R. W. Clough in 1960.

Since then there has been rapid development and the method is now firmly established as a general numerical

Fig. 2 Historical background



technique for the solution of partial differential equations subject to known boundary and initial conditions. The development of the digital computer and the increasing complexity in many areas of modern technology have ensured that the method now enjoys a unique position as a powerful and versatile solution technique for a large range of advanced engineering problems.

The increase in computing power over the last two decades has been truly remarkable and this together with the ready availability of desktop and minicomputers has contributed to the popularity of the method.

<u>The finite element method</u>

It is now appropriate to summarise the main features of the FEM and to examine the basic steps of the technique:

*As previously stated, the FEM permits the solution of complex problems hitherto considered impossible.

*From the engineering point of view the most attractive and yet possibly the most dangerous feature of the finite element method is the fact that it is approximate. In the hands of an experienced and careful analyst it is a very useful means of obtaining insight into certain problems for which no other analytical tool is appropriate. However it is a method which can be misused.

*The FEM is applicable to problems in all branches of engineering and science (i.e. systems governed by a set of partial differential equations and known boundary and initial conditions).

*The applicability and popularity of the FEM is attributable to the parallel development of digital computers – generally requiring large memory machines with extensive processing power.

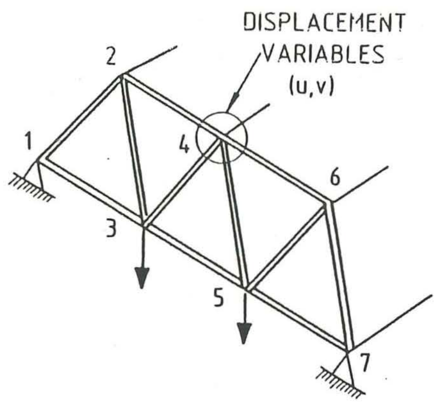
*The F.E.M. is now an accepted design tool in engineering and is no longer the sole province of the researcher.

In the various branches of applied science, problems can be classified as either discrete or continuous. It is in the solution of continuous systems that the FEM plays such a crucial role.

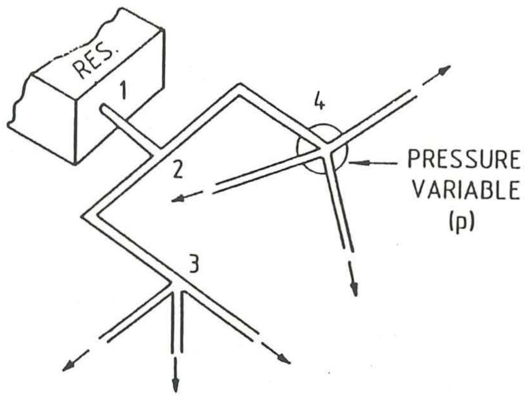
Discrete systems

In certain engineering applications, the engineer is faced with the problem of analysing a network system which consists of a series of physically identifiable and distinct members, links or elements that are inter-connected at their extremities or nodes. Examples of such discrete systems

DISCRETE PROBLEMS



BRIDGE FRAMEWORK



PIPE NETWORK

FOR A LINEAR BEHAVIOUR :

$$K_{11}a_1 + K_{12}a_2 + \ldots\ldots\ldots K_{1n}a_n = f_1$$
$$K_{21}a_1 + K_{22}a_2 + \ldots\ldots\ldots K_{2n}a_n = f_2$$
$$K_{n1}a_1 + K_{n2}a_2 + \ldots\ldots\ldots K_{nn}a_n = f_n$$

WHERE

a_i – BASIC VARIABLE FOR JOINT i
(u,v) OR (p)
f_i – GENERALISED FORCE FOR JOINT i
(X,Y) OR (S)
K_{ij} – GENERALISED STIFFNESS FOR JOINTS i AND j

Fig. 3 Discrete Systems

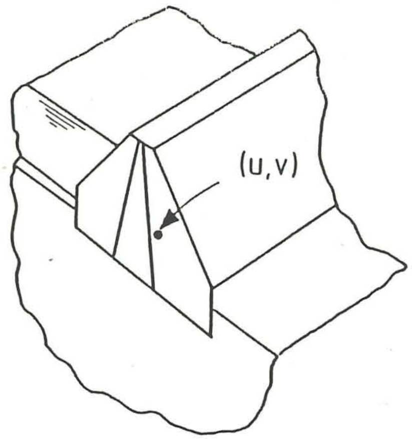
abound in engineering and two examples are shown in Fig. 3. In structural engineering, for example, we frequently encounter frameworks and grillages. In other areas of engineering, networks appear in hydraulic pipeline systems, construction management (CPM, PERT) systems, transportation systems and electrical circuits.

In the simplified analyses of the behaviour of network systems no formal mathematical discretisation is required even though it may be possible. It is only necessary to build a mathematical model representing the unknowns at the nodes linking the discrete system members. If linear behaviour in the network is assumed, it is possible to write the governing equations in the form of a set of linear simultaneous equations in terms of the unknown nodal variables $\underline{a}$, where $\underline{k}$ and $\underline{f}$ are obtained from the properties of the network system. The equation system can then be solved by any standard procedure to yield the nodal variables $a_1 - a_n$. It turns out that the basic computational steps in the solution of discrete systems are almost identical to the basic steps in the solution of continuous systems by the FEM.

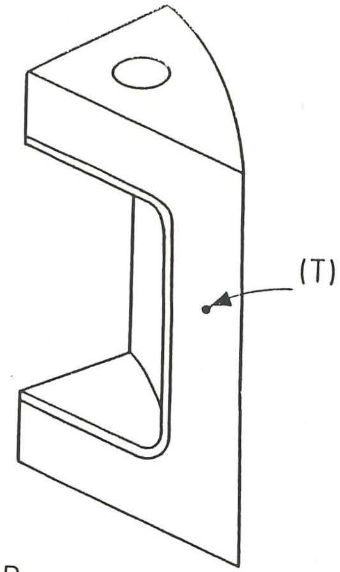
Continuous systems

Continuous systems are all inherently three-dimensional. However in building mathematical models to represent these systems, the predominant behaviour may be characterised as being 1, 2 or 3-dimensional. Examples of

CONTINUOUS PROBLEMS



GRAVITY DAM
- STRESS & GROUNDWATER FLOW DETERMINATION



NUCLEAR PRESSURE VESSEL
- TEMPERATURE ANALYSIS

- AT EACH POINT THERE ARE DISPLACEMENT VARIABLES (u,v) IN THE DAM OR TEMPERATURE (T) IN THE PRESSURE VESSEL
- HENCE THERE ARE AN INFINITE NUMBER OF VARIABLES IN EACH STRUCTURE
- THE F.E.M. ALLOWS THIS TO BE REDUCED TO A FINITE VALUE
- THEN SOLUTION PROCEDURE IDENTICAL TO TO THAT FOR DISCRETE SYSTEMS

Fig. 4 Continuous Systems

continuous systems are provided in Fig. 4. A continuous system possesses an infinite number of variables: In the gravity dam the displacement components, u,v at each point are unknown whereas in the pressure vessel the temperature value at each position is to be determined. The FEM is an approximate procedure which allows the number of variables to be reduced to a finite value. After the discretisation process has been accomplished the solution procedure is identical to that for discrete systems.

Basic steps of the finite element method

The basic steps of the FEM can be summarised as follows:

*The structure is first divided into distinct non-overlapping regions known as elements over which the main variables are interpolated.

*These elements are connected at a discrete number of points along their periphery known as nodal points.

*The variation of the basic unknown (displacement) within each element is specified in terms of the nodal values.

*Thus the variation in displacement through the structure can be expressed in terms of the finite number of nodal values.

*The resulting system of simultaneous equations is solved for the unknown nodal variables; which for structural problems are the displacement components.

*Finally subsidiary quantities such as stress components are evaluated for each element.

Classification of finite element solutions

Finite element problems can generally be divided into three categories.

Equilibrium problems in which no variation with time takes place (e.g. linear elastic structures, steady-state heat conduction and groundwater flow problems).

Eigenvalue problems These are extension of equilibrium problems in which, due to the system properties, solutions exist only for critical values of certain parameters (e.g. free vibration analysis and buckling problems).

Propagation problems in which some time-dependent phenomenon takes place (e.g. heat conduction under transient conditions, slow transient viscoplastic deformation

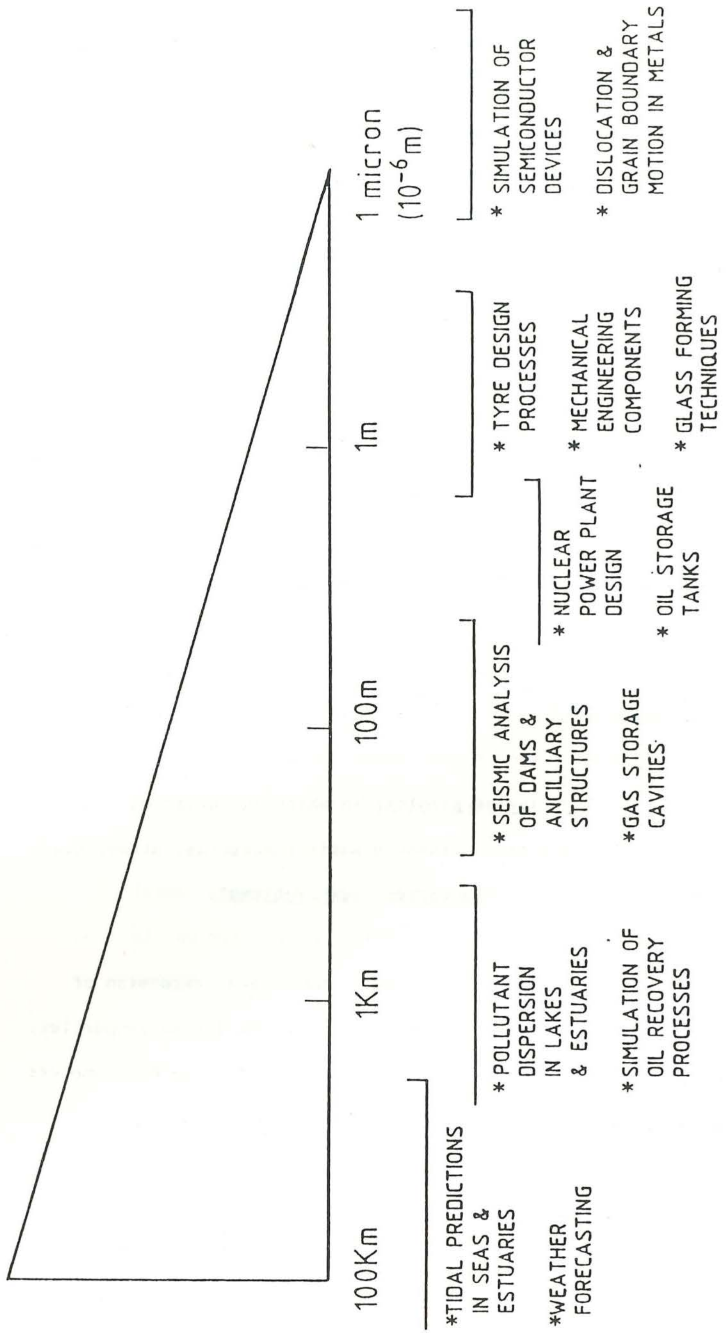


Fig. 5 Range of applications

and dynamic transient effects such as seismic or impact loading).

The range of applications

The range of problems to which the FEM can be applied is best illustrated by plotting the dimensional scale of problems addressed to date as shown in Fig. 5. The situations which have been successfully analysed span between areas in excess of 1000 Km considered for weather predictions and models less than 1 micron employed in transistor simulation. Between these two limits a wide variety of applications from almost every field of engineering can be found.

Illustrative examples

To illustrate the versatility of the method several applications of contrasting scale have been deliberately chosen from different engineering disciplines.

Channel tunnel

This example describes the finite element simulation of a heat conduction problem arising in a proposed channel tunnel scheme. This feasibility study considers a rail tunnel shown in Fig. 6, and the problem addressed here is the accumulation of heat generated by passing trains. The heat output per train is evaluated and for a given frequency of passing it is estimated that the average heat flux through the tunnel lining is 4.0 w/m^2. We wish to calculate the temperature distribution in the surrounding rock and more importantly to monitor the build up of temperature with time.

On the L.H.S. of Fig. 7 we see the mesh of finite and infinite elements employed in solution. The infinite elements extend to infinity and are used to model the far field behaviour of the surrounding rock. The R.H.S. shows the end result of a transient thermal analysis where the temperature distribution is determined throughout the model for successive time intervals until steady state conditions are achieved.

Fig. 8 shows the variation of temperature with time at points A and B. It is seen that the increase of temperature near the tunnel lining is relatively rapid with a rise of about 12°C occurring in 2 years. However away from the tunnel the build-up of temperature occurs very slowly - in fact steady state conditions are only achieved after 1000 years.

Wind turbine analysis

The next application, illustrated in Fig. 9 considers the finite element analysis of an aerofoil blade from a horizontal axis wind turbine. The wind direction and sense of rotation is indicated together with the stacking arrangement

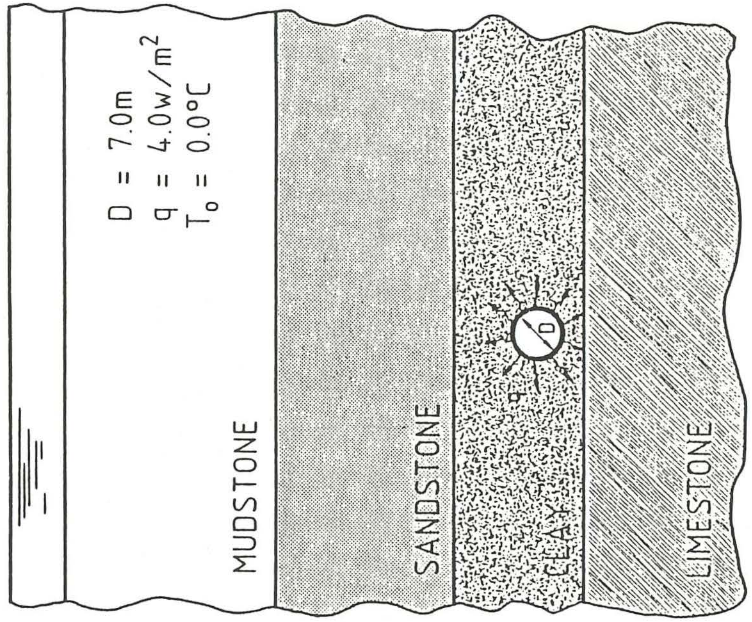


Fig. 6 Proposed tunnel scheme

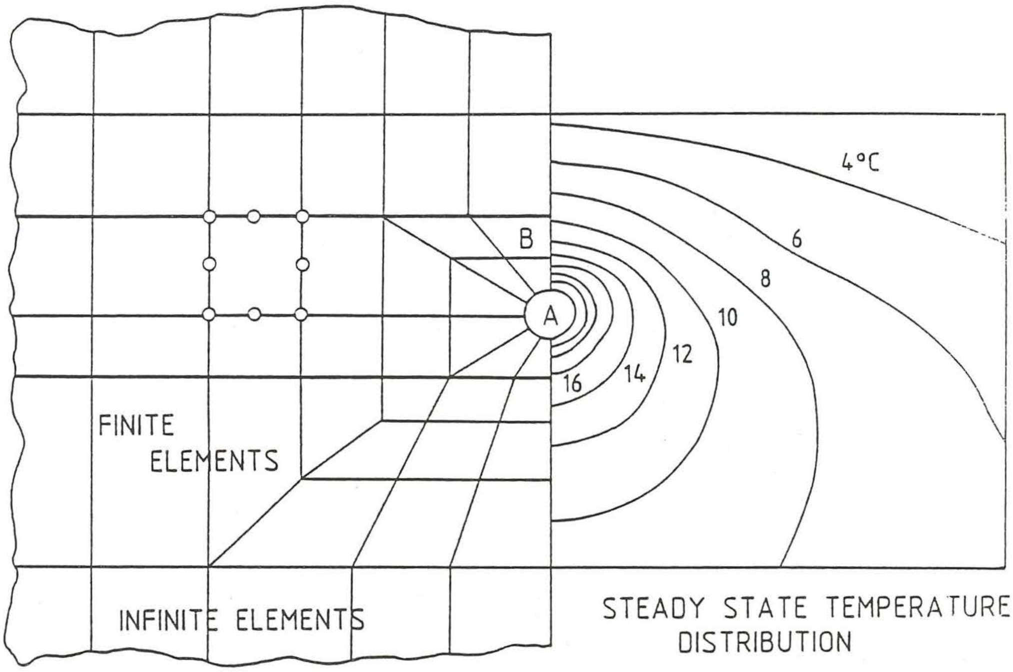


Fig. 7 Finite element discretisation and steady state temperature distribution for the tunnel problem of Fig. 6

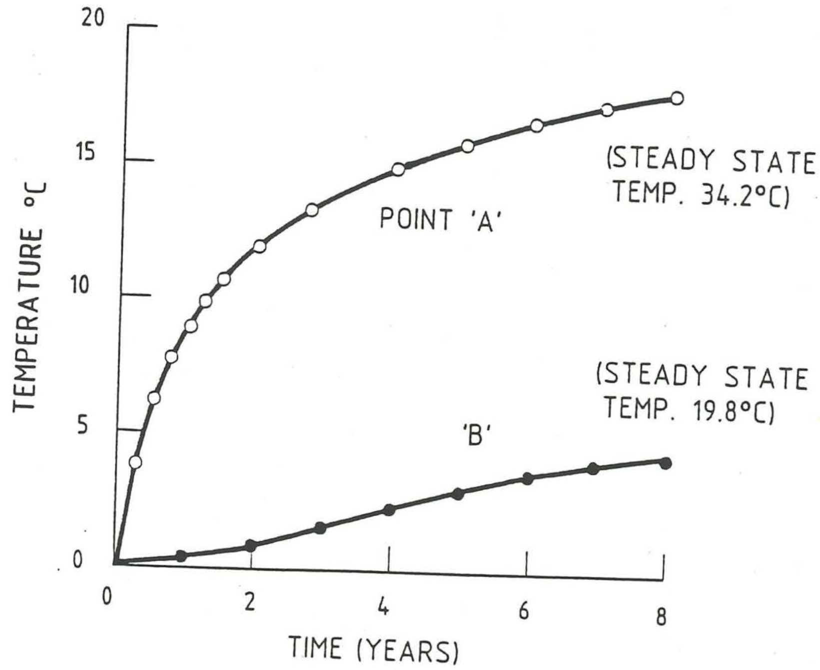


Fig. 8 Variation of temperature with time for the tunnel problem of Fig. 6

of sections of the blade. (The root of the blade corresponds to Section 0 and the tip to Section 7). The anisotropic 2.5m blade is constructed from a glass fibre outer skin, reinforced longitudinally with carbon fibre, and the internal void is filled with a non-structural foam to prevent buckling. The finite element idealisation, using Semiloof shell elements, is shown in Fig. 10 together with the stress distribution resulting from the analysis. As expected the blade operates predominantly in bending so that the upper surface is in a state of compression and the lower is in tension.

Fig. 11 shows the displacement of various sections of the blade under the design loading. Of course the maximum displacements occur at the tip and are approximately 23mm (i.e. 1 per cent of the blade length).

<u>Notch Bend Specimen</u>

The final example considers the elasto-plastic analysis of a notch-bend specimen used in fracture predictions. The geometry and loading, as well as the finite element mesh, for the problem are shown in Fig. 12. The problem was solved considering both a Von Mises and a Tresca yield criterion for the plastic material behaviour.

Provided that we consider a Tresca material which does not work-harden then a theoretical slip-line field solution exists for this problem which is considered exact. Comparison of the FE results with this solution (Fig. 13)

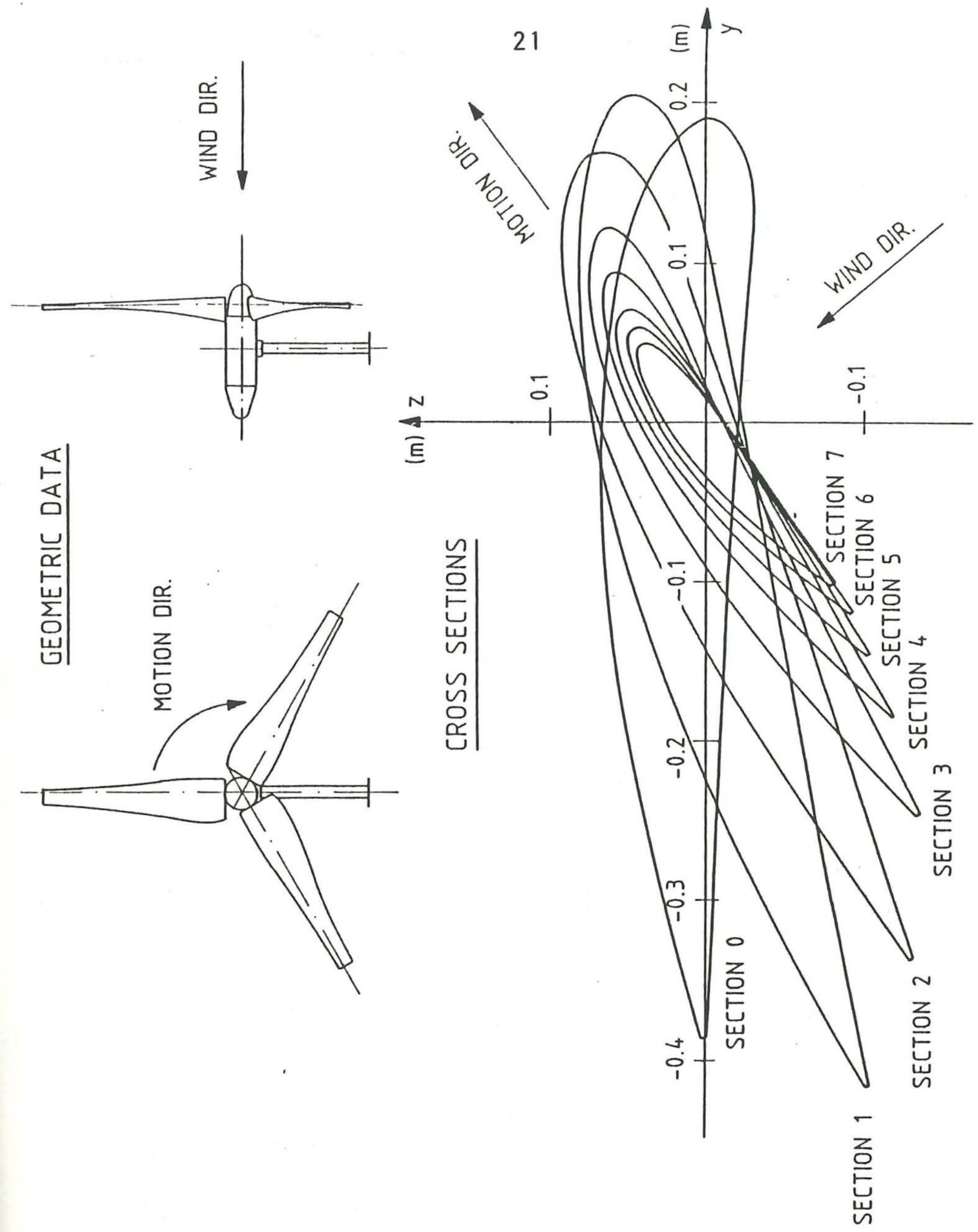


Fig. 9 Horizontal axis wind turbine

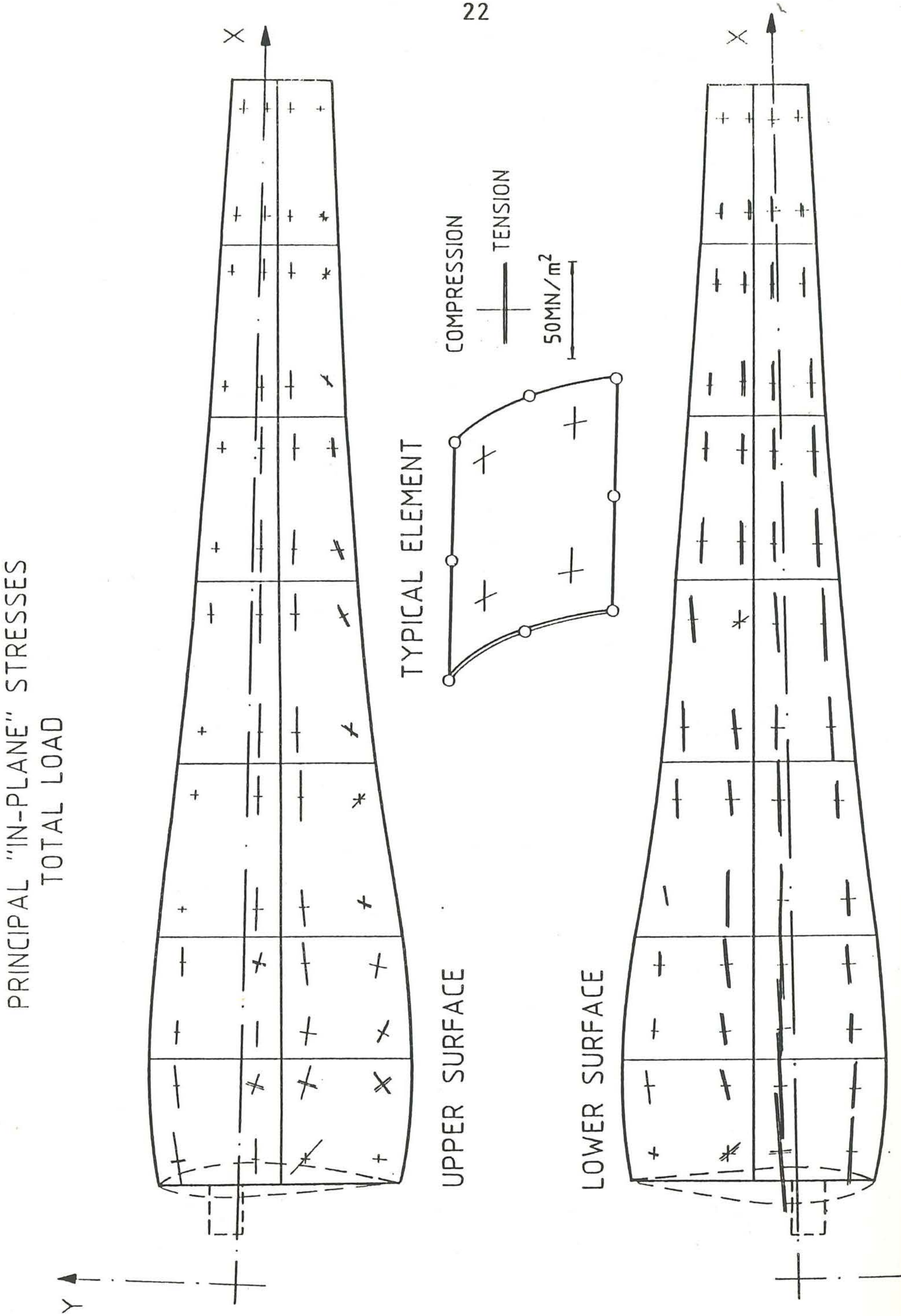


Fig. 10 Finite element idealisation and principal stress distributions

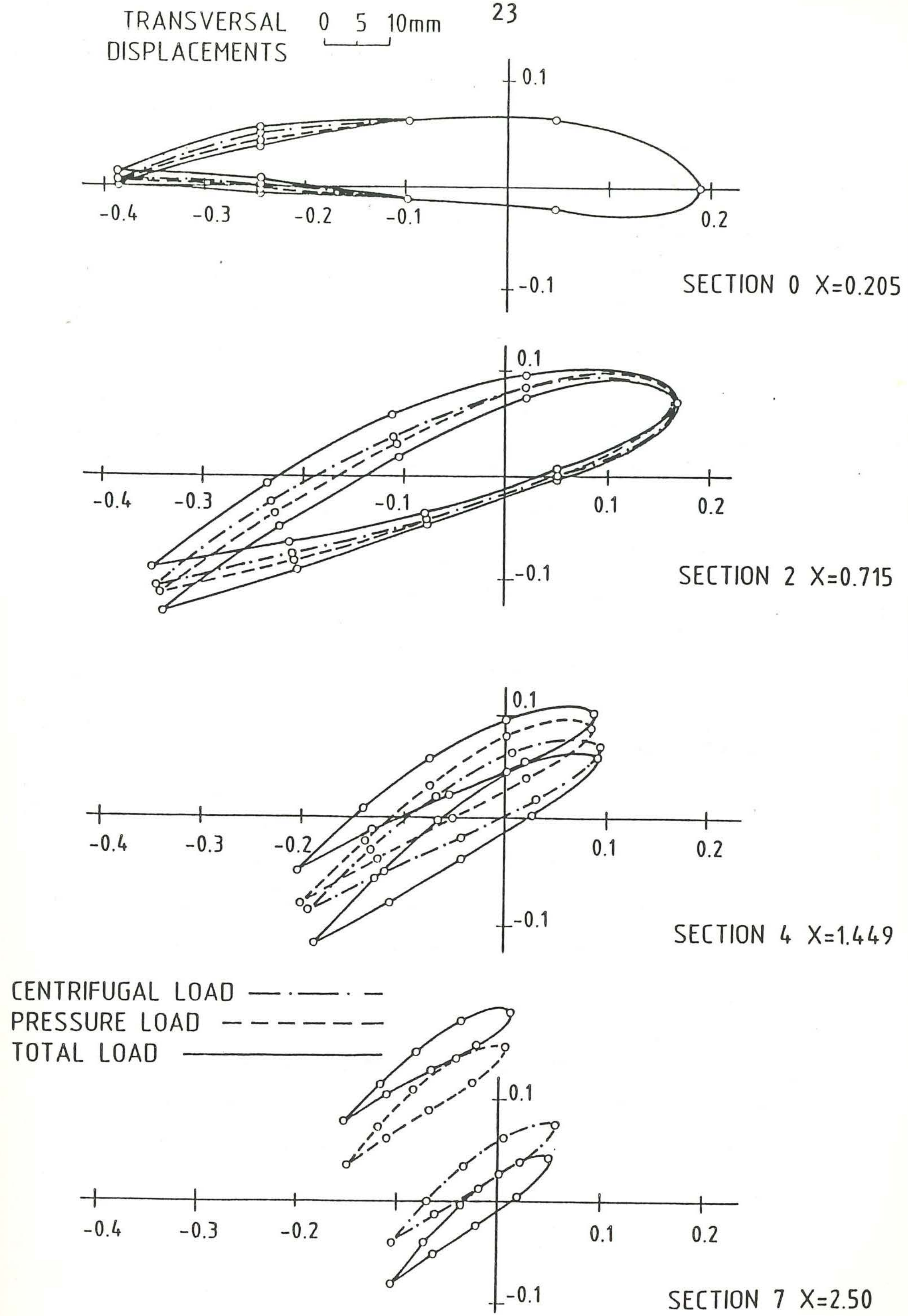


Fig. 11 Displacement profiles at various blade sections

showed agreement up to a certain distance below the notch root after which the two solutions diverged. However despite using different elements and different nonlinear solution procedures, the numerical approach always provided essentially the same results. Further examination of the theoretical solution highlighted the fact that the solution is based on the assumption that the through-thickness stress is always the intermediate one (i.e. it is neither the maximum or minimum principal value). From the FE results it is seen that σ_z becomes a minimum at a certain distance below the notch root. Provided that σ_z is intermediate, the numerical and theoretical results are in good agreement. Therefore this is rare example of a numerical solution being used to prove the deficiency of an established theoretical solution which had hitherto been used without question.

Computer Graphics and C.A.D.

The development of numerical solution techniques forms only one part of the total requirement of computer aided design. The design of an engineering component or structure employing numerical techniques must address, in turn, the four following considerations:

*Appropriate modelling of the problem Today's powerful solution capabilities offer a wide choice and permit great flexibility with regard to the modelling of structural

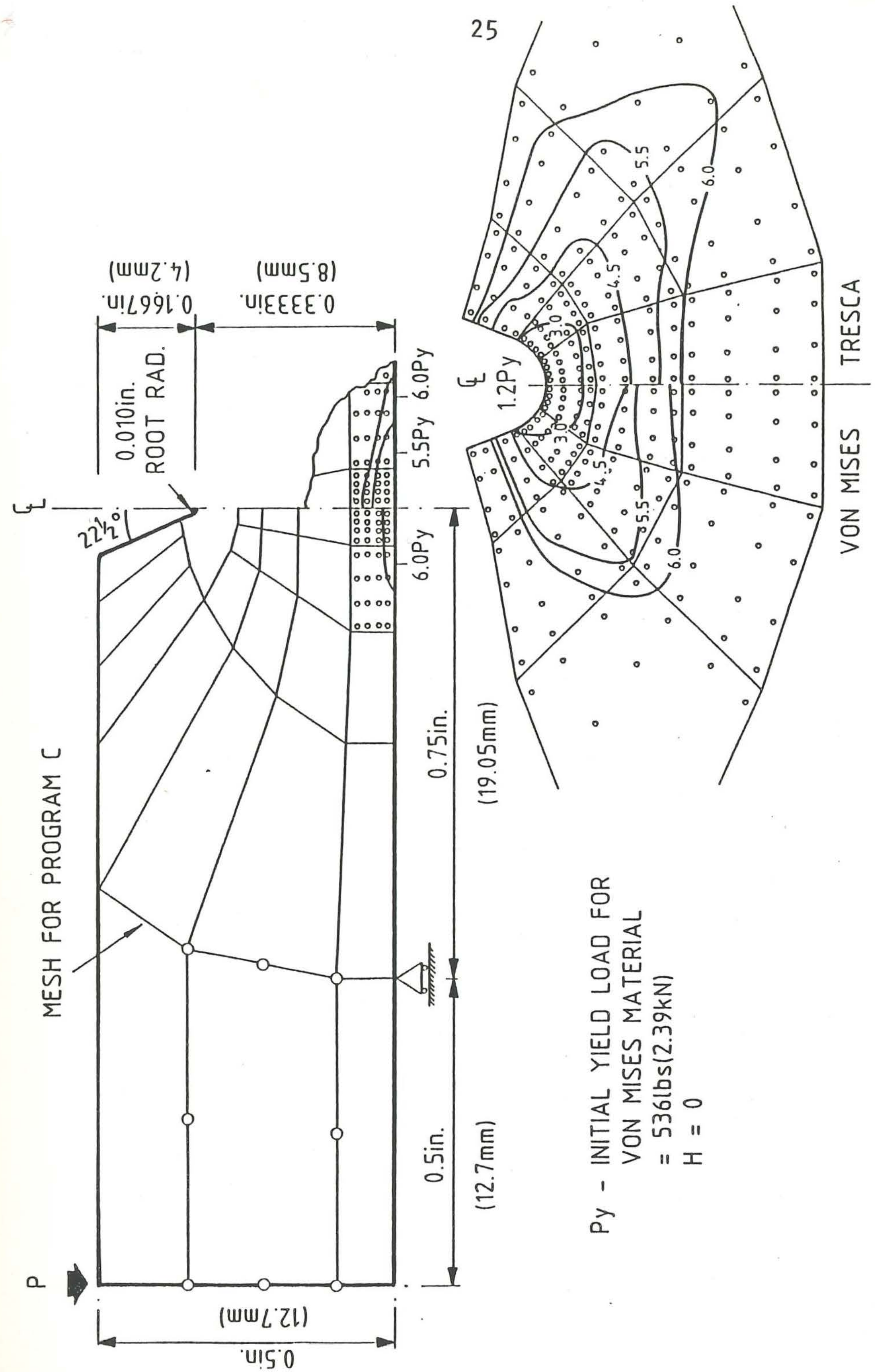


Fig. 12 Elasto-plastic analysis of a notch-bend specimen

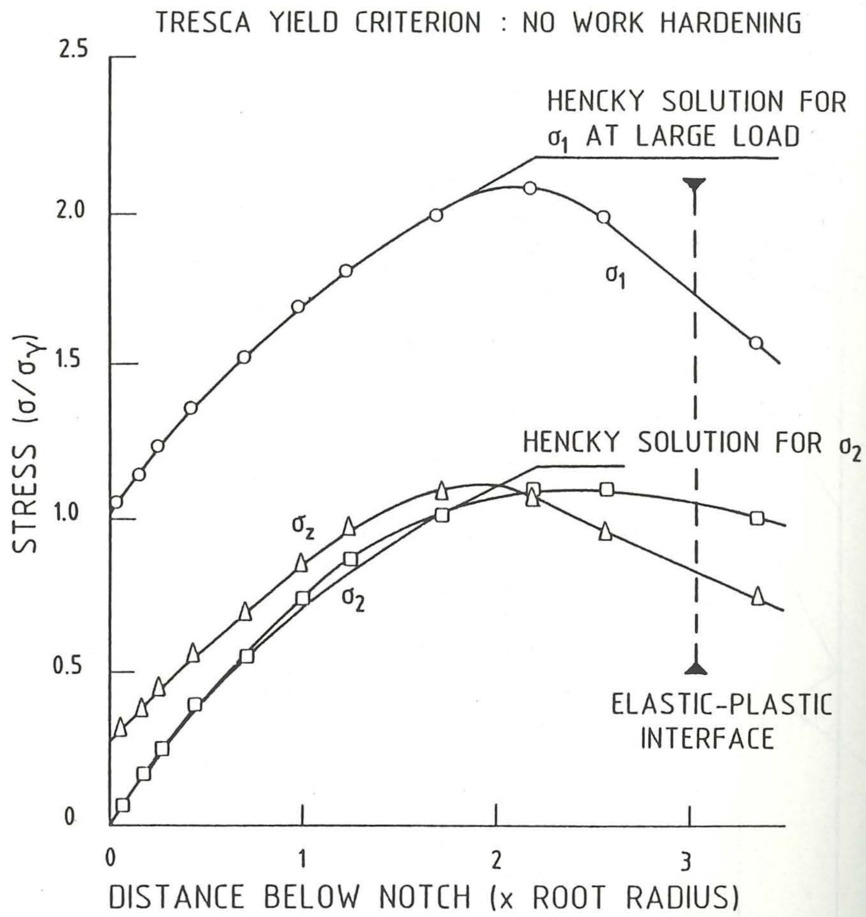


Fig. 13 Distribution of stress along the centreline of the notch-bend specimen

behaviour. For example, a variety of nonlinear effects may be included for describing material behaviour. In addition to quasi-static nonlinear action, time effects may be included in the material description. For composite materials, such as reinforced concrete, responses such as tensile cracking, compressive crushing, dowelling action and debonding effects can be numerically simulated. It is important that the designer chooses the most appropriate constitutive behaviour and equally important that he does not over-elaborate on the choice of model.

The designer must make a further choice on appropriate modelling of the structural action. For example, is a beam or plate bending representation sufficient? Or does the complexity of the load carrying action warrant a full three dimensional analysis?

The proper modelling of an engineering problem is a most important and difficult task and frequently requires considerable ingenuity on the part of the analyst. It is frequently claimed that computers kill ingenuity - in fact the converse can and indeed should hold.

*Applicability of numerical techniques Any innovative numerical process should be developed to such an extent that it can be employed with confidence by engineers in analysis and design. This requires the comparison of numerical and experimental results and application of the process to practical problems. It is not sufficient to test a method by the solution of a few academic problems and then assume that extrapolation can be made to practical problems without pathological exception.

*Associated software development Numerical algorithms must be implemented in good quality, reliable, user-friendly and well documented software which is readily applicable on appropriate computers for use by engineers and research workers. This software must be verified and the user educated in its correct use. Of particular importance in this respect is the quality assurance of computer applications software which is already a requirement in the U.S.A. and elsewhere for selected applications such as aero and astronautic design, nuclear plant design and defence work. This trend for software quality assurance is a growing one and should be encouraged.

*Relation to design procedures A numerical analysis is more often than not an integral part of engineering design. Therefore it is important that the results of a numerical computation can be interpreted in an unambiguous manner; especially in view of the approximate nature of computational models. The use of automated or optimal design procedures is of particular relevance in this context.

In any automated design process involving the finite element method, computer graphics play an important part.

Computer Graphics

Pre-processors

The use of graphical pre-processors is invaluable for the solution of practical engineering problems. Data preparation generally accounts for a considerable proportion of the total cost of a finite element analysis. The use of automatic data generators reduces the analysis time as well as minimising the number of data errors. The simplest form of mesh generation is by means of a software approach. The structure is divided into a minimum number of coarse regions of curved quadrilateral shapes and a computer program is then used to subdivide these regions into a specified number of elements.

A more sophisticated approach is provided by the use of a digitizing table used in conjunction with an interactive graphics system. The geometry of the structure to be analysed is drawn to some scale and placed on the digitising table. This geometrical information is transferred to a computer by means of a light pen - basically this has the ability of encoding in electronic form the Cartesian coordinates of the point to which it is applied on the table. In this way a finite element mesh can be formed and displayed and nodal points can be adjusted interactively from the computer if so desired. The material properties of elements, the appropriate boundary conditions and the loading to be applied to the structure can also be specified via the digitising table.

Post-processors

After performing a finite element analysis of the structure the results must be scrutinised in some way. This can be automatically done by use of graphical post-processor systems. A basic requirement is that the distorted shape of the structure be displayed and, for stress analysis problems, that stress contour plots be provided. Most problems contain local areas of stress concentration so it is important that a windowing facility be available to zoom in on these regions.

For three dimensional problems, a greater degree of sophistication is necessary so that information on specified sections can be graphically displayed, and also that the structural outline (with hidden lines removed) can be displayed from any desired viewing angle.

In any post-processor work the use of colour graphics provides a further dimension of information presentation and colour displays are now becoming far more widespread due to their ready availability and low cost.

The development of pre- and post-processor graphics systems is a highly involved task requiring considerable computing resources and equipment. The use of such systems is also relatively expensive with regard to computer costs and can equal the cost of the finite element analysis itself. However,

for practical design problems their use is invaluable from both a speed and safety viewpoint.

Future trends in engineering computing

It would be appropriate to complete this lecture by attempting to predict the likely advances in engineering computing during the next decade. Some of these predictions can be safely made insofar that the necessary technology for their development is already available. Other predictions will be somewhat more speculative and some significant technological breakthroughs will be necessary before they can be realised.

All the future trends in computing are aimed towards the quest of producing computers which are both faster and more intelligent than their present day counterparts. An initiative has been taken in Japan to produce such a machine which they term the fifth generation computer. A large investment of national resources and aid has been devoted to this project with a target date of the end of the century for the first prototype. A similar, but smaller, project is also underway in the U.S.A.

In order to achieve this goal, advances must be made on three broad fronts:

Artificial intelligence is considered to be the cornerstone of the next generation computers. Steady progress in this field has been made for the last 20 years or so and has led to the present day position where machines are available capable of heuristic (rule of thumb) reasoning based on a limited data bank of knowledge. (At the very simplest level we could cite the example of electronic chess games.) Artificial intelligence functions essentially by applying a sequence of IF....THEN logic operations to a number of stored items of information; typically 10,000, using a special processing computer language such as LISP (list processing language).

Computer systems and architecture Before AI can be used at the degree of sophistication envisaged for fifth generation computers, advances must be made in computer systems and architecture. Present day computers are based on a Von Neumann architecture in which all information is sequentially processed. For the processes involved in AI, a large increase in computing speed can be achieved by parallel processing, whereby many simple operations are simultaneously performed on many simple processors. Greater efficiency and computing flexibility may also be offered by the use of network based systems, in which either micro and/or mini computers are used interactively with a mainframe machine. Developments in this area are occurring at a fast pace with the eventual aim of arriving at one professional workstation for each user.

The development of computers can be put into perspective by observing that the data processing industry goes over 'minor cycles' (hardware generations) of 5-8 years and 'major cycles' (human generations) of about 25 years.

The first major cycle, from 1930 to 1955, was the era of punched-card equipment, which penetrated mainly administative departments of governments and large industrial organizations. The second major cycle, from 1955 to 1980, was the era of the general-purpose stored-program electronic computer. The impact was profound, but economic realities kept computers away from people.

The third major cycle began quietly, with the development of large-scale integrated circuits, which begat micro-processors, which begat personal computers. The next slide quantifies this phenomenon; by 1987 the personal computer base will grow to 80 million systems and shipment value will be on a par with mainframes. And as hardware costs steadily drop, software becomes a dominant factor, and 'computer literacy' will become an important social issue.

Microelectronics

The design of computers with sufficient power to undertake AI simulation will require significant advances in the field of microelectronics. The microprocessors incorporated in the next generation computers will need to be an order of magnitude more powerful than present day ones. The technology of designing and manufacturing such chips is termed VLSI (Very large scale integration). The next milestone to be reached in this area is the million transistor chip - but advances in processing technology will be necessary before this can be achieved.

The end objective of advances in the above three areas is the development of computers with the following abilities.

Understand languages Success in this area has already been achieved to a limited degree. However further significant advances need to be made regarding vocabulary extension and voice recognition.

Object detection Next generation machines should be able to detect objects from given pictorial images. Some advances are already being made on this front following at least two independent approaches.

Reasoning ability For the development of so-called "expert systems" the computer will require the ability to reason.

A present day cliche in the engineering world is that "computers are good drudges but no judges". The aim of expert systems is to make this statement obsolete. An expert system can be defined as an "user friendly" data base which stores the knowledge and experience of a host of experts. In this way it is envisaged that engineering design tasks currently requiring the services of a professional engineer could be performed by anyone with access to such a system. It is not expected that expert systems will be generally available much before the end of the century by which time systems with the following capacities will have been developed:

*A living system in continual transition in that the knowledge database is being progressively upgraded.

*The system should be able to learn from its own previous errors and experience.

*The user can interact with the system - the system may even learn and account for the user's idosyncracies.

*The system will have no human hangups. In particular pride or ego will be absent and the system will also not suffer from emotional problems.

The above specification summarises the dream - the reality may possibly turn out to be something quite different

*The knowledge input may be incomplete leading to incorrect decisions being made in inexperienced hands.

*The output may be sufficiently unreliable to require expert interpretation.

*There may always be a need for engineers to have a detailed knowledge of the software performance.

*For finite element programming the use of unstructured languages, such as the FORTRAN language used by most engineers, may still be unavoidable.

The foregoing section has summarised the future trends in computing. The following example illustrates how the FEM can play a role in this development.

Simulation of semiconductor devices by the FEM

The finite element method can be employed in the field of microelectronics for the analysis and design of transistor devices and also for simulation of the manufacturing processes. The behaviour of even a single transistor is highly complex and a better understanding of such device behaviours is necessary for VLSI design.

Fig. 14 illustrates the analysis of a typical semiconductor device, termed a triangular barrier device whose function is to act as a rectifier at high switching speeds. This new device is still at the development stage and promises to supercede existing versions. The region to be simulated is indicated where it is seen that the total device length is 1 micron. The device is formed by doping specified regions of the basic semiconductor material (silicon) either with electrons or holes to the indicated density by introducing impurities, for example potassium, into the silicon lattice. The physics of the device is characterised by three different phenomena:-

*Distribution of the electrostatic potential, ψ

*Variation with time of the electron density, n

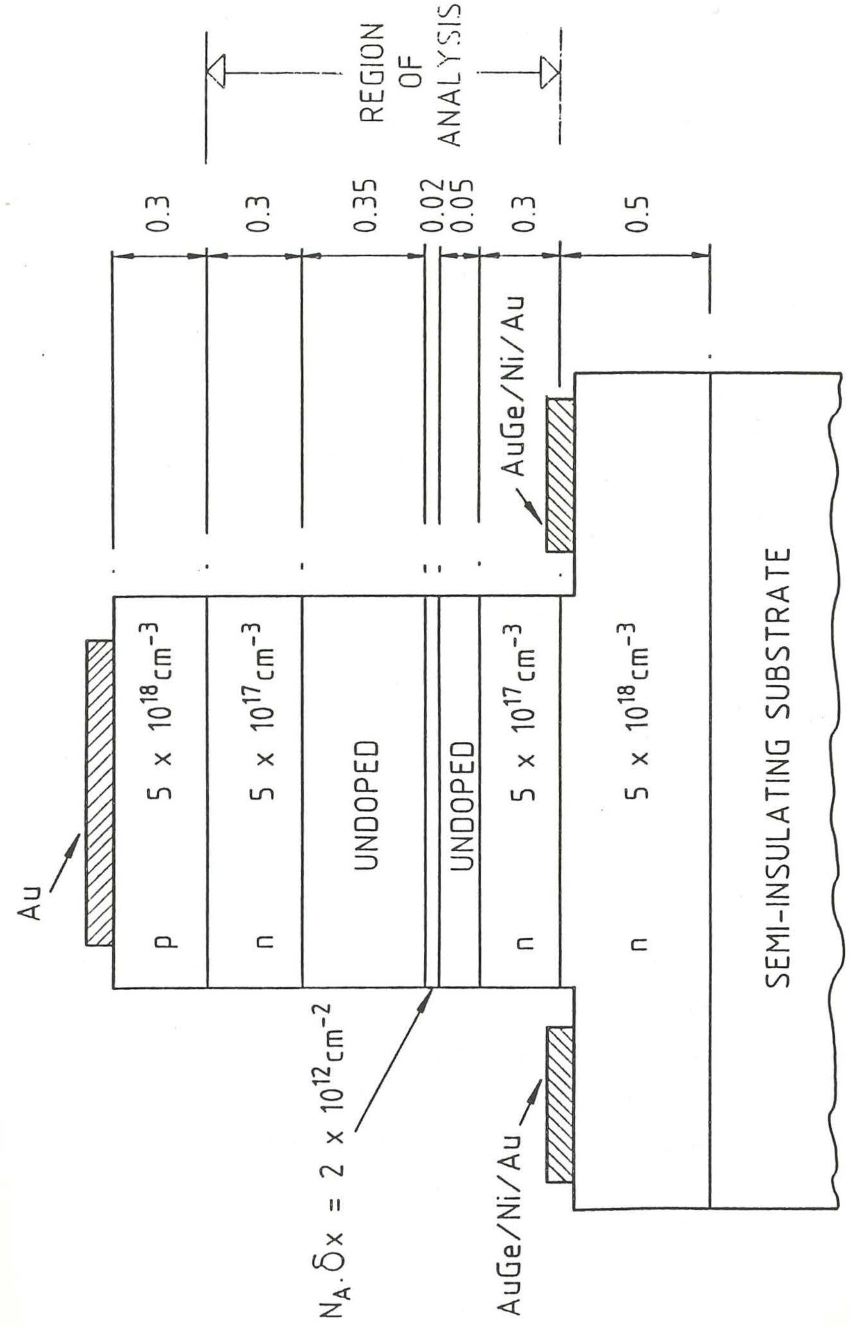


Fig. 14 Triangular barrier device

*Variation with time of the hole density, p.

These form a coupled set of equations which are highly nonlinear. Solution must be obtained by integrating in time until steady state conditions are reached.

The equations governing the behaviour of the device are summarised in Fig. 15. The three equations are coupled in the basic variables ψ, n and p and the problem is seen to be highly nonlinear due to the exponential dependence of n and p on the quasi-Fermi levels ϕ_n and ϕ_p. Typically ψ, ϕ_n and ϕ_p are in the range ±40 so that small variations in these quantities have a dramatic influence on n and p. For finite element analysis the problem is discretised by 120 linear elements. Starting from a consistent set of initial conditions the three sets of equations are integrated forward in time. Two solution strategies may be followed:-

Fully coupled procedure where all equations are considered simultaneously. This approach has the disadvantage that the resulting set of discretised equations are unsymmetric making their numerical solution an expensive process. Further, the system of equations is large, requiring substantial computer storage facilities.

Staggered solution technique In this technique each equation system is treated as uncoupled and the coupling variables are suitably extrapolated. This approach has the advantage that each equation set is symmetric and the iterative

procedure allows for the simultaneous treatment of the nonlinear behaviour.

The latter solution strategy is employed in this work. Figs. 15-17 show the distribution of all the variables throughout the device for several time intervals up to steady state. The main item of note is the short times involved with the time required to achieve steady state being approximately 0.2 pico seconds. The distribution of the electron and hole densities give rise to the name of the device, and the high values of these variables in relation to values of the electrostatic potential and the quasi-Fermi levels is clearly evident.

The example shown here was a relatively simple one and we are currently solving more complex two and three dimensional device problems. The results from such an analysis are essential for the design of integrated systems composed of such devices.

Concluding remarks

Throughout the course of this lecture, I have attempted to show the impact that computers have made on engineering research and design over the last decade or so. I hope that I have conveyed the impression that these developments have represented an exciting phase in the never ending quest for advanced solution methods in high technology fields. The ready availability of large scale and inexpensive

Distribution of electrostatic potential

$$\nabla^2 \frac{d\psi}{dt} = -\frac{q}{\epsilon}\left(\frac{dp}{dt} - \frac{dn}{dt}\right)$$

Continuity equations for electron and hole carriers

$$\frac{dn}{dt} = -\nabla.\ (\mu_n\ n\nabla\phi_n) - R$$

$$\frac{dp}{dt} = \nabla.\ (\mu_p\ p\nabla\phi_p) - R$$

in which

$$n = \mathrm{Exp}(\psi - \phi_n)$$

$$p = \mathrm{Exp}(\phi_p - \psi)$$

Nomenclature

ψ	Electrostatic potential	Prime variables
n	Electron density	
p	Hole density	
ϕ_n, ϕ_p	Quasi-Fermi potentials	

Fig. 15 Basic equations of the transient semiconductor problem

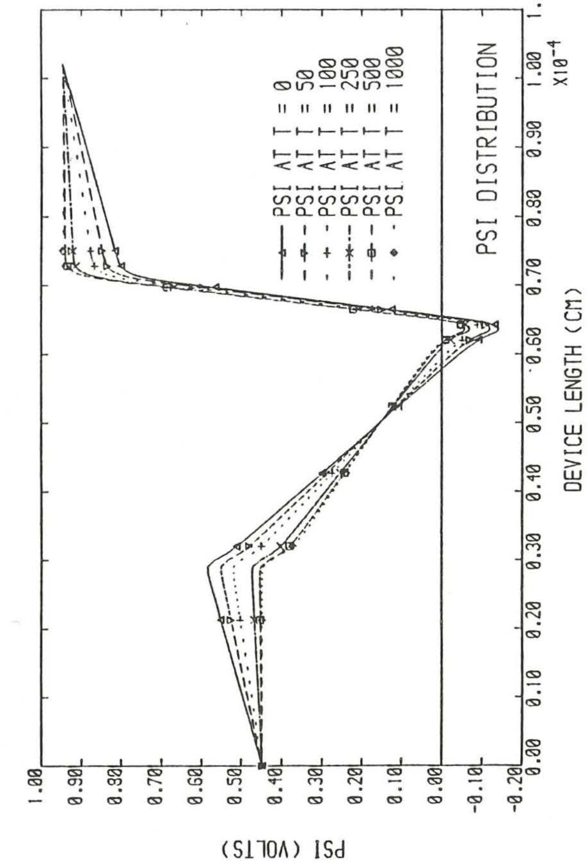
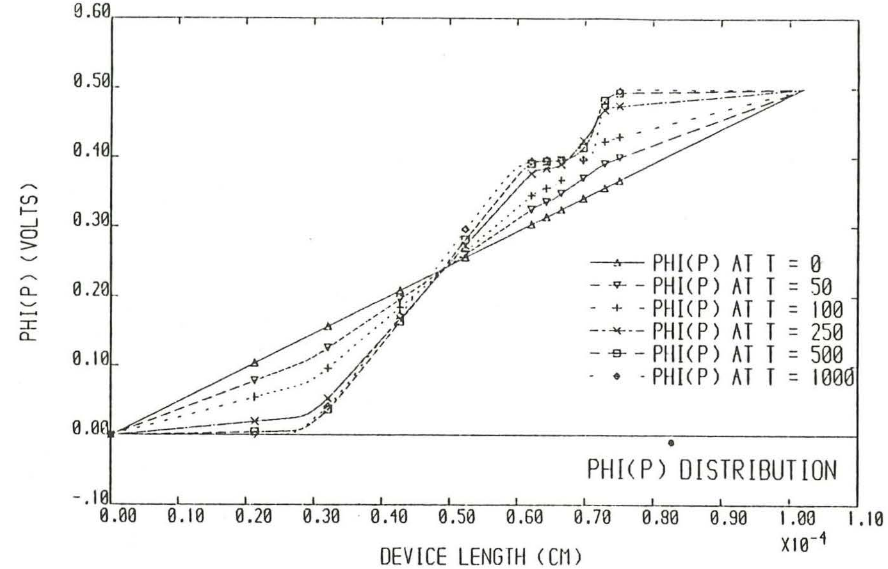


Fig. 16 Electrostatic potential distribution in the triangular barrier device



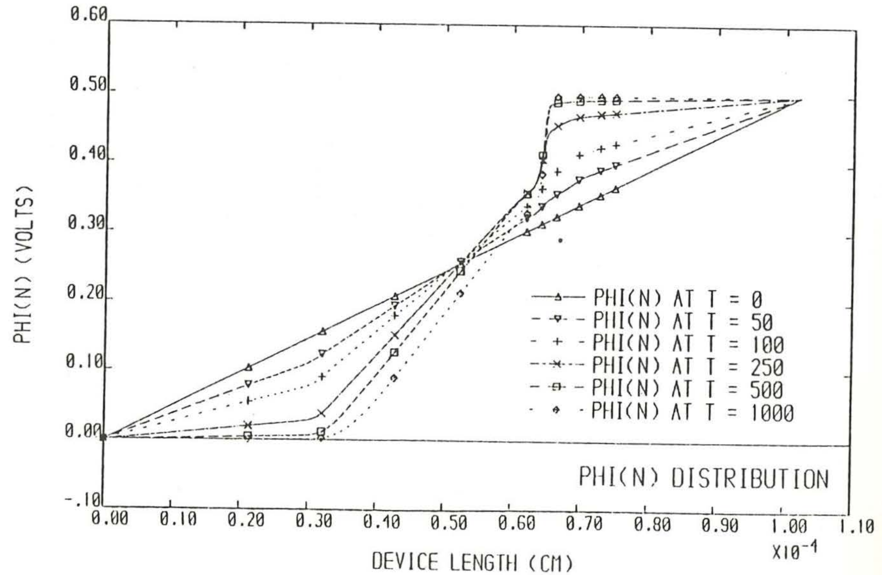
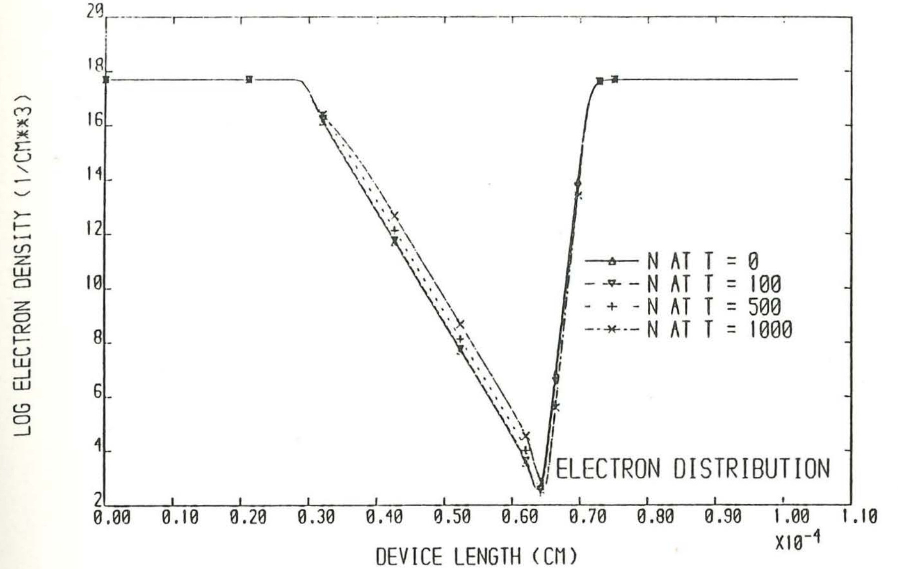
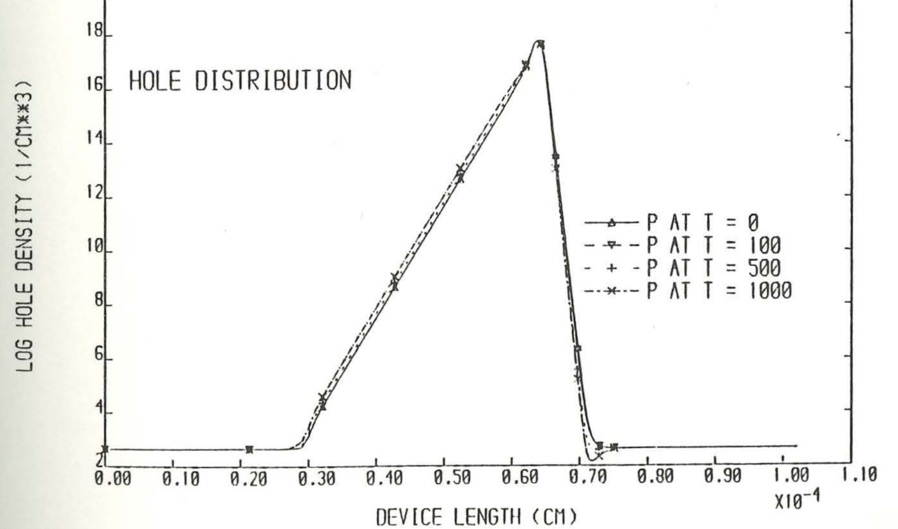


Fig. 17 Distribution of quasi-Fermi potentials in the triangular barrier device

Fig. 18 Distribution of electron and hole densities in the triangular barrier device





computer power and graphic techniques have ensured that progress during this period has been far greater than in any previous decade. But I believe, and I hope that the glimpse at future computing trends provided during the lecture illustrate the point, that advances in engineering computations both at the micro and macro level will take place at an even more breathtaking pace during the next decade and all of us who are working in this field are privileged to play a part in this progress.

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