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THE EFFECT OF COMPUTERS ON ENGINEERING PROBLEM SOLVING, THE BLACK BOX SYNDROME

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ABSTRACT

The introduction of personal computers have revolutionised the way we work. There is no single section of life where digital computers have not influenced the way we work. The benefits of computers in scientific and technical work are widely admired. The author applaud the benefits, but propose to discuss certain cautions, which may be overlooked. The remarks are directed mainly toward the use of general purpose computer programs but include generalisations about the impact of computer technology. Special attention is given to Finite Element application in engineering problem solving.

INTRODUCTION

Before computers were widely used, users and developers of programs were often one and the same. These capable people might well have obtained a satisfactory answer to many of their problems by traditional methods, e.g. by using analytical methods or non-computerised numerical methods. They were also aware of limitations of computer programs. Today programs are available to everyone. Digital computation inspires trust, with its speed, its graphic display, and the great volume of printout. It is so easy to accept computed results that some cannot muster the energy to probe the answers to see if they are entirely sensible. Yet, even those with the vigour to doubt the computations may be unqualified to do the necessary checking.

University students are currently expected to use computers when working on their assignments. One hopes that these computers are used productively, as word processors to speed and improve writing, in doing calculations from which insight and understanding will flow, and so on. One wonders what will give way in the curriculum to make room for computer-use topics. Possibly understanding will become less important than facility in computer manipulation because the latter is easier to assess. Just as in the industrial environment, there will be a tendency to seek enlightenment by making a great many numerical trials.

Numerical examples, if too complicated or if poorly chosen, may do little to aid one's understanding of the nature of a problem.

The large and growing capabilities of computers and programs provokes overconfidence in numerical methods. Programs have bugs, may not be based on the right physical theory, and may not account for all interactions. And I know of no user who thoroughly understands the physical problem, has memorised the user's manual, always generates a good mesh, invariably asks the right question, and never misinterprets the output[1].

In engineering education there is the nagging suspicion that the effort spent by today's students on mathematical topics somehow detracts from their physical grasp of a problem. Perhaps this is a natural tendency: skills of manipulation according to set rules seem to have a much wider appeal than the trackless ways of approximate physical modelling. Those who teach have seen many students who never become comfortable with mechanics of materials because the subject is procedurally vague as compared with statics and dynamics. Like the computer, students tend to become programmed rather than educated[2].

Due to the wide use of computer modelling people tend to jump to a three dimensional finite element model to solve a structure problem which can easily be solved by the simple flexure formula $\sigma = Mc/I$. It is interesting to note that although most people will not resist using Finite Element (FE) modelling in all cases of plate deflections, the problem can accurately be calculated with less than three terms in a series expansion. The reason is sometimes due to lack of physical intuition on the part of the user or someone is obsessed with computers such that he/she always believe that what comes out the computer is right. In other instances, students model a simple geometry with so coarse a mesh that the results have almost no relation to reality. In other cases, a false sense of physical intuition can be produced by a computer program because of a bug in the program. Examples like these show that rather than multiplying our intelligence, the computer may multiply our ignorance.

A survey conducted by Bushnell[3] on Finite Element Method (FEM) programs users reports the following example of the black box syndrome: "Often users indicated that they had used a program in a way that, according to the developer, is beyond the scope of that program. For example as the author of BOSOR4, a special purpose program for the elastic analysis of thin shells of revolution, I find it interesting that 12 percent of the users treated to a moderated or extensive degree general structures and solids of revolution with it. One respondent indicated that he had used BOSOR4 extensively for the analysis of solids of revolution. In the evaluation section he responded, understandably, that he did not like the program."

Computerised analysis can be seen as a magic box which responds instantly to our touch, does not ask us to think, and resolves problems in almost instantly. The responsiveness of a terminal can give the user a feeling of power and a mistaken sense of competence in his/her work. Manipulation of the keyboard has a immediate appeal that working toward the more distant goal of competence does not.

THE COMPUTER AS WORKTOOL

Throughout history, the development of tools to accomplish our tasks has been a continuous and diverse activity. Tools are neutral. Man can find ways to do more diverse tasks but cannot always supply the creativity and the analytical skill to do them well. The computer, the black box, is one of the modern tools of our lifetimes.

Without computers the finite element method would have remained irrelevant. Modern computers, with their powerful graphic devices and analysis software, have greatly boosted the use of finite element method in engineering problem solving. Probably all of us would abhor a return to earlier days, when the solution of all but trivial problems demanded experiments, prolonged operation of a desk calculator, or use of elementary formula pushed far beyond their intended range of application.

ERROR SOURCES IN THE APPLICATION OF FEM AND HOW TO REDUCE THEM

Computers have helped a great deal in solving many engineering problems that were difficult or unapproachable. Because of its versatility, the analyst can model many details and choose among many analysis options. For the same reason, the analyst can also misdirect the computational procedure in many ways. Errors are scarcely a novelty: before the advent of computational mechanics there was a tendency to apply elementary formulas beyond their range of validity because there was no practical alternative. Physical sense was needed to keep from going astray. Physical sense is still needed to produce a finite element model that represents reality. In addition it is useful to know how the finite element method works and how various elements behave.

Error Sources in the Application of FEM

Although finite element modelling have been used extensively to solve many engineering problems it have, unfortunately, a number possible sources of errors. The following are the common sources of error in FEM application.

i. *Element Choice.* Depending on the type of problem one asks questions such as the following. Should three-dimensional or plate elements be used? Are singularity or infinite elements needed? What kind of plane (or plate, or shell, or solid) element is best for the problem at hand? In other words, a proper choice of the type of element to be used is necessary for each physical problem.

ii. *Geometric distortion.* Element performance declines as aspect ratios increase, as corner angles become unequal, and as warpage increases. Moreover, differently formulated elements behave much differently in their response to distortion. For example, the eight-node plane isoparametric element can be very sensitive to curvature of its edges (depending on how it is loaded), while its nine-node relative is rather insensitive [4].

iii. *Mesh Error.* A mesh can be too coarse to respond to strain gradients that are physically present, or too fine to be economical. In some FEM computer programs, nodes in close proximity, or very stiff elements introduced to simulate a constraint, can degrade accuracy by way of numerical errors. Trying to model an incompressible material by setting Poisson's ratio close to 0.5 provokes that same kind of trouble as almost-rigid elements. On the other hand, if part of the structure is omitted because of a mistaken impression that it is lightly stressed or has negligible stiffness, one might miss important results.

iv. *Loads and boundary conditions.* The spatial variation of mechanical and thermal loads must not exceed the capability of element displacement fields if the details of load variation are to be noticed by the model. One must also ask if "fixed" supports are really fixed, or elastic, or offer restraint in only one direction so that the structure can part company with one or more of its supports. The usual uncertainty about the magnitude, direction and duration of loads is sometimes alleviated by finite elements. Rather than having to estimate what load one part applies to another, one can avoid the question by modelling the entire structure.

v. *Asking the right question.* One might err by asking for a linear analysis in a problem that has important nonlinearities or by requesting a transient analysis scheme inappropriate to the type of excitation. Buckling as a possible mode of failure will not be addressed by the program unless the user asks. Even if the question is asked and correctly computed by the program, the answer may be wildly misleading if the user believes that the lowest bifurcation buckling load is synonymous with collapse of the structure. (The collapse load may be several times higher or lower). In dynamic and non-linear analyses, unlike linear static analysis, the user choose an appropriate solution algorithm as well as choose an appropriate mesh.

vi. *User's manuals.* For a number of FEM programs user's manuals are rarely satisfactory. Many difficulties derive not from the inept user but from manuals that are incomplete, strangely organised, have a poor or no index, rely heavily on jargon and acronyms, and assume that the user is as familiar with the code as is the programmer. Part of the difficulty may lie with the program, which may have grown in patchwork fashion over the years and at the hands of many programmers rather than being the uniform product of a master plan.

vii. *Type of output.* Often the program output can be bizarre as the user's manual. For example, a print of nodal displacement may not include nodal co-ordinates, even though there is ample space for them. Input data, which can be supplied in a compact format, may be echo-printed with equal terseness, so that investigative abilities are needed to find out for example what modulus was used.

viii. *False confidence from previous use.* An analyst may repeatedly use a poor mesh, ask the wrong question, and misinterpret the output, yet if runs proceed without complaints from the computer, the analyst may believe that all is well. (Additionally, the program itself may contain errors. The user should suspect the coding or the element formulation if answers to a textbook problem are computed incorrectly, when the program should be able to produce exact answers.").

ix. *The occasional user.* An analyst whose main effort is apart from finite elements and computer work, and who occasionally use the program, is more likely to make errors than a heavily involved user. The occasional user may feel especially burdened if he must relearn the rules and deal with new features of a continually changing system. He may try to avoid these burdens by avoiding computer applications.

x. *Diversity.* A great many computer programs are available. Few are designed to work on a variety of computers and none are designed to work for all engineering problems. The proliferation of computers and programs creates confusion and requires a learning effort that might be more profitably spent in study of the physical problem at hand.

Despite so many ways of producing errors, there is today a welcome trend toward analysis and planning before construction. Regrettably, much work continues to be post-mortem analysis, including the curious custom of computational demonstration that a failure already observed did indeed take place.

What Can be Done to Reduce FEM Errors?

Although errors in FEM application can be reduced by providing some checks within the program, the analyst bears final responsibility. The analyst must have a physical grasp of the problem, understanding of the finite element method, knowledge of how various elements behave, familiarity with the computer program and its documentation, a sceptical attitude toward all results, a willingness to search for errors, and patience and time so that one can pay attention to detail. Classical and elementary methods must be used where possible to see if computed results are all close to the values expected. Fortunately, graphical output is now common. Rather than search for errors and trends by scanning columns of ten-digit numbers, the analyst can view plots of the original mesh, the distorted mesh, and various stresses.

The following are among the possible errors that can be automatically detected and flagged for the analyst's attention.

i. *Overdistortion of elements.* Typical element overdistortion occur in metal forming, where material undergo very high degree of plastic deformation. The program can check element aspect ratio, corner angles, the Jacobian determinant and quadrature points, and the position of side nodes in relation to adjacent corner nodes. The user can be warned if allowable limits are exceeded. One way of correcting element overdistortion is by doing mesh regeneration when a set out limit has been reached.

ii. *Large strain gradients.* Strains that are markedly different between adjacent elements, or that vary strongly across a single element, suggest a need for mesh refinement. A vibration wave form that contains very few elements is a suspect.

iii. *Numerical difficulties.* The decay of diagonal pivot coefficients during equation solving can easily be checked. In dynamic analysis, an error measure based on comparing the work of internal and external forces against the current kinetic energy can be computed and brought to the user's attention.

iv. *Mesh errors.* Nodal co-ordinates, elastic moduli, and element thickness or cross-sectional areas can be scanned to see if they lie within user-defined limits. Element edges defined once can be highlighted on a plot and should lie on the boundary of the structure. In a plane mesh an edge defined more than twice suggests that an element has been defined twice. Nodes that couple substructures must agree in number and in location. Repetition of a node or element number, nodes not referenced by any element, and different nodes with the same co-ordinates suggest an error. This can happen during simulation of a metal forming process - where billet material incorrectly interpenetrate the die material.

The long Term Solution

In order to cope with perversity it is proposed that a proper objective of education, formal and otherwise, be to equip us with the flexibility of mind and resource. Formal technical education does not discuss this. We are taught (and in turn reteach) faithful formulas, reliable mathematical relationships, and even computer programs that often have a rather mixed heritage but nonetheless work. We are evaluated on our assimilation of this knowledge by our ability to repeat it at scheduled intervals.

Software is a tool with a special propensity for error. It is not surprising that errors occur, but disappointing that we are prepared to anticipate them. There is a shared responsibility for errors in programs and errors in their use. It include

- those who produce analysis software for public use.
- those who are responsible for the engineer's education.
- those who are responsible for the engineer's management.
- the engineer.

The software provider is in a peculiar position. He/she must keep his/her analysis progressive, working, and saleable. He/she must train users in its application, support users while applying it, console them when the application disappoints them, and congratulate them on success. He/she must document his software system so that the computer response can be understood.

The engineering professor is also in a peculiar position. He/she must impart a prescribed quantity of knowledge in a prescribed period of time. His/her students will enter a world where productivity is the highest good. There they will use computational tools to implement their knowledge. The typical professor has, to be generous, a limited understanding of these tools. Why is this? Perhaps the technical education establishment, by reason of economy, bureaucracy, or sloth, is unable to gain or maintain a leadership role in contemporary technology.

Young technologists when they leave school are expected to solve problems - fast, accurately, and everyday. Accordingly, technical management must promote an environment for careful checking and careful analysis. That is, management must promote engineering judgement. In this context, the chief engineer is the most conservative and disbelieving individual extant.

What is the responsibility of the engineer himself? The engineer is commonly faced with a discrepancy between the exactitude of computational capability and uncertainty of knowledge: what really are the service loads, the constraints, where might high stress gradients be anticipated, is buckling possible, will separate components contact before maximum load, and so on. Simultaneously, there is pressure of time and budget. Communication with colleagues, thoughtful remembrance of mechanics of materials, and appreciation for their vagaries of nature, and even faith must supplement his commitment to professional performance.

RAPID CHANGES IN TECHNOLOGY

Time and money are required in our efforts to keep up to date. Rapid change impacts adversely on educational institutions. Obviously, a shortage of money means a shortage of up-to-date equipment. Sometimes a university is forced to decline to accept computers as gifts because there is not enough money to maintain them. Besides funding, there are other disadvantages for the computer user in a university. The computer centre has a captive audience: being under no imperative to please customers in order to stay in business, there is no compelling reason to assist users in dealing with changes in hardware, software, and procedures.

Teaching staff have demonstrated interest in learning by getting where they are through mastering certain analytical skills after great time and effort. It is understandable if some are reluctant to abandon older ways in favour of the new. The prestige of an academic staff, so important in academe, can sometime be maintained without keeping up with computational technology. One way is to write highly mathematical papers that are impressive but not practical. Since prestige can outweigh practicality, some staff may feel little pressure to learn new ways, understand new hardware, and cope with software. Incentive to do so, and try to span the gap between the real world and the university, must come more from within each individual than from the marketplace.

One aspect the computer presents is that users must adapt because it is there, it is in use, it does offer benefits, and is becoming indispensable. An analogy can be made with the industrial revolution. The machines had to run and people came from the country to tend them, despite the tough life in towns and long working hours. But they come willingly because of the more difficult country life which is dominated by subsistence farming, and the towns offered a better prospect.

For better or worse change is inevitable. New methods for dealing with old problems attract new and bigger problems to be dealt with. It is agreed that increased analytical capability and design insight is a desirable objective for engineering technology. Therefore such changes are indeed progress. These changes challenge engineering education to positively react to and stimulate further progress. The dynamics of innovation in the computer industry, and very limited educational funds for hiring good staff members and for capital acquisition and maintenance, all combine to restrict the exposure of staff members and their students to technological changes.

Should the computer industry itself or government contribute to widespread placement of new technology in academe? Or should engineering education refocus on the teaching of physical fundamentals and develop the flexible mind that can cope with progress during the professional career? The former seems more likely than the latter: there is a current favour for placing all students in contact with a computer, and it is easier to acquire a computer than to learn what is necessary to put it to good use.

RECOMMENDATIONS

Although university curricula must make room for the new ways, it should not be at the expense of the physical theory upon which programs and users alike must ultimately depend. For example, it is risky for someone to use a structural analysis finite element package in engineering design if the user does not know how to formulate the problem, the theory of mechanics of continua, plasticity, fracture and other fundamentals.

We used to be told, a few years ago, that computers would take over many human jobs. To date, the computer has not become an engineer. That human judgement is still needed to fill gaps between what computer processing gives us and belief in our own value. Philosophers of science and technology occasionally write at length about the morality of technology. Computers are a dramatic example of a technology that has rapidly become ubiquitous. Our task is not to make the world perfect but to deal effectively with its mistakes and imperfections.

The diversity of machines, languages, programs, and data bases could be made less daunting by standardisation. This is an obvious recommendation. It has been coupled with a suggestion that some central agency assist with the process [5]. A great deal can be done to make computer programs less susceptible to misuse and less irritating to the user. The coding of pre-processors, post-processors, and error traps is interesting work for the programmer. For example, a more palatable error message from a program can read "memory protection error" rather than "segment protection fault" followed by an abrupt stop.

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