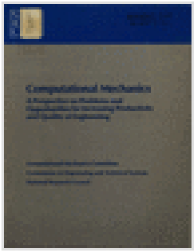

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COMPUTATIONAL MECHANICS:

A Perspective on Problems and Opportunities for Increasing Productivity and Quality of Engineering

Computational Mechanics Committee

Commission on Engineering and Technical Systems

National Research Council

NATIONAL ACADEMY PRESS
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NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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The preparation of a report such as this involves the dedicated efforts of people far too numerous to identify in the pages of the final work. The need for a review of the status of the field of computational mechanics evolved from many discussions held over several years, culminating in Nicholas Perrone of the Office of Naval Research making a formal request of the National Research Council to form this study committee. The committee was exemplary, not only in its willingness to commit time and effort, but also in sharing controversial ideas. Many of the committee members have drawn on support and thoughts of their colleagues throughout the country and abroad, all of which have enriched the debate. Our thanks are also due the staff whose tenacity helped focus and organize our discussion into a report.

All this involvement and assistance notwithstanding, this is a report of a very hard working volunteer committee, which we are privileged to have chaired.

Melvin Baron
Karl Pister

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PREFACE

Computational mechanics involves the study of physical phenomena by means of computational methods and devices (see fuller definition in Chapter 2). The discipline had its identifiable beginnings in the 1950s, at the start of the electronic computer era, and since then has advanced on many fronts, usually at exponential rates in given areas of specialization. Today, computational mechanics affects every aspect of engineering design and analysis. Moreover, the field is economically important in itself, in terms of both the efforts of the individuals involved and the value of the associated computer software.

Recent developments could profoundly affect computational mechanics. Promising new directions can be seen as a result of advances in computer hardware, including graphics devices. Interest by industry and the federal government in the development of a new generation of supercomputers creates the possibility of an entirely new scope of computation. At the same time, concern is growing over issues such as the practicing community's being outdistanced by research developments in the field, the shortage of people competent to use state-of-the-art tools, and the limited dissemination of software.

With these considerations in mind, the Commission on Engineering and Technical Systems of the National Research Council appointed a Committee on Computational Mechanics with the following objectives:

- To survey the status of computational mechanics in the United States;
- To identify important problems that are hindering the use of computational mechanics in improving the productivity and quality of engineering; and
- To identify solutions to these problems within the framework of engineering research in the United States.

As this report discloses, the field of computational mechanics is expanding rapidly. Exciting possibilities lie ahead, and many of them are related to the needs of our emerging technological society. A strengthened effort is essential if these opportunities are to be seized by U.S. industry, rather than by competitors abroad. This report identifies governmental and industrial actions that would permit major advances and the continued strong U.S. presence in this field.

In Chapter 2 of this report, we define computational mechanics more specifically and give examples of its areas of application.

Chapter 3 outlines the status of computational mechanics in the United States. The chapter identifies resources and problems in universities, government, and industry. Chapter 3 also discusses the status of computational mechanics abroad.

Chapter 4 identifies developing areas and future opportunities in computational mechanics illustrating the breadth of the discipline.

The committee solicited a series of case studies of applications of computational mechanics as a means of clarifying resources and needs in the field. These studies, with our commentary, appear in Appendix A. Appendix B illustrates uses of computational mechanics specifically in the development of weapons systems.

Computational mechanics provides the technical underpinning of computer-aided design and manufacturing (CAD/CAM). The nationwide attention to improvement of productivity has focused primarily on the graphics and management aspects of CAD/CAM. The potential mechanisms for linking CAD/CAM more effectively to computational mechanics are spelled out in Appendix C.

EXECUTIVE SUMMARY

Computational mechanics is that discipline of applied science and engineering devoted to the study of physical phenomena by means of computational methods based on mathematical modeling and simulation. Computational mechanics has had a major impact on modern engineering analysis and design. It is the cornerstone of computer-aided engineering and as such, is critical to the nation's industrial future. During the past 20 years the United States has advanced to a preeminent position in computational mechanics. Although the field relies on diverse scientific and engineering disciplines, computational mechanics is an intellectually rich and fundamentally important discipline in its own right. Computational mechanics software is an essential element in many U.S. industries such as aerospace, automotive, electric power and defense, and current U.S. software is predominant in other major foreign industrial countries.

As in any other aspect of high technology, rapid changes are occurring in computational mechanics. With this in mind, the Commission on Engineering and Technical Systems of the National Research Council formed a Committee on Computational Mechanics with the following purposes:

- To survey the status of computational mechanics in the United States;
- To identify important problems that are hindering the use of computational mechanics in improving the productivity and quality of engineering; and
- To identify solutions to these problems within the framework of engineering research in the United States.

As this report discloses, computational mechanics plays an important role in engineering practice and its application is expanding rapidly. Exciting possibilities lie ahead, but increased integration of computational mechanics into everyday engineering practice is essential if these opportunities are to be seized by U.S. industry rather than by competitors abroad. Concerted and integrated efforts by government, university and industry would make possible major advances and the continued U.S. leadership in this field, and this would provide an invaluable impetus in the transformation of low-technology manufacturing industries to high technology.

The major findings and recommendations of this report are:

1. The shortage of qualified faculty and engineers with advanced training in computational mechanics jeopardizes our continued leadership in the field. The trend can be reversed by a program involving both industry and government specifically aimed at supporting computational mechanics through special incentives such as fellowships, traineeships for younger faculty and increased research and equipment support.

2. In addition to mission- or project-oriented research, federal agencies should be encouraged to plan and directly support a coordinated program of computational mechanics research. In particular, the National Science Foundation should increase the level of support for research in computational mechanics by designating specific organizational entities for this purpose.

3. To foster the technology transfer of computational mechanics, selected centers for the dissemination of research should be created in the United States. A major focus of these centers should be the interaction with U.S. industry.

4. Industry development of supercomputers should be encouraged at every opportunity. Direct U.S. goverment financial investment in supercomputers should be encouraged particularly as federal government involvement would increase the access to supercomputer systems for researchers in computational mechanics.

These recommendations are made in the context of taking advantage of future opportunities and developing areas in computational mechanics. Opportunities are becoming increasingly available to make computational mechanics more widely applicable and economical. The expansion of new and developing areas is placing new demands on the computational mechanics community. These opportunities must be exploited aggressively if the U.S. is to maintain its economic edge in high technology. The importance of computational mechanics is vital to the health of our future economy and to national security interests.

These recommendations complement and support a recently published report on "Large Scale Computing in Science and Engineering" supported by DOD/NSF, particularly as to the need for increased access of research engineers to supercomputing facilities and experimental computers. However, the needs of U.S. industry in computational mechanics call for research and development of methods amenable to a large range of computers, ranging from microprocessors to supercomputers.

It is becoming clear that the unstructured interaction between research groups and industry will not suffice with today's more rapid pace of development and increased foreign competition. Mechanisms must be established for the orderly dissemination of research and for setting research priorities and goals. A synergistic interaction between practice and research is crucial if the increasing challenges of foreign competition are to be met.

1

OVERVIEW

COMPUTATIONAL MECHANICS TODAY: PROBLEMS AND OPPORTUNITIES

Advances in computational mechanics in the United States come from essentially three sources: academe, including engineering departments in the various disciplines and computational mechanics departments and institutes; U.S. government laboratories; and companies doing both government-sponsored and private research. No single source appears to be preeminent. From a problem-solving viewpoint, the current state of affairs appears to be satisfactory. Correction of significant deficiencies, however, could enormously increase the effectiveness of the research in computational mechanics and hasten the application of its result to engineering problems.

Technology Transfer

The field of computational mechanics lacks an efficient technology-transfer mechanism that would make algorithms, software, and specialized hardware developed in one field of application available to others in the same and other fields of engineering. A closely related issue is the lack of portability of codes and software packages. Software developed for research tends to be unportable because the transfer is expensive and is seldom funded by research grants. Proprietary software tends to be more portable--at a price--except that often codes and software are configured specifically for use in the developer's hardware and require extensive and costly reworking to be used in other computing equipment.

Technology transfer could be enhanced by establishing centers that would be responsible for collecting research results in specific fields, updating the software to make it current and improve portability, and making the updated software available to practicing engineers. Such activities would reduce the time required for technology transfer and could have a profound economic effect.

Such centers also could serve as sources of up-to-date research information in several fields of interest. Much time and money would be saved by eliminating the unnecessary duplication of effort that often occurs in the present research environment.

Funding of Research

When computational mechanics methodology is developed as part of problem-specific research, it is not surprising that difficulties with technology transfer occur. The situation could be much improved by addressing computational mechanics in terms of more general methodology. Such activities could treat the subject as a separate discipline. They should be concerned with improvements in mathematical models, algorithms, software development, program portability, and techniques for efficient technology transfer. Such an approach can yield enormous dividends in the solution of engineering problems vital to our national security and economic well-being.

A major difficulty with the current situation is inadequate funding for work not aimed at specific problems. Federal research agencies generally are more oriented toward problem solving and do not fund activities of this sort. Also, at agencies that do support basic research, such as the National Science Foundation (NSF) and perhaps the Defense Advanced Research Projects Agency (DARPA), funding is at a relatively low level. The committee believes that this situation is potentially very harmful and eventually could cost the United States its preeminence in computational mechanics.

Computing Equipment

Despite important advances in micro- and minicomputing hardware, it is likely that the demand for supercomputing capabilities will continue to grow in the United States. Industries involved in large-scale simulation will continue to require access to supercomputers for improvement in engineering designs.

At the same time, the continued development of supercomputers in this country is urgently needed. Many important classes of problems in computational mechanics involve simulations so large and complex that they cannot be adequately handled by the largest computers available today. Among these, we mention weather prediction simulations, nuclear effects, weapons systems, simulations such as penetration mechanics problems, and large-scale flow calculations. As we achieve successes in understanding complex physical phenomena by computational mechanics, our demand for more complicated and sophisticated analytic models increases, with the result that larger and more complex simulators are needed. For example, the balance of effort in aeronautical research is shifting from experimental testing to simulation by computation.*

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* National Research Council, "The Influence of Computational Fluid Dynamics on Experimental Aerospace Facilities," Washington, D.C.: National Academy Press, 1983.

Important design problems in aerospace and automotive vehicles, structures such as dams and long-span bridges, and effects of nuclear weapons on structures will require such computers. These observations underscore the importance of supercomputers to the healthy development of computational mechanics, and to the establishment of policies which will make such computers available to researchers and engineers concerned with these large problems. The need was recognized long ago in other countries. The Japanese government, for example, has allocated large sums for the development of supercomputers. The United States must take steps to keep highly qualified people working on such machines. The nation cannot risk losing its worldwide preeminence in large computer development technology.

These situations emphasize the importance of continued support of research on parallel and vector computing, and the development of large-scale scientific computing devices. The computing industry has already recognized the importance of research in this area, and many major companies have pooled their resources to develop the Microelectronics Computer Corporation (MCC), which has as its mission basic research in computing systems for the next generation of supercomputing. This sort of joint venture is gratifying, and should be encouraged, but provision should be made, perhaps with federal support, to make current and future supercomputing systems available to a wider spectrum of the scientific community than is possible today.

The committee believes that current one- and two-year contract funding by federal agencies is not well-suited to long-range planning of computer requirements. This situation has already been recognized by several DOD agencies, which have set up planning groups for computer usage and, in some cases, augmentation. A long-range approach of this kind at federal agencies can materially increase the efficiency and economic benefits of computer usage.

An increasingly difficult problem, particularly at universities, is the cost of operating and maintaining computing equipment. Many institutions that do research in computational mechanics are rapidly acquiring, through purchase and gifts, large numbers of minicomputers and microcomputers. While such equipment is a tremendous benefit to research workers, the institutions are severely pressed by the costs of operating and maintaining it. Such costs are approximately ten percent of the equipment cost per year. Since this computing power represents an important computational mechanics resource to the funding agencies, a way of contributing to maintenance costs as part of the funding cycle seems warranted.

The committee also sees a need to give the computational mechanics community increased access to supercomputing facilities and experimental computers. This need is recognized by NSF. A recent action by that agency permits NSF program managers to supplement research awards with money to pay for time on supercomputers if it is needed.

Graduate Education

Another serious problem concerns the education of U.S. graduate students in computational mechanics, a point already made by the DOD/NSF Panel on Large-Scale Computing in Science and Engineering. Actions to alleviate the shortage of engineers adequately educated in computational mechanics and to ensure the supply of faculty in this area deserve high priority attention.

DEFINITION OF THE FIELD OF COMPUTATIONAL MECHANICS

Computational mechanics is that discipline of applied science and engineering devoted to the study of physical phenomena by means of computational methods based on mathematical modeling and simulation, utilizing digital computers. The discipline combines theoretical and applied mechanics, approximation theory, numerical analysis, and computer science. Computational mechanics has had a major impact on engineering analysis and design. Although the field relies on diverse scientific and engineering disciplines, we believe that computational mechanics should also be viewed as an independent, intellectually rich, and fundamentally important discipline in its own right.

BREADTH OF APPLICATIONS

The application of computational mechanics to contemporary problems in engineering typically involves a sequence of steps: observation of the phenomena of interest, identification of a mathematical model that describes it, testing the range and validity of the model, development of computer algorithms, development and assembly of computer hardware to implement the algorithms, interpretation of computed results, and utilization of the results in the analysis and design of engineering devices or systems. Within this general framework, computational mechanics is being used today in a broad range of engineering and other practical activities. It is integrated into many aspects of the U.S. economy, some of which are described below. In addition, Appendix A presents case studies that illustrate specific applications of computational mechanics in industry.

Beyond commercial applications computational mechanics plays an important role in national security interests that includes weapons systems development and military aerospace programs. Appendix B details the role of computational mechanics in the development of U.S. weapons systems.

Other applications of computational mechanics are given below.

General Manufacturing

Most of the nation's large manufacturing companies use computational procedures regularly in the analysis and design of structures and mechanical equipment. Such work involves identifying the physical environment in which the structure or machine part is to operate, developing mathematical models to simulate this environment, developing computer software based on these models, studying the effect of changes in design parameters through the use of computer simulation on the adequacy of the design, producing design drawings and specifications for the system, and sometimes using computer devices in the manufacturing process to help hold the product within design specifications and tolerances.

Aerospace Industry

The products of the aerospace industry--commercial and military aircraft as well as aerospace vehicles--represent extremely challenging structural design problems. They must be of the lightest possible weight, perform safely, and strive for the lowest cost of manufacture. They are of complicated form, and in each succeeding decade they are planned to operate more efficiently and with greater range in more severe environments where they must incorporate new materials and new design concepts. Because of computational mechanics, major strides are being made in design for minimal structural weight and for aerodynamics, especially in the definition of shapes for drag reduction. Inevitably, aeroelastic interaction must be taken into account, wherein the structural and aerodynamic behaviors are dealt with in an integrated computational exercise. The computational needs will tax even supercomputers.

Nuclear Safety and Technology

The nuclear industry is deeply involved in computer applications of the principles of structural and fluid mechanics in analysis and design. The safety and structural integrity of nuclear reactor systems depends critically on the use of computational methods to simulate performance under a wide range of environmental conditions.

Automobile Manufacturing

All of the world's major automobile manufacturers now use large computer programs for stress analysis, structural design, and dynamic analysis of motor vehicles and for the design and manufacture of automobile parts. The Japanese and German automobile industries have been committed for nearly a decade to computer-aided design, and the

U.S. industry is making extensive use of computer-aided analysis and design concepts. Automotive applications typify the necessary coordination of the components of computational mechanics--in the description of the behavior of the vehicle by the equations of mechanics; in the numerical analysis of these equations by modern computational methods and machines; and in the use of computed results to shape parts, optimize weight and performance, and shape the vehicle aerodynamically.

Civil Engineering

Computational mechanics is used extensively by most civil engineering firms, ranging from large, national organizations to small consulting offices. Applications involve the analysis and design of buildings, bridges, dams, towers, highway and runway pavements, harbors, piping systems, canals, irrigation systems, and foundations. Such work includes studies of geological and geotechnical questions, earthquake effects, and wind loading on structures; water runoff and reservoir calculations; and analysis of flow in estuaries, rivers, lakes, and streams.

Naval Architecture and Offshore Engineering

Ships and offshore structures constitute a class of design problems that requires extensive and sophisticated analytical treatment because of structural complexity, structure-fluid interaction, extreme operating conditions, and cost. In recent years, there has evolved a significant research and development activity based on computational mechanics, aimed at improving reliability and the cost of ship and offshore structures.

Space Technology

Virtually every aspect of the nation's space program has relied on computer applications of mechanical principles. Examples include stress analysis and study of the stability of rockets, study of the aerodynamics of space vehicles, analysis of the mechanical behavior of fuels, analysis of various properties of materials, calculation of optimal orbits, and analysis of the vehicle dynamics of missiles and artificial satellites.

Petroleum Technology

Computational mechanics is used routinely to estimate the extent of reserves in oil fields, to simulate and design chemical and petrochemical processes, and to estimate the extent of secondary and tertiary recovery of petroleum from existing fields. The estimation of petroleum reserves and the analysis and design of equipment to exploit such reserves depends heavily on the use of many principles of computational mechanics and has been critically important in helping the nation meet its energy needs.

Air and Water Pollution

The methods of computational mechanics are key tools in simulating the dispersion of pollutants in the atmosphere and in rivers, streams, lakes, oceans, and aquifers. These simulations permit the prediction of dangerous levels of concentrations of pollutants and are extremely useful in designing and developing environmentally sensitive engineering systems.

Weather Prediction

Aspects of computational mechanics have been used for a number of years to model the earth's atmosphere and to make long-range weather predictions. This work is still in development, however. It is generally agreed that progress will require substantial advances in the following areas: modeling and characterizing the atmosphere and surface of the earth; development of reliable and efficient algorithms to analyze these models for various initial conditions; and further development of large, fast computers. Significant progress could yield major benefits in a variety of commercial, military, and agricultural activities that depend heavily on prediction and control of weather.

Electrical and Electronic Engineering

The procedures of computational mechanics are widely used today in electrical engineering for analysis of electro-magnetic fields and studies of their interaction with mechanical components. The design of magnets used in accelerators is another application that relies heavily on computational mechanics. Recently, efforts are evident in semiconductor technology where the design of computer chips uses such methods.

NEEDED--A DISCIPLINARY APPROACH

These areas of application of computational mechanics are not all inclusive, but nevertheless will serve to indicate the breadth of the field and its importance to technological strength. In this light we wish to stress our belief that computational mechanics should be treated as a discipline in itself, not as a collection of distinct engineering and scientific disciplines. Steady progress in the field demands coordination of endeavors in mechanics, physics, computer science, and numerical analysis by practitioners trained or qualified by experience to work from a unifying perspective.

This requires the expansion of graduate education to encompass such an integrated approach. Consideration should be given to the introduction of undergraduate courses to develop a new breed of engineers now so widely required by industry.

3

SOURCES OF COMPUTATIONAL MECHANICS

INTRODUCTION

Resources in computational mechanics in the United States exist essentially in three areas: colleges and universities, federal laboratories, and private industry. This chapter examines the resources and needs in each of these sectors.

The committee also assessed the status of computational mechanics in foreign countries. Through correspondence with individuals in 11 countries, the committee learned that centers of computational mechanics exist in most of the Western European countries contacted. The European picture provides an interesting comparison. Several centers that concentrate on computational mechanics research and teaching were identified at various universities.

The major and longest established centers are attached to engineering departments including such well known groups as I.S.D. (Institut für Statik und Dynamik der Luft und Rahmfahrt Konstruktionen) at Stuttgart, West Germany; The Institute for Numerical Methods in Engineering at Swansea, U.K.; the Structural Engineering Department at Trondheim, Norway; and others.

Similar groups representing more basic mathematical approaches can be identified, such as the Institute of Computational Fluid Dynamics at Reading, U.K.; the Institute of Computational Mathematics at Brunel University, U.K.; and, of particular importance, the INRIA Institute (Institut National du Recherche en Informatique et en Automatique) in France.

From the point of view of financial support, most of the organizations operate in a manner similar to that in the United States. They rely on relatively short-term contracts and grants together with continuing university support.

The situation is, however, substantially different in France. INRIA is a directly government financed center employing on a regular basis academics belonging to various universities and, at the same time, having many permanent employees. INRIA's personnel exceed 1500 and include many experts in computer sciences. Computational mechanics directly involves about a tenth of the total employment. This farsighted approach has had the effect of raising the standard of work in the computational mechanics field in France.

In many ways, the scale of operation of INRIA and the other European activities could well provide guidance and models for positive computational mechanics programs in this country.

UNIVERSITIES

Personnel

Computational mechanics is a primary interest of about 1,500 university faculty members nationwide. This estimate has several bases: mailing lists; attendance at national meetings concerned with the field; and the number of colleges and universities involved in mathematical, scientific, and engineering research, together with the average number of specialists in computational mechanics at these institutions. It must be recognized that these specialists may have sharply differing interests. It should also be noted that communication between specialists in different aspects of computational mechanics might be better when they are in different universities rather than in the same university. The key specializations include the following.

Solid and Structural Mechanics

The largest single group of research specialists in computational mechanics in universities probably is in solid and structural mechanics. The reasons are the long-time use of computational mechanics in solid and structural mechanics and the high level of practical applications and concomitant financial support. This is an active area at virtually every institution that pursues research and graduate education in solid and structural mechanics. Research in computational mechanics also is found in departments of mechanical and aerospace engineering, in theoretical mechanics, and, to a lesser extent, in naval architecture and nuclear engineering.

Computational Fluid Dynamics

A good deal of academic activity is under way in the United States on computational fluid dynamics. Much of this work is concerned with computational aerodynamics and the development of numerical schemes for designing airfoils and solving the full-potential and Euler equations for compressible flow. This work has already had significant impact on aircraft design and has lessened the need to rely entirely on wind tunnel testing. Additional work is under way on modeling Navier-Stokes equations and applying the models to a variety of problems in compressible and incompressible viscous flow.

Nonstructural Engineering Analysis

Computational mechanics is used in nonstructural engineering analyses in areas such as heat transfer, electromagnetics, and biomechanics. Specialists in these fields are rather more scattered among the universities, and investigators in solid and structural mechanics often contribute to these endeavors.

Applied Mathematics

Commencing about 1970, strong academic centers of activity have developed in the mathematical theory of finite elements and finite differences.

Although computational mechanics draws on fields other than applied mathematics, a very large share of mathematics departments are involved in research related to computational mechanics, specifically in numerical and applied analysis techniques.

Computer Science

Although the computer has become an essential tool of computational mechanics, the academic computer science community includes fewer specialists in computational mechanics than the specialties cited above. Nevertheless, the active group is significant and has made important contributions in the areas of algorithms and software management. This small group is likely to expand faster than the others because of the developing tie between computer hardware and software resulting from more sophisticated integrated circuitry.

Interactive Graphics

Work on interactive graphics is an academic area that is linked in some cases to computer science departments and in others to traditional engineering departments, most prominently mechanical engineering in the area of computer-aided design and manufacturing. Because of the high capital investment required, centers of activity in interactive graphics usually are created as independent entities drawing personnel from different academic disciplines. As in computer science, the number of people in the interactive graphics aspect of computational mechanics is growing rapidly.

Equipment

The committee finds three limitations with the current state of computer equipment in universities. First, although major universities possess large computer systems (such as the Control Data Corporation's Cyber 175 or the IBM 308Xs), access to this equipment is limited by the funds available to pay for computer time.

Second, research topics in computational mechanics today most often deal with inherently complex nonlinear problems. The software employed is expensive and often proprietary, and it requires equipment beyond the acquisition budget of most universities.

Third, the rate of change in hardware systems is such that universities have a difficult time replacing old equipment with state-of-the-art computational devices. To compound the problem, many of the departments doing research in computational mechanics have acquired minicomputers (realistically, "superminis" of the class of Digital Equipment Corporation's VAX 11-780 or Prime Computers' Model 750). This development in part has disengaged the departments from the university-wide computer centers. In many universities, the capabilities of individual departments have been outdistanced by the arrival of equipment such as array processors and peripheral graphics devices.

Centers of Research Specialization

Centers of activity in or allied to computational mechanics have been established at a number of universities. In general, these centers are able to exploit pooled resources by combining efforts in solid mechanics and applied mathematics, for example, or in interactive graphics and structural mechanics. Such centers have access to large computing resources, although they are not often in control of these devices (excepting interactive graphics laboratories). They attract research grants and graduate students on the strength of their own activities, rather than their affiliations with traditional academic departments. Few of these centers of research in computational mechanics, however, are able to operate continuously on a level consistent with the talents of the personnel available. They are limited seriously, in fact, by their lack of access to computational facilities and to the funds required to retain a state-of-the-art capability in that equipment. It is imperative to make available to students and faculty the best computational facilities available.

In the spirit of the second recommendation of the report, the establishment of research centers in computational mechanics at universities is worthy of strong consideration. Such centers should build on the existing expertise of established university centers. They should foster interdisciplinary activities to bring added expertise to complex problems. For example, behavioral scientists can help with understanding the massive data generated in a complex computer analysis.

Research Funding

The level of funding for basic and applied research in computational mechanics is limited by confusion in funding agencies about the nature of computational mechanics and how funds should be earmarked to encourage further development. Few state or federal agencies committed to funding research are receptive to proposals genuinely oriented toward computational mechanics. Most funding agencies are project oriented or structured more or less along traditional disciplinary lines and so are not organized to give proposals in computational mechanics a balanced review. Specialists in computer science and numerical analysis, for example, frequently regard computational mechanics as the province of the mechanics community, while specialists in mechanics and physics frequently regard the subject as the province of computer science and numerical analysis. Computational mechanics requires a team approach, a critical mass of disciplines including computer scientists and those from the mechanics community.

The committee considered this situation extremely serious, especially in view of the relative impact of computational mechanics on mechanical and civil engineering and on science and technology in general during the past two decades. It is generally not disputed that modern mechanical and physical theories can be applied to complex physical phenomena only by using modern, sophisticated computational methods. It is not adequately appreciated, however, that efficiency in research demands that the development and implementation of these methods go hand in hand with analysis of the physics of the problem itself. The result is that money is allotted to research on problems that can be treated reasonably only by using computational methods, yet no resources are provided to study and develop overall computer methods that can markedly increase the efficiency and technology transfer aspects of the research. It is noteworthy that funding entities in some competing industrialized countries do not confuse the components of computational mechanics with the subject itself; some have developed means of research funding that encourage healthy coordination of effort in all of the component areas of computational mechanics. This is the case in France, for example, through the mechanism of INRIA.

The current policy of allocating public funds to computational mechanics from the traditional disciplines of mechanics and civil and aerospace engineering has contributed strongly to the evolution of computational mechanics, but at this stage it is hampering the sound, long-range development of the field. The wiser course now would be to adjust funding mechanisms so that federal agencies can more readily foster and directly support research in computational mechanics.

Graduate Study

Domestic Graduate Students

It is a matter of record that educational institutions in the United States are training graduate students from abroad to become specialists in computational mechanics, while relatively few domestic students are pursuing advanced training in this general area. The committee believes that this situation is cause for concern. In essence, our universities are likely to be training the very people who will compete with this country in the marketplace within the next decade. The developing countries, as well as such industrialized countries as Japan, France, and Germany, apparently recognize the importance of computational mechanics and regularly subsidize top students to pursue graduate studies in the United States. Returning to their countries, these students are contributing to the development of products and systems that compete strongly with those of U.S. companies.

Some public and private organizations have attempted to correct the shortage of domestic graduate students in computational mechanics by establishing scholarships and fellowships. One example is the Computational Fluid Dynamics Fellowships of the National Aeronautics and Space Administration. These fellowships are awarded to U.S. citizens and enable them to pursue graduate study in computational fluid dynamics at major universities that have active research programs in this area. The fellowships carry stipends intended to be large enough to make graduate study attractive to exceptional students who might otherwise be inclined to enter industry immediately after graduation. While few private resources have been directed toward the study of computational mechanics, some companies have funded fellowships for U.S. graduate students in engineering. Such programs do directly address the shortage of new engineers entering computational mechanics, but at present are too limited to have a significant impact on the problem.

Faculty

The shortage of domestic graduate students in computational mechanics is reflected in part by a notable deficiency in manpower for university faculties. It is time for universities to consider adjusting their engineering curriculums and faculties to provide specifically for the development of programs and funding in computational mechanics. The committee found serious shortages of specialists in computational mechanics available for faculty positions in U.S. universities. This problem is shared by many other areas of engineering and has been the subject of a two-year study by the American Association of Engineering Societies (AAES).* To restore much-needed vigor to engineering education in this country, the AAES recommended initiatives that include provision of funds for:

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* "A Pilot Study of the Demand for Engineers," Engineering Manpower Commission, American Association of Engineering Societies, April 1981. Also, "Engineering Manpower and Education--Foundation for Future Competitiveness," Report of the Business Higher Education Forum, October 1982.

- A program to encourage 4,000 doctoral graduates per year for five years to accept assistant professorships;
- A fellowship program that would provide annual stipends of $15,000 to a total of 4,200 master's and doctoral students;
- A program designed to provide incentives for engineers from private industry and government to enter teaching; and
- A faculty enrichment fund that would encourage universities to plan long-range improvements in engineering programs.

The committee believes that it may be appropriate to focus some of these initiatives on computational mechanics in view of the broad impact of the field on engineering applications. We would note, moreover, that shortages of graduate-degree engineers and potential faculty are not distributed uniformly over all of engineering and that certain specific areas, including computational mechanics, could be identified as targets for special funding.

GOVERNMENT

Personnel

The Committee estimates that 800 to 1000 specialists in computational mechanics are working at federal laboratories (Table 3.1) in the United States. The number of federally employed scientists and engineers who are using computational mechanics, however, may exceed 2,000. In addition, an estimated 80 to 100 program administrators concerned with computational mechanics are employed in agency headquarters activities.

Equipment

Research in computational mechanics in federal laboratories normally is done with computer systems at the laboratories (as opposed to headquarters equipment). Scattered among the various government laboratories are 25 to 30 large mainframe systems. For many years, Control Data Corporation equipment was used most often in these large computing systems. Today, however, we see other large mainframes, such as the Cray, appearing more often, as well as a trend toward powerful minicomputers, such as Prime Computers' Model 750 or Digital Equipment Corporation's VAX 11-780. As in universities, moreover, these minisystems are appearing outside the jurisdiction of the computer center at the laboratory.

Relatively few computer graphics systems are evident at government laboratories and headquarters. An exception is the Navy which bought $63 million worth of Computervision terminals for use throughout their widely dispersed laboratories. This turnkey system will be used largely for computer-aided design (CAD). The lack of a finite-element-analysis package that is versatile and comprehensive enough for the Computervision system will inhibit its usefulness outside of the CAD area. Should the Navy decide to broaden its application, it would most likely have to use a mainframe-based system.

Funding

Government funding of research in computational mechanics is difficult to pinpoint, in part because computational mechanics does not appear as a line item in an agency's budget, and because a number of federal agencies fund work in this area for a variety of purposes. Table 3-1 lists just the laboratories involved in computational mechanics research.

The committee estimates that 15 percent of the government's total budget for contract basic reseach in mechanics is for computational mechanics. In 1982 this meant that the government spent approximately $13 million on contract basic research in computational mechanics, primarily through universities. The committee also estimates that $14 million was spent on in-house basic research in computational mechanics.

While considerable funding is estimated to be available for applied research related to computational mechanics, the committee did not reach any dollar estimates.

TABLE 3-1 Government Laboratories Involved in Research in Computational Mechanics

Army

Army Materials and Mechanics Research Center (AMMRC), Watertown, Massachusetts
Ballistics Research Laboratory (BRL), Aberdeen, Maryland

Navy

Naval Ship Research and Development Center (NSRDC), Carderock, Maryland
Naval Surface Weapons Center (NSWC), White Oak Laboratory, Silver Spring, Maryland
Naval Research Lab (NRL), Washington, D.C.
Naval Air Development Center (NADC), Warminster, Pennsylvania
Naval Weapons Center (NWC), China Lake, California
Naval Civil Engineering Lab (NCEL), Port Hueneme, California

Air Force

Flight Dynamics Lab (FDL), Wright Patterson Air Force Base, Dayton, Ohio
Air Force Weapons Laboratory, Albuquerque, New Mexico

NASA

Langley Research Center, Hampton, Virginia
Ames Research Center, Mossett Field, California
Lewis Flight Propulsion Laboratory, Cleveland, Ohio

Department of Transportation

Fairbank Highway Research Lab, McLean, Virginia
Transportation System Center (TSC), Cambridge, Massachusetts

Department of Commerce

National Bureau of Standards (NBS), Gaithersburg, Maryland
National Oceanic and Atmospheric Administration (NOAA), Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey

Department of Energy

Lawrence Livermore National Laboratory
Los Alamos National Laboratory
Sandia National Laboratory

Issues and Trends

Because computational mechanics is used to solve problems in diverse fields, individual programs of government agencies that may have related computational mechanics aspects are not coordinated with each other. For example, computational mechanics underlies much of the technology embodied in robotics, flexible manufacturing systems, computer-aided design (CAD) and computer-aided manufacturing (CAM), automated material handling, and automated production engineering. A number of federal agencies are concerned with development in and applications of these technologies. Efforts at interagency coordination center on these technologies, not on computational mechanics.

A second important issue is the significant number of powerful mainframe and minicomputers at government laboratories that are not normally used to full capacity. The solutions to many problems in computational mechanics are limited by the availability of computer time. Thus, it may be worth considering the possibility of making this excess computer capacity available in an orderly manner to scientists outside the government. The National Science Foundation has recently moved in this direction. The agency's program managers can now supplement research awards with money to pay for time on supercomputers when it is justified.

A third issue results from a trend in federal agencies to support fewer, but larger, research programs that high-level managers consider either strategically or politically important for their particular activity. Examples include programs involving laser effects, instrumentation purchases, and automated production and robotics. The concentration of research on a specific subject in a few institutions may result in less imaginative approaches to difficult problems.

A fourth issue is a shortage of knowledgeable personnel in government. The government, like universities, has a severe difficulty attracting computational scientists in the face of the significantly higher salaries usually offered by industry. The relatively modest number of computational scientists currently being trained greatly increases this competition. Failure to attract such scientists as prospective managers in federal laboratories and headquarters makes it difficult for agencies to conceive initiatives in computational mechanics. A related issue is the shortage of technical managers who understand the key issues associated with the development of computational mechanics and who have good insights into software development methods. Such managers need to possess a blend of experience not only of engineering but also numerical methods and computer science. Managers who control resources today often do not understand the costs and skills required for computational mechanics developments.

Fifth, software that could be used as general purpose in computational mechanics is being generated by private industry, making it proprietary and expensive, and not generally available to the computational mechanics research community (although applications software is more readily available). Software has several development stages ranging from experimental to prototype to production code. Experimental code is unlikely to be transferable. Production code, while visually transferable, is costly to achieve and maintain.

It should be noted that program managers in agencies that fund problem-specific research in computational mechanics have access to much information that could be disseminated. Failure to do so results in a great deal of research duplication and waste of resources. Means must be found to make available the information on what has been done and what is available in given areas in terms of theory, algorithms, and software.

Some federal agencies have been moving toward requiring that printouts of software developed and used under research contracts be appended to the reports on the work. This is a positive move because applied researchers and software developers do read reports and are able to generate new ideas. Practicing engineers, however, generally never see the reports and so may spend considerable time and money developing software that is already available.

Finally, the government plans to increase its support of the development of supercomputers. The National Science Foundation's budget for reseach in the area of scientific computing resources has grown more than threefold from $6 million in 1984 to $20 million in 1985. The monies will be used to provide access to advanced computers, for appropriate networking capability, and to support such local user needs as equipment, software, communications costs, remote workstations, local area networks, technical support, and maintenance. The NSF-supported research budget in architecture design and software applications specifically related to the development of supercomputers has increased from $8 million in 1984 to $10 million in 1985.

The government's action is a response in part to the "Report on Large-Scale Computing in Science and Engineering," the result of a study funded by DOD and NSF. The study panel, chaired by Dr. Peter Lax, recommended the establishment of a national program to spur the development and use of advanced computer technology. Supercomputers are essential to the solution of important design problems in areas such as aerospace and automotive vehicles; large structures, including dams and long-span bridges; and the structural effects of nuclear weapons. Other nations have recognized the need for advanced machines; Japan, for example, has earmarked huge sums for development of supercomputers.

INDUSTRY

From the perspective of many corporate managers, computational mechanics describes only a narrow range of activities in engineering design and analysis and is even more remote from product engineering, fabrication, testing, and other engineering functions. One can evaluate resources and needs in computational mechanics directly for companies sufficiently large and specialized to justify an engineering mechanics group, or for small firms that provide engineering design and analysis. For other types of companies, work in computational mechanics cannot be clearly distinguished, and evaluation of resources and needs is virtually impossible. Industrial computational mechanics, moreover, is not readily aggregated in terms of human resources.

Case Studies

The committee solicited a series of case studies of applications of computational mechanics that illustrate resources and needs in the field. These studies were intended to be illustrative. The case studies are summarized in Appendix A; the trends and generalizations we see in them are given here.

Trends and Generalizations

The committee's findings include the following principles:

- Organizations find that computational modeling capability is needed to remain competitive in the marketplace. Although the costs of the associated software and personnel are high, the costs of being uncompetitive are even more severe.
- Organizations without substantial computational experience are inclined to build the capability around an established, widely accepted applications software package; organizations with previous experience tend to build capability around an in-house version of a noncommercial package.

Computational Costs

In contradistinction to the optimistic projections that have appeared in the literature, computational costs--which include both personnel and hardware/software costs--are such that nonlinear and three-dimensional analyses are not yet competitive with the available alternatives, such as testing and/or simplified calculations based on engineering judgment.

The industrial engineering manager, in general, is keenly aware of these considerations. While each wave of new developments in computational technology tends to raise hopes that significant economic breakthroughs are at hand, the reality is that total analysis costs for well-defined increments of work (e.g., calculating the stress concentration factor at a geometric discontinuity) have declined only slightly over the past decade. The reasons have little or nothing to do with the price of hardware, software, or personnel. Rather, the two discernible trends are increased productivity of the engineer, which tends to speed problem-solving, and the increased complexity of computational models, as analysts tend to substitute model definition for the more time-consuming engineering judgment.

The increases in productivity have been substantial and are traceable to factors such as preprocessors, with emphasis on automated data generation, shared data bases, and graphic displays for rapid diagnosis of error; more reliable software, especially with the advent of widely used commercial applications software packages; and postprocessors, which have relieved the engineer of much of the drudgery of displaying results, so as to concentrate on interpretation.

The increase in the complexity of models may be attributed to at least three factors:

- Computational budgets have been able to tolerate the costs of the more complex models because of the improved productivity; therefore, analysts have been under no significant pressure to minimize modeling detail.
- Analysis has generally been the province of the inexperienced engineer; the educational background of the modern engineer--with its relatively greater emphasis on the theoretical foundations of analysis and relatively lower emphasis on design and physical behavior--produces a tendency to overmodel, rather than rely on engineering judgment.
- The improved capability of commercial applications software has given analysts a variety of modeling options, and they tend to use the most complex, affordable option available.

These countervailing trends--increased productivity and increased complexity--buttressed by the dramatic declines in central processing costs, were evident throughout this study.

Anticipated Trends

At this juncture, it might be useful to point out the effect of two relatively new developments on industry resources and problems in computational mechanics.

First, noncommercial applications software was generated primarily at universities and government laboratories, with an emphasis on the former, based in general on federal grants and contracts. As the commercial applications software market has grown, software from these noncommercial sources has virtually disappeared. The exception has been software developed at the atomic weapons laboratories of the Department of Energy (e.g., the Lawrence Livermore National Laboratory and Sandia National Laboratory). The availability of high-quality software from these national laboratories has enabled many industrial firms to acquire significant analytical capability at relatively low initial cost (total cost includes the costs of maintaining this software). While evidence is sketchy, this source of reliable, low-cost software appears to be in a declining stage.

The second development is the growth of the microcomputer industry which has encouraged speculation about further dramatic improvements in engineering productivity. The conventional image is a microcomputer in every analyst's office, linked to a large mainframe to accommodate the most memory-intensive or time-consuming computational tasks.

Some suggest, however, that the microcomputer revolution may actually reduce productivity. The potential problem arises because most engineers with graduate degrees and many with bachelor's degrees have mastered basic programming skills. Many prefer to develop their own special-purpose software to solve problems, rather than rely on unfamiliar software of uncertain quality. New graduates in computational mechanics are especially aware of the difficulty of finding universally applicable algorithms; some are suspicious of the claims of commercial software suppliers and of the results obtained with such software. A likely outgrowth of the microcomputer revolution is a surge in software development as the programming skills of thousands of users become honed to a fine edge because of the availability of essentially free local memory. Technical managers will resist this trend, applying administrative controls to force analysts to use existing software packages. Such controls are unlikely to be effective, however, and the portability and increased capacity of microcomputers should produce a renaissance of applications programming unlike anything since the 1960s.

Software Sources

This difference in attitudes between analysts and their technical managers is not confined to microcomputers. Perhaps no subject causes greater divergence of opinion than in-house development of software versus acquisition from outside suppliers. Technical staff tend to support in-house development, starting with robust software architecture (i.e., the basic modules are acquired from an outside supplier--nominally a university or government laboratory). Technical managers tend to prefer to obtain both software and its maintenance from outside suppliers. The arguments on each side are compelling. The technical managers are understandably concerned about the costs of software development and maintenance, and historical evidence suggests that technical staff seriously underestimates the true costs of these activities. On the other hand, management often fails to appreciate the subtleties of implementing unfamiliar software. The direct costs of dealing with outside software suppliers are readily understood, but the indirect costs associated with acceptance by the staff can be a problem.

To reconcile staff and management, all sorts of strategies are tried. Few are effective. Managers without software experience tend to be captive to the opinions of either staff or outside vendors, depending on their emotional attitudes toward the two. Managers with software experience tend to build their personal bias into decision making. Vendors of applications software realize that this predisposition can be cultivated and are actively distributing their software--virtually free of charge--to colleges and universities. The purpose is to create a generation of users and, eventually, managers oriented toward particular software. In general, however, one applications package will not satisfy the computational mechanics requirements for all users. Technical managers eventually discover this, to their chagrin, with the result that software development and maintenance costs become less controllable.

Industry Needs

In assessing industrial needs in computational mechanics, the committee in part considered views expressed at the World Congress and Exhibition on Finite Element Methods, held in 1982 in Los Angeles. Accepting for the present that such a gathering would be heavily biased toward developers of applications software, with less-than-adequate industrial representation, the needs identified by the speakers are of interest. Two such needs were cited frequently.

First, developers tend to be exasperated by the dearth of qualified users and, therefore, consider user training a high-priority need. The role of the university in this training process is controversial; many engineering faculty adamantly oppose a curriculum slanted toward software-user training. With the proliferation of commercial short courses aimed at particular applications software packages, and with some universities emphasizing the theoretical aspects of computational mechanics, industry has a variety of options available. A problem is that adequate means of measuring increases in productivity resulting from user training are elusive.

Second, if modern computational tools are to have an effect on the design process, advances in software are needed to give the designer the freedom to alter geometry, loading, materials, and other parameters.

The committee combined these views with its own findings to develop a broad perspective on industrial needs. We classify the needs in three categories:

1. Indirect Cost Control From the very beginning, applications software computing has been dominated by the indirect cost problem. As the relative cost of memory and other hardware items decreases, the need to identify the indirect costs associated with applications software computing becomes more important. These indirect costs arise from a variety of sources, such as the unrecovered costs of software development and maintenance, user training and qualification, and acceptance testing for software developed elsewhere. Technical managers view indirect cost control as their highest priority need.

2. Productivity Three major needs in productivity have been identified. We have mentioned two--greater impact of computational mechanics on the design process and more well-trained users. A third need relates to the direct coupling of the design engineering process with fabrication. The problem that inhibits this coupling is the

degree of modeling detail required for each step. Computational models can be quite detailed, but more often than not the detail is merely sufficient to determine that a particular design feature (i.e., a local model) is adequate to meet the design specifications. Such local models, even if sufficiently detailed, are not adequate for fabrication. From the point of view of technical staff, the highest priority for productivity is the development of user-friendly pre- and postprocessors, including integrated data bases for materials and geometric features.

3. Additional Capability Although additional capability could be classed as a productivity need, it is treated separately here for emphasis. Most of the additional capability identified as desirable by industrial sources can be lumped into material models (e.g., rubber elasticity, non-Newtonian flow, energy-absorption mechanisms, rate-dependent behavior, etc.) or kinematic behavior (e.g., forming and fabrication processes, etc.). In addition, however, improved algorithms for error assignment and control have been suggested.

4

DEVELOPING AREAS AND FUTURE OPPORTUNITIES

INTRODUCTION

This chapter is intended to identify and briefly characterize developing areas of application that will place new or increased demands on the computational mechanics community. These developing areas will provide new opportunities in the use of computational mechanics to improve the products and productivity of the nation and future opportunities to improve the development and utilization of computational mechanics models.

The developing areas and future opportunities sketched below are not meant to be exhaustive. Rather, the intent is to illustrate through examples the breadth of the discipline of computational mechanics.

DEVELOPING AREAS IN APPLICATIONS

Until the late 1970s, computational mechanics was exploited primarily in high technology areas such as nuclear power plants, the aviation industry, and nuclear weapons. Recently, intermediate technology companies, such as makers of automobiles, tires, and agricultural and construction equipment, have devoted considerable investment in computational mechanics as part of their engineering design process with substantial success.

In the past few years, the potential of computational mechanics has become apparent even to low-technology companies. Product design at many small to moderate size firms usually varied little from year to year, and new products were introduced through an evolutionary process after extensive testing with little analysis as to optimization or cost. The influx of computational mechanics in these firms has been caused by two factors: the decreasing cost and greater accessibility of computers; and the realization that the use of computational mechanics in design and engineering can substantially reduce manufacturing costs and improve the product.

At the same time, in areas of moderate and high technology, the tendency has been to use computational mechanics for increasingly complex situations. This trend promises substantial benefits in cost and productivity. The problems, however, are often beyond the computational mechanics methodologies and techniques developed to date by the basic research community. Examples of such problems include: the prediction of the nonlinear response of tires under severe cornering and braking forces; the simulation of metal forming processes; the simulation of manufacturing processes employing plastics; materials handling problems; prediction of the responses of automobiles and their occupants to crashes; and study of prosthetic devices and their longevity. Solutions to many of these problems will provide substantial benefits. For example, if improved engineering could increase the durability of hip or knee prostheses by a factor of three to four, they could be implanted at much earlier ages and the likelihood of additional surgery, which is now often needed, would be reduced substantially.

In manufacturing processes, the effects of computational mechanics are just beginning to be felt. It is apparent that the ability to simulate manufacturing processes can substantially reduce the cost and improve the quality of many products. In addition, it gives manufacturers a shorter engineering design time, which is essential to a company's survival in the increasingly competitive international markets.

The sections that follow describe developing areas in the application of computational mechanics.

Integration

Computational mechanics provides a tool for modeling and, thus, understanding physical phenomena. Frequently, this understanding is part of a larger context, most commonly in the design of a system or artifact embodying the computational mechanics model. The model must be viewed in this larger context, and the analysis must be integrated with the other design processes. Several major opportunities exist for effecting a more intimate and, therefore, more productive integration.

Geometric Modeling

Computational mechanics programs depend intimately on the geometric representation of the system involved. This geometric representation for physical modeling purposes has reached a high level of sophistication within the computational mechanics community. Essentially independently of this representational need, an entirely new subject--geometric modeling--has developed for the representation and manipulation of geometric objects by computer. Geometric modeling is widely used, not just for computer graphics displays, but for purposes such as composing or sculpturing objects, performing set operations (union, intersection, and difference) on objects, and generating numerical control tapes. At present, the two kinds of models are only weakly coupled; it is not uncommon today for a solid object, such as an automobile body, to be digitized twice: once to create a geometric model and once to generate the geometric representation for a finite element model.

The integration of the two models presents great opportunities. First, the highly developed curve, surface, and solid representations from geometric modeling could give rise to new classes of finite element shape functions. Second, problems of spatial conflict and clearances could be handled much more directly than at present. Third, the entire design process could be made much more effective and productive by having all disciplines operate from a common geometric model.

Data Base Management

A second aspect of integration is data base management systems (DBMS), which are being used increasingly in a variety of applications. They not only provide a central repository of data whose integrity and consistency can be controlled, but also facilitate program development by making programs physically and logically independent of the data storage and access mechanisms.

Computational mechanics programs interact with a variety of data bases, such as the geometric model, tables of properties of elements and materials, experimental data, and performance constraints. The full and effective interfacing of the programs to these data bases through DBMS provides major efficiencies in integrating computational mechanics analysis into the overall design process. It should be noted that computational mechanics programs also do an enormous amount of internal, run-time data management for functions such as secondary storage control, iteration control, saving and restoring, and substructuring. It is an open research question whether these functions would benefit from DBMS methodology, or whether their efficiency requires intimate data-dependence.

Of the major methods of organizing data bases for access, the relational method appears to be most suitable for integration with computational mechanics data bases because of its formalism and higher level of independence of physical and logical data. Achievement of full integration, however, requires further work, primarily in the extension of the range of attribute types supported by DBMSs to vectors and matrices and in the extension of the types of integrity constraints enforced by the DBMS to include typical constraints used in engineering.

CAD/CAM Integration

The most intimate integration of computational mechanics into the overall design process occurs in computer-aided design and manufacturing (CAD/CAM). The issue of CAD/CAM integration is addressed in detail in Appendix C. The important point here is that many CAD/CAM vendors and users have adopted a very narrow definition of CAD, one dealing almost exclusively with geometric design or spatial layout, with functional or physical analysis relegated to a design analysis function external to the CAD system. In an environment embodying this philosophy, computational mechanics--if used at all--is relegated to evaluation of design decisions previously made.

It is imperative that functional or physical analysis be more closely integrated with other design processes. Otherwise, the systems involved will either have to be grossly overdesigned, resulting in inefficient use of materials or resources, or will turn out to be physically unsafe, requiring major cycles of redesign and retooling. Admittedly, present-day computational mechanics programs must be vastly improved in speed and access methods to make them suitable for such tight integration.

It is interesting to speculate whether very tight integration of design and analysis may actually produce radically different design scenarios, in which functional performance is first verified (or optimized) on the computational mechanics model, and the geometric requirements satisfied later, subject to the established functional performance. In systems or products where physical performance is critical, such an inverted approach to design could produce radically new solutions.

Extensions

Computational mechanics has been used to date to analyze mathematical models of physical phenomena with deterministic parameters. The scope of computational mechanics can be extended far beyond this usage in a number of directions.

Adaptive Mesh Refinement

The area of adaptive mesh refinement in finite element analysis potentially has significant benefits. This is a technique which conducts an error analysis on one finite element analysis and automatically refines the mesh in areas of large errors. Therefore, the method not only generates its own mesh, but assures that the results are within some specified error limits. If this method can be effectively implemented in the profession, production and reliability will be greatly improved. At the present time, all the major proprietary programs in finite element analysis do not have this capability.

Optimization

Optimization is implicit in almost every design application. Large strides have been made in optimization methods in the past two decades. They include multiobjective, nonlinear, integer, zero-one, and semi-infinite programming. Linkages have been established between optimization and computational mechanics models, primarily by having the latter compute the technological contraints in the larger optimization model. Experience with such linkages indicates that new or modified optimization models and new approximation theories are necessary to make more intimate linkages practical.

Reliability-Based Models

The assumption of deterministic parameters of physical models, such as properties of materials and loading, is accepted by all analysts as a simplification necessary to get results. What is desired is computational tools to predict the reliability of the model's performance subject to assumed uncertainties in the variation of the parameters. The extension of computational mechanics into a practical reliability-based format would have far-reaching consequences. More rational design decisions and more realistic cost/performance trade-offs could be made.

Expert Systems

The application of computational mechanics to a physical situation involves three stages: modeling (translation of the situation into a mathematical model); analysis of that model; and interpretation of the results in terms of the original situation. While analysis is highly developed, modeling and interpretation depend largely on the analyst's needs, intuition, and experience.

A pertinent recent development from work on artificial intelligence is knowledge-based expert systems. These are computer programs capable of performing tasks currently performed by highly skilled experts. Such programs combine expert knowledge, acquired from practitioners, with general facilities for diagnosis and interpretation. A few prototype expert systems have been developed to assist structural analysts in modeling and model interpretation. The wide-scale extension of this approach, incorporating the expertise of practitioners, could provide very large benefits in the education and training of new users, as well as in assisting practitioners facing novel tasks in modeling or interpretation.

Improvements in Processes

A major developing area of opportunity is the intimate incorporation of computational mechanics into engineering processes. Some of these applications are discussed below.

Design Models

As noted above, in most design situations, including CAD/CAM, the computational mechanics model today is more an evaluation tool than a direct design tool. This is because a detailed computational mechanics model is extremely data-intensive. A great deal of information, such as geometry, physical properties, and environmental data, must be known to define the model, but the purpose of design is precisely to generate this information. Hence, a detailed model cannot be used until the artifact or system it represents has been essentially completely designed.

A developing area of extreme urgency and importance in all engineering design disciplines is the creation of realistic, approximate models usable in the early stages of design. Such models need to incorporate practical approximations of behavior in terms of key design or decision parameters under direct control of the designer. They must also be compatible with the more detailed models, so that results generated from the approximate models can be directly translated into and further evaluated with the aid of more detailed models.

Simulation of Manufacturing Processes

The full utilization of CAD/CAM requires the development of more effective computational mechanics procedures for simulating manufacturing processes. Today, even in CAD systems, a considerable burden is placed on the intuition of the engineer as to the feasibility of a manufacturing process, and little effort is made to optimize it in terms of cost, materials utilization, or process time. The simulation of manufacturing processes requires better understanding of the mechanics underlying processes such as casting, milling, forging, metal-forming, and extrusion of plastics, as well as the development of computational models for these processes.

Simulation of Failure Tests

In many fields, design criteria require the testing of products under extreme loads. Examples include crashworthiness of automobiles, strength of nuclear waste containers, behavior of nuclear reactors and components under extreme loads, and the survivability of military vehicles and installations under attack. The prediction of performance under such circumstances involves the simulation of complex, nonlinear mechanical phenomena, many of which are still poorly understood. Furthermore, the application of such simulations has been hampered by the comparatively high cost resulting from the large amounts of computer time required.

However, the decreasing cost of computer resources, coupled with the skyrocketing costs of physical testing, promise substantial benefits from simulation software. Highly nonlinear processes, such as impact tearing, cracking, and change of phase must be dealt with, and the development of appropriate computational methods is only beginning. The methods must be very efficient to be cost effective.

Computational simulation of failure testing offers significant payoffs. They include reduction in design time because of the elimination of much of the prototype construction required for testing, reductions in design cost, and the potential to develop more cost-effective designs.

Reevaluation of Design Criteria

The improved analytical capabilities afforded by computational mechanics, and the design criteria, specifications, and standards that define acceptable performance display an increasing mismatch. This mismatch is in two parts: in the definition of the performance characteristics to be evaluated, and in the acceptable numerical values for these characteristics. One example of the former is the American Society of Mechanical Engineers' Boiler Code, which is widely used for setting the performance of pressure vessels. This code deals with aggregate performance characteristics, such as bending moments and membrane forces, based largely on manual computations. A finite element model of a pressure vessel deals with much more detailed quantities, such as displacements and element stresses. A great deal of postprocessing is used to convert finite element results into "equivalent" gross characteristics to determine code compliance. The performance measures in such codes tend to be highly conservative.

Today, with a few iterations of computational analysis and resizing, essentially every component of a system can be brought up to the limiting performance measure. There is a real danger, therefore, that systems designed using computational mechanics will be less safe and reliable than earlier, manually designed systems. This danger may be further aggravated if the systems are optimized with respect to the same performance measures.

We face an increased need to reevaluate design criteria in many fields of engineering, design, and manufacturing. The goals are, first, to make design criteria more directly compatible with computational models and, second, to ensure that the intended level of safety and reliability is indeed properly specified.

Strength and Stability Evaluation

The well-known inverse problem in mechanics is to define the characteristics of a system from its observed response. Such responses can be observed through a variety of sensors and nondestructive testing and evaluation techniques. Computational mechanics models of the inverse problem are under development for quality control of manufacturing processes, performance monitoring of complex structures such as ships and offshore structures, and in-situ evaluation of the strength and stability of various structures.

Particularly important in this respect is the nation's deteriorating infrastructure, including roads, bridges, tunnels, railroad tracks, and water and sewer lines. Reliable and economically feasible computational mechanics methods for evaluating the strength, stability, and capacity of these lifelines could contribute greatly to their maintenance and improvement.

Improved Models

Virtually every area of application of computational mechanics needs improved models to advance understanding of increasingly complex problems. A sampling of these areas includes the following:

- Structures, Solids, and Materials: High-temperature structures, large space structures, inflatable membrane structures, tires, materials modeling, and fracture mechanics;
- Geology and Geotechnical Engineering: Resource recovery, rock mechanics, and tunneling;
- Fluid Mechanics: Transonic aerodynamics, plasma containment, lake and river hydraulics, and wave mechanics;
- Biomechanics: Bones, muscles, soft tissues, biological flows, and prosthetic and clinical devices; and
- Coupled Phenomena: Interaction of pumps and valves with fluids, interaction of wave forces with offshore structures, and interaction of controls and structures.

Robotics

Computational mechanics modeling in conjunction with complex robots is an emerging area that will be increasingly important in advancing productivity. Robots have evolved over the past decade from simple pick-and-place devices to programmable nonservo devices to programmable servo-controlled devices. A broad spectrum of sensory control and feedback mechanisms has also evolved. They range from simple force sensors to complex vision systems. As their capabilities grow, robots will be used increasingly in manufacturing, resource exploration, and other activities that are repetitious or involve hostile environments.

Robotics will affect computational mechanics both directly and indirectly. The direct impact will involve simulation and optimization of movements. A robot is a multiply articulated device. To plan and monitor its actions, it must continuously "know" its position, the loads acting on it, and other influences. In other words, the robot must continuously evaluate a computational mechanics model of itself. Therefore, a rapidly growing area of computational mechanics will be the development of behavioral representations and algorithms sufficiently compact to fit in the robot's control computer, yet fast enough to perform in real time.

Robotics will affect computational mechanics indirectly through the design and modeling of the systems and artifacts manufactured, operated, and maintained by robots. It is clear that such drastic change in production technology will effect an equally drastic change in the design and analytical modeling of the system being produced.

FUTURE OPPORTUNITIES IN DEVELOPMENT

The computational mechanics community can respond to the challenges of the developing applications outlined above only if it continues to avail itself of the most up-to-date concepts and tools from a variety of supporting areas.

New Development Methodologies

The development of computational mechanics models of physical phenomena could be readily enhanced, if not revolutionized, by means of development tools used or proposed in other areas of computing. Some of these opportunities are briefly described below.

Symbolic Computing

Until fairly recently, the computer has not been used in computational mechanics until the computational model has been completely derived. The derivation involves the use of mathematical symbols, not numbers; it has been a manual process and thus time-consuming and highly error-prone.

Symbolic computing, in which symbolic expressions are themselves manipulated through formal operations, has been used only on a few computational mechanics problems. With appropriate software aids, the symbolically derived expressions can be generated directly for conversion into machine language and execution. Wider use of the technique can eventually increase productivity in the derivation of computational models by the same order of magnitude as numerical computing has achieved in finding solutions.

Program Modules and Languages

The revolution in software engineering has barely touched the computational mechanics community. Technical and administrative tools developed for large software projects, such as structured program design, are used only in large software development projects aimed at developing large, complete commercial programs.* As a result, modular

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* Yourdan, E. and C. L. Constantine, Structured Design, Prentice-Hall, 1979.

building blocks for assembling custom programs for exploration or unique applications are not generally available. Utmost efficiency in execution is not required for such problems; what is sought is high efficiency in development. Very frequently, a new application differs from its predecessors only in few details: a new element model, or a new algorithm, or a new hardware/system environment. Yet, because of the lack of standard modules, the developer of a new application is forced to reinvent all, or at least a large part, of the standard capabilities.

A reliable collection of standard modular components for element generation, system assembly, solution algorithms, and the like would provide an enormous opportunity to increase both the breadth and depth of computational mechanics applications. It appears that the tools for developing such modules are available, and that high-level languages for composing programs from them can be adapted or developed. It therefore appears that institutional constraints within the computational mechanics community may be a major obstacle to the wide availability of standard modules.

Research and development in new programming languages is continuing and can significantly benefit computational mechanics. Among the developments with major potential impact are high-level languages capable of dealing with abstract objects, languages for specifying parallel computations, and languages designed to be used on a wide range of computers such as ADA, a standard language that the Department of Defense is asking its contractors to use.

Software Verification and Testing

The verification of a large computational mechanics software system is a major problem, involving both technical issues and organizational responsibilities. Even the generation of an adequate testing program for a major program is a monumental undertaking. These problems are not unique to computational mechanics; they pervade all aspects of computer use. In response, many approaches to software verification and testing have been developed and are being refined. The ultimate goal is correctness proving--the ability to make assertions about the performance of a program and use software to prove or disprove their correctness. This is an active area of reseach in computer science, presently dealing mostly with syntactic issues, but conceptually extensible to semantic issues.

Developers of large, commercial, computational mechanics programs use advanced software verification and testing tools. The same cannot be said, however, of the developers of the hundreds, if not thousands, of special-purpose programs. The opportunities offered by readily available, high-level verification and testing facilities would translate directly into higher levels of confidence, and permit analysts to concentrate more on modeling than on model debugging. Eventually, expanded correctness proving techniques could significantly raise the reliability, and thus the confidence level, of these programs.

New Implementation Opportunities

Computational mechanics programs run predominantly on medium-to-large serial computers, in a single-system environment. The major opportunities for implementing such programs in terms of hardware lie at the extremes of the current spectrum: extremely large parallel computers and personal computers. Complementing these opportunities are vastly increased networking capabilities and system facilities to make migration of software from one computer to another and partitioning of software into separate components or modules more feasible.

New Computer Architectures

Significant new developments are expected in extremely high throughput computers, using parallelism or vectoring. Extensive tests on vector and array processors have shown significant increases in processing efficiency for computational mechanics models. One of the most promising new architectures is the systolic approach, where data are pumped through arrays of simple processing units.*

Problems in computational mechanics, notably finite element models, have a structure well-suited to parallel processing. An ideal finite element parallel processor would consist of an array of processors capable of operating on elements, with the data flow between processors governed by the element interconnections. Machines of this class would permit the formulation and solution of computational mechanics problems one or two orders of magnitude more complex than currently feasible. This opportunity would open the way to numerous new applications.

Personal Computers

At the opposite end of the spectrum is a major trend toward personal computers, which ease the contention for resources typical of multiuser timesharing systems. Personal computers in the range of one MIPS (million instructions/second) to one MFLOPS (million floating point operations/second) are likely to be available within five to ten years. They will be capable of being tied together by local networks permitting access to shared resources, such as large files and high quality output devices.

The opportunities offered by such hardware are enormous. The expansions of the previous decade from batch to interactive processing

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* Kung, H.T., "Why Systolic Architectures," Research Report CMU-CS-81-14B, Dept. of Computer Science, Carnegie-Mellon University, Pittsburgh, PA (November 1981).

and from mainframe to minicomputers are only indicators of the explosion of new applications and approaches to be expected. As pointed out elsewhere in this report, personal computers suffer at present from lack of adequate software and unavailability of information about existing software, particularly for applications in computational mechanics.

Networking

Computer networking capabilities, both long-range and local, continue to expand significantly. With the cost of networking continuing to decrease, many new opportunities present themselves.

Inexpensive and ubiquitous long-range networking can have several significant effects. Issues of proprietary data can be significantly reduced if it is possible to send one's program to the location of the owner of proprietary data, have the processing done there, and receive only the processed, nonproprietary results. Similarly, many issues of one-of-a-kind proprietary programs can be alleviated by sending the data to the program and receiving the results. Local networking can provide similar opportunities by facilitating cooperative, interdisciplinary investigations and design projects among team members interacting through shared data bases.

Program Migration Tools

Networking notwithstanding, there will be a continuing need for migrating programs from one hardware/operating environment to another. The need will actually become more pronounced with the development of new hardware and computing environments. As a specific example, in a local network of personal computers backed by one or more powerful central processors, it will become increasingly attractive to develop demand-sensitive load-sharing systems. In the context of finite element applications, this may mean that interactive model building and evaluation of results would always be done locally on the personal computer. Global equation solving would be done on the central processor, but the intermediate steps (e.g., element generation and back substitution) could be done at either site, depending on the instantaneous load. However, it should not be necessary for the software developer to implement manually two versions of the respective program segments. With appropriate migration tools, one version could be automatically migrated to the second environment.

Concepts and techniques for facilitating the kind of program migration necessary are beginning to emerge. The most promising of these is the existence of many portable operating systems such as UNIX. Although many problems remain to be solved, it seems clear that if it is possible to provide portability for programs as complex as complete operating systems, it should be possible to develop similar capabilities for a class of applications such as those in computational mechanics. While full portability, requiring only a recompilation for a new environment, remains an elusive ultimate goal, migration costs can be significantly decreased by proper design of language and of advanced software that isolates machine- or system-dependent functions into easily identifiable and replaceable modules.

CONCLUSIONS

The developing areas and future opportunities outlined in this chapter illustrate the breadth of computational mechanics and the discipline's central role in many issues in modern engineering and science. In addition, the committee reached the following broad conclusions:

1. The vitality of computational mechanics depends on a continuing flow of concepts and tools among the discipline itself, its areas of application, and its supporting disciplines. The necessary flow can be sustained by means that include computational mechanics centers and public and private technology transfer mechanisms.
2. A serious and growing gap exists between CAD/CAM methods--relying only on geometric design--and computational mechanics modeling for physical and functional design. Every effort should be made to eliminate this gap. We need computational models and interfaces compatible with CAD/CAM design methodologies. More importantly, manufacturers and their clients must be made aware of the crucial importance of integrating physical and functional design, using computational mechanics models, in all designs employing CAD/CAM.

Appendix A

CASE STUDIES: USES OF COMPUTATIONAL MECHANICS

Cyclic Elastic-Plastic-Creep Analysis of a Thin-Walled Elbow

As part of the high temperature design program supported by the Department of Energy (DOE) for development of the liquid metal fast breeder reactor (LMFBR), a series of full-scale elevated temperature tests on thin-walled stainless steel elbows has been performed. One such test was a displacement controlled cyclic bending (in-plane) test with a constant internal pressure. The maximum bending displacement was held for one week (168 hours) during each cycle. The objective was to determine (a) whether such conditions would induce thermal creep ratcheting of the elbow, and (b) the extent to which current analysis methods are able to predict the elbow's behavior.

A thin shell finite element model was developed which had 140 doubly-curved, four-node, isoparametric elements. There was a total of 186 nodes and 2220 degrees of freedom. The finite element mesh was established after an initial convergence study. The finite element program was able to provide current elastic-plastic-creep constitutive behavior according to the Oak Ridge National Laboratory (ORNL) recommendations. The analysis simulated actual test conditions of temperature, imposed end rotation of the elbow, internal pressure, and creep hold time. Such a costly analysis is clearly not a production design procedure, but the expense is justified by the scarcity of valid comparisons between analysis and test for elevated temperature, time-dependent behavior of nuclear components.

Observations

While the evaluation of the analysis is not yet complete, it is possible to make some initial observations. First, it is possible to obtain a generally accurate estimate of complex nonlinear response of shell components at elevated temperature. The expense of such an estimate can be justified for a highly critical component. Second, the major limitation to the value of such an analysis is the state of knowledge of the material's constitutive behavior, especially with respect to creep. The inhomogeneities in as-manufactured components preclude casual acceptance of the detailed stress and strain results from the analysis. Prediction of ratcheting strains is difficult, and perhaps the best that can be obtained (even from detailed analysis) is a conservative estimate. Nevertheless, major aspects of the component's performance, such as overall deformation response, can be satisfactorily predicted. Third, for large-scale nonlinear analysis, the ability to postprocess the large volume of output data is crucially important. While key areas (e.g., the crown of an elbow) can be monitored directly, the majority of the output must be selected, tabulated, and plotted by an automatic postprocessor, or the value of the analysis may be largely lost.

Trends

While it seems to be generally accepted that detailed inelastic analysis must be the exception rather than the rule, its availability is vital to high technology design. Knowledge of constitutive behavior of materials will continue to present a formidable challenge and limit the applicability of analysis tools. Developments that will broaden the applicability are: (1) the advent of supercomputers (e.g., the CRAY); and (2) the creation of postprocessors that give the analyst the broadest possible capability for automatically extracting and reducing the results generated.

Analysis of a Beltline Flaw in a Reactor Vessel

To remove the significant conservatism inherent in two-dimensional, linear elastic fracture mechanics (LEFM) evaluations of flaws in weldments in pressurized water reactor (PWR) vessels, a three-dimensional elastic-plastic analysis was conducted by a large manufacturing company. Because of the anticipated expense, the analysis was approached carefully, with extensive two-dimensional analysis used to define the size of the pressure vessel sector (90°) needed, the number of elements through the wall thickness, the degree of mesh refinement, and other factors.

The finite element model consisted of more than 550 20-node isoparametric elements and almost 3,000 nodal points, resulting in about 8300 degrees of freedom. Special provisions were made to use the singularities of both elastic and elastic-plastic stress and strain fields. Because of the expense, incremental plasticity was eschewed in favor of deformation-theory plasticity. The findings demonstrated clearly that two-dimensional approximations of three-dimensional flaws seriously overestimate the severity of flaws in pressure vessels. The deviation from two-dimensional behavior is due primarily to redistribution of load in the wall of the vessel when the material around the flaw begins to deform plastically, and to the reduced bending permitted by the restraint of the rest of the vessel.

Observations

State-of-the-art software has long been available to solve this class of problems. Even for this one-of-a-kind analysis, the expense was the controlling factor to the extent that a plasticity theory of dubious value was used in lieu of the incremental theory. The analyst would normally have run the analysis on a minicomputer, but, because of size limitations, was forced into a service bureau, which compounded budget problems.

Trends

This particular laboratory has opted to use minicomputers, as have many others, with occasional connection to a large mainframe for difficult number crunching. This strategy has the effect of making one-dimensional and two-dimensional analyses even more attractive than three-dimensional analyses. Three-dimensional nonlinear analysis is, and will continue to be, a one-of-a-kind proposition. Because of uncertainties in nonlinear behavior, such analyses are rarely useful unless parameter studies are included.

Simplification of a Major System Model For Use in Subsystem Analysis

The task was to prepare a simple three-dimensional finite element model of a nuclear reactor system specifically for use in seismic analysis of the attached piping systems. Preexisting comprehensive (detailed) models of the reactor system (for separate horizontal and vertical earthquake motions) were simplified directly instead of creating a totally new simple model. A new simple model would have required dynamic tuning to yield the desired fundamental frequencies and displacements at piping attachment points at the expense of other similitude parameters. Selection of node coordinates was based on piping systems interfaces, plus enough supplemental nodes to generate a set of smooth reactor system mode shapes.

The mass distributions in the comprehensive models were simplified by summing entries in each row (or column) of the reduced dynamic matrixes and redistributing these "lump masses" among the nodes defining the simple model. Both local and global centers of mass were maintained, and the fluid coolant mass was separately distributed for horizontal and vertical degrees of freedom. The beam stiffness distributions in the comprehensive models were simplified by reducing them to single beam elements of equivalent stiffness between simple model nodes. Local stiffnesses (support structures) in the form of general matrix elements were transplanted directly without modification. Equivalent beam stiffnesses were calculated for both shear and moment end loading, providing guidelines for any necessary tuning of the simple model responses.

The finished simple model consisted of 13 nodes with 10 horizontal or vertical dynamic degrees of freedom (DDOF), as compared to about 340 nodes and 130 DDOF in the comprehensive model. The simple model exhibited conservative similitude of the required parameters ranging from +1 percent to +4 percent. Less important higher mode responses also showed very good similitude, as expected.

Observations

Because of the cost and complexity of the detailed three-dimensional finite element models in dynamic analysis, a simplified model of the system was developed from the existing comprehensive models which preserved the dynamic similitude and provided an efficient basis for follow-up analysis. Little fine tuning was needed because of the consistent and systematic approach to the task, and few hand calculations were involved in the process. Also, a generally accurate simple model readily lends itself to inexpensive general parameter studies, offering a potentially great return on the time invested in preparing the "general" simple model. Such studies may not be possible with a "specific" simple model.

Trends

This particular example reflects the sophistication and simplicity that in many cases go hand-in-hand in complex system analysis. The strategy is to integrate detailed comprehensive models with consistent simplified models and to use either, depending on the nature of the specific problem and/or requirements. In a general sense, each option has its strengths and weaknesses, and the most attractive option is the most efficient one, which in many ways is problem-dependent.

University Access to Finite Element Analysis Software

Future practitioners in computational mechanics usually receive their first exposure to finite element analysis models in university courses or individual student projects. It has long been recognized that the most popular commercial finite element codes demand far greater computer resources than a university computing center can devote to one course or even a cluster of courses. Universities, therefore, have three options:

1. Develop and make available to students locally built codes. This option is frequently a drain or diversion of faculty time and university resources. In addition, these codes tend to be unrepresentative of state-of-the-art practice.
2. Use commercial codes by access through a network. While this approach, on the surface, is the most logical, it is seldom used in practice because of accounting complications at many universities.

3. Install a miniversion of one of the commercial codes, made available at a very nominal fee by several vendors (e.g., NASTRAN, ANSYS).

The third option appears to be optimal. It gives faculty and students up-to-date tools tailored to reasonable resources at small internal cost.

A university chose the third option. The minisystem was adequate for a graduate course on finite element modeling. Several graduate students, however, embarked on projects and theses predicated on the use of the miniversion. The first student successfully implemented a static model of his project, but the dynamic model exceeded the capacity of the code, and his project had to be drastically revised. Other students had similar problems.

Observations

The availability of miniversions of commercial codes was hailed by many as an excellent mechanism for giving students access to the codes, with a demand on computer resources commensurate with university resources. Unfortunately, the rigid capacity limitations incorporated in these "packages" are a source of frustration to faculty and students alike.

Trends

This university attempted to choose the apparent best route to providing education and training to its students, but was frustrated by implementation details. It is to be expected that newer versions of codes designed for minicomputers will also provide better service for the education of future practitioners.

Piping Analysis

In the design of nuclear power plant piping systems, numerous analytical techniques are commonly available. Because of the costs of nonlinear inelastic analysis methods, most iterative design procedures are performed using linear elastic finite element analyses. For example, an LMFBR piping system must be designed to withstand seismic events. The response spectrum method, a relatively inexpensive, conservative technique, was used to analyze an LMFBR piping-loop response due to earthquake loading. Sensitivity analyses were conducted to obtain an understanding of the piping system's response. However, numerous design iterations were still required to reduce the piping stresses, interface loads, and restraint loads below the allowable limits.

Observations

Detailed, nonlinear inelastic finite element techniques are well-established and readily available in numerous computer programs. The costs associated with these methods prevent their general use in iterative design procedures. Most design analysis, therefore, is performed using linear elastic finite element techniques.

While sensitivity analyses provided some insight on the dynamic response of the piping loop, they did not substantially reduce the analytical effort required to solve the design problem. The need exists for greater computer/user interaction in the form of interactive computing and computer graphics. By graphically displaying results from an analysis, greater insight can be gained than from sensitivity analyses.

Trends

The use of linear elastic finite element methods has been, and will continue to be, the techniques most used in iterative design. Improving the user/computer interface is very important for analytical design. More effort is being devoted to developing computer graphics capability and interactive computation facilities for use in structural design.

Dynamic Analysis of a Transport Cask

A design/manufacturing company was attempting to license a high-level nuclear waste transport package, using three-dimensional nonlinear dynamic analysis to demonstrate compliance with federal regulations. A finite element code developed at a DOE national laboratory was obtained and converted from a high-order computing environment (Control Data Corporation and Cray) to a low-order computing environment (Univac). Since the code was anticipated to have long-term value, the overhead costs for converting the package were acceptable.

The code was exercised in an iterative design mode, since the individual analysis costs were reduced to about $2,000 per run (20 to 30 msec of structural response) by the in-house computer and the optimized programming structure. Three analysis models of successively increasing complexity were created and analyzed. Low-order, three-dimensional isoparametric finite elements were used in the models, together with a finite strain formulation and an elastic-plastic strain-hardening flow theory. The code used explicit time integration, had sliding interface logic, and was able to accommodate a variety of modeling tricks to treat bolting, closure surfaces, shear keys, crushable foam, and other design features. The first model had 1,815 nodal points and 1,122 elements; the final model had 3,134 nodal points and 1,980 elements.

Observations

This company made a commitment to provide the internal support to acquire state-of-the-art software and implement it in a nearly optimal fashion on an in-house Univac 1182. Such a commitment is sizable, and current trends are counter to this approach. The company had on its staff one or two professionals qualified to maintain, and even upgrade, the sophisticated software obtained. Most companies do not have the luxury of such highly qualified staff and are more dependent on software suppliers and service bureaus. These professionals were holdovers from an era when the company developed much of its own software. It is doubtful that they would or could be hired in today's marketplace.

Trends

This application represents the world as it used to be, and virtually every decision made by the company and its staff is contrary to national trends. The acquisition and retention of sophisticated computational mechanics professionals at design/manufacturing concerns is going to be difficult, if not impossible, in the face of competition from a burgeoning software services industry. Such decisions on computational strategy are almost never made these days; the trend is toward in-house microcomputers and minicomputers, with occasional forays to commercial, large-scale computing services.

Analysis of a Shell Intersection

A nuclear power plant was found to have a design deficiency--a thermal loading occurred that had not been anticipated during the design. The loading affected a series of thin shell-shell intersections that were not designed for it. Hard calculations suggested that resulting stresses at these intersections exceeded allowable values, although not by very much. An effort was initiated, therefore, to do detailed finite element analysis of the problem. Two groups attempted this job. Analysis budgets and available software were marginal for this effort, with the consequence that the analyses provided results of questionable value. These results suggested that the stresses during normal plant operation exceeded allowables, and the plant was derated for a lengthy period--a costly fix. Later reanalysis, performed with more careful management and better software, indicated that the stresses were not as high as had previously been calculated. This reanalysis included demonstration that the previous results were inaccurate.

Observations

The original analyses were poorly managed--budgets were too small, software was inadequate, and much effort and computer time were wasted on unnecessary modeling. In the end, a model was used not because it had been demonstrated to be accurate, but because the time and patience available had been exhausted in creating it. The reanalysis consumed less elapsed time and money than the original effort, because better software was available and the job was carefully managed. This effort also had to demonstrate that its results were accurate--which currently can only be done by regular refinement studies. It should also be noted that the effort involved in such analyses is substantial, and errors tend to propagate.

Trends

Generally available software for such jobs has improved substantially over the past 10 years or so. Analysis management is not a widely available or well-understood skill, but is critical in such efforts. Analysts too often interpret management pressure as a requirement to "give us some numbers" without measures of their accuracy. This very serious problem can only be addressed by education and training of analysts and managers.

Advanced Analysis at a Large Oil Company

Petroleum production requires more advanced design concepts as the drilling environment becomes more hostile (deeper water and harsher climate, for example). The capital investment in production facilities is extremely large, while difficult environments increase the risk of failure. Complex analyses, often at the state of the art with respect to modeling, are constantly required. Personnel involved in these projects tend to be highly trained (typically having advanced degrees and some years experience), and substantial computational and experimental resources are available.

The company in question acquires most of its numerical engineering software from outside contractors. Experience has suggested that too much time is required to bring in-house software to the point where it is solving problems. Outside contractors usually provide faster response because they specialize in the combination of engineering and programming that is required. However, these contractors are predominantly small companies. Problems have arisen with software being delivered that does not work, and support not being available from the supplier. In spite of these occasional difficulties, the approach seems effective. It has been important to the growth of several of the small contractors who provide software to this client.

Design and Analysis of Bolted Lattice Structures

Overhead electrical transmission structures are configured in a variety of ways. One common configuration is a four-legged lattice tower of bolted angle construction. Variations to the lattice concept include a number of guyed configurations which, in some cases, yield very compliant structural systems. Current design practices for lattice overhead transmission structures are substantially behind the state of the art. Analysis is limited to elastic response with no allowance for geometric or material nonlinearities, and the analysis programs commonly used are first-generation finite element programs such as STRAN or STRESS. The potential economic impact of improved design and analysis methods is considered very significant for electric utilities; therefore, it was deemed necessary to develop an analytical package oriented specifically to this industry.

The advent of microcomputers and the development of improved computer graphics animation schemes suggested that the expedient way to upgrade analysis was a software package that would permit the novice analyst or designer to interact with sophisticated third- or fourth-generation structural packages through a user-friendly work station. This work station would utilize the microprocessor technology for preprocessing, data checking, and postprocessing of transmission tower designs. Heavy emphasis would be placed on computer graphics. A data inquiry system utilizing menu and "help" features was also a fundamental concept. The microcomputer would have a data-base system that would permit straightforward expansion as the system was extended into computer-aided design and manufacturing areas in the future. Furthermore, it is anticipated that within five years, the microprocessor technology will be capable of direct solution of the finite element problem. The work station would then be a stand-alone, self-contained design and analysis system.

Observations

The primitive technology that is being applied to the design of overhead transmission structures presents a unique opportunity to leapfrog the technology that has been evolving in the past 10 years in computational mechanics. The concept of the work station is definitely state of the art, and the notion that it can be a fundamental tool for the designer and analyst is consistent with modern approaches of computer service bureaus. The low cost of a microcomputer permits the economical development of a front-end processor that can interface with service bureaus or other mainframe computers and thereby present the most sophisticated computational methods to the analyst or designer in a format that is both comprehensible and familiar.

The work station will free the analyst from language interfaces, both at the micro-to-mainframe connection and with the specific finite element program being used. Neither computer companies nor software developers seem the least bit inclined to standardize on formatting. Each operating system differs from every other operating system. Service bureaus with the same computers have variations that confound and frustrate designers. Software packages have individual idiosyncracies in the way data has to be entered. This situation has led to the creation of an army of highly educated, but totally frustrated, structural analysts who spend 80 to 90 percent of their time dealing with trivial data that are necessary to define the problem. Experience has shown that analysts can become so frustrated with the detail required to perform a meaningful structural analysis that they will find other work of a less demeaning nature. The computer must be converted into a friendly "slave" rather than a demanding one. The work station approach, which utilizes one language and is preprogrammed to provide job-stream to a variety of different service bureaus and different computer codes, is being developed.

Appendix B

COMPUTATIONAL MECHANICS FOR WEAPONS SYSTEMS ANALYSIS

Computational mechanics plays a predominant role in weapons systems development. Requirements in computational mechanics for the design and analysis of weapons systems cover most aspects of the field. These requirements include theoretical research; development of algorithms, computer codes, and computer hardware; and usage and dissemination of codes by a variety of users.

The development of modern military systems capable of surviving nuclear attack must contend with the reality that they are largely untestable in their design environments. (This is also probably true for military systems subject to conventional attack, because of economic and practical engineering restraints on testing.) The degree of dependence on analytical methods for the design and qualification of such systems, therefore, is unprecedented. This dependence translates into significantly increased demands on computational mechanics to study advanced structural and mechanical concepts and the behavior of complex materials subject to extreme dynamic loads.

In view of the use of increasingly complex materials and structural/mechanical concepts, coupled with increasingly hostile environments, a great deal of both basic research and algorithm development will be required. In some cases, mathematically sound theories are already available for development of computational algorithms. In other cases, well-defined, mathematically sound theories will require formulation (after completion of considerable basic research) before reliable computational methods can be developed. The topics of interest in which computational mechanics plays a predominant role and major research effort and algorithm development will be required include:

- Physics of Nuclear Explosions
  - Atmospheric Phenomena
  - Cratering and Ground Shock Phenomena
  - Multiple Burst Phenomena
  - Cavitation and Cavitation Shock

- Behavior of Materials at High Overpressures, Strain Rates, and Temperature Gradients
- Crack Formation and Growth Under High Intensity Dynamic Loading--High and Low Cycle Fatigue
- Block Motions in Large Rock Masses
- Structure-Medium Interactions
- Instability, Inelastic Buckling and Postbuckling Behavior of Structures

These seven problem areas represent only a fraction of those that are of direct interest and importance in weapons systems development. Nevertheless, a brief discussion of each will serve to illustrate the primary role of computational mechanics in this general area.

Physics of Nuclear Explosions

Atmospheric Phenomena

Atmospheric phenomena involved in nuclear explosions include air overpressure, dust and debris distribution, thermal effects, and radiation effects for both ideal and nonideal media. Computational mechanics must play the major role in providing analytical estimates of such phenomena because testing with aboveground nuclear explosions is banned by treaty.

To illustrate the complexity of the problem, let us consider the determination of the air overpressure in the very high pressure region of a nuclear height-of-burst explosion in the light of the current interest in ultrahard silos as a possible basing mode for the MX and/or Midgetman missiles. The conceptual development and subsequent design of ultrahard silos require the evaluation of the free field environment at extremely high overpressures and for large thermonuclear bursts. It is important to note that no experimental data exist for air overpressues above 1000 psi. Consequently, computational mechanics must be used to obtain information on overpressures one to two orders of magnitude larger than the highest measurements in the existing empirical data base.

The air overpressure from height-of-burst nuclear explosions has generally been computed in the past using existing two- and three-dimensional computer codes. These free field pressures versus time histories are characterized by sharp shocks with extremely fast decays; hence, special computational methods are required to achieve the required accuracy of solution. Such computations, especially when radiation transport is included, tax the capacity of even our largest computers (CRAY-1). They also may require special nondiffusive numerical techniques in order to calculate the proper sharp rise and decay in the shock waves produced by the explosion. Work on the development of such nondiffusive algorithms has been pursued at the Naval Research Laboratory.

The development of antiballistic missile (ABM) systems that will protect future silos, or our existing Minuteman installations, also requires the calculation of dust and debris distributions from thermonuclear explosions. The requirements for radar performance for such systems entail a configuration that is inherently dependent on dust distribution and debris impact for both performance and survival. The calculation of dust/debris fields for this purpose is currently not satisfactory and will also require the aforementioned advanced computers for more acceptable solutions.

Cratering Phenomena and Ground Shock

Assessing the impact of a surface or near surface thermonuclear explosion on ultrahard silos at or near the edge of a crater leads to a series of extremely important problems that can only be solved through computational mechanics. These problems include the calculation of the volume and shape of the crater for a variety of complex geological sites, the determination of the debris distribution from the crater, and the determination of the direct induced ground shock that progresses from the crater region through the medium and loads the silo. Such direct induced ground motions determine the design of the lateral components of the shock-isolation system in the silo.

An equally important requirement is the calculation of the debris distribution from surface or near surface nuclear explosions, since up to 20 feet of debris may have to be moved before the silo closure can be opened and the missile launched. The practical solution of such problems may well require a new generation of computers, and it is fairly evident that these new computers will be needed in the near future.

Because of the test ban treaty, the data base on cratering by atmospheric nuclear explosions consists essentially of the results of pretreaty experiments at the Pacific testing sites (water/wet coral geology). Thus, the investigation of cratering phenomena in geologies in which protective structures are more likely to be situated is an urgent major problem that can only be solved computationally. To solve cratering problems involving sites with multiple layers of diverse geological materials, improved computational mechanics methods as well as larger, faster, and more efficient computers are certainly required.

Multiple Burst Phenomena

Modern nuclear attack scenarios consider cases in which structures must withstand the loadings from a series of arbitrarily phased and located multiple bursts.

In view of the problems associated with multiple bursts, such as bursts within bursts, fireball interactions, and ground shock focusing, it is readily seen that computational mechanics plays a prominent role in this branch of physics. The determination of multiburst effects in the nonlinear regime is of urgent importance. It should be noted that the major problems in this field require a computational capability that severely taxes our present and even near future machines.

Cavitation and Cavitation Shock

With increasing emphasis on the role of naval power in national defense, problems involving the effect of underwater shock on surface ships are becoming increasingly important. Such problems often require a detailed finite element analysis of a ship lying in a cavitating fluid. Phenomena such as the formation of a cavitation region, cavitation shock from the collapsing cavitation region, and ship slamming present highly nonlinear structure-medium interacton problems that must be solved numerically. Computer codes have been developed and successfully used for such analyses. It is obvious, however, that these problems are barely accommodated by our largest computers, such as the CRAY-1, and that a new generation of computers will be required to give the detail required for the efficient use of such codes for both analysis and design. This conclusion is particularly true if the ship's structure is loaded by both combined air overpressure/thermal shock and underwater shock. The efficient solution of problems involving the dynamic response of ship structures to such combined loadings again will require major computational efforts.

Behavior of Materials at High Overpressures, Strain Rates, and Temperature Gradients

In terms of weapons effects, protective structures such as hardened missile silos and command and control centers are becoming subject to increasingly hostile environments. To survive, they must be designed well into the inelastic range. Hence, an understanding of the inelastic behavior of the structural materials, such as steel, reinforced concrete, aluminum, glass, and reinforced plastics, under high overpressures, strain rates, and temperatures is urgently required. This requirement calls for both an experimental and a computational iterative research effort in which the computations are used both to design the experiments and predict the materials' behavior. The algorithms here are the models of materials, which must first be postulated, then fitted to whatever experimental data can be obtained from tests, and finally extrapolated to the extremely hostile environments resulting from nuclear explosions. Computational mechanics plays a major role in all phases of this work. In fact, it must be noted that the behavior of materials can be extrapolated to thermonuclear explosion effects only in two ways: (a) testing the material in extremely costly underground tests and (b) by use of computational mechanics.

In addition, structural problems involving both low and high cycle fatigue are becoming of increasing interest, particularly in naval applications, such as those involving submarines. Again, computational mechanics plays a major role in their solution.

Crack Formation and Growth Under High Intensity Dynamic Loading--High and Low Cycle Fatigue

In recent years, great progress has been made in the analysis of crack formation and growth in materials assumed to behave elastically. While considerable work has been done in inelastic fracture mechanics, it is obvious that this field is still essentially in its infancy in terms of the requirements associated with the high intensity loadings and strain rates induced by nuclear weapons. Crack formation and growth under static and dynamic loadings in materials such as steel, titanium, reinforced concrete, and rock are perceived to be of increasing importance. These areas are intimately connected with the problems in behavior of materials discussed in the previous paragraph. For structures such as submarines that operate at great depth, the problem of crack formation in welded joints as a result of fatigue and the subsequent behavior of such structures under attack loadings must be of great concern. While much research on such problems is being done, the solution of them for complex structures may well require new developments in both computational mechanics and computers.

Block Motions in Large Rock Masses

Current concepts for the deep basing of command and control centers locate them within large rock masses. The response of the rock to dynamic loadings from nuclear bursts often involves the motion of large blocks of rock along fault lines and planes of weakness. The evaluation of such motions at structure-medium interfaces is a major computational mechanics problem. It requires fundamental research on behavior of materials, motion of rock along fault lines and lines of weakness in the rock, and structure-medium interaction phenomena including slip and debonding. While such problems are currently being solved approximately in our large computers, such as the CRAY-1, the efficient, detailed solution of problems of this type will also require a new generation of faster and larger computers.

Structure-Medium Interactions

In weapons effects technology, the analysis of structure-medium interactions such as slip, sliding friction, bonding/debonding, and contact/impact are of increasing importance. The entire range of problems in structure-air, structure-fluid, structure-rock, and structure-soil interactions associated with the highly transient dynamic loading/unloading phenomena produced by nuclear explosions depend for solution on computational mechanics.

In recent years, major strides have been made in the solution of structure-medium interaction problems by two computational mechanics approaches: a) the development of three-dimensional code capabilities for use on large machines such as the CRAY-1; and b) the use of interactive boundary techniques. Interactive boundary techniques effectively allow the decoupling of the structure and the surrounding medium by use of an interactive boundary algorithm by means of which the free field excitations caused by the nuclear burst can be applied to the structure. A more detailed discussion of these computational mechanics approaches is presented in "General Comments."

Instability, Inelastic Buckling and Postbuckling Behavior of Structures

The high pressures and temperatures to which protective structures are subjected under various attack scenarios, coupled with the requirements of structural survivability associated with multiple burst attacks, create conditions that effectively preclude the practical design of structures that stay elastic. The design of structures to withstand large deflections in the inelastic range requires the ability to analyze the inelastic buckling and postbuckling behavior of these structures under both the initial and subsequent multiple loadings. This type of behavior is currently predicted by computer codes for axisymmetrical and even fully three-dimensional problems. Still, the efficiency of utilization of such codes for the latter case would be greatly enhanced if larger and faster machines were available. The solution of large, fully three-dimensional, dynamic structure-medium interaction problems (three-dimensional both with respect to the structural configuration and the dynamic loadings from nuclear explosions) in the large deflection inelastic range stretches our current computer capability to its utmost. Again, computational mechanics is the only means of solving these extremely complex problems.

General Comments

In addition to basic theoretical work and its translation into computational algorithms, certain questions concerning code development and optimization are of major importance in the application of computational mechanics to weapons systems.

Three-Dimensional Analysis

A definite trend toward the solution of problems requiring full three-dimensional analysis seems to be accelerating in the weapons effects area. Such analyses, to be efficient and meaningful, will require both optimized software and large, fast computers. At the Defense Nuclear Agency/SPSS Workshop on Hardware and Software Trends in Computational Mechanics (September 15, 1981), this trend toward three-dimensional simulations was discussed at some length. Because of increasingly complex defense systems and the requirements of optimized design for both weapons systems and their shelters, it was concluded that three-dimensional analysis will be of greatly increasing importance in the coming years in the various fields associated with weapons systems development and utilization. Thus, improvement in such computational capability, through both hardware and software developments, is urgently needed.

As one example, consideration of multimaterial interaction problems has led to the development of theoretical techniques and software of several different types. In recent years, optimized computational interactive boundary techniques have been developed for use in inelastic structure-fluid (submarines and ships) and structure-soil/rock (silos) problems. These interactive boundary solutions generally require the solution of two problems: (1) a free field problem that produces inputs that are applied to (2) a suitable interactive boundary that surrounds a very detailed model of the structure to be analyzed. This approach allows a considerably more detailed analysis of the structure than did the soil island approach that preceded it.

Code Development

When code development itself is considered, several different approaches become apparent. First, a special purpose code can be developed and optimized for solving a special class of problems. A second approach involves the development of general purpose codes aimed at solving a much wider class of problems. A computational price (often considerable) is usually paid for the generality of the code. Finally, partitioned analyses--procedures for solving coupled-field problems by coupling single-field analyzers--have been utilized. This approach encourages the use of existing software rather than new code development. In view of the range of problems that must be solved, each of these three approaches will probably have its areas of application.

Ideas concerning integrated software--a collection of architectural utilities and independently executable processors (not subroutines) for interactive computing and processing--are also being developed. Efforts to systematize techniques such as decentralized code development, standardized data management, and friendly interfaces for both users and other software will require considerable work in the future.

Hardware Development

The problems involving hardware development are of great importance and complexity. The current market trend is toward many, relatively inexpensive, on-site mega- and minicomputers, as contrasted to a few multimillion dollar, remote-site supercomputers. A potential problem is that hardware companies that would normally expend major resources to develop such supercomputers (and the need for them in computational mechanics is generally acknowledged by the engineering community) may be very reluctant to embark on such ventures if they are likely to sell only very few pieces of hardware. If total funding for computer hardware is essentially fixed, the trend toward mega- and minicomputers may indeed pose a threat to the proper (and required) development of supercomputers. Special efforts, perhaps including federally funded development of advanced supercomputers, may be necessary.

This conclusion is highlighted by the recent decision of the Japanese government to make large grants to major Japanese hardware companies for the development of supercomputers. If such development is perceived as a major national goal by the Japanese, it should also be carefully studied by the United States. The requirement for advanced supercomputers must be stated, funded, and pursued as a national goal if the United States is to maintain its lead in computer development and manufacturing.

Technology Transfer

Another major problem that must be faced is the development of more efficient transfer of technology to Department of Defense contractors. At present, there is often a multiyear lag between the development of technology and its actual use in the design of weapons systems components. As new theories and methodologies are developed, some way to eliminate this time lag and make the information rapidly available to both contractors and the Department of Defense laboratories is urgently needed. One possibility might be the establishment of a group of national computational centers, each staffed by a consortium of universities. Such centers would gather software produced by universities, the government, and private industry, screen this software, and amend it as required so that it could almost immediately be made available in an efficient manner. Waste occurs even now because of inefficiencies associated with the use of bad software and reinvention of software that should be (but is not) readily available. Much more efficient technology transfer is required in the near future.

Summary

It is evident that computational mechanics plays a prominent role in the solution of practical problems related to the design, disposition, and protection of weapons systems. The urgent problems related to the development of advanced computer technology, technology transfer, and analysis/design integration will have to be solved in a timely manner if the United States is to maintain a predominant role in this area.

Appendix C

COMPUTER-AIDED DESIGN AND MANUFACTURING: INTEGRATION WITH COMPUTATIONAL MECHANICS

Declining manufacturing productivity in the United States over the past decade has resulted in a new focus on ways to engineer better products at lower cost. The application of computing to design, analysis, and manufacturing has been called computer-integrated manufacturing (CIM), and the design and analysis portion of CIM is frequently called computer-aided engineering (CAE). Computer-aided design and manufacturing (CAD/CAM) for design and geometry creation have become significant elements in attacking the engineering productivity challenge.

CAD/CAM systems have enjoyed a compounded annual growth rate of about 50 percent from 1975 through 1981. By the end of 1981, some 6,500 systems and 22,400 graphics work stations running CAD/CAM applications were installed worldwide (Table 1).

TABLE 1 Current Estimated Installed CAD/CAM Systems and Projections for Year-end 1985 and 1990, by Application

Type	1981		1985		1990	
	Systems	Work Stations	Systems	Work Stations	Systems	Work Stations
Mechanical	2,850	10,400	13,600	50,000	25,000	92,000
Electrical	2,400	7,700	9,300	25,000	16,000	42,000
Architectural and Engineering	750	3,200	3,200	12,000	5,500	20,000
Other	500	1,100	900	5,000	1,500	8,000
Total	6,500	22,400	27,000	92,000	48,000	162,000

SOURCE: International Technology Marketing, May 1982

Gross sales of CAD/CAM systems reached $800 million in 1981, $1.3 billion in 1982, and over $2 billion in 1983 (Table 2). Sales are projected at $4 billion in 1985 and close to $10 billion by 1990.

TABLE 2 Gross Sales of CAD/CAM Systems

	1981	1985	1990
Gross sales	$800 million	$4.0 billion	$9.95 billion
Compound growth rate	50%(1975-1981)	35%	20%

SOURCE: International Technology Marketing, May 1982

The compounded growth rates for the CAD/CAM industry are expected to drop to 35 percent by 1985 and to 20 percent by 1990 as sales increase and a larger number of firms and engineers have access to these systems. Despite the growth in sales, however, penetration of industry by CAD/CAM will remain quite low. Specific penetration studies are not available, but the committee's subjective estimates are shown in Table 3.

TABLE 3 CAD/CAM Penetration Estimates by Industry

Industry Type/Penetration	High	Medium	Low
Aerospace (prime)	X		
Automotive		X	
Electrical (electronic)	X		
Heavy equipment			X
Farm implement			X
Machine tool		X	
Architectural/engineering/ construction(AEC)		X	
Power plant construction		X	
Petroleum exploration	X		

CAD/CAM systems have evolved mostly as stand-alone, turnkey entities with very little tight linkage to computational mechanics systems, although some firms have developed their own integrated systems (McDonnell Douglas in aerospace and IBM in electronics, for example). Recently, we have seen a focus on building bridges between CAD/CAM systems and computational mechanics systems.

The needs for improvements in these communications links are significant and are the subject of the balance of this appendix.

A Neutral Data Base

The Interim Graphics Exchange Standard (IGES), maintained by the National Bureau of Standards, represents a beginning of a generalized, noncustom information transfer mechanism, which has been frequently referred to as a neutral data base.

A high-priority need is an extended version of IGES.* The characteristics of a neutral data base are the ability to handle the translation and transmission of a broad range of geometries and administrative data between elements of the CAD/CAM/computational mechanics process. Some of the critical requirements are the ability to handle more complex geometries, such as surfaces and solids; the ability to maintain associativity between various elements of a complex geometric entity; and the ability to carry geometry in binary form for compactness and efficiency of transmission.

The major barrier to the development of a neutral data base is the lack of a sponsor and development money. Much progress can be made without new research, but solving all of the problems does require some basic research to develop effective geometry standards on which such a system would be based. Potential sponsors in the private sector include the National Computer Graphics Association (NCGA) and ACM Special Interest Group on Graphics (SIG-GRAPH). Potential sponsors in the public sector include the Air Force, sponsor of the Integrated Computer-Aided Manufacturing (ICAM) program, and NASA, sponsor of the Integrated Program for Aerospace Vehicle Design (IPAD).

Any of these sponsors, to be effective, would have to pull together a consortium of users and vendors. The committee believes that a potential problem could be not only the degree of willingness of such a group to work together but also their ability to do so under current antitrust policies.

Data Base Management

A second high-priority need is the development of improved data base management systems (DBMS) to handle data in both centralized and distributed data systems. Some of the critical requirements are:

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* IGES Version 2.0, released in 1982 contains some of the recommended enhancements.

- The ability to handle geometry as well as the traditional administrative data;
- Access to data by both the relational and networking methods;
- The ability to distribute and control data at remote points in the computing network;
- The ability to construct queries in high-level languages common to the engineer, such as FORTRAN and PASCAL; and
- The development of standard data structures that will carry across various data management systems and techniques.

The major need for progress with DBMS is basic research to meet these requirements. Much work is under way in both the private and public sectors, but complete solutions are not yet evident. Continuing and additional research funding is necessary in both sectors. In the public sector, it would appear to be cost-effective to build on NASA's IPAD project. A follow-up to the workshop on the needs and latest directions in data-base management systems sponsored by the National Research Council's Committee on Computer-Aided Manufacturing in Dallas in April 1979 could provide a useful industry update and a new focus in this critical field.

Pre- and Postprocessors

Continuing work is needed on pre- and postprocessors that are either a part of CAD/CAM systems or provided as stand-alone tools. These tools sharply increase accuracy and productivity in the input and analysis portion of the computational mechanics process. The key is to be able to utilize the geometry created in the CAD/CAM systems in the input process. The ultimate in productivity would be the ability to create input data (mesh models) automatically from the raw CAD/CAM geometry. We expect that such systems, which already exist in simple forms, will be further enhanced in the next three to five years. Little research is required and we expect that commercial CAD/CAM vendors and computational mechanics software vendors will provide this capability as extensions to the application systems that they currently offer for sale.

Management and Organization

A final and very important need is the study of the management and organizational effects of the tight coupling of CAD/CAM with computational mechanics. The lines of demarcation between manufacturing engineering and engineering are disappearing, as are the distinctions between the various engineering disciplines. Management in some cases has not recognized and, in most cases, has not accepted the organizational implications of integrated computer-aided engineering for their firms. The National Research Council, perhaps through its Manufacturing Studies Board, could provide a focus on this critical issue. Much of the technology of computer-aided engineering is available today. The question is how fast and to what extent will U.S. industry accept this technology and the organizational changes necessary to achieve improvements in productivity from it.

Priorities

The committee assigned priorities to the developments needed to increase the use of computational mechanics in CAD/CAM. The priorities reflect a combination of high potential pay-off and feasibility of accomplishment by industry in a relatively short time. In order of priority the needs are:

1. Enhancement of the Interim Graphics Exchange Standard leading to a neutral data base;
2. Improved pre- and postprocessor systems;
3. Education to make U.S. industry more aware of the benefits of computer-aided engineering and to make them more willing to adopt it;
4. Data base management systems with full geometry, graphics, and relational query capability; and
5. Data base management systems that permit companies to distribute data through the computing system, but maintain full central control.