# FINITE ELEMENT ANALYSIS WITH PERSONAL COMPUTERS

EDWARD R. CHAMPION, JR.
J. MICHAEL ENSMINGER

# Finite Element Analysis with Personal Computers

Edward R. Champion, Jr.
J. Michael Ensminger

Consultants
Atlanta, Georgia

MARCEL DEKKER, INC. New York and Basel

Library of Congress Cataloging-in-Publication Data

Champion, Edward R.
Finite element analysis with personal computers / Edward R. Champion, Jr., J. Michael Ensminger.
p. cm. -- (Mechanical engineering ; 64)
Bibliography: p.
Includes index.
ISBN 0-8247-7981-9
1. Finite element method--Data processing. 2. Microcomputers----Programming. I. Ensminger, J. Michael. II. Title. III. Series: Mechanical engineering (Marcel Dekker, Inc.) ; 64.
TA347.F5C46 1988
620'.0015'15353--dc19
88-15574
CIP



MARCEL DEKKER, INC.
270 Madison Avenue, New York, New York 10016

Current printing (last digit):
10 9 8 7 6 5 4 3 2 1

PRINTED IN THE UNITED STATES OF AMERICA

# Preface

This book is intended to be a basic guide for those practicing engineers who have a need for the use of finite element analysis (FEA) in order to solve typical and not so typical problems. No previous exposure to FEA is assumed, but a basic understanding of differential equations is desirable. Moreover, this book is applicable to students in the science and engineering fields who wish to obtain a concise introduction to the subject of applied FEA and how to learn to apply this analysis technique to their particular situation.

In keeping with this theme, the reader will find the text directed toward helping the user solve general classes of engineering problems with FEA on personal computers. In general, the types of problems that may be solved on personal computers are primarily limited by the amount of memory and speed of execution of the system. Work problems that previously involved cumbersome or intractable solution can now be analyzed if the engineer owns or has access to a personal computer and the proper software.

There are advantages and disadvantages in using the personal computer in FEA. Certainly a motivating factor giving rise to the popularity of the PC/FEA combination is the relatively low cost of this type of analysis. However, there are restrictions on problem size and, in addition, long execution times are often encountered. These problems are addressed in the main text of the book. While this book is not an exhaustive treatise on the subject, we have tried to cover the major areas of applications: structural, fluids, heat transfer, and advanced topics. The section on advanced topics covers areas where FEA is being applied to such diverse topics as bioengineering and solid-state physics.

Chapter 1 addresses the history of FEA and why FEA is becoming a necessary tool for the solution of a wide variety of problems encountered in the professional engineer's career. The reader will find sections dealing with how one uses this book relative to the experience level of the user. We recognize that readers of this book have varying levels of experience in FEA. Those wishing a more detailed introduction to the mathematical theory behind applied FEA should consult the references at the end of Chapter 1.

Chapter 2 explains the hardware requirements necessary for analysis and the peripherals recommended for the enhancement of the modeling process. Discussions in this chapter range from the basic PC unit to the varied input and output devices available to the end user. The aim of Chapter 2 is to provide a basis for defining a system that will supply the necessary knowledge to "build" an efficient system of hardware and software for FEA.

Chapter 3 highlights the fundamentals of starting an analysis using the finite element technique. We discuss how to select the proper mesh size for a particular element and the mesh size/solution accuracy question, how to select the proper element, what basic elements are available in commercial packages, and what kinds of problems can be solved. We also discuss commonly used elements for various classes of problems. In addition, we include sections that discuss, in general, the steps in applying a typical commercially available FEA program to a problem.

In Chapter 4 a detailed presentation for a classical structural problem is discussed. The problem solution is presented from the classical standpoint and a detailed FEA evaluation of the problem is also given. This chapter provides an insight in tying together the theoretical aspects and practical aspects of FEA. In most cases, we will provide both the theoretical and FEA solutions for all applied problems.

Chapters 5, 6, 7, and 8 address specific topics of interest. Chapter 5 is concerned with the application of FEA to structural problems. We include discussions on the types of problems generally encountered and the type of FEA software that is applicable. For the various types of problems encountered, we discuss the types of elements normally used, mesh size, the setting up of a problem, the degrees of freedom that can be expected in light of problem size limitations, and an interpretation of the results. Sample structural problems are given that highlight the discussion areas addressed above. We try to impart to the reader the important parameters that should be addressed when considering the use or purchase of a particular modeling package. The last section describes commercially available FEA programs for structural analysis. We directly compare models available to us and note this comparison in the concluding sections of each chapter. Given a sample problem, the reader will find tables comparing features such as the number of elements available, problem size limitations, machine requirements, machines the programs will run on, advantages and disadvantages and hints on using a particular model.

Chapters 6 and 7 address the thermal/fluid areas of FEA. These areas of application are not as fully developed as FEA structural models. However, some models do include thermal/fluid elements. The format of both chapters follows Chapter 5. Again one of the strong areas of each chapter is the review of the commercially available programs and tables comparing each program feature by feature.

Chapter 8 covers the concluding remarks, suggestions for possible advanced applications, and reviews of the models used in the book. These are topics that have their roots in Chapters 5, 6, and 7 and are now being explored through the use of FEA. This chapter is intended to stimulate the user to apply existing FEA models to new and diverse problems.

Finally, Appendix A lists the necessary information from each FEA vendor with respect to programs and prices. Appendix B covers separate pre- and post-processor programs available.

In developing and writing this book, many people assisted us in obtaining the finite element models discussed herein. We wish to thank the following individuals and the staff at each organization for their particular help and discussions:

Mr. Peter Brooks (Brooks Scientific, Inc.)–PCTRAN Plus
Mr. Ken Tashiro (Celestial Software, Inc.)–IMAGES 3D
Mr. Perry Grant (MacNeal-Schwendler Corp.)–MSC/Pal2
Dr. M. Lashkari (Structural Research and Analysis Corp.)–COSMOS/M
Ms. Monica Kozar (Swanson Analysis Systems, Inc.)–ANSYS-PC/LINEAR
Mr. Michael Brodgly (Intercept Software, Inc.)–LIBRA
Dr. James T. Gordon (Number Cruncher Microsystems, Inc.)–SAP86
Mr. Ellis Morgan (Structural Analysis Corp.)–MICROTAB
Mr. Charles Paulsen (Algor Interactive Engineering, Inc.)–SUPERSAP

We also would like to thank the publisher Marcel Dekker, Inc., and in particular, Dr. Eileen Gardiner, Ms. Elizabeth Fox, and Mr. John Bottomley. Finally, but no less importantly, we are grateful to Mrs. Julie Goethe for reviewing the manuscript, Mr. Jimmy Ward for assisting in the drawings, and Dr. Douglas Boylan. Finally, we thank our families for their patience and encouragement.

Edward R. Champion, Jr.
J. Michael Ensminger

# Contents

# 1 Introduction

## 1.1 A BRIEF HISTORY OF FINITE ELEMENT ANALYSIS (FEA)

What is the finite element method? The finite element method is a numerical analysis procedure to obtain approximate solutions to problems posed in every field of engineering. Often problems encountered in everyday practical applications do not lend themselves to closed-form solutions. This is readily apparent if, for example, one wishes to analyze the flow of a fluid through a duct of varying cross section subjected to nonuniform boundary conditions. We can write the governing equations with the appropriate initial and boundary conditions. However, it is apparent that no simple analytic solution exists. This is found not only in the fluid mechanics area, but also in the area of structural mechanics. From the inability to solve many complex structural problems arose the foundations of the finite element method as we know it today.

The label "finite element method" appeared in 1960 in a paper by Clough (1) concerning plane elasticity problems. However, the basis for the finite element method goes back further to the early 1940s in the applied mathematics literature. We will not cover that period of development for there are sufficient reviews available concerning this area. During the mid- to late 1950s, the mathematical literature on the finite element method increased significantly. Books and monographs (2-4) were written to explain the mathematical foundations of the method during the early 1970s. Not only were the mathematicians exploring the finite element method basics, but also the physicists were developing ideas and concepts along similar lines. One such example is the development of the hypercircle method, a concept in function space, that allows a geometric interpretation of minimum principles when associated with the classical theory of elasticity.

During the mid- to late 1950s and early 1960s a series of papers were published covering linear structural analysis and methods to effect efficient solutions to these problems. Turner, Clough, Martin, and Topp (5) derived solutions to plane stress problems via triangular elements with properties determined from elasticity theory. With the development of the digital computer, these solution techniques allowed the analysis of more complex problems.

Concepts of the method began to be drawn into focus by the publishing of many papers and articles (6-10). The method was recognized as a form of the Ritz method, and the method was recognized as a technique to solve elastic continuum problems. In 1965, Zienkiewicz and Cheung (11) illustrated the applicability of the finite element method to any field problem that could be formulated by variational means. Most of the applications of the finite element method during the early- to mid 1970s were in the structural analysis area. This is the reason why most FEA programs today are heavily oriented toward the structural analysis area.

As the structural analysis are of FEA was refined, other areas of applications of FEA were nurtured during the late 1970s and early 1980s (6-12). Attention was and is being given to the application of FEA to the thermal/fluids areas. For example, many papers in the mid- to late 1970s applied the finite element method to the Navier-Stokes equations. Papers by Girault and Raviart (12) and Teman (13) have lead to further development of this method in fluids applications. The reader should refer to the works of Fortin (14), Griffith (15), Thomasset (16), Heywood and Rannacher (17), and Cullen (18) for basic understanding of the fluids modeling effort. In addition, Chung (19) gives an excellent text on FEA in fluid dynamics. If the user wishes a fundamental text concerning FEA in general, we recommend either the text by Gallagher (20) or that by Segerlind (21). Several mainframe programs are available to solve problems in these areas as well as in the structural areas.

## 1.2 APPLICATIONS OF FEA FOR PRACTICING ENGINEERS

Every area of engineering can use the power of the finite element method of analysis. From the history of the analytic technique, the most obvious application is structural analysis. The fields of civil and aerospace engineering rely heavily on FEA methods to analyze various types of structures ranging from buildings to spacecraft design. The analysis involves the determination of static deflections and stresses and the determination of natural frequencies and modes of vibration. In addition to these types of problems, the ability exists to analyze the stability of structures.

Other FEA applications lie in the thermal/fluids areas. Many models contain thermal and fluid elements which will allow the determination of temperature distributions in structures and such items as velocity, pressure, and concentration distributions in fluid flows.

There are three basic types of problems, from a mathematical standpoint, that the practicing engineer faces. These are time independent (equilibrium) problems, eigenvalue problems, and time dependent (propagation) problems.

When engineers are faced with problems that do not lend themselves to easily tractable solutions, they have to make judgments as to the best solution approach in light of their background and familiarity with the tools available. The available tools include, but are not limited to, computer resources and programs to utilize the computer resources.

Unfortunately, not every engineer has at his disposal a large mainframe computer, the finite element code, and the time to solve whatever problems arise. Consequently, the engineer is forced to make approximations based on similarity to classical, closed-form soluble problems or the engineer may rely on physical prototyping. Physical prototyping is generally expensive and increases the cost of the design process. These approximations may or may not result in an adequate design. An overdesigned (or overengineered) product may be noncompetitive from a cost standpoint and/or may actually perform less well than intended. However, this design process is often tempered by experience.

With the proliferation of personal computers and with the availability of software to aid the design process, it is no longer necessary to rely heavily on intuition and settle for approximate solutions to real-world problems. FEA programs are available to aid the design engineer in developing a product to withstand its environment.

## 1.3 HOW TO GET THE MOST FROM THIS BOOK

If the engineer is not as experienced as he wishes to be, then this book can aid in the development of a better foundation of understanding in the basics of analysis. The application of FEA to a wide variety of problems that may be encountered in day-to-day engineering activities can be readily handled.

The following section addresses how one uses this book as an aid and guide to FEA with personal computers. Since the basic objective of this text is to familiarize the novice as well as the experienced user with what tools are available and necessary to analyze and solve problems with finite element methods, we suggest the following two approaches in the use of this book.

### 1.3.1 The Novice or Casual User

If you are a part of the novice category, the first question to be answered is "Do I have an application or problem that requires the use of finite element techniques?". We recommend that you review Chapter 3. Section 3.1 addresses the criteria for selecting the finite element approach to solving a problem. Perhaps there may be alternative solution techniques you may have overlooked. However, if you are convinced FEA is the direction you wish to pursue, then continue in Chapter 3 and develop a familiarity with the basic concepts and terms of FEA.

The next step is to evaluate the equipment requirements in order to perform an analysis. We have attempted in Chapter 2 to cover the minimum system requirements for most programs. In the sections of Chapter 2, you will find discussions of many kinds of peripheral equipment available. This equipment and combinations of equipment enhance the actual modeling process for a given problem. In most cases, the right combination of equipment makes the analysis an enjoyable task rather than a tedious task.

Following the selection of the equipment, you must define the type of problem to be analyzed. We suggest that you review Chapters 5, 6, 7, or 8 so that you can familiarize yourself with the ins and outs of setting up and running a particular type of problem. For a more in-depth look at FEA, read Chapter 4. In Chapter 4 we set up and run a simple finite element problem. This example lends some insight into the operation of commercially available programs.

The next step in selecting a program is often a difficult choice. In Chapter 8 we have listed several programs that we are familiar with and have run on various computers. The programs listed in no way carry our or the publisher's stamp of approval. However, we feel that they do represent the present state-of-the-art programs available for finite element analysis with personal computers.

In summary, you must consider the extent of your modeling efforts, both short term and long term. It is best to purchase a system that will provide a comfortable environment when performing an analysis. In addition, the FEA program should fit your needs. Some programs allow purchase of modules depending on the type of analysis and depth of analysis you need. Again, one purpose of this book is to assist in your selection of the correct hardware/software combination for your particular situation.

### 1.3.2 The Experienced User

If you are familiar with computers and the use of computers in the analysis of scientific and engineering problems, this book provides an introduction to FEA or a refresher to the subject. In addition, we have attempted to provide up-to-date information on the types of new products available to aid in your analysis. Therefore, a review of Chapter 2 would be in order.

Chapter 3 may be bypassed if you regularly use FEA. If not, this chapter provides an excellent refresher on the analysis technique. Chapter 4 addresses in depth a sample finite element application.

Chapters 5, 6, 7, and 8 provide useful information in specific areas and areas that show how to extend the application to the fields of medicine to solid-state physics.

## 1.4 SUMMARY

The programs used in and referenced in this book have been developed and verified. The user must learn how to apply a particular program or model to his analysis problem. Note that it is not necessary to learn all of the capabilities of a particular program or model. The goal is to learn how to apply that part of a program that will, in an efficient and simple manner, solve the problems at hand.

Since finite element analysis methods are widely used and have proven to be a necessary analytical tool in many areas of science and engineering, the information obtained from this book will be a stepping stone to further development of the user, not as just a user, but perhaps as a program developer.

With many finite element programs available for the personal computer, it is difficult to select the "right" program. The user could review the program demos to help him select the correct program for him. Manuals would also be helpful. However, the demo programs will feature a very professional graphics presentation and they do not let the user interface with the program to a great degree. In evaluating a program, the user must examine the following items:

### Program Accuracy

In order to validate the program accuracy, the program developers must include numerous test problems that have a classical or analytical solution. The accuracy of each type of element and capability must be checked out as well as the application of the program to both small and large problems.

### Problem Size

Many advertisements for programs promise the solution of thousands of static and dynamic degrees of freedom. The user should verify that the program(s) will actually handle a large problem. Requests should be made of the program developers to provide the documentation.

### Capabilities

The user should review current requirements and future requirements as to the type of problems he may encounter. If large problems are to be solved, the program should contain solution options such as guyan reduction, substructuring, or cyclic symmetry. Perhaps buckling capabilities or composite material analysis should be included.

### State-of-the-Art Techniques

As with any technique, advances are being and will be made. The user should determine if the code contains the latest in element formulation, numerical techniques, and the development of new finite element techniques.

### Mesh Generation

A time-consuming task is the problem formulation and mesh generation. All programs reviewed in this book contain some form of mesh generation. This may work well for simple rectangular plates, cylinders, or conical shells. In order to check the mesh generation capabilities try generating meshes for intersecting pipes or plates with elliptical holes.

### Program Execution

It is imperative that the user check the execution times of benchmark programs. Speed of execution is of importance, especially in the execution of large problems.

### Graphics

In order to evaluate correctly and in a timely manner the program must be capable of displaying the undeformed and deformed structure, stress contours, and animation of the results of the dynamic analysis.

### Manuals

In order to use the program for a long period of time, the program should come with thorough and complete documentation. This includes program use, verification problems, and a theoretical background for the program.

### Support

This is a most critical item, especially for the novice user. The user must determine whether the organization has the background to support the program.

### Mainframe Capability

For some large problems the PC-based finite element program must be capable of interfacing to some of the more well-known mainframe programs such as NASTRAN or ANSYS.

### Cost

The cost of the programs vary and this cost does not seem to depend on the program capabilities or the efficiency of the program. Some programs have limited capability and are expensive. Other programs contain all the capabilities the user may need and the cost of these programs is quite reasonable.

# 2

# The PC: Hardware Requirements for FEA

With the advent of the personal computer (PC), scientists and engineers have had available an invaluable resource with which to perform a wide variety of computing tasks. Tasks ranging from simple word processing, spread sheets, and report generation to sophisticated data analysis, machine control, and computer aided engineering (CAE). Convenience is the prime motivation behind the ever-increasing numbers of PCs. In general the PC can address a wide variety of computing needs at a fraction of the cost of its larger cousins, the much larger mainframes. While it is still true the PC may never compete with the mainframe, newer and faster PCs are reaching the market with steady resolve.

This chapter deals with the general hardware requirements needed to address finite element analysis (FEA) with the personal computer. The chapter begins with two important performance items one may address when determining hardware requirements for a PC which will be used to perform FEA, the memory and disk subsystems. Next, we shall discuss devices and methods with which to input and output data for subsequent analysis. In addition, we shall look at memory size, input/output devices, and PC performance as a function of processor speed and the particular microprocessor chip used.

## 2.1 GENERAL HARDWARE REQUIREMENTS

The basic hardware requirements for FEA are not particularly special. Almost any "off-the-shelf" PCs with not much more than the main chassis assembly and a keyboard can provide a basis for reliable FEA. But, to derive the maximum benefit

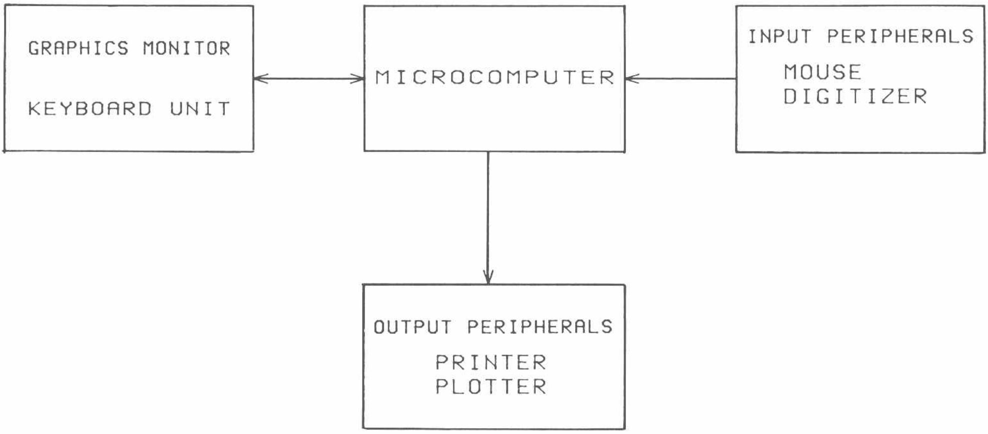


**Figure 2.1** Typical PC-based FEA hardware configuration.

from a PC-based FEA system, a minimum hardware configuration is usually specified by the FEA software vendor. The following paragraphs in this section address some of the options an FEA program may require in order to perform its function efficiently. Figure 2.1 presents a pictorial example of a typical PC-based FEA hardware configuration.

### 2.1.1 The Main PC Unit

The most popular PC (1987) is the ubiquitous IBM PC and its compatibles. The IBM PC product line consists of the PC, PC/XT, PC/AT, and more recently the IBM PS/2 series. Each of these computers is able to execute the same operating system, PC DOS, but each offers additional performance over the previous unit. The original IBM PC offered basic computing capability utilizing the 8088 CPU chip. It had the ability to utilize the 8087 math co-processor, but lacked a high capacity hard disk drive. The next unit, IBM's PC/XT added the hard disk and provided additional capacity for optional plug in cards. The PC/AT was a much needed architectural change for the PC line. This computer offered additional speed, increased memory capacity, and increased hard disk storage. Moreover, the PC/AT uses the 80286 CPU instead of the 8088 thereby providing a true 16 bit data path. The 16 bit data path increases the system throughput which increases performance.

IBM's success spawned a large and aggressive compatible market. In order to compete, the PC compatibles generally offer enhanced features such as higher clock speeds and larger standard memory sizes. When selecting a PC compatible