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FINITE ELEMENTS IN CIVIL ENGINEERING EDUCATION

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ABSTRACT

This paper reviews the application of the Finite Element Method in engineering and research with the objective to identify the areas which require additional emphasis in the formal training of Civil-Structural engineering students. The applications of FEM are broken down into concepts, skills and tasks. The areas of interest for the common engineer engaged in structural engineering consulting work are pointed out. Subjects which are to be stressed at the undergraduate level for adequately equipping the young graduate in meeting the demands of engineering consulting are described.

INTRODUCTION

The Finite Element Method (FEM) is recognized as a powerful analytical tool for solution of structural engineering problems, in particular in continuum mechanics. It is a relatively new entry in the field of structural analysis, having only 25 years of active history. Research and development in this field have culminated in clear and commonly acknowledged interpretation and formulation techniques, as we move toward second and third generation computer codes and textbooks. As a consequence of standardization which is being achieved, the structural analysts , using different formulations and coding, can now exchange and verify their results with other analysts with relative ease.

Industry

Increased use of computers has resulted in smaller consulting firms reaching for automated structural analysis. At the same time, structural analysis software, which was primarily based on simple matrix formulation (slope-deflection method) is being replaced by the more general and popular FEM formulation. The latter allow non-skeletal non-prismatic members to be readily implemented in the analysis. A common example is software which handles shear walls and rigid floor diaphragms in conjunction with columns and other skeletal members.

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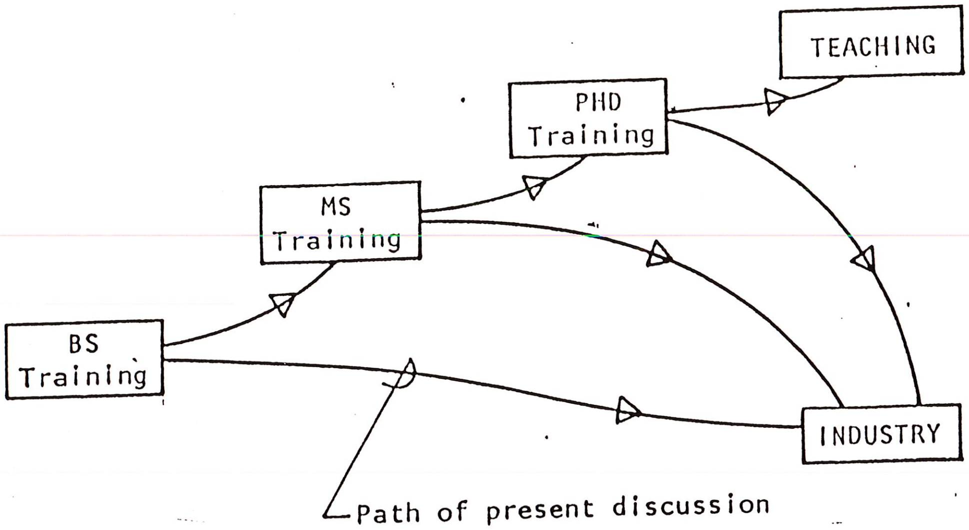

FIGURE 1

To remain competitive, consulting firms with as few as five employees are now being forced to computerize their analysis.

The common practice of smaller firms is to purchase a computer code, which is normally developed and marketed by independent software agencies. Larger organizations, on the other hand, tend to develop or commission their own software. Some firms retain outside consultants to update and modify public domain FEM codes to suit their particular needs.

Teaching Institutions

FEM, as a subject of study or as a research tool was initially confined to PhD students. Subsequently, it became part of standard graduate courses in structural engineering. To-day, almost all structural engineering MS or PhD students receive some exposure to FEM as part of their formal education. The major concern of this discussion is the BS graduate (see Fig. 1) who enters the industry without having been formally acquainted with this tool. The civil engineer is going to use FEM, in one form or other, if he or she is going to engage in analysis or design work.

A common pitfall of FEM is that it is a powerful tool. The young engineer, equipped with a user's manual of a purchased code and a terminal, is sometimes tempted to engage in the analysis of complex problems for which he or she may not be well prepared. The engineer may not understand the tool being used, may not be familiar with the expected behavior of the structure, or, more importantly, may be unable to judge whether the output generated is an acceptable solution. Establishment of validity of results, interpretation of results and accuracy evaluations are, in the case of unusual structures, challenging tasks even for the well experienced engineer.

Innovative engineers succeed in developing the required understanding and skills within the environment of their consulting firms. Others with adaptive capabilities may pull through, provided they have competent supervisors. However, the bulk of engineers, who skillfully produce calculations of the kind they have been taught, are those who face the greatest difficulty if they are not pre-exposed to FEM.

There are only a few institutions in which FEM is presented at an undergraduate level. It is still a matter of controversy as to whether the students at this level have the required background and maturity. At San Francisco State University, an elective senior course in FEM for civil/structural and mechanical students was introduced four years ago. The author's involvement in teaching of this course, his work as a FEM code developer, his research using FEM as a tool, and finally his activities as a structural engineering consultant have resulted in the formulation of the material offered herein.

This paper presents a breakdown of concepts, skills and tasks which are part of the total realm of FEM and structural engineering. The tasks which most engineers will encounter as part of their professional work are clearly identified. The concepts and skills they need to master for the effective handling of their duties are itemized. It is concluded that through slight modifications and changes of emphasis in the regular undergraduate courses, it is possible to orientate and equip the young graduate with sufficient information to enable him to satisfactorily use the FEM tool. The student will be stimulated to build upon the foundation presented to him as part of his formal training.

CONCEPTS AND TASKS

In order to identify the types and scopes of work which a structural consulting engineer is likely to encounter, the development and application of FEM is broken down in Concepts/Skills and Tasks, as shown in Table 1. From this table areas of interest are selected for implementation in undergraduate teaching.

Concepts and Skills

STATICS, THEORY OF STRUCTURES : The emphasis will have to be on an in-depth understanding of (i) Equilibrium, (ii) Compatibility , and (iii) Material laws with specific applications as described herein under suggested course material.

STRUCTURAL MODELING : This is a critical step normally requiring experience and a good appreciation of the structural behavior with a commanding overview of all the factors affecting the design and their relative significance. It consists of, but is not limited to: the definition of the load carrying structural system; its geometry, boundary conditions, and material properties; loading; and applicable design criteria (including codes and governing specifications).

DISCRETIZATION : This is the breaking up of the structural system into sub-regions and elements based on (i) The desired accuracy of the results, (ii) Capabilities of the program to be used, and (iii) Budgeting and computer (hardware) limitations. Understanding the

TABLE 1

CONCEPTS, SKILLS AND TASKS IN FEM AND STRUCTURAL ENGINEERING		CONCEPTS & SKILLS: ENGINEERING ANALYSIS AND DESIGN								CONCEPTS & SKILLS: CODE DEVELOPING RESEARCH			
ACTIVITIES	TASKS	STATICS, THEORY OF STRUCTURES	STRUCTURAL MODELING	DISCRETIZATION	DATA PREPARATION	EXECUTION OF THE PROGRAM	ACCURACY & VALIDITY CHECKS	EXTRACTION OF DESIGN DATA	STRUCTURAL DESIGN	MATRIX FORMULATION OF STRUCTURES	THEORY OF FEM	COMPUTER PROGRAMING	SPECIALIZED THEORY
ENGINEERING	CONCEPTUAL DESIGN	○	○										
	ANALYSIS	●	●	●	●	●				●			
	DESIGN	●					●	●	●				
CODE DEVELOPING	COMPUTATIONAL EFFICIENCY									○	○	○	
	USER FRIENDLINESS				○	○	○	○				○	
	MEET SPECIAL APPLICATIONS									○	○	○	
	DEVELOP PRE- AND POST-PROCESSORS		○	○	○	○		○	○			○	
	ENHANCE MARKETABILITY		○	○	○	○		○	○			○	
RESEARCH	ELEMENT TECHNOLOGY	○	○	○							○		
	SOLUTION SCHEMES/ STRATEGIES						○				○	○	
	NEW FORMULATIONS	○	○				○			○	○		
	UNKNOWN STRUCTURAL BEHAVIOR	○	○	○			○						
	NON-LINEAR BEHAVIOR						○			○	○		○
	TIME DEPENDENT NON-LINEAR PROBLEMS						○			○	○		○
	FRACTURE MECHANISMS						○				○		○
	SOIL FOUNDATION INTERACTION						○				○		○
	LIQUID STRUCTURE INTERACTION						○				○		○
	HYDRAULICS						○				○		○
	OTHER NEW AREAS OF APPLICATION						○				○		○

● Areas applicable to undergraduate training

○ Areas of major emphasis

behavior of the structure the limitations of the elements and coding to be used is essential for successful discretization of the problem.

DATA PREPARATION : At this step detailed familiarity with the manuals of the code being used is required. In most cases the engineers are expected to prepare their own data sheets for the execution of the code.

EXECUTION OF THE PROGRAM : In larger organizations, data prepared by engineers is run by computer operators, or other engineers trained for such duties.

ACCURACY AND VALIDITY CHECKS : This is a crucial step in any FEM analysis. It consists of equilibrium and deformation checks, as well as a review of stresses at critical points. The response of the structure is evaluated against its expected behavior.

EXTRACTION OF DESIGN DATA : From the pile of output normally generated by FEM analyses, the designer will have to identify and select the critical values of deformations and stresses. Often the critical actions and deformations are extracted and presented in tabular or graphical forms for the purpose of design.

STRUCTURAL DESIGN : This is the standard design procedure as taught and practiced in structural consulting firms.

MATRIX FORMULATION OF STRUCTURES : This skill is required for code development and research. It consists of matrix algebra and matrix formulation of structural problems.

THEORY OF FEM : The theory is well documented in its standard basic form in several good textbooks. Except for an attempt at stiffness generation of a new element, the FEM algorithm is well defined for routine problems. Knowledge of details of FEM theory is generally not necessary for the regular work of a structural engineer.

COMPUTER PROGRAMING : This is required for code generation and development. It is not part of a routine structural analysis using FEM.

Tasks

The tasks normally encountered in relation to a FEM analysis are itemized on rows of Table 1 . These are subdivided into three activities, namely engineering, code development and research.

CONCEPTUAL DESIGN : This is the conception and evaluation of different structural options to a project. It is normally handled by senior engineers, who possess other skills beyond the scope of Table 1, such as engineering economics, construction techniques and management.

ANALYSIS : This is defined as the task of obtaining numerical values for sectional actions, stresses and deformations of the structure under given loading and boundary conditions.

DESIGN : This is the process of sizing the structural members for the actions determined in the analysis, and checking with the governing building or regulatory codes for compliance of member selections.

COMPUTATIONAL EFFICIENCY : This is a code developing task. It is primarily directed toward (i) reducing the computing time, (ii) reducing the memory requirements, and (iii) increasing the computational accuracy. For example, improved equation solvers and eigenvalue extraction technics are placed in this category.

USERS' FRIENDLINESS AND ENHANCEMENTS IN MARKETABILITY : These are efforts toward simplifying the use of existing codes, such as preparation of input data and improvements in the manuals. This task is particularly popular with public domain programs, which may be obtained at nominal costs and marketed after improvements in their usability.

SPECIAL APPLICATIONS : This includes tasks such as modifying a public domain program to solve pipe stress analysis problems.

DEVELOPING PRE- AND POST-PROCESSORS : Pre-processors are generally directed toward the automated generation of input data, or simplifications thereof, as well as schemes for display and verification of input information. Post-processors include plotting output, and in some cases extension of the coding to perform design checks against ACI, ASTM or other regulatory requirements.

ELEMENT TECHNOLOGY : Development of new stiffness matrices is not as popular a research topic as it used to be at the advent of FEM. There are libraries of elements for most common problems. However, increased expectations, new materials and structures have sustained a demand for new developments. Examples are for cheaper shell and brick elements; composite shell elements; ice elements in connection with offshore structures in arctic regions; and elements with nonlinear properties.

SOLUTION SCHEMES/STRATEGIES : Extensive research is in progress to improve solution technics for non-linear problems. Examples are the event-to-event approach and displacement controlled iteration methods.

NEW FORMULATIONS : These are primarily directed toward automated modeling of the structure.

UNKNOWN STRUCTURAL BEHAVIOR : This is the application of FEM as a tool to parametric studies of structures whose response is to be studied.

TIME DEPENDENT NON-LINEAR PROBLEMS, and the remainder rows of Table 1 are examples of areas of current research using FEM. These applications are of lesser significance to the objectives of the present work.

PROPOSED UNDERGRADUATE EXPOSURE TO FEM

The foregoing categorization of skills and tasks leads to the conclusion that for the majority of engineers, whose principle function in a consulting engineering firm is the analysis and design of common structures, there is a manageable number of concepts and skills which have to be emphasized as part of the undergraduate courses. These are shown with full circles in Table 1 and are described in more detail in the following.

1 - In-depth understanding of static equilibrium, compatibility and material laws. Numerous examples of equilibrium checks in two and three dimensional continuum problems such as plate elements.

2 - Stresses and strains at a point in two and three dimensions. Stress-strain transformations and relationships.

3 - Stress and strain fields with various degrees of complexity. Examples to evaluate stresses, strains and deformations in various continuum problems.

4 - Description of sectional actions (moments and forces) and deformations on elements of plate, shell and bricks. Numerical examples aimed at developing an appreciation of the behavior of such elements.

5 - Theory of virtual work as applied to FEM. Simple examples to establish relationships between actions and deformations on Finite Elements based on assumed displacement fields.

6 - Matrix algebra and matrix formulation of structural problems.

7 - Introduction to commercially available FEM programs such as SAPIV and STRUDL. Review of their users manuals. Course works using commercially available programs.

8 - Examples in interpretation and evaluation of outputs of commercially available programs. Validity and accuracy checks. Selection of critical information from FEM printouts.

CONCLUSIONS AND CHALLENGES

It is concluded that it is necessary to expose the students of civil - structural engineering programs to certain features of FEM analysis during their undergraduate training. This is particularly true for those students who terminate their formal education at BS level. The desirable extent of exposure may be achieved through moderate changes in emphasis and treatment of material which is commonly taught at undergraduate level. The work presented describes the areas which required additional emphasis.

It is a challenge to strike a healthy balance between (i) generating enough confidence in the young graduate, so that he or she will effectively use FEM in practice, and (ii) on the other extreme, creating a feeling of over-confidence . This may result in the engineer believing he or she has a solution to all structural engineering problems.

If the training provided will encourage the young graduate to critically review and evaluate the results of FEM prior to handing it over to his or her supervisor, or starting a design, the effort spent will be well rewarded.