Teaching Finite Element Modelling at the Undergraduate Level: A PBL Approach

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***Abstract**: Finite Element Modelling (FEM) was first introduced into the undergraduate civil engineering program at the University of South Australia ten years ago as part of a third year course, undertaken by all civil engineering students. In contrast to the traditional teaching method which focuses on FEM theory, a project-based learning (PBL) approach has been utilised, where the students are required to apply the knowledge of FEM to analyse and solve a structural problem using the commercial software package Strand 7. The teaching method is focussed on the development of a student's ability to select a suitable element for a given problem, and the ability to interpret and evaluate the accuracy of the results. The project is selected by the students (working in pairs) and approved by the lecturer to ensure the suitability of the project. This paper describes both the project design and learning outcomes of the students.*

Introduction

The finite element method (FEM) is a mathematical technique and computer based procedure that can be used to analyse structures and continua. FEM is probably the most widely used form of computer-based engineering analysis and design nowadays due to the availability of commercial software packages that have significantly reduced the complexities of the actual application of FEM. It is more usual to teach FEM at the postgraduate level due to the complicated theories behind the method. However, there is also a benefit in introducing students to the application of FEM at undergraduate level.

FEM was first introduced at the University of South Australia ten years ago as part of a third year course (Structural Analysis and Computer Applications), undertaken by all civil engineering students. In contrast to the traditional teaching method which focuses on FEM theory, a project-based learning (PBL) approach has been introduced where the students are required to apply the knowledge of FEM to analyse and solve a structural problem using the commercial software package Strand 7. The teaching method is focussed on the development of a student's ability to select a suitable element for a given problem, and the ability to interpret and evaluate the accuracy of the results. The choice of object or structure to be modelled is made by the students (working in groups of 2 or 3) and approved by the lecturer to ensure that the project will not be too complex to be achieved within the timeframe. The students are also required to present their project prior to its conclusion to their peer students and the lecturers, enabling formative feedback and modifications before final submission of the report. This paper describes both the project design and learning outcomes of the students.

Project-based learning and FEM

Projects model industrial practice and enable students to understand the synthesis of analysis, material behaviour, constructability, environmental, social and economic realities that influence solutions in the practice of engineering. Using projects as a means of teaching engineering encourages students to develop critical thinking and independent learning skills along with developing both their written and oral communication skills and teamwork skills. Projects are a form of experiential learning and as Kolb (1984, p. 41) asserts "Knowledge results from the combination of grasping and transforming experience." Project-based learning in engineering may be implemented in various ways at different institutions. These variations are described by Heitmann (1996) who differentiates between 'project-oriented studies' and 'project-organised curriculum'. Project-oriented study involves the use of small projects within individual courses, where the projects are usually combined with traditional teaching methods within the same course, focusing on the application, and possibly the integration of previously acquired knowledge. The merits of project-based learning within engineering programs have been increasingly recognised in recent years (Perrenet *et al.* 2000; Mills & Treagust, 2003). The program at University of South Australia utilises project oriented studies throughout its four years, culminating in a final year that consists of two capstone projects that make up half of the final year load. Third year courses such as the one described in this paper all utilise major projects worth at least 35% of the assessment combined with some traditional lecturing and exams. The primary purpose of the project as described for this course, and others in the program, is to enable students to apply the knowledge that they have gained from the introductory theory component delivered through standard lectures, but then also to extend this knowledge through self-directed and guided experimentation and exploration in a project of their own choosing.

Typical courses in FEM at the undergraduate and graduate levels in academic engineering programs are mainly theoretical in nature (Rencis *et al.* 2007), rather than focussing on project-based applications. Although it is true, as Rencis (2007) notes, that to carry out a proper finite element analysis, one must have a grasp of the problem area and an understanding of classical analysis tools, the reality is that with the widespread availability of economic, commercial FEM software packages they are now widely used in industry. As Karadelis (1998, p. 92) states "this is a discipline which is undergoing rapid changes and developments and, as such, one should focus on the more cost-effective area of applications and use rather than theory". Ideally the team leaders who utilise FEM packages in industrial practice should have the technical qualifications and experience to fully understand the FEM, but it is also important that all graduate engineers in such teams have at least some understanding of the application and limitations of FEM. We believe that the project based teaching philosophy is the most effective way to provide this introduction and understanding of FEM to undergraduate students. This approach was also endorsed by Karadelis (1998) who noted that " the user-friendly approach offered by the new generation of finite element systems can stimulate the teaching and learning experience and can provide the student with the satisfaction of learning by discovery and deep understanding" (p. 92).

Some previously published accounts of using projects to teach FEM in undergraduate courses include Miner & Link (2000) who utilised a FEM project to design, analyse, build and test a specific bracket element in a mechanical engineering program; Shakerin & Jensen (2000) who asked students to undertake finite element analysis of a prescribed object and compare this with experimental stress distribution observed using photoelasticity testing, again in a mechanical engineering program and Karadelis (1998) who used small group projects selected from a range of real-life construction scenarios in a civil engineering program. The techniques and findings of the latter author are similar to those discussed here, but the major difference is the extension of the projects so that they are free choice by the students, rather than prescribed by the lecturers. This leads to a fascinating and stimulating range of projects being undertaken but does require significant expertise in the area of FEM from the lecturer.

Undergraduate FEM course design

FEM was first introduced at the undergraduate level in the Civil engineering program in 1999 and has been progressively developed and improved over the past ten years. The teaching structure that is now employed comprises of six weeks of formal lectures (two hours per week) and ten weeks of project sessions (two hours per week) at the computer pool. It forms approximately half of the contact hours and assessment of a course that also includes a module on traditional structural analysis. The lectures in FEM focus on correctly using finite-element technology rather than fundamental theories, as the course is offered at the undergraduate level with short contact hours (12 hours of lecturing). The topics covered in the lectures include the introduction to finite element method; revision of matrix algebra; 1D element: spring, bars and beams; finite element analysis of truss; 2D plain stress/strain element, plate and shell element; introduction of 3D element; loading conditions; interpreting results; errors and accuracy in linear analysis. At the same time, the two hour per week computer project sessions are designed to enable students to set up a FEM model using a commercial software package and run the program successfully to produce a successful model of their chosen project topic. In order to promote lifelong learning or self-directed learning, only three weeks of basic software training with a few examples are provided by the lecturer. Then the students are required to choose a project themselves for finite element modelling. Therefore, they are forced to learn many program features and modelling strategies on their own, with the lecturer present in the remaining computer project sessions only in a consulting role. Over the years that the course has been run it has been clearly demonstrated, that this type of learning is efficient and effective. Several students have become "expert" in using the software and gained employment due to such skills. The lecturer has also learned many new features of the software from the students. A more detailed discussion on the project design is carried out in the following sections.

Educational objectives

In accordance with the philosophy of project-based and authentic learning, the educational objectives for our teaching of FEM focus on hands-on experience in solving various simple engineering problems by FEM and correctly interpreting and evaluating the quality of the results. The educational objectives for the FEM component of this course are as follows:

- Understand the basic theory of the FEM
- Know the behaviour and usage of each type of element introduced in this course
- Have some hand on experiences in solving various simple engineering problems by FEM
- Develop the ability to interpret and evaluate the quality of the results

Project design

The project requires students to apply the knowledge of finite element method to analyse and solve a structural problem. The structure may be traditional or non-traditional, but the finite element model of the structure must involve at least one type of 2D element (either plane stress, or plane strain or plate/shell element). The project is selected by the students and approved by the lecturer. It is in the students' best interest to propose a project that interests them but that is also in their area of study. The challenge is to select a project that is sufficiently complex and of engineering interest to warrant finite element analysis but that is also achievable within the constraints of this half semester introductory course. This is where the expertise of the lecturer in FEM and their prior experience with past student projects is critical so that students are guided in their project selection to maintain interest but provide a challenge as well.

It is suggested that the students work as a group of 2 or 3 for this project. Each group is required to submit to the lecturer a typed description of their proposed project, not exceeding two pages in length including figures. This is due at the beginning of week 5, after they have had lectures about all of the basic types of 2D elements. The project description must include one or more graphical representations (drawings, sketches, etc.) of the proposed project. The students must also indicate what their analysis objectives are and what major modelling assumptions they expect to be able to make (i.e. 2-D versus 3-D, material properties etc.). The lecturer discusses the suitability of the project with the group during computer project sessions of that week.

In the 11th week of the semester, each group gives a maximum 15 minutes presentation (including question time). The presentation is judged for general quality of presentation, speech, illustrations, keeping to time and quality of answering questions. The presentation enables modelling errors to be picked up and remedied before final submission of the student report.

Assessment

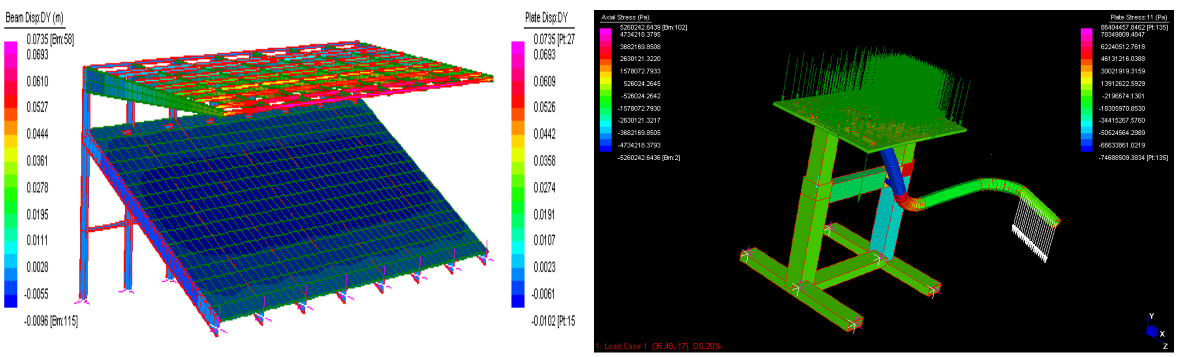
As Boud (1995, p. 36) notes "Assessment is the most significant prompt for learning." McCarragher (1999) also found that the most prominent influence on the learning approach taken by the students was the form of assessment. Whether we like it or not, students will frequently structure their learning and commitment within a course around the assessment tasks that are set. In order to encourage students to both value the theory content as well as develop the familiarity with software and report presentation required in professional practice, the assessment of the FEM component of the course has two parts. The first is a one hour, in-class test on FEM theory worth 15%, which is held after the 6 weeks of lectures. The other is the final project report required to be submitted by each group, worth 35%. (The remaining assessment in the course worth 50% is an assignment and exam on the structural analysis module) The FEM project report is expected to be technically sound and professional in nature. The detailed marking scheme for the report is provided in Table 1. The students may achieve higher marks and up to 3 bonus points for innovation, such as design of new structures or components; use of new materials for higher strength or cheaper outcomes; optimisation design of the structures or a more complex level of modelling. However, they are also warned that if they make a major basic modelling mistake they are likely to be severely penalised. Therefore, the students are encouraged not to be too ambitious in their initial plans unless they are sure they have the time and skills to perform a more challenging task. A prize of a $50 book voucher is also awarded each year to the group with the best result based on the final report, seminar presentation and assessment by their class peers.

Table 1: Marking scheme for FEM project

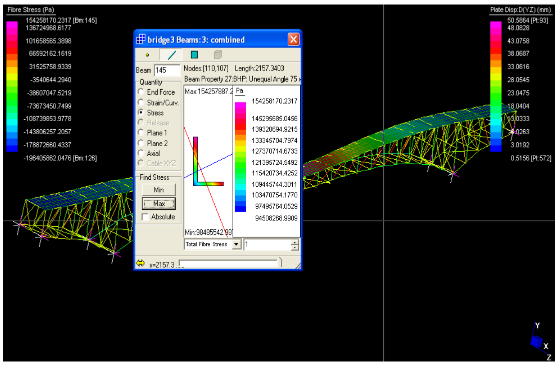
	Possible mark
Proposal	5
Quality of modelling	9
Results and discussions	8
Report Structure	3
Level of difficulty	5
Oral presentation	5
Bonus (innovation)	Up to 3

Examples of past FEM projects completed by students

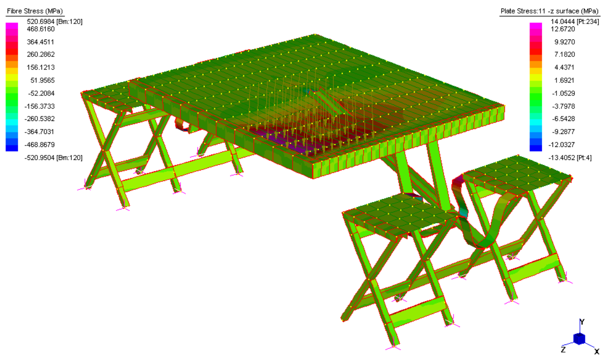
Many different kinds of project have been proposed by students each year, ranging from traditional building structures to non-traditional structures. Some projects created the user defined complicated curved cross sections and some other projects used special master-slave link element and 3D brick elements in their model. A few interesting projects have been demonstrated in the following figures.



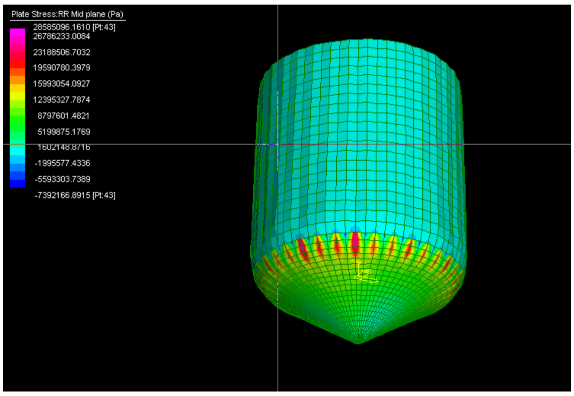
(a) Grandstand (b) Motorbike stand



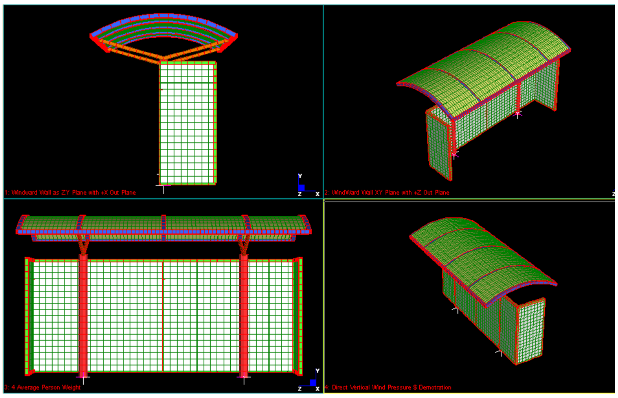
(c) Foot bridge



(d) Picnic table



(e) Grain silo



(f) bus shelter

Figure 1: Examples of student's projects

Course evaluation and student feedback

In general, good course evaluations have been received consistently since PBL was introduced and most students react positively to PBL. The most relevant questions on student evaluations of the course which indicate the value of PBL are: "The ways in which I was taught provided me with opportunities to pursue my own learning" and "The course developed my understanding of concepts and principles. For each of these questions the mean values of responses average approximately 50 over the years since PBL was introduced. A value of 50 indicates that students agree with the statement (-100 = strongly disagree, 0 = neutral, +100 = strongly agree).

Some student comments regarding the best features of the course included:

- *The project gave an excellent approach to understanding finite element analysis.*
- *Computer work interesting and you feel good when you learnt the few features and program works.*
- *Using the programs gave me a much clearer idea of finite element and how they worked.*
- *The project is most valuable for today's engineer, it allowed us for creative thinking.*
- *The project was quite interesting and was of great benefit to learn such a useful program. I enjoyed analysing something that had interested me.*
- *The freedom given with the finite element project was very good. The difficulty of the project was dependant on personal preference.*

However, some students raised issues that PBL may be a bit hard for them and time consuming:

- *The FEM project is good, but too hard. It took a lot of time due to not good knowledge of programs. The workload was too heavy due to this project.*
- *More detailed guidance on what a suitable project will be and how to use the program*

Although PBL has many advantages to teach finite element modeling of structures, a well designed facilitating procedure and continuous guidance and support are essential for the success of student learning in this course. Weekly discussions with each group are time consuming, but they are necessary to make sure the students are on the right track.

Conclusions

In this paper, a project-based learning (PBL) approach has been utilised to teach finite element to undergraduate students. PBL has now become a widespread learning method in engineering education, it has many advantages over traditional teaching method to encourage student learning in a more effective and efficient way. However, such methods will require a significant amount of time for the lecturer to design and prepare a project. Project marking is also time-consuming. Nevertheless, we fell that the benefits gained outweigh these drawbacks. Most students enjoyed PBL and many of them become confident with the software and are keen to incorporate it into their final year capstone research and design projects the following year.

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