EXPERIENCES OF FINITE ELEMENT ANALYSIS COURSE ASSESSMENT

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Abstract *— The goal of this paper is to discuss the common assessment experiences of a sample introductory course on finite element analysis (FEA) taught at two different local 4-year undergraduate engineering colleges. The assessment is based on the common course (or student) learning experiences and on the common course topics taught at these schools. Assessment tools such as class work, home work, quizzes, tests, and final project, as well as final exam have been used to assess the performance of the students. Both math and CAE tools have been used for this course. Math tools involve using matrix algebra for most part to solve the equations obtained by either direct stiffness method or by energy methods. CAE tools involve solid modeling components and solving using UG and/or I-DEAS, and/or ANSYS software. Validation of the CAE results by hand calculations is an important aspect of this course.*

Index Terms — CAE, Finite element modeling and analysis.

INTRODUCTION

More and more universities are teaching basics of finite element analysis at the undergraduate level with more emphasis on theory at the graduate level. For the undergraduates though, there should be a balanced approach with basic theory coverage and more simulations using numerical computation. In this paper the experiences gained by teaching this course at two different schools under two different students and class settings is discussed. For most part, common course learning objectives (CLOs) have been identified and the assessment based on those is discussed using charts and tables.

Common Course Learning Objectives (CLOs):

1. apply the knowledge of Matrix Algebra, Statics, CAE and Mechanics of Materials courses to a basic understanding of the Finite Element Method and its engineering applications
2. understand the assumptions and model a given physical system for analysis by the Finite Element Method (Pos:
3. formulate the Finite Element equations for 1-D and 2-D finite element problems
4. familiarize with the math and CAE tools used for the FEA process
5. understand the validation process to correctly interpret the results in a view to make any design changes to a component or a subsystem
6. understand the risks and limitations of FE solutions and simulations

Each CLO is given a weightage while mapping those with ABET's Program Outcomes (POs). For example, CLO 1 is assigned 70% weightage with PO (a), namely, "An ability to apply knowledge of mathematics, science and engineering", 20% with PO (e): "An ability to identify, formulate and solve engineering problems", and 10% with PO (k): "An ability to use the techniques, skills and modern engineering tools necessary for engineering practice". The total weightage for each CLO adds to 100%. Similarly, other CLOs are mapped and weighed with the appropriate POs as conceived by the instructors teaching this course. Both the CLOs and their weightage may have to be changed based on the assessment of the course once every few terms or years as needed. However, the instructors teaching this course would ideally meet at the end of every term they teach to do an assessment report that identifies and acts on the deficiencies in the course topics or its coverage. This is primarily based on the students' performance on each assessment tool (homework, class work, labs, quizzes, tests and project & project presentations).

For the finite element analysis course, normally the main topics of coverage include the following:

Common Course Topics:

Review of Statics and Solid Mechanics; Introduction to structural finite element analysis and modeling; Review of matrix algebra; Direct stiffness method and its application to 1D element problems (axially loaded bars and planar beams); Application of 1D element formulation to planar trusses and planar frames; Applications of 1D element analysis to heat conduction problems; Introduction to energy methods and their application to the solution of 1D problems; Application of 2D formulation to plane stress, plane strain and axi-symmetric problems; Course review.

In this course, math software tools such as MATLAB®, MathCAD® [1 to 3] and Excel® are used mainly to solve the system of linear algebraic equations resulting from the finite element formulation by the stiffness method. FEA

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formulations involve breaking a continuum (real system) in to several smaller bodies called elements that are connected to each other by nodes to model the entire original system. This is called meshing of the model. In so doing, however, it is often impossible to match the finite element mesh with the original geometry of the object being analyzed. The model is constrained using boundary conditions. Boundary conditions for structural analysis include specifying the displacement and load at nodal locations. These are equivalent to the way the real body is constrained using supports and the way the load acts on it. Applying boundary conditions to a finite element model is not an easy task and the final results of an analysis may be different if proper boundary conditions are not used. To summarize thus far, the results of a finite element analysis are only approximate that will never match 100% with exact solutions, if any available. This is true even for the analysis of problems involving simple geometry. In addition to the modeling errors, finite element analysis involves solving the equations using numerical methods, which again yield approximate solutions. Depending up on the type of analysis performed, namely, structural, thermal, dynamic, NVH, etc., validation of results by simple models is necessary.

The goals in FEA are thus to (a) use correct formulations to attain results close to exact results or results from testing, and (b) to achieve convergence of the such results in the fastest time. There are other goals in terms of the development of theory and constitutive relationships to model complex geometries consisting of advanced materials (such as composites), modeling joints (for example, welds), etc. As the technology advances both in terms of computational power and theory, performing FEA has become routine in many industries that engineers with undergraduate education are able to validate and interpret the results of FEA with experimental data or with other models.

A simple structural 1D bar or beam element consists of two end nodes with zero or one or more mid-nodes. Each such element in the linear analysis is treated as an axially-loaded member or transversely-loaded beam (or a combination of these as a beam) for which stress and deflection equations are used. The unknown parameters in FEA are usually the displacements of each node in an arbitrarily selected global coordinate system. Stress in each element is calculated using the deflection values and the material properties (moduli of elasticity and Poisson's ratio). For a detailed FEM and matrix operations procedure, the reader may refer to standard text books; for example, see references [4 to 6].

In addition to the above guidelines and information, at Saginaw valley State University, the format of the FEA course is lecture with embedded interactive workshop sessions. The course is a 3-credit, senior level and a design-elective course. The additional course objectives are:

Gain an understanding of fundamental theory and essentials of FEA; become proficient in efficient modeling and use commercial FEA tools.

Because many student projects in the capstone design courses need to do FEA, this course is offered regularly. The course prerequisites are differential equations and, solid mechanics, computational methods and engineering analysis. Majority of students enrolled in the FEA course are familiar with the heat transfer and fluids topics and it is convenient to assign a wide variety of problems in the homework and as projects.

In the light of the above, a suitable undergraduate textbook for FEA must have the following characteristics:

Formulation is based on matrix methods or the weighted residual approach (Galerkin approach). However, the following types of books should be avoided due to their higher level of topics coverage:

Highly condensed books; Books that are compilation of research results; Highly mathematical-oriented books; Books that are based on variational Calculus; Books without ample examples; Books that contain excessive computer printout of a particular commercial tool; Books that concentrate on only one topic, e.g., structural analysis or thermal problems.

While at Kettering University the students are open to use any CAE software like NX5, I-DEAS, etc., at Saginaw Valley State University, students normally use SolidEdge software in which ANSYS [7, 8] is embedded and the FEA processes are conducted following completion of the model.

Computer facilities:

At both the schools, there are several CAE labs in which the state-of-the-art FEA software is available to students.

Assessments Items:

To some degree of variation, both schools use the following assessment items: Homework and Class work; Quizzes; Math and CAE Laboratory work; Mini-project assignments; Mid-term Exams; Final Exam; Final Project Presentation.

At SVSU, there are at least 14 in-class presentations in which students or a team of two students use the podium to use FEA and analyze a problem. The problem titles and presentation times for individual students are provided in the course syllabus. Students are required to send a power point presentation prior to the presentation to the class and to the instructor. This requirement was added in the fall 2009 semester and seems to be an effective way of learning the FEA and to communicate the results to audience.

Grading Scheme:

Homework Assignments:	100 points
Project Assignments:	50 points
Presentation:	25 points
A Design Problem:	25 points.
Midterm Exam:	100 points
Final Exam	100 points
Total	400 points

A minimum of 280 points (%70) is needed to pass the course with a C-grade.

Observations from course assessment:

Course Delivery

FEA course at Kettering University is a senior level elective undergraduate/graduate (mezzanine level) course offered to full time on-campus students and to part time off-campus students by distance learning mode. The on-campus students are mostly undergraduate students (seniors or those in BS/MS program), with a few full time graduate students. Usually the graduate students get 3 to 4 weeks additional time to complete this course, and hence are expected to do additional graduate level work compared to the undergraduates. Traditionally this course is offered two times a year – as a "Live" course during the summer terms and as "On campus only" course during the fall terms. Offering twice a year covers both the A-Section and B-Section students wishing to take this class at Kettering University. In the "Live" mode, lectures are delivered to the on campus students in a studio room while at the same time the lectures are videotaped (recorded) for later distribution to the off campus students. The "On campus only" classes are taught in a traditional classroom and are not recorded. Therefore, the off campus students wishing to take this course during the fall (or in another) term are sent the pre-recorded video material under a 'Directed Study' option that is available to students. Copy of pre-recorded lecture material is also kept in the university library for reference to the students enrolled in the class.

The number of topics and the amount of course coverage varied depending on the available time, availability and familiarity of using particular CAE tools, and depth of students' knowledge in pre-requisite courses. Undergraduate students being a majority population in this course, usually FEM theory (with math tools) and modeling, analysis and validation by CAE tools is around 50-50 or 60-40, while for graduate students this ratio tends to be 70-30. Following are the observations & course concerns along with remedial steps taken to address the concerns of this course.

Class room facilities and class timing issues versus learning:

The "Live" delivery of lectures during summer term in the video room posed several issues including the passive delivery mode of lectures that made active learning a challenging issue for many students. The Fall term classes are scheduled during mid-day in a regular lecture room or in a computer lab that provided active learning environment. Therefore the above issues for early morning lectures in summer term did not pose major difficulties for the fall term students.

Over the course of two to four three years, many of the summer class issues have been resolved to some extent. As an example,

- Streaming video technology made it easier for almost synchronous learning by the on or off campus students.
- Advanced Math and CAE tools were installed to do FEM demonstrations while covering theory.
- Short answer quizzes are given to hold students attention to lectures and motivation to attend classes.
- Guest lectures from industry experts made the classes more active since a short quiz followed the guest lecture. (this also addresses CLO 6)
- On some days students have been engaged in the CAE lab to do hands on exercises on matrix formulations and solution by a math tool or to do CAE modeling and validation studies. The off campus students are given instructions to do the same learning activities using their own or the university provided facilities for them. (CLOs 4, 5)
- Breaking up the two one-hour block class periods in to several shorter module sessions was considered but could not be implemented.

Course learning issues/Action items:

Although the above mentioned room facilities and class timing issues have been addressed to some extent, there are still course related problems that some students had as follows:

- Many students continue to have problems with basic pre-requisites knowledge – Statics and Mechanics of Materials to decide which mechanics formula (axial, bending or torsion, or combined loading) to use for validation of results. Therefore, considerable amount of time is spent reviewing those while at the same time covering the FEM theory using the same examples, namely, statically determinate and indeterminate 1D and 3D bar and beam formulations and their applications to truss and frame problems. Plane stress and plane strain problems are also covered the same way while

reviewing the Machine Design and stress concentration effects.

- Some students have problems understanding what type of element formulations to use for 1D (truss and frame problems), or 2D problems. This addresses the issue of a clear understanding of the degrees of freedom of each node in a model, as well as the degrees of freedom of the entire structure. Many practice problems have been discussed to address this issue.
- Many students have problems using the appropriate (displacement and load) boundary conditions to a (FEM or a CAE) model. Several worked examples from Statics and Mechanics of Materials textbooks have been discussed to see what type of boundary conditions if used in the FEM formulations (or in the CAE modeling) yield the closest answer as the mechanics textbook answers and why. In tune with this, several real life examples and scenarios have been discussed to decide what type of boundary conditions may be most appropriate to use. For example, what is the effect of clearances in a real pin joint, or a roller support, etc., on the output (nodal displacements, stresses and reaction loads)? This addresses all CLOs to a great extent.
- There were some issues with type of software used versus the renewal of license. When ANSYS was used for this class, delays in renewing the license, budget, as well as installing newer versions and upgrades became an issue partly because of the hardware limitations. Since ANSYS was not part of the PACE program, separate budget was allocated to procure the (limited) university license. Most CAE software was available on unix machines which soon became obsolete. Currently the unix machines are replaced with high end PCs. To address the software issues, it was decided to use either NX and/or I-DEAS with NASTRAN for this class.
- There are some issues with using NX5 for this class since the current (2009) students used NX3 when they took MECH-300 course. MECH-300 course uses only NX, and is not a pre-requisite to MECH-516. On the other hand, MECH-516 students are free to use any CAE tool besides NX, which gives them experience of using an alternative CAE tool. NX3 is no longer available in the CAE lab and hence students seeking to use NX5 or its newer versions may have a learning curve since for example, NX3 and NX5 modeling and structural simulation modules are not quite similar. Also, neither NX3 nor NX5 appear to have proper cast tutorials based on 1D and 2D element modeling that would satisfy part of CLO 4, namely, validation of 1D and 2D FEM (MatLAB/Maple) formulations by a CAE tool. Under these circumstances, many students preferred to use NX I-DEAS or NASTRAN with some learning curve since they both have a few online practice tutorials for 1D, 2D and 3D modeling. Also I-DEAS workbooks developed by private publishers such as S.D. Corporation (www.sdcpublications.com) are available at very moderate cost to students.
- Use of proper mesh size and mesh refinement for obtaining convergence is another issue that was addressed and resolved to some extent by showing them the difference between free and mapped meshing through examples from textbooks and CAE online tutorials.
- Understanding and properly using planar/axi-/cyclic symmetry boundary conditions and the associated theory is still an issue that is partially addressed by showing the worked examples and having them practice the CAE online tutorials.
- The rigor of teaching optimization/redesign, heat transfer and dynamic analyses could not be achieved due to time constraints. However, students practiced few examples using the online CAE tutorials on these topics, and analyzed the simulation results. This satisfies CLO 5 to some extent. However, more time needs to be devoted to cover dynamic analysis.
- Finally, students are provided guidelines and asked to select their own structural component for the final project. However, selection of an appropriate open-ended topic (structural component) that involves ambiguous boundary conditions and design modifications needed based on results obtained, has always been a challenge. They tend to think of components that are too simple to analyze. Therefore more guidelines have been provided on how to select an appropriate component for the project that addresses all CLOs. Where necessary, an engineering component has been selected for them to work on.

As a side note to this, few students always creatively think of a common project topic that addresses different aspects and requirements to satisfy another course(s) they take during the same term, for example, a senior capstone design course (MECH-512 or MECH-514 or MECH-548 or MECH-584) or another ME elective course such as MECH-515 or IME-575. This is a highly desirable as it provides a total learning experience for the students. This aspect should be looked in to and discussed further by the concerned faculty offering those projects to carefully define and differentiate the individual aspects and requirements of each final project so that the students can turn in a single quality report to all courses rather than individual reports for each courses. This minimizes any cheating practices that may arise due to non-coordinated projects by students trying to claim 'double credit' for the same amount of work done for more than one class.

Assessment of Course Learning Objectives (CLOs) and action plan (See Figure 1):

CLO 1:
Students used MatLAB or Excel for the most part of HW/CW/Quizzes and Tests. They used CAE tools to some extent on the Tests but more on the Final Project/practice more HW problems to assemble matrices.

CLO 2:
Still a few students had problems modeling the HW/CW/QZ/Test problems to determine whether to use 1D bar or beam elements to solve the truss or frame problems. Also problems were there in understanding plane stress versus plane strain applications. Action plan included additional discussion of these to show more examples.

CLO 3:
With modeling problems as mentioned above, the stress and deflection values go wrong. Understanding stress concentration effects and remeshing of part geometry seems to be an issue for some students. Action plan included spending more time to discuss these issues.

CLO4:
Use of proper load and boundary conditions on CAE models has always been a problem. Also use of new/upgraded CAE tools in the laboratory posed a learning curve. Action plan included development of more tutorials or use a workbook if using NX3 or NX I-DEAS.

CLO5:
Discussed both direct stiffness method and the energy method for structural 1D elements and 2D constant and linear strain triangles (CST/LST), Quadrature formula. Action plan included more coverage of thermal and dynamic analysis and in more in depth.

CLO6:
It is required that all work be validated using Statics and Mechanics approach. While validating the CAE results, some students have problems with using the correct formula for computing stresses. Action plan included asking the students to review solid mechanics book or to use Internet for material they have problems with.

Figure 1 shows the average performance charts based on homework, class work, quizzes, etc. for the summer of 2008 class taught at Kettering University. The students' overall performance in the course shows a satisfactory level.

CONCLUSIONS

In this paper some of the experiences of teaching the same course at two different engineering colleges is briefly discussed. Assessment procedure has been carried out that indicates some problem areas in students' prerequisites knowledge and also in the course delivery methods. Overall, it was a good experience and new methods of innovative teaching are certainly necessary to keep the motivation of the students learning of this state-of-the-art and industry-standard course.

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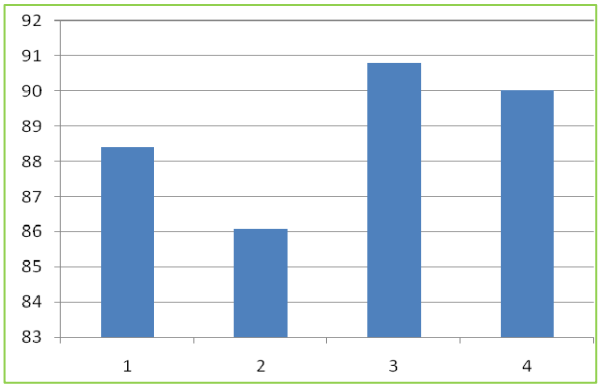

Fig. 1: Overall performance (Summer 2008); Number of students: 29
Chart legend: 1: Classwork/Homework/Quizzes/Labs (40%); 2: Tests (50%); 3: Final Project (10%); 4: Overall grade (100%)