When is a Truss not a Truss: A 'Do-Say' Pedagogical Laboratory Exercise

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Abstract

Contrary to common perception, engineering mechanics in undergraduate education does not need reform. Basic aspects of mechanics (strength of materials, mechanical behavior of materials, experimental mechanics, etc) are still necessary components of any Mechanical Engineering program. However, the delivery system and the tools used by students and faculty in learning and teaching engineering mechanics does need reform. In this paper, an example of such a change in the delivery system and learning tools is highlighted. The course which contains this example is an experiential learning "do and say" environment entitled "Mechanics of Materials Laboratory". The highlighted example is a strain gauged bicycle frame. The premise of the laboratory exercise is that although the bicycle frame appears to be a truss, it is not. This is because many of the assumptions inherent in a truss analysis are violated. Students must prove that the bicycle frame is not a truss by triangulating on proof of their hypothesis (i.e., that the bicycle frame is not a truss) using analytical, experimental and numerical methods. Student surveys and course evaluations indicate that this laboratory exercise is one of their favorites in the course. In addition, students indicate that the exercise is particularly good at helping them "put the pieces together" so as to really understand the subject.

Introduction

Experiential learning is not only "in-vogue" in engineering education, it is an acknowledgment of how human beings assimilate information. Because human beings are tactile animals, we learn best by coupling our sense of touch with our senses of sight, hearing, smell and even taste to provide maximum efficiency to information uptake and utilization.

Communication (oral or literary), when coupled with experiential learning exercises reinforces the information assimilated during the exercises. Indeed the "cone of learning" shown in Figure 1 clearly indicates that greater than 90% retention can be achieved if a learning experience involves a "do-say" aspect. A laboratory experiment with a formal written laboratory report is an example of such a "do-say" exercise. This 90% level of retention is in contrast to only 10% retention achieved through reading only such as in reading assignments out of a text book or an information search on the world wide web. The efficacy of active versus passive learning for increasing retention of new information is shown graphically in Figure 1.

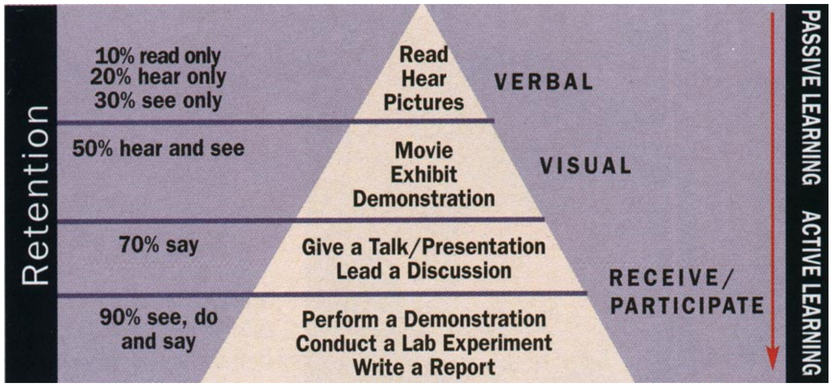

Figure 1 – Cone of learning showing increased retention of information with active learning (from Ref [1])

Engineering mechanics, and in particular, mechanics of materials (MoM), is an essential aspect of any mechanical engineering program. Although it is possible for engineering students to apply the appropriate equations and perform well on homework exercises and exam problems within any academic period, there may be concern about how long students retain their new-found MoM knowledge following the academic period in which they first learned it. This concern is especially important for instructors of courses that require MoM courses as prerequisites.

How much and how well students learn can be assessed if engineering instructors (who seldom have formal training in pedagogy) are cognizant of such concepts as Bloom's taxonomy of cognitive domain[2] and Sousa's illustration of the complexity and difficulty within the taxonomy[3]. The lowest to the highest levels of complexity of the taxonomy include knowledge, comprehension, application, analysis, synthesis, and evaluation. While complexity is associated with the level within the taxonomy, difficulty establishes the amount of effort required within each level[4].

Interpreting the taxonomy from the passive versus active learning illustration shown in Figure 1 implies that acquiring knowledge (lowest level of complexity) can be achieved primarily passively (point of the cone of the learning) but with the lowest level of retention. Evaluating and synthesizing information and concepts (greatest level of complexity) can only be achieved actively (base of the cone of learning) thereby promoting the greatest level of retention.

Thus, experiential learning coupled with communication (e.g., a laboratory exercise followed by a formal engineering laboratory report incorporating description, analysis, and discussion), has long been employed to promote understanding and retention in engineering education. In the past, experiential learning has been employed not because it was dictated by formal training in pedagogy, but also because its efficacy is apparent by observation of the success of students in learning the subject matter.

The advent of new accreditation criteria (EC2000)[5] introduced by the Accreditation Board for Engineering and Technology (ABET) has formalized how engineering instructors view not just teaching, but also how students learn. Program objectives, educational processes, assessment

/evaluation, and feedback are essential aspects of how engineering programs achieve their academic aims. Teaching students to learn as well as assessing how well students learn are integral parts of this new paradigm in engineering education.

In this paper, the background of an evolving "do-say" course in engineering mechanics, ME354 "Mechanics of Materials Laboratory" is first described. Then, one of the exercises (Structures) within ME354 is presented in detail followed by a brief discussion of assessment and evaluation of the success of student learning. Finally, some conclusions are drawn regarding the teaching and learning aspects of this exercise.

Background

Starting in 1995, the Department of Mechanical Engineering at the University of Washington, has revised its curriculum partly to realign the number of required credits for graduation with College of Engineering guidelines, and partly to respond to changing needs of BSME graduates entering engineering practice. Within the Mechanics, Materials and Manufacturing (MMM) interest group a decision was eventually made to combine several lecture-only (ME352) or laboratory-based (ME343) mechanics of materials courses into an expansive experiential-based mechanics of solids/behaviour of materials course (ME354). The rationale behind this move was that a single experiential-based course would promote more retention and enhance student learning by focusing on the active learning mode of "do-say" exercises[1,6].

As shown in Figures 2 and 3, an additional benefit of this curricular change was that students were given more flexibility in option courses. Credits in the remaining MMM courses were also adjusted to reflect re-emphasis of experiential learning within those courses.

Of particular importance in this curriculum revision was the synergism of ENGR220 "Mechanics of Materials" and ME354[6]. ENGR220 is based on computer-driven lecture and tutorial course material, team-oriented quiz/homework sections, and in-class demonstrations. This course lays the groundwork of Mechanics of Materials

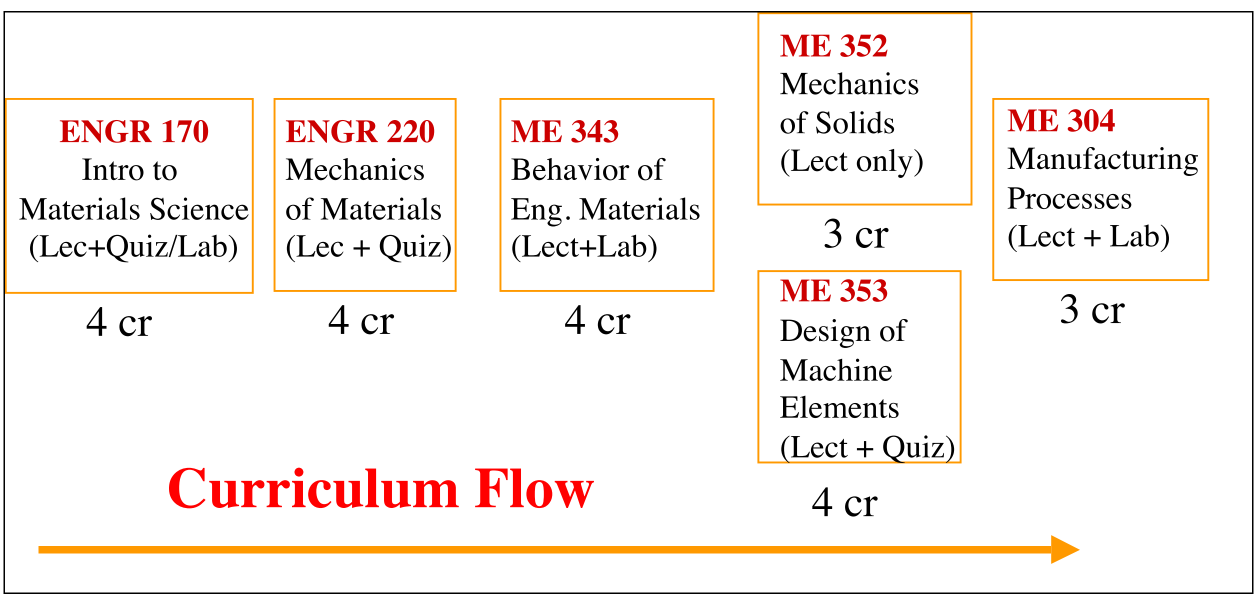

Figure 2 Original curriculum flow within the Mechanics, Materials, Manufacturing interest area

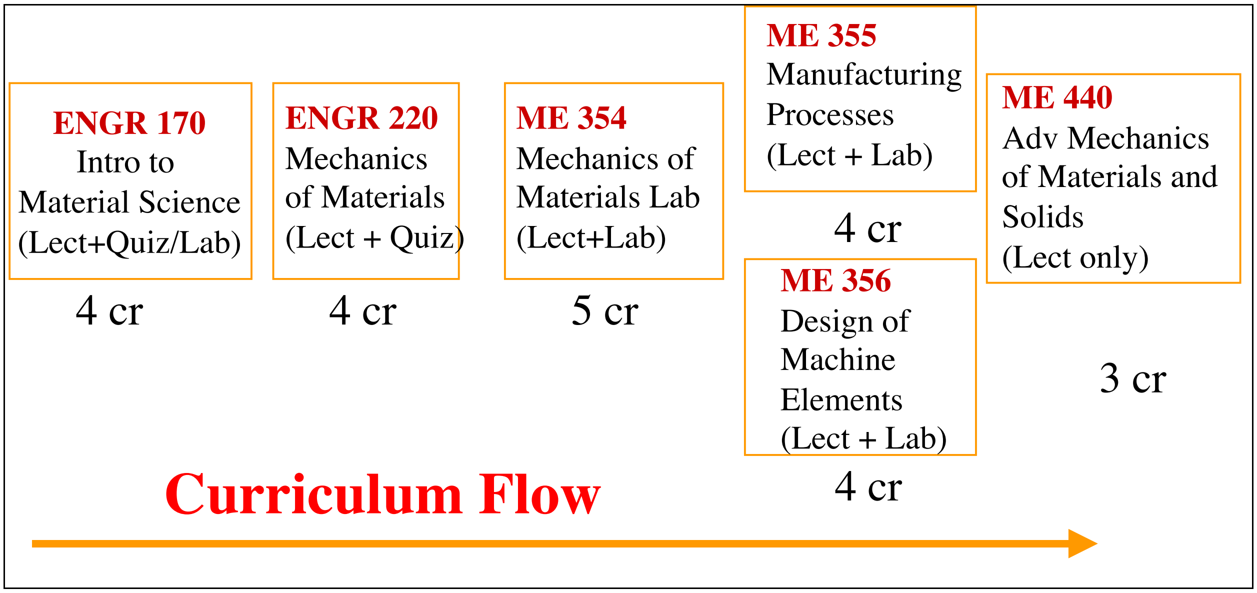

Figure 3 Revised curriculum flow within the Mechanics, Materials, Manufacturing interest area (note that ME354 is the new experiential learning course)

ME354 has an experiential-learning, hands-on laboratory format (see Figure 4) which reinforces concepts of ENGR220 as well as extending basic Mechanics of Materials into more advanced concepts. Web-based course/lab notes, spreadsheet-based solution paths, comparison and contrast of experimental, analytical and numerical solutions are key features.

LABORATORY EXERCISES

1) Measurement, Significant Figures, And Statistics
2) Strains, Deflections And Beam Bending
3) Mechanical Properties and Performance of Materials
   Tension, Hardness, Torsion, Charpy V-Notch Impact
4) Stress Concentrations
5) Fracture
6) Fatigue
7) Creep
8) Structures
9) Compression and Buckling
10) Combined Loading: Pressure Vessel+Tension
11) Curved and/or Non Symmetric Cross Section Beam

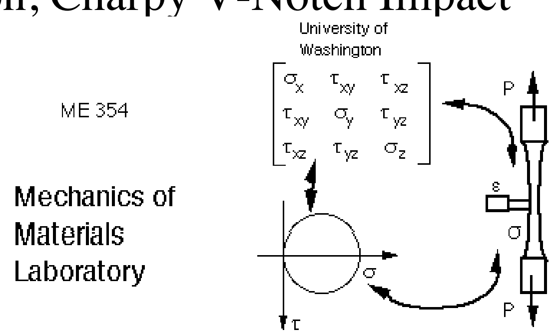

Figure 4 Experiential "do-say" laboratory exercises within ME354

ME 354 involves the application of fundamental mechanics of materials in "hands-on" laboratory exercises. The two pedagogical goals are 1) to "do" the exercises, observing and applying the aspects of mechanics of materials either learned in previous courses or introduced in ME354, and 2) to "say" in formal and informal laboratory reports how basic concepts were applied, analyzed and evaluated in laboratory exercises. The stated learning outcomes for ME354 as follows:

By the end of this course, the student will be able to:

1) List and explain applicable experimental methods for characterizing material and component behavior.
2) Compare (and quantify differences) measured experimental results and calculated theoretical values.
3) Predict component behavior using experimental test results and engineering formulae.
4) Analyze experimental data, theoretical models and their scalability to components.
5) Analyze (deduce) the inherent variability of materials subjected to multiple modes of loading and apply the results to component behavior.
6) Formulate a solution path for analyzing an actual multi-component structure using experimental, theoretical, and numerical tools/methods.
7) Evaluate the limits of structures by extending the experimental measurements using theoretical and numerical methods.

Subsequent to the introduction of ME354, a similar course, partly based on the successes of ME354 was introduced at the University of Maryland Baltimore County. This course, ENME 331 "Mechanics of Deformable Solids Laboratory" features a refined version of the Structures laboratory exercise discussed in the following section. Due in part to the success of this pedagogical approach, a laboratory exercise has been introduced in ENME 331 centered around the currently popular scooter to highlight the treatment of dynamic loads in structures.

Structures Laboratory Exercise

Within ME354, there are two types of experiential laboratory exercise reports/exercises: in-lab pre-formatted reports and formal engineering laboratory reports. Both these types of exercises emphasize the hand-on aspects of the exercises by requiring students to examine, set up and operate apparati. In addition, team work is fostered by arranging students in groups to act as leaders, operators, recorders, and calculators. In the pre-formatted reports, students are not only guided through calculations using their measurement results but are asked both directed and open-ended questions to stimulate the analytical, synthetical and evaluative levels of their cognitive domain. In the formal laboratory reports, students are encouraged to work collaboratively on the analysis and interpretation, but ultimately each student must generate an individual laboratory report, thus stimulating the same cognitive domain levels, but uniquely.

The Structures laboratory exercise is the subject of this paper because it has been found to strongly reflect the "do-say" aspects of the active learning base of the cone of learning by incorporating all six levels of Bloom's taxonomy.

In this exercise, the question is posed "When is a truss not a truss?" in regard to a bicycle frame subjected to a static load. The overall purpose of this exercise is to the study the effects of various assumptions in analyzing the stresses and forces in an engineering structure using engineering mechanics, experimental mechanics, and numerical modeling. The learning outcomes are as follows:

By the end of this exercise, the student will be able to:

1) List the necessary assumptions and apply a simple truss analysis to a bicycle frame.
2) Apply an appropriate energy method to determine the deflection at a designated point in the bicycle frame using the results of the simple truss analysis.
3) Use strain gage conditioning equipment and dial indicators to experimentally measure relevant strains and deflections on an instrumented bicycle frame.
4) Apply appropriate transformation and constitutive relations to obtain stresses at strain gage locations.
5) Interpret results from a numerical model (finite element analysis) of the bicycle frame to extract relevant stresses and deflections.
6) Compare the analytical, empirical and numerical results and evaluate the appropriateness for each in describing the stress state and deflection of the bicycle frame.

Students are first asked to review what they know about truss structures including the assumptions of pinned joints, members that are uniformly, axially-stressed only, externally-applied forces at joints only. Several examples of truss structures (including bridges) are examined either directly or through photographs. Students are then asked to examine a bicycle frame and note the similarities between a truss and the bicycle frame: triangular sections and reaction loads at the axles. Next, the dissimilarities between a truss and the bicycle frame are discerned: lack of pinned joints and nonuniform, non axially-stressed members.

After making this comparison/contrast of a truss and a bicycle frame, students are asked to hypothesize that a bicycle frame is not a truss and, therefore, probably cannot be analyzed as such. Three methods are then employed to prove or disprove this hypothesis: analytical, experimental, and numerical.

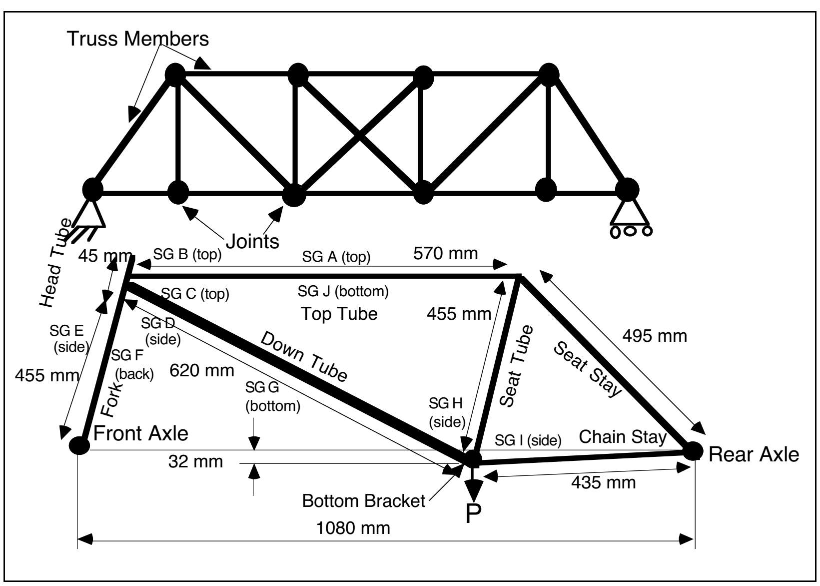

Figure 5 Comparison of truss and assumed lengths and angles of bicycle frame for truss analysis

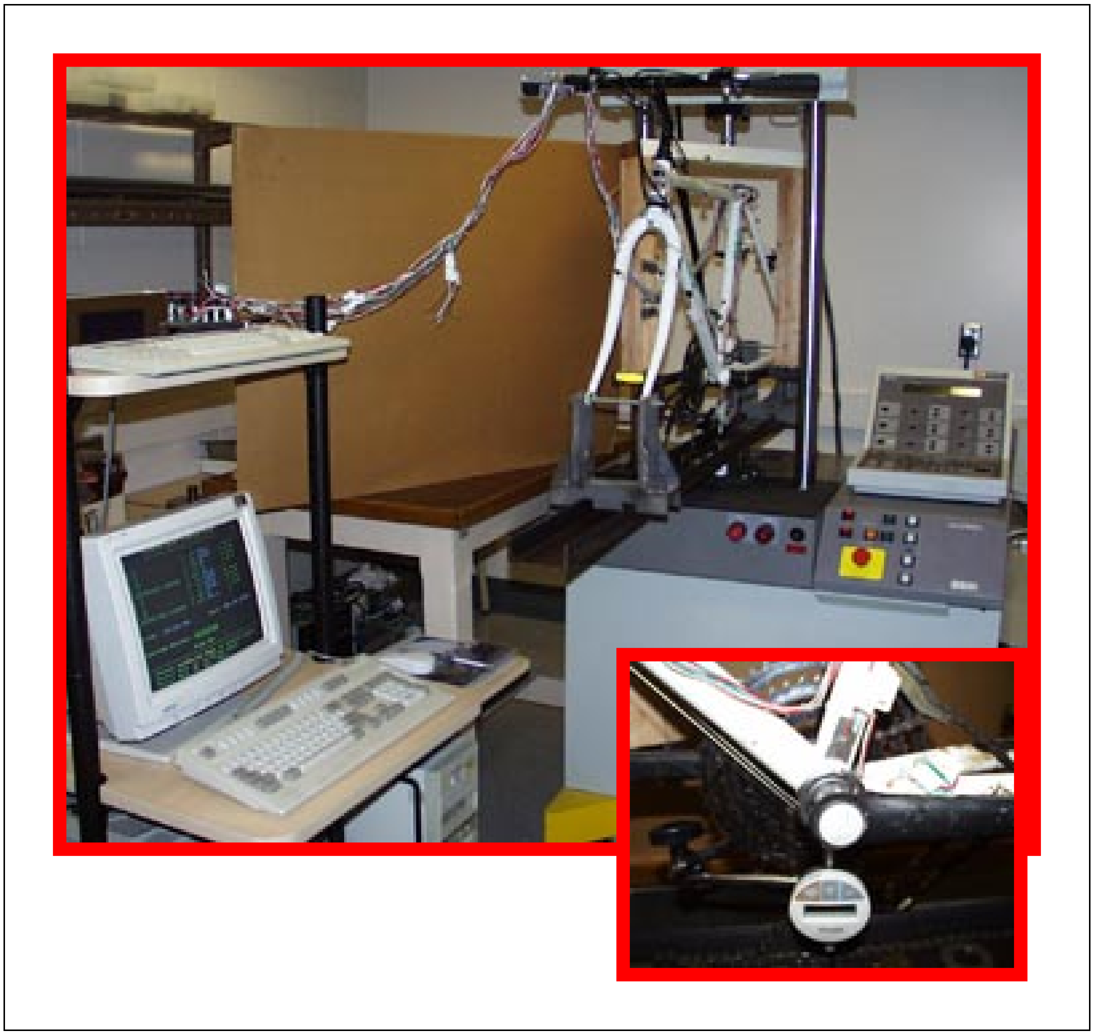

Figure 6 Experimental setup showing the strain-gauged bicycle frame mounted in a universal test frame (inset shows displacement measured at the bottom bracket)

Analytical: Similarities of a simple truss to the bicycle frame are noted. Assumptions regarding the reaction and loading points are made such that the resulting planar truss is statically determinant (i.e., b=2j+f-r where b=number of members, j=number of joints, f=special conditions, and r=number of reactions) and geometrically stable (det A=0 where A=matrix of direction cosines for the equilibrium equations). After the reaction forces are determined, the force in each member is determined using the assumed lengths and angles of each member and the appropriate truss analysis (see Figure 5). Finally, the unit load method is used to determine the deflection at a designated point (e.g., bottom bracket).

Experimental: The ten locations at which rectangular rosettes have been applied to the bicycle frame are identified (see Figure 6). Selected strain gages are connected to the conditioning equipment. A dial indicator is positioned at the same location on the bicycle frame as that designated for the unit load method. The outputs from the instruments are zeroed with no load applied to the frame. A load representative of a rider and equipment (50 to 80 kg) is applied to either the pedals or the seat and the strains and deflection are recorded. The load is removed and any changes in the zero points are noted.

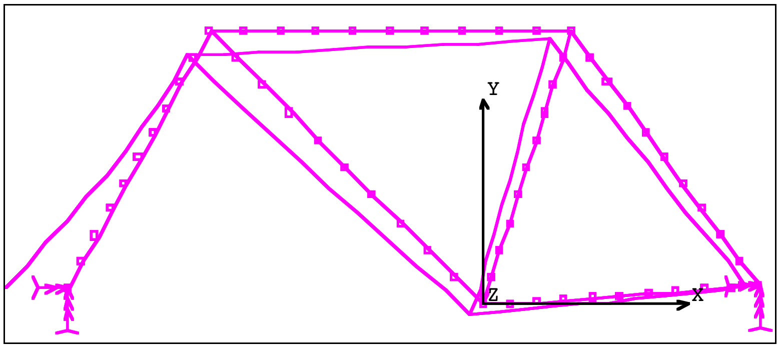

Figure 7 Numerical (FEA) model of bicycle frame in undeformed and deformed states.

Numerical: The results from a simple finite element model are made available through the course website. The 90 “pipe” elements (with dimensions similar to those for the relevant bicycle frame tube) are connected through 88 nodes in a linear elastic three dimensional model (see Figure 7). Boundary conditions are applied to vertically and horizontally, but not rotationally, constrain the reaction points to approximate the experimental conditions. The results (i.e., elemental and nodal forces, stresses and deflections) in tabular and graphical form are made available in digital file format.

Once all three methods have been completed, the results are compared to ascertain whether the validity of the hypothesis that the bicycle frame is not a truss. Generally, students conduct the experiments and perform the analyses and interpretation of the results as small teams. However, each student must write an individual formal report containing the following sections: executive summary, introduction/objectives, description, results, discussion/conclusions, and appendices.

Assessment/Evaluation

The success of this “do-say” exercise in achieving the objectives and learning outcomes is assessed several ways: formal engineering report, targeted exam questions and discussions in a post laboratory recitation section. Evaluations of the success of the exercise occur through comparisons of grades for the Structures lab report to grades for other lab reports completed in ME354 during the same academic period, feedback from student course evaluations and individual interviews with students. In the three academic years since the Structures laboratory has been in place, approximately 165 students per year for a total of 495 students have participated in this exercise at the University of Washington.

Assessment: Typically there are two to four formal engineering laboratory reports during the course of the quarter in ME354. Individual students generally score about ten percentage points greater for the Structures laboratory report as they do for the non Structures reports. Exam questions directly aimed at the Structures laboratory have not been as straight forward to interpret, although students are generally able to connect the exam questions to the laboratory exercises. During the post laboratory recitation section, students are asked questions about the laboratory and are allowed to opine on the results and their interpretation. No formal assessment measures have been put in place for this part of the course although anecdotally, students express satisfaction with the flexibility of this lab exercise for analyzing and interpreting the results (i.e., this is not a “canned lab”).

Evaluation: Of the two to four formal engineering reports required per academic quarter, the mean scores for the non Structures reports are in the 70 to 80% range. The mean scores for the Structures reports are in the 80 to 90% range. This difference in grades is directly linked to students' performing a more complete and in depth analysis and evaluation of the results of the exercise. Course evaluations completed by students are comprised of two parts: fixed questions for the broad range of questions requiring numerical answers (range of 1 (very poor) to 7 (excellent)) and fixed, but general, open-ended questions requiring written responses. Little information regarding individual laboratory exercises can be gathered from the numerical answers, however students often offer opinions on what contributed most to their learning. In this case, the Structures laboratory report is often cited as a positive experience. Finally individual interviews with students that specifically target the Structures laboratory exercise have been quite revealing. Comments such as, "fun," "most useful," "putting the pieces together," "pertinent," and "realistic" have been extracted from these interviews.

Conclusions

Experiential learning based on "do-say" active learning exercises have been shown to be beneficial in many aspect of engineering mechanics. A revision of the Mechanical Engineering curriculum at the University of Washington resulted in a new experiential learning course, ME354 "Mechanics of Materials Laboratory." Within this course a particularly successful activity has been the Structures laboratory exercise which allows students to determine the answer to the question "When is a truss not a truss?" in regard to a bicycle frame using analytical, experimental and numerical methods. Assessment and evaluation methods applied to this course and the Structures laboratory exercise, in particular, have validated the efficacy of the "do-say" active learning concept.

Acknowledgment

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Biographical

Michael G. Jenkins is an Associate Professor in Mechanical Engineering at the University of Washington (UW) in Seattle. He is the developer and on-going coordinator of ME354 “Mechanics of Materials Laboratory” at UW. He is also the chair of the Departmental ABET subcommittee and has been an advocate of the active learning and teaching philosophy in support of the Department’s Program Objectives per ABET EC2000. Prof. Jenkins is a registered professional engineer in Washington and is actively involved through leadership roles in national/international committees such as ASTM, ASME, and ISO. Prof. Jenkins received his BSME from Marquette University in 1980, his MSME from Purdue University in 1982 and his PhD from the University of Washington in 1987. He worked nearly 3 years at the PACCAR Technical Center as an R&D engineer and nearly 5 years at Oak Ridge National Laboratory as a development staff member before joining the faculty at the UW in 1992. His research and teaching interests include characterization of advanced materials (e.g., ceramics), experimental mechanics, data base development, and probabilistic design and reliability.

Dwayne A. Arola is an Assistant Professor in Mechanical Engineering at the University of Maryland Baltimore County (UMBC). He is the director of Laboratory for Advanced Manufacturing and Production (LAMP). He has also been instructor and co-developer for ENME 331 “Mechanics of Deformable Solids Laboratory” at UMBC in which he implemented many of the lessons from ME354 at UW. Prof. Arola received his BSME, MSME, and PhD from the University of Washington in 1989, 1991 and 1996, respectively. His research and teaching interests include advanced manufacturing, experimental mechanics and materials, and the influence of net-shape machining to the performance (fatigue and fracture behavior) of engineering and biological materials.