ASEE's 123rd Annual • Conference & Exposition • New Orleans, LA • June 26-29, 2016

New Orleans JAZZED about Engineering Education

Paper ID #14512

Inquiry-Based Learning to Explore the Design of the Built Environment

Ms. Anahid Behrouzi, University of Illinois, Urbana-Champaign

Anahid Behrouzi is a doctoral student of civil engineering at the University of Illinois at Urbana-Champaign. She has been involved with STEM education beginning in 2003 as a volunteer and summer instructor with the North Carolina Museum of Life and Science. She has been engaged with undergraduate/ graduate course delivery in the topic areas of engineering problem-solving, structural engineering, and reinforced concrete design at North Carolina State University (2008-2011), the University of Illinois at Urbana-Champaign (2012-2015), and Tufts University (2015-present). She has a BS in civil engineering and BA in Spanish language & literature from North Carolina State University, and a MS in civil engineering from the University of Illinois at Urbana-Champaign.

Prof. Daniel Kuchma, Tufts University

Dan Kuchma is a Professor of Civil and Environmental Engineering (CEE) at Tufts University. He obtained his PhD from the University of Toronto, and was a professor at the University of Illinois from CEE from 1997-2014. He serves in professional capacities at the American Concrete Institute, the International Concrete Federation, and the International Electrotechnical Commission. He areas of academic interest include the design, modeling, and analysis of structures, and how students can gain insight into structural engineering through demonstrations and hands-on experiences.

Inquiry-based Learning to Explore the Design of the Built Environment

Abstract

Typically in introductory structural engineering courses with a lab component, the instructional approach is to present the underlying theory via pre-lab lecture/reading and subsequently have students conduct guided experiments that affirm that theory. The new Fall 2015 course offering described in this paper took the reverse approach where students' hands-on exploration of a concept occurs prior to formal instruction. In the course, student exploration of fundamental structural engineering concepts was facilitated through the following activities: (i) full-class physical demonstrations led by the instructor during lecture, (ii) small-group experimentation in a laboratory setting, and (iii) case studies highlighting both failures and exemplary natural/engineered structures presented via instructor lectures and supplementary multi-media materials. The objective of this paper is demonstrate how the "exploration before theory" approach can be implemented and what is required to accomplish the hands-on, inquiry, discussion, and formal teaching aspects that comprise this teaching style. Associated with this objective, the authors will also share student feedback on the course that was collected through mid- and end-of-semester surveys for nearly twenty undergraduate students. The authors believe that a classroom environment that emphasizes discovery – where students act as researchers and play an active role in building their own knowledge – is a format that can be readily adapted to other engineering disciplines; furthermore, it can inspire higher-level thinking and lead to a more engaging learning experience.

Introduction

In a status report prepared for the National Research Council's Board of Science Education, Fairweather[1] states there is prevailing evidence that there are greater student learning gains in Science, Technology, Engineering, and Math (STEM) undergraduate classrooms when active and collaborative instructional strategies are utilized; these are commonly referred to as inductive teaching methods as compared to traditional lecture and discussion (deductive). However, this document indicates that for more systemic change across STEM instruction, researchers need to develop/evaluate pedagogical innovations that do not require substantial external funding or time, and therefore can be easily adopted by other educators.[1] This was one of the motivations for undertaking the study presented in this paper.

The inquiry-based learning activities described in this paper address the necessity for engaging, student-centered experiences in the freshman civil/structural engineering curriculum with a relatively modest financial and time investment consistent with an equipment-light laboratory course. In particular, the course is based on an "exploration before theory" teaching approach where students participate in guided inquiry associated with experiments/demonstrations to discover fundamental engineering concepts before formally being taught the underlying theory. As such, the course is founded upon Leonardo da Vinci's perspective that: *in the examination of physical problems I begin by making a few experiments,…we must commence with experience, and strive by means to discover truth.*[2]

The course aims to motivate students' interest in structural engineering as to train them to become more self-directed investigators and designers. This is consistent with the development of skills identified by the engineering accreditation board (ABET) in Criterion 3, including:

(a) apply knowledge of mathematics, science, and engineering;
(b) design and conduct experiments, as well as to analyze and interpret data;
(e) identify, formulate, and solve engineering problems; and
(g) communicate effectively.[3]

This paper provides details of the course under investigation including: a high-level description of the inquiry-based learning techniques used in the class, particulars on a selection of effective activities the instructors developed, a student assessment of the pedagogical approach, and lessons learned from this research study.

Institutional Context & Details of Course

The research described in this paper on this course *Design of the Built Environment* (ES 0093-11) was conducted at Tufts University, a private research institution which offers eight ABET accredited Bachelor of Science degree options in engineering. The freshman year, fall semester curriculum for each of these degrees includes an introductory engineering elective (ES 0093). During the research study's period of Fall Semester 2015, nine such course sections were offered from faculty across the School of Engineering [biomedical (1 course offering), civil (2), electrical (2), environmental (1), mechanical engineering (1), and computer science (2)] with topics ranging from music/art in engineering to basic robotics. In general these courses aim to provide students with an interdisciplinary perspective of a given field by: introducing fundamental engineering theory, examining historical/innovative design examples, as well as engaging students in hands-on laboratory and project activities. Students can select from any of the ES 0093 offerings; however, many utilize this opportunity to sample their intended major, or for those who are undecided, to investigate one of many potential engineering options at the university.

The initial offering of *Design of the Built Environment* (hereafter "*DBE*") in Fall 2015 was intended to fill a void in the first year curriculum, as there was no structural engineering ES 0093 option provided in Fall 2014 and offerings in prior years emphasized specialized topic areas of bridge engineering or structural art. The *DBE* course was a broad survey of (i) structural response (tension, compression, shear, torsion, bending); (ii) failure mechanisms (fracture, buckling); (iii) common structural systems (beams, trusses, arches, domes, tension structures); and (iv) dynamics. The wide scope of the course generally appealed to prospective civil/mechanical engineering and architectural studies students. Of the 20 enrolled students, 18 were freshman and 2 were juniors, while 15 were in the School of Engineering and 5 were in the College of Liberal Arts (including both juniors). The group had a range of backgrounds in math/science subjects: some having recently completed advanced calculus and physics courses in high school, others that were concurrently enrolled in these classes while taking *DBE*, and yet another set who had these classes two years prior as freshmen. Understanding the class population will become relevant when examining student feedback on course activities and overall teaching efficacy.

Course Structure

General Pedagogical Approach

The *DBE* course curriculum was developed on the premise of "exploration before theory" where students take part in hands-on investigation (via small group experimentation or class demonstrations) prior to formal instruction on a topic. The objective was to encourage ***deep-level processing*** by requiring students to observe and evaluate cause-effect relationships to address questions or problems posed by the instructors, and in doing so, they began to construct new knowledge related to structural engineering concepts.[4] The course instructors believed that a combination of inquiry-based/inductive learning activities and traditional deductive teaching (lecturing on basic principles, discussing associated mathematical models, working through examples, etc.) would be very effective based on Prince and Felder's[5] discussion of introducing young undergraduate learners to inductive learning methods. A balance between inductive/ deductive methods in the *DBE* course was anticipated to provide students with adequate structure to effectively engage in inquiry, while insuring that the conclusions they formulated from these experiences were complete and accurate.

Details of Course Pedagogy

During the initial class sessions of this course, the instructors discussed the syllabus and course emphasis on inquiry-based learning. Students were informed that they would be given open-ended questions to explore by observing instructor demonstrations or conducting experiments themselves. For the latter exercise, student teams were told they would be provided with experimental equipment and specimens, but would be expected to develop and document their test procedure, data collection and analysis methods, as well as observations/conclusions in a laboratory notebook. The instructors explained that their own role for these activities would be as facilitators to track groups' progress and answer questions (students were not told the instructors also intended to be motivators in instances when students felt confused/frustrated). Formal lectures followed the activities to help students interpret and organize their new-found knowledge in the context of structural engineering theory. This deliberate discussion of inquiry-based learning attempted to address the need for ***customer buy-in*** as described in Buch and Wolff[6] by making students aware of what inquiry is and their role in the inductive learning paradigm. Additionally, the instructors wanted it to be clear that the *DBE* course was intended to promote self-directed investigation (like that practiced by leading scientists and engineering researchers), rather than providing extensive, step-by-step guidance similar to what they may have received in high school.

The 14-week course consisted of two 75-minute sessions each week. The topics/activities for each week and their type classification(s) are listed in Table 1. In this table, classifications A-C were developed by the authors to describe teaching approaches used in the *DBE* course that range from fully deductive to a combination of deductive/ inductive; D-G are based on the inquiry classification scheme proposed in Tafoya et al.[7] and expanded by Staver and Bay[8]; and H-L are drawn from a comprehensive review of inductive teaching approaches assembled by Prince and Felder[5]. In general the classifications are listed left to right in Table 1 ranging from deductive to increasingly self-directed, inquiry-based methods. The remainder of this section will define each classification in the context of the *DBE* course.

Table 1. *DBE* Course topics/activities and associated pedagogy classifications

Week	Topic/Activity	(A) Theory-based Lecture	(B) Case-based Lecture	(C) Instructor Demonstration	(D) Confirmation	(E) Structured Inquiry	(F) Guided Inquiry	(G) Open Inquiry	(H) Problem-based Learning	(I) Project-based Learning	(J) Case-based Teaching	(K) Discovery Learning	(L) Just-in-Time Teaching
1	Tension Response of Rubber band						X						
2	Tension Response of Construction Materials	X											
	Bending/Curvature of Beams						X						
	Compressive Response of Household Materials					X							
3	Compressive Response of Construction Materials	X											
	Torsion/Shear Behavior & Failure Modes	X		X [v]									
4	Rotational Equilibrium[#]					X	X						
	Rotational Equilibrium & Statics Review	X		X [e]									
5	1-D & 2-D Force Equilibrium					X							
	3-D Force Equilibrium[#]						X						
6	Parameters Effecting Beam Deflection/Stiffness					X							
7	Beam Deflection & Euler-Bernoulli Beam Theory[#]	X		X[v]									
	Introduction to Trusses	X		X [v,e]									
8	Building Truss Bridges[#]								X				
	Arches & Domes	X	X	X [v]									
9	-- Midterm Review & Midterm --												
10	Tension Structures	X	X	X [v]									
	Strain Energy & Fracture[#]	X	X	X [v]									
11	Buckling	X	X	X [v,e]									
12	Structural Dynamics	X		X [v]									
	Final Projects (Teams/Topics known in Week 11)								X	X			
13	Final Projects								X	X			
	Frontiers in Structural Design	X	X										
14	-- Final Exam --												

[#] Students completed homework assignment associated with topic.

[v] Demonstration involved **v**isual aid (physical model or table-top experiment).

[e] Demonstration involved calculation **e**xamples.

A. ***Theory-based Lecture*** – lecture using projected slide-set or chalk-and-talk that focused on: concept definitions, basic figures, free-body diagrams, mathematically or empirically derived equations, and data graphs or videos describing material/structural response. These lectures sometimes contained superficial coverage of research or field examples. Student engagement was mostly through think-pair-share discussion to respond to posed questions.

B. ***Case-based Lecture*** – lecture using projected slide-set to present basic figures, free-body diagrams, photographs, and videos related to a ***specific*** structural engineering case study (project or failure). Examples of covered topics included the collapse of the Quebec bridge in 1907 and the Hyatt Regency walkway in 1981, the sinking of the Titanic in 1912, and the design of Burj Khalifa (world's tallest building in 2009). This was often accompanied by an ***Instructor Demonstration***. Student engagement was primarily via think-pair-share where students were asked to predict how design decisions affected a structure's performance. Note: This is distinct from classification (J) ***case-based teaching***.

C. ***Instructor Demonstration*** – consists of two sub-categories designated in Table 1 by subscript ***v*** and ***e***:

v – Use of visual aids (physical model or table-top experiment) which were presented to the full class as a supplement to content in a ***theory-based*** or ***case-based lecture***.

e – Calculation examples which often progressed through three stages where instructor(s): (i) presented fully worked out examples, (ii) solicited student input when completing similar but more complex examples, and finally (iii) provided students with problems to work on in small groups with limited instructor intervention.

D. ***Confirmation*** – inquiry-based, student-centered exercise where the intended outcome of the known *a priori* and the directions for the activity were detailed explicitly. This inquiry technique was ***not*** used in the *DBE* course since it violates the "exploration before theory" approach and does not allow students to engage in self-directed investigation and/or design.

E. ***Structured Inquiry*** – cooperative laboratory activities where the instructor(s) posed question(s) to student teams and *provided them with the procedure/materials to accomplish the task(s)*. The students did not know the solution(s) in advance, but the activities were structured so they were able to collect data that would help them identify specific relationships and enabled them to draw conclusions related to the engineering concepts under investigation. The authors believe that this is the first stepping stone for young undergraduate students accustomed to the ***confirmation*** approach to laboratory exercises.

F. ***Guided Inquiry*** –cooperative activities where *teams were responsible for determining the experimental procedure and types of data to collect* in order to address the instructor-posed question(s). Guided inquiry was more open-ended and allowed for greater creativity on the part of the students. The instructors tended to utilize this approach when the engineering topic under investigation was rather straightforward. In some cases, a single laboratory had portions that were structured and others that were guided.

G. ***Open Inquiry*** –activities where the students generate both the problem statement and the approach for addressing it. This technique was ***not*** used as the instructors felt that it was too advanced based on the students' knowledge of engineering theory, and that it would not be effective in terms of time versus learning gains (or amount of incurred frustration).

H. ***Problem-based learning*** – collaborative exercises (associated with the course final project) where students selected an open-ended, realistic problem from a set of prompts prepared by the instructor(s). In developing their solution, teams were expected to apply knowledge they had gained throughout the course, seek out external resources, and utilize instructors as a sounding board for their ideas or for fabrication assistance. The problem-based learning approach was combined with ***project-based learning*** in what is more commonly referred to as ***hybrid problem/project-based learning***.[5]

I. ***Project-based learning*** – this collaborative approach expanded upon ***problem-based learning*** by requiring teams to execute a series of tasks in order to produce a final design that addressed their specific engineering problem. Teams responsible for communicating their design process and solution via written/oral presentation. The projects ranged from ***task*** to ***discipline projects***. The former is where the instructor defines the problem statement and largely outlines the solution method, while with the latter the instructor defines the subject area and provides comments on general solution approach(es) that can be used.[9] These project types were deemed very appropriate for the limited engineering knowledge of students and the short timeline allotted for completing the final project.

J. ***Case-based Teaching*** – activities where instructors provide students with a historical or hypothetical case study requiring them to conduct technically rigorous, multidisciplinary analysis or problem solution approach. ***Case-based lecturing***, rather than case-based teaching, was used in the course because the freshman students had limited engineering analysis/design experience. This alternative allowed for the learning gains (and student interest) of examining complex authentic case studies, and better coincided with the students' ability level.

K. ***Discovery Teaching*** – similar to ***guided inquiry*** where instructors pose questions or problems for students to address; however, they provide no guidance to the students as they engage in the inquiry process. The instructors selected guided inquiry <u>***instead of***</u> this approach. Literature indicates that discovery teaching is effective when an inquiry task relates to previously learned principles[5], which is not consistent with the "exploration before theory" objective of the *DBE* course. Furthermore, guided inquiry has shown to be more efficient and as effective in acquiring new skills/knowledge to discovery teaching.[10]

L. ***Just-in-Time Teaching*** –Web-based exercises that students complete before class which quizzes them on textbook or supplemental readings, videos, conceptual questions, etc. The instructor reviews the student submissions shortly before the class session and modifies their teaching material accordingly. Instructors did <u>***not***</u> utilize this approach; there were instances where student questions during office hours impacted the content of the subsequent class session, but this was not a formalized or Web-based practice.

Note: For the topics/activities associated with classifications A-C, class was held in a standard lecture hall; all other activities (E, F, H, I) took place in a laboratory classroom.

Description of Inquiry-based Learning Activities

Classroom/Laboratory Setting Exercises

The following section includes a description of select inquiry-based activities developed for the *DBE* course:

- ***Load vs Deformation (Stress vs Strain) Response of Household Materials:*** Students were asked to qualitatively/quantitatively predict and then test the tensile response of a rubber band, and the compressive response of marshmallows, sponges, wafer (composite) cookies, spaghetti noodles, drinking straws, and eggs. The second group of materials shows a range of compression behavior including: splitting, buckling, crushing, and interface failures. Additionally some materials showed a propensity to creep over time or to exhibit early out-of-plane instabilities during loading.

- ***Rotational equilibrium:*** Students were provided a wooden board of known mass/length, a wooden pivot, and assorted masses. Students were to describe rotational equilibrium algebraically by conducting a variety of studies. With the pivot at the mid-span of the board, students determined how to balance masses of various magnitudes/ locations on one side of the pivot with a single mass on the opposite side. They repeated this activity with multiple masses on the opposite side, and finally when the pivot was relocated. After developing an understanding of how to express rotational equilibrium in terms of forces/ distances, students utilized their knowledge to determine the unknown mass of an object.

- ***Force equilibrium***: Students were provided with rope, tension scales, and an assortment of masses to investigate 1-D, 2-D, and 3-D force equilibrium (as shown in Figure 1). The 1-D force exploration was posed as a team tug-of-war where a tension scale was placed between every individual pulling on the rope, and students could examine their contribution to axial force. The 2-D and 3-D cases involved hanging a known mass from ropes at multiple orientations either within a plane or in 3-D space and taking measurements to compare to their equilibrium calculations for the system.

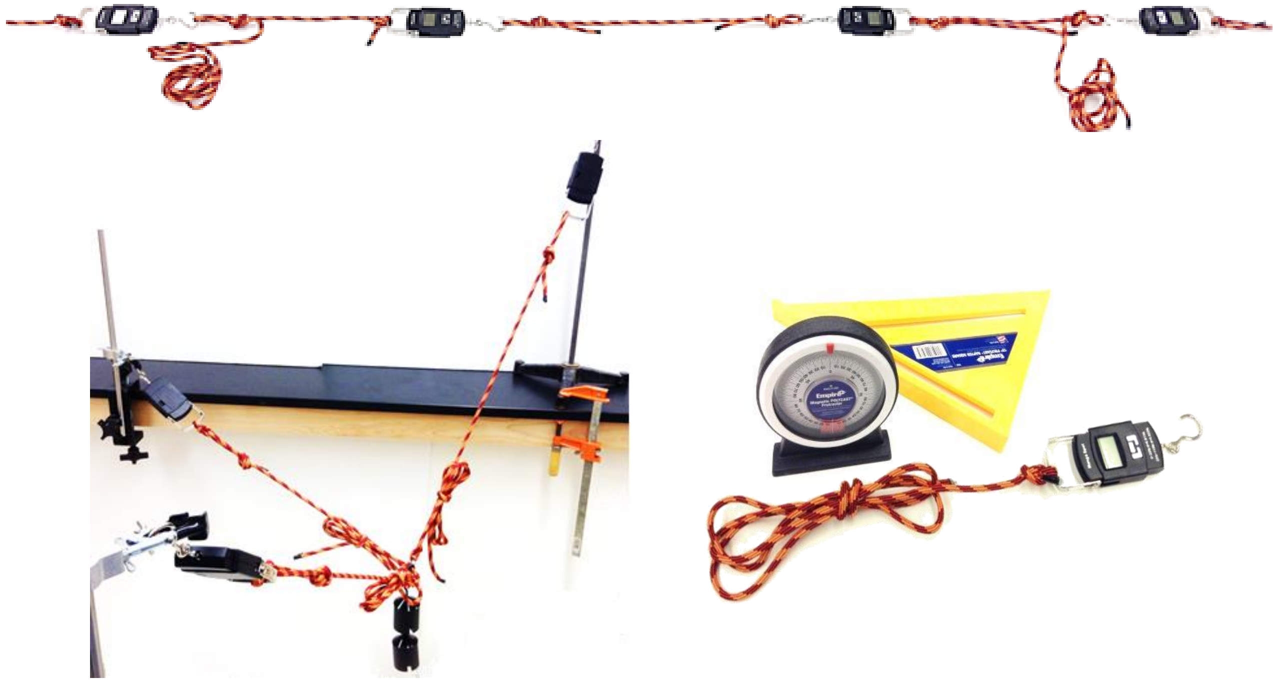

Figure 1. Force equilibrium activities: (Top) 1-D Equilibrium “Tug of War”, (Bottom Left) 3-D Equilibrium, (Bottom Right) Force & Angle Measurement Devices

- ***Beam Deflection/Stiffness:*** Students were provided multiple beams consisting of flat vinyl trim molding material to predict and investigate the deflection of beams with different thicknesses (one vs. two stacked or glued layers, as shown in Figure 2), geometries (rectangular vs. square), lengths (0.75m vs. 1.1m), boundary conditions (simply supported vs. fixed-fixed), and loading (concentrated vs. distributed loading). Beyond general observations, students were asked to use deflection measurements to quantitatively determine effects of length, height, width, and load distribution.

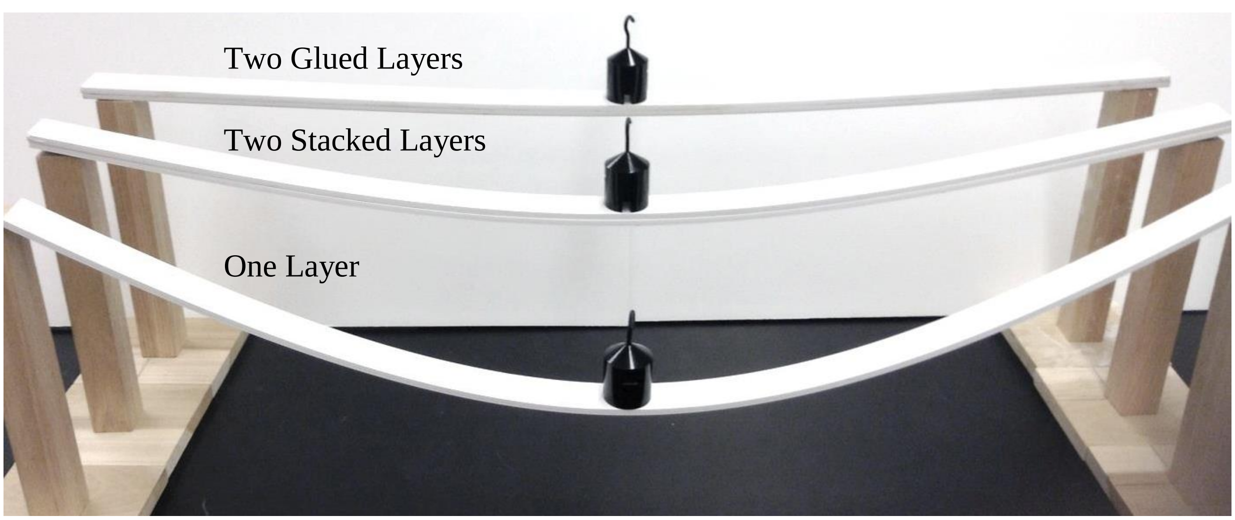

Figure 2. Beam Deflection/Stiffness activity (*example with effect of different thicknesses*)

- ***Strain Energy & Fracture:*** Students were asked to predict and examine the response of a thin aluminum yardstick with sharp and round-tipped notches that had been cut near the location of the fixed support; the yardstick was loaded at the free-end using hanging masses. Students were able to observe the effect of stress concentrations and the phenomena of crack propagation. This activity alluded to the design of the expansion joints of the Titanic and allowed students to consider the physics of this historic failure.

Other demonstrations or hands-on activities included the class were: torsion of a circular cross-section[10], effective buckling length based on boundary conditions[11,12], and fundamental structural dynamics with a "lollipop model"[13].

Final Projects

The final projects consisted of seven topic/problem areas listed below. A brief description of how the student team decided to address each design challenge is also included:

> ***Project 1:*** Design of a 20-foot long portable truss bridge that would support the weight of one student and included calculations to determine capacity of the truss members.
>
> Students conducted material tests to evaluate tensile/compressive strength of provided construction material. They decided to use a Pratt truss form and used method of joints to determine the critical load in each member based on the location of the human load (with safety factor of approximately two). The cross-sectional area of each member was selected to meet both estimated tensile and buckling demands. Figure 3 is a class photograph during the team's final presentation of their truss bridge project.

Figure 3. Truss Bridge Project

Project 2: Design of vault over an irregularly-shaped expanse to support concentrated loads, this included consideration for connection design to insure vault stability.

Students ended up using a hanging mass approach with tensile members to create the compression-only structural system as shown in Figure 4. Forces in the members were determined using 3-D force equilibrium approach.

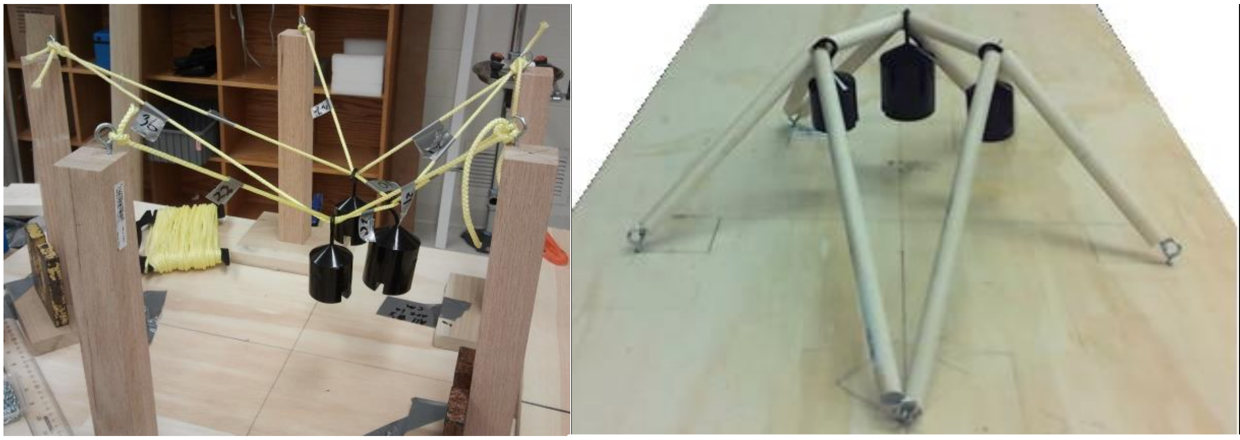

Figure 4. Vault Project: (Left) Hanging Mass Structure, (Right) Compression-only Structure

Project 3: Design of a thin-shelled reinforced concrete (plaster) dome supported at given locations.

As shown in Figure 5, students ended up utilizing an inverted catenary arch approach where they hung a net of metal chains from multiple supports, sewed a thin mesh material on each side of these chains, and covered the surfaces with a coat of plaster.

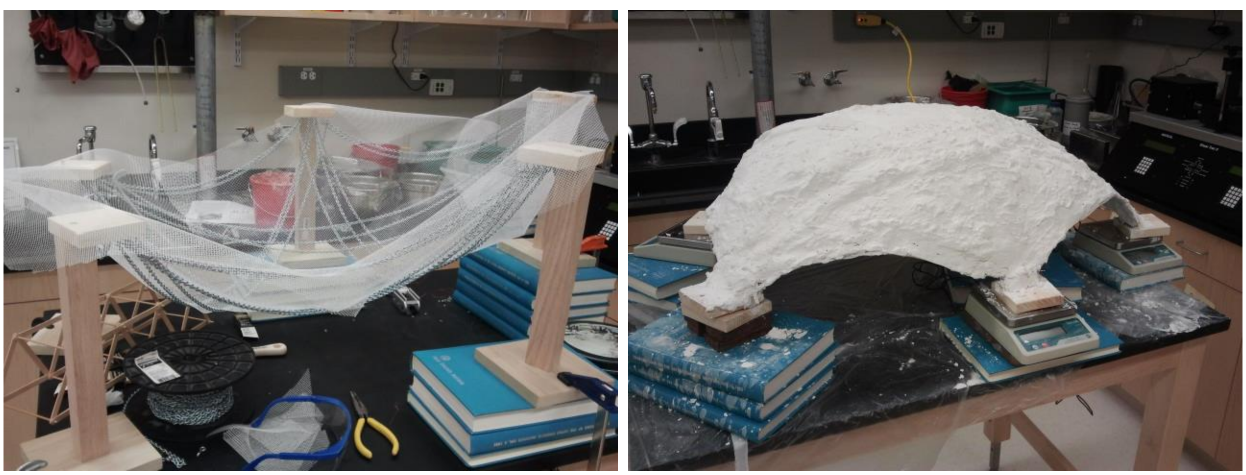

Figure 5. Thin-shelled Reinforced Concrete Dome Project:
(Left) Hanging Mass Structure, (Right) Finished Dome Structure

Project 4: Design of buildings in a city to be subjected to an earthquake; including: basic calculation/description of structural performance.

Students decided to examine structures with different lateral load resisting systems (column-only, cross-bracing, shear wall), masses, and heights as shown in Figure 6.

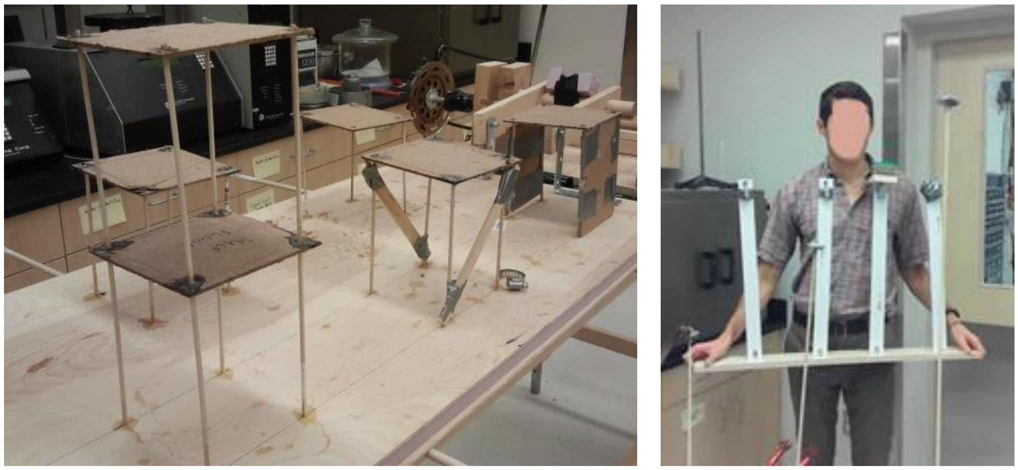

Figure 6. Earthquake City Project: (Left) Structures on Manual Shake Table, (Right) Student Presenting Towers with Different Masses

Project 5: Design of medieval weaponry and prediction of how far the associated projectile would travel compared to actual performance.

As shown in Figure 7, students built a catapult that incorporated a torsion spring consisting of twisted ropes and determined projectile distance using strain energy principles.

Figure 7. Medieval Weaponry Project: (Left) Team Presenting their Catapult Design, (Right) Testing of the Catapult at the Athletic Field

Project 6: Design of an egg protection device whereby an egg suspended in a box would be prevented from cracking when dropped from a second-story window.

Students conducted material tests on various rubber bands to determine the number and length of bands to affix between the walls of the box and the leather pouch that would hold their egg. They used strain energy and other basic physics principles to ensure the forces on the egg were not excessive nor did the egg hit the bottom of the box during its descent. The student’s final product is shown in Figure 8.

Figure 8. Egg Protection Device

Project 7: Design a tension membrane structure that would enclose a certain volume of space and carry concentrated point loads at designated locations.

Students conducted directional tests to evaluate the performance of the membrane material, developed an architectural/aesthetic concept, and experimented with various membrane-to-support connection designs. They utilized their understanding of 3-D force equilibrium to approach this complex structure system. Figure 9 is a photograph taken during the team’s final presentation of their tension membrane structure.

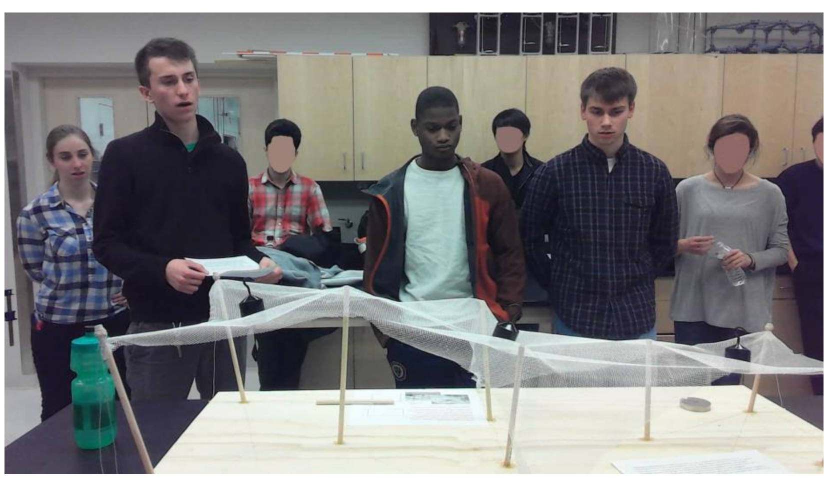

Figure 9. Tension Membrane Structure

Student Assessment

In addition to the instructors' assessment of student performance (grading of homework, project, and exams, as well as interactions in office hours and facilitation during inquiry activities), mid-semester and end-term surveys were used to collect student feedback on the pedagogical approaches used in the *DBE* course. The surveys were intended to capture student perspectives on: the use of inquiry-based learning prior to formal instruction; the role of instructors as facilitators during these inquiry-based exercises; the balance between student and teacher-centered teaching activities; the effectiveness of demonstrations, experiments, and case studies to learning; and the utility of major deliverables such as lab notebooks and the final project.

Each of the surveys consists of three primary sections: (i) general questions with five-point Likert scale addressing the topics described in the previous paragraph; (ii) rating of specific class exercises, also with a five-point Likert scale, where students were provided the class topic and reminded of details of the activity (they were also encouraged to refer back to their lab notebooks); and (iii) open-ended questions to comment on course strengths/weaknesses and suggested improvements. The mid-semester survey was comprised of 17 questions which included (i) 6, (ii) 9, and (iii) 2 questions for each of the three sections. Comparatively, the end-term survey had 19 questions of (i) 11, (ii) 4, and (iii) 4 questions. All the original questions from sections (i) and (iii) were maintained and supplemental questions were added. Section (ii) was modified to reflect class activities that had occurred since the mid-semester survey. Specific questions will be discussed in greater detail in the following section analyzing student feedback.

Summary of Student Feedback

Eighteen of the twenty students enrolled in the *DBE* course consented to participate in the research study, sharing their assessment of this new curriculum. The remainder of this section aggregates both the responses from Likert scale rating and open-ended questions. In regards to the latter, student quotes have been selected in an effort to show positive and negative perceptions.

Perceptions of "exploration before theory" teaching approach

When students were asked about their opinion on the learning-before-theory approach used in class, the average mid-semester (MS) and end-term (ET) responses were both 4.22 where 5 indicated students strongly favored the approach and 1 was strongly opposed.

In the surveys, students indicated some of the *strengths* of the instructor team and/or the class, related to inquiry-based teaching, was:

> "The hands-on learning has been very effective, allowing me to make sense of a situation where an equation would not suffice. The instructors provide little guidance during the lab, which is ideal for us to grapple with the concepts before formally learning them." (MS)
>
> "A major strength of this course is the ability for students to explore the concepts in the lab. It is much easier for me to begin to understand a concept when I can return back to my own personal experience." (MS)
>
> "Creating good labs that allowed us to learn about topics through experience." (ET)
>
> "I liked the way [the instructors] let us test things/concepts in the lab before lecture. …" (ET)

Some *weaknesses* or *suggestions to improve the course* from students, related to inquiry-based learning, were:

> "Sometimes I would be very confused with what exactly we were trying to accomplish or how I should go about accomplishing the goal [in lab activities]." (MS)
>
> "Didn't really get a lot of background of concept before the lab." (MS)
>
> "…Sometimes it was hard to know what to record/how to do calculations because there wasn't a lot of discussion on the topic before the lab." (ET)

Perceptions of the role of instructors as facilitators during inquiry-based learning

There were two survey questions that addressed the students' perspective on the instructor as a facilitator during inquiry activities. The first examined whether sufficient guidance was given to students teams so they could be effective in addressing questions/problems posed in lab exercises. The second was to evaluate if the types of questions posed by the instructors (formally in lab exercises or spontaneously during team interactions) led students to think critically and motivated them to investigate to structural engineering phenomena. For both questions, 5 indicated strongly agree and 1 was strongly disagree. The average response for student perception of adequacy of guidance with lab activities was 4.06 (MS) and 3.89 (ET), while their views on effectiveness of instructor questioning was 4.33 (MS & ET).

A selection of *positive* student comments on the role of instructors as facilitators during inquiry-based learning (including case-based lecture/instructor demonstration where questioning was used) were:

> "It is helpful to have the instructors walking around asking questions that guide us in the right direction." (MS)
>
> "Very strong at facilitating labs ..." (ET)
>
> "Having us work in groups to brainstorm answers to a question during lecture for a minute or two. …" (ET)

A majority of *negative* feedback or *suggestions for improvement* had to do with providing more scaffolding or support; however, there were students that felt they were capable of working in a more self-directed manner consistent with ***open inquiry*** or ***discovery learning***:

> "Give more initial guidance in lab. Spend more time on subjects that are more confusing (mainly torsion and shear)." (MS)
>
> "…Group time in lab was not very effective, could have used more guidance." (ET)
>
> "…Less lab/guided worksheet during lab…" (ET)

Perceptions of balance between student and teacher-centered teaching

Students were asked to share their thoughts on amount of time spent on lecture versus cooperative, inquiry-based activities. The results from MS and ET surveys using a modified, five point scale are presented in Figure 10.

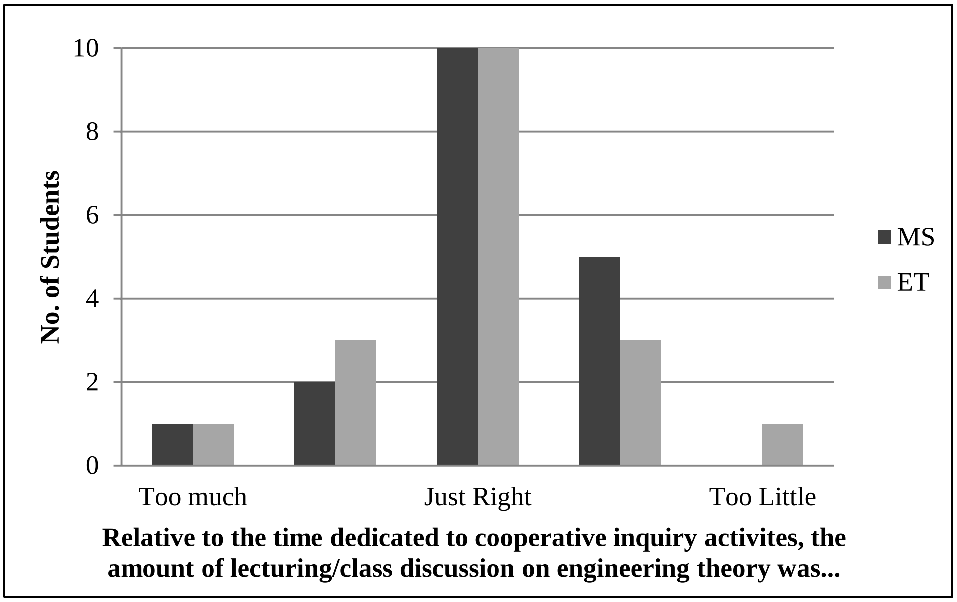

Figure 10. Student perception of balance between lecture and inquiry-based activities

Based on the quantitative feedback, by the end of the semester there was a symmetric distribution in student responses which likely indicates that a reasonable balance was struck between the deductive (teacher-centered) and inductive (student-centered) type activities.

Positive comments from students relating to the balance of course activities include:

> "The combined use of lab demos/experiments and class time helped further understand concepts." (ET)
>
> "Decent balance between activities and lectures,…" (ET)

Common complaints from students that felt there was too much lecturing identified that lecture classes were sometimes dull, assumed prior knowledge of concepts and terms from physics or math courses (which led to confusion or disinterest), progressed through topics too rapidly, or should have included more class interaction and demonstrations. Comments from students who believed that there was too little lecture, include:

> "I think we could spend more time going over the math/physics aspect of solving structural engineering problems." (MS)
>
> "I would appreciate a more advanced class with more demos and more lecture." (MS)

Effectiveness of demonstrations, experiments, and case-study discussions

Students were asked to share their thoughts on how effective the course activities were at helping them learn and engage with different engineering concepts. One set of survey questions focused on individual topics and another set on different teaching techniques. For the topic-based assessment, the survey listed each topic area with a short description of the associated demonstrations, experiments, and/or case-study discussions. Students are asked to use a five-point rating scale where a 5 represented that the course activities for that topic were effective/interesting and 1 was that they were ineffective/ uninteresting. The results from the entire semester are summarized in Figure 11.

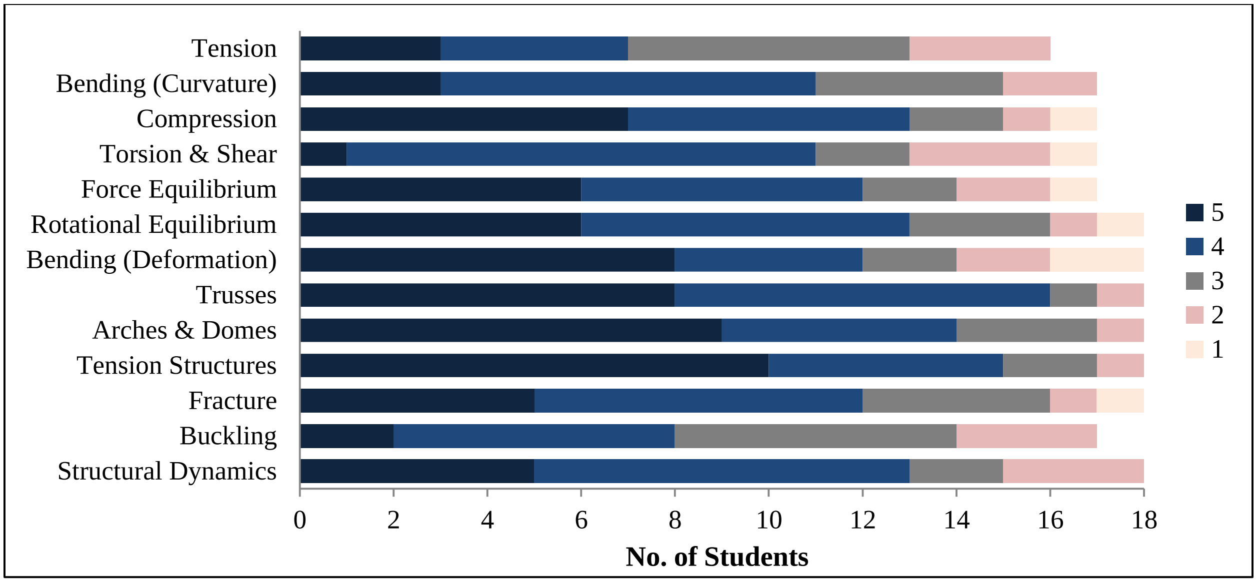

Figure 11. Student perception of effectiveness of activities related to specific engineering topics covered in *DBE* course curriculum, 5 = effective/interesting and 1= ineffective/uninteresting (*note: some students omitted questions*)

From a teaching approach-based assessment, students were asked to indicate their level of agreement with the following statements (paraphrased from the survey), where 5 was strongly agree and 1 was strongly disagree:

(i) cooperative inquiry activities were helpful to understanding course material (response: 3.89 – MS, 4.28 – ET);
(ii) demonstrations/experiments were a valuable physical reference when completing assignments/exams (response: 4.33 – ET only)
(iii) case studies presented in class were interesting and helped in making connections between theory and the built environment (response: 4.33 – ET only)

The following represent the *positive* comments on <u>specific</u> class topics/activities:

> "Lecture and real-world experience were interesting ways to learn more about the field [of structural engineering]. I especially found the experiences relating to engineering forensics and design of the Burj Khalifa very interesting." (ET)

> "The ship section [discussion of Titanic failure related to fracture] was interesting, more of that would have been interesting. …" (ET)

For the most part, *negative* aspects or *suggested improvements* on <u>specific</u> class topics were captured by student comments presented in earlier sections. The only notable addition was:

> "Clear explanation of how to go about [beam] problems would have been helpful, but over time (through practice and further classroom discussion) they began to make sense. Perhaps more of class time should be spent clarifying the concept first."

Perceptions of cumulative lab notebook and final project

Two of the major course deliverables (and time investments on the students' part) were the cumulative lab notebook and final project; therefore, it was important to examine whether students felt these activities were worthwhile. Students were asked if they felt keeping a lab notebook was beneficial to their communication skills and as a method to reflect on class activities (response: 3.44 – ET only), and if the final project was a beneficial learning process that helped them bring together knowledge gained over the course (response: 4.39 – ET only). For both questions, 5 is strongly agree and 1 is strongly disagree.

None of the students mentioned the lab notebooks in their open-ended responses; however, there was a question on the ET survey targeting students' project experience. In general students appreciated the chance to design, construct, and test a solution with a team of other students. Some even indicated that they felt the project was of greater value to them than the smaller experiment-type, inquiry-based learning activities that occurred throughout the semester. The following is a summary of some additional student remarks:

> "I was in the tension structure project. I gained a greater sense of tension as well as conceptually understanding equilibrium. I like that the project had a purpose and we got to design it. If anything, I would have more projects that were hands-on and engaging like [this project]."
>
> " [Working on the m]edieval weaponry [involved] energy methods. I really enjoyed the openness and freedom of our design process, but had difficultly applying the principles we learning to the design, more easily relying on intuitive understanding."
>
> "[The egg safety protection device] was fun to build and test. We mainly used tension and strain [energy] principles to calculate safe falling distances and forces on the egg."
>
> "My topic was thin-shelled domes. I enjoyed the application of things learned, such as Hooke's inverted chain for arches, to a project. What was most challenging was the amount of time given [to complete the project]. …"

Lessons Learned

After examining student performance through submitted deliverables and the survey feedback, the authors conclude that future course offering should consider the following items:

- Students' comfort with inquiry-based activities in an introductory structural engineering course depends on previous math/physics preparation and exposure to laboratory-type courses. Therefore, surveys should be administered at the start of the semester to gauge students' knowledge level. This information can be used to create teams that represent a range of levels and to tailor activities to students' abilities.

- Frustration with the "exploration before theory" approach is common among young undergraduate learners: some embraced struggle as part of the discovery process, others expressed dissatisfaction when comparing *DBE* to their other courses. To address this, the initial discussion of inquiry-based learning objectives should be clear; also, facilitation/

scaffolding provided by instructors during activities is critical to motivate students, especially those with more limited preparation.

- Presentation of case-studies, especially those associated with the instructors' personal research/consulting experience, received highly positive feedback and students would often approach the instructor to ask follow up questions. These types of case-studies should be more fully integrated throughout the semester, rather than concentrated at the end as they were in the Fall 2015 semester.

- Students enjoyed the creativity associated with the final design project and the fact that each team's problem statement was unique. Many requested that some of the experiment-based activities from earlier in the semester be replaced with small design challenges. Instructors would have to be selective to insure curriculum topics are still addressed if this change was implemented.

- Development of new experiments requires careful vetting by the instructor team. While the experiments that students conducted in teams were always tested extensively, this was not always the case with in-class demonstrations presented in the Fall 2015 semester. This illustrated how any inconsistency with a demonstration and the associated theory can impede, rather than assist with, student understanding.

- Most students had haphazard organization or incomplete descriptions of inquiry-based learning activities in their lab notebooks. Students need more than a list of items (with descriptions) and peer student examples of what need to be included in the notebooks. The instructor should prepare formal, high-quality examples of what should be submitted for the different types of learning activities. Also, the process of enlisting student buy-in to maintain a lab notebook needs to be more deliberate.

- Students developed their own on-line community to reach out to each other to ask each other questions on homework. While this showed initiative, a bulletin or forum should be built into the course online platform by the instructor. Doing so allows instructor to intervene if there are questions beyond what students can resolve amongst themselves; there are also learning gains for those unable to attend in-person office hours.

Acknowledgements
The authors would like to thank Dr. Donna Qualters of the Tufts University Center for the Enhancement of Learning and Teaching for her support in developing and administering surveys associated with this research. Additionally, the authors would like to thank colleague Dr. Christopher Swan for his feedback on the overarching research program, and all the students who participated in the research study. The research in this paper was completed under IRB Approval No. 1510032 from Tufts University.

References

[1] Fairweather, J. (2010), Linking Evidence and Promising Practices in Science, Technology, Engineering and Mathematics (STEM) Undergraduate Education. Report for The National Academies, National Research Council's Board of Science Education, p. 31.

[2] Frontinus, S.J., and Herschel, C. (1913), The Two Books on the Water Supply of the City of Rome of Sextus Julius Frontinus, Water Commissioner of the City of Rome, A.D. 97. Longmans, Green, & Co, London, England.

[3] Accreditation Board for Engineering and Technology, Inc. (ABET). (2015), Criteria for Accrediting Engineering Programs. Accreditation Board for Engineering and Technology, Inc., Baltimore, MD. <www.abet.org>.

[4] Marton, F. and Säljö, R. (1976), On Qualitative Differences in Learning: I – Outcome and Process. British Journal of Educational Psychology, 46(1): 4–11.

[5] Prince, M.J. and Felder, R.M. (2006), Inductive Teaching and Learning Methods: Definitions, Comparisons, and Research Bases. Journal of Engineering Education, 95(2): 123-138.

[6] Buch, N.J. and Wolff, T.F. (2000), Classroom Teaching through Inquiry. Journal of Professional Issues in Engineering Education and Practice, 126(3):105-109.

[7] Tafoya, E., Sunal, D.W., and Knecht, P. (1980), Assessing inquiry potential: A tool for curriculum decision makers. School Science and Mathematics, 80(1):43-48.

[8] Staver, J.R. and Bay, M. (1987), Analysis of the project synthesis goal cluster orientation and inquiry emphasis of elementary science textbooks. Journal of Research in Science Teaching, 24(7):629-643.

[9] de Graaff, E. and Kolmos, A. (2003), Characteristics of Problem-Based Learning. International Journal of Engineering Education, 19(5):657-662.

[10] Singer, R.N. and Pease, D. (1978), Effect of Guided Vs. Discovery Learning Strategies on Initial Motor Task Learning, Transfer, and Retention. Research Quarterly, 49(2):206-217.

[11] Kunz, R. (2013), Simple Demonstrations in Basic Mechanics Courses. Proceedings 2013 ASEE Southeast Section Conference.

[12] Meyer, K.F., Ressler, S.J, and Lenox, T.A. (1996) Visualizing Structural Behavior: Using Physical Models in Structural Engineering Education. Proceedings 1996 ASEE Annual Conference.

[13] Ji, T. and Bell, A. (2008) Seeing and Touching Structural Concepts. Taylor & Francis, New York, NY, p. 267.

[14] Medley, T.D. (2011), Demonstrating Frequency using a "Lollipop Model". NEEShub. <www.nees.org>.