Hands-On Learning for Statics in the Smaller Classroom and Potential Scale-Up to the Larger Lecture.

Sinead C. Mac Namara¹, Joan V. Dannenhoffer²

Abstract — This paper describes ongoing efforts at Syracuse University to re-engineer the traditional statics course. The courses described form part of a larger NSF funded project aimed at increasing innovation and creativity in engineering curricula. The principal aim of the overall project is to find strategies to foster and reward creativity in engineering students. This study examines hands on teaching tools deployed in a smaller classroom and the resultant student outcomes and student response. This paper will also present the expert evaluation of both the smaller course and a larger more traditional course, and will present strategies to scale-up those teaching methodologies found to be successful in the smaller course to a larger lecture course.

Keywords: experiments, statics, hands on learning, smaller class size, creativity

INTRODUCTION

At Syracuse University, Statics is taught in the fall of the second year and for the last three years the civil engineering students have been taught in two different groups, one smaller, one larger. This paper contrasts the efforts made in the smaller experimental statics course that uses classroom demos, small-scale experiments, real life examples, smaller class sizes, and group work in class with the efforts made in a larger more traditional lecture course. The aim of the experimental course is to improve creativity and innovation in problem solving and increase students’ enthusiasm for engineering and perception of engineering as creative and innovative. There were 40 civil engineering students in the smaller course. The large lecture course had between 70 and 100 civil engineering students and in addition to lecture demonstrations, it also tested some teaching methodologies better suited to large courses such as the online tools of: OLI (an online teaching tool developed by Steif and Dollar aimed at improving students capacity to self learn¹); SAGE (a self-assessment tool that aims to foster a culture of continuous improvement in students by requiring them to reflect on their learning practice and ask for help in a timely manner²); and an in-house developed statics online learning tool, ARCHIMEDES, that helps students learn a logical process to solve traditional statics problems³. This paper aims to examine and compare the use of hands-on learning in both courses. The authors will evaluate the relative success of the strategies deployed in each course and make a series of recommendations regarding the scale-up of some successful strategies from the smaller class to the more practical and more common large lecture format in which statics is usually taught.

BACKGROUND

Leading engineering education experts have described “creative experiential, problem-based learning” as the model for future engineering curricula if the US is to maintain a technologically and economically competitive workforce.⁴ Teaching engineering design and using hands-on learning as a vehicle to incorporate creativity into engineering curricula is widely acknowledged by engineering education researchers.⁵,⁶ Engineering students have difficulty

¹ Assistant Professor, Syracuse University School of Architecture and LC Smith College of Engineering and Computer Science, Syracuse, NY 13244, scmacnam@syr.edu
² Associate Professor, Syracuse University, LC Smith College of Engineering and Computer Science, Department of Civil and Environmental Engineering, Syracuse, NY 13244, jvdannen@syr.edu
integrating their studies into real engineering situations because of lack of exposure. It is this capacity to integrate knowledge and skills into the practice of engineering that signifies the creative engineer.

Engineering education researchers and practitioners have acknowledged the problem of design education and connection to real world phenomena in course work in engineering programs. In the 1990s, first-year design courses were widely introduced in engineering programs in an attempt to introduce students to the nature of their chosen profession earlier in their college careers. Capstone design courses at the end of engineering programs likewise represent an opportunity for students to take on both design work and a holistic real world project. However, design or explicit engagement with real world physical manifestations of their new engineering knowledge is not generally included as part of the curriculum in core courses in the second and third years of study. There is a critique that this bookending approach (with cornerstone courses in the first year and capstone in the final year) can create a “valley of despair” in the second and third years and that the benefits of the kinds of learning in the capstone and cornerstone courses are limited when they are not spread throughout the curriculum. The project described in this paper represents an attempt to fill in the valley of despair by testing a series of additions (lecture demonstrations, experiments and a design competition) to the required statics course for civil engineers, all focused on engaging students with the physical reality of the new topics they are learning.

Previous studies in the area of teaching statics lament the difficulty that students often have translating the knowledge encountered in early mechanics courses to the analyses required in later courses. Steif and Dollár argue for introducing new material by grounding it in existing knowledge, being open to multiple modes of learning, and having students begin to learn about forces, couples etc. by working with those examples that they can perceive either by manipulating with their own hands or by viewing resulting deformation or motion. They also argue for significant interaction and discussion in the classroom. Williams and Howard discuss the value of a laboratory experience or classroom demonstration in helping students learn the elementary statics concepts and further advise that students estimate and evaluate expected outcomes in advance. O’Neill, et al report on a successful lab lecture hybrid interdisciplinary mechanics course that uses longer meeting times and inexpensive models and equipment to get students to “discover” engineering concepts.

**SMALL CLASSROOM INVESTIGATIONS INTO HANDS-ON LEARNING**

**Small Scale Experiments**

Constraints of time and money are the biggest obstacles to implementing the recommendations (discussed above) of engineering education researchers for hands-on learning and physical observation of the manifestation of the forces, moments and other phenomenon that students are learning. In the smaller course, described in this paper, a series of cheap, quick experiments were designed to introduce statics concepts and help students discover knowledge and see the engineering principles in action.

All the experiments were designed to use simple, cheap and readily available materials. Although the class size was small, it was still necessary to provide a series of very explicit written instructions for each step of the experiment, as 20 pairs of students would be working in a classroom with one instructor and two TAs. The purpose was to allow students to “discover” the formula. For example, when learning vectors in 3D the students were told nothing about i, j, and k or any formula for finding the 3D vector form, nor were they reminded of their coordinate geometry formula for the length of lines from high school before undertaking the small experiment illustrated in Figure 1. They were merely given a flat square of foam core, a dowel to make a vertical axis, and a pin and string. They had instructions to make a line in a 3D space over which they had total control and only then they were told that the distance vector between two points in the photograph was \( \mathbf{r} = 0i + 0j + 2.5k \) inches. Based on this, they were asked to figure out the distance vector they had created and propose a formula or set of instructions on how to do this for all vectors in 3D they might encounter in future. After they had completed this step they were told to imagine they knew the magnitude of the force in the string and propose a formula or set of steps to arrive at the force vector in i, j, k form. Figure 1 also shows the handout for an experiment designed to allow the students to study the relationship between the forces on either side of a non-frictionless pulley with a soda bottle, ribbon and weights. The class then collectively plotted their results on the blackboard. Between the graph and the sheer tedium of trying to get slip on one side, once the ribbon had been wrapped 2.5 times, – the exponential relationship between the two forces became obvious. Only then was the formula for belt friction given to the students.

A series of other small scale experiments were also deployed in the course. These included:
- a small dry erase board with a string, fishing weights, a protractor and a marker used to investigate the addition of vectors on the first day of class,
- balancing foam core shapes on the end of pens to find the centroid and propose formulae for each shape,
- playing with various pieces of an erector set to build rollers, pins and fixed connections and to learn that these connections only exist on paper and that all real fixed connections will have some rotation, and all real pins and rollers will have some friction resisting movement,
- building frames from erector set pieces and estimating the direction and relative size of reaction and connection forces before calculating the actual answer,
- the classic foam beam to estimate the shapes of bending moment diagrams before attempting the mathematical solution,
- trying to pull each other’s static text books off their upturned palms and noting the difference when multiple books were added or when wax paper was placed between their books and their hands,
- bringing a students’ bike to class to postulate the maximum number of free body diagrams that could be made of the system and the inter-relationships between those diagrams,
- a series of homework assignments that required students to find examples of the phenomenon they had just learned in their everyday environment, and if they could not find an obvious one to create something themselves.

Images of the experiments and of students performing these activities are presented in Figure 2.

The Design Competition

The Design Competition was assigned at the mid-point of the semester, after the subjects of vectors, moments, and equilibrium in both 2D and 3D had all been covered. The students were shown a series of sculptures designed using static equilibrium. They had also undertaken an analysis of the mobiles of Alexander Calder as an in-class assignment and as homework (Figure 3). They were asked to form teams of two and brainstorm ideas for their entry into the design competition for the duration of the class period. The design aim they were given was to create a sculpture/mobile/device/assembly that was statically determinate and in static equilibrium, but one that looked like it should fall over.

The competition was entitled “Asymmetric Equilibrium” and was introduced in a dedicated lecture period. The two teaching assistants and the instructor provided feedback and help to each team during the class period. At the end of the class period the students were asked if there were things they did not know that they would need to understand in order to complete the project. It emerged that the primary missing piece was a method (or methods) to find the centroid of complex shapes or the center of gravity of a complex object. So the next two lectures focused on centroids and center of gravity (topics that were at least somewhat familiar from previous physics courses). Definitions of these properties of shape, mathematical methods for finding the center of a complex shape made up of shapes of known centroid, and experimental methods for finding the (approximate) center of gravity of an object were all covered.

In the next 10 days each group was offered the chance to meet with the instructor for a one-on-one design consultation. In the meantime they were required as part of their homework assignment to sketch up the centroid/center of gravity problem they had chosen for their design and submit their proposed solution to the TAs for feedback. One of the principal issues for most groups was how to construct the types of connections they needed (pins, rollers etc). This prompted some interesting discussions of what connections really are, how most real connections only approximate the behavior of the idealized conditions assumed in their text, or how some connections might be assumed to be pins while there was enough friction to resist applied horizontal forces, and that if those horizontal forces got bigger, then the connection would really act like a roller. Another group set out to build a perfect pin complete with the appropriate fixings from the hardware store, only to discover when they tightened the bolt that they had a moment connection (under the small loads on their sculpture) and had to start again. The only other building experience that most of the students reported was in the first-year design course where model bridges were made from a predetermined subset of provided materials. As such, these meetings were a good opportunity to allay any concerns that students had about the assignment, offer practical assistance, and push some students to more complex designs.
Figure 1: Instruction Sheets for Small Scale Experiments to investigate 3D vectors and Belt Friction

Figure 2: Students engaged in experiments

Figure 3: Examples of sculpture and static equilibrium shown to the students. L-R Two sculptures by architect engineer Santiago Calatrava, Sculpture by Architecture Students at the Harvard GSD, Two Mobiles by American Artist Alexander Calder (trained as an engineer at Stevens Institute for Technology!)
Examples of the students’ work are shown in Figure 4. There were a mix of mobile-like devices in the vein of Calder and assemblies that borrowed from Calatrava’s sculptures. Extensive use was made of fishing wire as a tie back or tie down in order to add to the asymmetric illusion. In addition to the design project, students were required to turn in a report detailing their design process and including a full set of calculations showing how they estimated the centroids of their elements, the reactions at their connections, and the tensions in any wires. A fuller discussion of this assignment was presented at the ASEE Annual Conference and Exposition in 2012.

![Figure 4: Examples of Student Work for the Design Competition](image)

**STUDENT RESPONSE AND EVALUATION**

The primary aim of the smaller course is to improve innovation and creativity in engineering student problem solving. Specifically it was hoped that the students would become: more comfortable taking on unfamiliar problems and working on open-ended problems; more confident in their ability to take on unfamiliar problems; and more knowledgeable and enthusiastic about the role of innovation and creativity in engineering design. There were forty students in this smaller course, and the remaining sixty or so students in the cohort experienced a more traditional lecture format with another instructor. An evaluation plan for the courses has been prepared and implemented by a team led by Dr. Scott Shablak who directs the Office of Professional Research and Development at the Syracuse University School of Education. As part of the evaluation of this course two researchers conducted classroom observations for a number of sessions for both the smaller course and the larger course. These classroom observers did not read the experimental course proposal and were merely instructed to observe both courses and comment on the differences found.

The most encouraging result from the observers report was that they readily identified the smaller course as “engaged in creative problem solving” even though they had not been informed of the aims of the course in advance. Observations in their report for the smaller class included:

- considerably higher attention paid by the students in the experimental course (no sleeping, considerably less cell phone checking),
- students in the larger lecture were very passive (taking notes from the board) while students in the experimental course were actively engaged (working on problems, discussing their designs with other groups, presenting their work to each other),
- students were much more responsive to the instructor in the experimental course (responding to questions from the instructor, initiating questions, verbal and non-verbal affirmations as the instructor explained new ideas).
- students in the experimental course displayed confidence and enthusiasm for engineering problem solving while presenting their design competition entries (note there was no analogous activity in the larger course for comparison).

These observations suggest that the teaching methods deployed in this course, including the design competition and the small scale experiments have resulted in increased engagement on the part of the students, confidence in taking on unfamiliar problems, and comfort with open-ended problem solving.

In order to investigate student response to all aspects of both statics courses including the various hands-on assignments students were surveyed both before and after the course. The pre- and post-survey yielded a large amount of data on students’ perceptions of both the discipline and themselves with regard to a series of attributes: creativity, innovation, logic, intelligence big-picture thinking, etc. A full discussion of these results for both groups as they pertain to all the teaching strategies deployed in the courses is presented in an upcoming paper at the ASEE.
In the surveys, a series of course specific questions were asked to each group. The results from the specific questions asked to the smaller group (group A) who experienced the hands-on assignments described in this paper are presented in Figure 5 and the results from the larger lecture course (group B) specific questions are presented in Figure 6. Figure 5 shows that a large majority (approximately 90%) of students in the smaller class understood the instructors’ goals and had responded positively to the methodologies aimed at meeting those goals. In particular the students overwhelmingly agreed that the hands-on activities were instrumental in learning the material and that this course was different than other engineering courses they had taken. Figure 6 shows that between forty and fifty percent of the students in the larger class found the on-line learning tools useful in learning the material. This result is not surprising to the authors, as the instructor for the large group has found that students in the mid-range benefit most from on-line learning tools such as ARCHIMEDES and OLI.

The pair of courses have been taught in this way for three iterations, and in two of those years the students in both groups have taken a common final exam (in large part to ensure that the time taken for the experimental methodologies in the smaller group did not inhibit learning the necessary volume of material for such an important course). For the common final exam in the most recent iteration the average grade for students in the smaller group that had experienced the hands on learning was 84%, the average grade for the large group was 77%. In the first iteration of the courses the difference was even larger. However, these results are absolutely not conclusive and require much closer study and an analysis of the GPAs of both groups along with the number of students from both groups who had withdrawn from the course before the final exam was taken.

When the students in the smaller group were asked about the design competition, 100% of respondents agreed that the design competition was useful in learning the course material. Further, approximately 85% of students agreed that the design competition made them more enthusiastic about engineering, and that in doing the project they learned something over and above the course material. Very few students felt that the project took too much time from their other work, or that they were unprepared for the assignment by their training so far. Finally, and most encouragingly, 100% of respondents indicated that they would like to undertake similar assignments in future courses.

In addition, students in the smaller course were given an opportunity to expand on how the design competition helped them learn the course material (if in fact they agreed that it had). Interestingly a number of the comments addressed the “reality” of the project.

“It helped me see the actual application of it rather than a problem that was taken out of the book, which may not make sense to me at the moment but this just allows me to see that everything we did in the class was relevant.”

“It was cool to see that what we learned in class really could apply to something that we could make.”

“it helped realize how the concepts in the course applied to real life situations”

“understanding the fundamental concepts, what we learned is real.”

“Helped understand how something, that would normally look like it was falling over, actually was in static equilibrium rather than just believing it because we were told to in class. Provides practical engineering skills to the real world.”

The project required students to build a model sculpture or mobile-like assembly (as opposed to a model bridge, or crane, or machine). These were not hugely different from the kinds of things they might find in a textbook problem. It would appear that it was the physical and hands-on nature of the assignment that made the students feel it was more “real” as opposed to the subject matter. Other students commented that visual and physical learning are useful but are not the normal mode of learning that they encounter in their other engineering classes.

“It helped me see the actual application of it rather than a problem that was taken out of the book, which may not make sense to me at the moment but this just allows me to see that everything we did in the class was relevant.”

“It was cool to see that what we learned in class really could apply to something that we could make.”

“it helped realize how the concepts in the course applied to real life situations”

“understanding the fundamental concepts, what we learned is real.”

“Helped understand how something, that would normally look like it was falling over, actually was in static equilibrium rather than just believing it because we were told to in class. Provides practical engineering skills to the real world.”

The project required students to build a model sculpture or mobile-like assembly (as opposed to a model bridge, or crane, or machine). These were not hugely different from the kinds of things they might find in a textbook problem. It would appear that it was the physical and hands-on nature of the assignment that made the students feel it was more “real” as opposed to the subject matter. Other students commented that visual and physical learning are useful but are not the normal mode of learning that they encounter in their other engineering classes.

“It allowed me to visually and physically see what I am learning instead of just writing down formulas and drawing diagrams.”
The smaller class size in this course encouraged me to ask more questions during lectures than I would have in a larger group. The mini-experiments (e.g., finding centroids) were important for my understanding of the statics principles. The hands-on learning focus of this class was an effective way for me to learn the course material. The way this course was taught was different than other engineering courses that I have taken. Real-world examples were helpful to me in learning the course material. The mapping activities increased my understanding of the connection between concepts. Using Archimedes helped me learn strategies for solving Statics problems.

Figure 5: Student Responses to course specific questions for the smaller course.

Figure 6: Student Responses to course specific questions for the larger course.

Surprisingly, a number of students cited the lack of an “answer in the back of the book” as a positive aspect of the project.

"The competition had me take material learned in the classroom and implement it into a real life scenario that I created like real engineer and had to solve all the unknowns and had no answers in the back the textbook to go off of it really had me think and work hard to arrive at my conclusions and had me feel confident in my own answers were correct and prove it."

The respondents were also offered an opportunity to comment on the experience of hands-on work more generally as a method of exploring and learning engineering course material.
“the physical world is rarely as well behaved as the calculations and adjusting to and accounting for unforeseen problems is a good engineering lesson”
“I realized that even though we had the same task in mind we all went about it differently by using different materials to add an illusion to our work.”

**SCALE UP POTENTIAL**

The main goal of the instructor of the large class is to have engineering students leave the Engineering Statics class with a set of skills that they can use in other classes and in their careers, long-term understanding. Since these students are first semester sophomores developing long-term skills has an affect on how the students view themselves in the context of becoming an engineer. Questions students may ask themselves include “Do I like engineering enough to stick with it?” and “Am I smart enough to be an engineer?” The challenge of meeting this skills goal in a large class of size ranging from sixty to one-hundred-fifty students in amphitheater style class rooms is daunting. The current techniques being used in the large class during lectures include using physical models and small group assignments. Some successes in helping students develop long-term skills have been seen as evidenced by student comments in end-of-semester evaluations and in weekly student feedback. Physical models can give the students a basis to understand the type of problems they may need to solve later in their career. The models help students that have the ability to imagine how the models relate to larger problems. Unfortunately, when a physical model is displayed in a large class room many of the students do not engage themselves in understanding the model. If they are sitting in the back of the class, the model may be thirty feet from them. As would be expected, even with the ubiquitous availability of technology in the class rooms, projecting the model on a screen does not have the same effect as being able to manipulate the model. Many of the students do not have prior hands-on experience with hardware and building things. As a result, their ability to imagine cause and affect relationships and their knowledge of vocabulary associated with technology is limited. In problems in the text, terms like “thrust bearing” or “pinned joint” for example, are meaningless to the students. Having hardware and models available for the student to manipulate gives them first hand experience. Small group assignments that two or three students work together to solve have the advantages that students talk about the problem, they get to see that, like them, other students have some but not all of the answers, they can research vocabulary on the spot, and they can ask for clarification without being in the spotlight of the entire class. The “assignment” can be traditional problems, development of formulae, concept maps, sketching, thought questions, etc. The down side is that in a class of sixty-five students, therefore a minimum of twenty-two groups, it is difficult for one instructor and one teaching assistant to be available and to make sure that all students are actively involved during a fifty-five minute class period.

The classroom setup has a definite effect on the results of implementing techniques. Benson, et al, describe the successful implementation of the Student-Centered Activities for Large Enrollment University Programs (SCALE-UP) to Statics, Dynamics, and Multivariate Calculus. In this model classrooms were equipped with round tables with power and wired-internet to facilitate laptop use, interactive digital pen displays, dual projectors, and multiple white boards to accommodate up to sixty-three students. Also, the professor’s role in the classroom was viewed as “more of a facilitator and coach than that of an orator”17. Attempts to use student-centered activities in an amphitheater style classroom have not been successful when the room is not large enough for students to move to a different seat, for students to form groups separate from each other, and for the instructor and teaching assistants to move freely around the room. Since it is not currently possible to guarantee that the Statics class will be assigned a particular room or that class size will be small, alternatives need to be considered. Creating these student-centered activities that many studies have documented as helping students develop the long-term skills and the creativity they need to become successful engineers is our goal. New strategies that use classroom time, recitation time, and homework differently so that as a whole there is greater percentage of time devoted to student-centered activities are necessary.

Despite the challenges outlined above, the success of the hands-on learning in the smaller class is such that there is a desire to scale-up the activities to a larger lecture course. As such a series of strategies are proposed:

- The small-scale experiments described in this paper could easily be converted to recitation/precept/tutorial activities. A list of supplies to purchase over the semester could easily be coordinated with the student store and could easily be kept under $20-$30 for the semester for each student (which in the context of a $125 textbook is
reasonable). This would require some training for TAs and some very careful editing of the worksheet/instructions to ensure maximum clarity. In some schools, this would also require a shift in the culture surrounding recitations, which can be viewed by some students as ancillary at best and optional at worst. However, such a shift could well be beneficial as many engineering educators and engineering education research are currently much concerned with moving the engineering classroom away from the passive modes of learning that make up the majority of student contact time. Further, such a strategy would contribute to the professional development of graduate student TAs who make up the future generation of engineering educators.

- The design competition described in this paper could be scaled-up for a large course. In the smaller group, two of the successful elements of this activity were the individual meetings between the students and the instructor, and the fact that the students ultimately had to present their project publically. These issues could be addressed for a larger group by allowing students to work in groups of more than 2, giving the students access to a library of previously successful projects to give them inspiration and some models for solving the most common issues, and/or creating a two-tier competition where all groups are required to make a two minute video presentation of their project which could be used to either make a much denser (and thus reasonable in terms of time commitment for students, instructors, jurors) public presentation, or to pick the best 10 or 15 projects that might then be presented publically (perhaps as part of a recruitment weekend or similar school-wide activity).

- There is the potential to create teaching materials that might guide students through an at home experiment or activity. This has already been trailed in a small way in the smaller group, where each homework assignment required students to find an example of each new topic in their everyday environment (dorm, campus etc). When they could not find an immediately obvious example they were encouraged to “rig something up” from whatever they had lying around. This resulted in an interesting collection of photographs of students balancing chairs in the student center, yoga poses as examples of tension and compression, weight equipment from the student gym analyzed, untidy dorm rooms with strings and trash cans deployed to look like something they had seen in the textbook. Anything we can do to encourage our students to identify examples in the world around them and the physical phenomena we are teaching them and to think of themselves as those who create, who make, who do, will be of huge value in training the engineers who have to face the technical challenges of the 21st century.

CONCLUSIONS

In conclusion, the authors are enthusiastic about the positive results seen from the hands-on activities in the smaller classroom and determined to further investigate the potential to scale-up those activities to the larger lecture format, test the proposed methodologies and evaluate the results.

REFERENCES


Sinead C. Mac Namara is an Assistant Professor joint appointed at the Syracuse University School of Architecture and L. C. Smith College of Engineering and Computer Science. She teaches structures, engineering design, and design-build to architecture students, and mechanics and engineering design to engineering students. Her research interests include structural art, engineering education, applicability of architectural pedagogy to the engineering education culture, design-build and structural design as methods for teaching.

Joan V. Dannenhoffer, P.E. is an Associate Professor of Civil and Environmental Engineering at Syracuse University. She received her M.S. in Environmental Engineering from the University of Connecticut, an MBA from Rensselaer Polytechnic Institute and B.S. in Civil Engineering from Rensselaer Polytechnic Institute. She is a Professional Engineer in the State of Connecticut. Her research interests are in engineering education pedagogy, especially in implementing active learning strategies in large classes. She currently teaches Engineering Statics, Mechanics of Solids, and Civil Engineering Materials.