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Active Learning Pedagogies Promoting the Art of Structural and Civil Engineering

Dr. Aatish Bhatia, Princeton University

Aatish Bhatia is an Associate Director (Engineering Education) in Princeton University's Council on Science and Technology. He works with faculty in engineering and related disciplines on incorporating active learning in the classroom and bringing science and engineering to a wider audience.

Peter Christopher Chen

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Introduction

Students who switch out of STEM majors frequently cite uninspiring introductory lecture courses[1] and poor teaching[2] as among the reasons for this decision. An active learning approach to teaching (i.e. one that emphasizes learning by doing) has been shown to improve student performance and retention in STEM[2,3], as well as increase student motivation and interest[1,4]. Students taught using active learning remember more, and are better able to apply their knowledge[5–8]. Furthermore, an active learning based approach has been shown to reduce the achievement gap and differentially benefit underrepresented minorities in STEM[9–11].

Introductory engineering courses taught with forms of active learning such as project-based learning and problem-based learning have led to increased retention of engineering majors[12–15], improved student performance[13,15], higher quality of peer interactions[13], and more positive student attitudes about engineering[13,16]. In addition to the strong case for adopting active learning in introductory engineering classrooms[17], there is growing concern about how to effectively disseminate innovations in engineering education[18]. Recommendation for adoption and dissemination include attending to the specific needs of varied university cultures and curricula, supporting educators in becoming reflective teachers, and providing long-term support and feedback in the adoption and refinement of these teaching methods and materials[18].

Motivated by these findings, a group of faculty at Princeton University, University of Massachusetts Amherst, and Virginia Polytechnic Institute and State University were awarded an NSF Improving Undergraduate STEM Education Award to advance the dissemination of the Creative Art of Structural/Civil Engineering. The aim of the proposal is to transform an introductory course on civil engineering with research-based pedagogical techniques, and to support the dissemination of this course for STEM and non-STEM students at other colleges and universities.

Our main goals are to

1. Transform an introductory engineering course with dramatically improved interactivity and accessibility for non-STEM students.
2. Ensure that the course takes a form that can be readily adopted into the engineering and general education curricula of many types of institutions of higher learning.
3. Facilitate dissemination, adoption, and continuous improvement of the courses beyond the audience already being reached.

Structures in the Urban Environment is a large-enrollment introductory course that introduces liberal arts and engineering students to the creative discipline of civil and structural engineering through case studies of the works of great engineers and designers. This course is based on the extensive scholarship of Princeton University Professor Emeritus David Billington[19–23], recipient of NSF Distinguished Teaching Scholar Award, and has been disseminated to multiple institutions beyond Princeton University, including Columbia University, Johns Hopkins

University, Bucknell University, Dartmouth College, California Polytechnic State University, Virginia Polytechnic Institute and State University, and University of Massachusetts Amherst.

A National Academy of Engineering report[24] on the future of engineering education emphasizes the importance of case studies in engineering education, stating that "*Engineering educators should explore the development of case studies of engineering successes and failures and the appropriate use of case-studies approach in undergraduate and graduate curricula.*"

In this course we make extensive use of historical examples and case studies to highlight engineering in the context in which it is practiced. These case studies illustrate how great works of engineering integrate scientific skills and innovations, are a product of social needs and conditions, and can symbolically manifest the individual vision of the engineers. A central focus of this course is for students to experience engineering as a creative discipline, allowing for aesthetic exploration within a set of constraints. Students examine the interplay between economy, efficiency, and elegance, and critically examine the idea of structural art.

Recent Course Enhancements

We are currently in the first year of enhancing this course with active learning exercises including think-pair-share questions, interactive lecture demonstrations, and project-based exercises. Below, we list a few such recently developed course enhancements.

1. Kinesthetic activities - Eiffel Tower and Forth Bridge

Kinesthetic activities have the potential to engage students with principles of engineering design, and can be effective in introducing structural engineering concepts to students outside of engineering majors[25,26]. By experiencing and observing how bodies respond to external loads, students can discover and intuitively understand structural concepts, and can better visualize the flow of forces in a structure. These demonstrations are then followed by think-pair-share clicker questions encouraging students to discuss their conclusions, and serving as an introduction to the corresponding force diagrams and equations.

For example, when introducing the structural principles behind the Eiffel Tower, students are asked to participate in an activity where they model a tower with their bodies. When students are asked to resist an external 'wind load' in the form of another student pushing at their shoulder, the first student intuitively widens their base by moving their feet apart, thus resisting overturning. Furthermore, they can directly experience which of their legs is under compression and which is under tension in response to this 'wind load'. This understanding is assessed using a think-pair-share question on a clicker-style classroom response system, encouraging discussion among the students. The instructor may remark that a similar phenomenon occurs when people widen their stance to prevent toppling when standing in an accelerating subway car. This activity is followed by a discussion of the moment diagram of the Eiffel Tower. Thus, the students can assimilate the new knowledge in the context of their discussions and experiential activities. The moment diagram of a wind-loaded tower is thus connected to everyday experience.

When introducing the Forth Bridge, students participate in a kinesthetic activity to understand the structural principles of a cantilever bridge, based on a demonstration by Forth Bridge engineer Benjamin Baker. We begin this activity by illustrating the role of balance in a cantilever bridge by comparing a section of the Forth Bridge to a simplified model (Figure 1). Through a think-pair-share clicker question, students are asked to relate the suspended weight to the forces in the anchors. This begins building the students' intuitions for how the load is transferred in a cantilever bridge.

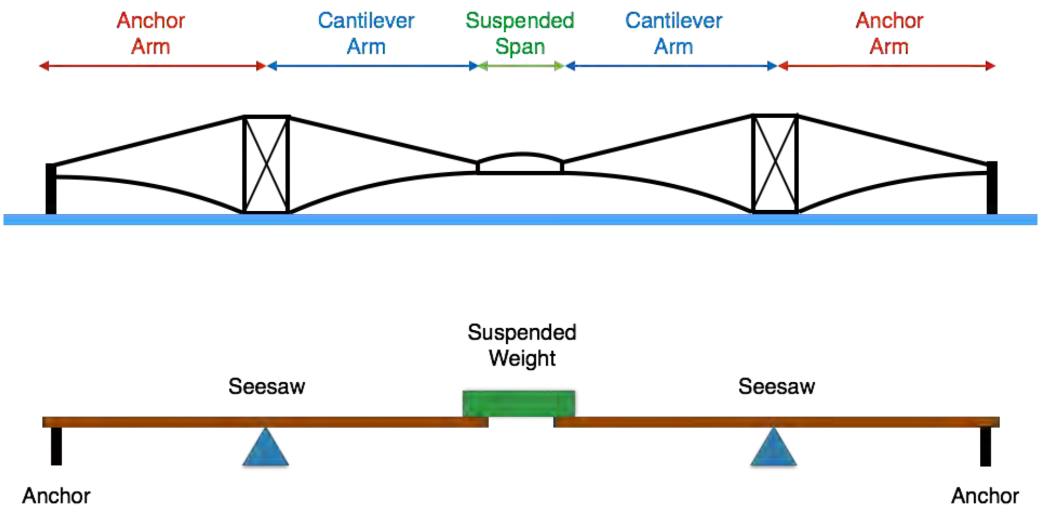

Figure 1: Simplified model of a cantilever bridge

To gain a more in-depth understanding of this bridge, we proceed to the kinesthetic activity. To demonstrate the stability of the cantilever, Benjamin Baker designed a demonstration with three men, two chairs, two piles of bricks, four broomsticks, and rope (Figure 2). With their outstretched arms, the people on the left and right act as cantilevers, and serve to transfer the load of the suspended person (center) to the anchors on the left and right.

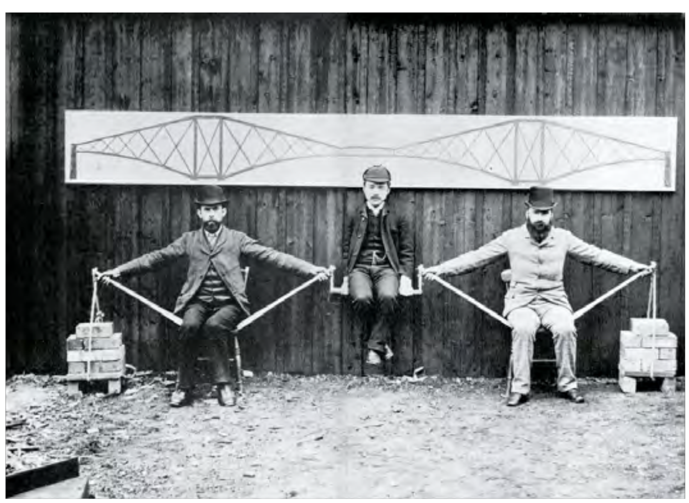
Figure 2: Benjamin Baker's human cantilever demonstration of the Forth Bridge
(Public Domain Image)

Teaching assistants in *Structures in the Urban Environment* recreated this demonstration with planks of wood and rope (Figure 3). Five students can participate in this activity at a time - one serving as the load in the center, two serving as the cantilevered arms on each side of the load, and two serving as anchors on the left and right ends.

Figure 3: Students participate in a human cantilever demonstration in class

Students can use this demonstration to experience and observe how the load is distributed in a cantilever bridge, thus gaining a first-hand understanding of the stability of a cantilever and its role in bridge design.

Understanding of this exercise is then reinforced and assessed by asking think-pair-share clicker questions to predict the consequences of changing the suspended load. Students are also asked to identify which of the structural elements are in compression and which are in tension (Figure 4).

After completing this activity, students should be able to: 1. Demonstrate how a cantilever bridge relies on a balance of forces; 2. Describe the role of the different structural elements in a cantilever bridge and identify those that are under compression or under tension; 3. Reason about the stability of the cantilever and relate changes in one part of the bridge (e.g. greater load) to changes in other parts of the bridge. Thus a theoretical understanding of the cantilever principle in the Forth Bridge is grounded in experiential learning.

2. Activities Using West Point Bridge Designer

We incorporated the use of the *West Point Bridge Designer* (WPBD) simulation software[27] to help students visualize how forces flow through the structures they study in class. For example, in a module on the Golden Gate Bridge, we made use of WPBD in an interactive lecture demonstration[28–30]. Students are first asked to make a prediction involving the role of the cable in a suspension bridge. After reasoning and sharing their answers, the students are shown a physical demonstration of a suspension bridge as well as a virtual simulation of a suspension bridge in WPBD. Having experienced this demonstration, they are asked to reflect on the outcome, and specifically to focus on whether the demonstration confirmed or contradicted their original prediction.

We also designed a virtual bridge design competition conducted in recitation using WPBD (to complement a physical bridge design competition conducted in lab). Here, students apply the principles of optimization they have learned, and compete to design bridges that are both efficient and elegant. Through the use of bridge simulation software such as WPBD, students can gain a clearer understanding of how structures respond to loads, and can identify the different elements under compression and under tension. Further, the use of these simulations provide insights into how structures are optimized for greater safety and efficiency.

3. Interactive Lecture Demonstrations on Earthquake and Wind Resistance

In Spring 2015, we are introducing a new lecture and recitation on the topic of designing structures to withstand wind and earthquakes. Through case studies such as the Mexico City Earthquake of 1985, students will be introduced to the concept of resonant frequencies of buildings. We have built a version of the *Building Oscillation Seismic Simulation* (BOSS) model, a pedagogical physical demonstration developed by the American Geophysical Union and revised by the *Incorporated Research Institutions for Seismology* (IRIS) consortium[31,32]. We will incorporate this in an interactive lecture demonstration where students will go through stages of predicting, experiencing, and reflecting on the outcome of this demonstration, to investigate the concept of resonant frequency and its relationship to building height. We have also built a version of an IRIS building strength demonstration, which will allow students to investigate the role of shear walls in resisting wind and seismic loads[32].

Additionally, we will use case studies such as the Citicorp Tower and Burj Khalifa to further illustrate the concept of resonance in relation to wind load, and the phenomenon of vortex shedding and cross-wind motion. We have built a K'NEX model and shake table to demonstrate the effect of a tuned mass damper on the vibration of a tall building, following instructions developed by Jason Lloyd for the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES)[33].

Future Directions

While currently in the first year of implementing this project, we are also in the process of collecting data to assess the extent to which our 3 main objectives are being met.

Goal 1: Transform course with dramatically improved interactivity and accessibility

To assess the effectiveness of these active-learning based course enhancements, we will take a mixed-method approach, collecting quantitative and qualitative data. Quantitative data such as course grades and surveys will measure the impact of the course on cognition and affect. We have adapted the Student Assessment of their Learning Gains Survey[34] for this purpose. Focus groups, individual interviews and open-ended questions on surveys will garner qualitative data to complement the mostly quantitative surveys. One of the learning goals of this course is for students to appreciate that engineering is a thoroughly creative discipline, and these surveys and interviews will allow us to study the extent of this belief, and its effect on STEM engagement, enrollment and attrition.

Goal 2: Ensure that the course can be readily adopted into curricula of many types of institutions

We are in the process of modularizing this course to a publicly accessible website from where course materials can be downloaded for adoption at various institutions. These materials will include teaching materials such as lecture slides, assessments, active learning exercises such as polling questions, interactive lecture demonstrations, and workshop handouts.

Goal 3: Facilitate dissemination, adoption, and continuous improvement of the courses

In addition to the public repository of teaching materials, we are hosting workshops for institutions interested in adopting this course, and conducting follow-up surveys with educators expressing interest in adopting the course. We will conduct both formative and summative analyses, receiving feedback from partner faculty, and maintaining contact with educators interested in adopting this course, providing support as needed to facilitate adoption.

The resulting modularized course materials and research findings will be widely disseminated to contribute to the growing body of literature on STEM teaching and learning.

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