AC 2010-1858: INTRODUCTORY STRUCTURAL ENGINEERING EDUCATION THROUGH COMPUTATIONAL AND PHYSICAL MODEL BUILDING

Powell Draper, Manhattan College

Edward Segal, Simpson Gumpertz & Heger

Robert Sicurelli, Princeton University

Introductory Structural Engineering Education through Computational and Physical Model Building

Introduction

This project explored new ways of teaching introductory structural engineering concepts through computational and physical model building. An educational project was organized in which students would study actual structures, create accurate computer models of their geometry, and then build to scale physical models of them. This project is intended to augment the ways that structural engineering is traditionally taught.

Background

This project was inspired by work done at Princeton University and other schools in which physical models of structures have been used to provide examples of exemplary works of structural engineering and to demonstrate engineering principles. At Princeton, for example, models of structures have been used either for museum display or previously built models are used for structural experiments.[1] Here we instead sought to examine how a student designing and building a model for loading, experimentation, and display could provide an opportunity for a different type of learning experience.

This project was first tested with a rising sophomore student of engineering. The student had taken first year courses in mathematics and physics. In addition, the student had taken a survey course of exemplary works of structural engineering, but had not yet taken any other engineering courses on, for example, statics or mechanics. This project sought to explore how a model building project could augment or perhaps even supplant traditional approaches to teaching introductory engineering topics.

This project was formed as a collaboration between industry (a structural engineering firm) and academia (a college's civil engineering department). The student spent the first half of the project at the engineering firm under the guidance of a practicing engineer and the second half in the college's civil engineering department under the guidance of a member of the faculty there.

First, the student was introduced to three dimensional computer-aided design (CAD). Next, a structure was chosen that the student would be able to visit and study and one for which details could be obtained. The structure chosen for the project was the George Washington Bridge in New York City. With drawings of the bridge and details from technical journals, the student created a three dimensional computer model of the relevant parts of the structure. The three dimensional CAD program Rhinoceros® was used for this project.[2]

Next, the student was guided through physical model construction. After investigating material options, the model materials were selected (K'NEX) and then a plan for model construction was arranged. The student had to select an appropriate scale that would adequately represent the structure with the materials available. The student created an Excel spreadsheet to predict how many K'NEX parts of each size would be necessary to correspond to a scale model of the bridge. The student then created to scale a physical model of the bridge in which loads can be applied and reactions measured.

Tasks and Learning Objectives

For the initial trial of the project the student was encouraged to work through a set of tasks. Table 1 lists these tasks and the core learning objectives associated with the completion of each task.

Table 1. Student Tasks and Learning Objectives

	Task	Learning Objective
1	Complete introductory tutorials for three dimensional computer-aided design (CAD)	After completing this task the student will be able to execute drawing commands such as: line, trim, rotate, mirror, and length. Also, the student will be able to assign elements to layers and snap to objects
2	Interpret plan, elevation and section drawings for the George Washington Bridge	After completing this task the student will be able to look at a section cut indicated on an elevation, find its related section, read its dimensions, and recreate the section in a computational model.
3	Determine appropriate materials and scale for the physical model	After completing this task the student will be able to examine a structure and determine its pertinent features in order to create a representative, rather than a replica, small scale model.
4	Perform a parts count and determine the cost for materials	After completing this task the student will be able to write simple formulas in Microsoft Excel.
5	Construct a physical model that is not only for display, but also for teaching and learning	After completing this task the student will be able to describe the process of building a physical model and the reasons underlying decisions.

The tasks listed in Table 1 form the steps in the student's design process.

Design Process

Task 1: Complete introductory tutorials for three dimensional computer-aided design (CAD)

Creating a 1:385 scale model of the George Washington Bridge started with computational modeling. The idea was to create an accurate computer model using the actual plans. Then, from this computer model, the student could determine which components of the computer model would be unfeasible to include in a scaled-down model.

In preparation for modeling the George Washington Bridge the student completed introductory CAD tutorials. The program's tutorials presented examples requiring commands such as: line, trim, rotate, mirror, and length as well the use of layers and snapping to objects. Following completion of the tutorials the student generated his own models of a chess rook (Figure 1) and "Leonardo's Bridge" located outside Oslo, Norway (Figures 2 and 3). The structural drawings for the bridge were obtained from the Norwegian Public Roads Administration and included most of the major measurements of the bridge. These additional examples allowed the student to apply what he had learned in the tutorials to real objects while following his own design procedures and discovering new CAD features and commands.

Task 2: Interpret plan, elevation and section drawings for the George Washington Bridge

The structural drawings for the George Washington Bridge came from a primary source, designer Othmar Ammann's article in the ASCE Transactions.[3] The student obtained dimensions not listed on the drawings by scaling from listed dimensions. As in the case of "Leonardo's Bridge" the student had to interpret plan, elevation, and section drawings. Whereas the only sections necessary to determine the geometry for "Leonardo's Bridge" were through the deck and arches (solid rectangle and triangles), the George Washington Bridge's geometry is defined by a set of sections representing the two dimensional trusses forming the deck and towers. The student recreated all tower truss sections as line elements in CAD that were then moved and rotated to form the three dimensional truss (Figure 4). This exercise allowed the student to actively see how sections shown on a drawing relate to one another. Many of the sections are intricate and unique, prompting the student to think about how things could be simplified for a scaled down physical model.

The deck was not recreated in CAD due to a lack of information in the Transactions; however, its proportions and basic structural characteristics were noted and included in the physical model. Also at this time, the student began to address the derivation of the equations for the parabolic suspension cable, but much of this was accomplished when construction of the physical model began.

Task 3: Determine appropriate materials and scale for the physical model

After the computer model was created, the student began to determine how the digital rendition could be scaled down so that the physical model would be:

1) as accurate as possible with respect to the geometry of the real structure
2) straightforward to construct
3) recognizable to those familiar with the bridge and aesthetically pleasing

In order to fulfill these three objectives, the first step was to determine the scale of the bridge. 1:385 was chosen to accommodate the desired length of the model (~14 feet) that would allow for both articulation of the bridge's features and a reasonable length (i.e., not larger than a typical classroom). The next step in the process was determining the model's materials.

The primary options for materials were initially determined to be small wooden pieces ("matchsticks") and K'NEX. Matchsticks were appealing because they can be cut to different lengths to provide a scaled match to each member in the actual structure. However, it was determined that the potential result, although accurate and strong enough, could not be easily mended if broken. Also, the process of individually cutting each member to the proper size would be time consuming.

In the end, micro K'NEX (a smaller version of K'NEX, roughly one-third the original size) was chosen for its durability, ease of construction, and ability to be ordered in bulk. However, this material required changes from the digital model. For example, the gentle taper along the vertical edges of the towers could not be accomplished with K'NEX. After editing the computer model to determine how a rectangular tower would look, it was determined that on a small model, the inclusion of the taper would have minimal aesthetic impact. Other edits were made to the computer model to accommodate this material. The spacing between each horizontal member in the vertical direction was made equal. Although this gave the tower a "blocky" feel when critically analyzed, in general the structural and aesthetic impact was minimal. Due to the larger scale of the K'NEX in cross-section than the overall scale of the model and the limited lengths available in K'NEX, some of the two dimensional trusses were omitted. Structurally, this had minimal impact on the tower design (the model was rigid without these two dimensional trusses). This change also had minimal aesthetic impact as enough layers were included in the eighteen-inch tall towers to give a sense of the bracing of the actual bridge towers.

Task 4: Perform a parts count and determine the cost for materials

Once the materials were determined and the computational model was scaled down to the appropriate size, the student created a spreadsheet to determine the number and types of parts necessary for construction. The three dimensional line drawing of the George Washington Bridge was used to estimate what parts would be used to represent the structure. Micro K'NEX are only available in certain sizes, so the student had to adjust the plan for construction to build the bridge out of available parts. This task gave the student some experience entering values into Excel and manipulating simple formulas.

Task 5: Construct a physical model that is not only for display, but also for teaching and learning

After constructing a tower based on the digital edits, one can see that the K'NEX tower is a representative model of the George Washington Bridge (Figure 5). The next step was constructing the deck with properly scaled out-to-out dimensions (length, including back-spans, depth, and width). Once the deck was complete it was inserted into the towers and was able to translate laterally and longitudinally. The deck was temporarily propped up from underneath until the cables could be attached (Figure 6).

We decided to use four cables, two on each side of the deck, as in Ammann's design. To produce the same vertical reactions, in proportion to the actual bridge, it was important to achieve the same span-to-cable sag ratio. To accomplish this, points were found along the original bridge's cable (treating the cable line as a parabolic function) to determine the equation of the parabola using linear algebra. The equation representative of the actual George Washington cable was scaled down and used on the 1:385 model. The student and some of his parabolic calculations are shown in Figure 7.

The materials to be used for the main cable and the suspender cables required engineering design, as well. For the main cables we found 1/16-inch diameter steel cable. For the suspenders the student sought to find a material that would be relatively easy to connect repeatedly (there are many suspender cables) and also look right in terms of representing the actual suspenders. Initially we chose small gauge wire so that the connections between the suspenders and the main cable and deck could be twisted as opposed to tied. But in place and under load the wires kept their deformed shape. Kinks in the wire kept the suspenders from displaying a straight form. This provided a quick lesson on the difference between elastic materials and plastic materials. This wire was deemed unsuitable for the final model. After some intermediate experimentation with fishing line (that tended to disappear at a distance), it was ultimately decided to use simple string for the suspender cables. This was labor intensive in terms of tying knots to connect them, but resulted in straight cables that clearly represented the bridge's suspenders.

The next task was figuring out how to construct the parabola following its formula. It was determined that the parabola should be created by the string suspenders pulling on the main cable. The suspenders were evenly spaced along the span and back-spans, and according to their "x position" along the deck, each suspender was given a length "y", corresponding to our function. The suspenders were then tied and cut accordingly, and then fastened to the main cable directly above.

The full-scale George Washington Bridge has abutments molded into the rock that lies along the Hudson River. To emulate this, wooden abutments were created that rested on a large plate (one plate for each tower and abutment) that would hold both the abutments and the towers. So long as the two large plates were kept at the proper distance (not sliding inwards like the natural forces want them to), the bridge would sustain its own weight. The cables were fed into adjustable turnbuckles, which were then attached to a wooden block that maintained their proper separation. This wooden block was attached to a larger block that temporarily held the place of a scale that would be able to measure horizontal reactions. The adjustable turnbuckles permitted one to fine tune the structure to obtain even weight distribution between the four cables, as well as the desired upward camber of the deck (Figure 8). In the end, the bridge was able to stand on its own, and provide viewers with the proportions and intricacies of the George Washington Bridge.

Student Commentary (by the Third Author)

From this project, I learned countless lessons about commissioning an engineering project. One of the first lessons is that often, many ideas never make it out of the project room. Certain desirable applications are simply not practical in various situations. However, when given a job to complete, one must compensate for such changes and work with what he has to produce something truly elegant and functional. Also, even with severe planning, one will always run into certain on-the-job brainstorming and problems. I learned that this is what engineering is all about – coming up with solutions to physical problems that stand in the way of progress. On the grand scale, the "physical problems" here were to create a model bridge where the vertical and horizontal reactions can be measured, and that aesthetically demonstrates the beauty of the George Washington Bridge. Generally, the overall picture that provided the solution to this problem was simple (a micro K'NEX bridge that falls within "x" proportions). However, at each and every micro level of solving this problem, more issues arose that required instant brainstorming and consulting with peers to uncover solutions. Also, of course, taking on a project like this teaches one about suspension bridge basics in a hands-on manner. These lessons are countless, but some examples are listed below:

1) How does one read structural engineering drawings?
    a. How can one utilize such drawings to reproduce a model, whether digital or physical?
        i. What is "CAD" and why, as a prospective civil engineer, is it important for me to learn the ropes of three dimensional computational modeling?
    b. How do these drawings give us the insight the chief engineer had when crafting the structure of the bridge?

2) How does a suspension bridge work?
    a. Why is there a cable and how are forces distributed?
    b. Why does the cable take the form that it does, and why are the proportions of this form even important?
        i. What equations govern the forces in a suspension bridge?
        ii. How and why is the camber in the deck achieved?

Every step of the process, as well as every struggle along the way, had a purpose and provided an invaluable lesson. Beyond the computer model, I believe there should be no fixed or basic procedure one should follow when given such a daunting task. The learning experience one gets from struggling with finding a solution on one's own is priceless.

Assessment

The student demonstrated an ability to work creatively both independently and collaboratively while completing all of the tasks set at the beginning of the project within the timeframe allotted (twelve weeks). . He is able to describe the process that he went through and the reasons underlying decisions (the student made significant contributions to the section "Design Process" above in addition to the section "Student Commentary"). These reasons include concerns for structural strength and stability, ease of construction, cost, and aesthetics. Some of the engineering concepts that the student was introduced to during the structural modeling process include:

- Units
- Scale
- Forces, moments, and reactions
- Tensions and compression

- Dead load and live load
- Deflections
- Elasticity and plasticity
- Cables

Learning objectives were associated with the completion of each task. The final products, an accurate computer model of the George Washington Bridge's geometry and a physical model for loading, experimentation, and display as well as the student's ability to articulate what he achieved and how he was able to it achieve it indicate that the tasks were completed and the learning objectives met.

To fully evaluate the effectiveness of this project, particularly alongside or in comparison to traditional methods of introductory structural engineering education, we will need to establish formal methods of assessment. As of now we consider this project an initial exploration of different teaching and learning methods, and hope to both expand the project and to develop formal methods of assessment.

One method of doing so will be a comparative critical analysis. The authors plan to initiate student model design and build competitions. These competitions, either as a part of coursework or outside of the curriculum, will allow for interpretation of the effectiveness of student model design and creation as a part of engineering education. By including both students who have had courses on statics, mechanics, and structural analysis as well as those who have not (and students who have built models and those who have not), and by thoroughly evaluating student creations for economy, efficiency, and elegance, we will be able to investigate how the design and creation of models aids student understanding of introductory structural concepts.

Future Work

The process has since been extended to a group of students in a junior-level introductory structural analysis course. Seventeen students worked as a team to create a computational model and physical model of a structure. In this case the students, while studying cables and arches, built a computational model and physical model of the Bayonne Bridge (Figures 9 and 10). Because there were more students working on this project, they were divided into specific roles, such as "Project Leaders," "Data Collectors," "Scalers/Parts Estimators," "Computer Modelers," "Constructors," and "Report Writers." Upon completion of the model, students indicated that they felt they were able to understand the design and construction of an arch/cable structure more so than had they solely relied upon classroom instruction, homework assignments, or tests. This project shows promise for using model building exercises to not only enhance structural or engineering education, but also to develop leadership and teamwork skills in engineering students.

Having had students build models of existing structures, we now hope to extend this project to include student design projects. After using model building to enhance introductory engineering skills, we will next have upper level students use model building as a way to develop creativity and design skills by having them create models of their own structures.

Conclusion

This project is intended to form an initial investigation into new approaches to engineering education. This project seeks to find ways to augment traditional methods of instruction such as the blackboard, homework assignments, and demonstrations. Student model building as both an independent research project and as a group project in a course shows promise as a new way of learning introductory principles of structural engineering. Existing physical models have previously been used for demonstrating engineering principles, but this project sought to investigate how the process of model design and creation could enhance student learning early in their education. This project sought to find ways in which student model building projects can reinforce traditional engineering instruction while also developing the creativity of the engineering student. From this initial investigation it is believed that computational and physical model building hold great promise as tools for introductory structural engineering education.

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3. Ammann, O.H. "General Conception and Development of Design." *Proceedings of the American Society of Civil Engineers*, Transactions Number 1933, Volume 59, Number 8, Part 2, October 1933.

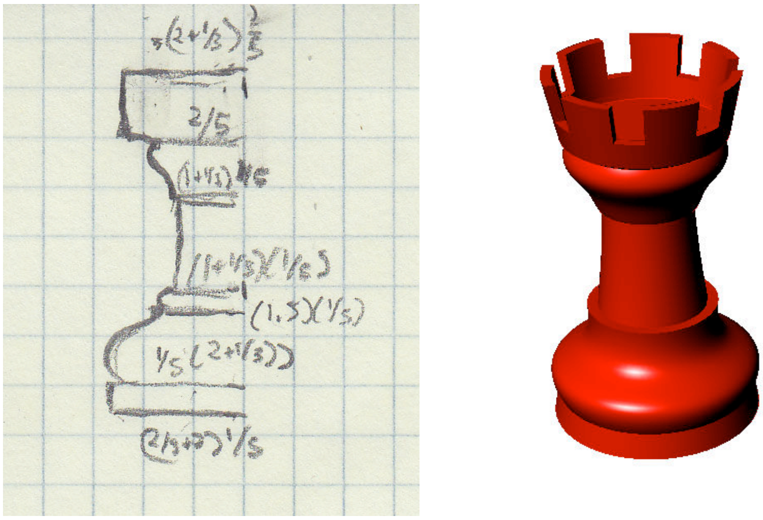

Figure 1. Student's Measurements and Computer Model of a Chess Rook

Figure 2. Leonardo's Bridge, Oslo, Norway (Photograph courtesy of Ryan Woodward, HNTB)

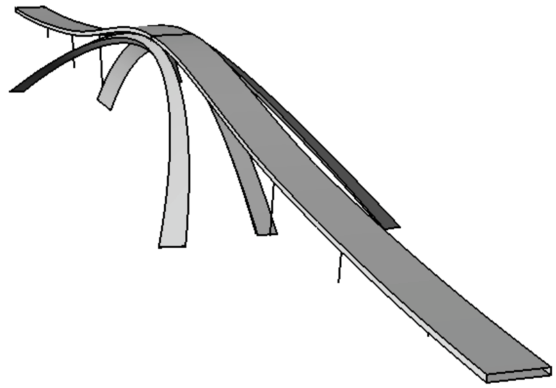

Figure 3. Student's Computer Model of Leonardo's Bridge

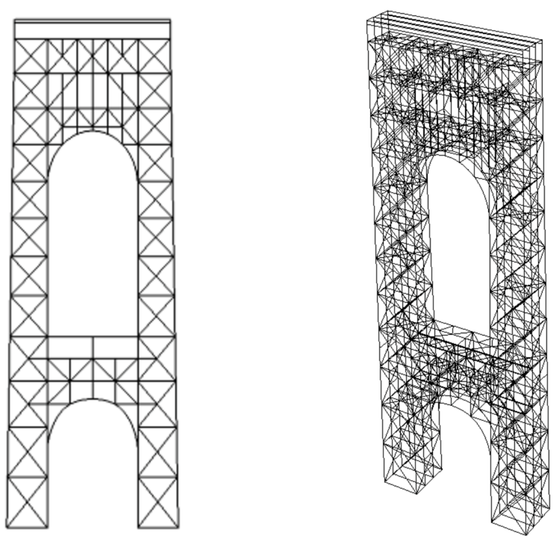

Figure 4. Student's Computer Model of the George Washington Bridge Tower (tower truss section reproduced from Ammann's drawings, this section was simplified for construction of the physical model)

Figure 5. Student's K'NEX Model of the George Washington Bridge

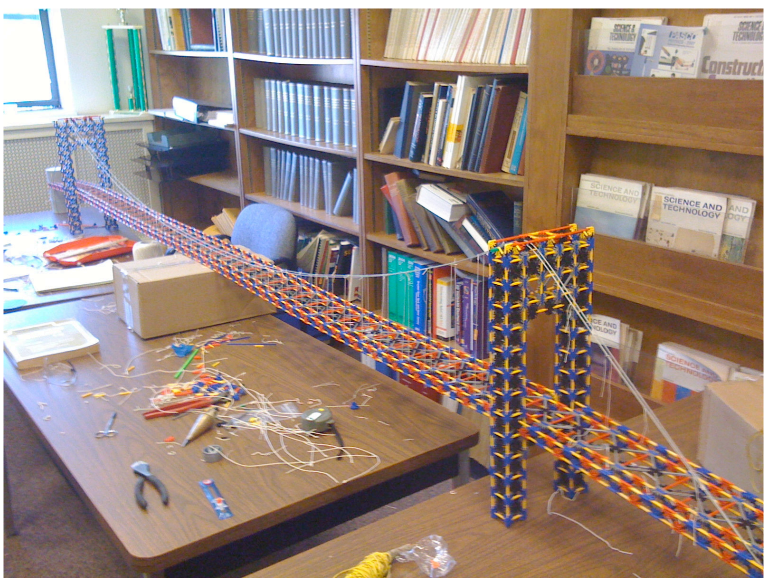

Figure 6. Student's K'NEX Model of the George Washington Bridge during Construction

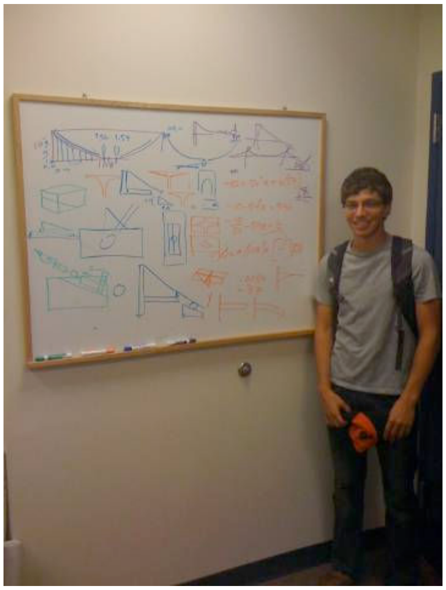

Figure 7. Student with Calculations

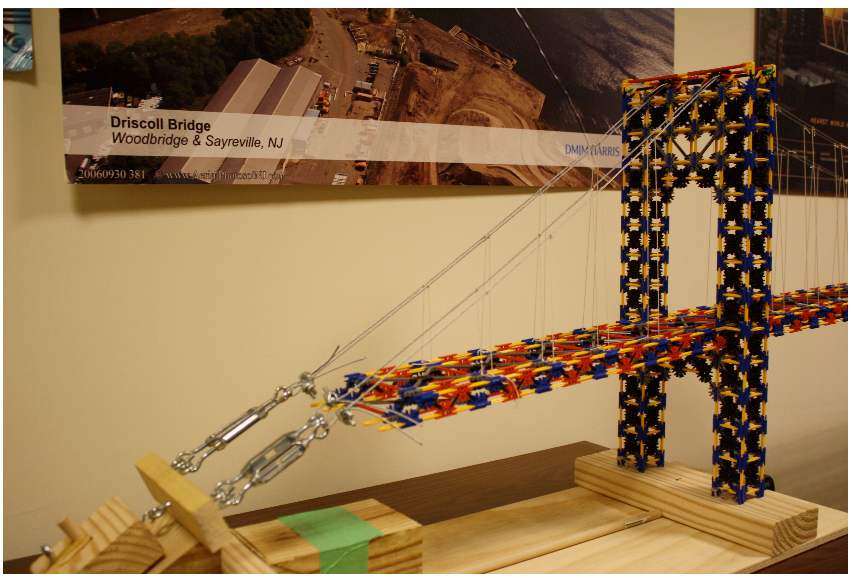

Figure 8. Student's George Washington Bridge Model Anchorage

Figure 9. Students Constructing Bayonne Bridge Model

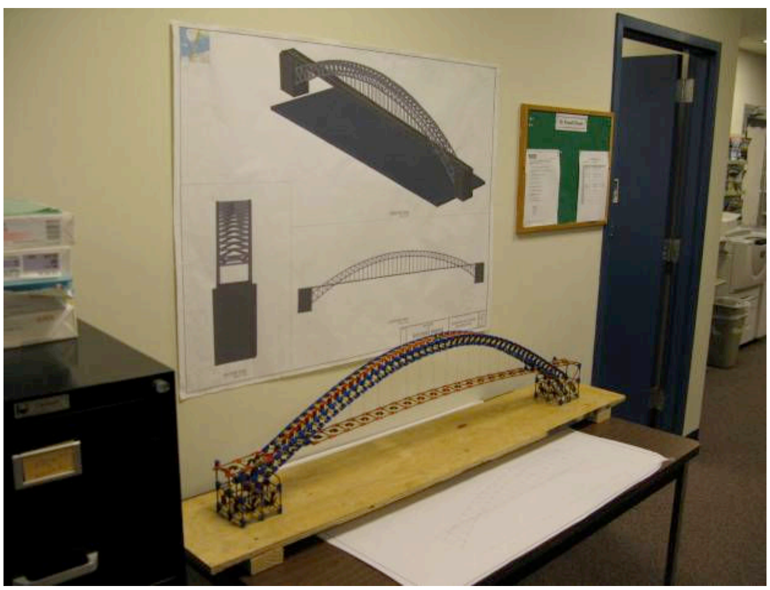

Figure 10. Students' Bayonne Bridge Model