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

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Paper ID #15076

Manipulatives in Engineering Statics: Supplementing Analytical Techniques with Physical Models

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Abstract

In order to assist students, gain conceptual understanding of internal forces, a physical manipulative of a truss was developed in order to help students visualize, feel, and analyze the behavior of the material being manipulated. The purpose of this qualitative study was to understand how a physical manipulative of a truss contributed to the conceptual understanding of truss analysis in statics. In this study, six students were presented with a simple problem of a truss, where no measurements or numerical quantities were provided, and asked to determine which members where in tension or compression. Subsequently, the participants were given a model of a physical manipulative resembling the same problem they were given before and asked the same questions. Preliminary qualitative results indicated that physical manipulative helped students visualize concepts taught in the classroom and provided a venue to gain conceptual understanding of internal forces.

Introduction

Engineering statics is a fundamental course, and a core building block, that prepares students for subsequent courses such as dynamics and mechanics of materials. This course helps engineering students develop a fundamental understanding of basic mechanics areas of statics critical for the analysis of other core engineering courses throughout the engineering program. It lays the foundation of Newtonian mechanics that students utilize to analyze and design in future courses.

However, studies have shown that students tend to have different misconceptions in statics. [1-5] Statics remains one of the courses where achievement levels are sometimes not satisfactory,[6] even though it is one of the basic courses in engineering that forms the foundation for the engineering curriculum. One particularly challenging area for instructors is to show "intangible" mechanics principles that may seem too abstract for students. For instance, analysis of internal forces of members in a truss system may be easily procedurally calculated leading to a solution that may not have a true intuitive meaning for the student. Thus, visualization is necessary to help the student move from procedural fluency to conceptual understanding of statics concepts. It is through conceptual understanding that the student will demonstrate her/his ability to reason in settings that involve not only mathematical manipulation but also application of concepts, relations, and representations. Conceptual understanding is the bridge that could enable students to solve new kinds of problems and achieve success in statics.

Enhancing a student's ability to mentally visualize and intuitively assess foundational concepts in statics can create a significant advantage for students in their pre-professional engineering courses.[6, 7] Simple mathematical analysis often leads to a solution that may not have a true intuitive meaning for the student. Therefore, innovative teaching methods in engineering statics are necessary in order to emphasize specific concepts in statics. Showing students "abstract" mechanics principles is not an easy task and usually requires proactive measures to improve learning. In an effort to improve visualization and learning in a mechanics course, a physical manipulative was used investigate its pedagogical impact on students. The objective of this exploratory study was to help students improve their ability to assess foundational concepts in statics. The following sections describe how the physical manipulative contributed to the conceptual understanding of truss analysis in engineering statics.

Physical Manipulatives

Mathematics instructors have used manipulative models to help students identify different mathematical concepts. Physical manipulatives in mathematics are concrete objects which students use to explore mathematical concepts through the students' visual and tactile senses.[8] These models not only allow students to see and feel different objects, but also manipulate the objects to form a concrete representation of the concept. The advantage of using physical manipulatives is the fact that manipulatives enhance spatial visualization for engineering students.[1] Based on the same idea of physical manipulatives used in mathematics, this study intends to examine the impact of physical manipulatives in the learning of statics concepts.

Physical manipulation is an effective strategy to learn about complex and abstract concepts.[9] Some studies have indicated the importance of physical manipulation in learning. Different manipulative devices have been created to teach students concepts about characteristics of viruses and cells,[10] forces in electromagnetic fields,[11] and mathematics.[12] The ability to manipulate these dynamic objects connects the student with the real teaching and learning power of the manipulatives.[12] This manipulation gives students an opportunity to make meaning of concepts and see relationships as a result of their actions. At the same time, physical manipulatives present an opportunity for constructing knowledge – wherein student learning goes beyond the content that was explicitly presented to them. Thus, the use of physical manipulatives in engineering courses could provide an authentic laboratory experience that helps improve students' conceptual understanding of engineering mechanics concepts. Moreover, physical manipulatives are easy to implement, easy to duplicate and distribute,[13] and can be extended to include different engineering subjects.

Other studies have investigated the use of physical manipulatives in a variety of STEM areas. The use of hands-on (physical) manipulatives has helped engineering students in modeling and engineering problem solving.[7] For instance, Coller indicated that the manipulatives helped students increase their understanding of engineering concepts when they used manipulatives and were able to see and feel reactions created by the manipulative.[7] Another study, involving physical and virtual manipulatives, indicated that manipulatives affected not only learning but also engagement and knowledge transfer.[14, 15] Students developed skills to correctly identify variables based on word problems. It was observed that students with concrete materials, or manipulatives, led to better procedural use and, therefore, a reduced cognitive load.

The use of physical manipulatives could help the learning outcomes of engineering statics students, especially when those concepts may seem abstract to many students, like internal truss forces. However, not enough studies have been done related to the potential educational uses of physical manipulatives in engineering mechanics learning contexts. No known educational manipulatives for truss analysis have been developed or been the subject of studies. The intent of this study was to gain insight into and document how a physical truss manipulative affects students' understanding of internal forces. Some studies suggest that analysis of internal forces is difficult for students – leading to a series of errors commonly made by students.[16] The emphasis was on seeking feedback from students to learn how they used the manipulative, rather than seeking to quantify their improvements. This qualitative study contributes to the ongoing evidence-based research of physical manipulatives in engineering.

Context of the Study

The project was presented to the students in the statics class, and six volunteers were selected randomly from the statics courses taught by the first and second authors. All participants attended the same engineering statics class, which eliminated confounding variables related to pedagogical approaches to classroom instruction. All six participants were male and had already completed the sections relevant to truss analysis in class. The engineering statics course consisted of both lecture and recitation instruction. Lecture time included different instructional strategies that combined active learning, discussion-based teaching, and web-based learning logs (journaling). Recitation time was devoted to help students develop problem-solving skills through active learning. Some of the approaches used in active learning included think-pair-share activities, large group discussion, peer review, and cooperative group activities.

This study did not look into gender or ethnic/racial differences; therefore, there was no emphasis on gender, ethnicity, or race of selected participants. In terms of academic performance, all six participants had demonstrated mastery of skills needed to solve engineering statics problems. Each participant met with the first author, an engineer trained in qualitative research, individually and presented with the physical manipulative of a truss. The primary role of the first author was to facilitate discussions with the interviewee and make observations. Each interview lasted approximately 30 to 45 minutes. The responses from the participants were audio-recorded and transcribed for further analysis.

A phenomenological approach to qualitative research was used in this studythe.[17] Creswell stated that phenomenological research is a strategy of inquiry in which the research explores the experiences of participants about a phenomenon as described by participants.[17] The intent of this research was to describe how participants interacted with the physical manipulative and how they made sense of concepts related to truss analysis using the physical manipulative and how the physical manipulative can be best utilized by students. The physical manipulative cannot have any meaning in itself without having students who experience it.

Method

In this exploratory study, we developed a physical manipulative that could help students gain conceptual knowledge of internal forces when solving truss problems. The physical manipulative was designed with movable parts that could help students visualize the propagation of external forces throughout the structure. A truss problem was selected because it posed different challenges for the students, primarily the identification of zero-force members and the direction of internal forces. Each truss member was printed using a 3D printer, and connected with the other truss members using screws. In this case, the screws simulated connecting pins in a truss as shown in Figure 1.

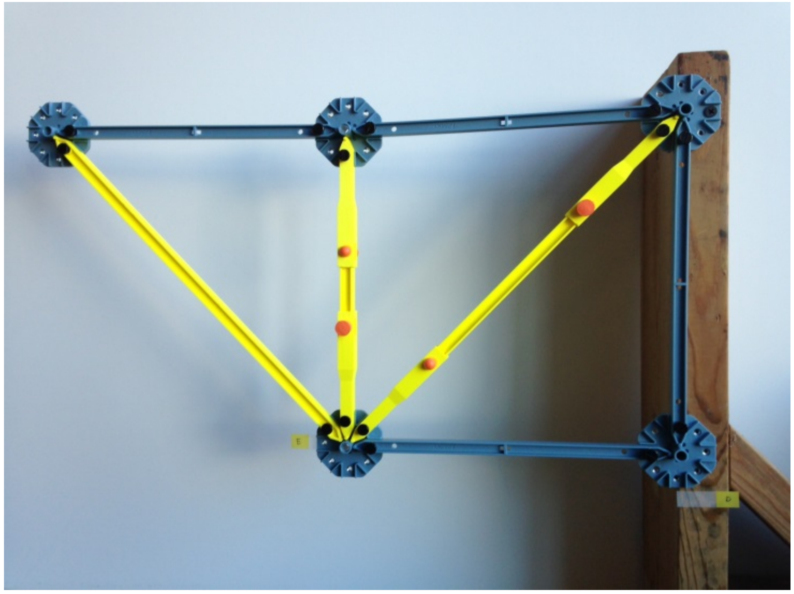

Figure 1. Physical manipulative of a truss.

In order to show the direction of the internal forces, 3D-printed truss members were printed as different sections and connected using foam inserts (polyurethane). Each piece had an orifice at opposite ends of each member piece, which would allow the three pieces to connect. The foam inserts, similar to those used for hearing protection, were compressed and put into the orifices to connect all pieces. The foam inserts were then allowed to expand to connect all pieces together, as shown in Figure 2.

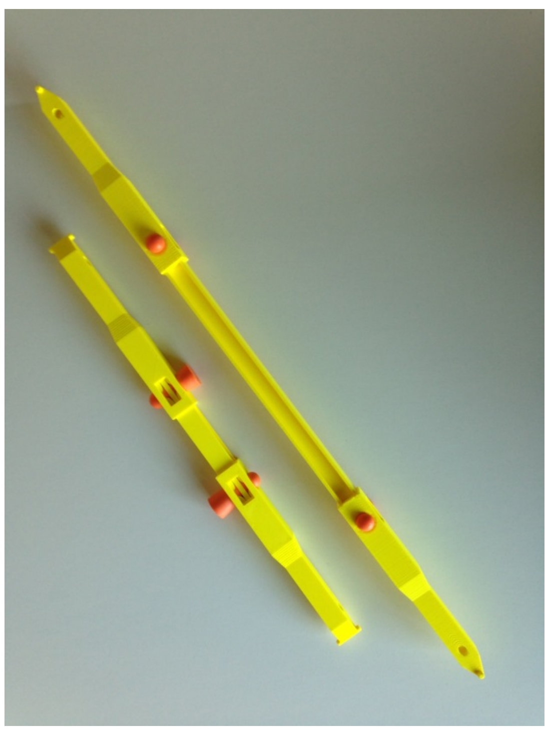

Figure 2. Three-piece members connected with polyurethane foam.

After the truss was assembled, six participants were presented with a simple truss problem, where no measurements or numerical quantities were provided, and asked to determine which members were in tension or compression. All participants had already been taught how to do truss analysis in their engineering statics courses. The participants were given the problem on a piece of paper with no force or length dimensions, as shown in Figure 3. The layout of the problem presented to the participants was similar to the assembled truss shown in Figure 1.

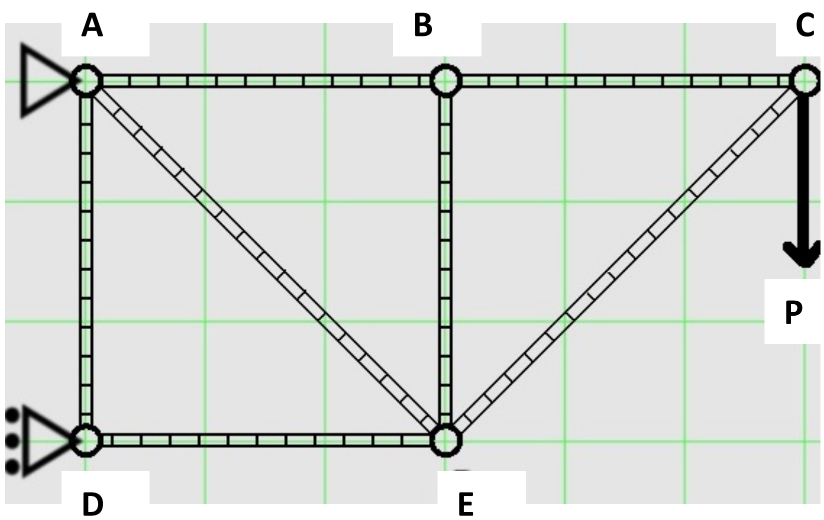

Figure 3. Representative image of the truss given to students. Note the absence of dimensions and force magnitudes.

Using think aloud protocols, the participants were asked to draw a free body diagram of the truss, verbally describe the steps necessary to determine if the members in the truss were in tension or compression, identify the zero-force members, and indicate the direction of the internal forces. Then, the participants were given a model of the physical manipulative and asked the same questions. The participants were allowed to touch and move the pieces of the physical manipulative during the think aloud protocol. Finally, an exit interview was conducted with each participant in order to obtain more information about their experience with the physical manipulative and discuss the differences between their first and second approach to answer the questions asked. Their comments and responses to questions were later transcribed to support the qualitative analysis of their experiences.

Overall, four different types of data were collected in this study: concurrent protocols, retrospective protocols, exit interviews, and participants' artifacts. Concurrent protocols involve a series of questions in which the participant thinks aloud during the process of completing a task.[18, 19] For instance, the participants were asked to indicate what should be included on a free body diagram or the steps required to solve the problem while the participants drew the free body diagram and engaged in problem solving. Retrospective protocols involve questions in which a participant completes components of the task, or the whole task, and then is prompted to reconstruct the process from memory.[18, 19] For example, participants were asked to explain how they determined the members in tension or compression and then the participants was asked to guide the researcher through the process. This process also allowed the researchers to investigate how different artifacts can be used as prompts to encourage students to reconstruct processes from memory. Participants' products or artifacts were collected after the participants were asked to provide solutions to the problem. These products included representations generated during the problem solving process (e.g., free body diagrams and hand-written solutions.).

Every one-on-one session with each participant lasted approximately 30 to 45 minutes. Each session was audio and video recorded and subsequently analyzed. All questions asked during these sessions were open-ended to allow for more verbalization of tasks from the participants. The use of open-ended questions also were used to prompt discussion and follow-up questions. The data set was analyzed following a four-step process described by Sjöström.[20] This analysis approach describes how individuals make sense of their experience. The first step is to get familiarized with the material in the transcripts. The second step is to compile the answers from the participants. The third step is to gather the data in such a way that information is reduced to central significant parts of the dialogue obtained from the participants. The fourth step is to group the data or classify it into similar answers (i.e., find common patterns). One of the goals of phenomenography is to understand the collective meaning of an experience and how it is understood. Thus, using Sjöström's approach allows the researchers to describe participants' experience working with a physical manipulative.

Results

This paper focuses on specific telling cases that are representative of the whole data set. The work centered on a Qualitative research into how students interact and use the truss model. The data selected for this highlights responses obtained from Participant 6 and also includes common patterns observed during data analysis from the other participants.[20] The excerpts shown in this section represent "identical general theoretical principles" similar to those exhibited by other participants.[21] This simplistic form of analysis allows for detailed examinations of the participants' responses that "stimulate generalizations and induce theoretical interpretations about contextual circumstances."[22] By focusing on these descriptions, we intend to provide a "thick description" of the phenomenon.[23]

Data analysis showed that the participants were able to correctly draw free body diagrams of external forces, which is a critical step when doing truss analysis. However, it was very difficult for some of the participants to identify the zero-force members and mentioned having a difficult time trying to solve the problem without dimensions. For instance, Participant 6 indicated that,

> [I] need to do it with a calculation, I just can't see it. I can do [the problems] fairly well, I haven't had problems with the homework or anything, but there have been a couple that have taken me longer to figure out and some of my assumptions are wrong like with the compression and tension. But once I do the math that comes out.

In fact, Participant 6, even though he drew a good free body diagram, was not able to indicate what was the zero-force member without any calculations. His free body diagram is shown in shown in Figure 4. Moreover, he also had a difficult time identifying the members in tension and compression.

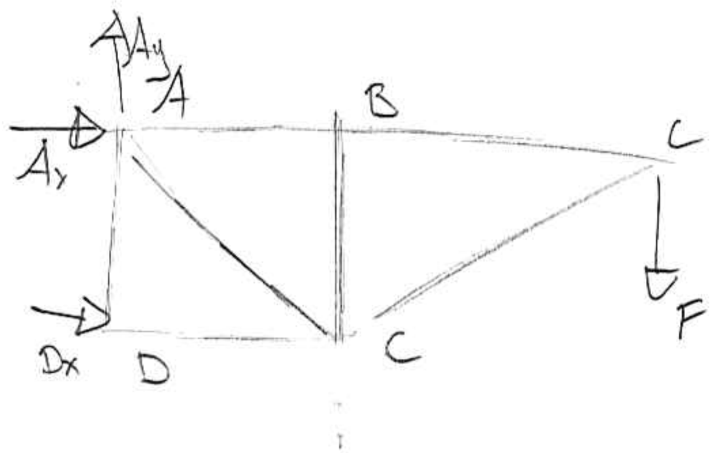

Figure 4. Participant 6 free body diagram.

The heavy use of mathematical manipulation was emphasized by most participants in the study. The thought of using formulas and calculations to identify zero-force members or members in tension or compression was shared by five out of the six participants. In fact, when asked about the procedure to find the members in tension or compression, five of the participants started to work on the problem on paper even though the original problem had no dimensions. Some of the participants were fixated on trying to solve the problem mathematically without indicating other strategies to solve the problem.

When the participants were presented with the physical manipulative, four of the six participants mentioned removing truss members as a strategy to identify zero-force members. Five of the six seven participants noticed that their prediction before using the physical manipulative were wrong. Removing the members helped them visualize the structure. Participant 6 mentioned that working with the manipulative "helped to visualize it better, instead of just imagining it – it's actually there so you can see it." As shown by this example, the participant was able to retain and understand information by doing something active with the physical manipulative. This experience helped the participants identify different characteristics of the structure, such as being structurally sound, once the zero-force members were removed.

When asked to describe the benefits of the physical manipulative, the participants all concurred that the manipulative would be a good tool for learning. Some of the discussions with the participants, after using the physical manipulative, revolved around the simplicity of the model and the potential for learning. Some of the participants indicated the benefit of "having the physical experience" and "looking at if it was stretching or compressing." Other participants expressed what they observed while working with the physical manipulative such as "I can take my work from paper to real life," "I can see the effects of forces at different points," and "I can look for deformation and I can feel confident assuming directions using the model." The latter has large potential impacts upon self-efficacy for those who crave a visual confirmation of what they analytically prove. One of the participants mentioned that "it took me going through multiple homework problems to figure out what I could figure out here in just a couple of minutes of looking and dealing with this actual model." Overall, the manipulative proved to be an informative pedagogical tool with a lot of potential – especially in helping students make connections between the physical world and theoretical material learned in the classroom.

Implications

The results from this work indicate that the physical manipulative helped participants visualize intangible concepts learned in the classroom and provided a venue to gain conceptual understanding of internal forces in truss analysis. The benefits of physical manipulatives can be extended to other engineering courses to help students gain conceptual understanding of material that is difficult to learn. In addition, as observed in this study, the physical manipulative could also help students change their erroneous answers, or change misconceptions, when seeing a physical manipulative in use. Finally, the physical manipulative allows students to authenticate an analytical answer that improves their self-confidence within a problem solving process and allows for immediate feedback through observation. Recognizing self-confidence as a dimension of self-concept,[24] which is shown to be heavily influenced by reinforcements and evaluations from significant others,[25] is pivotal for the learning outcomes of students in engineering mechanics courses. This work describes how physical manipulatives may also act as a significant reinforcement for the same effect.

The physical manipulative also allowed participants to reflect on their work and analyze their own problem solving approaches. For instance, some participants were able to use the physical manipulative so answer questions very quickly or to reinforce concepts. Some participants were able to use the physical manipulative without problems, but other felt that the physical manipulative was not as intuitive and they required guidance. Although the physical manipulative was designed to be very user-friendly, some of the participants required a certain degree of guidance on how to use the physical manipulative. Some of the participants didn't know what to observe or how to detach some of the members in the truss. Thus, the implementation of the physical manipulative in an engineering mechanics course may require more than designing the manipulative but also spending some time showing students how to use the models. The long term impacts of this works may influence students' self-efficacy and motivation through new instructional approaches used in engineering mechanics courses. The data obtained from this exploratory study show the potential of the physical manipulative and how it can be used effectively in the classroom if the necessary guidance is provided to students.

Although the participants emphasized the need to work on the problems using mathematical manipulation, the physical manipulative helped the majority of the participants understand concepts without analytical calculations or mathematical manipulations. The physical manipulate enabled participants to more accurately anticipate truss member loading in the absence of mathematical quantities. If developed and practiced regularly, this intuition can reinforce the results of analytical calculations used in truss analysis. The use of both analytical calculation and the physical manipulative may increase students' comfort when working on truss problems. The physical manipulatives may supplement analytical techniques with physical experience.

Finally, the results obtained from this study can be used to inform future research involving physical manipulatives. Research stemming from this study may include using physical manipulatives to provide culturally responsive practices for underrepresented minorities in engineering. Physical manipulatives can be used to actively involve the students in the learning process by connecting everyday life experiences to what is learned in the classroom. Physical manipulatives can be designed to address the needs of many students, for example English Language Learners who may struggle with the verbalization of concepts and who are highly underrepresented in STEM. Eventually, materials can be generated to create attractive, yet challenging, and culturally responsive materials for engineering students.

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