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Innovative Pedagogical Tools for Applied Mechanics Using Physical Models

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Abstract

Teaching engineering courses can be challenging especially when they are taught using abstract methods. While it is safe to assume that engineering in general needs a strong foundation in math and science, it is also primitive to think about engineering as the real-life application and utilization of math and physics. Many courses in engineering, such as statics, explain the engineering of components, systems and products we use in our daily life. In this research, I focus on the concepts taught in statics, and I propose an innovative pedagogical method that integrates physical models with theoretical instruction. This course aims to provide students with a solid understanding of statics concepts and their applications in real life and these models will help ensure this aim is met. Importantly, an understanding of statics is a prerequisite for other courses including strength of materials, dynamics, and even control courses.

This innovative pedagogical method provides instructors with pedagogical tools to implement in the classroom. Focusing on the statics course, this approach requires organizing the course into modules based on ten basic concepts starting with simple forces and their effects and ending with equilibrium and structures analyses. For every concept, the instructor will link the concept to a real-life application and have a physical model for students to experience the concept visually. Many students learn more by visual methods and by getting a feel for the application. This teaching method links the math and applications tightly together through the physical method. This course design includes a component where students are assigned or given the opportunity to select a concept to explain for the class in the last week of the semester.

The following research will go over five main concepts in statics and provide an explanation of their physical models. Two surveys were collected to check for students' perception of the usefulness of the models and the role the models have in aspects including understanding, retention, and motivation.

Introduction

One of the most significant challenges in teaching statics is helping students develop strong spatial visualization skills. Research has indicated that students who are able to effectively visualize force systems are more likely to succeed in statics (Tariq, 2018). As such, various methods have been developed to improve students' ability to visualize forces and structures. Handsonmechanics, is a service site by the American Society for Engineering Education (ASEE)–Mechanics Division. It is like a bank of ideas related to all applied mechanics and thermal applications. It is a great site and integrating it with the applied mechanics will add value for the teaching/learning activities. This research takes those ideas one step further, by adding a controller to the model and not only that demo the concept with a physical representation, but also the calculation and display the answer. Students can compare their calculations with the model answer.

Incorporating computational tools such as finite element analysis (FEA) software, dynamic simulations, and 3D modeling platforms (e.g., Autodesk, SolidWorks) has proven effective in bridging the gap between theory and practice (Koh & Koh, 2017). Such tools allow students to manipulate and experiment with virtual models, giving them a tangible understanding of how forces affect structures. The challenge is how to model the actual scenario of the real application. Additionally, the use of virtual labs and simulation tools in the classroom has been shown to enhance student learning by providing immediate feedback and enabling experimentation without the constraints of physical resources (Nguyen et al., 2019).

A more hands-on and physical approach to teaching statics is explored by Anna Dollár and Paul Steif in their article "Reinventing the Teaching of Statics" (2023). Dollár and Steif explore innovative methods to enhance student engagement and comprehension in statics courses by having students work on physical representation of the different concepts in statics. Their article proposes a more hands-on and physical approach to teaching statics and it explores innovative methods to enhance student engagement and comprehension in statics courses.

The article, "A Study of the Usefulness of Physical Models and Digital Resources in Teaching Biology", by Robels-Moral et al., is not exclusively focused on statics, but provides an insightful investigation on the impact of physical and digital models on teaching complex concepts. The findings suggest that both types of models can be effective, with digital models offering advantages in cost and accessibility.

Assessing students' comprehension of statics requires more than just traditional exams; it requires innovative assessment methods that test students' conceptual understanding as well as their ability to apply knowledge to real-world situations. The use of physical models can be used to confirm the students' understanding of the concepts that are the foundation of statics understanding. This will additionally serve to guarantee that students will be able to actively apply their understanding to real life situations.

Furthermore, virtual learning environments (VLEs), such as learning management systems (LMS) and virtual classrooms, provide instructors with tools to deliver content, facilitate discussions, and track student progress in real time. These platforms allow for a more flexible and personalized learning experience, particularly in a subject like statics, where students may benefit from revisiting specific lessons or accessing additional resources outside the classroom (Mayer & Moreno, 2003). With the physical models the authors are planning to video tape the use of the physical models and make it available on the course VLEs on the LMS. A strong understanding of Statics is critical for future courses and real-world applications in engineering and documenting the experience by the students for future use comes handy.

The Need for Innovative Teaching Methods

Statics is often perceived as an abstract and difficult subject for students to comprehend particularly because it involves complex mathematical models that are sometimes disconnected from the tangible applications that students will eventually face in their careers. The challenge is twofold: students struggle to connect theoretical principles with real-world engineering problems, and the abstract nature of the subject makes it difficult to engage them meaningfully (Rex et al., 2015). This paper proposes an innovative approach that integrates physical models with theoretical instruction to improve the understanding of statics. By using simple, visual, physical models, students can better visualize, experience, and grasp the physical realities that these abstract mathematical principles represent. They can observe how the forces act on objects, enabling them to directly link theoretical knowledge with real-world applications.

The integration of physical models is especially important in courses like statics, where visualizing force systems, moments, and equilibrium can be particularly difficult for students (Johnson et al., 2018). The models proposed in this research offer an alternative to abstract equations, allowing students to experience firsthand how forces and reactions manifest in real-world engineering systems. By using simple, tangible models, students can better understand how engineering systems respond to forces and how these systems are designed to maintain equilibrium. Importantly, the ability of the physical model to display answers based on loads provides sensitivity analysis live for students. They are then able to change the load values and points of application, and this reinforces their understanding of the concepts and provides a lasting experience to the students.

Proposed Methodology

This paper proposes an innovative teaching pedagogy methodology for statics that divides the course into ten core concepts. Five main concepts have been demonstrated through both mathematical analysis and corresponding physical models that allow students to visually experience and manipulate the forces and principals involved. These physical models are setup with an Arduino controller with sensors that read the value of the forces at the support points. Beam support is configurable. It can be set to rollers or fixed support at one or both ends. The sensors will read the reaction forces and does calculations based on the units of load. The results will be displayed, and students can change the load location or the load type and the system will recalculate the reactions instantly. In the figure there are representative shapes of different load types (i.e. uniformly distributed, distributed with increasing or decreasing rates, etc.). The beam is graduated and allows to incorporate the point of application of the force based on the type of load.

The five concepts covered in the course include:

1. **Basic Forces and reactions** as shown in figure 1, loads could be placed at any point on the red beam at different locations, the reactions at both ends of the beam will be displayed in the x & y directions.

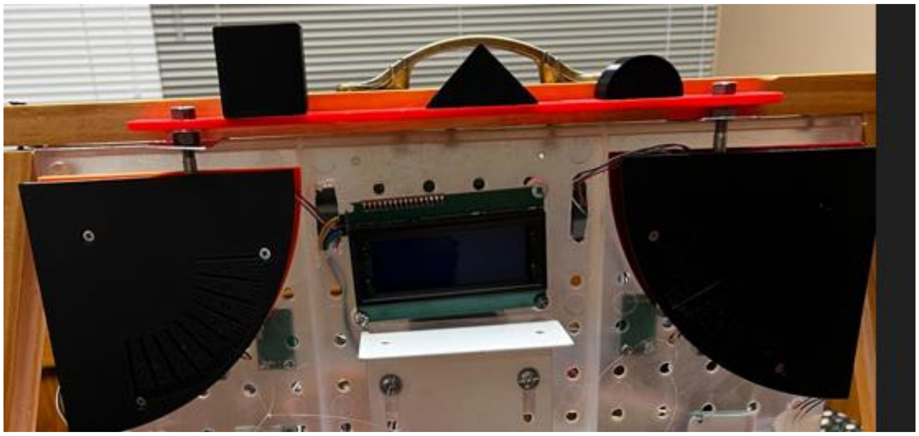

Figure 1, loading a beam with different distributed loads shown in black.

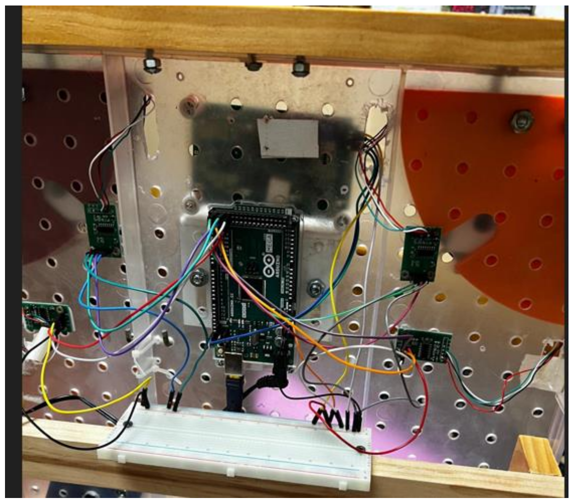

Figure 2, Arduino controller is used to process the load sensors at the support points.

2. **Friction model:** Understanding how friction forces balance based on a slope ramp and different materials are demonstrated using the setup shown in figure 3. The angle of the ramp can be adjustable to achieve equilibrium between the load and the coefficient of friction for different materials pads placed on the ramp. The white box can be loaded with weights. It is pulled from the hooks with a negligible weight string through a pully and connected to the sensors' brackets to be able to measure the forces based on the angle of the string. However, an additional digital protractor shown in figure 3 can read the angle directly and the two values can be compared. This will give the student more assurance and understanding

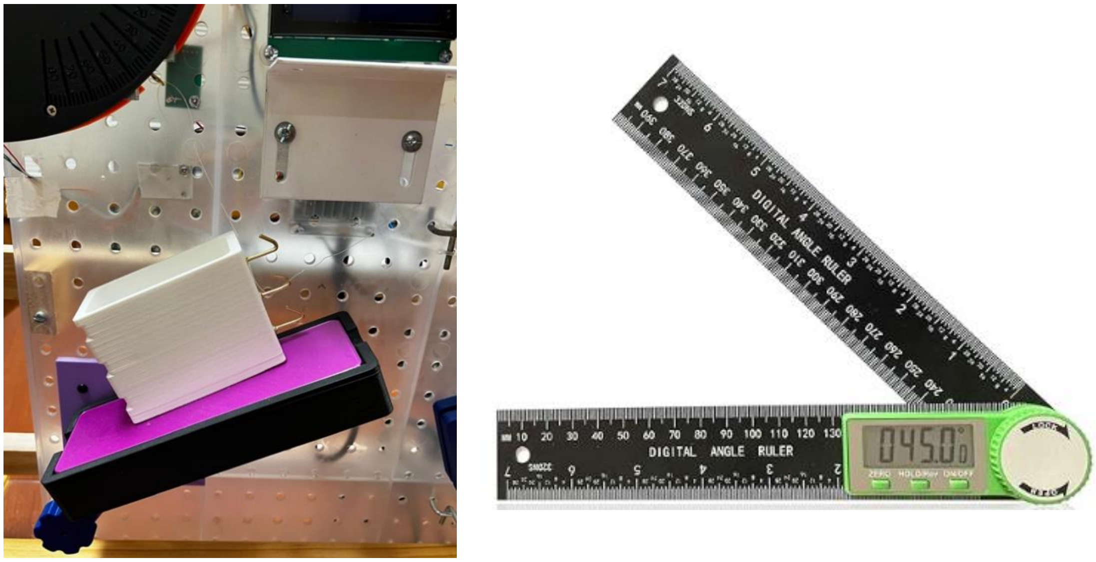

Figure 3, friction model, sloped ramp with adjustable angle

3. **Torque Model:** As shown in figure 4, the torque module has two plates that are placed against each other with a thin layer of friction material between them. A hex-head bolt is used to apply a certain torque to hold the two plates with each other.

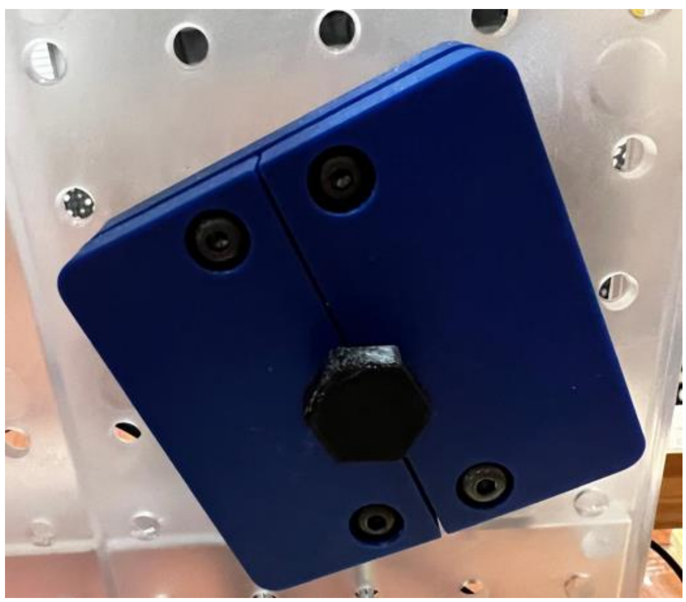

Figure 4, torque model, two plated are attached with a hex-head bolt.

4. **Center of Gravity:** Determining the balance point of an object based on the center of gravity.

   Physical Models: blocks with a rectangular, semi-circle, and triangular cross sections were used to load a beam at different points and the center of gravity is found based a balance of the material of the block.

5. **Cable Tension Problems:** cables are connected the brackets that are attached to the sensors block. Behind the cables, Angle protractor 0-90^o are set such that the angles of the cables connected to one or both sensors brackets are read. Tension in the cables will be displayed.

Each of these concepts will be demonstrated in class using physical models. Students will have the opportunity to manipulate the models, experiment with different forces, and observe the results. Instructors will encourage students to perform the calculations and predict the outcomes before manipulating the models, fostering a more interactive and engaging classroom environment. Additionally, at the end of the semester, students will select one concept from the course to explain in a group presentation using both theoretical calculations and physical models results. This process will help reinforce their understanding and provide an opportunity for peer teaching.

Survey Model for Assessing Teaching Effectiveness

Two surveys were conducted to evaluate the success of this teaching method. The first was a general survey distributed to students who took the statics course last year (spring-fall 2024). The sample size for this survey was 34 students. The physical models were shown and explained to the students, then they were asked two simple questions:

1) 'If you had access to these physical models when you took your statics course, do you think they would help you gain a stronger understanding of the material?' 91% of the survey respondents answered yes.
2) 'Do you think using these physical models would have helped you to get a better grade?' 87% of the survey respondents answered yes.

The second survey was collected from students currently taking the statics course (in spring 2025). This survey was more detailed for the sake of gauging their experience with the models and their overall learning experience. The models were introduced to the students for the appropriate concepts before they were given the survey. The survey has 11 questions including one open-ended question asking for students' suggestions for other ways to help understand statics concepts. Though this survey is qualitative, a third survey is planned for next year to evaluate the impact on students' grades.

From the students' responses it was evident that different students have different preferences for teaching aids. Figure 5 below shows the breakdown of students' responses. While interactive physical models received the highest percentage, the results show that multiple methods are recommended. Thus, instructors can mix and match different methods for different concepts. It does help to use multiple types of teaching aids not only to entertain all learning styles, but also to provide a comparison among different methods and their applications.

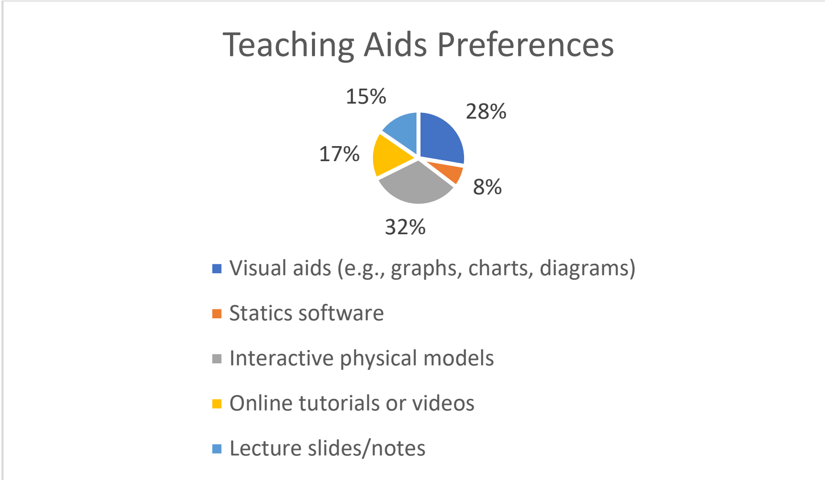

Figure 5, Teaching aids preferences

The second survey included some questions on performance and retention. The results showed that 89% of students believed that using the models would make it easier to retain an understanding of statics concepts. 71% of students believed that using the models would improve their performance in their course assessments. 77% believed that using the models would contribute to their ability to apply statics to real-world problems. better in their assessments. Notably, the survey also showed that 91.3% of the surveyed students like the models, the interactions it allowed them, and they found that the models helped them understand the demonstrated concepts more clearly.

This survey also sought feedback regarding student engagement and motivation. The results showed that 97% of students believe that the use of physical models would make learning statics more engaging for them, and 78% believed that the models would increase their motivation to learn.

Expected Outcomes

The primary goal of this teaching method is to improve student engagement, comprehension, and retention of statics concepts by integrating physical models that link theory with real-world applications. The main contribution of this paper is that the physical models have a controller that will find the forces of the different models and display the results. Figure 6 shows few combined implementations. Students will gain a deeper understanding of the fundamental principles of statics by experiencing the effects of forces and equilibrium firsthand through hands-on learning. Additionally, students are likely to feel more confident in their ability to apply these concepts to real-world problems, as the physical models allow them to visualize and interact with complex systems in a tangible way. It is anticipated that the integration of these models will foster more active learning and student engagement.

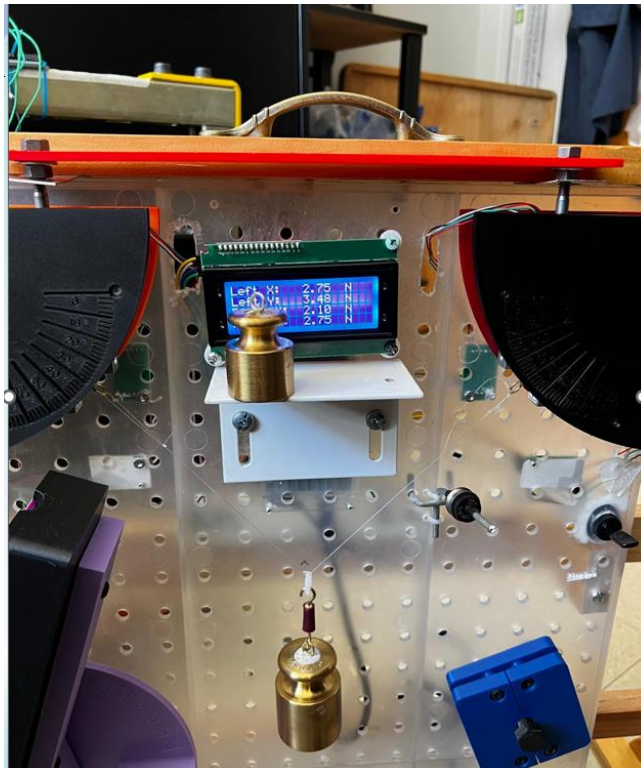

Figure 6, combined concepts combined in one system

Conclusion

The integration of interactive physical models in statics courses offers students the ability to engage with the relevant concepts. They are able to find values and see them displayed instantly. This allows students to do “what-if-analysis” by changing the load types and points of application. This concept will be extended to other concepts in statics and could be extended to dynamics and strength of materials.

The novelty of this research is the ability to be able to configure a setup and get the results instantly. Students can ask the question, then configure the setup that describe the question, and get the answer. This research introduces an effective way to bridge the gap between theoretical concepts and real-world engineering applications. By making abstract principles more accessible through hands-on learning, students are likely to develop a deeper understanding of statics and enhance their ability to solve engineering problems. The first survey results reveal that students think they would have a better understanding and score better with the physical models than without it. The second survey points to the need to have multiple methods to fit different learning styles. For future work, a quantitative evalution will done to analyze the impact of using the system on the performance of students. More physical models will be developed with more configurable setups that help to get students more engaged.

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