Integrating a Design Project to Bridge Experiment for Statics learning in General Engineering Education

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Abstract

Engineering Statics, a foundational course for most engineering students, is typically undertaken early in their academic careers. Integrating hands-on experiments, such as the classic bridge experiment, is essential not only for a deeper understanding of mechanical concepts and theories but also for fostering active learning. While the traditional use of commercial bridge modeling kits, like the Pasco Bridge set ME-6991, has been standard, this approach often falls short in effectively engaging students in learning the principles of static equilibrium and truss analysis. This paper introduces an innovative design project that enhances the conventional bridge experiment. It involves students optimizing and 3D printing truss member dimensions, replacing them in the model, and evaluating performance. This hands-on approach in design and manufacturing significantly enriches the learning experience in truss analysis. Additionally, the paper discusses the integration of this project, assessment methods, the students' backgrounds, and their feedback.

Introduction

Project-based learning, particularly design-based projects, represents an extraordinarily effective pedagogical method [1]. Similar to problem-based learning, design-based projects engage learners actively in solving real-world challenges. This approach is widely acknowledged among engineering educators as a means of shifting from passive to active learning paradigms within the classroom [2] [3] [4]. In this paper, I elucidate the integration of a design project into a bridge experiment within a Statics class, exemplifying the practical application and benefits of this educational approach.

Class Profile

Statics, a fundamental branch of mechanics within engineering education, holds great importance for students across a wide array of disciplines, including civil, mechanical, and aerospace engineering, among others [5]. This field is dedicated to analyzing bodies that are either at rest or in a state of equilibrium, where the net forces and moments are balanced. The pedagogical approach to teaching statics commonly encompasses both lectures and laboratory sessions, providing a comprehensive learning experience. Typically introduced at the sophomore level or first year engineering projects, this course builds upon the foundational knowledge acquired in introductory engineering courses i.e. CAD. At this stage, most students may not have delved into mechanical design. However, towards the conclusion of the statics course, an integrative design project serves as a preliminary step, warming students up for more advanced studies in mechanical or capstone design.

Bridge Experiment

Bridges serve as quintessential examples of structures that combined the principles of equilibrium, force analysis, and structural design, making bridge experiments a typical experiment of engineering statics education, particularly in the study of truss analysis [6]. In typical bridge experiments, students construct bridges using standardized beams made by wood, paper, etc., incrementally apply loads, and measure the resultant forces on each beam. While the fabrication of beams and the assembly of bridges are integral to the learning process, they are also time-intensive. Consequently, the adoption of commercial bridge kits equipped with force sensors, known for their ease of installation, has become increasingly popular.

This paper highlights an integrated project utilizing the PASCO® Bridge Set ME-6991 [7], which comprises uniform beams of various lengths, connectors, and pre-drilled screw holes, facilitating the assembly of different truss-type bridges. One such example is the Pratt Truss Bridge, which students assembled using the kit, as depicted in Figure 1. This hands-on approach not only streamlines the experimental setup but also enriches the students' understanding of statics through practical application.

Figure 1. Pratt Truss Bridge assembled by students using Pasco Bridge set ME-6991

The objectives of this bridge experiment were twofold: firstly, to assemble the assigned bridge using truss elements, and secondly, to apply statics methodologies learned in coursework to improve upon previous designs. The learning outcomes targeted through this experiment included: gaining a deeper understanding of the design process; observing the practical applications of statics principles; appreciating the importance of empirical testing in engineering; and recognizing the value of effective communication, as demonstrated through detailed reporting.

Methods

The bridge project serves as an advanced extension of the foundational bridge experiments, wherein students are grouped into teams and assigned a specific bridge type, such as Howe or Pratt, to analyze. The primary objective is to assess the force distribution across each structural component of the provided bridge set. Subsequently, teams embark on a mission to refine the existing design through strategic modifications, which may include the replacement, addition, or removal of one or more elements. This design process is divided into four phases:

(1)Experimental Analysis-Teams conduct a detailed experiment on the bridge to gather baseline data on the force experienced by each structural member, establishing a point of comparison for subsequent optimizations.

(2)Design Modification-Based on the initial analysis, teams conceptualize modifications to the bridge's components aimed at enhancing the structure's overall performance and efficiency.

(3)Digital Fabrication-Students bring their redesigned components to life by creating CAD (Computer-Aided Design) models and utilizing 3D printing technology for manufacturing, enabling a tangible exploration of their proposed enhancements.

(4)Performance Evaluation-The final phase involves a rigorous assessment of the newly integrated members' force resistance capabilities and an overall performance check of the modified bridge structure, ensuring the effectiveness of the design optimizations.

Time Management

Design projects are time-intensive endeavors, and this bridge design project is no exception, as detailed in Table 1. The initial phase, which involves the original bridge experiment, typically requires one hour for each team to complete. In the second phase, teams dedicate at least an hour to sketching the bridge design, measuring dimensions, and engaging in discussions to finalize their concepts.

Moving on to the third phase, the creation of the CAD model is relatively swift, usually taking less than thirty minutes, provided the design has been clearly defined beforehand. However, the subsequent 3D printing process is more time-consuming, often exceeding four hours. This duration can vary significantly based on the complexity of the model and the capabilities of the 3D printer being used.

The final testing phase, where the assembled bridge is evaluated under load, typically takes about an hour. Given that truss analysis is covered towards the end of the course, it is logical to schedule this project as the concluding lab session.

To optimize time management and enhance flexibility, phases 1 and 4 are conducted during lab sessions, while phases 2 and 3 are assigned as out-of-class activities. This structure allows students to engage deeply with the project while accommodating their varying schedules.

Table 1. Time Management for Bridge Project

Task Number	Task Description	Duration
1	Collect data from bridge set	1 hour
2	Design Process	>1 hour
3	Digital Fabrication	>5 hours (assume 6 hours)
4	Test	1 hour

Learning Outcome Assessment

The assessment methods for this comprehensive bridge project encompasses two primary assessment methods: performance-based assessment and technical writing. The assessment framework is structured to ensure a multifaceted analysis of each team's output, focusing on both quantitative and qualitative metrics.

The performance of the student-designed bridges is appraised according to two main criteria: data comparison, which accounts for 70% of the overall assessment, and peer reviews, which contribute the remaining 30%. The quantitative assessment hinges on the comparison of the maximum force sustained by structural members in both the original and the redesigned bridges. This comparison is determined by Equation (1), which calculates the difference in the maximal forces, serving as a key indicator of structural performance enhancement.

$$\text{Differences} = \frac{\text{Force}_{\text{original}} - \text{Force}_{\text{new}}}{\text{Force}_{\text{original}}} \times 100\% \qquad \boldsymbol{Eq}(\mathbf{1})$$

In addition to the data-driven evaluation, peer reviews play a crucial role in assessing the broader aspects of each project. Students are encouraged to critically evaluate their peers' work, focusing on functionality, aesthetic appeal, and the degree of innovation manifested in the bridge designs. This peer assessment mechanism fosters a collaborative learning environment, encouraging students to engage with and learn from each other's creative and technical solutions.

The integrated bridge project represents a significant enhancement in the alignment with ABET's student outcomes compared to the traditional bridge experiment. This advanced project aligns with six distinct ABET student outcomes, as outlined in the ABET Criteria for Accrediting Engineering Programs (2023) [8], marking a considerable expansion from the two outcomes addressed by the previous experiment. This alignment is detailed in Table 2, illustrating the broader educational impact of the integrated project.

ABET Student Outcome #1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.

ABET Student Outcome #2: An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.

ABET Student Outcome #3: An ability to communicate effectively with a range of audiences.

ABET Student Outcome #5: An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives.

ABET Student Outcome #6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.

ABET Student Outcome #7: An ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

Table 2. Comparison of ABET Outcomes between Bridge Experiment and Integrated Bridge Project

ABET outcome	#1	#2	#3	#5	#6	#7
Bridge Experiment					✓	✓
Integrated Bridge Project	✓	✓	✓	✓	✓	✓

Discussion

The integration of the design project with the bridge experiment is a work in progress, yet its introduction as an optional component in the Fall 2023 Statics course has already sparked considerable student interest. Feedback collected via a post-lab survey revealed that more than half of the participants—five out of nine—selected the bridge project as the highlight of the course, showcasing their enthusiasm and engagement with this hands-on activity. An illustration of student creativity is shown in Figure 2, which features an innovative bridge design crafted by one of the participants.

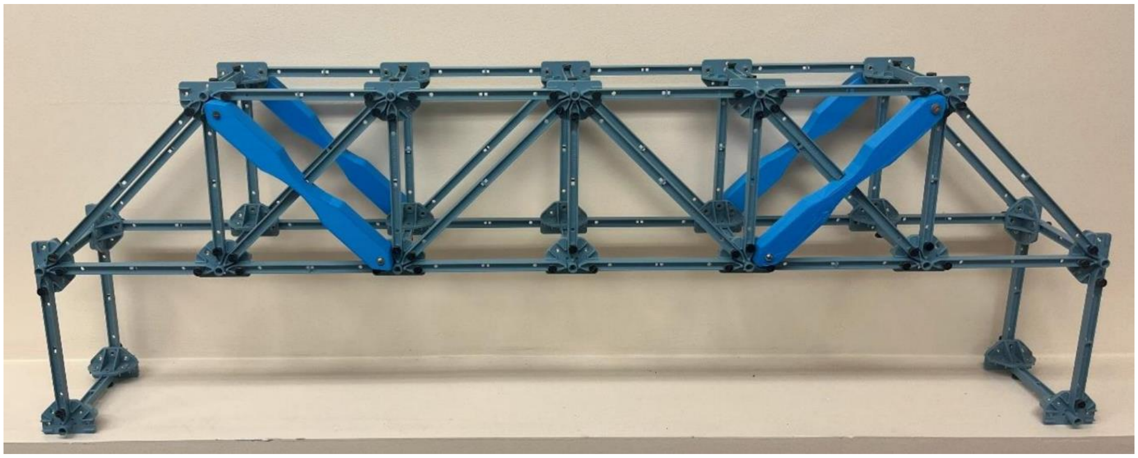
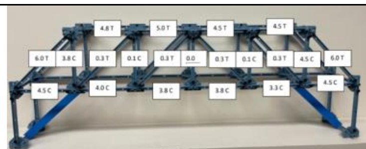
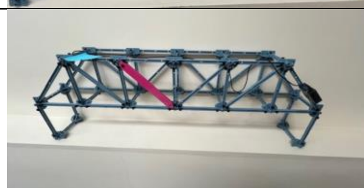
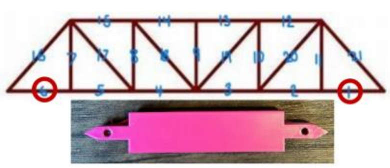


Figure 2. Pratt Truss Bridge with designed components assembled by students using Pasco Bridge set ME-6991

This Lab enrolled eight students, who were divided into four teams, to investigate the structural performance of bridge designs under static pressure. The experiment involved applying a static load at the center of each bridge model, with the resultant forces on individual structural members recorded using force cells. Comparative analysis of the pre- and post-intervention data revealed that three of the four teams successfully enhanced their designs, achieving reductions in maximum force exerted on the structures by 29.4%, 8.2%, and 4.2%, respectively. One team, however, did not realize any improvement in their bridge's performance. A comprehensive account of the team collaboration and design modifications is presented in Table 2, which details the new and original structural designs, the maximum forces before and after the modifications, and the corresponding percentage changes in force values.

Table 2. Overview of students' teamwork

Team #	Changed Components	Original Maximum Forces	New Forces	Percent change	Improvement
1		8.5 N (Tension)	6.0 N (Tension)	29.4%	Yes
2		8.5 N (Tension)	9.0 N (Tension)	-5.9%	No
3		8.5 N (Tension)	7.8 N (Tension)	8.2%	Yes
4		8.37 N (Tension)	8.72 N (Tension)	4.2%	Yes

Despite the positive reception, there are areas identified for enhancement to further enrich the learning experience. An initial survey to gauge students' theoretical understanding related to the project could offer valuable insights, ensuring that foundational concepts, such as truss analysis, material properties, and design principles, are well grasped before embarking on the project. Key areas identified for improvement include:

Materials Effect

The choice of materials is critical to the project's success. The transition from ABS, used in original bridge beams, to PLA, commonly employed in 3D printing, affects test outcomes significantly. Future iterations could benefit from either utilizing ABS-compatible 3D printers or calibrating the material properties by substituting the bridge kit with PLA beams of identical geometries. Additionally, introducing concepts from the mechanics of materials prior to the project could provide students with a better understanding of material behavior and its impact on structural integrity.

Advanced Analysis

Students encountered challenges in interpreting the results of their designs, indicating a need for a more comprehensive analytical approach beyond mere geometric considerations. Incorporating stress analysis through the finite element method (FEM) could offer deeper insights, yet the complexity of FEM might be daunting for sophomores. Simplifying this aspect by using bridge member analysis as a case study could serve as an introductory pathway to FEM, enhancing students' ability to rationalize their design choices and the observed outcomes.

Conclusion

By addressing these areas, the project can not only become a more effective tool for applying statics principles but also a bridge to more advanced topics in engineering analysis and design.

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