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Implementation of a Hands-On Timber Truss Design Project in Structural Analysis

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Abstract

Many undergraduate civil engineering programs do not offer timber design courses in their curriculum. However, timber design is commonly used for low-to-midrise buildings, pedestrian bridges, and residential construction. The timber design and construction industry that produces these projects benefits from civil engineering programs including timber design in their curriculum. Exposure to timber design offers students entering the field greater knowledge and confidence with the material. To provide students with the opportunity to understand the fundamentals of timber design and construction without introducing an additional required course into the curriculum, a hands-on engineering design project was implemented in an undergraduate structural analysis course. In this project, students worked in teams to design, analyze, construct, and test a 16-ft long timber truss. Students learned the basics of approximate analysis, design of axial wooden members and connections, and principles of timber construction. The engineering design project has been included in the structural analysis course since 2017. This paper presents the six-year evolution of the engineering design project, student feedback on the structural analysis course, and student performance data from the course and on the Fundamentals of Engineering (FE) Exam. Although the engineering design project took a significant amount of time and resources within the structural analysis course, it was a great opportunity for civil engineering students to solve a well-defined design problem and gain exposure to timber design. Student feedback showed the timber truss design project was a great hands-on learning experience, which allowed the students to apply their structural analysis knowledge within the engineering design process. The student performance in the course and on the FE exam demonstrated that the course did not have an adverse effect on achievement of the course objectives for structural analysis.

Introduction

Concrete, steel, and wood are the three most widely used construction materials. Design courses for two of these materials are offered at nearly all the colleges and universities in the United States, while only half of these institutions offer a course on the third [1]. A recent survey by the National Council of Structural Engineers Association (NCSEA) found that only 52% of programs offered wood design, with most of those institutions only offering it once every two years [2]. The lack of wood design education is not limited to the United States. Canada, Germany, and Australia have also identified shortcomings in civil engineering education, specifically focused on wood design [3]–[6].

Although the prevalence of wood design in education is low, it is still essential in industry for low-rise buildings, residential construction, and pedestrian bridges. Wood is used to such an extent that the Civil Engineering Professional Engineering Exam requires applicants to have a basic understanding of wood design. The National Design Specifications (NDS) for Wood Construction published by the American Wood Council is one of nine design codes referenced for the Professional Engineering Structural Exam [7], [8]. Recently, wood has become more popular primarily due to an increased use of mass timber, updated code developments, and a growing focus on sustainable construction [1]. Both the International Building Code (IBC) and the Canadian Commission on Building and Fire Codes have updated design requirements to increase the allowable height of timber structures [9], [10].

Many curricula do not cover wood design due to a lack of faculty experience, research funding, industry involvement within academic institutions, and decreased engineering credit hours for graduation [11]–[13]. However, previous research indicates that merely exposing students to the basics of wood design benefited the students by increasing their confidence upon entering the workforce [3]. For example, York University investigated the implementation of two timber design learning modules into a steel design course [4]. These modules provided students with a foundational knowledge of timber design. Students who completed these modules experienced an increased level of confidence and a desire to pursue timber structure design after graduation.

Introducing wood design as an engineering design project is an opportunity to teach and reinforce other engineering concepts. Research has shown that project-based learning allows students to apply course concepts to solve design problems [14]. Many academic faculty have developed course design projects which utilize wood as the construction material [15]–[21]. Engineering statics and mechanics courses have implemented design, build, and test projects for students to fabricate trusses constructed from balsa wood [15]–[17]. These projects reinforce the students' fundamental knowledge of analyzing a truss and designing structural members. These projects also provide hands-on experience in construction and experimentally testing prototypes. These projects are educational and inspiring for students learning the fundamentals of structural design.

A few design projects have been implemented in wood design courses [19]–[21]. For example, Floyd and Freyne developed a project in which students designed, built, and tested custom beams with unique cross-sections out of wood [19]. The designs were required to meet specifications for height and span and were evaluated based on their strength-to-weight ratio. The project provided students with a basic understanding of how wood performs, allowing them to visualize different failure modes and experience some of the difficulties of construction. Research has shown that providing students with physical demonstrations may increase learning and retention of the course material by increasing the students' intellectual excitement [22]–[24].

Cardinale et al. implemented a multi-dimensional problem for which students had to develop a code-based solution [20]. The project was designed to replicate what would be expected of the students in industry. Instead of being presented with a traditional design problem, the students were tasked with designing a timber shear wall in a seismic area. The project required students to use structural analysis software, practice construction management skills, develop design drawings, and construct their final design. Students who participated in the project were encouraged to pursue further experimental research projects or join a civil engineering competition team. This study demonstrated that project-based learning can instill in students the motivation and passion for pursuing further inquiry.

Brake [21] implemented a design project in a junior-level design course to better prepare students for their senior capstone project. The open-ended design project required the students to apply design philosophies and building codes and make simplifying design assumptions to increase their confidence and abilities. The students familiarized themselves with ASCE 7 [25], structural analysis software, and the properties of glue-laminated timber.

The culminating design experience for undergraduate engineering students is the senior design project [13]. These projects are ill-defined and should require the students to stretch their capabilities in the context of a real-world problem. Many of these projects require students to design, construct and test their solutions. Several require an understanding of wood design [26]–[28].Other design projects are national design competitions such as the ASCE/AISC Steel Bridge Competition, ASCE Concrete Canoe competition or the National Timber Bridge Design Competition. The United States Military Academy has multiple senior capstone project opportunities including community service projects and national design competitions. One of the community service projects is to design and build timber pedestrian bridges for the local community. For this project, it is essential that these students have a strong understanding of wood materials and the application of design codes. Similar to the motivation of Brake [21] and the observations of Cardinale et al. [20], it is important to provide undergraduate engineering students with multiple opportunities during their education to apply the engineering design process and gain fabrication and testing experience prior to their senior capstone project. Similar, it is valuable for students to participate in design competitions prior to completing a national design competition as a capstone project. The national design competition projects are growing increasingly more challenging for students to decipher the rules, which may stifle creativity [29]. Teams that have been successful in these competitions often have significant experience, which aids in their ability to interpret the rules and specifications.

This paper presents the implementation of a large-scale timber truss design project in a basic structural analysis course. The motivations for this engineering design project were for students to gain hands-on experience, learn the fundamentals of wood design, apply newly acquired structural analysis knowledge, and pursue future design opportunities. The research question that this paper sought to answer was: *can a civil engineering program incorporate a wood design project into an existing structural analysis course without degrading the existing curriculum?*

Engineering Design Project – Timber Truss

In 2017, the civil engineering program removed all content on wood design from a required Design of Steel and Wood Structures course, creating a traditional Design of Steel Structures course (CE404). The Design of Steel and Wood Structures course was a 3.5-credit hour, 35-lesson course. Six of the 35 lessons covered wood design topics including material properties and behavior of wood, wood design values, tension members, columns, beams, and wood connections. Although the content was removed from CE404, the faculty believed that it was still critical to provide students with an introduction to wood design and, therefore, developed a design project for the required Structural Analysis course (CE403). The Structural Analysis course was a 3-credit hour, 40-lesson course. The course covered traditional structural analysis topics such as loads and load path, truss and frame analysis, virtual work, influence lines, and force- and displacement-based methods for indeterminate analysis. Wood design topics and a design project were added to CE403 in 2017, but the lesson content and project scope have evolved over six years. Table 1 shows how the wood lesson content and project assignments in CE403 have changed. Table 1 also provides the historic averages of these metrics when the wood content was taught in CE404.

Table 1: Comparison between Design of Steel and Wood Structures and Structural Analysis course

Year	2017	2017	2018	2019	2020	2021	2022
Course	Design of Steel and Wood Structures (CE404)	Structural Analysis (CE403)					
Credit Hours	3.5	3.0					
Lessons	35 @ 75 minutes	40 @ 55 minutes					
Iteration	-	1	2	3	4	5	6
Lessons on Wood (% of total course)	17%	15%	21.3%	22.5%	22.5%	22.5%	22.5%
Credit Hours on Wood (hrs)	0.60	0.45	0.64	0.68	0.68	0.68	0.68
Course Grade for Wood (%)	7.8%	15%	33%	10%	7.5%	10%	18.3%
Number of Project-Related Assignments	1	5	12	3	3	3	5

The first iteration of the design project in CE403 was implemented in 2017. The project required students to apply their structural analysis knowledge to design the most efficient truss, practice hands-on construction skills, and experimentally test their truss to failure. The initial concept of the project replicated a real-world engineering problem for which the students were presented with a scenario, design requirements, specifications, and timeline. The goal was to develop an experience like what students may expect from their senior capstone project, but also similar to what they should expect from projects in the profession after graduation. The student-generated designs were evaluated based on structural performance and estimated cost. The project was completed over a two-week period which included six in-person lesson periods and five out-of-class assignments. The six in-person lessons covered only project-specific concepts. Adding the six project-based lessons to the course required the removal of six structural analysis lessons: three on the direct-stiffness method, one on moment distribution, and two on force-based methods.

In the first iteration of the project, no class time was dedicated to teaching wood design. The students were expected to review supplemental material covering wood design independently outside of class and apply this knowledge to the design project. The wood design content was provided to the students as a PowerPoint presentation, premade Mathcad® calculation sheets, and access to the NDS [7]. For the project, the teams consisted of groups of 3-5 students. The organization of the lesson activities and assignments was developed to encourage the students to apply the engineering design process outlined in Figure 1.

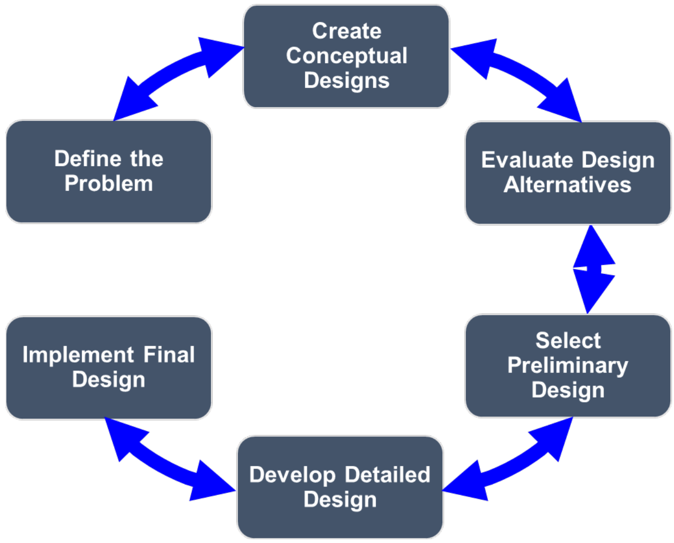

Figure 1: Engineering Design Process

During the first in-person lesson, students were provided with design requirements and specifications which included dimension limitations, available material, evaluation criteria, timeline, and service loads. The trusses were required to be 12 ft long and no more than 14 in tall. The trusses were constructed completely from a supply of 8 ft long 2 in x 4 in dimensional lumber members, 15/32 in thick plywood for gusset plate connections, and common wire nails. At the end of the first in-person lesson, a commercially manufactured timber truss was experimentally tested as a demonstration of the test setup and the requirements for the student designs. The trusses were tested in a universal testing machine using a four-point bending test shown in Figure 2. The test setup recorded the applied load and the displacement at the center of the bottom chord.

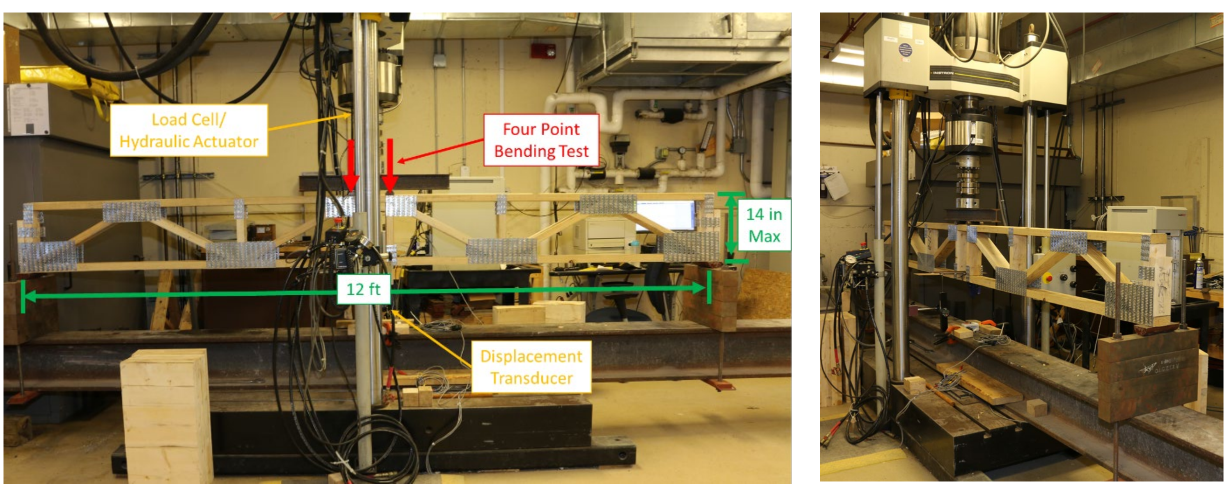

Figure 2: Four-point bending test demonstration of a commercially manufactured timber truss

The students' first assignment was to individually develop a conceptual design for the truss and analyze it using structural analysis software. The students calculated the design load for the truss using service loads in ASCE-7, Load and Resistance Factored Design (LRFD) load case combinations, and load-path analysis on a roof truss spacing of 16 inches [25]. As part of the first assignment, the students were encouraged to submit requests for information (RFIs) to assist with future steps in the engineering design project.

The second in-person lesson focused on selecting a preliminary design. Students compared the individual conceptual designs developed by their team members using a weighted decision matrix. Their decision matrix weighed the evaluation criteria of strength, stiffness, weight, and cost based on their own engineering judgment. The second assignment required teams to use the NDS to determine the tension and compression capacity of each truss member for their selected design and create an influence line for one truss member. Creation of the influence line was done to meet two objectives: 1) determine the critical location of the applied load and 2) reinforce one of the more challenging structural analysis topics covered in the course.

The third lesson focused on finalizing the detailed design of the truss. This was the most challenging portion of the project: each team had to determine the number of connectors (nails) and size of each gusset plate without formal instruction on wood connection design. Instructors used this in-person lesson to assist teams with their connection designs and details. The third out-of-class assignment was to create detailed drawings. Students were allowed to submit hand sketches or computer-aided drawings. Each team was also required to model one of the truss joints with the gusset plate and nail connection using rudimentary finite element analysis to verify the design capacity, as shown in Figure 3.

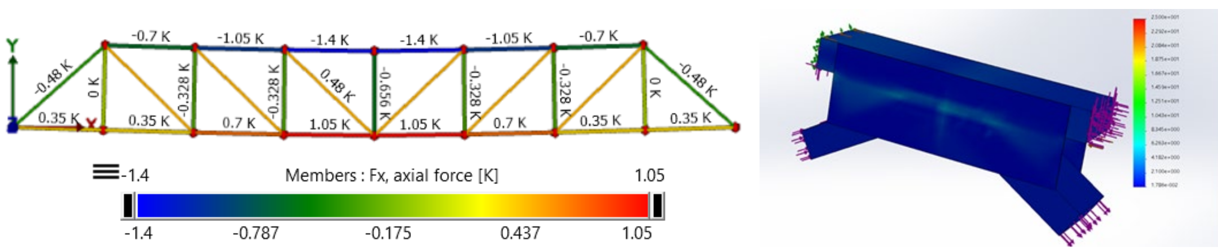

Figure 3: Sample structural analysis of a truss and individual connection

The fourth lesson was reserved for fabrication of the group-designed trusses. Each team was required to cut the structural members using a compound miter saw or circular saw, cut the gusset plates with a panel saw and table saw, and form their connections using a hammer and common wire nails. Figure 4 shows the equipment and setup for fabrication of the trusses. The fourth assignment was to predict the truss deflection under the design load and a separate prediction of the maximum load prior to failure.

The fifth in-person lesson was dedicated to experimentally testing the trusses (see Figure 5 for experimental results). With tests complete, students included the data in their final project report. This report included the design requirements, each conceptual design, the final decision matrix, structural analysis of the final design, analysis of the structural testing results, and a cost estimate for the truss based on material costs and labor costs in terms of person-hours spent during fabrication. The report allowed the students to practice and receive feedback on their written communication. Each team submitted this design report at the start of the sixth in-person lesson.

The first iteration of the design project received positive feedback; however, the students expressed important concerns: 1) the project was difficult due to the lack of familiarity with wood design and construction and 2) the course points associated with the project did not match the time required to complete the project.

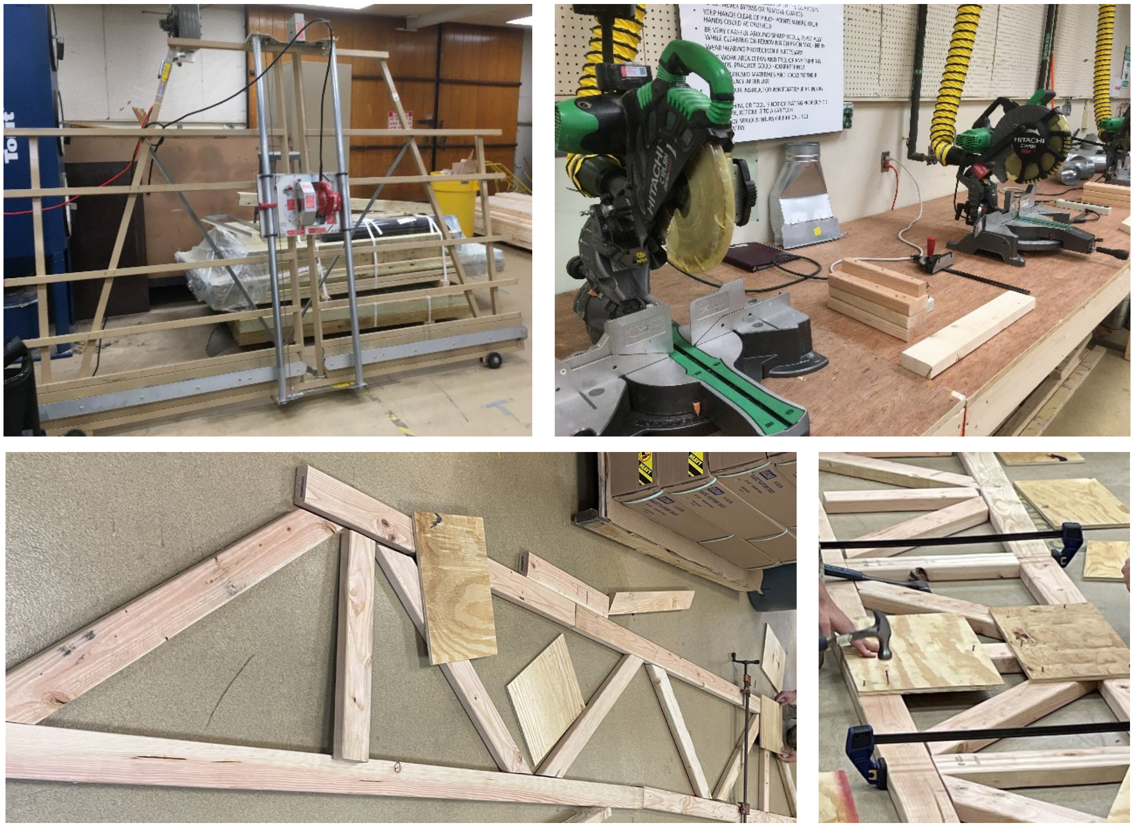

Figure 4: Truss fabrication equipment and set up.

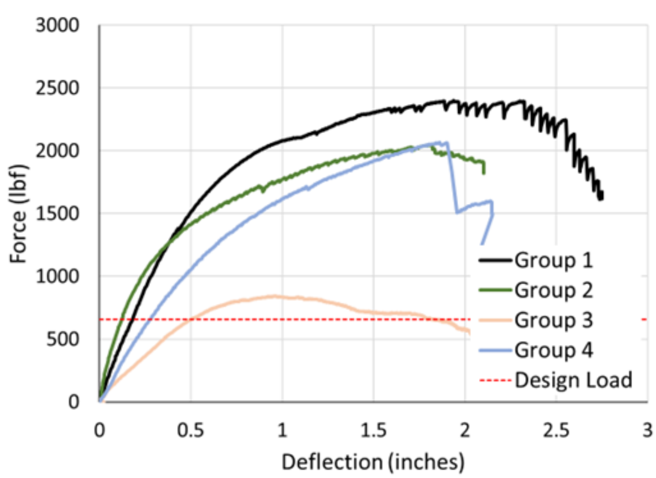

Figure 5: Experimental force vs. deflection results. Red dashed line shows design load used for the project.

In the second iteration of the project, in 2018, additional course time and credit were dedicated to the design project. Rather than relying on out-of-class learning, three and a half additional lessons were dedicated to teaching the fundamentals of wood design for axial members and connections. These lessons discussed the anisotropic behavior of wood, grading and material properties for different wood species, types of fasteners, and factors that influence both wood member and connection strengths according to the NDS. To create the necessary space in the structural analysis course, three additional lessons were removed: the two remaining lessons on moment distribution and one lesson on approximate analysis. The five out-of-class assignments for the project remained relatively unchanged and were still due on each of the last five lessons of the course. However, an additional subproject was included which was integrated throughout the semester to prepare the students for the final project. This subproject required the students to design, build and test a mini truss, as shown in Figure 6. The goal of the subproject was to provide students the opportunity to gain confidence with truss analysis and wood design, practice fabricating with wood, and compare failure predictions based on structural analysis to experimental tests. The results of the second iteration of the design project indicated that the students benefited from the in-class time dedicated to learning wood design.

Figure 6: Subproject truss construction and testing

During the third iteration of the project, in 2019, the faculty made multiple changes that simplified the design project. The first change moved all the wood design lessons and project-based lessons to the end of the course. This change allowed the course to have two distinct blocks; the first block was on the traditional structural analysis topics (31 lessons) and the second block was on the wood design and the engineering design project (9 lessons). Three of the nine lessons were dedicated to teaching wood design: one lesson on introduction to wood and approximate analysis for design, one lesson on the design of axial wooden members, and one on the design of wooden connections. The second modification was for the entire class to fabricate a demonstration truss to be tested instead of testing a commercially manufactured truss. This required two in-person lessons but gave each student an opportunity to gain experience with wood construction and equipment prior to constructing their own designed truss. Each student was trained to use all the equipment during this lesson, and the construction practice improved the building efficiency of the student-designed trusses later in the semester.

The third change involved modifying the evaluation criteria for the truss designs to resemble the construction and structural efficiency equations used in the ASCE/AISC Student Steel Bridge

Competition [30]. An example of the cost equation for the design project is shown in Equation 1. The motivation behind this change was to provide students with exposure to competition-style projects in preparation for their senior capstone project [29]. Designs were awarded higher scores for shallower depth trusses, fewer nails, less weight, and less deflection under the given design load of 656 lbf.

$$Cost = \$20k \cdot (Depth) + \$10k \cdot (Nails) + \$1k \cdot (Weight) + \$100k \cdot (Deflection) \quad (1)$$

The evaluation criteria modification turned the project into an optimization problem in which students used a client-defined cost criteria to select their final design instead of creating a designer-defined decision matrix. As the depth of the truss was now an evaluation criterion, the maximum allowable depth of the trusses was increased to 24 inches. This increase in depth made the trusses more susceptible to lateral torsional buckling. To reduce the effects of the lateral torsional buckling, two lateral restraints were added to the testing apparatus. Another change was to simplify testing by using a three-point bending test setup, as shown in Figure 7, rather than the four-point bending test that was used in previous years.

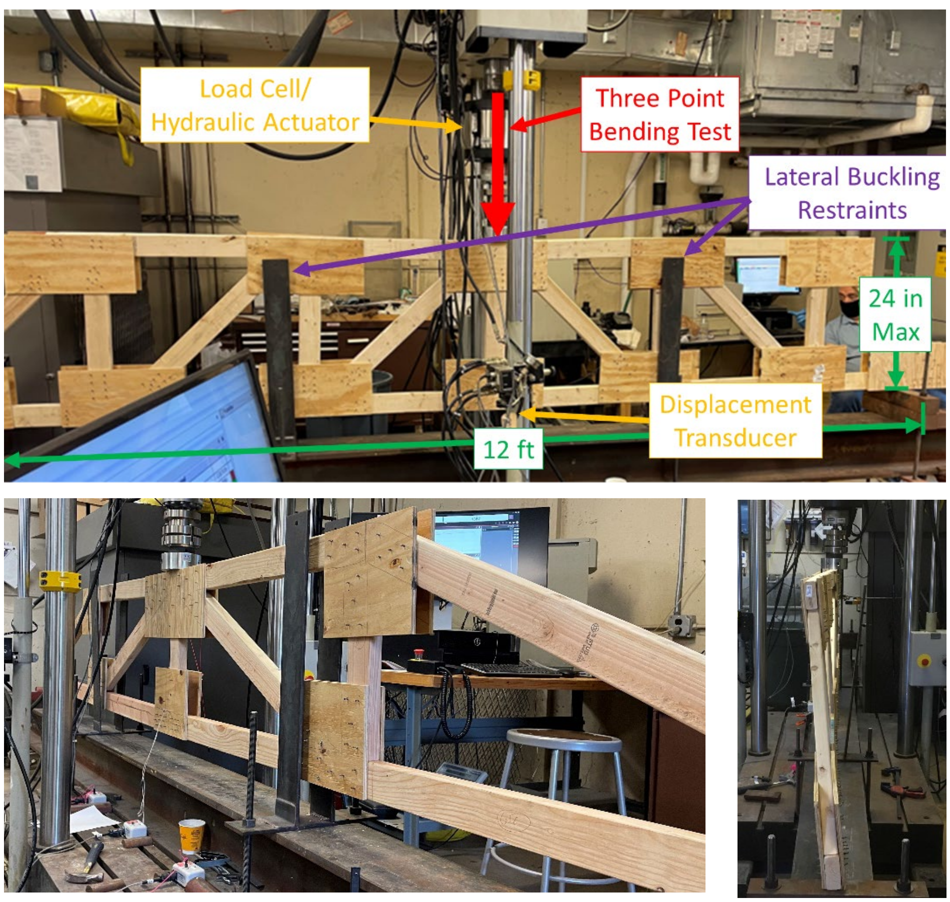

Figure 7: Experimental three-point bending test setup for the timber truss with bracing to resist lateral torsional buckling

The faculty also reduced the scope and number of out-of-class project assignments from 12 to 3 during the third iteration. Five of these assignments were associated with the mini truss project. The mini truss project was removed because it required significant time and resources to complete. Also, since the wood design content was moved to the end of the course, the two homework assignments on wood were removed. The first assignment in the 2019 iteration required student teams to calculate the design load for the truss, develop conceptual designs, and estimate the maximum deflection of each conceptual truss design using approximate analysis. The second assignment required teams to design each of the individual wood truss members and connections. In addition to calculating the strength of the members and connections, each team submitted detailed fabrication drawings, including a member cut sheet and connection details depicting nail patterns and gusset plate sizes.

Teams were then provided two lessons to construct their truss and one lesson to test their truss. The final modification made to the project in 2019 was the presentation of results. Teams were no longer required to submit a detailed final report but were instead required to brief their results in a five-minute presentation. The presentation focused on the accuracy of their predictions compared to the experimental results. This modification allowed the instructors to provide feedback on the students' oral communication skills and reduced the work hours required to communicate the project results.

During the fourth iteration, in 2020, minimal modifications were made. However, there were significant restraints placed on the institution and the course due to COVID-19. Each section of approximately 18 students was divided into two groups of 9 students each. For each lesson, half of the section attended the lesson in person, and the other half attended virtually. The entire section was able to attend the building and testing lessons, so each team was able to construct and test their truss in person. Another small, but critical change made during this iteration was the use of duplex nails, which allowed the students to observe shear deformation in the fasteners during testing, as shown in Figure 8.

Figure 8: Shear deformation of duplex nails and axial failure of tension members during experimental testing.

During the fifth iteration, in 2021, a slight modification was made to the final submission: each team created a one-minute video summarizing their project. This assignment built off a previous requirement to video the experimental testing of their truss. The assignment intentionally did not have strict requirements. It was intended as a creative outlet for students to present their results.

The sixth iteration, in 2022, focused on better integrating the project into the structural analysis course rather than having two distinct blocks in the course as described above. Instead of all project assignments being due at the end of the semester, the first project assignment was due on

Lesson 9. This first assignment included calculations of the design load and conceptual designs of the truss. After submission of the first assignment, Lessons 13-15 of the course focused on in-class instruction on wood material, design, and connections. The second assignment required teams to select a preliminary design, design each of the truss members, and design a single connection, as well as correct any mistakes identified in the first submission. The student teams were also required to identify at the top of each calculation sheet which team member created the calculation, reviewed the calculation, and verified the calculation. Previous research has shown that including explicit design review processes in a project can enhance learning opportunities, improve the communication of interdisciplinary teams, and improve the students' ability to solve complex problems [31]. The second assignment was due on Lesson 21.

Lessons 22 and 23 were focused on fabricating and testing the demonstration truss. This gave students an opportunity to experience the construction process prior to submitting their final design and preparing their fabrication drawings. The final design and fabrication drawings were due on Lesson 30, which provided teams with additional time to make any corrections associated with the design of the connections. The third submission included a new requirement to conduct a parametric study on how truss depth influenced truss performance. To provide the students with even more design flexibility, the maximum allowable depth of the truss was increased to 29 inches. For the parametric study, each team analyzed their preliminary design with four different depths in a structural analysis software. They also were instructed to evaluate the influence of orienting the 2x4 wooden cords about the strong and weak axes. The goal of including the parametric studies was to encourage students to pursue additional design iterations to optimize their final design prior to making their selection. The last four lessons in the course were dedicated to fabricating, testing, and presenting results. Figure 9 presents trusses that student project teams designed, constructed, and tested in 2022.

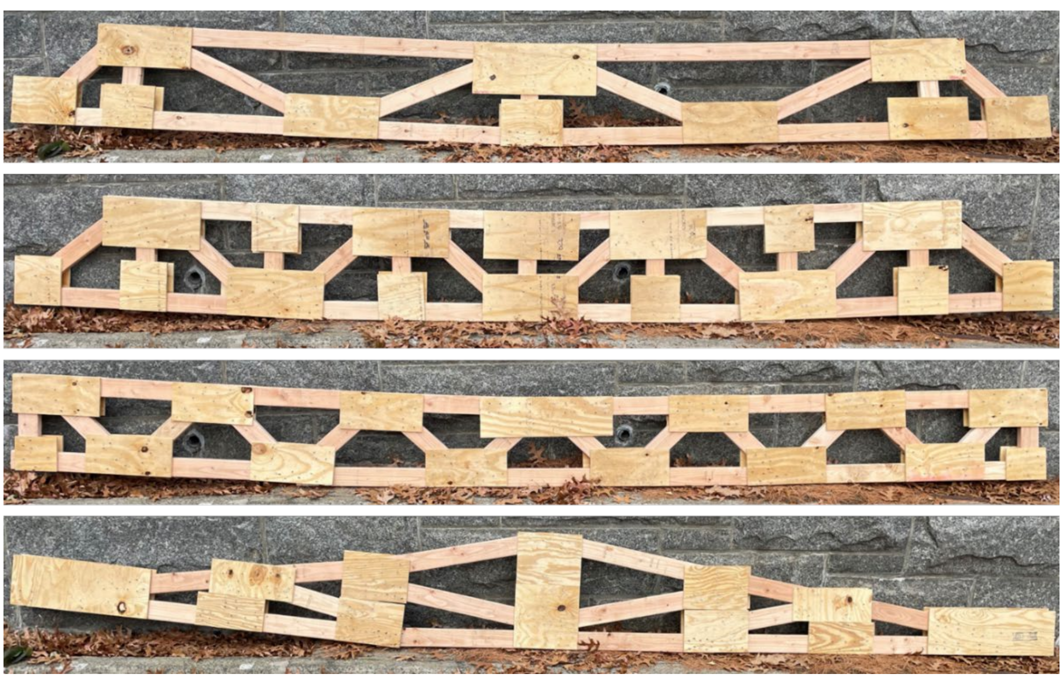

Figure 9: Examples of trusses designed, constructed, and tested in 2022.

Results and Discussion

While there were clear benefits of adding the wood design project to the structural analysis course, doing so came at the cost of removing nine lessons of content: three lessons on moment distribution, one on approximate analysis, two on force-based methods, and three on the direct-stiffness method. The content removal raised a concern about whether the benefits of the wood design project outweighed the risks of covering fewer structural analysis methods and some methods in less depth. The authors evaluated the impact of the wood design project by examining four areas of student performance: 1) performance on the structural design portion of the Fundamentals of Engineering (FE) Exam compared to the national average, 2) time spent out of class working on course material compared to the course historical average, 3) performance on the wood design question presented on the course final exam compared to the historical average, and 4) student feedback on the course end-survey compared to the historical course averages.

Fundamentals of Engineering Exam

The modification to the structural analysis course had no effect on the civil engineering students' performance on the structural design portion of the FE Exam. Figure 10 shows the average score of West Point Civil Engineering students divided by the national average score from 2014 to 2022. The students that took the first modified course in 2017 took the FE Exam in 2018. The four years of data prior to the change and the five years of data collected after the change nearly all fit within one standard deviation of the nine-year performance average, and the data does not indicate any clear upward or downward performance trend. While using data from the FE Exam has been found to have confounding issues [32], this nine-year comparison, 6 of which included the engineering design project, indicated no significant change in student performance on the structural design portion of a standardized test.

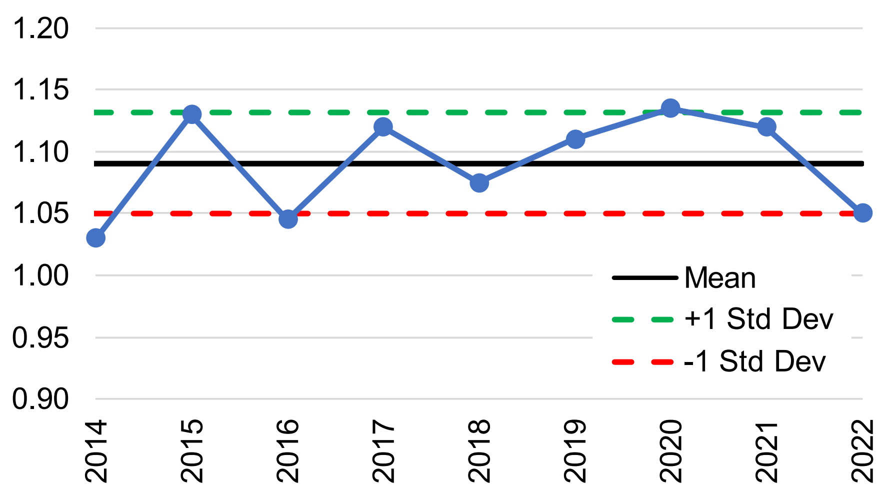

Figure 10: Ratio of Civil Engineering student performance to national average on the Structural Engineering portion of the Fundamentals of Engineering Exam. Note: NCEES combined two topic areas ("Structural Analysis" and "Structural Design") into one topic area ("Structural Engineering") in 2021; used average of analysis and design to compare to previous years

Student Time Survey Data

The modification to the course increased the amount of time students invested in the course outside of class. Table 2 lists the average student-reported minutes spent preparing for each lesson. The historical average for the six years prior to the implementation of the new wood design project was 81 minutes spent outside of class per lesson. Due to other factors which may have affected the average time per lesson, such as changes to homework and course instructors, the time specifically spent on wood content was also recorded. Implementation of the wood design project increased the average time spent per lesson by a maximum of 64 minutes (79% increase in 2018) and a minimum of 13 minutes (16% increase in 2019). During the 2018 iteration, only 26% of the students' time was spent on wood content, which indicates that the increase in average time spent by students was not solely a result of the wood design project. During this iteration, the students had to submit homework assignments at the start of every lesson. The iterations where the wood design content was spread throughout the semester in 2018 and 2022 saw the largest increase in student time spent on the wood design content. The iterations in 2017, 2020, and 2021 saw an increase in time spent on the course; however, the time spent on wood was relatively low (less than 18%).

The increase in student-reported time spent out-of-class for the iterations with the wood design project may be attributed to the course instructors adding additional assignments and requirements to ensure the students achieved the structural analysis course objectives even with the added demands of the project requirements. The variation in the time survey data across the six years of course modification indicated that the wood design project module in the structural analysis course can greatly increase the required workload for the students. Faculty must be careful when crafting project requirements and should monitor student time.

Table 2: Student Performance in the structural analysis course

Year	Historical Avg.	2017	2018	2019	2020	2021	2022
Iteration	-	1	2	3	4	5	6
Course Average (%)	85[a]	85	81	87	84	86	87
Final Exam Average (%)	83[a]	81	74	84	81	85	87
Final Exam Wood Design Question Average (%)	86[b]	81	76	79	-[c]	83	88
Average Time per Lesson (min)[d]	81[a]	117	145	94	103	105	110
Average Time per semester (min)[d]	3320	4810	5960	3840	4120	4330	4520
Average Time Spent on Wood (min)[d]	-	726	1560	738	762	657	1050
Approximate Time on Wood (%)	-	15	26	19	18	15	23

[a] The historical course average, final exam average, and time data averages were calculated from CE403 for the six years prior to implementation of the project (2011-2016).
[b] The historical wood design question average was calculated using data from CE404 for the six years prior to removal of the wood content (2012-2017).
[c] The wood design question was removed in 2020 due to COVID-19 restrictions on exam time.
[d] Average time is self-reported time by students spent outside of class

Student Performance in Wood Design

While implementation of the design project created more work for the student, the wood design module covered fewer concepts than students had previously covered when wood design was combined in the steel design course. Despite the reduced wood design content, students were able to demonstrate a similar level of knowledge on course-end exams in 2021 and 2022. Table 2 contains the course average grade for the wood design question for each year of interest. The historical average was taken from the student performance on the wood design question when the wood design material was covered in the steel design course for the six years prior to its removal. For the purpose of assessment, the wood design question year-to-year, and across the two courses, was managed carefully to ensure a comparable question type and level of difficulty. However, the authors acknowledge that slight modifications were made to the question on wood design during the six-year study, which may have influenced the results. Each year the study was conducted, the students scored within 10% of the historical average. In 2018 and 2019, significant decreases of 10% and 7%, respectively, were observed in student performance on the wood design question. In 2021 and 2022, the student performance was within three percentage points of the historical average. Except for 2019, the performance on the wood design question was a good indicator of the students' performance on the final examination, within three percentage points. This finding indicates that even a reduced exposure to wood design content can provide a comparable competency on the final examination. The authors acknowledge that limited analysis is presented. Although a historical final examination was used with limited changes to the questions, assessments using these grades may be influenced by confounding factors such as the student population and the instructor grading the examination.

Student Feedback

The final analysis used to evaluate whether the wood design project had a detrimental effect on student learning considered anonymous end-of-course survey data. As stated in the Introduction, one of the primary motivations for developing the engineering design project was to provide students with wood design experience. The second motivation was to provide students with a hands-on experience to inspire them to seek additional design opportunities.

The first set of Likert survey questions inquired about the students' perception of the project experience. Overall, students found the project to be a valuable and enjoyable experience, as shown in Figure 11 (the question was not asked in 2017 and 2019). The students also believed that the project was effective in helping them learn the course material. An interesting trend was that as the project requirements became more refined over time, students perceived that they were providing less leadership in completing the team assignments. In future iterations of the project, explicit leadership opportunities should be made available to all students.

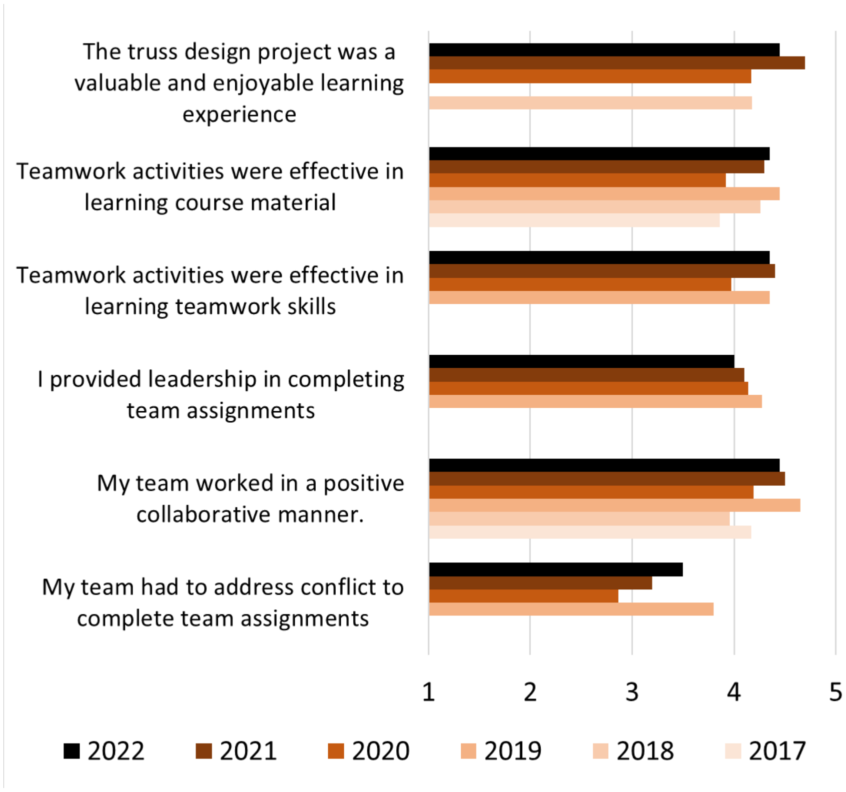

Figure 11: Student Feedback on their experience with the engineering design project (5: strongly agree, 4: agree, 3: neutral, 2: disagree, 1: strongly disagree)

The open-ended course end feedback provided by the students also indicates that students appreciated the project experience. Based on the students' free response, strengths of the project experience were divided into six categories: hands-on activities, design process, applied knowledge, team/competition, experimental testing, timeline/schedule of events, and the video presentation, primarily in the most recent iteration in 2022. Open-ended comments were coded by a faculty member into these categories, as shown in Figure 12. Results showed that, overwhelmingly, students appreciated the hands-on experience of the project. The second most cited strengths were the opportunity to apply the engineering design process and their course knowledge to solve challenging problems. Some specific comments from students are below:

> "Being able to bring forth knowledge of construction to the course and demonstrating understanding of engineering work through something other than a sheet of paper."

> "The EDP was a great way to apply our learning with hands-on experience."

> "I really liked how we got to design it from start to end, with challenges to meet along the way that made us consider cost/benefits."

> "I liked the flexibility and total control. It was especially fun and challenging to come up with our own personal design that fits the parameters and then actually build it ourselves."

“I liked how the design process was left up to the students. We were able to decide on what truss we believed would produce the best results. Classroom examples gave us the tools to complete the EDP but the majority of the design process was on our group.”

“I liked that the EDP was a fun way to apply our learning of structural analysis learned in the course and allowed us to physically design something using our learning as most of the course is just solving problems on paper. It was a good new way to look at a structural analysis problem that helped to deepen my understanding of the material.

“I liked how there were many iterations of design in the EDP. It shows that design is a very time-consuming aspect of engineering that is extremely important.”

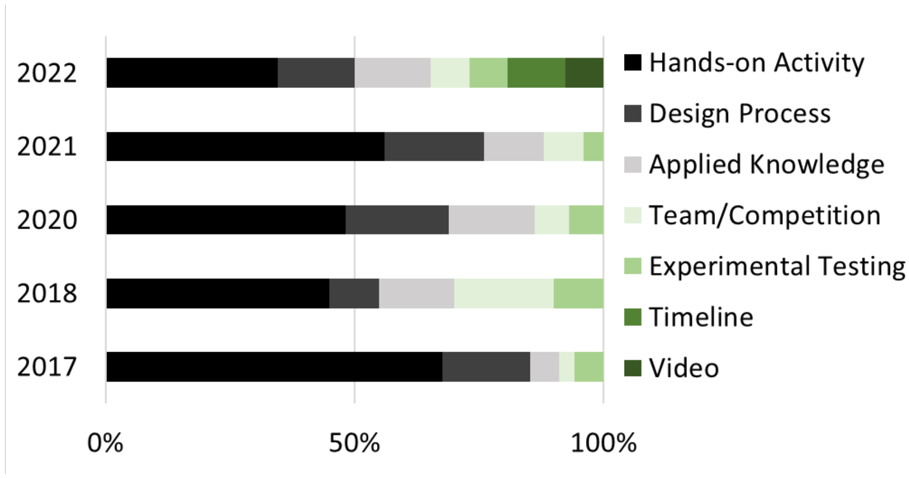

Figure 12: Student Feedback on the open-ended question: “What did you like most about the engineering design project?”

The students were also asked how they would improve the project experience. The student-free responses were divided into five categories: schedule and organization, more fabrication time, more resources or information on different aspects of the project, changes to the design restrictions or evaluation criteria, and fewer assignments. As shown in Figure 13, open-ended comments were coded by a faculty member into these categories. For the first five years of implementation of the project, the schedule and organization of the project were the most commonly cited frustration for students. In the most recent iteration, in 2022, the integration of the project over the entire semester seemed to be appreciated by the students, and their comments primarily focused on having additional time for hands-on activities and more information to make more educated engineering and design decisions. Some specific feedback from students over the six iterations is included below:

“The lessons on nails and wood calculations should be sooner because my group spent so much time trying to figure it out since we had never practiced it before and still ended up doing it incorrectly.”

“Spread out the due dates because it was fast and furious between submissions”

"Give more time to reflect and think on the process. It would also allow us to design a better structure and build it better."

"Use more CE403 concepts. Could work on different pieces of it throughout the semester as we learn the relevant concepts."

"Providing more example/reference material because the first few assignments were very confusing and took a long time. Videos or other resources on it would be very helpful."

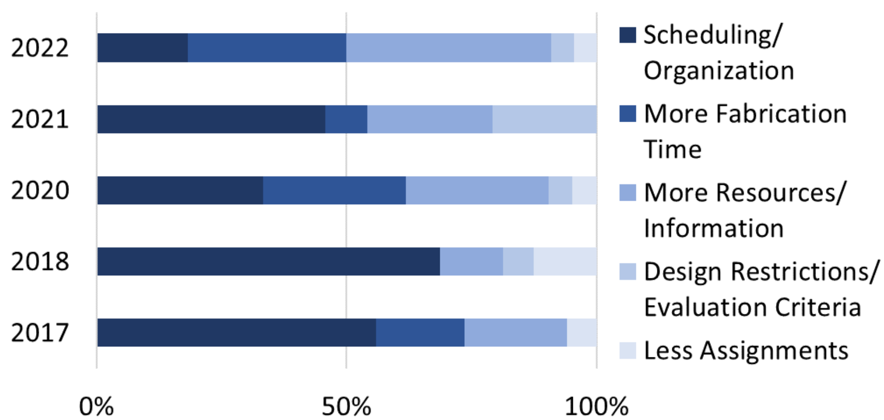

Figure 13: Student Feedback on the open-ended question: "What changes do you recommend making to improve the engineering design project experience?"

The final student feedback data analyzed were responses to Likert questions included in the anonymous course-end-feedback survey for the last 12 years which focus on overall perception of the course. Student responses to five questions shown in Figure 14 were compared to the student average responses for the six years prior to implementation of the project. The results show that, except for 2018 when the students reported spending 64 more minutes per lesson than the previous average, student feedback did not experience a significant change due to implementation of the project.

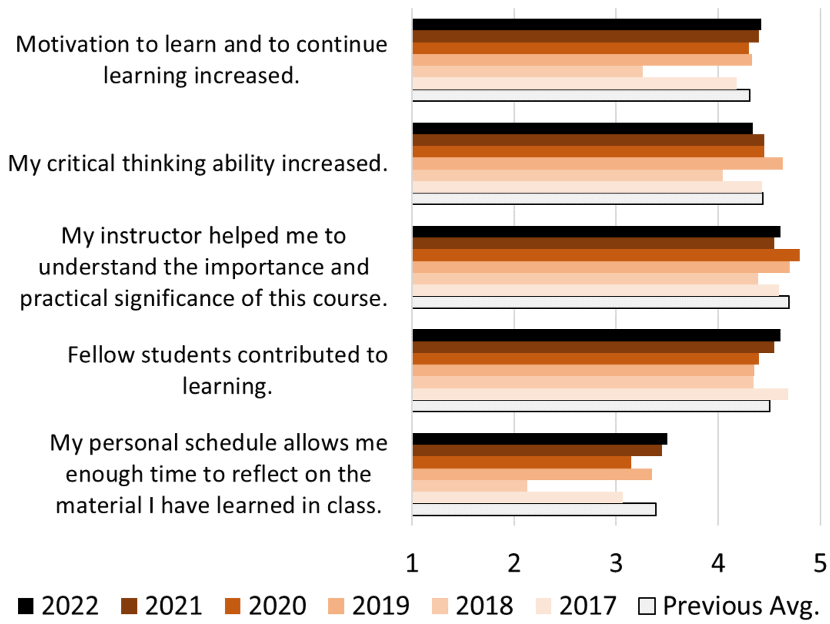

Figure 14: Student Feedback on an annual course end survey for CE403, Structural Analysis

Conclusions

Wood design remains a relevant topic for civil engineering students, but many civil engineering programs do not provide dedicated courses on the subject. Not exposing undergraduate civil engineers to wood design runs the risk of reducing interest in a material which is essential for many projects. This paper presented results from the iterative approach taken by the civil engineering program at the United States Military Academy to incorporate a wood design project into a structural analysis course. Introduction of the project provided two benefits: 1) it introduced wood design and 2) provided students with the opportunity to complete an engineering design project. The research question which this paper sought to answer was: *can a civil engineering program incorporate a wood design project into an existing structural analysis course without degrading the existing curriculum?*

The addition of the wood design project within a structural analysis course did pose some risks to the learner in terms of their ability to achieve the structural analysis course objectives and the amount of time required to complete the assignments outside of class. Through analyzing nine years of FE Exam data, the authors concluded that the students' knowledge of structural analysis was not adversely affected. The students' performance on twelve years of final exam questions on a wood design problem showed that students could develop a similar competency in wood design with just a few lessons on the topic. The student-reported time spent outside of class showed the addition of the wood design project increased the workload required of students between 16% and 79%. The increase in time depended on how the project assignments were scoped and integrated into the existing course. Finally, the authors analyzed twelve years of course-end feedback. Implementation of the wood design project resulted in an experience that the students found to be an effective and enjoyable way to learn the course material. The success of the wood design project was contingent on the students being required to apply their structural analysis knowledge throughout the process. At every opportunity, students should compare their hand-calculated results using structural analysis methods to their findings from structural analysis software and experimental results. Implementation of the wood design project came at a cost, as the students were required to spend more time outside of class to complete the project assignments. There is also additional financial and administrative costs associated with the purchase of the material for the project and experimental testing of the trusses. The results of this study demonstrated that a wood design project may be implemented into a structural analysis course without significantly impacting the student outcomes for the course, however, the assignments and workload must be properly scoped to not overextend the students. Future research will assess the impact the wood design project had on students of the United States Military Academy. The authors would like to survey students on whether this experience was helpful in preparing them for their capstone project and work in industry and whether it inspired them to seek future design opportunities.

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