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Work in Progress: Reformulation of a Truss Competition Course Project to Improve Educational Outcomes

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Abstract

The sophomore-level Statics and Mechanics of Materials course provides the solid mechanics foundation for many undergraduate students. Since trusses are already a familiar sight to most students, this structure provides a good bridge between the abstract conceptual knowledge which has predominated their class to this point and a concrete practical application, while also tying many course concepts together. The design and physical construction of a truss lets students participate hands-on while providing the opportunity to self-assess and to evaluate their coursework against an objective standard: does it work in "real life"? Demonstrating the applicability of abstract theories in the real world to relatively inexperienced students is critical to their educational foundation. If project results can be predicted, then students receive a confidence boon and will be encouraged to delve deeper into their learning. Alternatively, if students cannot predict outcomes, they may conclude that what they've learned is not useful and lose motivation. The educational stakes of an in-depth course project like the design and construction of a truss merit a careful formulation of the project to definitively enhance students' educational formation rather than hindering it.

As with any experimental work, many complexities may arise which are well beyond the scope of the course and the capabilities of the students at this stage. To ensure that students can observe their theory work out in practice, the project should be designed to eliminate, mitigate, or highlight these factors as much as possible. The truss competition project had several features which brought out these issues, including significant statistical variation in (craft sticks) material properties, geometric limitations due to the material dimensions, and subsequent deviations from truss theory. The variations and emerging discrepancy between the design model and the physical structure being constructed undermined students' confidence in the analysis taught in class, evidenced by a predominance of heuristic failure load predictions rather than predictions directly resulting from the analysis.

The authors made some fundamental changes to the competition materials and rules, seeking to improve the educational impact of this project for the 2021-22 school year. First, a closer correspondence to theory should increase student self-efficacy in engineering analysis broadly at this early stage in their technical education. Second, a project outcome determined by correct application of course concepts rather than external aspects (e.g. craft skills or luck) should establish a deeper understanding of course content and cement longer-term retention. Finally, a sense of mastery over basic principles should empower students' creativity, leading to innovation rather than a reliance on traditionally successful approaches. The first year of project revisions achieved partial success. An overall increase in material repeatability and student confidence was

achieved compared to the previous year. However, some new problems were also revealed, preventing the expected dramatic improvement across the board.

As a work in progress, the next steps in this project involve addressing the remaining technical challenges and testing solutions, establishing assessment instruments, and streamlining the project with built-in year-to-year variations to make it more manageable for future instructors.

Introduction

In this paper, an overview is presented of in-progress work to refine a truss competition course project for a sophomore-level statics course. This project was intended to extend the analysis techniques learned in lecture to include a design component and hands-on application and had been carried out with only minor changes for many years. Upon teaching this class for the first time, the first author identified educational outcomes for this project as (1) developed self-efficacy in analytical methods, (2) ability to use engineering analysis in creative design, and (3) ability to apply engineering judgment despite uncertainty and incomplete knowledge. After the project was completed, informal assessment of the outcomes indicated that some improvement was needed. The literature strongly suggests that hands-on project work and laboratories are a critical component of engineering education, providing substantial motivation for this work. Several specific features of the project seemed to hinder these educational outcomes, so a significant overhaul of the project was undertaken to mitigate the technical issues underlying these weaknesses. While addressing these concerns, general improvements of the project as an educational tool were also considered, which will be discussed in terms of the general objectives of educational laboratories. Additionally, this course project presents an opportunity to expand the students' focus from strictly technical details to include problem formulation, project management, teamwork, and reporting activities, exposing them to the wider and more ill-formulated problem solving tasks required outside an academic context. Finally, the results of these changes in the first year will be presented, with both positive and negative effects.

Background Motivation

Engineering is the directed application of science and mathematics to solve human problems. In the bulk of their academic experience, undergraduate engineering students are primarily faced with closed-ended problems requiring only the proper application of a small set of physical and mathematical principles and resulting in a unique correct answer. However, according to the accreditation agency for engineering programs, students are expected to graduate with "an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics." [1] A significant gap exists between what is required in the problem solving processes in the workplace compared with the well-scoped homework and test problems making up the bulk of the engineering student's experience. McNeill, et al.

explored this gap in terms of students' beliefs about engineering problem solving [2]. Significant takeaways include a fundamental difference between classroom and workplace problems styles, with the former being bounded (closed-ended, contrived, math-focused) while the latter tend more towards unboundedness (complex, open-ended, requiring diverse criteria). Further studies have been conducted indicating the preeminence of experience in decision making in a "real-world" engineering context [3-4]. Given that engineering is a profession of practice, it seems crucial that engineering education not only provides a solid foundation of scientific and mathematical fundamentals in the context of well-formed classroom problems, but a basis of experience in more open-ended problems as well.

Exposing students to open-ended problems is a challenging endeavor, given the potential overwhelm they may experience, and especially for underclassmen. Nevertheless, the literature suggests that making these connections through laboratories or other active learning means may prove beneficial not only to students learning in general, but in making them more comfortable with "real-world" problem solving [5-6]. Hands-on learning approaches mesh well with active, collaborative, cooperative, and project-based learning (PBL), providing synergistic benefit to students in solidifying their learning and by exposing them to more open-ended problems, which they may tackle in groups. However, not all projects are created equal. Cheville, et al. outlined several factors which contribute to or detract from positive outcomes for senior capstone problems [7], suggesting that careful design of educational projects is necessary. Nevertheless, a strong integration of PBL into engineering curriculum can have a positive effect on the development of broad competencies in engineering graduates, beyond the scope of basic technical competence [8].

The features of successful PBL experiences depends on many factors. One significant aspect is the academic maturity of the students. For example, a successful project for seniors may attempt a significant amount of complexity and in-discipline knowledge [7] while projects geared towards freshmen may rely more on instinctual or qualitative judgments than any engineering analysis skills. To facilitate the transition of students from this "seat-of-the-pants design" mode to a more mature, industry-ready approach, the design of PBL for sophomore and junior-level coursework should be developed and applied [9]. Specifically addressing the needs and capabilities of second- and third-year students is critical to bridging the gap between the simplistic closed-form classroom problems and more complex, open-ended "real-world" problems because of the need to develop students' maturity in handling problem formulation and uncertainty.

In the field of mechanics, PBL is quite often applied in the form of course projects or laboratories dealing with structures [10-13]. By causing students to build physical structures and test them, they are forced to confront nature, showing them the limitations of any theory and assumptions which have been applied and introducing some measure of the complexity of the “real-world” design problems they will face in industry. It is critical to expose students to nature to ground them in reality, making them useful in the practical context of engineering practice. Although disagreement undoubtedly abounds in precisely defining the most important aspects of laboratory or project learning, Fiesel and Rosa have provided a series of useful objectives, including experience with instrumentation, models, experimentation, data analysis, design, learning from failure, creativity, psychomotor skills, safety, communication, teamwork, ethics in the laboratory, and sensory awareness [6]. These criteria provide a useful framework for evaluating and improving PBL element of coursework, especially in the context of the rapidly expanding skillset of students at the sophomore and junior levels.

Structural design projects and competitions are a frequent way to include PBL in college-level statics and mechanics courses and even in K12 STEM programs. Many similar projects are described in the literature [9-13], where each case differs somewhat, adapted to the skill level and desired educational outcomes of the students. For example, Marlor created a competition where students designed and built balsa wood structures to carry a prescribed load [11]. The analysis here assumed failures would occur in the elements, and allowable loads were provided to students based on the dimensions. Crittenden, et al. formulated a project where students used paper and card stock to fabricate a single plane truss constrained by two sheets of acrylic to avoid buckling and warping [12]. Here, the project was tailored to high school students, so many complexities were removed, including any buckling or joint strength analysis. Other projects have utilized prefabricated construction kits. One example of this is discussed by Fernández-Sánchez and Millán, where two projects were used, one involving detailed calculations with reusable construction kit pieces not loaded to failure, and one qualitative design project using a variety of disposable materials [13]. The project described in this paper differs from these examples in that students are confronted with designing for additional failure modes, some of which they are well-prepared for (e.g. joint failures and design of cross-section for buckling resistance) and some of which they are not (e.g. truss warping and eccentric buckling). The present work also uses more advanced manufacturing methods, which encourages the students to design complex structures that are nonetheless easy to accurately assemble.

Previous Truss Project Formulation

The truss competition was designed to have students compete in constructing truss structures according to the principles learned in their statics class. In lecture, students have learned about trusses as an idealized assembly of two-force-members which come together at concentric nodes in statically determinate structures. Their assumptions have included rigid body elements, loads and boundary conditions applied only at nodes, and a two-dimensional space. The project required students to work in teams of two or three, design a truss, and then construct two of them using craft sticks and glue. Cross-beams were then applied, also with craft sticks, to form a truss bridge, which would be placed on a fixed base supporting each end of the truss in a load frame.

A bridge deck would be placed across two nodes centered in the span as shown in Figure 1, and a stinger would apply an increasing force to the center of the deck until the structure failed. Since all structures were required to be statically determinate, all failures were catastrophic failures. Student performance in this competition was primarily assessed in two ways, a design metric and an analysis metric. For the design metric, teams tried to achieve the highest amount of load carried per truss weight, indicating a well-optimized design. For the analysis metric, teams tried to predict the load at which their truss would fail.

The performance of each truss in both categories is dependent on the previously mentioned analysis assumptions as well as the accuracy and consistency of material properties. The craft sticks were relatively thick, so there was simply not enough space for concentric joints to be typical. This led to members being beams (which students did not yet know how to analyze) and an unavoidable ambiguity in the rules regarding gusset plates. The thick pieces are clunky in design, and students often end up with out-of-plane asymmetry, which causes bending moments that greatly amplify the tensile stresses predicted by the truss model. Furthermore, since beam design has not yet been covered in the course, the students were not equipped to properly design the cross-beams, so many trusses failed in the decking rather than the truss. Of those that didn't, the cross-beams were necessarily located offset from the nodes since there is no way to attach them. Although the deviations from the assumptions of the model may be small, in many cases they were not. This detracts from the educational goal of the project to reinforce the relevance and usefulness of analysis.

To accurately predict the structural strength, reliable material properties are needed. Mechanical testing was conducted on craft stick samples to verify the properties provided to the students and to evaluate the repeatability of these properties. Ten tension samples were tested, revealing an average ultimate tensile stress of 12.3 ksi, but an ensemble range of 13.6 ksi. The elastic modulus from these tests was 1219 ksi on average with a range of 579 ksi. Twenty-four lap-shear samples were also made up, half with sanding prior to gluing and half without. These yielded an average glue shear strength of 0.495 ksi and 0.783 ksi for unsanded and sanded specimens, respectively, with a range of 85% of the average in each case.

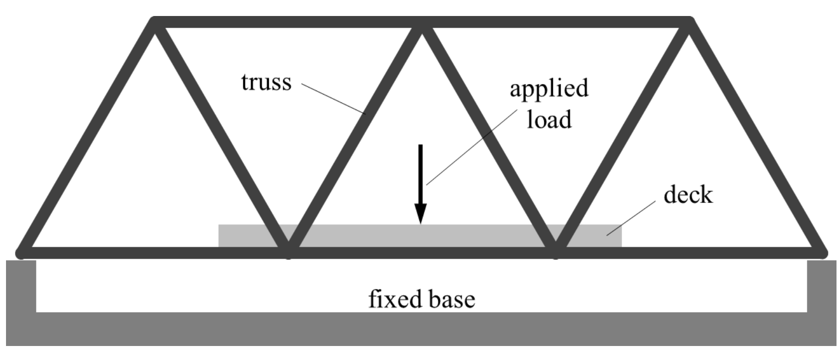

Figure 1. Truss loading schematic.

Finally, the overall quality of the truss was observed to be very largely a factor of the students' craft skills and their access to tools to ensure good alignment, proper clamping, and appropriate pre-glue preparation of their elements and joints during fabrication. While manufacturing is an important aspect of the hands-on engineering project, the particular skills and equipment involved here are not those taught in coursework, nor generally those expected of engineers in practice.

These issues conflict with the educational objectives of the project. First, analytical competence and confidence were weakly reinforced. From the outset, students knew the relatively low probability of predicting the failure load from watching the competition in previous semesters, which served to disconnect the analysis from the design to some degree. Their low confidence is evidenced by the ubiquitous application of large "safety factors" in their reports. Effectively, virtually all teams simply guessed what the failure load would be after disbelieving their own analysis. Second, while the engineering analysis did foster creativity in the overall configuration of truss structures, very few teams exceeded this level of analysis. In general, joints and element design were determined by the necessities of construction, which tended away from creative innovation. Third, although students did make judgments in the face of incomplete knowledge, the level of uncertainty seems to have overwhelmed the available insights. Students typically did not report informed judgments at all levels of analysis, but rather followed the analysis purely until the end, at which time their intuitive expectations of the overall system drove the predictions.

Technical Improvements

The technical issues with the craft stick truss project primarily revolve around two aspects of the format: the cumbersome dimensions of the material and the large variability in mechanical properties. In addition to resolving these, the authors hoped to empower students to greater creativity at each level of analysis. Selecting a material which fits well with these objectives was a critical step, so several new materials were considered as a replacement for craft sticks, including plastics, aluminum, and composites. All of these had more consistent properties and can be shaped to virtually any planar geometry in a CNC laser cutter. A high-density fiber board (HDF) was selected for its moderate strength, offering good strength-to-weight ratios but avoiding a safety risk during testing. Mechanical testing was conducted on ten HDF tension samples cut at five different orientations in the HDF sheet, indicating an average ultimate strength of 4.6 ksi with a total range of 1.3 ksi. The elastic modulus was determined to be 324 ksi on average with a range of 76 ksi. Twenty-four lap-shear specimens were also tested, divided into three sets, since the HDF material has dissimilar faces. The average shear strength between bonded dissimilar faces was 696 psi with a total variation of 142 psi.

Direct comparison between the material variation of HDF and craft sticks was undertaken by computing the standard deviation of each salient property (elastic modulus, ultimate tensile strength, and shear strength) and dividing by the average for that material. This yields a unitless variation which may appropriately compare the variation even though the actual values might be quite different between the two materials. In all categories, the HDF shows significant reduction in variation as shown in Figure 2. Additionally, while the craft stick shear failures occurred in the glue and were thus strongly impacted by surface treatment, clamp strength, etc., the HDF material delaminated in all shear failures. This means that the shear strength is much less sensitive to joint preparation and assembly factors and is primarily a function of the HDF material's consistency. Choosing HDF therefore resolves, or at least mitigates, the material variability issue.

Since the HDF comes by the sheet and may be easily cut in a CNC laser cutter, almost anything that can be drawn can be built. This opens enormous possibility in the design space, which allows for creativity and open-ended design study. Providing additional rules may limit the options somewhat, but it can also serve to provide guardrails to keep the students on track. As such, two rules were generated to better formulate the problem:

1) The plane truss must be symmetric about the plane containing the elements
2) All joints must use a specified gusset format

Enforcing symmetry helps to ensure that the mechanics of the structure stay in-plane, corresponding to the analysis. Requiring all joints to use similar construction ensures that the basic truss assumptions are reasonable and helps to keep all of the teams on the same playing field. This prescribed gusset format, shown in Figure 3, still leaves plenty of room for flexibility in the design, but requires all truss elements to be in a single plane and restricts the maximum diameter of gusset plates. Within this framework, gusset plates and elements can have any desired geometry, allowing freedom to allocate glue bond area as needed.

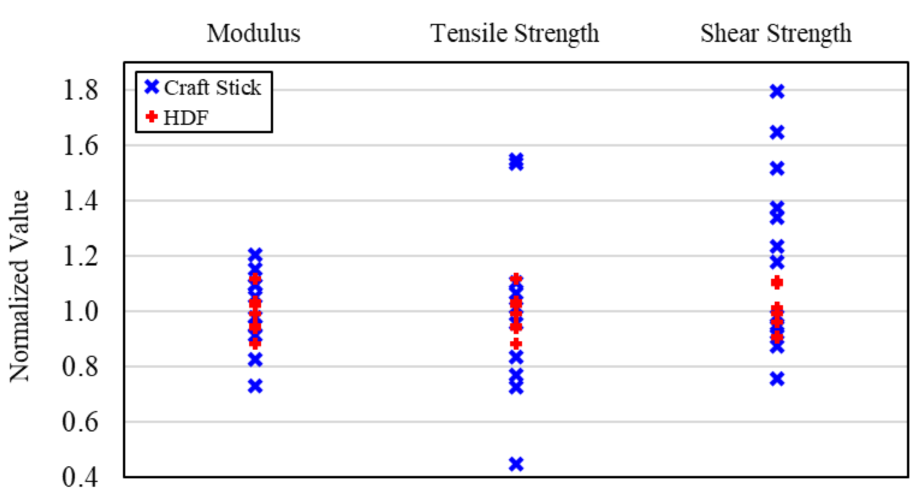

Figure 2. Normalized variation in material properties of craft sticks and HDF. Each property of each material is divided by the average of all values for that property and material.

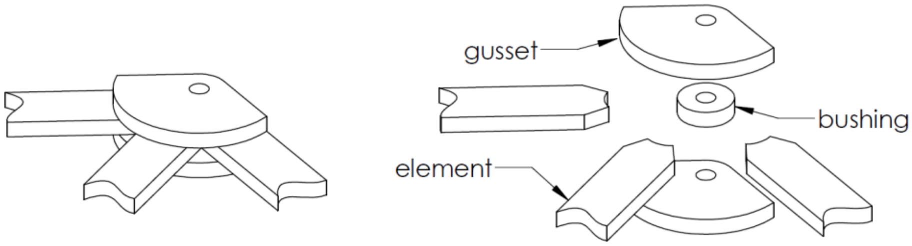

Figure 3. Prescribed joint format, showing components and how they connect together, maintaining all truss elements in a single plane.

The holes in each node facilitate assembly, and clamps made with short 6-32 bolts and fender washers ensure that each team is capable of assembling solid and precise joints. These holes also provide attachment points for the cross-beams, which were long 6-32 bolts that could support the bridge deck without needing to worry about shear failure.

With the constraints focused on the node configurations, students creatively attempted more complex element geometries, such as I-beams, x-shaped cross sections, and box beams to improve buckling resistance. Some ambitious teams had tried this approach with craft sticks, but the difficulty of assembly led to virtually all teams simply layering the sticks for rectangular cross-sections. The CNC laser cutter made it feasible for students to achieve precise element widths, notches for alignment, and generally more complex geometries without prohibitively difficult fabrication. This freedom produced many possible avenues of improvement in the element design stage, so students had to exercise engineering judgment to weight the benefits suggested by analysis against the drawbacks of manufacturing difficulty and the time and effort involved in optimizing their design.

In the new truss competition format, the manufacturing process was also improved to provide a more coherent process. Formerly, a truss design was developed in terms of elemental loads, and then a 3-D model of the truss would be constructed, but not really used for anything else. Students would then work through the difficulties in assembling the craft sticks into this format. In the revised format, precise geometry is needed for all parts, since the students have freedom in designing elements and gussets. After designating node locations, students were required to generate a layered 2D drawing of their truss. This led them to an iterative design process wherein they decided upon geometry for their elements, used this geometry in a strength and buckling analysis, and then redesigned the geometry accordingly. They then accounted for kerf and created a toolpath drawing for the Universal Laser Systems VLS3.50 laser cutter, which students operated themselves under supervision. The CAD therefore served as a useful tool in the design process, which empowered many students to undertake more exotic and innovative designs than had previously been attempted.

Discussion of Results

From the first author's faculty perspective, these first steps towards improving the project were quite successful. The technical issues which had been identified in the old problem were resolved: material variability was reduced substantially, the structures more neatly followed analysis assumptions, and the playing field was leveled with respect to the assembly. Providing clamps to all teams and using the laser-cut HDF material transferred the difficulty from actually assembling the truss to designing a truss that would be easy to assemble, placing more control in the students' hands. On average, the quality observed in the students' fabrication of complex designs was quite good compared to the prior year. Two examples are pictured in Figure 4.

To foster a more robust student perspective on changes to the competition, the second author, who had himself participated in the previous format as a student, designed, constructed, and tested a truss under the new format as well. From this comparative student point of view, the updated project allowed for increased freedom in design, improved accuracy in simulating a professional design project, and was more integrated with the statics course. In conversations with peers, some participants of the old format expressed that they saw the assignment as a more complicated version of a high school competition. This, along with the other previously mentioned factors, led to student frustration and hindered their motivation and ability to learn from the project. The revised competition facilitates use of the techniques taught in class, and eliminating the out-of-plane asymmetry and material variability only improves student confidence in these methods. Furthermore, the updated competition is quite different from a high school project as it implements higher-level, iterated analysis and design as well as engineered materials, tools, and construction techniques if students design for more advanced geometries.

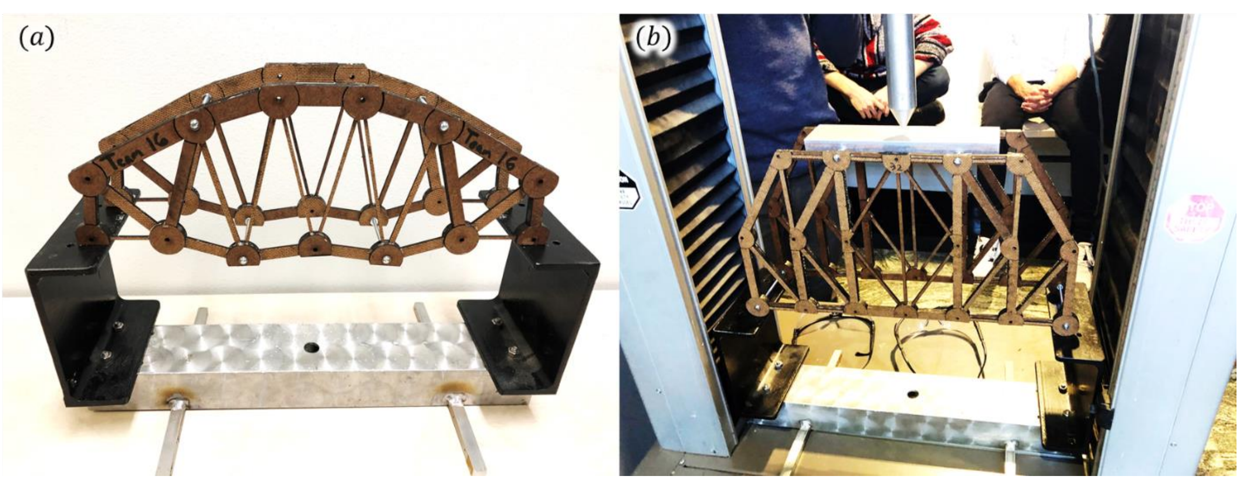

Figure 4. Example trusses (*a*) on display and (*b*) about to be tested in the load frame, with the loading mechanism visible.

In terms of the fundamental objective categories for engineering laboratories laid out in [6], the modifications outlined in this paper have generally improved or not impacted the scope of the project's educational outcomes. The categories of *instrumentation*, *experiment*, *safety*, *teamwork*, and *ethics* remained essentially equivalent in both formats. However, the new format improved the *models* category, where both system and component (element) level models could be constructed and their interactions studied. The *data analysis* and *design* categories were similarly expanded, as meaningful data processing occurred in the synthesis of given material information with student-designed geometries. *Creativity* and *learning from failure* categories were also expanded through the increased capacity of most teams to iterate their design. (This features is also correlated with positive outcomes in [7].) The *communication* element was slightly improved from the instructor's point of view, as students were able to provide more precise and detailed descriptions of their design activity in the context of specific analyses rather than "seat-of-the-pants" design modes. Finally, the *psychomotor* and *sensory awareness* categories were improved in that the fabrication process shifted from craft skills and a steady hand towards the use of engineering software and tools.

Resolving these issues has not come without drawbacks, however. It was expected that the tightening of material variability and maintaining closer alignment with analytical assumptions would greatly reduce the average prediction error in the truss competition. In the Autumn 2020 semester under the old format, the average prediction error was 131.6%. In the Autumn 2021 semester under the new format, the average prediction error increased to 140.0%. The most likely reason for this is that the average prediction increased from 454 lb to 549 lb, despite the use of a weaker material. The somewhat less reasonable predictions stem from the fact that the students in 2021 had real confidence in their analysis and their ability to execute the fabrication of their designs. This improved confidence did not materialize due to the violation of assumptions which were not considered in the present project iteration. First, the loads were assumed to be transferred to the truss in the truss plane, whereas in fact they were applied to the cross-beams, which transferred a bending moment to each plane truss. This was reduced if the students were careful to minimize the space between the two trusses, but many teams did not, and this issue was not highlighted in the provided guidance. The second unconsidered factor was the propensity of the truss structure to buckle across multiple segments. Only buckling between nodes was considered in the analysis, so the buckling of two or three segments together came as a surprise to many student teams. Both issues occurred simultaneously in the structure shown in Figure 5, where the entire top of each truss buckled in towards the stinger. Experiencing failure in an unexpected mode was frustrating to many students, but these emerged as dominant failure modes only because the students were able to successfully design against the expected modes: tension, shear, and buckling of individual truss elements.

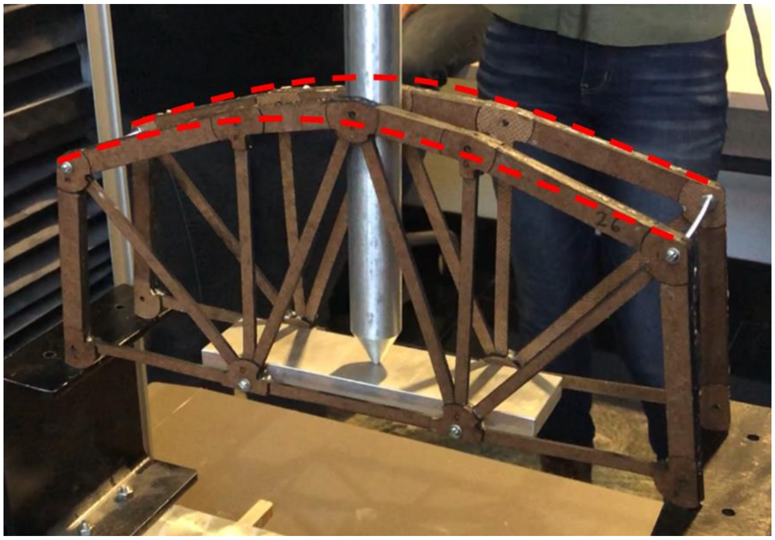

Figure 5. Example of multi-member buckling ahead of catastrophic failure. The red dashed lines show the approximate original position of the top surface of each structure.

Conclusion

The reformulation of the truss competition was largely successful. In terms of the broad educational outcomes, success was generally achieved. Student confidence was greatly improved, as evidenced by not one team employing a failure prediction fudge factor, compared with nearly all teams including unsubstantiated “safety factors” under the previous format. Engineering analysis provided the basis for creative design in much greater depth due to the ability to draw and fabricate virtually any element geometry as desired. In the more exotic designs, students were well aware of working on the edge of uncertainties where assumptions were not strictly valid. However, the limitations of other assumptions were not understood, so there is still work to be done improving the project.

In particular, changes which should be made for the next competition include (1) altering the load application to reduce or remove the applied moments, (2) teach the students how to analyze other failure modes (and/or adjust the project specifications to avoid them), and (3) collect more formal assessment data (including student feedback and quantitative performance data) so as to better evaluate whether this project met its educational objectives. Such assessment should include failure prediction accuracy statistics and before/after results of a survey on the project educational outcomes, student interest, and conceptual understanding of mechanics.

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