An Innovative Solution to Teaching the Principle of Virtual Work

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Mrs. Sustersic is passionate about increasing student engagement and encouraging deep understanding to develop in her students. She incorporates a variety of demonstration materials (both traditional and non-traditional) and interactive activities into her lecture-based delivery format.

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In May, 2015, Ms. Klatman will graduate with integrated Bachelor of Architectural Engineering/Master of Architectural Engineering degrees.

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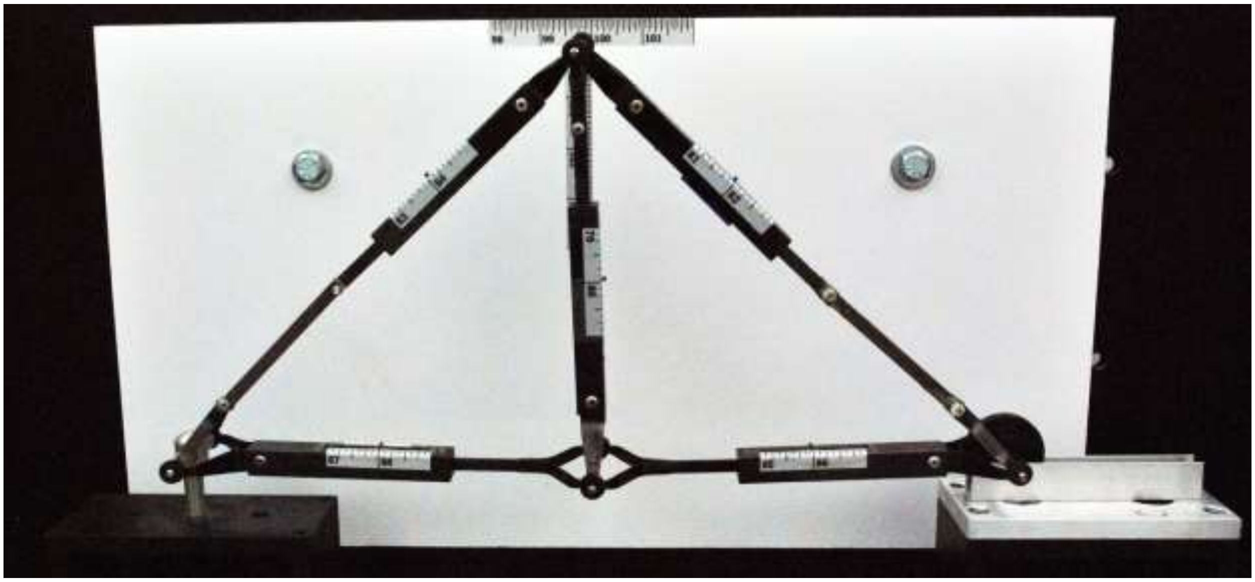

Figure 1: Truss model used for virtual work interactive class demonstration (16" wide x 8" tall). Each truss member is capable of +/- 1" of elongation. The left support is idealized as a pin; the right support as a roller.

Introduction

Providing a balance of abstract theory and concrete practical application, in a manner that encourages active learning when teaching structural engineering courses, is an ongoing challenge for educators[1,2]. Student learning styles and attitudes toward their education vary considerably, even within a small group of individuals. While procedural learners rely on memorization of facts and a surface understanding of the concepts, other learners are interested in a deeper understanding and being able to provide context to the material[3]. Each type of learner has different needs which must be addressed when delivering course content. Adding further complexity to this issue, even the most passionate student has difficulty focusing for the full duration of a 75 minute lecture. Focus problems are exacerbated by general fatigue experienced by students enrolled in rigorous engineering programs, where there are high expectations for student work completed outside of instructional contact hours. Educators must thus be vigilant in monitoring the level of interest they engender in their students during lectures[4].

One solution as to how to maintain interest is to develop demonstrations to accompany traditional lecture materials, thereby encouraging students to interact and engage in hands-on learning. Hong[5] noticed that many structural engineering students are too focused on “problem-solving procedure[s]” with limited attention to developing true understanding. In response, Hong proposes active learning techniques with emphasis on “visual thinking” instead of “mathematical thinking” be employed in the classroom. Student response to this approach has been very positive. Prince[10] further demonstrates the benefits of active learning. Improvement in student performance is shown through his compilation of prior studies and means of quantifying the effects of active learning techniques.

Educational truss models are not new to engineering education. Bigoni, et. al.[6], developed a modular 3-dimensional truss model for the purpose of teaching global truss behavior, including stability issues out of plane. Taylor, et. al.[7] used lego pieces and string to teach non-engineering students the concept of tension-only members in a planar truss. Interactive wood truss models to demonstrate the concept of zero-force members are shown to be effective for introductory engineering mechanics classes.[8]

Many existing truss models have already proven effective in demonstrating various concepts to students and promoting student engagement, but to the authors' knowledge, there are no published studies demonstrating the use of physical truss models to teach the concept of virtual work. By using a custom-built truss model made of recycled lab materials, this study, conducted within the Architectural Engineering Department at The Pennsylvania State University, explores the effectiveness of providing a physical truss demonstration, accompanied by a traditional presentation, to teach the abstract concept of work-energy methods for determining nodal deflections in truss structures.

Scope and Objectives

The primary objective of this study was to investigate the effectiveness of incorporating an inexpensive, interactive, hands-on truss demonstration model to teach work/energy methods for computing truss deflections and compare and contrast it with a more traditional lecture-example presentation format. A secondary outcome of the study was the observation that the combination of presentation styles is both preferable from the student perspective, and effective from an assessment standpoint.

A group of 24 students, enrolled in the required 400-level indeterminate structural analysis course, AE 430, were invited to participate in this pilot research study. Twenty-three students agreed to participate in the survey and were present on the day of the study.

Methodology

Students received a background lecture in work-energy methods for computing deflections the week before the study began, and were assigned relevant readings in their course textbook to be completed before attending the study, similar to a flipped classroom. The study began with a brief presentation of the principle of virtual work for trusses after which students were divided into two groups, Group A and Group B. Group assignments were posted prior to study commencement. Mid-term exam #1 grades were used to ensure equal ability levels were present in each group. Informed consent, under approval of Institutional Review Board (IRB) human subject research protocol, was obtained for 23 participants.

Group A witnessed a lecture example worked for them in a traditional lecture format. A student teaching intern provided instruction on a tablet PC for an example truss problem, and led students in filling out a worksheet with step-by-step guidance.

Group B participated in an interactive demonstration using a custom-fabricated truss model – further described in the next section - capable of displaying measurable axial member elongation and shortening (Figure 1-7). Students took turns reading measurements, calculating values, and loading/unloading the model.

After Group A watched the traditional lecture and Group B viewed the truss demonstration, all students took a 15 minute timed quiz to evaluate their initial understanding of the material. The students then switched rooms, viewed the alternate style presentation, and re-took the quiz. Students were also asked to complete a survey to rank the perceived benefits of each instruction method.

Finally, a simple truss problem, requiring the use of work-energy methods, was included on the course final exam. Scores for the quizzes, final exam truss problem, and overall final exam score were recorded and compared. Survey results were compiled and analyzed.

Description of the Truss Model

Preliminary model configuration, including dimensions, loads, and desired elongation properties of each axial member, was developed by the author in 2013. Undergraduate students were recruited to fabricate the truss model, pictured in Figure 1. Under collaborative consultation with the author, the undergraduate students repurposed existing materials and fabricated selected new components to meet the design specifications. Each truss member is able to elongate or shorten – in the axial direction only – through the use of springs placed on either side of the member mid-point, as shown in Figure 2.

The members are sufficiently stiff to prevent any flexural response in the members when the truss is loaded at joint locations. Each truss member includes an elongation measurement scale, as shown in Figure 3, which permits users to make differential elongation measurements at different stages of loading. Aluminum extension pieces were fabricated to create members of varying lengths, particularly for the truss diagonals, with epoxy resin used to affix the extension to the original dashpot pieces.

Figure 2: Close-up view of spring dashpot truss axial member (center vertical member shown here)

Figure 3: Detail view of diagonal top chord member of elongation measurement scale; shown in neutral position

Figure 4: Close-up view of right roller support. An aluminum channel prevents lateral movement of the roller when the truss is loaded.

Truss members are available in differing stiffnesses, afforded by variable spring constants within the dashpots. Note that the exact stiffness of each truss member is not documented – ΔL_{pi} includes this information without needing it to be individually parametrized.

All truss members are interchangeable and are easily removed by releasing the U-shaped prong flaps on either side of panel point pin connections. When all members framing into a joint are released, the pin is unsupported. Members are thus free to rotate about the pin. The U-shaped prong flaps remain in place by a slight compressive clamping force parallel to the longitudinal axis of the pins. This force does not inhibit free rotation of adjoining members. Lateral stability is attained through the left end pin support (Figure 7) and the right end roller channel support (Figure 4) which prevent rotation at the base of the truss. Care must be exercised when applying loads to the truss to prevent lateral torsional buckling effects. Not pictured in Figure 5 are two rubber stops positioned on the center pin to keep the load in the plane of the supports.

Figure 5: Center panel point with 2 pound point load applied at the joint (Not pictured: rubber stops were added to pin to prevent lateral translation of the load)

Figure 6: Typical pinned joint; 3 members connected

Figure 7: Close-up view of left pin support

Finally, the truss model is installed in an AN/EX rolling cabinet/display case with predrilled tapped holes throughout all interior faces for modular attachment of variable sized models. This is particularly useful to accommodate planned expansion to the model size.

Traditional Lesson Plan

An undergraduate student teaching intern led students in a 15 minute traditional step-by-step worked example on tablet PC. An abbreviated version of the worksheet used by presenter and students is provided on page 10 in Figure 12 (left). The nomenclature presented is consistent with the course textbook[9].

Problem geometry and member forces for the P system (actual loads) and Q system (virtual loads) were provided. Students filled in the table provided based on the given information, then calculated row and column summations to determine the total embodied strain energy in the truss. Then students inserted values for member area, A, and modulus of elasticity, E, and solved for truss deflection at the point of virtual load application.

Interactive Lesson Plan

One detached member of the truss was circulated among the students so they could exert axial compressive and tensile forces on member and experience individual member elongation and shortening. Then, a brief description of the model joints, geometry, and support conditions was provided. Students received a blank worksheet (see Figure 12, right, for the full worksheet) containing a graphical representation of the model truss (Figure 8), governing equations, and a table for recording member elongations and forces. The goal of the exercise was to determine the horizontal and vertical displacement at joint B due to a load, P, applied at joint D. Neutral readings for individual member elongation were noted, so that only the differential elongation would be considered for the analysis.

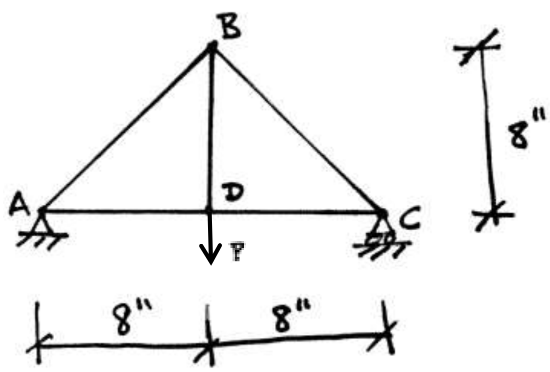

Figure 8: Problem statement for truss model example presentation

Figure 9: Spring scale connected at the top panel point applies "virtual" load.

Students voted on the magnitude of point load P to be applied in the downward sense at joint D, ranging between 1 and 3 pounds (Figure 5). With point load P in place, students took turns reading the axial elongation or shortening, ΔL_{pi}, for each member, using the sign convention that elongation, caused my member tension, is positive. Point load P was then removed. A volunteer student next applied a unit load in the positive x direction at joint B (Figure 9), representing a unit "virtual" load applied in the direction of the desired nodal displacement. Students performed static truss analysis to determine the resultant force in each member due to the applied virtual load. With the virtual load in place, another student reapplied the point load P. Then the virtual load was removed. This process was repeated for translation in the y direction at joint B. Students filled in the table on the worksheet, solving for individual member strain energies for the work done by the virtual load moving through the real elongation. The summation of internal strain energies was then divided by the magnitude of the applied virtual load, resulting in final nodal displacement in the direction indicated. Students compared their calculated nodal displacement with the ruled measurement positioned behind joint B and found agreement between calculated and actual nodal displacements in the x and y directions.

This method separates the elongation term, ΔL_{pi}, from the expression for strain energy in a truss so that it is clear that work, $load \times deformation$, is being done *on the system* and *by the virtual force*.

Students then selected the member(s) that should be stiffened to most efficiently reduce displacement in the x and y directions at joint B, respectively. Truss members with a stiffer spring were then substituted for the original members, according to analysis results. Displacement at joint B was then evaluated once again to determine the % reduction in nodal displacement. Fifteen minutes was allowed for the entire demonstration.

Assessment Results

Table 1, below, summarizes the assessment results for all study participants. The first value listed in each cell represents the arithmetic mean of the scores, reported as a percentage. Below the reported mean, the median score and standard of deviation for the sample are provided parenthetically.

Students were assigned to their respective groups according to their Exam #1 scores such that the mean Exam #1 scores in each Group (reported in the first column) were comparable. Overall final exam average scores by Group are reported in the last column, for comparison. These items are shaded in grey because both assessed skills outside the scope of this study and are included to provide context only. Future work associated with this study will incorporate a more rigorous statistical analysis of each students' overall performance in the course, with possible inclusion of a pre-test, to ensure that the groups are as equivalent as possible prior to assessment.

Group A initial quiz scores were higher than their Group B counterparts, but the participant-wide initial quiz average was a low "C" at 71.01%. After receiving the second type of instruction, the combined average quiz score increased by 24% to 95.36%. The combination of teaching methods appears to have significantly improved understanding overall, but there are several additional factors that may have influenced the scores on the second quiz. These include familiarity with the quiz format/expectations and the ultimatum of being quizzed. Students in Group B scored slightly higher on the second quiz than did students in Group A. It is important to note that during the second truss demonstration, the authors fielded far more detailed questions from students in both groups. This, combined with the increase in quiz scores, suggests that the experience of struggling through the first quiz heightened attention and peaked student interested during the second demonstration, thus also causing the second attempt scores to be higher.

*Table 1: Assessment Results for Study Participants (n=23); results reported by "*Mean *(median, standard of deviation for the sample, σ)"*

Group Assignment	Exam #1 Score	Quiz Scores		Final Exam Scores	
		1st Attempt	2nd Attempt	Problem #1	Overall
Group A (control)	77.45% *(80.00%, 11.18)*	78.79% *(86.67%, 20.18)*	94.55% *(93.33%, 5.83)*	85.45% *(88.00%, 14.56)*	76.55% *(76.00%, 9.64)*
Group B (trial)	77.00% *(80.00%, 9.13)*	63.89% *(66.67%, 21.92)*	96.11% *(93.33%, 3.43)*	75.00% *(72.00%, 19.08)*	80.17% *(80.00%, 8.61)*
Combined	77.22% *(80.00%, 10.04)*	71.01% *(66.67%, 21.98)*	95.36% *(93.33%, 4.69)*	80.00% *(80.00%, 17.52)*	78.43% *(78.00%, 9.09)*

A final exam for the course was administered approximately 9 weeks after the study was performed. Problem #1 on the final exam measured student mastery of work/energy methods for computing truss nodal displacements. Group A students scored one letter grade higher on this problem than did Group B students. However, Group B students performed better overall on the final exam than did Group A students. Since both groups received both treatments, however, the final exam scores do not provide solid evidence that either instructional method is superior. It is difficult to ethically separate the class into treatment-only and control-only groups to gauge independent behavior due to sample size and frequency of the course offerings.

Student Evaluation and Surveys

After each presentation-quiz module, students were asked to complete a survey to rate perceived effectiveness of the presentation that they just viewed. A total of 20 students completed the surveys; however, 2 surveys were removed from tabulated results due to student failure to clearly identify presentation format. The survey included 6 questions and one "additional feedback" section, as shown in Figure 10. The first 4 questions included quick-select Likert scale rating options ranging from "Strongly Disagree" to "Strongly Agree". Results from the Likert scale questions are tabulated in Figure 11, below. The remaining 2 questions on the survey were short answer response and requested students to comment on what they liked best and least for each presentation style.

In general, students rated the clarity of the truss demonstration slightly lower than the traditional example, but rated both methods as effective teaching tools. Both methods were rated as helping students understand the concept of virtual work for trusses, with slight preference for traditional methods of instruction.

In the open comment section of the survey, there was a mix of student reviews for the presentation styles, with equal quantity of negative and positive comments for each. The majority of students responded positively to the interactive truss model; they felt that this presentation style was "more engaging," citing "seeing it actually happen" and "visually understand[ing] what was going on" as reasons for this. Several students commented that the truss model helped them "understand a lot better how forces affect truss members" and found that visually seeing member elongation helped them understand the sign convention and axial deformation of truss members. However, students indicated that the truss model demonstration did not prepare them well for the quiz, the format of which more closely aligned with the traditional example presented. Students commented that this presentation style lacked clarity in terms of whether virtual work or real work was being evaluated.

In contrast, most students thought that the traditional method was “simple,” “easy,” “clear,” and “straight-forward.” Some students attributed this distinction to a comfort level developed with the traditional style of presentation, due to its similarity with other examples provided in this and previous courses. They also commented on the traditional method’s similarity and direct applicability to the quiz question, indicating that this method provided more immediately transferable tools for the assigned quiz problem. However, several students indicated that the traditional approach was “boring” and “lacked interaction.” There were also several negative comments regarding the pace of the presentation (too fast) and that force values were given to them.

Several students recommended combining the two presentations styles into one such that the truss demonstration matched the traditional worked example. Both presentations were described as “rushed,” with specific student recommendations to increase the time devoted to each presentation. Other responses included recommendations for specific changes to handout materials, clarifying real versus virtual work in the truss demonstration, and more time spent on theory in an introductory lecture prior to introducing the examples.

Voluntary Survey Response (Optional)

Please circle which virtual work presentation you viewed first: Truss Demo Traditional Example

1. Considering the **FIRST presentation** that you attended, please answer the following questions:

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Was the example clear to you?	❍	❍	❍	❍	❍
Did the presentation method help you understand the concept of virtual work for trusses?	❍	❍	❍	❍	❍
Would you recommend this style of presentation to be used in future course offerings of AE 430?	❍	❍	❍	❍	❍
Was this presentation method effective as a teaching tool?	❍	❍	❍	❍	❍

What **did you like best** about this presentation method?

What **did you like least** about this presentation method?

Please **provide any additional feedback** or comments that might improve the quality of this presentation.

Figure 10: Partial Voluntary Survey Response Form for the Study (completed by 18 participants)

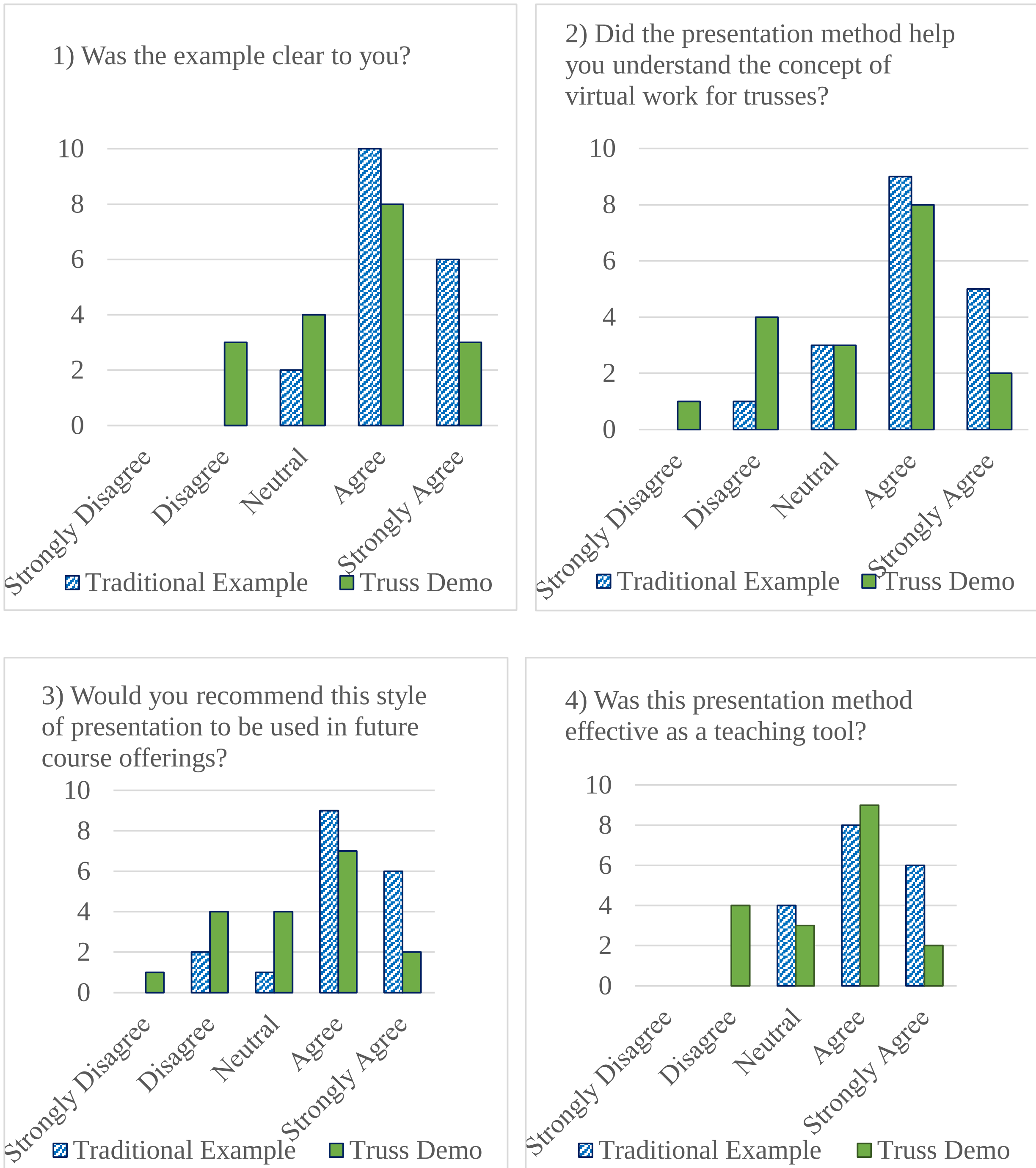

Figure 11: Student perception of teaching effectiveness - survey results by question

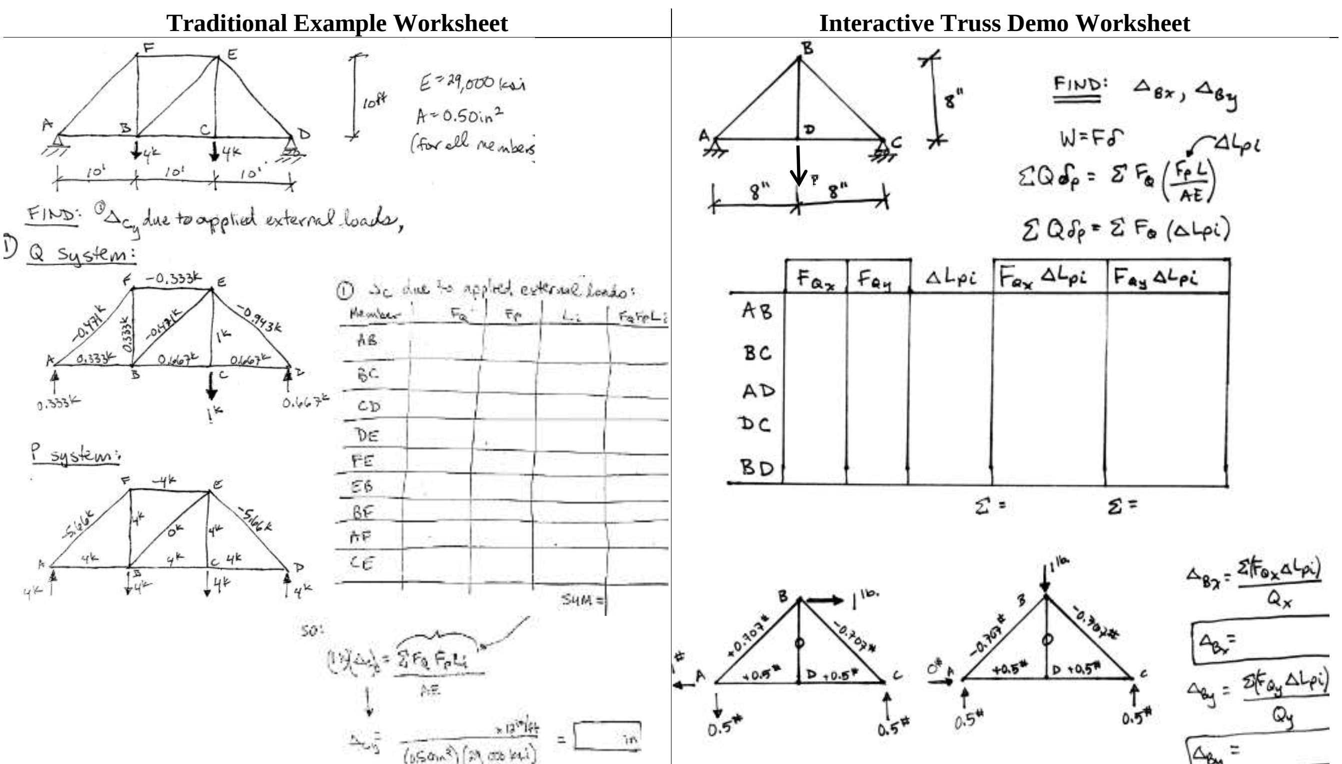

Figure 12: Student worksheets provided for the traditional and interactive examples

Proposed Study Revisions

In response to student feedback and observations from this preliminary study, a continued evaluation of the effectiveness of the truss demonstration model will be implemented annually, with data collection to align with the offering of this course. Specific changes that will be made include:

- Schedule more time for the presentations and assessments.
- Increase the time spent on theory and introductory material provided prior to the presentations.
- Reserve two immediately adjacent classrooms for the duration of the study so that both presentations are provided in a controlled environment.
- Restructure the virtual work quiz problems to be neutral of presentation style.
- Make minor edits to handout materials to improve context.
- Fabricate more truss members so that different truss configurations can be modeled.

Additionally, IRB approval will be requested for an expanded study in future course offerings, allowing for the collection of more data over the course of the full semester to identify trends, rather than limiting the data acquisition to specific quiz scores.

Conclusion

Two different instructional methods were used to teach the concept of work-energy for calculating truss nodal displacements. An innovative truss model was used to engage students in an interactive, hands-on analysis experience, as was traditional teacher-led worked example. Students were assessed after receiving each treatment, with quiz scores suggesting that it is the *combination* of teaching approaches, among other factors, that increases proficiency.

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