Integrating a 3-D Printer and a Truss Optimization Project in Statics

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Abstract

There is a need to integrate hands-on engineering analysis and design problems and exciting build technology in lower division engineering courses to stimulate interest and increase students' capacity to solve divergent, open-ended based problems. In this evidence-based practice paper, we discuss the development, execution, and impact of a truss optimization project given to students in Statics. The students were required to optimize two different polyactic acid (PLA) 3D printed trusses using compression and tensile mechanical strength properties. The students were required to provide the optimal tension and compression member cross-section to be 3D printed, provide a three-dimensional drawing using a user-friendly open source CAD software, and provide a summary of the results in a poster presentation. The optimal truss design was then printed, assembled, and tested in the classroom and the results were compared to the engineering design solutions. Students perception of their ability to interpret and analyze data, organize presentations, solve engineering problems, tinker, engineer, and design was assessed using a 21 item online survey. The survey items were taken from both validated instruments and the ABET Criteria 3 course outcomes: a, b, and e. Survey data was collected from the test population (students given the project) and compared to a control population (students not given the project) to assess the impact of the project on engineering self-efficacy. The results indicate there is a statistically significant gain in student engineering skills self-efficacy, student perception of their ability to analyze and interpret data, ability to solve engineering problems, and organize a presentation.

Introduction

According to the Accreditation Board of Engineering and Technology (ABET), engineering graduates must have the ability to apply math and science to engineering problems, conduct experiments, design a system, function in multi-disciplinary teams, and communicate effectively, among other skills[1]. The challenges of student retention are significant and a difficult problem to solve because of the analytical and technical skills required to succeed in engineering. Students' decision to leave engineering often depends on self-efficacy and self-confidence[2]; preparedness, race, and gender[3]; and social pressures[4,5], among other factors.

Educators have attempted to address the declining numbers of engineering students by changing the educational paradigm and utilizing project-based and active learning pedagogies to better engage and prepare them for the rigor of the upper division courses. Project Based Learning (PBL) is a pedagogy where students learn by completing a series of investigative problems that require them to develop practical and knowledge-based design solutions, practice effective team

management, and require oral or written communication[6,7]. PBL has been shown to be effective in increasing retention and positively changing students' perception of the complex engineering design process[6] and shown to increase student confidence[8].

Statics is a sophomore level engineering mechanics course often taken after completing Calculus I and Physics I. The course covers topics on two- and three-dimensional rigid body equilibrium, truss and beam analysis, and moment of inertia, among other topics. It is often recognized as a gatekeeper course, and certainly is at Lamar University (where the failure rate typically ranges from 30%-40%). In general, the objective of the course is to improve student ability to solve engineering problems. At larger universities, the course enrollment in Statics is typically high; in some cases, surpassing 300 students which places limitations on an instructors' ability to assign hands-on projects that require space to tinker with physical objects. Several researchers have however, reported successful integration of project based assignments, which includes but is not limited to: analysis, design, and construction of a machine[9], truss bridge[9,10,11,12,13,14], and a friction climbing machine[9].

Although most students by their sophomore year have taken a computer course requiring them to use a spreadsheet or other basic programming software, they have not been asked to apply their current engineering skills and knowledge to solve tangible and realistic engineering design problems. Integrating project-based engineering design exercises into the curriculum at the lower levels can reinvigorate student effort and help connect classroom theoretical concepts to real-world design problems. These design exercises, if implemented properly, can also serve as a source of student-faculty engagement leading to increases in engineering self-efficacy and self-confidence.

This evidence-based practice paper describes the implementation, cost, and impact of a low-cost project-based assignment integrated into a sophomore level Statics course that includes the use of a 3D printer, Microsoft Excel®, Powerpoint®, and Google SketchUP. The students were required to analyze, design, and optimize a truss using experimentally obtained mechanical strength data of tested polyactic acid (PLA) plastic members in both compression and tension. The students were then asked to construct a poster summarizing their findings, which includes: final dimensions, member forces, sample calculations, and a three-dimensional drawing of the final designed truss.

Implementation

The truss optimization assignment was incorporated into the classroom in the Spring 2015 semester, to a class of 57 students. The course topics and associated number of lectures are summarized in Table 1. Each lecture was 55 minutes.

Table 1. Course Topics

Topic	2D and 3D vector resultants; particle equilibrium	2D and 3D moment of a force; distributed load; rigid body equilibrium	Truss analysis: method of joints and sections	Beam analysis	Friction	Area centroids; moment of inertia
No. of Lectures	9	12	5	5	2	5

The students were given two mid-term exams and one comprehensive final exam. The instructor used Powerpoint® slides to present the lectures via a projector and completed approximately two hand-worked examples on the blackboard per lecture. The homework assigned to the students was managed online through MasteringEngineering®, where the students were able to access their homework problems, submit solutions, and view video tutorials. A total of 12 online homework assignments were given to the students throughout the semester.

Project Summary

The project was assigned to the students on week 14 (one week after completing mid-term exam 2 and the truss analysis lectures). The instructor allowed the students to work in groups of 4-5 to complete the assignment. The project was weighted as two homework assignments.

The students were required to minimize the mass of two different trusses (with given geometries) by selecting the appropriate thickness of each member. The trusses were constrained by mechanical strength and required to resist a 190 N vertical force placed on the bottom mid-span joint. The students were provided experimental mechanical strength data and regression equations that were collected and derived, respectively, by the instructor and teaching assistant. The regression equations used the geometric dimensions of the truss members as inputs: truss member thickness in tension; and truss member thickness, truss member length, moment of inertia, and elastic modulus in compression. The Euler buckling equation was discussed in brief. The students were required to use the regression equations to calculate the strength of the members using Excel and submit their optimized solutions on week 16. On the day of the submission, the instructor demonstrated the 3D printing process by drawing a sample truss member in an open source CAD software, saving the file with a .stl extension, generating the g-code with the open-source software Slic3r®, and printing a sample truss member. The instructor

then tested two fully assembled optimized trusses to determine if the strength capacity met the load demands. The following week, the students were required to submit a poster presentation which included: sample calculations, a CAD drawing of their final designed truss, the member forces, and a photograph of the truss loading test setup using a template provided to them in Powerpoint®. The project statement is provided in the Appendix.

Description of the Printer, Accessories, and other Testing Equipment

The 3D printer used in the demonstration and to construct the truss components was manufactured by printrbot® which has a 150x150x150 mm build volume and processes 1.75 mm polyactic acid (PLA) filament. The cost of the printer was $659. The cost of the filament was $23 for a 1 kg spool and it was mounted on a $12 rack. The software used to generate the. stl file and g-code was open source: Slic3r®. The total cost of the material and supplies was under $700.

To collect experimental strength data, the instructor used a hydraulic actuator and unconfined compression testing apparatus with data acquisition capabilities. For the tension tests, the truss members were connected to custom-built welded pin connectors. In compression, the members were pin connected using heavy duty paper clips.

Methods

Survey Instrument

The 3D printer truss project contained multiple tasks that required students to engage in computer and data processing, truss analysis, optimization, CAD drawing, and the creation of a poster presentation. A 21 item online survey instrument was given to the students and used to assess engineering skills self-efficacy, tinkering self-efficacy, engineering design self-efficacy, and the criteria 3 ABET outcomes a, b, and e. The survey is shown in Table 2. The survey was given to the students during week 17 of the semester. The survey was comprised of statements from the questionnaire published by Mamaril[15] (items 1-13) that is a modification of previously published survey instruments[16,17,18]. The survey uses a six point Likert scale ranging from 1 to 6 with one point increments, and has a good internal group reliability (Cronbach alpha ranges from 0.93 to 0.86; all grouping categories). The remaining items (items 14-21) were taken from the the Lamar University civil and environmental engineering department criteria 3 ABET assessment instrument which uses a four point Likert scale ranging from 1 to 4 with one point increments. Note, quantitative performance data via a midterm or final examination was not included here

since it would only be reflective of one component of the project (truss analysis) and not of the others (computer and oral presentation skills, CAD, data analysis, and engineering design).

Table 2. Online survey instrument

Statement ID	Statement	Scale
Skills SE 1	I can perform experiments independently.	1-6
Skills SE 2	I can analyze data resulting from experiments.	1-6
Skills SE 3	I can communicate results of experiments in written form.	1-6
Skills SE 4	I can solve problems using a computer.	1-6
Skills SE 5	I can work with machines.	1-6
Tinkering SE 1	I can build machines.	1-6
Tinkering SE 2	I can manipulate components and devices.	1-6
Tinkering SE 3	I can assemble things.	1-6
Tinkering SE 4	I can disassemble things.	1-6
Design SE 1	I can identify a design need.	1-6
Design SE 2	I can develop design solutions.	1-6
Design SE 3	I can evaluate a design.	1-6
Design SE 4	I can recognize changes needed for a design solution to work.	1-6
ABET Outcome a1	Perform mathematical calculations to solve problems.	1-4
ABET Outcome a2	Apply scientific principles in engineering.	1-4
ABET Outcome a3	Apply engineering knowledge in design and analysis.	1-4
ABET Outcome e1	Perform design process correctly.	1-4
ABET Outcome e2	Identify the type of engineering problems.	1-4
ABET Outcome e3	Solve engineering problems.	1-4
ABET Outcome b1	Organize data for presentation.	1-4
ABET Outcome b2	Interpret data and perform analysis based on data.	1-4

Hypotheses

The objective of this study is to assess the impact of the 3D printed truss optimization project on student engineering self-efficacy. The hypothesis is the following:

- The mean ranks in engineering self-efficacy, which includes student perception to solve engineering problems, interpret and analyze data, and ability to organize presentations, will not be significantly different between the students given and not given the project.

Student survey response population and demographics

Tables 3 and 4 show the demographics of the student survey response population. The test population is defined here as the group of students given the project in the Spring 2015 semester. The control population includes the group of students not given the assignment, which includes students from the Summer 2015 and Fall 2015 semesters. A total of 43 and 68 students in the test and control populations, respectively, fully completed the online survey. Surveys that were not

fully completed were discarded from the analysis. As shown in Tables 3 and 4, the demographics were very similar between the test and control student group.

The control and test group were given identical homework assignments (administered through MasteringEngineering®), Powerpoint® lecture notes and in-class sample problems, and given similar examinations. The Summer 2015 and Fall 2015 control groups were tested for homogeneity and the results indicate that each of the individual survey item sample populations do not have a significantly different mean rank (Mann-Whitney U test, $p \leq 0.05$), and variance (non-parametric modified Levene's, test $p \leq 0.05$). The control populations from the Summer and Fall 2015 semesters were pooled.

Table 3. Demographics: Gender/Race

Course	Gender		Race			
	Male	Female	Asian/Pacific Islander	African American	Hispanic	White
Test, N= 43	78.3%	21.7%	10.3%	8.6%	15.5%	52.6%
Control, N=68	78.6%	21.4%	12.8%	8.8%	11.2%	60.8%

Table 4. Demographics: Engineering Major, Academic Standing, Qualitative SAT, GPA

Course	Engineering Major					Standing		Q SAT	GPA
	Civil	Chem.	Elec.	Indust.	Mech.	Sophomore	Junior		
Test, N=43	12.2%	37.4%	5.2%	13.0%	32.2%	63.5%	34.8%	551	2.98
Control, N=68	11.0%	33.3%	3.2%	8.9%	43.6%	68.6%	29.3%	556	2.95

Data analysis

The survey responses were pooled based on engineering dimension, which included: engineering skills self-efficacy (Skills SE 1-5), engineering tinkering skills self-efficacy (Tinkering SE 1-4), engineering design self-efficacy (Eng. Design SE 1-4), and Criteria 3 ABET[1] outcomes a (ABET Outcome a1-3), b (ABET Outcome b1-2), and e (ABET Outcome e1-3). Where ABET outcome a is "an ability to apply knowledge of mathematics, science, and engineering", ABET outcome b is "an ability to design and conduct experiments, as well as to analyze and interpret data", and ABET outcome e is "an ability to identify, formulate, and solve engineering problems." The ABET items were statements obtained from the Lamar University civil and environmental engineering department. Note, ABET items were preceded by the statement: "Rate your

confidence in performing the following tasks". This statement is not included in Table 1 for brevity.

The hypothesis was tested using the non-parametric rank-sums Mann-Whitney U test. Note, while a significant change cannot be directly attributed to the project itself, the survey provides a reasonable estimate of how students perceive their skills within a given error.

Results and Discussion

The pooled item means are provided in Table 5 and the individual item means are provided in Table 6. Items that are significant at both 95% and 85% confidence are demarcated.

The results indicate the test population given the design project has significantly higher engineering skills self-efficacy, significantly higher perception of their ability to analyze/interpret data, organize presentations, and solve engineering problems. Students' tinkering and design self-efficacy, and ability to apply mathematics, science, and engineering was not significantly higher in the test population. Although not statistically significant, among the questions in ABET outcome a, question 3: "ability to apply engineering knowledge in design an analysis", had a relatively large mean difference at +0.13. The most significant mean rank differences of the individual items, was item Skill SE 3: "I can communicate results of experiments in written form", and ABET outcome b1: "Organize data for presentation". This result seems reasonable since the students were required to construct a poster of the design solutions, which included organizing the three-dimensional CAD drawing, sample calculations, final design dimensions, and photographs of the in-class tested printed truss.

The evidence collected in this study suggests the 3D printed truss analysis and design project can yield significant gains to perceived ability in engineering analytical and communication skills. After the semester was over, the students had positive comments and showed considerable enthusiasm regarding both the course and project.

Table 5. Results of grouped survey responses

Group ID	Test, N= 43	Control, N=68	Mean Difference
Skill SE	4.77	4.57	0.20[**]
Tinkering SE	4.40	4.40	0.00
Design SE	4.28	4.27	0.01
ABET Outcome a	3.29	3.21	0.08
ABET Outcome e	3.12	3.00	0.12[*]
ABET Outcome b	3.41	3.21	0.20[**]

[**] Statistically significant difference in mean rank between test and control population: $p \leq 0.05$

[*] Statistically significant difference in mean rank between test and control population: $p \leq 0.15$

Table 6. Results of individual item survey responses

Item ID	Test, N= 43	Control, N=68	Mean Difference
Skills SE 1	4.58	4.46	0.12
Skills SE 2	4.77	4.59	0.18
Skills SE 3	4.91	4.60	0.31*
Skills SE 4	4.86	4.66	0.20
Skills SE 5	4.72	4.68	0.04
Tinkering SE 1	3.81	3.90	-0.09
Tinkering SE 2	4.26	4.28	-0.02
Tinkering SE 3	4.67	4.63	0.04
Tinkering SE 4	4.84	4.81	0.03
Design SE 1	4.19	4.31	-0.12
Design SE 2	4.26	4.24	0.02
Design SE 3	4.42	4.22	0.20
Design SE 4	4.28	4.32	-0.04
ABET Outcome a1	3.42	3.38	0.04
ABET Outcome a2	3.30	3.24	0.06
ABET Outcome a3	3.14	3.01	0.13
ABET Outcome e1	3.00	2.88	0.12
ABET Outcome e2	3.21	3.04	0.17
ABET Outcome e3	3.16	3.09	0.07
ABET Outcome b1	3.60	3.22	0.38**
ABET Outcome b2	3.21	3.19	0.02

** Statistically significant difference in mean rank between test and control population: $p \leq 0.05$

* Statistically significant difference in mean rank between test and control population: $p \leq 0.15$

Alternative implementation

The Statics course at many universities is 3 credits and taught to a large number of students which can limit further expansion of this project into the curriculum. However, if a course instructor has the ability to purchase or use multiple 3D printers and allows an additional week for completion, the project can be expanded to include more variables: additional truss geometries, which inclueds member orientation, length, and thickness. In addition, an instructor can require each individual group to 3D print their own truss (rather than simply demonstrating the printing procedure and conducting the failure loading test of the two optimized trusses). This type of expansion, of course, will require a significant time investment. It typically takes one hour to print the members needed to fully erect the truss at normal printing speeds (60-80 mm/s). The time required to train the teaching assistant (TA) to install and troubleshoot the 3D printer, and work with the g-code generator should take approximately 5-10 hours depending on the assistants' familiarity with CAD software and their general computer competency skills.

Alternative 3D printers

There a several modestly priced 3D printers on the market that can be purchased for this type of project, which are summarized in Table 6. When choosing a 3D printer, it is also important to consider available technical support to assist in troubleshooting, replacing broken or missing parts, or other general inquiries.

Table 6. Low cost 3D printers, and support options

Manufacturer	Max. Printing Volume (mm)	Plastic	Min. Layer Thickness (mm)	Technical Support	Cost
Pintrbot®	150 x 150 x 150	PLA	0.1	Tutorials, Forum, Email	$659
Dremel®	225 x 150 x 138	PLA	0.1	Tutorials, Forum, Email, Phone	$999
FlashForge®	225 x 145 x 150	PLA, ABS	0.1	Tutorials, Forum, Email	$1,199
XYZprinting®	200 x 200 x 200	PLA, ABS	0.1	Tutorials, Forum, Email, Phone	$499
HICTOP®	270 x 200 x 170	PLA, ABS	0.1	Email, Skype	$363
Makerbot®	285 x 153 x 155	PLA	0.1	Tutorials, Forum, Email, Phone	$1,803
LulzBot®	152 x 152 x 152	PLA, ABS, HIPS, Nylon	0.05	Tutorials, Forum, Email, Phone	$1,250
Ultimaker®	230 x 225 x 205	PLA, ABS, CPE	0.02	Tutorials, Forum, Email	$1,999

Conclusion

This evidence-based practice paper summarizes the details of effectively implementing a project-based assignment that integrates engineering analysis, design, 3D printing, testing, and a poster presentation into a Statics course. The students' overall response to the project and the course were positive. Student perception of their ability to solve engineering problems, ability to interpret and analyze data, and organize presentations was shown to be positively affected by the 3D printer project. Expanded implementation of this project can be done if multiple 3D printers are available to the instructor. It is suggested however, in three credit Statics courses, this project be implemented in the form described in this paper unless additional time is given to the students to become familiar with the CAD tools and 3D printers.

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Appendix: Project statement and sample student poster

Project Statement

You are a structural engineer working for a Toy corporation and asked to design a polyactic acid (PLA) plastic truss with a span of 150 mm, a height 50 mm, and a width of 50 mm. The truss must be designed to withstand a vertical concentrated force of 95 N at both mid-span joints using the least material possible. Your design strategy will be to conduct a series of mechanical tests on the PLA material in both pure tension and compression, collect data, and design the truss using your knowledge of statics and known material critical failure forces. Your objective is to design the thickness, *T*, of each truss member needed to satisfy the objective.
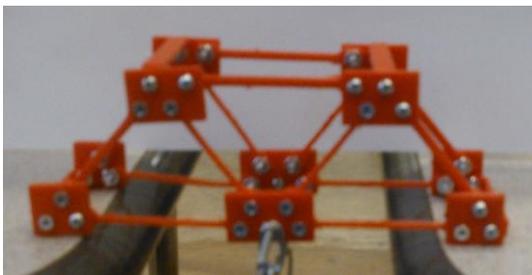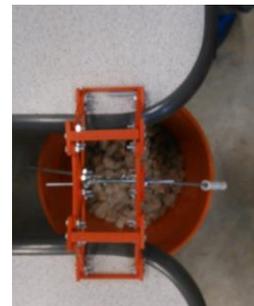
(a)   (b)

Figure 1. Photograph of assembled Pratt Truss connected with gusset plates and nuts and bolts and loaded at mid-span: a) side view, b) top view

Objective: i) Determine the member thickness, *T*, of each truss member needed to withstand a 190 N concentrated force at the mid-span of the truss, **ii)** minimize the weight of the truss using the least amount of material possible.

Experimental Program: After deliberation with the Research and Development group, a standard truss member design was constructed as shown in Figure 2. The length, *L*, is measured center to

center from the holes located at the ends of the member. The diameter of each hole is 3.4 mm. The end member width, W, is 7 mm and the interior cross-section is square and has a thickness T.
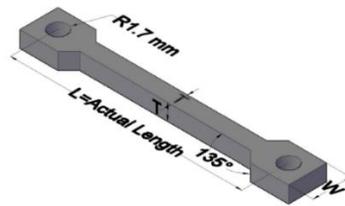

Figure 2. Standard truss member geometry

A test factorial was constructed to determine the effects of member length, L, and member thickness, T, on the critical material failure force in both compression and tension. A total of 24 specimens were tested: twelve in tension and twelve in compression. The length was varied from 25 mm to 100 mm and thickness was varied from 1 to 3 mm. The members were loaded until failure. In tension, failure was defined when the specimen fully ruptured, and in compression failure was defined when the specimen buckled and was unable to adequately transfer load.

A photograph of the test setup is provided in Figure 3 for both the compression and tension tests. The tension specimens were pin connected at the holes at both ends of the member using a lab fabricated pin support as shown in Figure 3a. The compression members were also pin connected at both ends as shown in Figure 3b.

(a)   (b)

Figure 3. a) Tension test setup, b) compression test setup

Experimental Results: Upon completion of the test, the data was tabulated in EXCEL and used to derive a set of continuous regression functions to predict member mass, critical tensile force, and critical compressive force.

Tensile Tests: A photograph of the failed tension members is provided in Figure 4a in addition to a CAD drawing showing the ruptured cross-section (Figure 4b). The specimens failed at the pin

connection due to the reduction in crossectional area and stress concentration. This creates a scenario in which the tensile critical load only depends on the thickness T since the width of the member ends, W, is constant and will not change the effective cross-sectional area. A linear regression was derived to predict the tensile strength, $F_{T,Fail,}$ using the data obtained from the tensile tests. The data is shown in Figure 5 superimposed over the regression line and the derived regression equation is shown in equation (1). Note, when designing tension members, engineers typically use material strength data (given in terms of force per unit area, MPa). The tensile strength data presented here, however, is written in terms of thickness. This was done because there was considerable variability in the failure mode between the 1 mm and 2 mm tension members which lowered the accuracy of the predictive model when interpreting the data in terms of material strength.

(a)   (b)
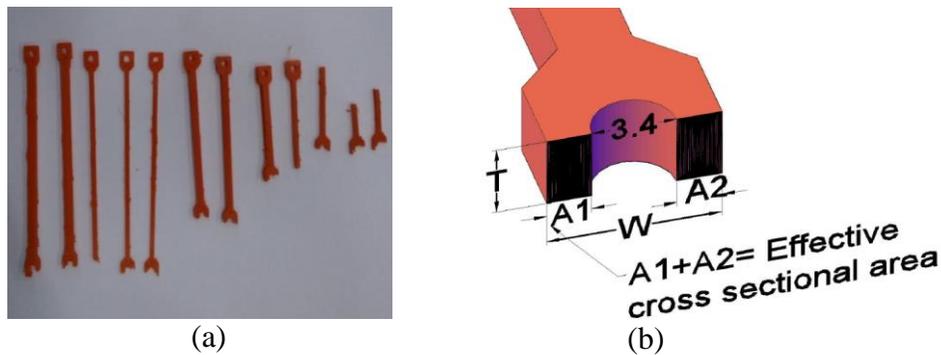
Figure 4. a) photograph of failed tension members, b) CAD drawing of failed cross-sectional area
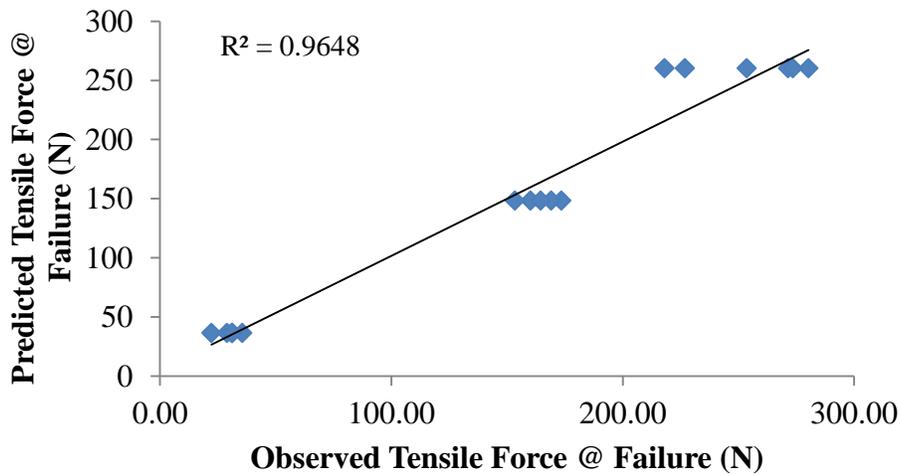
Figure 5. Tensile strength at failure v. member thickness

$$F_{T,Fail}(N) = 111.9 * T(mm) - 75.4 \qquad\qquad (1)$$

Compression Tests: The strength of the compression members varied as a function of length, L, and thickness, T. The compressive strength can be predicted using the elastic Euler buckling equation using an effective length factor, K, of 1.0 and an elastic modulus, E, of 3500 N/mm², the moment of inertia, I, and the member length, L. The experimental results are provided in Figure 6 which shows the predictive and observed compressive strength and the regression line. The compression strength can be predicted by equation (3), which uses Euler's elastic buckling formula as an input. Note, the regression equations act as calibration tool to match theory to observed results.
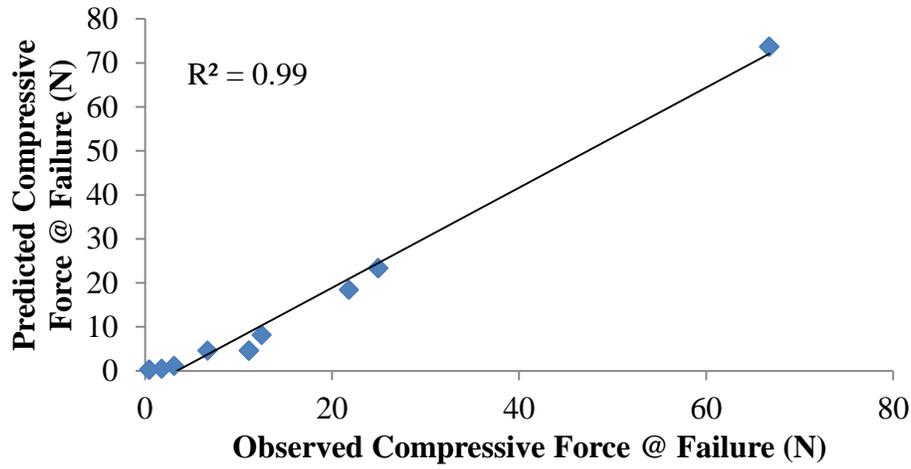
Figure 6. Predicted v. observed compressive strength

$$F_{C,Fail}(N) = 1.14 * \frac{\pi^2 EI}{(KL)^2} - 3.88 \qquad\qquad (2)$$

Where

$K = 1.0$, $E = 3500$ N/mm², and $I = \frac{T^4}{12}$ (mm), $L =$ member length (mm)

Member Mass: The mass of each member, M_{mem}, was also recorded. The effective volume of the member, LT^2, was used to predict the mass using a regression equation. Figure 7 shows the data and superimposed regression line. The member mass predictive formula is shown in equation (3).
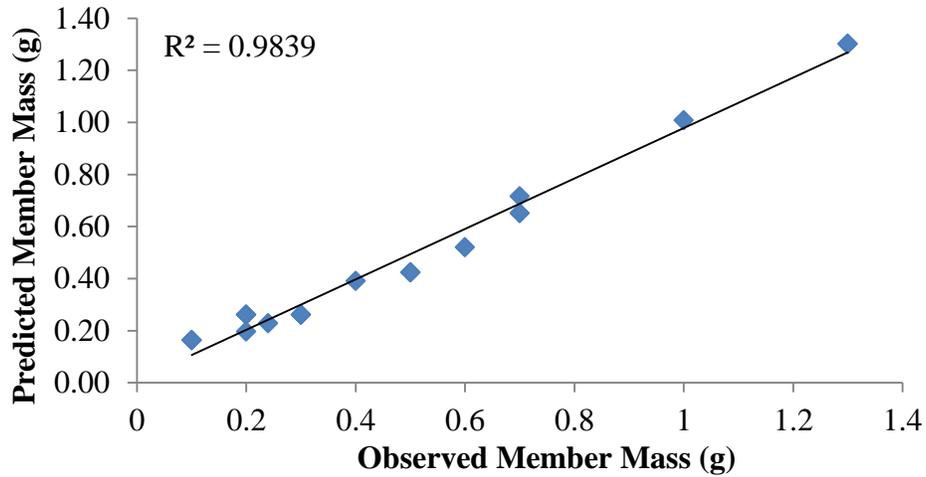
Figure 7. Member mass v. effective volume

$$M_{mem}(g) = 0.00132 * LT^2(mm) + 0.1315 \qquad (3)$$

Truss Geometry: The geometry of each of the proposed trusses is shown in Figure 8 and 9. Truss # 1 is a Pratt truss and Truss # 2 is a Camelback truss. Each group will be assigned one truss to design.
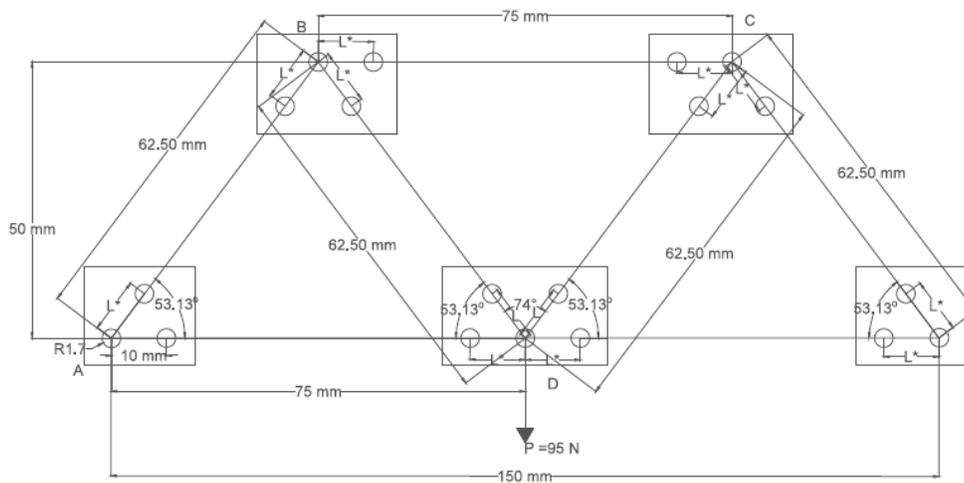

Figure 8: Geometry of Truss # 1: Pratt
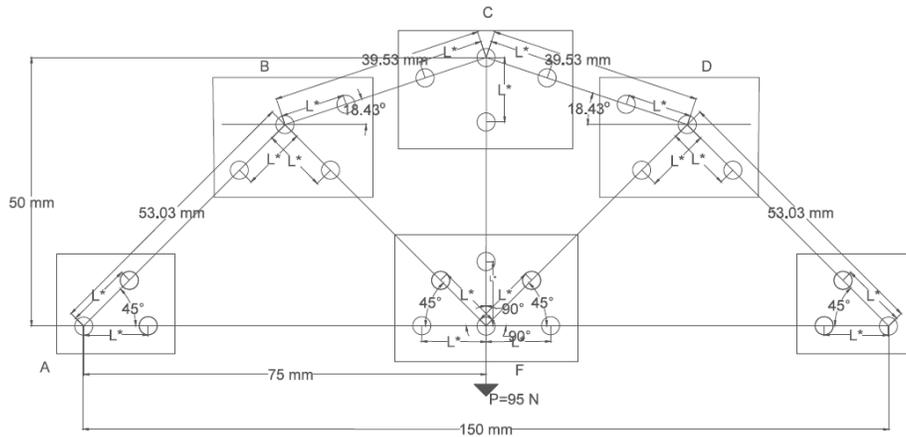
Figure 9: Geometry of Truss # 2: Camelback

Each member will be connected with a gusset plate and bolted. The gusset plates are shown at each joint. The effective length of each truss member are shown in the drawings. Please note these lengths are NOT equal to the actual member length. The actual member length, in terms of the effective length is provided in equation (4). The effective length is defined as the distance between each joint. For example, the effective length of AB in Truss # 2 is 53.03 mm. The actual length of the member is 53.03 - 2L*. The L* for Truss # 1 is 10 mm and for Truss # 2 is 12 mm.

$$L = Effective\ Length - 2L^* \qquad\qquad (4)$$

Structural Analysis: Each group is to conduct a structural analysis of their assigned truss to determine the internal forces in each member as a result of the 95 N applied force at midspan (half of the 190 N load). To determine the internal forces caused by the applied load, you are to use the effective length of each member given in Figures 8 and 9. To determine member strength, the actual member length, L, must be used.

Deliverables: Each group is to create an excel spreadsheet (submitted electronically) that shows the internal forces acting in each of the members as a result of the 95 N concentrated force at mid-span in addition to the member mass and strengths.

1. Each group must minimize the truss mass while ensuring the internal forces do not exceed the member strengths.
   a. Conditions:
      i. All compression members must have the same thickness, *T*.
      ii. All tension members must have the same thickness, *T*.
      iii. The thickness of the compression members <u>do not</u> have to equal the thickness of the tension members.

2. Each group is to draw a 3D drawing of the design truss using Google SketchUp.

3. Attend the 3D printing demonstration.

4. Attend the truss test day.

5. Each group must submit an electronic copy of a 36 in. x 24 in. (Horizontal x Vertical) poster presentation that summarizes their findings. This should include the following:

   a. Introduction, Experimental results, 2D and 3D Truss drawing (SketchUp), Photograph of truss, Sample calculations, and the Conclusion/Final design recommendations

Group Assignments: Groups 1-7 will design Truss # 1 and Groups 8-14 will design Truss # 2.

3D Printing: Upon completion of the design, the dimensions will be submitted to the TA for 3D printing. One print of each truss will be completed and tested under the 95 N load on the truss test day.
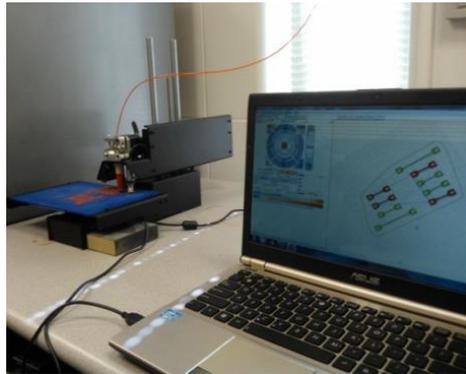
Figure 10: Photograph of 3D printing with printrbot©

Downloads: Here is a link to Google SketchUp tutorials: http://www.sketchup.com/learn/videos/58. You can download the SketchUp here: http://www.sketchup.com/download SketchUp Make is free to download and SketchUp Pro is free for 30 days.

Truss Testing:

After the students submitted the proposed design, the instructor assembled and tested the optimized truss as shown in the photographs in Figure 11.
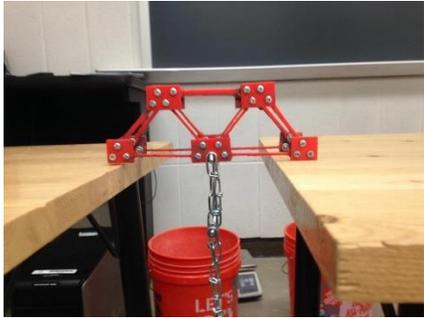
(a)   (b)

Figure 11: Photographs during the truss loading tests: (a) Pratt, (b) Camelback

Sample student poster
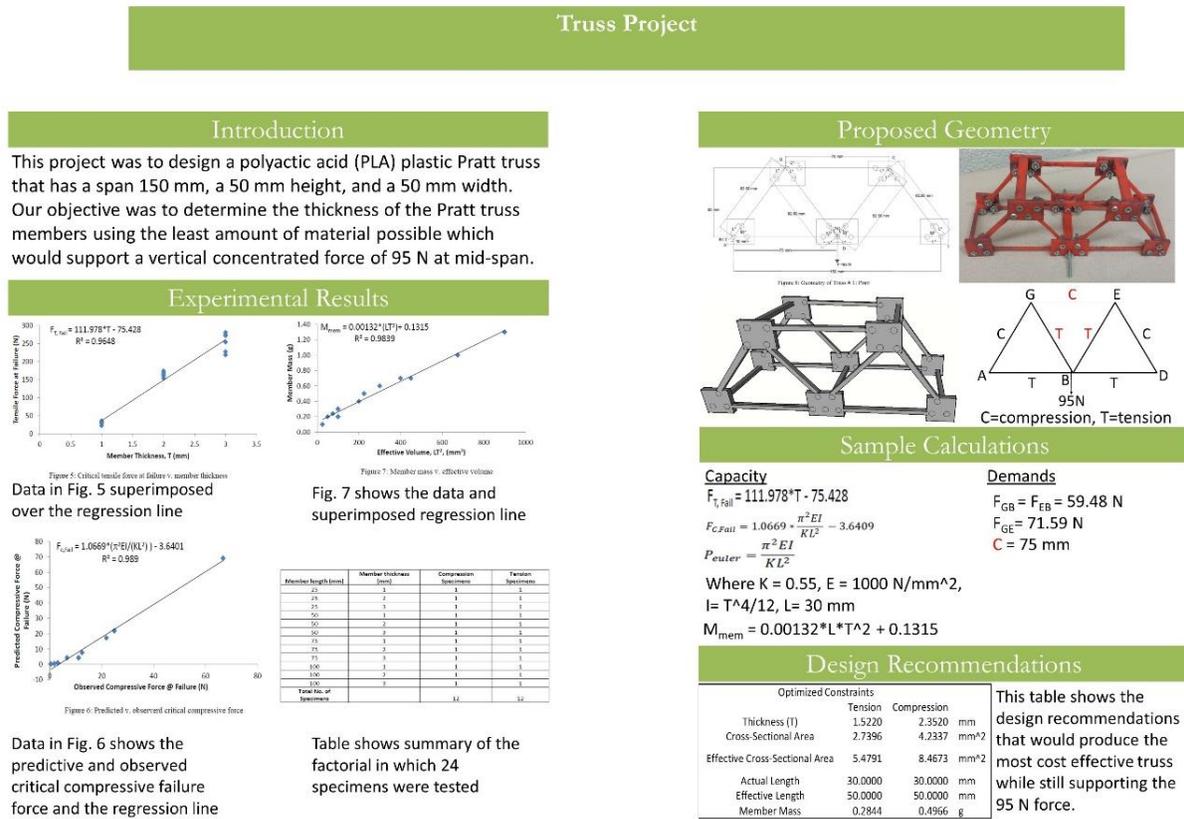
Figure 12: Sample student poster