INCORPORATING A TRUSS DESIGN PROJECT INTO A MECHANICS & STATICS COURSE

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INTRODUCTION

When teaching engineering design concepts in engineering technology programs, instructors are challenged to create realistic, hands on, intuitive design experiences at an early stage in the students' development. This paper describes a balsa wood truss design competition used in a Statics & Mechanics course at NMU to motivate the learning of the concepts of static equilibrium and truss analysis.

Balsa wood bridge projects have been used to promote learning at several educational levels. In this particular student design project, the student must first analyze the forces in each member of a truss, then determine the cross-sectional dimensions of each truss member and finally build and load test the truss. Over the course of more than twenty semesters, the details of this project have been refined to produce a realistic design experience that solidifies the learning of truss analysis by requiring the student to both design and build a model truss.

In this paper, detailed information will be presented on how to successfully incorporate this project experience into a Statics class in a time efficient manner.

TRUSS DESIGN PROJECT DESCRIPTION

The objective of this truss design competition is for a team of two students to design and build a balsa wood truss bridge which will span 36 inches and hold a 24 pound load at midspan. The span length, amount of the load, and location of the load vary each semester. The only material used is balsa wood and glue. The lightest bridge to hold the 24 pound load is the winner. The complete project rules can be found in Appendix A.

Each student is required to first determine the member forces in their chosen truss configuration using the Method of Joints and/or the Method of Sections. The students then determine the cross-section size required for each truss member, using a table of balsa wood member capacities provided by the instructor (see Appendix B for an abbreviated version of this table). By determining the volume of wood required for each truss, the students can compare the weight of each truss design. The two partners then decide which of the two partners' truss to build, by considering the truss weight, factor of safety, and ease of construction.

Prior to building the bridge, each student submits a design report which includes a scale showing all truss dimensions, the member force analysis calculations, and the member size design. The member size design can be summarized in a single table as shown for a simple three member truss) in Table 1.

Member Number	Force (lb)	Length (in.)	Size (in.x in.)	Capacity (lb.)	Factor of Safety	Volume (cu.in.)
AB, BC	8.3 C	10	1/4 x 1/4	19.3	2.3	0.625
AC	10.0 T	20	1/16 x 1/8	26.6	2.7	0.156

Table 1: Truss Design Summary

PROJECT SCHEDULE

As shown in Table 2, the truss project is introduced into the Statics course in the seventh week of a fourteen week semester, just after the topic of Concurrent Force Equilibrium has been covered. The topic of Truss Analysis is not covered until the ninth week, but the project is introduced in advance so that students can start brainstorming potential truss configurations. Preliminary design sketches (showing all dimensions, but no members forces or sizes) are then due in the ninth week. Once the topic of Truss Analysis has been introduced in the ninth week, students can begin to analyze the forces in their preliminary designs. A design report showing the truss analysis calculations and member size selections is due in week 11, and then students are paired with a partner and asked to compare the merits of their two designs. The students then decide which truss design to build and each student is then required to build one of the two truss panels used in the bridge. The individual truss panels are due in the thirteenth week, which gives each team one week to connect the two panels together.

Week	Topic
1,2	Introduction, Math Review ,Forces and Vectors, Components of Force
2-6	Resultants of Concurrent Forces, Moments & Varignon's Theorem Resultants of Parallel Force Systems and Non Concurrent Forces
7	Equilibrium: Free-Body Diagram, Equilibrium of Concurrent Forces **Truss Design Project Assigned**
8	Equilibrium of Parallel and Nonconcurrent Force Systems
9	Analysis of Trusses - Method of Joints **Preliminary Truss Sketches Due Wednesday**
10,11	Analysis of Trusses - Method of Sections, Analysis of Frames
11	**Truss Design Report Due Wednesday**
12	Center of Gravity, Centroids
13	Moment of Inertia of Simple Shapes and Composite Areas **Fabricated Truss Panels Due Wednesday**
14	Radius of Gyration, Polar Moment of Inertia, Final Exam Review **Truss Testing Wednesday**

Table 2: Design Project Schedule 1

GRADING AND PROGRESS MONITORING

A schedule of project submittals and a grading system have been successfully used to monitor the students' progress and to encourage a relatively equal sharing of the work load for each of the two team members. The project grade accounts for 20% of the class grade. One half of the project grade is based on the design report and is graded individually, and the other half is based on the performance of the bridge and this grade is assigned to the team. The two weeks allotted for preparing the design report has consistently proven to be an adequate amount of time, and a heavy penalty of 10% per day late is levied to keep the project on schedule.

The second two weeks provided for building the truss provides enough time for students to meet to decide upon a final design and build the truss panels. Each student is responsible for submitting one of the two truss panels used in the bridge, and this individual accountability has successfully kept all but a few projects on schedule.

One week is left for connecting the two truss panels together and then the bridges are tested. The bridge performance grade is then assigned based on the load-to-weight ratio of each bridge with a 10 percent penalty for bridges that do not hold the entire 24-pound design load. The load-to-weight ratios of all the bridges in the class are ranked from highest to lowest, and one percent is deducted from the performance grade for each place a given bridge is lower in the standings. Thus, for a class with a total of 16 teams, the lowest possible performance grade is 85 percent if the bridge holds the full load, and 75 percent, if it does not. The objective of the perfomance grading system is to encourage students to optimize the design by making the truss as light as possible, while including a reasonable factor of safety to account for the variability of construction quality and balsa wood strength. If a very well designed and built bridge fails under a high load, its load-to- weight ratio will rank well, and the grade will be in the upper end of the 80 percent range.

CONSTRUCTION TECHNIQUES & MATERIALS

It is important to emphasize the importance of building a straight and square truss. If a truss is bowed, skewed, or twisted, it will hold only a fraction of its full design strength. One way to enable good truss construction is to draw a full scale sketch of the truss on a sheet of paper, then build each truss panel on top of the sketch. The top and bottom chord members are placed on the paper first, with tape or a drop of glue to hold them in place, and the web members are then cut to length with a knife or scissors by first holding them in position over the chords to mark the location and angle of the cut. This provides a nicely mitered joint, which can then be reinforced with 1/16-inch thick plates cut from balsa wood sheet stock.

The top and bottom chord members are best constructed by starting with one continuous length of balsa wood, and then laminating pieces to it in the middle region where the higher loads require a thicker cross-section. It is very difficult to construct straight chords by piecing them together in shorter lengths from joint-to-joint.

To keep the bottom chords parallel when connecting the two truss panels together, one can tape the chords to a sheet of paper with two parallel lines drawn on it. To keep the truss square and plumb, the trusses can be held in a vertical position with a carpenter's square or other rectangular object while the cross members are glued into place. In addition, all cross members should be cut to the same length.

Balsa wood is available in 36 inch lengths from most local hobby supply stores, but for the quantities used for a class of over thirty students, it is best to either order the balsa wood online or to place an advance order with a local hobby supply store. To simplify ordering and stocking, one can limit the purchase to 1/16-inch, 1/8-inch, and 3/16-inch square stock and 1/16-inch by 2-inch sheet stock. The gussets for the connections are made from the 1/16-inch by 2-inch sheets.

Most members sizes can be built (laminated) from combinations of the three square sizes indicated above (e.g. a 1/4-inch square member can be built from four 1/8 inch square members). Since the strength and stiffness of balsa wood are highly variable, laminating members dramatically improves their strength reliability.

Students are also encouraged to perform a simple flexure test on their balsa wood to cull out the weaker pieces. To test the balsa stock, all pieces of a given size are cantilevered the same distance off the edge of a table, then a coin is hung from the end of each member and the deflection is measured. The weaker pieces of balsa wood will deflect much more, so precise measurements are not necessary.

Cyanoacrylate (CA), commonly known as Super Glue, is used for connections. Using CA saves construction time because it cures so quickly. Joints can be glued by simply holding the members in place for a few seconds. Larger bottles of CA are available from hobby stores, and are much easier to use than the small squeeze tubes more commonly available in stores.

LOAD TESTING

The bridges are load tested in a public area to generate student interest. Each bridge is weighed by an official, and then impounded for protection. The loading apparatus is relatively simple; please refer to Figure 1 for a photo of the testing apparatus. Two tables are placed 36 inches apart and leveled. A one-inch square steel tube is placed on top of the bridge to distribute the load between the two truss panels, and a bent steel rod with a circular plate welded to the bottom is used to hold a series of two-pound weights. A two foot square piece of plywood is placed below the load to dampen the impact generated by the weights should the bridge fail. An alternative to using the bent rod and weights is to suspend a bucket from the bar with rope or cable and have the students fill the bucket with sand or steel shot. Each team places its bridge across the two tables, and then places the loading apparatus on the bridge. At this point shims can be placed under one of the four supports if the bridge is not resting evenly. The students then have five minutes to load the bridge.

Figure 1: Load Testing Apparatus

SUMMARY AND FUTURE IMPROVEMENTS

This project can be a valuable learning and motivational tool in a Statics course. Student comments in course evaluations consistently rate this project as their favorite part of the course. Students feel this project gives them a much deeper understanding of force analysis and Statics as a whole.

One aspect to this project that needs improvement is that a successful project is highly dependent upon the students' construction skills. Quite often a team comprised of two students with strong academic abilities will produce an excellent bridge design, but the bridge will not hold the full design load because it is constructed poorly. Conversely, a pair of students with poor academic abilities, and good construction skills will produce a poor design report, but will partially compensate using very good construction technique. The best teams are those that combine a good design with good construction. Such a team recently won this completion with a bridge that spanned 36 inches and held a 24 pound load while weighing a mere 0.062 pounds.

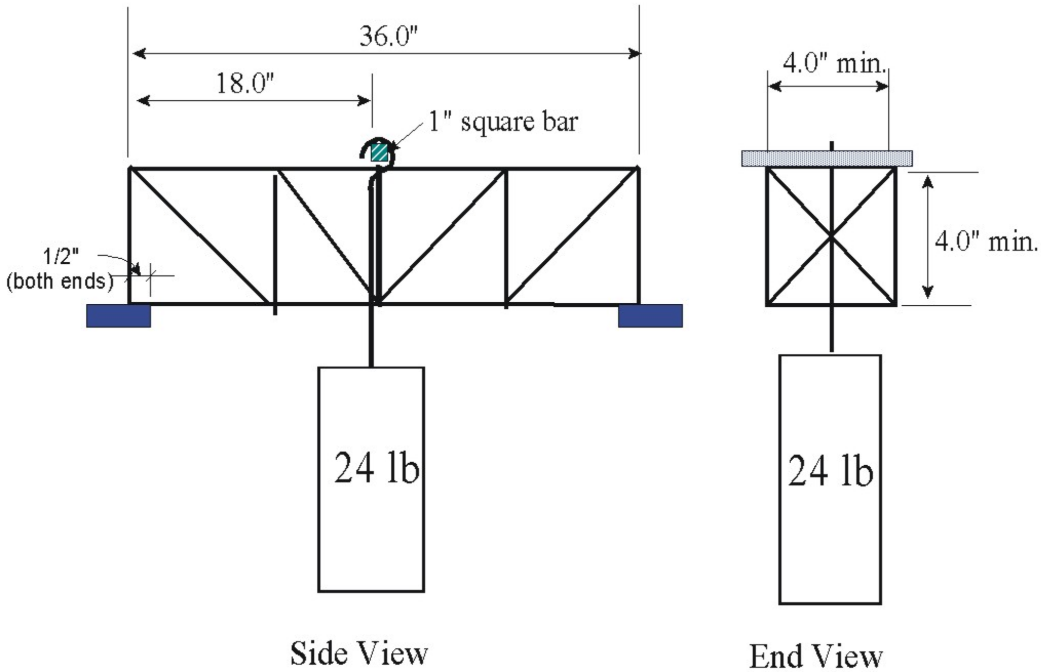
Future improvements to this project will include efforts to build teams based upon a combination of academic ability and construction skills. Quiz and test scores garnered in the first seven weeks will be used to identify the students with the strongest academic abilities. A simple survey will be generated to identify construction abilities.

BIOGRAPHICAL INFORMATION

Robert Marlor is an Associate Professor in the Engineering Technology Department at Northern Michigan University. He received a Ph.D. in Civil Engineering (Structural Engineering) from Michigan Technological University in 2003. His current research interest is load testing panels for panel-constructed log structures.

APPENDIX A - TRUSS DESIGN COMPETION RULES

The rules used for the truss design competition in the author's Statics course for the winter semester of 2007 are included on the following three pages:



The object of this competition is to design and build a structure which is capable of supporting a load of 24 lb. in the center of a 35-inch clear span, with 1/2-inch overlap at each support.

The material shall be balsa wood. The structure must be three dimensional and capable of fitting in the testing fixture provided. Maximum points for the testing portion of the grade will be awarded for the lightest structure which will support the full load. Bridges will also be graded on the bridge's structural efficiency (Max. load supported/weight of bridge).

Students will work in teams of two. It is expected that the work will be shared equally between team members. The Design Report will be graded individually for each student, but team members will receive the same grade for the testing portion of the project.

Construction Details:

- No materials other than the balsa wood may be used except for some sort of adhesive (CA or "super glue" is recommended). No part of the bridge may extend more than 0.50 inches below support elevation. The bridge must be at least 4 inches high and 4 inches wide over its entire length.

- A point of attachment for the bucket must be provided at the top of the bridge 12 inches from one end (see "side view"). A 1" square steel bar dowel will be placed on the bridge and weights will be hung from the center of this bar (see sketch). You must build the structure to accommodate the loading apparatus. It is suggested that this area be 'beefed' up to accommodate the point load. It is also suggested that the points of contact with the supports be 'beefed' up.

- Since the strength of balsa wood can vary from piece to piece, you should make members by laminating smaller pieces together. For example a 1/4"x1/4" member can be made by combining four 1/8"x1/8" pieces.

Testing Procedure:

- The bridge will be placed across a 35" gap between two tables, allowing a ½" of overlap at each end.

- A hook will be attached to the 1" square bar at the midspan of the bridge and the load will be applied by the student adding 2 lb weights to the hook until failure occurs or the maximum load is supported for a minimum of **5 seconds**. Maximum time for loading will be 5 minutes. Failure is defined as the inability of the bridge to carry additional load without sagging more than 2.0" below the supports.

The Grade:

This project will count as 20% of your final grade and will be weighted as follows:

- 50% **Design Report** (graded individually). The grade will be base on completeness and accuracy. All truss analysis calculation calculations must be shown in a neat and orderly fashion. A design summary table must also be shown completely. Points will be taken off for things such as calculation errors, missing information, difficult to read work, missing dimensions or member labels on the drawing, etc.

- 50% **Testing of the Model**. The lightest bridge to hold the full load will receive a full 50 points. The bridges will then be ranked by strength-to-weight ratio, and a half point will be deducted from 50 for every bridge that has a higher ratio than yours. Any bridges that do not hold the full load will lose an additional 5 points.

Submittals:

The following submittals shall be turned in on the dates indicated for instructor review.
Late submittals will have **10%** deducted from the grade for every day they are late!

- Preliminary Sketches- due in class Wednesday, March 21:
Two truss drawings must be prepared by each student, showing the basic layout of two different trusses you are considering for your design. No calculations are needed. Use standard drafting practices (straight edge, drawn to a given scale).

- Design Report - due in class Wednesday, April 4:
A separate design report will be prepared by **each** student. The preliminary design cannot be the same as your partners. The idea is to compare the merits of two different designs. The design report must include the following information for your proposed truss panel design :

> Page 1.) A **scale drawing** showing the dimensions and individual member forces in the main truss panel. Use a **max**imum sheet size of 11"x17". Use standard drafting practices (straight edge, drawn to a given scale).
> Page 2.) A **"design summary" table** showing the force (lb.), length, size (no of strands) (in), capacity (lb.), Factor of Safety, and total volume of balsa wood required for each member.
> Pages 3+.) Complete, detailed truss analysis **calculations** ("method of sections" and/or "method of joints") used to determine the member forces.

This report can be done neatly in pencil on grid paper. **Make a copy of this report** for your own use because it will not be returned to you immediately.

- Fabricated Truss Panel - Due in class Wednesday, April 18:
Following the preliminary design, partners will meet to discuss the merits of each of the designs they submitted. Select the design you think will work the best. Factors to consider in making your selection include total weight of the bridge, ease of fabrication, and degree of confidence in the overall design. One a design is selected, each partner will be responsible for building one of the two truss panels. The instructor will briefly inspect each panel in class on the due date and immediately return the panel to the student.

- Bridge Testing – 11:00 , Wednesday, April 25
After the two truss panels have been built and shown to the instructor, partners can finish the bridge construction by connecting the two panels together with lateral bracing members and all bridges will be tested in the Jacobetti Center Commons on the same day.

APPENDIX B – BALSA WOOD MEMBER LOAD CAPACITIES (lb)

Member Size:	1/16"x 1/16"	1/16"x 1/8"	1/8"x 1/8"	1/8"x 1/4"	3/16"x 3/16"	1/4"x 1/4"	5/16"X 5/16"
Tension	13.3	26.6	53.1	106.3	119.5	212.5	332.0
Compression							
1	7.5	15.1	53.1	106.3	119.5	212.5	332.0
1.5	3.3	6.7	53.1	106.3	119.5	212.5	332.0
2	1.9	3.8	30.1	60.2	119.5	212.5	332.0
2.5	1.2	2.4	19.3	38.6	97.6	212.5	332.0
3	0.8	1.7	13.4	26.8	67.8	212.5	332.0
3.5	0.6	1.2	9.8	19.7	49.8	157.4	332.0
4	0.5	0.9	7.5	15.1	38.1	120.5	294.1
4.5	0.4	0.7	5.9	11.9	30.1	95.2	232.4
5	0.3	0.6	4.8	9.6	24.4	77.1	188.2
5.5	0.2	0.5	4.0	8.0	20.2	63.7	155.6
6	0.2	0.4	3.3	6.7	16.9	53.5	130.7
7	0.2	0.3	2.5	4.9	12.4	39.3	96.0
8	0.1	0.2	1.9	3.8	9.5	30.1	73.5
9	0.1	0.2	1.5	3.0	7.5	23.8	58.1
10	0.1	0.2	1.2	2.4	6.1	19.3	47.1
11	0.1	0.1	1.0	2.0	5.0	15.9	38.9
12	0.1	0.1	0.8	1.7	4.2	13.4	32.7
13	0.0	0.1	0.7	1.4	3.6	11.4	27.8
14	0.0	0.1	0.6	1.2	3.1	9.8	24.0
15	0.0	0.1	0.5	1.1	2.7	8.6	20.9
16	0.0	0.1	0.5	0.9	2.4	7.5	18.4
17	0.0	0.1	0.4	0.8	2.1	6.7	16.3
18	0.0	0.0	0.4	0.7	1.9	5.9	14.5
19	0.0	0.0	0.3	0.7	1.7	5.3	13.0
20	0.0	0.0	0.3	0.6	1.5	4.8	11.8
22	0.0	0.0	0.2	0.5	1.3	4.0	9.7
24	0.0	0.0	0.2	0.4	1.1	3.3	8.2