120th ASEE Annual Conference & Exposition
FRANKLY, WE DO GIVE A D*MN
June 23-26, 2013

Paper ID #7867

2D Paper Trusses for K12 STEM Education

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Introduction

Truss projects have long been used as a hands-on demonstration in K12 school systems. There are truss projects that use spaghetti and marshmallows[1], computer simulations[2], manila folders[3], and the ubiquitous Popsicle stick[4]. Many times these design projects are not tied to fundamental principles, and are used primarily to "excite" the participant. Computer simulations such as the West Point Bridge Design Competition can include deeper excursions into the fundamentals, but in the end there is no physical model. Other truss projects cover many of the fundamental concepts that are needed, but use a 3-dimensional truss that is hard to construct within the constraints of a high school class or has difficulty in matching the results of analytical and experimental testing.

The project described in this paper is similar in many ways to other truss projects, such as the comprehensive "File Folder Bridges" approach taken by Ressler[3] and the "Physics Balsa Bridge Building Contest" by Vogel[5]. While these approaches and others are outstanding, we could not find an existing approach with all of the following features:

- A design analysis utilizing the "method of joints"
- Pinned (not glued) truss joints
- Tensile members that limit truss strength (no buckling)
- Physical testing of truss members prior to design
- Minimal out of plane deformations (no warping)
- Predictable truss strength based on design analysis
- Ease of fabrication and inexpensive materials

This truss design project was developed as part of a NASA sponsored, project-based, high school curriculum aimed at integrating engineering, mathematics and physics. The Integrated STEM Education Research Center (ISERC) at Louisiana Tech University partnered with high schools in our region to develop a project-based physics curriculum, NASA Threads. The National Integrated Cyber education Research Center (NICERC) currently manages delivery of the curricular content to the partner schools. The entire curriculum is presented online to registered users at www.NICERC.org/physics. Summer workshops are used to train new and experienced teachers in the various projects associated with the curriculum.

This physics curriculum provides school systems with a rigorous program that showcases a systems-level understanding of mathematics, science, and engineering that STEM-professionals use every day. The course uses a microcontroller platform, along with various other hands-on activities, that drive physics fundamentals in the five curricular threads – Electricity & Magnetism, Work & Mechanics, Waves & Sound, Light & Optics, and Thermal Fluids. By using a project-driven approach, students become engaged early and maintain a high degree of interest and curiosity throughout the course.

As part of the Work & Mechanics module within this hands-on curriculum, 2-dimensional paper trusses are used to introduce the concept of forces and vectors to students. As an application of these fundamentals, the truss project tasks students with analyzing and building a 2-dimensional truss using mat board (used in picture framing) and common manila folders. One of the unique features of the trusses used in this project is the use of pinned joints. Typically, truss projects use glue or other methods of assembling the joints. Part of the error between calculated results and actual performance of the trusses is a result of this mounting. Methods for analyzing trusses are based upon true pinned joints. Our approach of using screw-type pinned joints allow for the student design to match the analytical solutions. An additional advantage of this type of construction is that the trusses can be easily built in the classroom without the need for expensive equipment or a significant amount of time. Additionally, the method of joints can be applied to analyze and predict the forces associated with each member. A testing apparatus is used to validate the ultimate force that the truss can withstand.

This paper presents the project materials, the testing apparatus, and examples of the curricular material for the truss project. This paper also provides examples of the hands-on 2-dimensional truss project for teaching STEM fundamentals, as well as assessment data regarding the experiences of high school teachers.

The truss project

The truss project is divided into eleven lessons plus six related lessons leading up to the project. These lessons can be presented over a number of days that is dependent on the style and length of the class periods. The topics covered before and during the project include:

- Class 13 - Newton's Laws of Motion
- Class 14 - Force Components
- Class 15 - Resultants
- Class 16 - Static Equilibrium
- Class 17 - Simple Machines
- Class 18 - Simple Machines
- Class 46 - Introduction to Trusses
- Class 47 - Method of Joints
- Class 48 - Stress
- Class 49 - Tensile Testing
- Class 50 - Tensile Testing
- Class 52 - Truss Design Challenge
- Class 53 - Truss Design
- Class 54 - Truss Fabrication
- Class 55 - Truss Fabrication
- Class 56 - Truss Testing
- Class 57 - Truss Presentations

The finale of the project is for the students to design, analyze, build, and test a truss of their own creation. The truss is loaded in the center and supported on each end with a “roller”. The students are given a diagram similar to Figure 1 shown below to help them visualize the loading. The assignment for the teams is to:

- Design a truss on paper to meet the specified requirements (shown below).
- Draw a diagram of the truss and compute dimensions of members and angle measures.
- Use the method of joints to calculate the forces in each member and show if they are in tension (T) or Compression (C).
- Use this computation to predict the external force that will cause the truss to fail.
- Build the truss based on the dimensions and the rules for the design.
- Test the truss.
- Turn in the design with a written post-test analysis of the test results.

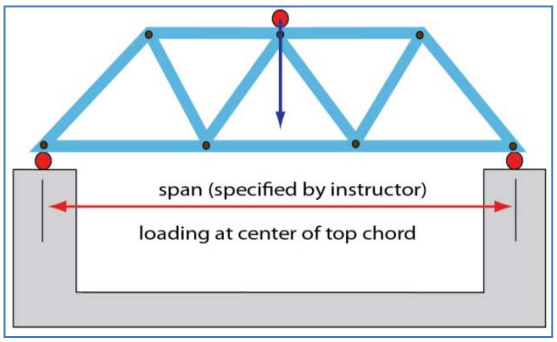


Figure 1. Sample loading configuration for the truss.

A key feature of the design competition is that the truss is analyzed and failure is predicted before the truss is tested. In order to simplify the failure modes, the truss is limited from buckling by "sandwiching" a single truss between two rigid acrylic sheets. Another benefit of using a single truss is the assurance that the external force is applied evenly to the truss versus being unevenly shared between two parallel trusses. Figure 5 and Figure 7 show examples of the two parallel sheets of acrylic. Students are taught that buckling is a primary mode of failure in trusses, and should not be neglected in practice. However, buckling calculations are beyond the scope of this project.

In order to make predictions on the performance of the truss, the axial strength of the tensile members must be determined. Classes 49 and 50 of the curriculum discuss the fabrication and testing of the appropriate tensile test specimen. The students create test specimen from the same material that they will later use to create their actual tensile members. The pattern for the test specimen is shown in Figure 2. An actual test specimen with end stiffeners to eliminate tearout at the connection is shown in Figure 3.

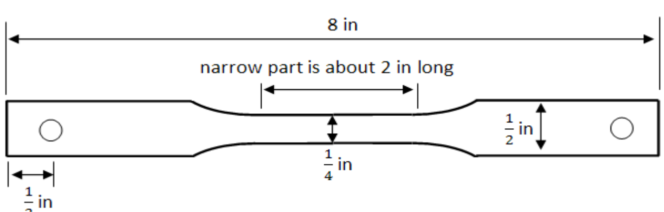


Figure 2. Tensile test specimen pattern.

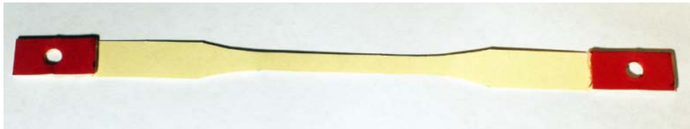


Figure 3. Actual test specimen with end stiffeners.

Another key feature of the truss is the use of screw posts as joints. Screw posts similar to those shown in Figure 4 allow for the joints to better simulate pinned joints, as opposed to gluing or stapling. Using actual pinned joints eliminates (or at least reduces) any moment carried at the joint. These moments are not accounted for in the method of joints and would cause any predictive calculations to have errors.

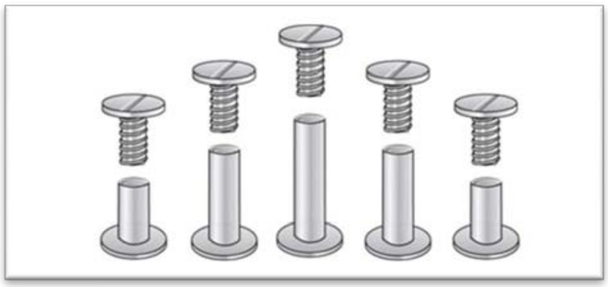


Figure 4. Screw posts.

Additional rules for the truss design competition include:

- The truss must be analyzed using the method of joints.
- The truss is to be loaded at a joint in the center *(bottom center joint if a turnbuckle style tester is used)*.
- Two joints separated by the required span must be present and able to be supported from below.
- The truss failure will (should) occur in a tensile member.
- The truss must be built using the materials provided to teams by the instructor.
- The maximum combined length of all truss members is five times the span…where member lengths are measured between the centers of joints.
- Tensile members must be made of manila folder material, and compressive members must be made of mat board.
- The tensile truss members must have a max width of 0.25 inch in the center and a max width of 0.50 inches elsewhere. The “narrowed region” of the tensile members must be at least 1 inch long.
- Up to two tensile truss members may be doubled to improve the strength of the most critical members based on truss calculations. These two parallel members cannot be glued together along their lengths.
- Extra segments of mat board may be glued to each side of the compressive members to keep them from “bowing” or “buckling.” These extra mat board segments must be at least two inches shorter than the length of the member.
- The truss can’t be painted, dipped in glue, or treated in other ways to improve the strength of the paper.
- The truss must fit in the testing device and move freely between the clear acrylic side plates.

Testing apparatus

Two different styles of testing apparatus have been designed as part of this project. The first style is larger and uses a hanging weight to apply the external load to the truss. This tester uses an external scale to weigh the hanging weight, or the weight is added in bags that each weigh one pound. A diagram of this system is shown in Figure 5 below. A paper truss loaded in this test fixture can be seen in Figure 6. The other style tester is a turnbuckle style fixture. The turnbuckle is tightened in order to add force through a lever to the truss. In addition, a scale measures the force as it is being applied. The turnbuckle tester has the advantage of laying flat on a table top and not requiring as much space to store when not in use. A turnbuckle tester can be seen in Figure 7. Both of these truss testers have been designed and fabricated by the NASA Threads team and are provided to the original partner schools through the NASA grant funding. For future schools, the testing fixtures are available for purchase.

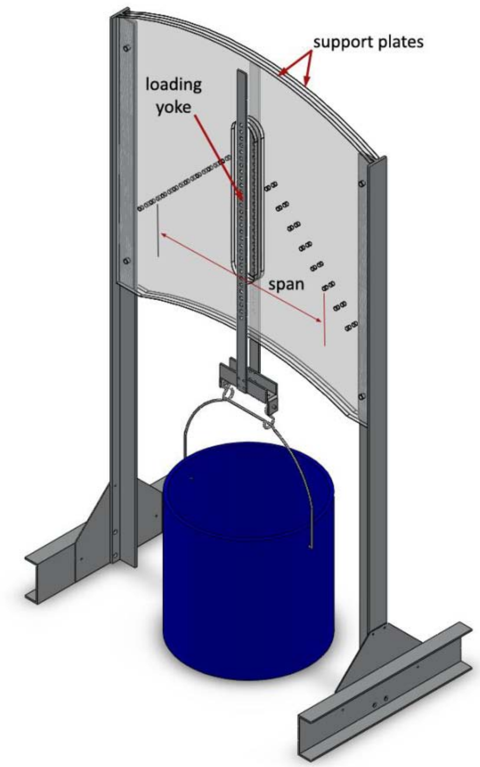


Figure 5. Hanging weight truss tester.

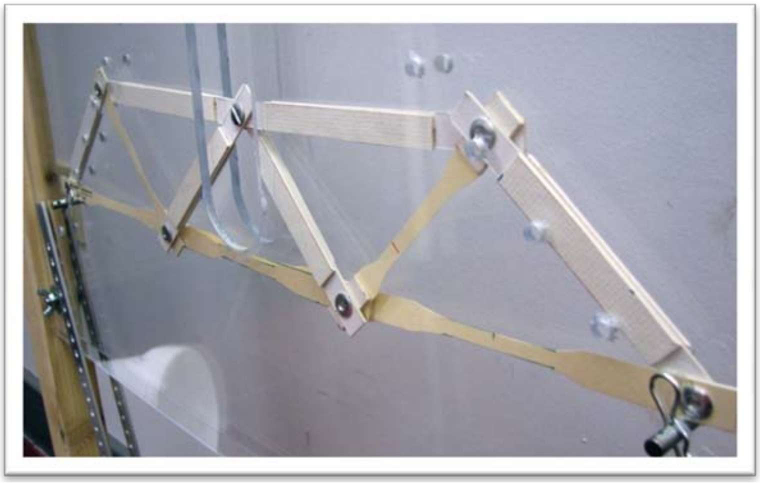


Figure 6. Paper truss loaded in a hanging weight truss tester.

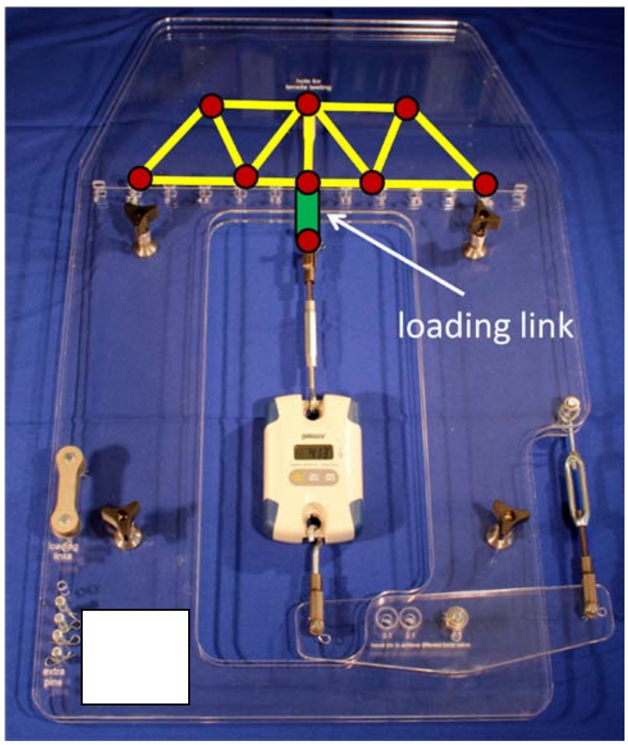


Figure 7. Turnbuckle style tester with the location of the paper truss shown.

Example course material

In total, there are seventeen lessons related to the truss project. Each of these lessons contains lesson plans, master notes, and homework assignments. Additionally, MS PowerPoint, MS Excel, and other additional files have been added as the curriculum continues to evolve. The three following figures are selected examples of the lesson plans, master notes, and homework assignments. Figure 8, Figure 9, and Figure 10 show examples of portions of the Lesson Plans, Master Notes, and Homework assignments respectively. The entire physics curriculum, along with curricula covering other subjects, is hosted at www.NICERC.org and is accessible to registered users.

NASA-Threads | Work & Mechanics | 47: Method of Joints

Learning Outcomes	• TLW apply the method of joints to determine the unknown forces in truss members

Materials List		

Lesson Summary	• Show a picture of a bridge truss along with its FBD
	• Provide the steps for applying the method of joints; this should be somewhat of a review based on the previous class and homework
	• For the bridge truss, apply the method of joints to determine the member forces (ask students to do this on their own, circulating through the class and working portions of the problem when needed)
	• Show that symmetry simplifies the problem
	• After determining all member forces, check to make sure that equilibrium exists at a node not analyzed initially
	• Teaching Tips:
	  ○ Emphasize the importance of drawing FBDs for each joint (don't draw them too small, show angles, show axes, . . .)
	  ○ Make sure students write $\sum F_x = \ . \ . \ . \ . = 0$. Students are often forget to write "$\sum F_x =$", and they will often fail to put "=0" on the right side.

Homework	Solve truss problems using the method of joints

Resources	Text Reference:

Relevant Standards	
GLEs	
Guiding Questions	

Figure 8. Example Lesson Plan.

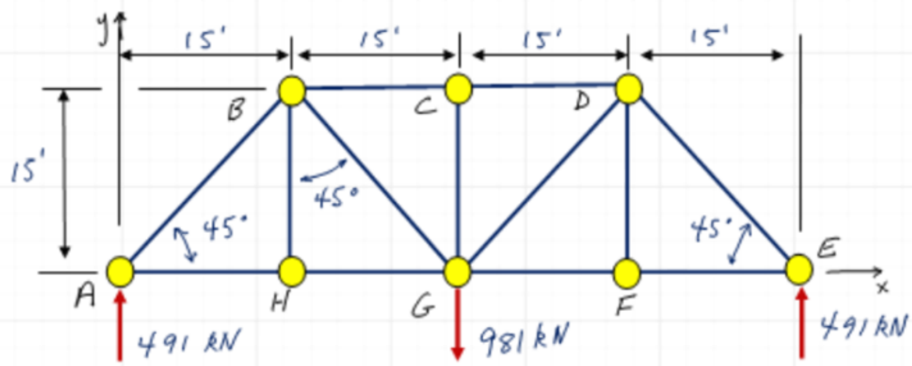
NASA-Threads | Work and Mechanics | Lesson 47: Method of Joints

Lesson 47: Method of Joints

<u>Truss Analysis – Method of Joints</u>

Assume that a 200,000 kg locomotive sits at the center of the bridge below. Since there are two parallel trusses (one on each side of the locomotive), let's assume that the center joint of one of the two trusses carries 100,000 kg (981,000N). Find the forces in each truss member assuming the dimensions provided in the sketch.

Old railroad bridge (Leonard G./Wikipedia)

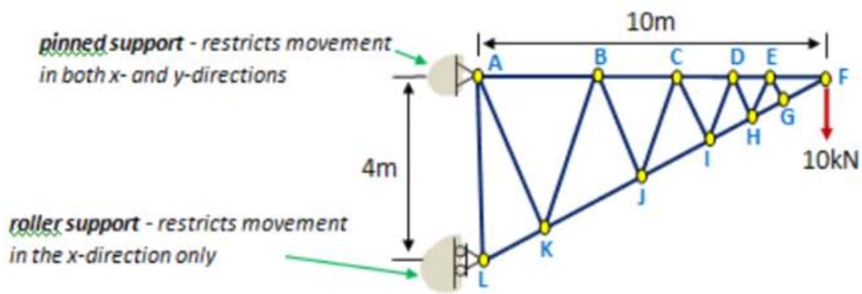


The *method of joints* involves drawing a free body diagram at individual joints and solving for the unknowns until all forces are known. It is usually easiest to start at a joint where there are not too many unknowns. We will start at joint A where there are only two unknowns.

Figure 9. Page 1 from Master Notes for lesson 47.

Truss Tips: Apply the method of joints to solve the truss problems below. For each joint analyzed, draw a FBD of the joint which includes all forces acting on the joint (properly labeled, such as T_{AB}), the angles between members, and the directions of the x- and y-axes. Carefully apply $\Sigma F_x = 0$ and $\Sigma F_y = 0$ to the joint to find the unknowns. Try to find a joint where you can solve for an unknown in one step. If you want to find the force in a member that intersects several other members, you may need to work your way in to that member (or joint) by finding the forces in other members first. The important thing is to "think" a little before you start trying to solve for the unknowns; having a good strategy will reduce the total effort and help to minimize mistakes.

1. Find the force in member FG for the truss below.



2. Find the force in member FG for the truss below. All horizontal members have a length of 10 ft.

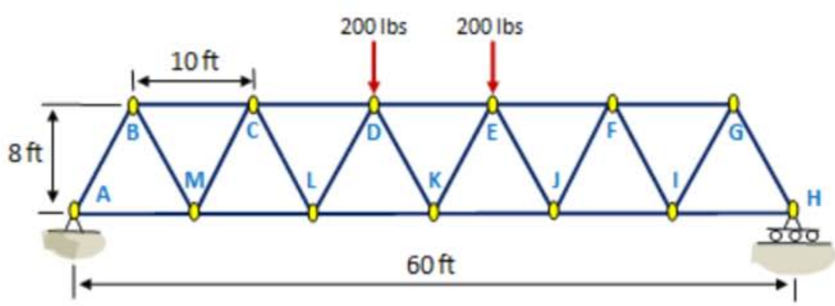


Figure 10. Example of Homework.

Results from teacher self-assessment

In order to be qualified to deliver this curriculum, teachers must complete a summer workshop during which they are trained by the curriculum development team. This is a week-long workshop during which the various modules of the physics curriculum are presented and explained to the teachers. In order to gage the effectiveness of the material, the teachers are surveyed multiple times. Survey 6 relates to engineering design, the use of design software, and the fabrication and testing of materials for the truss project. The results of this survey are shown in Table 1.

Table 1. Assessment of results from a previous training workshop.

Teacher Self-Assessment	Before Workshop	After Workshop	Change
A. Definition of a truss as a component of structure	1.96	3.17	+1.22
B. Knowledge of truss members as "two force members" acting in either tension or compression	1.74	3.00	+1.26
C. Application of $\Sigma Fx=0$ and $\Sigma Fy=0$ to determine the unknown forces in the members of a simple truss	1.87	3.09	+1.22
D. Application of the method of joints to determine the unknown forces in a truss	1.61	2.96	+1.35
E. Comprehension of the concept of axial stress as force divided by cross-sectional area (stress= Force/Area or $\sigma=F/A$)	1.61	2.78	+1.17
F. Computation of the stress in axially loaded members with circular and rectangular cross sections	1.57	2.70	+1.13
G. Fabrication and testing of paper tensile test specimens	1.43	2.87	+1.43
H. Computation of the failure load of a truss as limited by the strength of truss members	1.52	2.61	+1.09
I. Designing, fabricating, and testing a 2D truss	1.43	3.00	+1.57

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