Truss Bridge

The American Association of State Highway and Transportation Officials (AASHTO) needs your help in designing a model of a truss bridge made completely out of paper. The goal of this project is to investigate the tensile and compressive forces in structural members.

DESIGN REQUIREMENTS

- Horizontal span: 61 cm (24 in)
- Width of bridge deck: 11 cm (4¼ in)
- Structural material: 110 lb cardstock
- Joint attachment: white glue or rubber cement

TESTING EQUIPMENT

- Vernier Interface
- Dual-Range Force Sensor (component testing)
- Force Plate (bridge testing)

DELIVERABLES

- Prototype
- Detailed design drawing showing dimensioned front, side, and top views
- Structural profile showing calculated tensile and compressive forces
- One tensile and one compressive structural member, 5 cm long
- Tensile and compressive test results from sample components
- Impact statement discussing the factor of safety in your bridge design

CONSTRAINTS

- The bridge must rest on two vertical supports, 4 cm x 14 cm on end (1½" x 5½")
- The open spacing between the vertical supports is 61 cm (24 in)
- The cardstock cannot be treated through the application of paint, glue, or other medium

JUDGING CRITERIA

- Maximum applied load
- Component test results
- Feasibility of design
- Aesthetics

TEACHER TIPS

Teachers are encouraged to modify this activity to meet the capabilities of students, equipment available to the teacher, and time constraints of the curriculum. The following provides some guidance on bridge building and testing. To make this a meaningful activity, students will require a significant amount of time to construct their bridges. This can be accomplished in class or assigned as work outside of class.

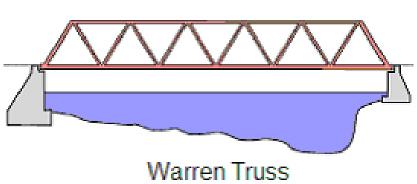
BACKGROUND

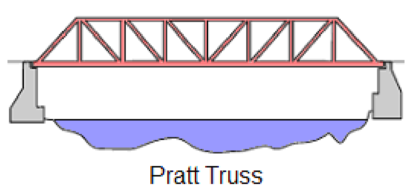
A truss is a rigid framework whose internal members are connected in a triangular pattern. Trusses have a very high strength-to-weight ratio, which allows them to span long distances. Historically, trusses were frequently used in bridge design, but are becoming common elements for roof and floor framing in home construction due to their efficiency and low cost.

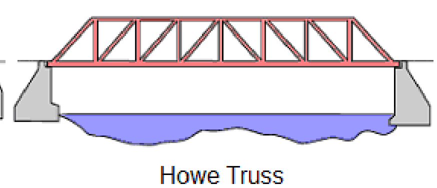
A truss bridge is built from two trusses (one on either side) connected by a horizontal bridge deck. The bridge deck serves as the vehicle navigation surface and can be located at the top or the bottom of the bridge. Additional lateral bracing is applied as necessary to improve stability, but it must not obstruct the travel pathway along the bridge deck. Pins and gusset plates (the connections that join bridge members together) are critically important to the overall structural integrity of the bridge. Bridges are supported by abutments – a foundation that supports the weight of the bridge and holds back the soil behind it. If additional supports are required in the middle, they are called piers. Abutments and piers are usually made of concrete, while bridge members are made of steel.

Bridges must carry three different kinds of forces: loads, reactions, and internal forces. Loads are the external forces that are applied to the bridge, such as the weight of the cars and trucks that cross it. Loads also include the weight of the bridge itself, the weight of snow, wind, and rain in inclement weather, and the forces caused by earthquakes. Reactions are the support forces supplied by the abutments or piers. Internal forces are the tension and compression forces developed along structural members when a load is applied. Members in tension are being pulled or stretched, while members in compression are being pushed or shortened.

One of the most common truss configurations is the Warren truss, known for its simplicity because no vertical members are used. Two other common designs are the Pratt and Howe trusses. In the Pratt truss, all inner diagonal members slant down toward the center, while in the Howe truss they slant toward the outside. The Pratt truss is much more economical to build than the Howe truss. Most of its diagonal members are in tension allowing them to be thinner than the compressive diagonals in the Howe truss.







Truss bridges are statically determinate. Their support forces are equal to the applied load, and the moments about any point are zero. The strength of a bridge is determined by the largest internal force it can withstand before failing, but no internal force can exceed the material strength of the individual member. Tensile and compressive strength depend on the material used in fabrication, as well as the width and thickness of the structural member cross-section. The compressive strength is also dependent upon the length and shape of individual structural members, but length and shape have no influence on tensile strength.

The internal forces in a truss bridge can be determined using the method of joints (see below). During design, a safety factor is applied to reduce the chance of bridge failure. A safety factor is a measure of the load a structure can withstand beyond the load for which it was designed. Most truss bridges are designed for a safety factor greater than 1.6.

TEACHER PROCEDURE

1. Show pictures to the class of different bridge types and discuss the strengths and weaknesses of each. Students should be able to identify the most appropriate structure to span a variety of environmental landmarks.

2. Discuss the different shapes of structural members that are used in building truss bridges and their impact on bridge strength. Students should be aware of the differences between a tensile and a compressive force.

3. Have students build paper beams using 3 x 5 index cards and white glue. Use the Vernier Dual-Range Force Sensor and Testing Device #1 to determine the tensile and compressive forces in their beams.

Tip: *For best results, build and test the beams on different days to allow ample time for the glue to dry.*

4. Instruct the class on using the *Method of Joints* to calculate the tensile and compressive forces for the individual components within a truss.

Optional: *This step involves the use of trigonometric functions. If you feel your students are not ready to tackle math problems of this rigor, there are a number of programs available online that will calculate truss forces automatically.*

5. Have students design and build a truss bridge from cardstock.

Tip: *Integrate the Bridge Design simulation software found at http://bridgecontest.org/resources/download/*

6. Using the *Method of Joints*, have students calculate the maximum internal member forces assuming a 50N load on their bridge design. Have students make predictions as to the structural members most likely to fail first.

7. Use the Vernier Force Plate and Testing Device #2 or the Vernier Structures and Materials Tester to determine the maximum applied load for each bridge.

8. Have students determine the maximum force that should be applied to the bridge assuming a safety factor of 1.6. Have students make an appropriate warning sign for the bridge.

Optional: *You can determine the maximum load without completely crushing the bridge by loading the bridge slowly and stopping the process when you see the beginnings of a crimp or tear in one of the external members.*

TIME ALLOTMENT

5–7 class periods. This activity requires one class period to build the beams, one class period to test the beams, 2–4 class periods to build the truss bridge, and one class period to test the bridge. The time spent in building the truss bridge will be dependent upon the span length you assign to the class.

CONSTRUCTION TIPS

- Hollow tubes are much more efficient in carrying compression loads than solid bars, because tubes resist buckling. However since tension strength is not dependent upon shape, bars are preferred over tubes because they are simpler and cheaper.
- The load-carrying capacity of your bridge is significantly impacted by the neatness of your construction.
- When drawing the fold lines for your beams, press down hard with your pen or pencil to score the cardstock; it will make folding it much easier.
- Assemble the side trusses on pieces of waxed paper to prevent the glued joints from sticking to the table.
- Gusset plates can be added to help strengthen joints.

CALCULATING SAFETY FACTOR

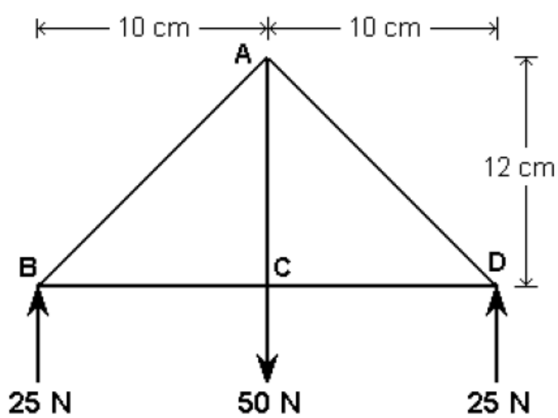
To calculate the safety factor in a structural member, use the formula:

$$SF = FF/DF$$

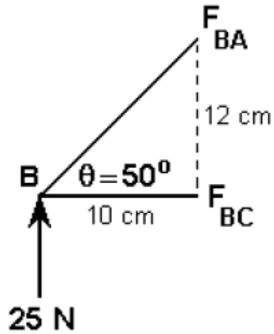
SF (safety factor) = Use a safety factor of 1.6 for this project
FF (actual failing force) = Maximum force the bridge withstood before failing (N)
DF (calculated design force) = The amount of load this bridge should safely support (N)

INTERNAL MEMBER FORCES - THE METHOD OF JOINTS

1. Draw a free-body diagram of the bridge. A *free-body diagram* is a sketch of the bridge showing all forces acting on it. The entire applied load should be drawn as a downward force acting on the center of the bridge (50 N in the example shown below). Calculate the upward reaction forces at the outer supports so that the bridge is in equilibrium.

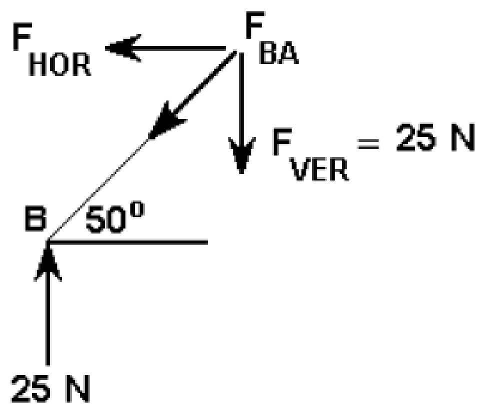


2. Isolate the left-most joint. Use trigonometry to calculate the angle between the diagonal and horizontal members (assume the diagonal member is the hypotenuse of a right triangle).

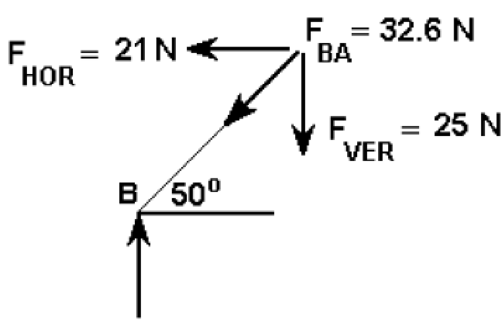


$$\tan\theta = \frac{\text{opposite}}{\text{adjacent}} = \frac{12\text{ cm}}{10\text{ cm}}$$

3. Resolve the diagonal member into its horizontal and vertical components. For the joint to be in equilibrium, the sum of all forces in the vertical direction must equal zero. Since there is only one vertical force of 25 N acting in an upward direction, the vertical component of F_{BA} must also equal 25 N, but it must be acting in a downward direction. Notice that both vertical components are "pushing" on joint B, so the force in member BA must be a compressive force.



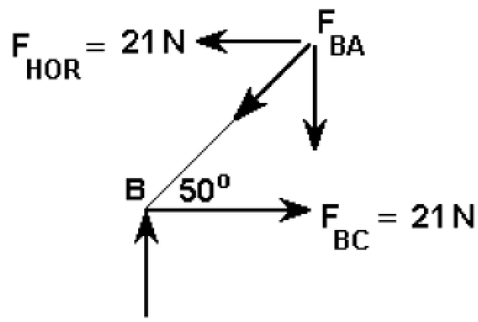
4. Use trig twice more to calculate the horizontal component and the magnitude of the resultant force for F_{BA}.



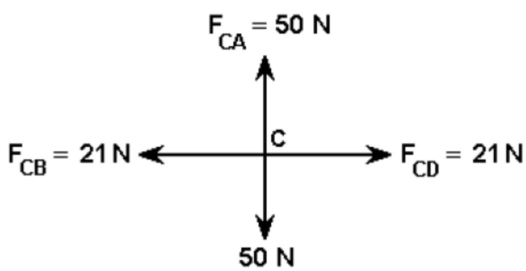
$$\tan 50^{0} = \frac{25\text{ N}}{F_{HOR}}$$

$$\sin 50^{0} = \frac{25\text{ N}}{F_{BA}}$$

5. For the joint to be in equilibrium, the sum of all forces in the horizontal direction must also equal zero. Since there are only two horizontal forces, F_{BC} is equal but opposite to the horizontal component of F_{BA}. Notice that F_{BC} is "pulling" on joint B, so the force in member BC must be a tension force.



6. Repeat steps 2-5 to calculate the forces acting on joint C. When transferring the value of any known forces (in this case the force in member BC), be sure to apply it in the opposite direction.



7. Steps 2–5 are repeated until the entire bridge is complete. Since this example is symmetrical, we can assume that the force in member DA is identical to the force in member BA (32.6 N in compression).

BUILDING THE TESTING DEVICES

Test Device #1: Dual-Range Force Sensor Test Stand

1. Go to http://bridgecontest.org/resources/file-folder-bridges/ and download Appendix C of the Designing File-Folder Bridges activity. Build the test stand described with one critical modification: do not cut the notch in the right end of the loading arm.

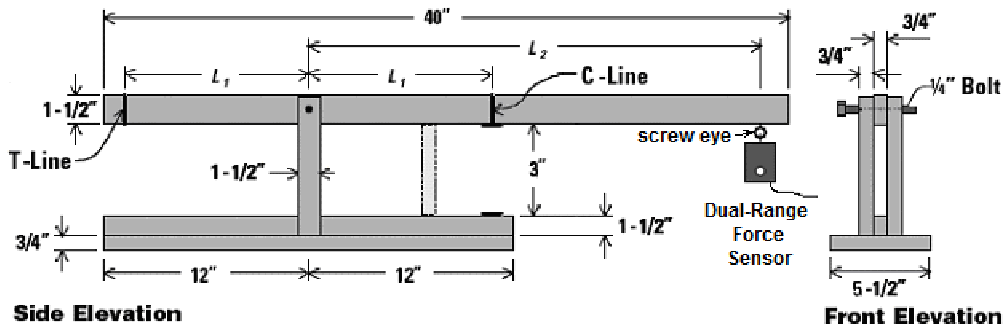


Figure 1 Test Device #1 using Dual Range Force Sensor to measure applied force

Tip: *We bolted the loading arm 3" above the bottom support since we are building test specimens from 3x5 index cards.*

2. Screw a 3/4" screw-eye to the underside of the loading arm.

Tip: *Pre-drill the hole to prevent splitting the wood.*

3. Hang the Vernier Dual-Range Force Sensor from the screw-eye.
4. Insert the utility handle (included with the sensor) through the hole on the Dual-Range Force Sensor so that it protrudes equally on either side and secure it with the thumb screw. For best results, encourage them to use a steady, slow pull.

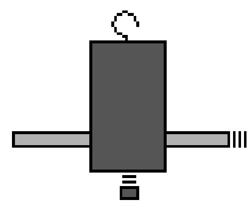


Figure 2 Students pull directly down on the force sensor.

Theory behind Test Device #1

Test Device #1 uses a lever arm to determine the maximum tensile and compressive strengths of individual components. A lever is a long bar resting on a pivot point called a *fulcrum*. When a force is applied to the bar, the perpendicular distance from the force to the axis of rotation is called the lever arm. Torque is the product of the applied force and the lever arm. When the test stand is balanced, the torque due to the applied load is equal to the torque resulting from the tensile or compressive forces and their corresponding lever arms.

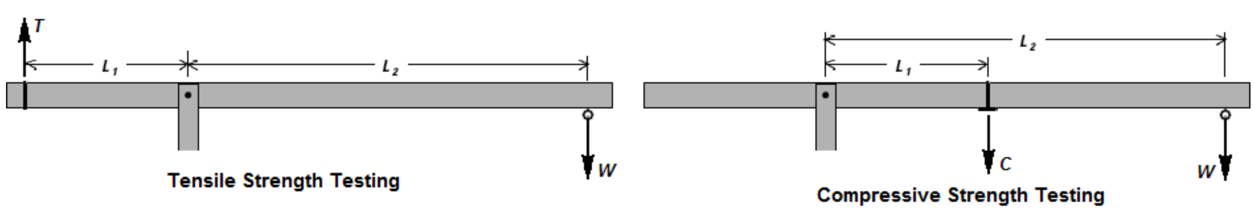


Figure 3 Test Device #1 can be used for compression or tension testing

When the test stand is loaded for tensile strength, a structural component is clamped to the T-Line and a force, W, is applied to the screw-eye using the Dual-Range Force Sensor. The resulting torque relationship is:

$$T * L1 = W * L2$$

where L_1 and L_2 represent the lever arms and *T* represents the tensile force. Rearranging the variables results in the following equation for tensile strength:

$$T = WL2/L1$$

When the test stand is loaded for compressive strength, a structural component is placed under the felt compression pad and a force, W, is applied to the screw-eye with the force sensor. The resulting torque relationship is:

$$C * L1 = W * L2$$

where L_1 and L_2 represent the lever arms and C represents the compression force. Rearranging the variables results in the following equation for compressive strength:

$$C = W * L2/L1$$

Notice that if the dimensions of your test stand are different, you will need to modify your strength equations accordingly.

Test Device #2: Force Plate Test Stand

1. From a 2 x 6 piece of lumber, cut two pieces 5" long and one piece 23½" long.
2. Screw the two 5" pieces to both ends of the 23½" long piece.
3. Center the test stand on top of the Vernier Force Plate.

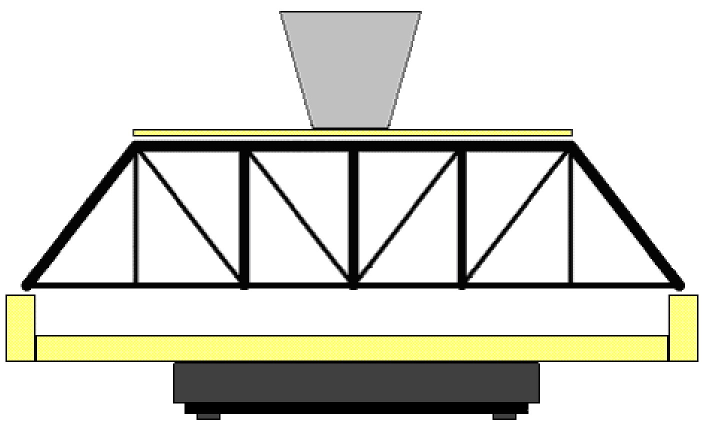


Figure 4 Test fixture resting on Vernier Force Plate

4. Center the bridge on the test stand so that the ends are evenly supported.
5. Cut a piece of foam core board 4 ½" x 16 ¼" long, and place it on top of the bridge. This board will serve as the load support.

Tip: Before loading your bridge, be sure to zero your data-collection software so the weight of the test stand is ignored.

Test Device #3 Vernier Structures and Materials Tester

The Structures and Materials Tester is designed for bridge building activities and competitions, among other engineering projects. You may prefer using this as a test device if available. Refer to the User Manual for details on using this tool for your class bridge building activity.

RESOURCES

- http://pghbridges.com/basics.htm
- http://www.pbs.org/wgbh/nova/tech/build-bridge-p1.html
- http://bridgecontest.org/