Activity: **Wimpy Radar Antenna!**

GRADE LEVELS: 6-8

SUMMARY:

2 preparatory class periods will be devoted to teaching about forces if necessary (see Preparation). Students will reinforce an antenna tower made from foam insulation, so that it will withstand a 480 N-cm bending moment (torque) and a 280 N-cm twisting moment (torque) with minimal deflection. One class will be used to discuss the problem, run the initial bending and torsion tests and graph the results. The second classes will be used for design and construction of a sturdier tower, its testing and graphing of the results.

LEVEL OF DIFFICULTY [1 = Least Difficult : 5 = Most Difficult]

3 - Moderately Challenging

TIME REQUIRED

200 minutes (4-5 class periods)

COST

$6 per class

STANDARDS:

5.3 Explain how the forces of tension, compression, torsion, bending and shear affect the performance of bridges.

2.2 Demonstrate methods of representing solutions to a design problem, e.g., sketches, orthographic projections, multiview drawings.

2.3 Describe and explain the purpose of a given prototype.

2.4 Identify appropriate materials, tools, and machines needed to construct a prototype of a given engineering design.

2.5 Explain how such design features as size, shape, weight, function and cost limitations (i.e., ergonomics) would affect the construction of a given prototype.

WHAT WILL THE STUDENTS LEARN?

Students will learn the concept of a moment (torque) of a force and learn how to calculate moments. Students will also learn how moments (torque) ("turning forces") create bending and torsion loads on structures; they will understand the effects of bending and torsion loads, and will gain some appreciations of how engineers can design a structure to resist bending and torsion.

BACKGROUND INFORMATION:

2 classes- students need a basic understanding of tension, compression, shear, bending, torsion and concept of a moment (torque)- go over "Fairly Fundamental Facts about Forces and Structures" and do "Intro. to Loads on Structures" Activity. Do "Wait a Moment" worksheet.

Moment and torque can be use interchangabley, physicist tend to use the word torque and engineers tend to use moment when refering to forces that cause rotation.

The ability of any beam or structural member to resist bending and torsion, depends on the following factors (variables):

- material: every material has a different yield strength, tensile strength, and shear strength which ultimately determine the load which the material can withstand and the amount of deformation (stretching, bending, twisting) that will accompany a given load
- size: engineers calculate the moment of inertia of a beam or column, which is a measure of the size and shape of its cross-sectional area, and how far away the area is from the center of the beam. The greater the moment of inertia, the greater the load that can be carried by the structural member. This means that increasing the cross-sectional area of a beam or taking a certain amount of area and spreading it out farther from the center, will increase the strength and stiffness of the beam (see Figure A). It might be instructive for kids to draw different designs for beams on graph paper showing how the cross-sectional area, or the distribution of area can increase to make a stronger, stiffer

beam. Have them try to draw two beam cross-sections, which have the same area, but different moments of inertia (meaning that the area of one beam is spread out farther away from the center, and the area of the other is more concentrated around the center).

reinforcement / composite structure: many structural members are actually composite materials, which means that they are made from two or more materials bonded together. Foam board is an example of a composite material - it is a layer of foam sandwiched between two layers of paper. Reinforced concrete has steel rods (called rebars, short for reinforcing bars) that are placed inside the form before the concrete is poured. Concrete is a material that is very strong in

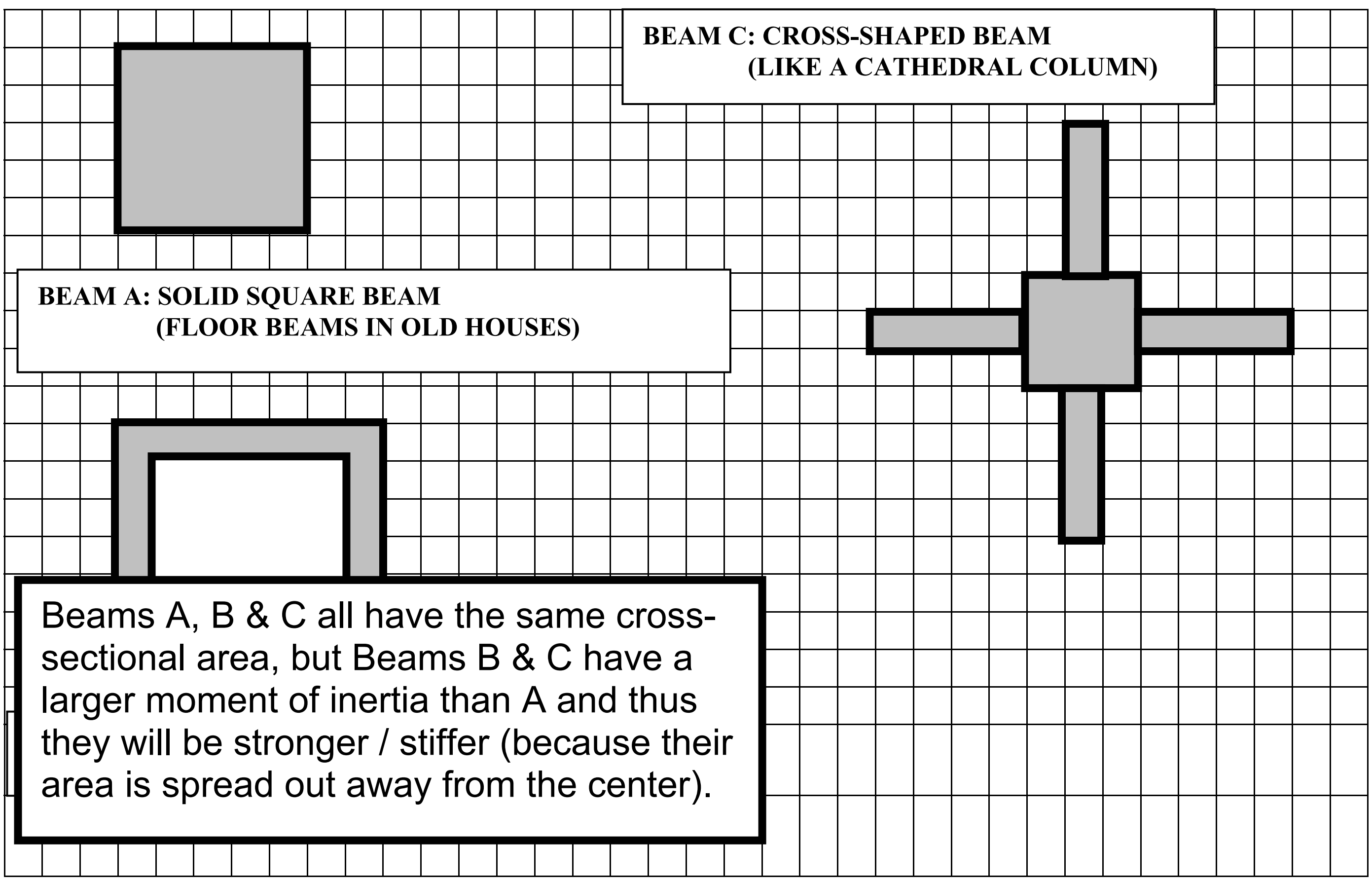


Figure A: Moment of Inertia

compression, but very weak in tension; the steel rebars can take great tensile loads and thus they overcome the weakness of the concrete and make the composite material much stronger. Fiberglass, which is used to make canoes, is mostly a plastic epoxy resin; the epoxy resin by itself would not be that strong, however, it is reinforced by glass fibers inside that are very strong in tension.

Structural bracing: any members which help the structure to resist bending and/or torsion - examples: wire cables (called guy wires) bracing a tower; truss bracing used for bridges, towers and skyscrapers (a truss structure is a triangular formation of long, thin bars pinned together at the ends); brackets and braces such as those used to hold up book shelves and store signs, and strengthen table legs and dump truck bodies.

MATERIALS:

Comprehensive list of materials

TEAM TOOLS:

table top vise and small c-clamp- 15$

Two 20 N spring scales- $10

rulers, protractor, mini glue gun, Exacto knife- $5

black sharpie marker

duct tape

1"x 1" x11" extruded foam insulation block

14" x 14" foam board

coat hanger wire 9 1/2 "

bolt cutters or aviation snips (to cut coat hangers)

scissors

STUDENT MATERIALS

$6 per class

extruded foam insulation 1" thick, 12"x 48" piece

foam board, 20"x20" sheet

popsicle sticks (6 allowed per design)

masking tape

string

coat hanger wire 2 12" pieces per design (get donations or buy from dry cleaners)

hot glue sticks

PREPARATION:

Cut up the extruded foam insulation into 1" X 1" X 4' strips for the tower models - if you have access to a small benchtop bandsaw, you can cut these pieces up in no time - otherwise, use a utility (razor blade) knife.

Make the radar antenna models and the angle measuring plates ahead of time (6 of each will be enough for classes of 24 students). See "Constructing the Torsion Test Set-up." (near the end of the preparation section)

Before beginning this lab, go over the handouts and lab activities provided, unless students already have an understanding of the 5 fundamental loads and the concept of a moment of a force.

You will need to make two extra wimpy towers to use for a class demonstration. Before students do the project, you will demonstrate the procedure for the bending and torsion tests; be sure to record the data for this baseline test on the board and have all students graph this data in their handouts.

On the day you introduce the project and do the class demonstrations, challenge students to go home that evening and do some background research and preliminary brainstorming to help them create good designs. Ask students to look around and think of various structures that are bent and twisted, and what it is about their design which makes them stiff enough to withstand these loads (ex flagpole, street-sign pole, large highway-sign structure, highway guard rails, tower, bridge, dam, steel I-beam, concrete beam, airplane wing, tree, human bones, bicycle frame, snowboard, kitchen table, different shoe soles).

You might choose to run only 2 or 3 class testing stations instead of each team having their own test setup. The advantage is that students can see the results of their classmates' tests, which may in turn help them to make design improvements. The disadvantage is obviously the amount of class time that will be required for testing (each test will take about 10 minutes). I recommend having each team run their own tests, and then have the class present their results after each round of testing.

CONSTRUCTING THE TORSION TEST SETUP

For the torsion tests, you need to make a model of the radar antenna to mount on the tower being tested. You will also need to make an angle measuring plate to measure the angle of twist of the tower.

Materials and Tools (only those required for torsion test setup):

two wood (or metal) rulers

protractor

black sharpie marker

duct tape

1" X 1" X 11" extruded foam insulation block

14" X 14" foam board

coat hanger wire (9 1/2")

small c-clamp

Exacto or utility knife

bolt cutters or aviation snips (to cut coat hanger wire)

Procedures:

1) Radar Antenna Model:

The model radar antenna must be attached to the tower for torsion tests only; it serves as both the means of applying the twisting moment, and it also has the pointer which is used to measure the angular deflection of the tower (see Figure B). First, cut two small blocks of extruded foam insulation that are 1" X 1" X 5 1/2" long. Place the two foam insulation blocks end to end place the two wooden (or metal) rulers flat against the sides of the blocks. Slide the two foam insulation blocks apart so that each one lines up with the ends of the rulers - there should be exactly a 1" square hole between the two blocks at the center of the ruler. Holding everything in place, duct tape the ruler together on each side of this center hole (but do not cover the hole. Then slide the top of a model tower into this square hole, making sure that it fits fairly snugly. If not, untape the rulers and readjust the position of the foam blocks. When you actually conduct a torsion test, you are going to use the c-clamp to firmly secure the antenna to the tower; the clamp will be placed right across the square hole in the middle of the antenna (see torsion test procedure). Finally duct tape the 9 1/2" piece of coat hanger to the middle of one end of the antenna so that it points straight down.

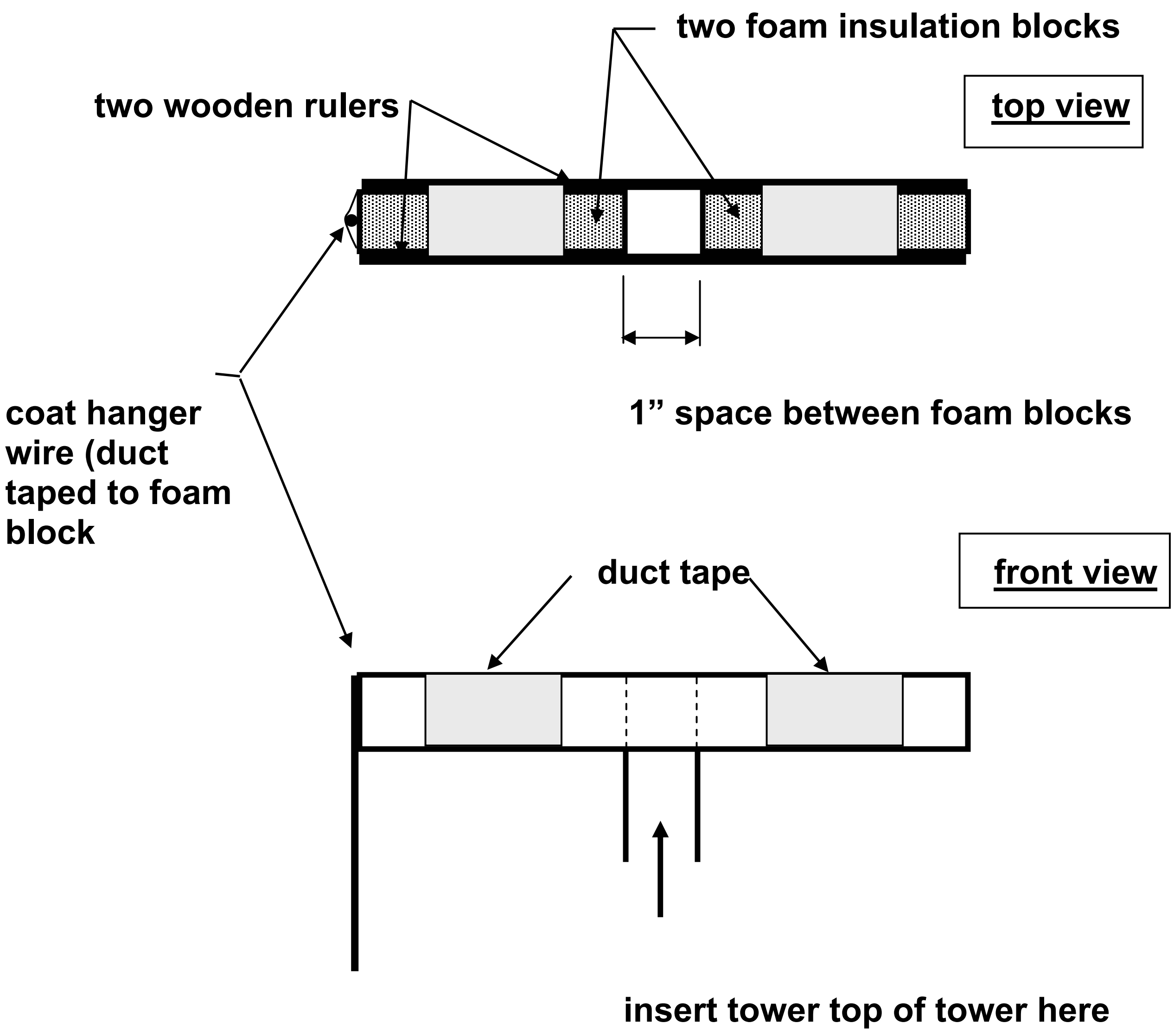


Figure B: Making the Antenna Model

2) Angle Measuring Plate:

The antenna tower to be tested will be placed in the square cut out in the angle measuring plate and then clamped in the table-top vise (see Figure C). Find the center of the 14" square foam board plate using diagonal lines. Draw a line through the center, parallel to a side, running the entire length of the board. Align the protractor at the center of the line (center of the board). Mark 5-degree increments around the protractor on the board. Draw straight lines that radiate from the center through the 5-degree marks, out to the edge of the board; label each line with its degree measure. Next draw and cut out a 1" square that is at the center of the board, and has its sides parallel with the outside edges of the foam board.

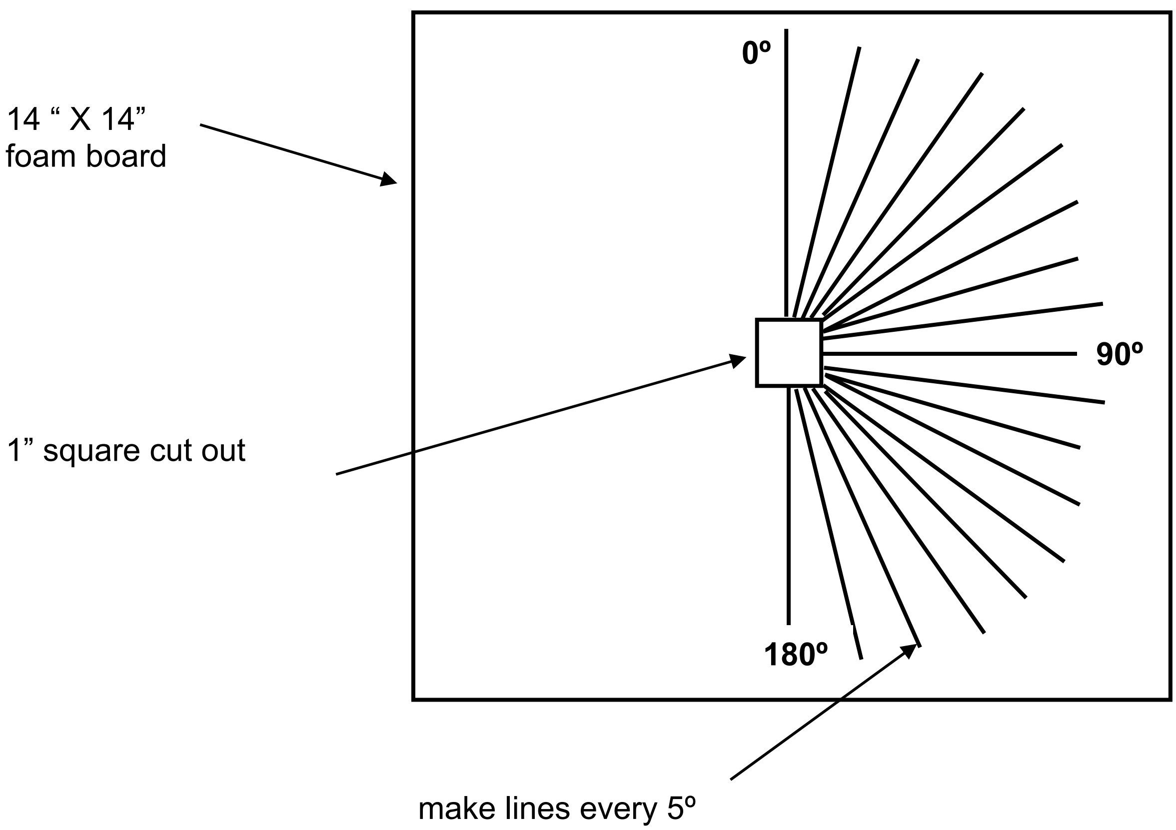


Figure C: Making the Angle Measuring Plate

DIRECTIONS:

Problem Statement

Recently, a team of Raytheoff engineers was asked to design a huge radar antenna tower to be mounted atop the United Nations building in New York City. However, they forgot to take into account the wind loads when they designed the tower; now, when the wind blows, it rocks back and forth, and twists so much that the antenna does not work properly. Needless to say, these engineers are out looking for jobs!

Your engineering consulting team has been called in to fix the problem. You will make models of the radar antenna tower (shown in Figure 1) out of extruded foam insulation and foam board. For this problem, you will not build a new tower. You must use the materials provided to redesign (modify) the existing tower so that it will resist bending and twisting.

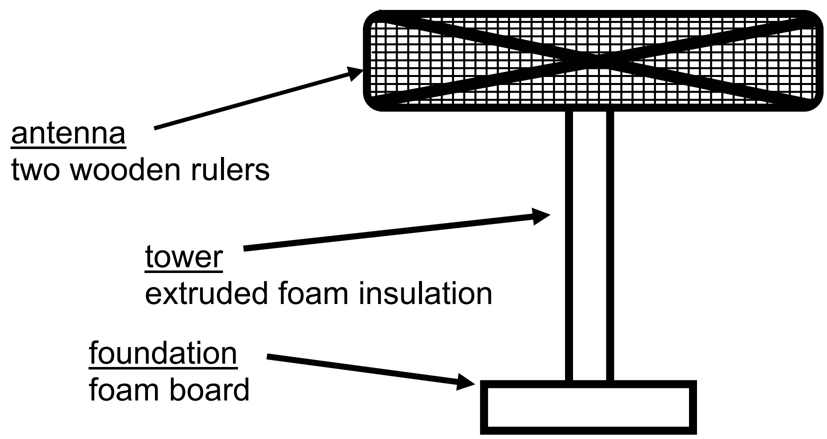


Figure 1: Raytheoff Radar Antenna Tower

Your team's goal is to reinforce and brace the existing radar tower so that it will withstand a 480 N-cm bending moment (20 N applied at 24 cm above tower foundation) and a 280 N-cm twisting moment (20 N applied at 14 cm from center of the tower) with the smallest amount of deflection (movement) possible. Any materials that you use to reinforce the structure must be attached to the existing tower and/or to the 5" square foundation block. No materials may extend from the tower more than 2" in any direction.

Procedures

1) Build 4 models of the Raytheoff wimpy radar antenna tower:

Measure and cut (8) pieces of foam board, 5" X 5"

Cut a 1" square out of the middle of each foam board square - make a template on graph paper, like the one shown in Figure 2, and use it to mark the location of the cutout on each piece.

Cut out (4) extruded foam insulation blocks, 1" X 1" X 12" (the teacher may provide 1" X 1" x 4' blocks which can be cut in fourths).

To assemble the model, see Figure 3: hot glue (2) foam board squares together making sure to line up the cutouts - then slide the foam insulation block through the cutout, so it sticks out 1 1/2", and hot glue in place

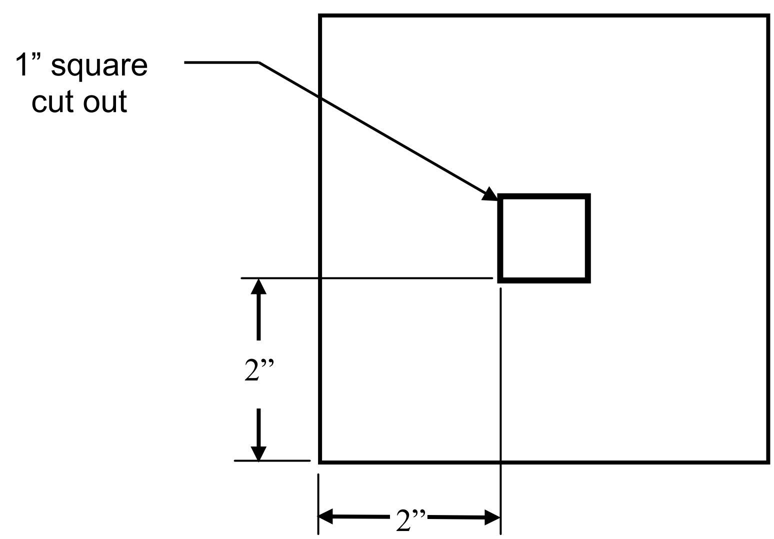


Figure 2: Template for making foam board foundation squares.

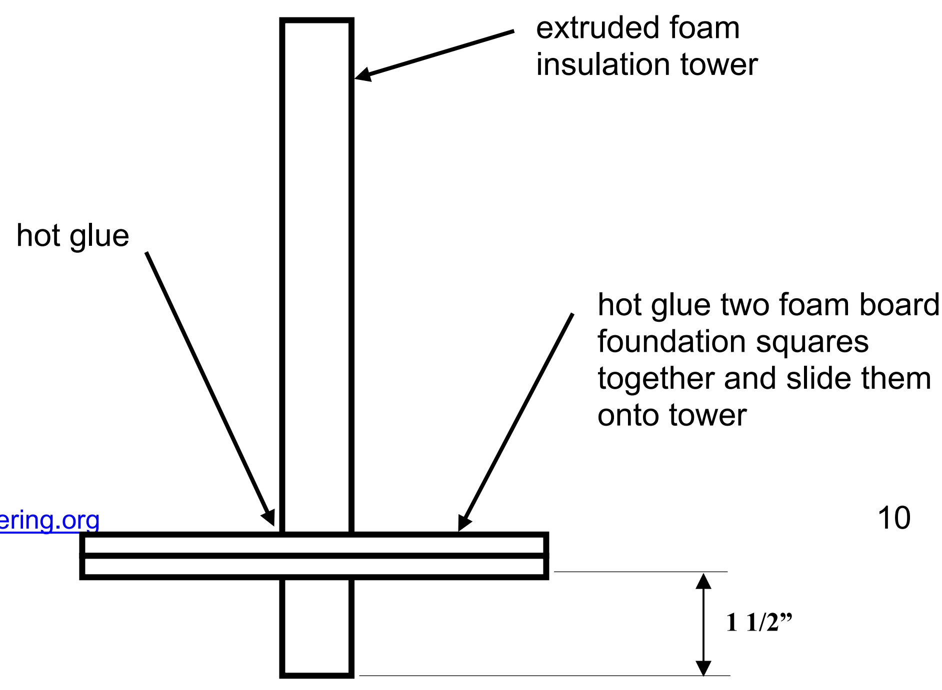


Figure 3: Assembly of Radar Antenna Tower Models

2) Brainstorm ideas for redesigning the tower. You must talk about and sketch several different ideas (at least 5) for bracing and reinforcing the wimpy antenna tower before you will be allowed to get your materials and build your designs. You may only use the materials provided to solve the problem. You should spend at least 20 minutes on generating possible solutions.

3) Select and build models of the two ideas that you believe to be the best tower designs: using the wimpy models you assembled above and the materials provided, build two identical models of each of your two best tower designs - one will be used for the bending test. and the other one for the torsion test.

4) Bending Test Procedure (see Figure 4) :

Stack up a pile of books on each side of the antenna tower, and lay a strip of foam board across the books so that it touches the tower exactly where the string loop is tied on - use masking tape to attach the foam board to the books and keep it from moving - this piece of foam board will be the zero mark from which you will measure the deflection of the tower when it bends

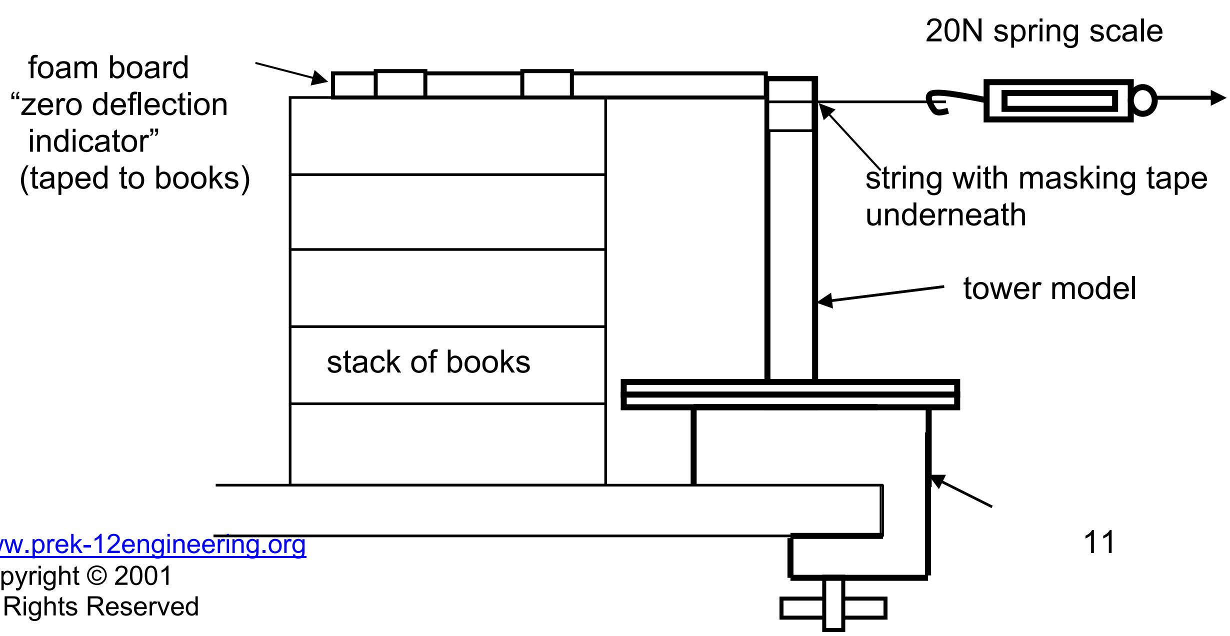


table top table-top vise

Figure 4: Experimental Setup for Bending Tests

You need 3 students to run the test: one student will use the spring scale to apply force to the top of your tower, the second will measure the deflection of the tower from the foam board upright; and the third will record all results in your data table, Table 1 - load the tower until you reach a force of 20N (20N applied at 24 cm = 480 N-cm) - stop every 2N to measure and record the tower's deflection

Repeat the bending test for your other tower design, and record your results in Table 2, and graph the results of both tests on Graph #1

5) Torsion Test Procedure (see Figure 5):

Place tower model into the angle measuring plate, and then into the table-top vise so it sits flat against the vise - clamp with just enough pressure to hold tower from moving.

Place the antenna (two wooden rulers) onto the top of the tower, and clamp it firmly in place using the small C-clamp.

Take (2) 8" pieces of string and tie them into loops - place one loop of string over each side of the antenna, and tape them in place exactly 14 cm from the center of the tower - 14 cm is the moment arm for the twisting moment because these loops are where the spring scales will be inserted to apply the load.

Cut a 9 1/2" piece of coat hanger wire and attach it to one end of antenna so it hangs straight down and comes within 1/2" of touching the angle measuring plate - this pointer will be used to measure the angular deflection of the tower when it is twisted- make sure the pointer starts out pointing to zero degrees

You need 4 students to run this test: one student will hold the foundation from twisting and will also measure the angular deflection of the tower; two other students will each use a spring scale to apply a force to each end of the antenna to make the tower twist; and the other student will record all test results in Table 3.

Two students will load the tower together trying to keep exactly the same force on both sides of the antenna at all times - keep loading the tower until both spring scales record 10N at the same time (which makes a total of 24 N being applied at a distance of 14 cm from the tower = 280 N-cm) - stop every 2N (1N on each scale) to record the angular deflection.

Repeat the torsion test for your other tower design, and record your results in Table4, and graph the results from both tests on one graph on Graph #2.

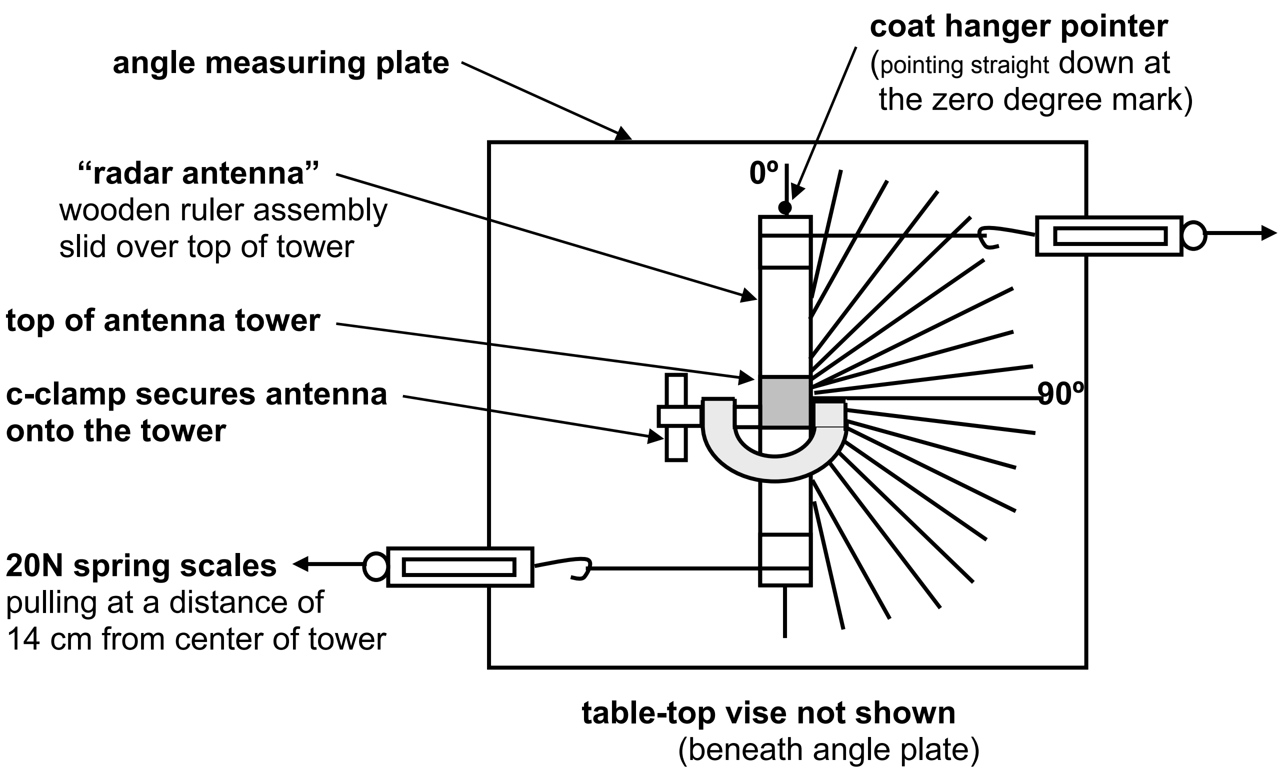


Figure 5: Experimental Setup for Torsion Tests (Top View)

Table 1: Bending Test Data for Design #1

applied force (N)	moment arm (cm)	Bending moment (N-cm)	tower deflection (cm)
0	24	0	0
2	24		
4	24		
6	24		
8	24		
10	24		
12	24		
14	24		
16	24		
18	24		
20	24		

Table 2: Bending Test Data for Design #2

applied force (N)	moment arm (cm)	bending moment (N-cm)	tower deflection (cm)
0	24	0	0
2	24		
4	24		
6	24		
8	24		
10	24		
12	24		
14	24		
16	24		
18	24		
20	24		

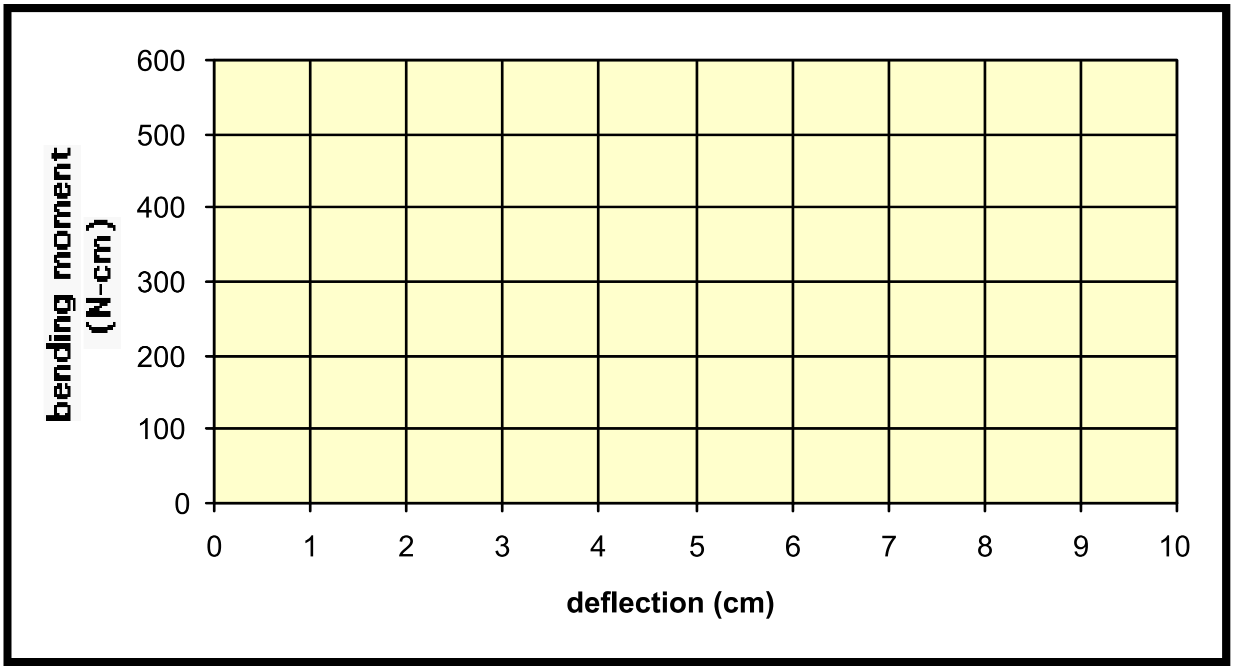
Table 3: Torsion Test Data for Design #1

applied force (N)	moment arm (cm)	twisting moment (N-cm)	angular deflection of tower (degrees)
0	14	0	0
2	14		
4	14		
6	14		
8	14		
10	14		
12	14		
14	14		
16	14		
18	14		
20	14		

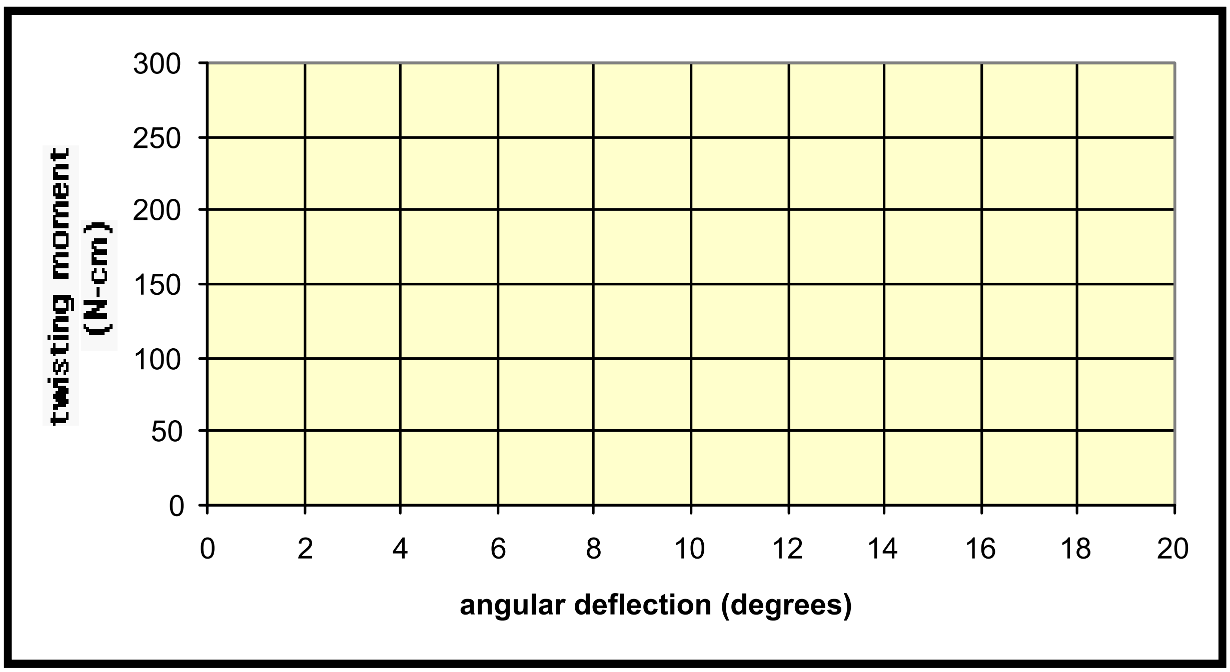
Table 4: Torsion Test Data for Design #2

applied force (N)	moment arm (cm)	twisting moment (N-cm)	angular deflection of tower (degrees)
0	14	0	0
2	14		
4	14		
6	14		
8	14		
10	14		
12	14		
14	14		
16	14		
18	14		
20	14		

Graph #1: Bending Moment v. Deflection of Raytheoff Radar Antenna Towers – Comparison of Designs #1 & #2



Graph #2: Twisting Moment v. Angular Deflection of Raytheoff Radar Antenna Towers – Comparison of Designs #1 & #2



INVESTIGATING QUESTIONS:

What is a moment (of a force)? How is it different from a force?

How do you calculate moments?

Describe the effect of a bending moment on a structure.

Describe the effect of a twisting moment on a structure.

How can you design and build a structure that can resist bending and torsion loads?

REFERENCES:

THE WIMPY RADAR ANTENNA: DESIGNING A RADAR ANTENNA TOWER TO RESIST BENDING AND TORSION by Douglas Prime

Tufts University, Center for Engineering Educational Outreach and Brad George, Hale Middle School, Nashoba Regional High School

WORKSHEETS: (see Links)

Teacher Diagrams

Student Diagrams

Fairly Fundamental Facts about Forces and Structures

Wait a Moment

SAMPLE RUBRIC:

Minimum deflection in bending; minimum angular deflection in torsion; minimum amount of materials used in design.

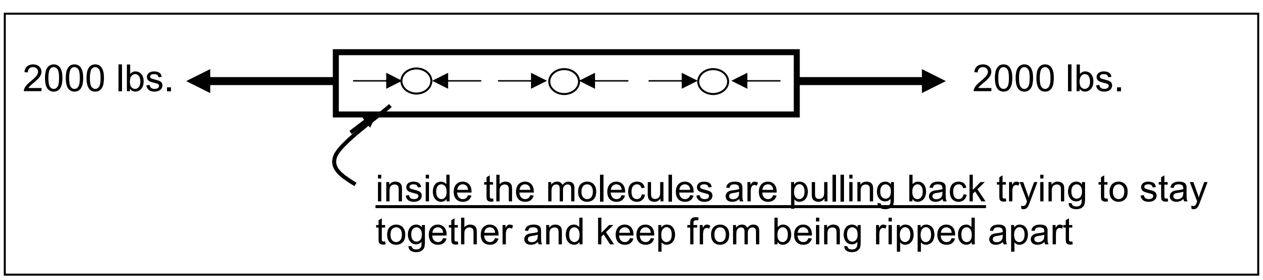
FAIRLY FUNDAMENTAL FACTS
ABOUT FORCES & STRUCTURES

by Douglas Prime
Tufts University
Center for Engineering Educational Outreach

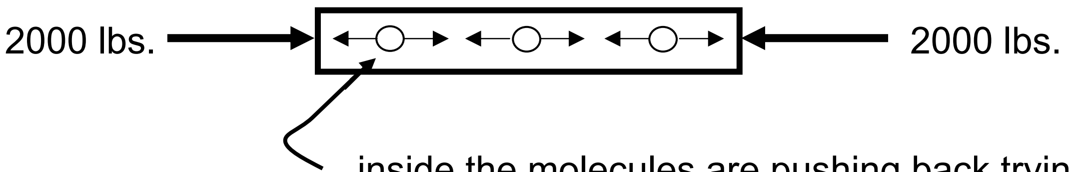
Everyone knows from experience that a **force** is a pushing or a pulling action which moves, or tries to move, an object. Engineers design **structures**, such as buildings, dams, planes and bicycle frames, to hold up weight and withstand forces that are placed on them. An engineers job is to first determine the **loads** or external forces that are acting on a structure. Whenever external forces are applied to a structure, **internal stresses** (internal forces) develop inside the materials that resist the outside forces and fight to hold the structure together. Once an engineer knows what loads will be acting on a structure, they have to calculate the resulting internal stresses, and design each **structural member** (piece of the structure) so it is strong enough to carry the loads without breaking (or even coming close to breaking).

The 5 types of loads that can act on a structure are tension, compression, shear, bending and torsion

1) **tension**: two pulling forces, directly opposing each other, that stretch out an object and try to pull it apart (ex. pulling on a rope, a car towing another car with a chain – the rope and the chain are in tension or are "being subjected to a tensile load")



2) **compression**: two pushing forces, directly opposing each other, which squeeze an object and try to squash it (ex. standing on a soda can, squeezing a piece of wood in a vise – both the can and the wood are in compression or are "being subjected to a compressive load")

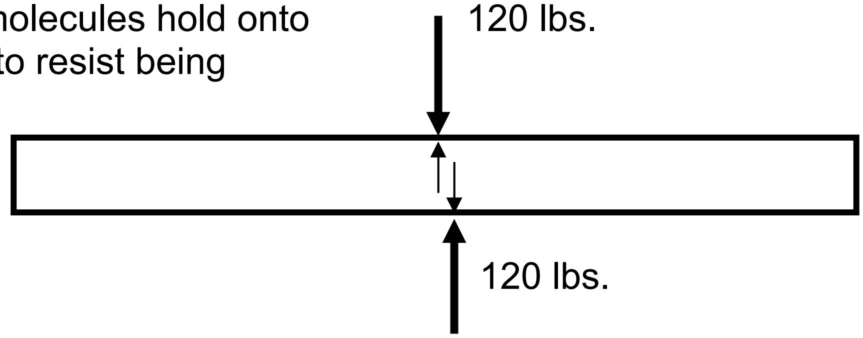


inside the molecules are pushing back trying to stay apart and not get crushed

3) **shear:** two pushing or pulling forces, acting close together but not directly opposing each other – a shearing load cuts or rips an object by **sliding its molecules apart sideways**

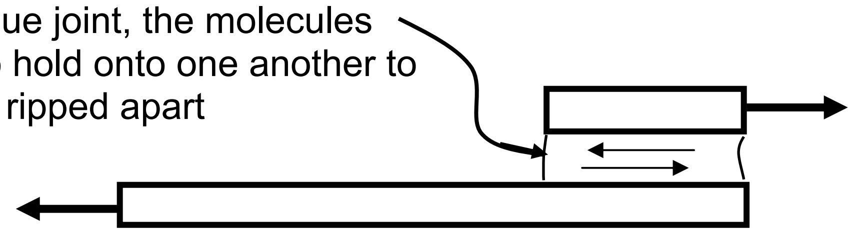
ex. pruning shears cutting through a branch
paper cutter cutting paper
(the branch and the paper are "subjected to a shear loading")

inside the molecules hold onto each other to resist being slid apart



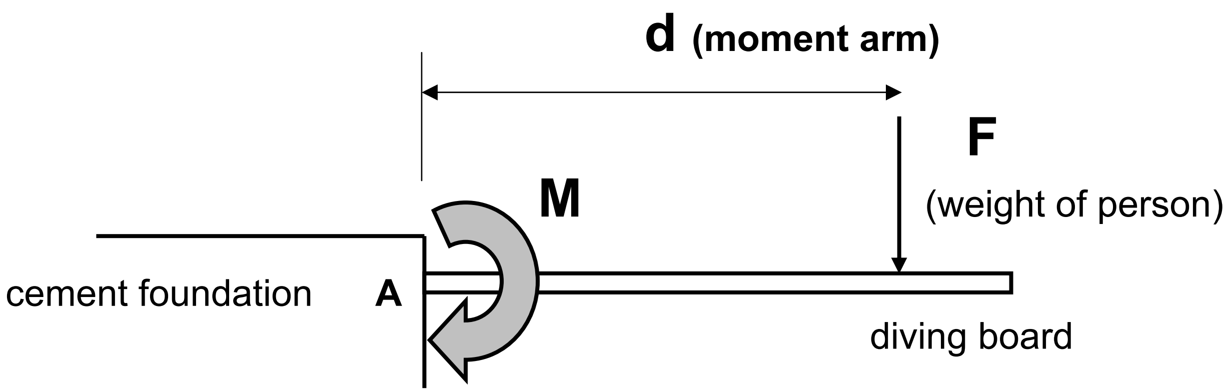
ex. pulling on two pieces of wood that have been glued together (the glue joint is "being subjected to a shear loading")

inside the glue joint, the molecules are trying to hold onto one another to resist being ripped apart



A Moment of A Force

Before you can understand the last two types of loads, you need to understand the idea of **a moment of a force**. A moment is a "turning force" caused by a force acting on an object at some distance from a fixed point. Consider the diving board shown below. The heavier the person, and the farther he walks out on the board, the greater the "turning force" which acts on the cement foundation.



the force (F) produces a moment or "turning force" (M) that tries to rotate the diving board around a fixed point (A) – in this case the moment bends the diving board

The stronger the force, and the greater the distance at which it acts, the larger the moment or "turning force" which it produces.

A moment or "turning force" (M) is calculated by multiplying a force (F) by its moment arm (d) – the moment arm is the distance at which the force is applied, taken from the fixed point:

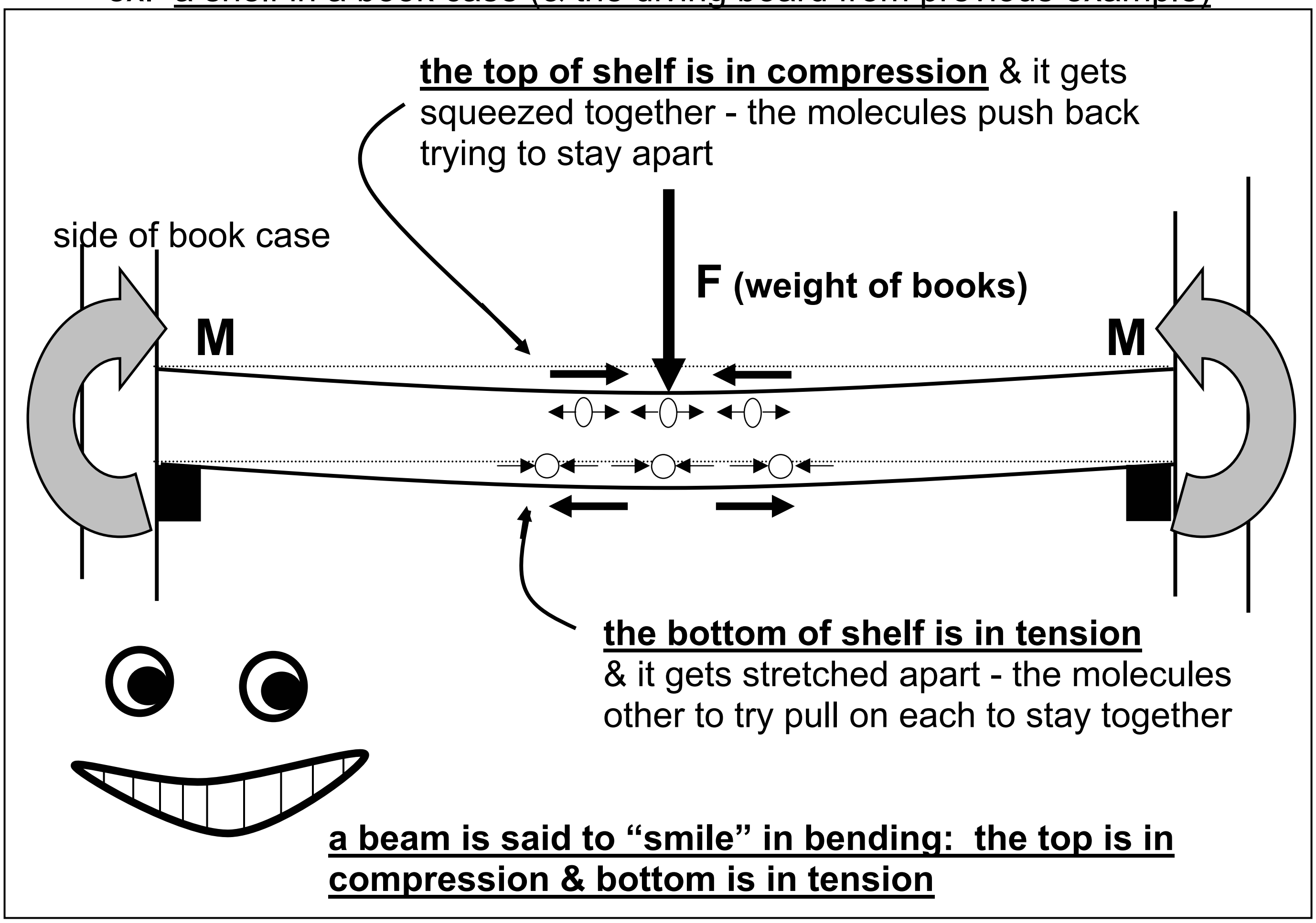
$$M = F \bullet d$$

(as long as the force acting on the object is perpendicular to the object)

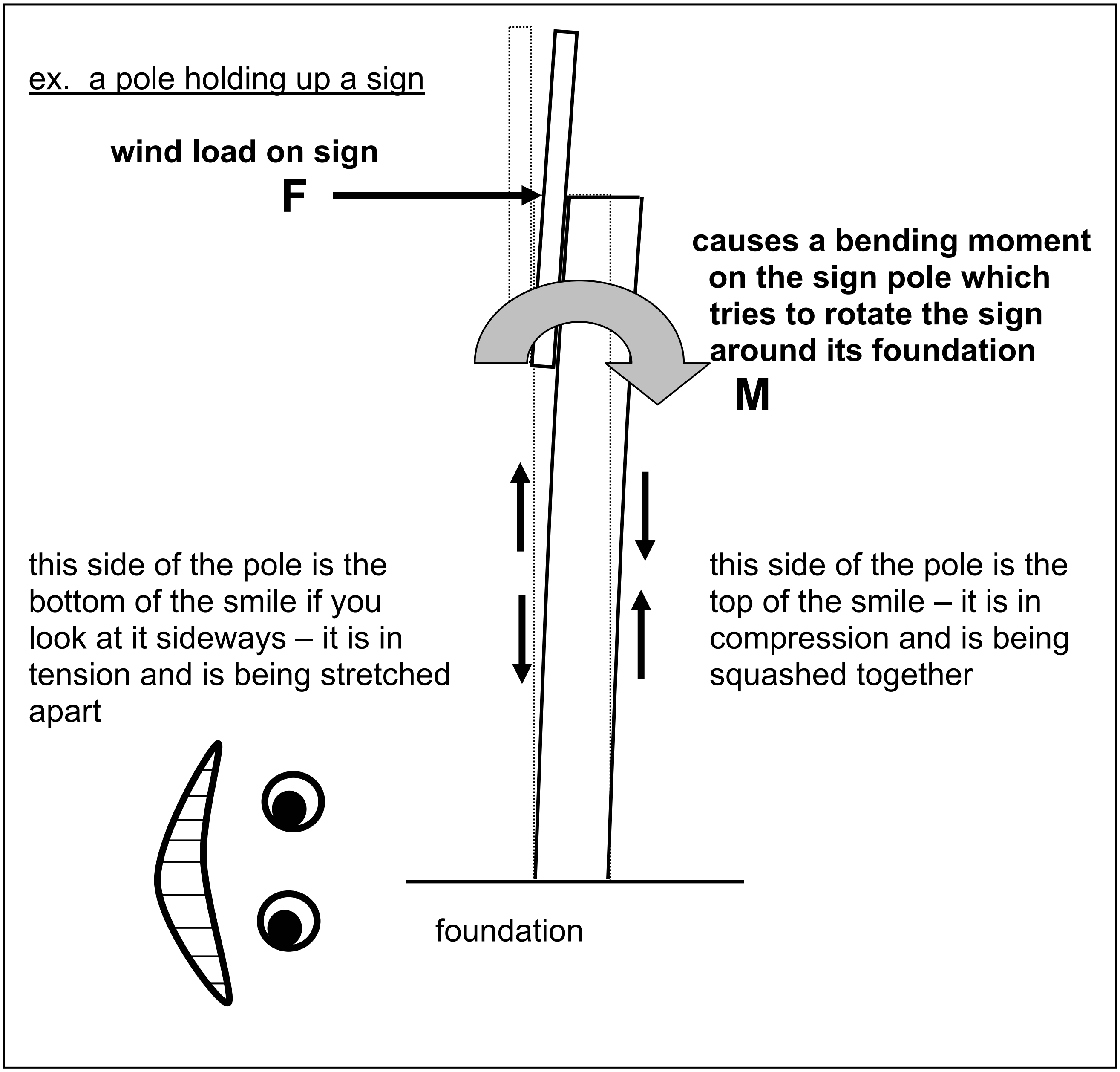
If you have a force measured in Newtons multiplied by a distance in meters, then your units for the moment are N-m, read "Newton-meters". If your force is measured in pounds and you multiply it by a distance given in inches, then your units will be lb-in., read "pound-inches". The units for moments can be any force unit multiplied by any distance unit.

4) **bending:** created when a moment or "turning force" is applied to a structural member (or piece of material) making it **deflect or sag (bend), moving it sideways away from its original position** - a moment which causes bending is called a **bending moment – bending actually produces tension and compression** inside a beam or a pole, causing it to "smile" – the molecules on the top of the smile get squeezed together, while the molecules on the bottom of the smile get stretched out – **a beam or pole in bending will fail in tension** (break on the side that is being pulled apart)

ex. a shelf in a book case (& the diving board from previous example)

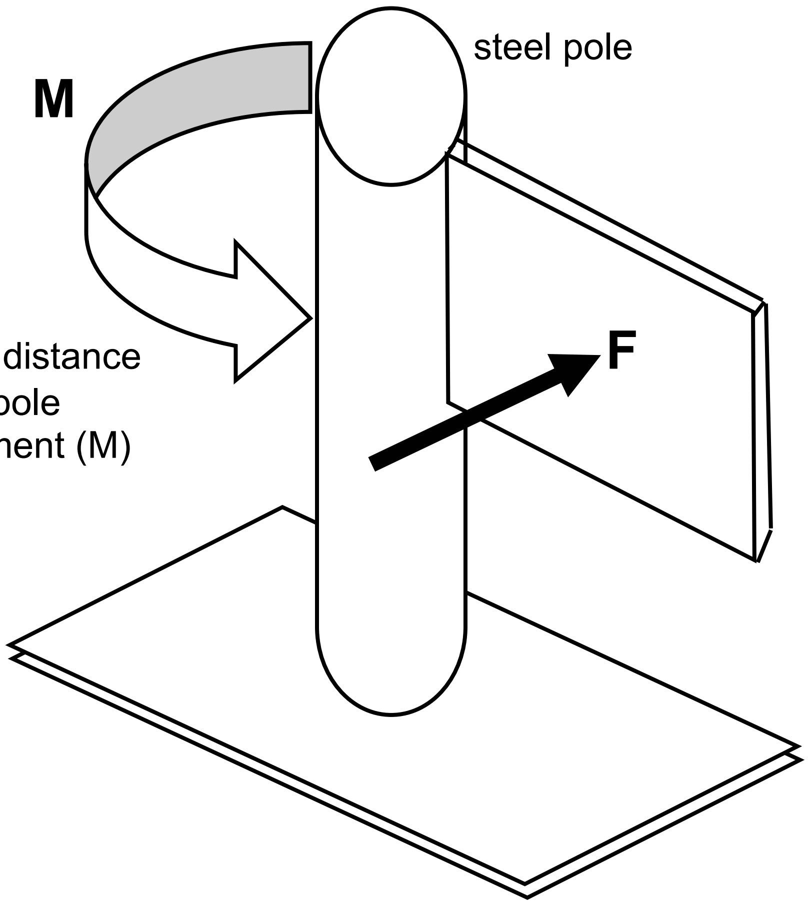


<u>Glue stick experiment to show tension and compression created by bending.</u> Take a glue stick used in a glue gun and use a ruler to mark four straight 4” lines which run down the length of the stick – the lines should be spaced 90 degrees apart: one on the top, one on the bottom, and one on each side of the glue stick. Hold the glue stick between a finger and your thumb, and apply a force to the middle. Notice how the lengths and shapes of the lines change. <u>What happens to the line on the top of the glue stick (side where your finger pushes)? What happens to the line on the bottom? What happens to the lines on the two sides of the glue stick?</u>



5) **<u>torsion (twisting):</u>** created when a moment or “turning force” is applied to a structural member (or piece of material) **making it deflect at an angle (twist)** - a moment which causes twisting is called a **twisting or torsional moment – torsion actually produces shear stresses inside the material - a beam in torsion will fail in shear** (the twisting action causes the molecules to be slid apart sideways)

<u>ex. a pole with a sign hanging off one side</u>



wind load (F) acts at a distance from the center of the pole causing a twisting moment (M)

mounted to a steel plate that is bolted to a cement foundation

<u>Glue stick experiment to show torsion.</u> Again take a glue stick used in a glue gun and use a ruler to mark a series of straight lines along its length, similar to the experiment above. Hold one end of the glue stick, and get a partner to twist the other end as hard as possible. <u>What happens to the lines on the glue stick</u>? Imagine that each vertical line represents a line of glue molecules – **notice how they have been slid sideways out of position by the twisting moment – this is the sign of shear forces acting inside the material.**

WAIT A MOMENT – I DON'T GET THIS!

An Experiment Demonstrating the Moment of a Force

Here is an experiment you should try so you really get a good understanding of moments acting on structures, and how they are different from the forces themselves:

a) Hold a meter stick with both hands, at one end; hold it out slightly in front of your stomach, parallel to the floor. Get a partner to take a spring scale connected to a loop of string, and apply a force of 5N at the 40 cm mark. Your job is to hold the meter stick level at all times. Now have your partner increase the load by 5N at a time, until you cannot hold the meter stick up straight anymore. What did you notice about the amount of turning force that your arms and wrist muscles had to apply to the stick to keep it up? Why did this happen?

1. Now have your partner apply a 5N force at the 10 cm mark. Then have them move the 5N load further away from the persons hands – move it to 20 cm, and keep moving it out , 10 cm at a time, until you get to 100 cm, all the while keeping the applied force at 5N. What did you notice about the amount of turning force that your arms and wrist muscles had to apply to the stick to keep it up? How could this happen when the **force applied to the ruler never changed**?

2. Repeat both these experiments with your arms extended, holding the meter stick straight out in front of your body. Was it easier or more difficult to hold the meter stick level in this position? Why?

Activity Evaluation Form www.k12engineering.org

Activity Name:____________________________________

Grade Level the Activity was implemented at: __

Was this Activity effective at this grade level (if so, why, and if not, why not)**?**

What were the Activity's strong points?

What were its weak points?

Was the suggested Time Required sufficient (if not, which aspects of the Activity took shorter or longer than expected)**?**

Was the supposed Cost accurate (if not, what were some factors that contributed to either lower or higher costs)**?**

Do you think that the Activity sufficiently represented the listed MA Framework Standards (if not, do you have suggestions that might improve the Activity's relevance)**?**

Was the suggested Preparation sufficient in raising the students' initial familiarity with the Activity's topic (if not, do you have suggestions of steps that might be added here)**?**

If there were any attached Rubrics or Worksheets, were they effective (if not, do you have suggestions for their improvement)**?**

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