Lab 1: Stress in Tensile and Compressive Structures

Cable Shape and Strength and the Washington Monument

Lab Setup

There are three stations for this lab: Cable Strength; The Washington Monument; and Cable and Arch Shape. The primary purpose of each station is explained in the sections below.

Part I - 1st Half of Lab
Groups A and B will begin on Cable Strength, for which there are two identical stations. Groups C and D will begin on the Washington Monument and Cable and Arch Shape respectively. Once each of group C and D have completed their first station, they will switch with each other.

Part II - 2nd Half of Lab
Groups C and D will now work on Cable Strength, one group on each station. Groups A and B will now work on the Washington Monument and Cable and Arch Shape respectively. Once each of group A and B have completed their first station they will switch with each other.

Cable Strength

The laboratory will explore the breaking strength of steel. The strength of a material is the determining specification that sets the minimum safe cable cross sectional area. The minimum safe cable cross-section is a factor affecting the cost and appearance of the cable suspension bridge.

In this experiment, our "cables" are single strands of steel wire. You will test steel wires of three different diameters by subjecting them to increasing tension loading until they break. By recording both the breaking load (T) in units of pounds force, and the area (A) in units of square inches, you will calculate the breaking stress ($f_T = T / A$) in units of pounds force per square inch (often abbreviated "psi") for each of the three wires. If all goes well you will find that the breaking stress in all three cases will be the same because the breaking stress is a property of the material. We find that the stronger the cable material, the smaller the cable diameter that is needed. For example, wrought iron has a breaking stress of about 30,000 psi. Modern high strength steel has a breaking stress of about 250,000 psi. A steel cable would be about $\sqrt{\frac{30{,}000}{250{,}000}}$ or about one third of the diameter of an iron cable supporting the same load.

The Washington Monument

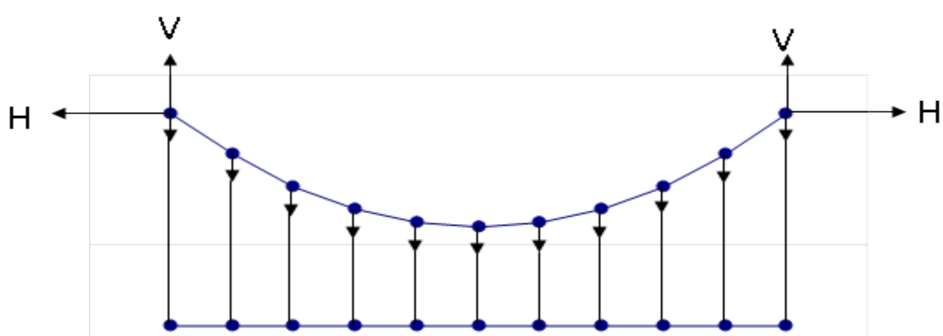
The laboratory will show how the principles learned with respect to tensile forces in the Cable Strength lab also apply to compressive structures such as the Washington Monument.

You will work with two models of the Washington Monument, one of the complete structure, and one of only the top half of it. By recording the cross-sectional area (A) at the base of each of the models and the weight (Q) of each of them, the stress ($f_Q = Q / A$) that is acting on the base of each model can be calculated. Through your knowledge of the relationship between area, force, and stress, you will see that a relatively consistent level of stress is maintained at both the base and midpoint of the structure as the cross-sectional area of the monument decreases with height to accommodate the decreasing load.

Cable and Arch Shape

It is important to note that a cable can act in tension only as it is flexible and cannot resist bending or compression. Thus, the main cable of a suspension bridge will be in pure tension. The shape of the main cable of a suspension bridge is a parabola because parabolic shape naturally results when the total suspended load is uniformly distributed along the span. The natural occurrence of the parabolic form will be demonstrated in the laboratory by hanging equal weights at regular horizontal intervals along a chain.

One of the attractions of working with cables is that the direction of forces can be visually determined. One can visualize how the bridge works *because* a cable acts in tension only. By observation, one can see how hangers bring the deck load to the main cable. Observation also reveals how the main cable brings the deck load to the towers. The towers hold the main cable up through vertical and horizontal reaction forces at the top of the towers. The vertical force goes through the towers to the ground, whereas the horizontal force is taken by an anchorage to which the main cable is fixed at some distance from the towers. All of these forces are shown below.

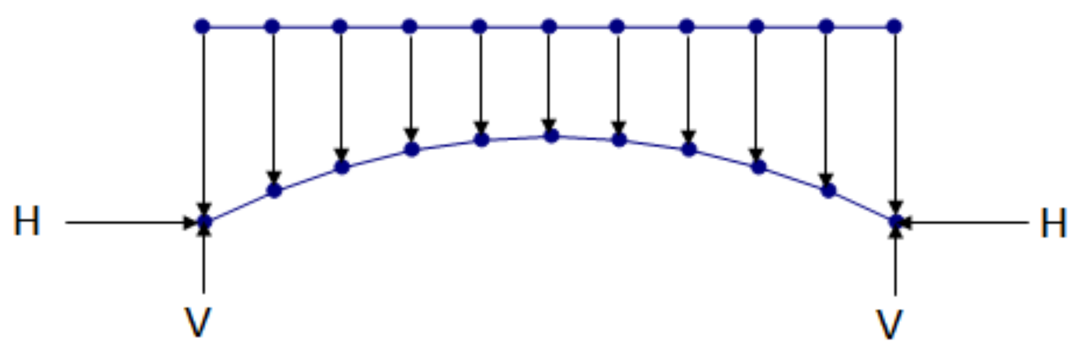


Forces in a Cable Suspension Bridge

Arch bridges are in a sense similar to cable bridges. The arch form is complementary to the cable form. Their respective functions differ in the sense that the arch must act in compression whereas the cable acts in tension. Consequently, horizontal abutment reaction forces on the arch are inward, in contrast to the outward tower reaction forces in cable bridges.

Arches must be rigid in order to resist compression, but a rigid structural member can also resist bending. In spite of what one might think, this is not advantageous as it adversely makes possible the additive effect of combined compression *and* bending forces within the arch. However, this adverse condition can be avoided through proper form, thereby yielding the very advantageous combination of efficiency, economy, and elegance.

Based on our discussion of cable shape under a uniformly distributed load, one could correctly conclude that the correct form for an arch under uniformly distributed load is again a parabola. It makes sense that if a cable naturally assumes a parabolic shape in pure tension under uniformly distributed load, then a parabolic arch would be in pure compression under uniformly distributed load. In other words, the natural cable shape reveals the correct arch shape!



Forces in an Arch Bridge

Important Equations

Variables

Q = Compressive load in units of kips, where 1 kip = 1000 pounds force (lbf)
T = Tensile load in a cable
D = Diameter
A = Cross sectional area of a cable or column (in^2)
f = Stress in cable or column (kips/in^2, or alternately lbf/in^2)
S.F. = Safety Factor

Equations

Area of a circle = $\pi D^2/4$
Compressive stress in a column = $f_Q = Q / A$
Tensile stress in a cable = $f_T = T / A$
Minimum S.F. = (breaking stress) / (allowable stress)
Percent difference = 100 * (experimental - theoretical) / theoretical

Notes

1. For most parts of the course, we use historical units, eg. pounds, feet, inches etc.
2. Use consistent units when adding, multiplying, etc.

APPARATUS

This experiment is in four parts. The first two parts involve measurements using a board apparatus with two hooks at the top as seen in figure 1. A chain supported by these hooks will be loaded in various ways using weights. The first part is done with a Plexiglas panel marked in the shape of a grid. The second part is done with a Plexiglas panel marked in the shape of a semicircle. The third part utilizes a materials testing machine as seen in figure 2.

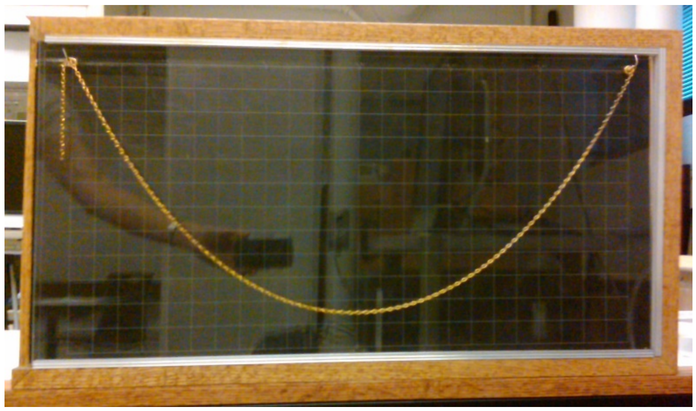


Figure 1: Cable Shape Apparatus

Figure 2: Strength of a Cable apparatus

Lab 1a: Cable Strength

This part of the lab uses the Pasco Materials Testing Machine apparatus to determine the tensile load necessary to cause failure of a cable. Our "cables" will be individual strands of steel wire. From these tests, we can determine the breaking strength of the material. **You will test three different diameters of steel wire. It is important to note that all three diameters are made of the same material.**

1. Open the Capstone file "Cable strength" from the folder "cee102_262" on the computer desktop. Delete all previous data if it is already open. To delete data, go to the "Delete Last Run" icon at the bottom of the worksheet, click the dropdown, and select "Delete All Runs" (note that the dropdown here also enables deletion of individual test runs). **Save the file with a new file name in the desktop folder "CEE 262 Lab Group Data."**

2. Familiarize yourself with the Capstone data acquisition controls on the computer screen. Look to the bottom left of the Capstone worksheet. If necessary, change the data acquisition mode to "Continuous Mode" by clicking the dropdown. Note the record button to the left.

3. Take a look at the materials testing machine and familiarize yourself with the following features from top to bottom: FRAME HEAD, CROSS HEAD, LOAD CELL, and the actuator crank. The crank is turned clockwise to raise the cross head and counter-clockwise to lower it.

4. See figure 5. Wire holding fixtures are mounted to the cross head and to the load cell. When both black knobs are turned counterclockwise until they stop, two small holes will be visible near the left side of both screws. **This is the starting position for the screws each time a sample is tested.**

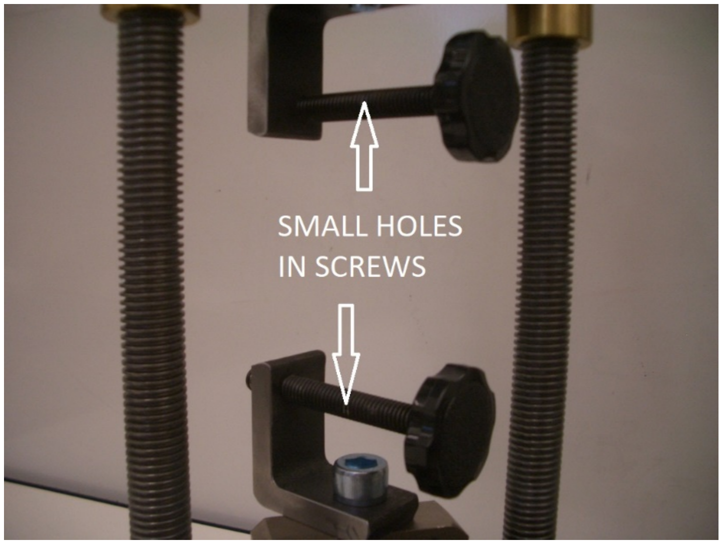


Figure 5

5. Measure the diameter of all three samples using a caliper. Press the green button to turn the caliper on. **Do not press the yellow zero button.** For accurate results, cut off a short length (about one inch) of each sample. As seen in figure 6, grip the short sample in the narrowed tip of the caliper jaws by rolling the thumb wheel to the left. Release thumb pressure from the wheel (the sample should remain gripped), and read the display. The instructor can demonstrate if necessary. Record the diameter in Table 1 below. Determine the cross-sectional area **(A)** of each sample and record in Table 1 **being sure to retain significant figures**.

Figure 6

6. **Position the cross head to make the space between the CROSS HEAD and the FRAME HEAD about 2.5 inches, and turn both black knobs counterclockwise until they stop.** Select the wire diameter to be tested, and cut a length that reaches from the LOAD CELL label to the CROSS HEAD label. **Handle the wire sample carefully and avoid excessive bending.**

7. Insert one end of the wire into the hole in the lower screw. Squeeze the wire between your fingers, and start turning the screw clockwise while keeping the wire in the hole and bending it sharply around the screw. Keep tension on the wire while making about three turns of the screw so the wire wraps neatly in the screw threads without crossing itself or the threads. Correct wrapping is shown in figure 7. The instructor can demonstrate and assist.

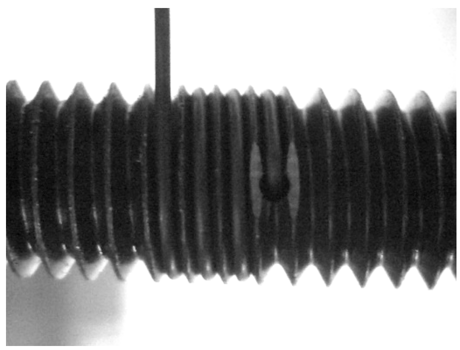


Figure 7

8. Insert the other end of the wire into the hole in the upper screw and repeat the wrapping technique until the upper screw is lightly tightened. Verify that the wire is neatly wrapped on both screws as described above. **It is important that you now slightly loosen either screw so there is a small amount of slack in the wire.**

9. Click on the record button, and start turning the crank clockwise (about one turn per second) to apply tension to the wire sample until it breaks. Once broken, stop recording data by clicking on the stop button.

10. To determine the breaking tension **(T)** in lbf (or pounds force) for this sample, use the mouse wheel to zoom in on the highest area of the plot that appears flat. Go to the toolbar at the top of the chart, and click on the highlighter button (fourth button from left) to create a data highlighter box. Drag the box to the flat area, and read the mean value displayed next to the vertical axis. Record the breaking tension **(T)** for this sample in table 1 below.

11. Remove broken pieces of wire by pulling on the broken end while turning the black knob counterclockwise. It might be necessary to pick the broken end out of the screw threads. **Please throw broken wires in the trash.**

12. Repeat steps 6 through 11 for the other wire samples.

13. Calculate the stress required to break each wire by using the formula $f_T = T / A$, and enter the values in table 1.

    NOTE: If the difference in breaking stress between any two samples exceeds 5,000 lbf/in^2, check accuracy of your calculations being sure to retain significant figures. If calculations are correct, seek guidance from your lab instructor, as a test may be invalid for various reasons. Verify diameter measurement(s) first and proceed to the tension test if necessary.

14. You can view the plots for all tests simultaneously or individually. Go to the colorful triangle button on the toolbar and use the dropdown to click on Select All to view all test runs. You can also check off individual runs as desired. Double clicking on any plot activates it so one can acquire use of the statistical tools (mean value for example) enabled by the highlighter tool, **but do not change any statistical tool settings.**

15. Using Excel, plot the breaking tension (**T**) of the samples as a function of their cross-sectional area **(A)**. Apply a linear trendline to the data with equation displayed, and observe the fit of the data points to the trendline. The points should be on or very close to the trendline. Note the slope of the trendline from the displayed slope-intercept form of the linear equation, and interpret its significance. Save the Excel file in the desktop folder **CEE 262 Lab Group Data** along with your Capstone worksheet.

Material	**Diameter D (in)**	**Cross-Sectional Area A (in^2)**	**Breaking Tension T (lbf)**	**Breaking Stress f_T (lbf/in^2)**
Steel				
Steel				
Steel				

Table 1: Data Table for Cable Strength Experiment

Lab 1b: The Washington Monument

Evaluation of the Real Monument

1. Calculate the stress at the base of the real Washington Monument using the values given in Table 2, and record in table 3.
2. Calculate the stress at the mid-height of the real Washington Monument using the values given in Table 2, and record in table 3.

Part I - Evaluation of the Full Monument Model

1. Remove the Washington Monument full model of the monument from the force sensors. Ask your lab instructor for help if you are unsure how to do this.
2. Measure the height and base dimensions of the model. What is the approximate scale of these dimensions to those of the real structure?
3. Determine the cross-sectional area of masonry that is at the base of the tower as represented by the foam.
4. Open the Capstone worksheet ‘Towers.cap’ found in the desktop folder ‘cee102_262’. There should be seven digital force displays visible. The four displays on the bottom of the screen correspond to loads measured at the four corners of the structure at its base. The display at the top left of the screen shows total vertical force – this is simply the sum of the loads at the four corners. By placing the model on the base/balance assembly and reading the total vertical force, you will be able to determine the dead load of the structure. Before attaching the model, select ‘Fast Monitor Mode’ from the pull-down menu near the bottom left of the Capstone worksheet. Then click the ‘Monitor’ button to the immediate left of the drop-down menu. Tare (zero) the force sensors by pushing the ‘tare’ button on the side of the sensors – you may have to do this multiple times. Now return the model to the base/balance assembly. Once the structure has stabilized (the values are fairly constant), record the dead load of the structure. Stop the computer from monitoring by selecting ‘stop.’
5. Calculate the stress experienced in the foam at the base of the full model due to gravity acting on the model structure above, and record in table 3.
6. Compare the experimental stress value to the value of the real monument by calculating percent difference.
7. Given that the various geometric dimensions of the model are scaled to roughly the same extent, calculate the weight of full model required for the percent difference to be zero.

Part II - Evaluation of the Partial Monument Model

1. Remove the half model of the monument from the force sensors. Ask your lab instructor for help if you are unsure how to do this.
2. Determine the cross-sectional area of masonry that is at the mid-height of the tower as represented by the foam.
3. Open the Capstone worksheet 'Towers.cap' found in the desktop folder 'cee102_262'. There should be seven digital force displays visible. The four displays on the bottom of the screen correspond to loads measured at the four corners of the structure at its base. The display at the top left of the screen shows total vertical force – this is simply the sum of the loads at the four corners. By placing the model on the base/balance assembly and reading the total vertical force, you will be able to determine the dead load of the structure. Before attaching the model, select 'Fast Monitor Mode' from the pull-down menu near the bottom left of the Capstone worksheet. Then click the 'Monitor' button to the immediate left of the drop-down menu. Tare (zero) the force sensors by pushing the 'tare' button on the side of the sensors – you may have to do this multiple times. Now return the model to the base/balance assembly. Once the structure has stabilized (the values are fairly constant), record the dead load of the structure. Stop the computer from monitoring by selecting 'stop.'
4. Calculate the stress experienced in the foam at the base of the half model due to gravity acting on the model structure above, and record in table 3.
5. Compare the experimental f_Q value to the value of the real monument by calculating percent difference.
6. Given that the various geometric dimensions of the model are scaled to roughly the same extent, calculate the weight of half model required for the percent difference to be 0.

Table 2: Comparison of Model & Structure			
	Model	Real	Scale Factor
Height		500 ft	
Width		55 ft	
Dead Load (Q_{full}) of full column		89,600 kips	
Dead Load ($Q_{top\ half}$) of column top half		44,800 kips	
Area at Base		345,600 in^2	
Area at Mid-Height		194,400 in^2	

Table 3: Stress				
	Real	Experimental	Percent Difference	Corrected Model Weight
Stress at Base				
Stress at Mid-Height				

Lab 1c: Cable and Arch Shape

Part I: The shape of a cable under uniform loading

The first part of the lab uses the cable shape apparatus to derive the shape of a cable under uniform horizontal loading. Uniform loading is characteristic of the conventional cable suspension bridge as shown in Figure 1.

Figure 1: Shape of Cable in a Suspension Bridge

1. Using the plexiglas board with the x,y grid, suspend the chain from the hooks at (-12,0) and (12,0) so that the sag of the chain at mid-span is about 11 inches. The shape of the chain under only the load of its own weight is a curve known as a catenary.
2. To create the uniformly loaded chain, hang seven weight clusters (4 ounces each) along the chain. The seven weights should freely hang at *x*-coordinates of -9, -6, -3, 0, 3, 6, 9. as seen in figure 2. It will be necessary to iteratively adjust the weight positions as they are added until they hang at the designated x-coordinates.

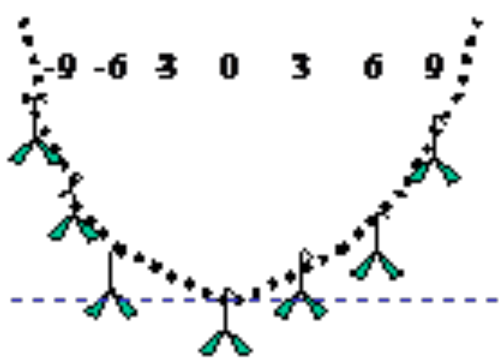


Figure 2

3. Observe the chain under uniform loading. Discuss as a group what shape you think it is taking. Is it a semi-circle? Check with your lab instructor that you understand what shape it has taken and how this is relevant to suspension bridges.

Part II: The Semicircular Form

The second part of the lab will again use the board apparatus but with a different Plexiglas panel. This template panel has a semicircular shape etched on it and a chain fixed on hooks at both ends. You will distribute weights on the chain to make the chain shape semicircular. This experiment illustrates that a cable can take on a circular form only when loaded with a non-uniformly distributed load.

1. Slide the Plexiglas panel from Part I out of the board apparatus, and install the semicircle template panel.
2. There are seven segments etched in the semicircle template panel. In the center of each of these segments is a dot. There are seven hooks fixed to the chain. Hang a string with looped ends (provided at your station) on each of the seven hooks. Your job is to hang loads at the ends of the strings in a distribution such that the vertices of the polygonal chain are as close as possible to the dots etched on the template panel, thus making the chain as close to semicircular as possible. Start with the heavy loads (large gold weights) at the two outermost positions. Now add various amounts of steel shot to plastic vials and distribute them on the other five strings until the chain shape is circular.
3. Once you have obtained a circular shape, take the seven weights hanging from the chain and distribute them in order on the strings attached to the seven blocks that make up the circular arch. Get your lab instructor to help you erect the circular arch. You should find that the arch is able to stand with the weight distribution used in the hanging chain.
4. Discuss as a group why you think the arch is able to stand with this loading pattern. Check with your lab instructor that you understand the relationship between arch and the chain that you loaded beforehand.