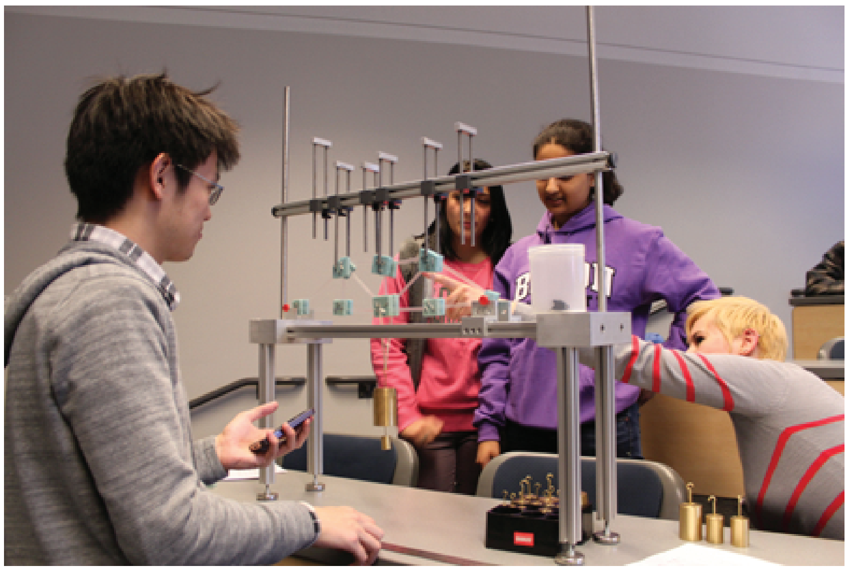
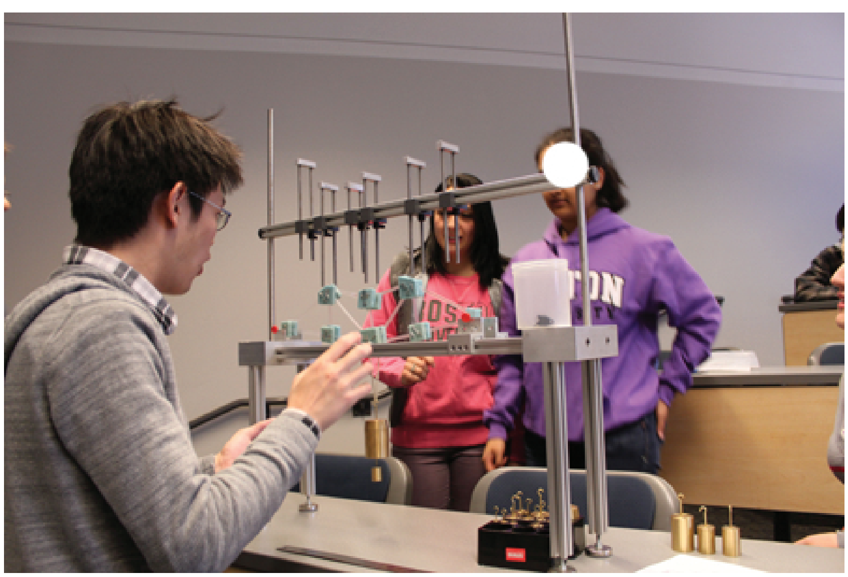
EK 301: Truss Design Project Description

Spring 2013





1 Overview

Working in teams of three students within your section, you will design, construct, and test a simple planar truss made from soda straws (structural members), foam core gusset plates, and T-pins (pin connectors). The truss must satisfy a given set of specifications, such as span, minimum load, and cost (see Section 2 below). You will go through several design stages and your final design and build will be evaluated based on its theoretical maximum achievable load, the accuracy of your theoretical load with respect to the actual maximum load, and the cost of the truss.

This effort will require material testing to determine the strength of the straws, failure analysis, and a final physical test of the maximum load bearing capability of your final design. The project will not only test your understanding of trusses, but will also require you to interpret and utilize test data and to judge the merit of alternative designs, all while exposing you to the benefits of teamwork and allowing you to exercise your creative muscles. And, of course, it is going to be ***fun!***

The project consists of four main components. These are

1. **Materials analysis:** In this element you will measure, analyze, and report on the relevant physical properties of your primary material – soda straws.
2. **Preliminary design:** Everything has to start somewhere. Here you will use both your creative and analytical skills to design and analyze two trusses that meet the specifications.
3. **Redesign and build:** Having never built a truss before, it is unlikely your first attempt will be the best you can come up with. Thus, you will come up with at least two more alternative designs. After picking your dream truss, you will build it using materials provided by us.
4. **Testing:** Every good thing must come to and end and so it is with your truss. You will load up your truss with increasing weight until it fails, hopefully in a crash of glory.

The project deliverables are a report on your straw testing, a preliminary design report, and a final report. Oh, and your completed truss of course.

Important dates:

February xx: Straw testing (in B01, 110 Cummington Street)
February 28: Straw testing report due (in lecture)
April 9: Preliminary design report due (in lecture)
April 26 by 4 p.m.: Final report due (in the ME Department office)
April 27: Truss testing (note that is is a Saturday!) (Pho 203, Pho 205)

2 Specifications

The truss you design and built must conform to the following specifications.

1. **The truss must be a single, upright, planar, simple truss. No truss member may be designed to extend below the line connecting the two end joints.**

   A simple truss starts with three members and three joints configured in a triangle and then is built up by adding two members and one joint each time to complete an additional triangle. Members are not allowed to cross each other and can only be joined to other members at their ends. Doubled up members are not allowed.

   There are two simple checks to make sure your truss is a simple truss. First, it must be comprised only of triangles. If any squares are formed, your truss is incorrect! Second, the number of joints, J, and the numbers of members, M, must be related by

   $$M = 2J - 3.$$

2. **You must use only the materials provided to you.**

   A week before the straw lab you will be provided a bag with soda straws and pins, and later in the semester you will be given a bag of form gusset plates. This collection is meant to serve all aspects of the project (straw testing and final build) so hold onto it until you complete your testing.

3. **Members must be joined concurrently at joints using the provided pins and double pinned to the guest plates as described below. Further, there must be a gusset plate on each side of the joint.**

   Each straw should be sandwiched between two gusset plates and double pinned in their center, with the outer pin 5 mm from the straw end and the inner pin another 5 mm from the outer pin, as illustrated in Fig. 2.1. The center axes of the straws should intersect at a single point to prevent the generation of a moment. (Such a moment can cause premature buckling. This has been known to have several adverse affects, including a lower grade.) The ends of the straws should be as close as possible without actually touching. Pins should have their points on the same side of the truss. Note that pinning jigs will be made available to help you achieve these specs.

4. **Gusset plates may be any geometry but must have an area of less than 16 cm^2 with no straw extending along the gusset plate by more than 2.5 cm from the point of concurrency.**

   The gusset plates provided are initially cut from foam core material into approximately square shapes. Truss performance is improved by using the smallest gusset plates possible so you are encouraged to shape the gusset plates for your particular truss design.

   There are two special joints. The first is the end joint that will act as the pin joint when placed in the testing apparatus. A pin will be pushed through the center of this joint before loading it into the testing unit. For everything to fit properly, **this gusset plate should be trimmed** so that it as flush as possible with the bottom of the adjacent horizontal straw.

   The second is the joint that will support the applied load. That load will be suspended from a pin shoved through the center of this joint. Despite the fact that they are made of soda straws, well-designed and built trusses (such as yours, right?) can hold a surprising amount of weight. So much, in fact, that they can rip right through your gusset plates. Thus for this joint only, you should double up the gusset plates so that they are twice as thick.

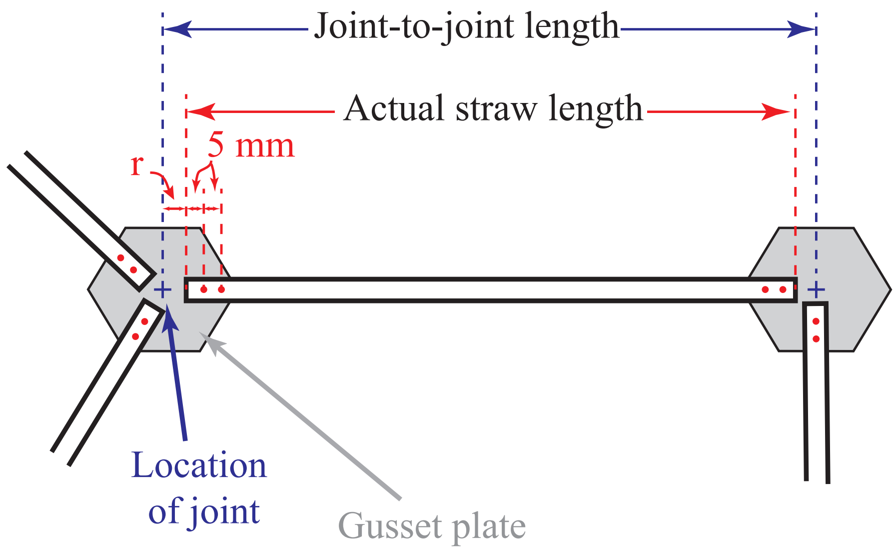


Figure 2.1: A cutaway schematic of two connected joints in the truss. NOTE: The distance from the end of the straw to the true center of the joint should correspond to the straw radius. r The hexagonal grey shape represents the 'back' gusset plate, and a fully-formed joint will also have an opposing gusset plate that will cover the 'top' of the joint exposed in the figure, sandwiching (but not squeezing) the straw.

5. **All *joint-to-joint* distances (as defined in Fig. 2.1) must be at least 8 cm and no longer than 15 cm.**

   Since the straws don't quite go joint to joint, the shortest straw length allowed is 7.5 cm. The longest allowed is a single complete straw.

6. **The truss must span a distance of 55 cm $\pm$ 1 cm.**

   This must be true not only of your designs but also of the constructed truss you bring to testing.

7. **The truss must support for 60 seconds a minimum load of 4.91 N (that is, a 500 g mass) placed on a joint located 27 cm $\pm$ 0.5 cm measured from the pin-jointed end along a line connecting the two end joints.**

   This clearly implies that there must be a joint at that location along the bottom line. You are free to have any other number of joints along that line but you must at least have that one.

8. **The unloaded truss must not sag more than 2 cm below a line connecting the end joints.**

9. **The loaded truss must not have any member sag more than 6 cm below the end joint.**

   If that happens prior to the truss failing in a spectacular buckling event, it will be deemed to have failed.

10. **The total (virtual) cost of the truss must be less than \$335**

    The cost of the truss is defined to be

    $$\text{Cost} = \$10J + \$1L$$

    where J is the number of joints and L is the total joint-to-joint length.

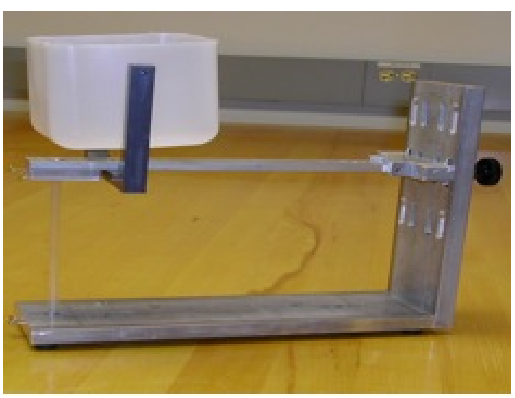
3 Straw testing lab and analysis

In order to determine the failure load for your truss, you need to know the strength of the materials you are working with. In a properly designed and built truss, all the load is carried by the straws. The purpose of the straw testing is to determine the buckling strength as a function of the length of the straw. In this section, we detail the straw testing lab, the analysis to be performed, and the report that you need to write.

3.1 Straw testing lab

Straw testing will take place in a lab during February xxat specific times to be arranged. The lab will take place in room B01 in 110 Cummington street and should take approximately 1.5 hours to complete. Sign up will be done using a sheet posted on the door of B01 with times taken on a first-come, first sign up basis. **All the members of your team must be present at testing.** If any of your team is missing, you will not be allowed to test. If you do not test, or if you show up late for your test or are not being prepared for testing, there will be a significant reduction in your grade. Let's just make sure that doesn't happen, ok?

The straw properties will be tested using a simple lever/hinge mechanism shown in Fig. 3.1. This tester applies an axial load force to the straw. This force is generated by masses you will add to the high-tech bucket on the top of the tester. Note that the weight you add is **not** equal to the load experienced by the straw. You will need to analyze the tester to determine the relationship between the added weight and the applied load by drawing a free body diagram of the testing apparatus.



(a) Side view

(b) Front view

Figure 3.1: Straw testing apparatus in (a) side and (b) front views.

You will test at least three straw lengths in the range 8 cm $\pm$ 0.1 cm to 15 cm $\pm$ 0.1 cm. You are free to choose the lengths as you see fit. For accurate modeling of the straws, we need as many different lengths as possible so please try to choose differently than your colleagues on other teams. For each straw length you must run a minimum of 5 tests for a total of 15 tests. To ensure accurate results, please make sure that

1. All straws used are straight.

2. All straws are double-pinned at both ends with the first pin 5 mm from the end and the second 5 mm in from that (see Fig. 2.1).
3. All pins (at both ends) are aligned perpendicular to the straw axis and parallel to each other.
4. The straws are oriented vertically in the tester.
5. The straws are supported by the pins sitting squarely in the slots, not by the straw ends.
6. The hinged lever arm is horizontal and perpendicular to the straw in all directions.

3.1.1 Prior to coming to lab

To ensure timely performance in the lab, there are a few items you need to complete before coming into your testing time.

1. Read this document carefully (hey, you're already doing that one! Good work.)
2. Sign up for a testing time.
3. Decide upon the three lengths of straws you will test and then carefully cut at least six straws in each length. A pair of scissors is sufficient for this.

3.1.2 Prior to commencing data collection

Once you arrive in the lab but before beginning your data collection, you need to do a few things.

1. Pin all your straws carefully. To ensure your pinning is consistent, it is highly recommended that you take advantage of the pinning jigs.
2. Record necessary experimental information. There are a few data points you will need in your analysis and report. Among the items you should record are
   (a) the number of the tester,
   (b) the mass of the straw tester arm (engraved on the arm),
   (c) the distance from the center of the arm's pin to its center of gravity as noted by a line engraved on the arm.
3. Draw a FBD of your apparatus. This needs to be checked off by the GTF and included in your report. Note that the GTF is *only* verifying that you did a FBD, not checking its accuracy. Be sure to double-check (and maybe even triple-check) your FBD to ensure it accurately describes the testing scenario.
4. Consider the rigid body static equilibrium analysis of the straw tester to be sure you have recorded all the information you need.

3.1.3 Data collection

It is important to have accurate results. This means you will need to load the straws in small increments. As buckling nears (indicated by a straw that is bending), you should go in sizes of no more than 20 g. Of course, you have no idea where to start or what the onset of buckling looks like. That's why you cut *six* straws at each length, even though only five straws are needed. This first straw is a sacrificial straw. This one should be quickly tested first to get a sense of where buckling will occur and what buckling will look like. This will then guide your initial choice of loading and your initial step sizes.

For each straw, testing should proceed as follows.

1. Place the next mass in the bucket. Ensure the increment is less than 20 g if buckling is imminent.
2. Record the mass increment.
3. Wait for 60 seconds or until buckling occurs.
4. Repeat until buckling occurs.

Note that the max load is the last one to successfully hold for 60 seconds, not the one at which buckling occurred.

3.1.4 Before leaving the lab

There are a few things you need to do before leaving the lab.

1. Report your results to the GTF.
2. Obtain data from your colleagues for three other lengths.
3. Clean up your area.
4. Check one more time that you've done everything you needed to.

3.1.5 After leaving the lab but before doing your report

Your recordings of the load were in terms of the mass placed on the tester. The relevant number, of course, is the axial force applied to the straw. Using your FBD and the physical measurements of your apparatus, do a static analysis of your tester and convert the mass load into the actual force load (in N).

You should then organize your results. For each straw length, create a table that reports the final load (in N) for each of the five straw trials. Arrange these in descending magnitude. Report also the average magnitude and the standard deviation. An example is shown below.

Straw length: xx cm

Trial 1	147 N
Trial 2	146 N
Trial 3	146 N
Trial 4	140 N
Trial 5	120 N
Average	140 N
Std. dev.	11.4 N

3.2 Straw analysis

The load that the truss can hold is related to the strength of the straws from which it is made. Hopefully this comes as no surprise to you! The goal of this straw analysis is therefore to obtain the best estimate of the buckling strength W for a given length l of straw from that data you have obtained. It is of course impossible to test all possible lengths of straw. Therefore, the best estimate of buckling strength will be obtained from testing a finite number of lengths, and then fitting a curve (a functional relationship between the strength and the length) to that data to obtain a functional relationship between buckling strength and straw length.

3.2.1 About fitting a curve to data

There are several different techniques for fitting a curve to a data set, depending on how much information and knowledge you have about the system you were testing. Below we discuss three approaches. The first, an empirical fit, is the one **you** will use in your analysis. The second and third fit types will be investigated by GTFs, where the second is a fit to a functional form that is based on a theoretical model of the straw. The final is a semi-empirical fit, that relaxes the theoretical relationship to allow for a better fit.

Empirical fitting

This method is perhaps the most straight-forward to apply. It is not, however, based on a physical theory that relates buckling strength and straw length. This method relies on the belief that a physical relationship does exist and that the data will reveal this fit. One method to display this relationship is to use a polynomial function given by

$$W(l) = a_0 + a_1 l + a_2 l^2 + a_3 l^3 + \cdots + a_m l^m$$

where m must be smaller than the number of data points in your data set.

Since you have only three data points to work with, it is most appropriate to select a *linear* fit, so ignore the nonlinear terms and fit the data with the linear fit equation.

Fit to a theoretical curve

Since the GTFs will have the entire set of class data to analyze, they have a basis for investigating a fit that better matches buckling theory. A treatment of the straw as a long, thin, and massless rod yields the relationship for the buckling strength W as a function of the straw length l to be

$$W(l) = \frac{\pi^2 EI}{l^2}.$$

Here E is a material property known as Youngs modulus, I is the moment of inertia, and l is the length. The moment of inertia and the length are easily determined from the straw geometry but E is not easily found. It can therefore serve as an adjustable parameter to find the best fit.

Semi-empirical fit

The equation relating the buckling strength to the straw length given above is theoretically justified. However, the straws may not be kind enough to obey our theoretical derivation (perhaps due to material imperfections, experimental error, etc). A better fit may be achieved by selecting a function motivated by the theory but which can be adjusted based on the measured data. For example, recognizing that the theory predicts a buckling strength inversely proportional to some power of the length, we could define

$$W(L) = \frac{A}{L^{\alpha}}$$

where both A and α are to be chosen to get the best fit.

3.2.2 What you need to do

You have in your hands measurements from three lengths of straws (plus another three you so cleverly obtained from your colleagues – more on that in a bit). You will fit these three mean load values with a linear curve. Note that while in reality, the use of software is common place for doing curve fits, all your calculations here must be done by hand. (Why? Because we believe it is important to see and experience the details to better understand the technique.)

As your multiple trials revealed, your experimental data is uncertain due to a variety of reasons. In order to decrease this uncertainty, one can increase the number of different lengths tested, as well as the number of tests per straw length. This larger data set would allow you to obtain a better idea of the functional relationship between buckling strength and length. Of course, these two approaches are not equal in dealing with experimental uncertainty. **In your straw testing report, discuss which measurement (increasing number of tests per length, or increasing number of lengths tested) will result in a more certain estimate of buckling load versus length.**

Procedure for fitting and analyzing your data

1. Calculate the sample mean of the buckling load for each straw length according to

$$\text{Mean}_j = \overline{W}_j = \frac{1}{N}\sum_{i=1}^{N} W_i$$

   where j is an index running from 1 to 3, denoting the straw length, N is the total number of trials you performed at the length (which will be at least, and probably exactly, five), and W_i is the maximum load at that length in trial i.

2. Calculate the sample standard deviation for each mean according to

$$\sigma_j = \sqrt{\frac{\sum_{i=1}^{N}\left(W_i - \overline{W}_j\right)^2}{N-1}}$$

   where again j is an index running from 1 to 3 and denoting which straw length the data refer to.

3. Plot your sample means for each of the straw lengths you measured on a linear graph of buckling weight ($y-$axis) versus straw length ($x-$axis). This plot should be either drawn by hand to appropriate scale (graph paper is available on the course website) or using computer software (such as Excel or Matlab). Be sure to include appropriate axis labels, a legend, a figure number, and a descriptive caption. Furthermore, be sure to minimize the data range for the weights and lengths. In other words, do not draw a vertical axis spanning 200 N if all of the averages for your weight fall within a 20 N range. The smaller the range, the more accurate your fits for the graph will be. Fig. 3.2 shows an example of an acceptable plot, albeit from a completely different application.

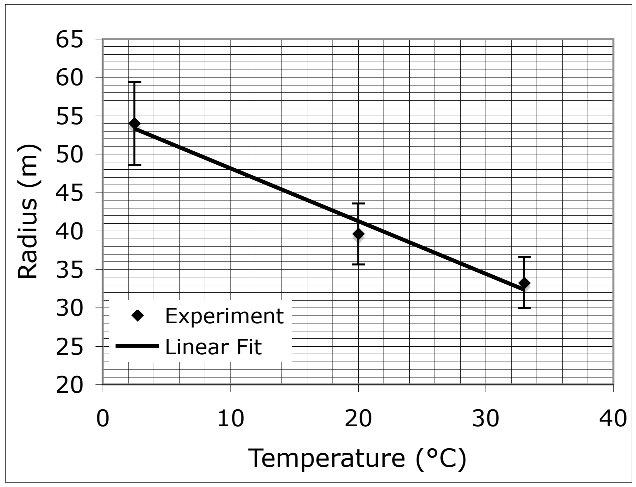


Figure 3.2: Example of an acceptable plot: Maximum expansion radius vs. temperature for a single bubble sonoluminescence experiment at 23.1 kHz.

4. Draw vertical error bars symmetrically about each data point. The error bar should extend above and below the data point by an amount equal to twice the sample standard deviation for that data point. (Recall that you calculated this above as σ_j.) This range corresponds to 95% of randomly distributed data falling within the limits defined by the error bars (known as 95% confidence intervals). You can see such error bars on the example plot in Fig. 3.2.

5. Fit a line to the data by drawing the line that visually minimizes the sum of the vertical distances between the points and the line. Determine the equation of this line by finding the slope and intercept. Report these values. Note that this line represents the best estimate of the buckling strength of any length of straw, given the data that you collected.

6. Estimate the error of the fit by determining the average vertical distance from your data points to the line. This error will have units of Newtons. In your report, discuss whether the error of the fit is small or large relative to the error bars. Discuss in your report whether it is more appropriate to use the error of the fit or the sample deviation of any single measurement when determining the failure load of your truss.

7. Plot at least three more load points for different lengths using the data you acquired from your colleagues (I did say we'd talk about these later. Later is now.) Plot these data points using a different symbol. In your report, discuss how well your fit describes their data and any reasons for the discrepancies you may find. Then, determine a new best-fit line using all six data points. In your report, discuss also the benefits of using all of the class data to determine a fit (using the results of your six-point fit as a guide).

3.2.3 What the GTFs will do

Data analysis

Recall that you reported your results to the GTF in the lab. The GTFs therefore have a data set that includes the results from the entire course. They will use this large data set to fit the data to both the theoretical model (allowing the Young's modulus to be varied to find the best fit) and the semi-empirical model (allowing both the constant A and the exponent α to be varied to find the best fit). The GTFs will report both and indicate which is the better fit.

Note that the GTFs' result will be much more accurate than yours since it is based on a much larger data set and a better model. Therefore, despite all your hard work in doing your own analysis and generating a linear model, for your truss design and failure analysis, **you must use the curve fit produced by the GTFs in all of the analysis of your trusses**.

Uncertainty analysis

Experimental expectation and historical data both agree that the curve fit will not accurately describe the data. The inherent nature of data, especially when working with a mass-produced product such as a plastic drinking straw, results in a deviation of results about a mean value. The GTFs will apply an uncertainty analysis that will account for the scatter in the data, resulting in a length-dependent uncertainty in the buckling force. This uncertainty is important to recognize and incorporate in your ultimate design analysis, since it will allow you to determine range of loads that your truss can reasonably be expected to hold before collapse. Pay close attention to the uncertainty results that the GTFs report after they analyze the data. You'll need these numbers when you design your truss.

3.3 Report on straw testing and analysis

Due on February 28.

The goal of this report is to describe your straw buckling experiment, present your data reduction and analysis, and give a discussion and interpretation of those results. For general guidelines on report writing, please see Appendix A.

The specific elements that need to be included in this report are as follows:

1. Introduction

   Describe the goal of the experiments and why you are doing them (which is not because you have to do it as part of this course...).

2. Procedure

   Describe the experimental setup and give the details on your tester, including the dimensions you measured and the number of the tester. Describe how your experiments were carried out.

3. Analysis

   Describe your method of analysis. Provide a FBD of a straw in the tester unit. Present a static equilibrium analysis of the testing machine based on that FBD. Note that it is OK to submit a revised FBD that differs from the one you showed to the GTFs during the testing. Describe your method of curve fitting.

4. Data

   You have data. Present it in a clear format. That almost certainly means a well thought-out table that includes the mass (in grams) on the tester just before buckling (not the failure mass), the size of the increment that caused buckling, the corresponding load applied to the straw (as derived from your statics analysis), and the average and standard deviation for each straw length. Organize your results for each straw in descending magnitude.

5. Results

   This is basically the plot described above.

6. Discussion

   Describe your results, the errors in your results, and how your results will impact your truss design. Answer all questions asked in this handout related to the straw testing and analysis. Provide a short commentary on any points of interest such as methods you used to cut the straws, methods for pinning, and other items that may be particularly useful to you when you design and build your truss.

This report will be graded according to the rubric given in Appendix B.

4 Computational analysis

As you are by now no doubt aware, the main thrust of this project is to design the best truss you can that meets or exceeds the specifications laid out in Section 2. That of course implies that you will need to analyze your truss designs to determine their maximum failure load. You have learned (or will learn soon) how to do this in the course of the course. You will also have learned that figuring everything out for even a small truss is no treat as determining the forces in each of the members with a known load and known support reactions leads to m coupled linear algebraic equations, where m is the number of members in the truss. The trusses you design will almost certainly have more than ten members leading to essentially a big pain in the brain. More seriously, it leads to the possibility, in fact the almost certainty, of human error if the calculations are done by hand. Thankfully, they do not need to be done by hand. Instead, you will leverage your knowledge and experience in EK 127 (or EK 128) to create a Matlab program to do this for you.

Matlab excels at solving systems of equations, particularly linear systems as in this scenario. The use of Matlab here will refresh your coding skills and is good practice for future courses and indeed your future career. Matlab may be found on the computers in the ME CAD lab (room 302 in 110 Cummington Street), in the Ingalls Engineering Center, or online through your personal computer (access instructions can be found at `http://collaborate.bu.edu/engit/MatlabRemoteAccess`).

When building any piece of software, it is essentially that you verify its correctness. This is especially true in this project since your design results rely entirely on your code. Therefore, you will need to verify the results of your program against a problem you solve by hand. A small problem will be assigned on the main class website. You will need to solve this problem by hand (on paper) and using Matlab. The results must, of course, agree. You will need to report both results in your Preliminary design report (see Sectiion 5).

4.1 Program description

The purpose of the truss analysis is to determine the internal tensile force in each member and the support reaction forces. Here we assume that all loads are known and that the structure is a simple truss. Start off by numbering each of the J joints and each of the M members, in no particular order, along with the reaction forces S, as illustrated in Figure 4.1. where $S_{x,1}, S_{y,1}$ are the unknown support reactions at joint 1 and W is an

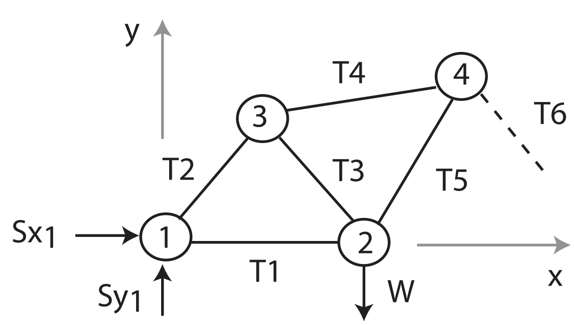


Figure 4.1: Illustration of joint and member numbering

applied load (i.e., the weight on the relevant joint in your design).

There will be M+3 unknowns, M coming from the unknown loads in the members and three coming from the unknown reactions since there is one pin joint and one rocker joint. By doing an equilibrium analysis at all the joints (i.e. using sum of forces in x equals zero and sum of forces in y equal zero), we can obtain $2J$ equations. In order to solve for the member tensions in a simple truss, the number of equations should be equal to the number of unknowns. Of course, you are asked to build a simple truss in which the number of joints and the number of members is related by $M = 2J - 3$. How fortuitous.

4.2 Algorithm

The following algorithm consists of two stages:

1. A definition of the truss parameters: the joint locations, the member-joint connections, the reaction forces locations, and the load magnitude.
2. A construction of the system of equilibrium equations and solution for the unknown forces.

4.2.1 Defining the truss parameters

First we define a *connection matrix* **C**. This matrix has j rows and m columns, where the row represents the joint number and the column represents the member number (thus, the first column corresponds to member 1 and the first row corresponds to joint 1). We indicate the connection of member 1 to joints 1 and 2 by placing a '1' in column 1 of rows 1 and 2. If a given joint is not connected to a given member, we place a '0' in the matrix location that corresponds to the joint and member numbers. This can summarized as:

$$C_{j,m} = \begin{cases} 1, & \text{if member } m \text{ is connected to joint } j \\ 0, & \text{elsewhere} \end{cases}$$

The end result should work out such that the sum of each $column$ is 2, since each member is only connected to two joints. The sum of each row should equal the number of members attached to the corresponding joint. For the arrangement shown in Fig. 4.1 (ignoring member 6), we would have the following connection matrix:

$$C = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 \\ 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 \end{bmatrix}.$$

Next we construct a connection matrix for the support forces along each axis, where $\mathbf{S_x}$ and $\mathbf{S_y}$ are matrices with j rows and 3 columns. Note that for our statically-determinate truss, supported by one pin and one roller joint, we will have a total of three unknown reactions. In each matrix, for each unknown reaction force, put a '1' in the column that corresponds to the joint j (there should be only a single entry of '1'; note that this is true in both matrices even though we know that for the loading conditions in this project, there are no support forces in the x direction) (and, another parenthetical note: be sure you understand and agree with the previous parenthetical remark!). For the example in Fig. 4.1, we get

$$\mathbf{S_x} = \begin{array}{c} \begin{matrix} S_{x1} & S_{y1} & S_{y2} \end{matrix} \\ \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \end{array}, \qquad \mathbf{S_y} = \begin{array}{c} \begin{matrix} S_{x1} & S_{y1} & S_{y2} \end{matrix} \\ \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \end{array}$$

The truss is also defined by the location of the joints; to capture these we construct two location vectors X and Y. Each has j elements corresponding to the relevant location of the jth joint; that is

$$X = [x_1, x_2, x_3, x_4, ...], \ Y = [y_1, y_2, y_3, y_4, ...];$$

Choose your reference frame carefully and then locate the position for the joints accordingly.

Finally, we define the load vector L. This vector has $2j$ elements; the first j elements correspond to loads in the x direction for each of the j joints, and the last j elements represent loads along the y direction. In our example in Fig. 4.1, the vertical force W for the load is placed on joint 2 and therefore

$$L = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ W \\ 0 \\ 0 \end{bmatrix} \begin{array}{l} \text{no horizontal load at J1} \\ \text{no horizontal load at J2} \\ \ldots \\ \ldots \\ \text{no vertical load at J1} \\ \text{load } W \text{ in the negative vertical direction at J2} \\ \ldots \\ \ldots \end{array}$$

4.2.2 Constructing the equilibrium equations

We would like to construct the equilibrium equations using only the matrices and vectors described above. We can achieve this by using the method of joints of determine the forces at each joint j. To describe the method, we turn to our example in Fig. 4.1. Consider, then joint 1, pictured in Fig. 4.2.

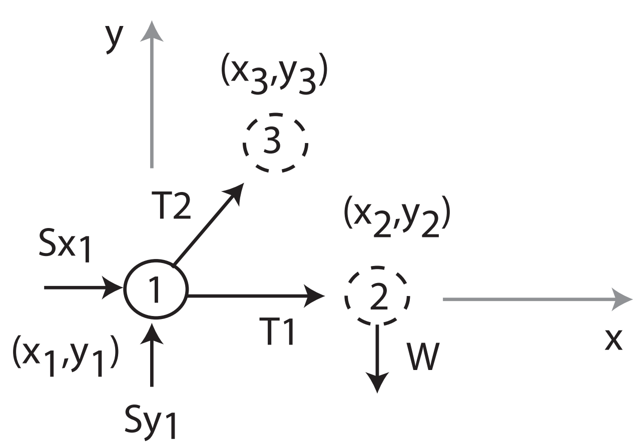


Figure 4.2: Illustration of the method of joints at joint 1.

Summing the forces in the x–direction, we get

$$\begin{aligned} \sum F_{x,1} \quad : \quad & \left(\frac{x_2 - x_1}{r_{1,2}}\right) T_1 + \left(\frac{x_3 - x_1}{r_{1,3}}\right) T_2 + 0 \cdot T_3 + 0 \cdot T_4 \\ & +0 \cdot T_5 + 1 \cdot S_{x,1} + 0 \cdot S_{y,1} + 0 \cdot S_{y,2} = 0 \end{aligned}$$

where $r_{1,2}$ is the distance between joint 1 and 2. Pay close attention to the direction along which you are defining the tension force! The rest of the joints would be considered by working out the equilibrium equations along the

x axis, resulting in a total of j equations along the x–axis. For the arrangement in Fig. 4.1, the second equation would represent $\sum F_x$ for joint 2, and so on. After considering the x–axis, we move on to the y–axis. The sum of the y–forces at the first joint is given by

$$\begin{aligned} \sum F_{y,1} \quad : \quad & \left(\frac{y_2 - y_1}{r_{1,2}}\right) T_1 + \left(\frac{y_3 - y_1}{r_{1,3}}\right) T_2 + 0 \cdot T_3 + 0 \cdot T_4 \\ & +0 \cdot T_5 + 0 \cdot S_{x,1} + 1 \cdot S_{y,1} + 0 \cdot S_{y,2} = 0 \end{aligned}$$

Note that this is written in a general form given the position of the joints. For example, the first term in the equation $(y_2 - y_1)$ is clearly zero since those two joints are on the same horizontal line.

The goal now is to use linear algebra to solve of the unknown forces by separating the system of linear force equations into three matrices, A, L, and T where

$$A \times T = -L \tag{4.1}$$

and A is a matrix that should be populated by the coefficients of the force for the respective member tension at each joint, starting with the forces along the x axis for rows 1 to j, and finishing with the forces along the y axis for rows $j + 1$ to $2j$. It should be $2j$ rows and m+3 columns, where the last three columns are the S_x and S_y matrices. That is,

$$A = \begin{array}{cl} \begin{array}{|ccccc|ccc|} m_1 & m_2 & m_3 & m_4 & m_5 & & \mathbf{S} & \end{array} & \\ \begin{bmatrix} \frac{x_2-x_1}{r_{1,2}} & \frac{x_3-x_1}{r_{1,3}} & 0 & 0 & 0 & 1 & 0 & 0 \\ \frac{x_1-x_2}{r_{1,2}} & 0 & \frac{x_3-x_2}{r_{2,3}} & 0 & \frac{x_4-x_2}{r_{2,4}} & 0 & 0 & 0 \\ 0 & \frac{x_1-x_3}{r_{1,3}} & \frac{x_2-x_3}{r_{2,3}} & \frac{x_4-x_3}{r_{3,4}} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{x_3-x_4}{r_{3,4}} & \frac{x_2-x_4}{r_{2,4}} & 0 & 0 & 0 \\ - & - & - & - & - & - & - & - \\ \frac{y_2-y_1}{r_{1,2}} & \frac{y_3-y_1}{r_{1,3}} & 0 & 0 & 0 & 0 & 1 & 0 \\ \frac{y_1-y_2}{r_{1,2}} & 0 & \frac{y_3-y_2}{r_{2,3}} & 0 & \frac{y_4-y_2}{r_{2,4}} & 0 & 0 & 0 \\ 0 & \frac{y_1-y_3}{r_{1,3}} & \frac{y_2-y_3}{r_{2,3}} & \frac{y_4-y_3}{r_{3,4}} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{y_3-y_4}{r_{3,4}} & \frac{y_2-y_4}{r_{2,4}} & 0 & 0 & 0 \end{bmatrix} & \begin{array}{l} \text{x components} \\ - \\ \text{y components} \end{array} \end{array}$$

The magnitudes of the unknown forces will be T are defined in a matrix consisting of one column and m+3 rows:

$$T = \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \\ S_{x,1} \\ S_{y,1} \\ S_{y,2} \end{bmatrix}$$

The L matrix was defined above. Since we are interested in solving for the unknown forces in T, but know the magnitudes that populate A and L, we can invert Eq. 4.1 to solve for T to get

$$T = A^{-1}(-L). \tag{4.2}$$

Important note: When there is no loading on the truss along the x-axis, as will be the case for your straw truss load, you must make sure to still represent the $S_{x,1}$ constraint in the matrix calculation. Failure to do so will prevent your matrix from being invertible.

4.2.3 File format

To ensure uniformity (and to help guide your programming), the following requirements must be followed for your Matlab program so that it can accept a standard input and create a standard output.

Input format

1. The first line should start with the character % (the Matlab comment command), followed by 'EK301', your section, group number, and the current date.
2. The next line(s) should start with the character % and list all names of your group members and their ID numbers.
3. Next comes the definition of the connection matrix C.
4. Then the definition of the matrix of reaction forces in the x-direction.
5. Then the definition of the matrix of reaction forces in the y-direction.
6. Then the definition of the vectors X and Y joint locations.
7. And finally the definition of the vector of applied external loads L.

As an example, for the geometry in Fig. 4.1, an acceptable program would accept a file with the following **EXACT** format.

```
\% EK301, Section A1, Group 1, 2/15/11.
\% Billy Bob, ID 234323234
\% Suzy Q ID. 2340980982
C = [1 1 0 0 0;
     1 0 1 0 1;
     0 1 1 1 0;
     0 0 0 1 1];
Sx = [1 0 0;
      0 0 0;
      0 0 0;
      0 0 0];
Sy = [0 1 0;
      0 0 1;
      0 0 0;
      0 0 0];
X = [0 1 .5 1.5];
Y = [0 0 1 1.3];
L = [0 0 0 0 0 1 0 0];
```

Output format

The output from your code should reproduce the input file header, give the date the file was executed, the applied load, the truss cost, and the load/cost ratio for the truss. Your code should print out the label for each member, and the magnitude of the member's load with a (T) if in tension or a (C) if the member is in compression. It should also list the label for the reaction force, followed by the calculated value. For example, if the load you apply is 1 N, and the members have been designated as m1, m2, ... m15, the output should appear as:

```
\% EK301, Section A1, Group 1, 2/15/11.
\% Billy Bob, ID 234323234
\% Suzy Q ID. 2340980982
\% DATE: 04/29/11
Load: 1 N
Member forces in Newtons ± uncertainty in force:
m1: 0.991 ± 0.03 (C)
m2: 0.273 ± 0.008(T)
. . .
m15: 0.827 ± 0.023 (T)
Reaction forces in Newtons:
Sx1: 0.0
Sy1: 0.75
Sy2: 0.25
Cost of truss: $319
Theoretical max load/cost ratio in N/$: 0.0031
```

4.3 Modeling details

There is a bit of an odd drawback to the computational analysis. It is best illustrated by referring back to Figure 2.1. Notice that there are *two* relevant straw lengths: the joint-to-joint length and the actual straw length. Think for just a minute: which one of these lengths determines the **load** in the individual straws?

Did you think for a minute and try to answer this? Please do so! (Really, it does help with understanding.) We'll wait...

OK, hopefully you see that it is the **joint-to-joint** length that matters in determining load. After all, in all your analysis of trusses in class, that is exactly the length you used. Your program will return the load in all the straws in response to a test load of, say 1 N. To determine the theoretical failure load, F_{theory}, you essentially ramp up that test load until one of the straws is at its maximum load (as determined by the straw testing analysis and the joint-to-joint lengths). Note that adjusting that load up by hand is a terrible way to find that max load – that's just the concept behind it. You should come up with a better way of actually determining it. In fact, if you read this entire document carefully you'll find a better way.

The strength of the straws, however, is determined entirely by their actual length. Thus F_{theory} under-predicts the actual failure load. Why under predict? Think for a moment – we'll wait... The reason, of course, is that shorter straws are stronger than longer straws and the actual straws are all shorter than the joint-to-joint lengths. You therefore need to adjust your theoretical failure load based on the ratio of the joint-to-joint length and the actual length of the straw that's going to fail to find the actual failure load F_{actual}. That adjustment is given by

$$F_{actual} = \frac{l_{joint-to-joint}}{l_{actual}} F_{theoretical}.$$

5 Preliminary designs

This project specifies a set of somewhat conflicting requirements for the truss. In general, stronger trusses are more expensive. There is not really a “best” solution and thus you will need to balance strength, cost, and load-to-cost ratio. The primary goal of the preliminary design phase is to explore (at least) two different options to get a sense of how the different design decisions affect the results. Each truss should be fully analyzed, a process that includes the following:

1. **Prediction of the force in each member for a given vertical load given at the specified load joint.**

   This prediction should be computed using your Matlab program. It should include not only the magnitude of the force in each member but also whether that member is in tension or compression and the uncertainty of the force (to 2 significant figures).

2. **Determination of the member to buckle first.**

   This should be calculated based on the class average best-fit nonlinear relationship between buckling load and straw length. This should be based on the *joint-to-joint* length. (Keep in mind, however, that the *actual load* the straw can support is determined by its actual length.) Report the member, its length, its predicted buckling strength, and the uncertainty in that strength.

   Note that in your Matlab analysis, you determine the loads in each member for a given load of, say, 1 N. Since the analysis is linear, as the applied load is scaled up, the loads in each member are also scaled up proportionately. Thus, to find the member that buckles first, you can calculate the ratio of compression force to buckling load. The member with the largest ratio is the one that will fail first. This ratio can then be used to calculate the maximum theoretical load for the truss (which is the next step, below).

3. **Specification of the maximum load that the physical truss could support.**

   This maximum load should again come be based on the joint-to-joint lengths. (You cannot use the actual straw lengths because you are not building the truss...yet.) Report the maximum load and the uncertainty in that load. To calculate this last item, use the uncertainty in the strength of the member that will buckle first, expressed as a percentage uncertainty. Then multiply your maximum load by this percentage to get the uncertainty.

4. **Calculation of cost and theoretical load-to-cost ratio.**

   The cost of the truss should be calculated based on the joint-to-joint length. Please note that you are not actually paying any money; this is a artificial cost from an artificial formula. The formula (given in the Specifications section), however, captures some real engineering considerations. For example, the number of joints is weighted heavily, partly because joints are expensive to fabricate but also because it is a reflection of the number of shorter straws that must be used. Shorter members may be desirable due to their increased strength, but they require custom lengths. Such custom operations cost money. The formula also depends on the total strength length; this of course represents the total amount of material needed.

   The load-to-cost ratio is exactly that: the ratio of the maximum load to the cost for the truss.

It is strongly suggested that you develop an automated means for calculating the member to fail, the cost and load-to-cost using Excel, Matlab, or similar. This will allow you to easily compare different designs. To encourage design optimization, the cost, load, and load-to-cost ratio will be graded relative to the performance of the rest of your section.

5.1 Preliminary design report

Due on April 9

The goal of this report is to describe and discuss your two preliminary designs. For general guidelines on report writing, please see Appendix A. The grading rubric can be found in Appendix C.

The specific elements that need to be included in this report are as follows.

1. Introduction

   Describe the motivation for your preliminary designs, the rationale for using a computer program to analyze a truss, and how you plan on using the results of the analysis for the remainder of the project.

2. Procedure

   Describe also any procedures you used for coming up with your designs.

3. Analysis

   Describe your computational approach. Demonstrate that you can use Matlab to correctly analyze a truss by working the problem assigned on the web site in two ways,

   (a) by hand (Note that it is OK to submit a handwritten solution so long as it is neatly presented.)
   (b) by Matlab. Include a print-out of the Matlab code and of the final result

   Of course, the results from the two methods must agree. If they don't, you need to figure out and correct the problem before submitting your report.

   Describe your uncertainty analysis and any other relevant methods you used.

4. Data

   Data in this portion of the project includes the diagram of each design with all members and joints clearly labeled in a fashion consistent with the output of your software. Highlight the member that will buckle first. It also includes the output of the Matlab code with the load in each member. This is probably best reported using a table that includes:

   (a) member number (consistent with the design drawing)
   (b) Joint-to-joint theoretical member length
   (c) Buckling strength and uncertainty based on the joint-to-joint length and the class average buckling strength fit and uncertainty of the buckling strength
   (d) Magnitude and uncertainty of the force at theoretical maximum truss load
   (e) Whether in tension or compression

5. Results

   The results include the critical member, its length and buckling strength and uncertainty, the maximum theoretical load and uncertainty, truss cost, and load-to-cost ratio for each design.

6. Discussion

   Discuss your results, comparing the two designs. Draw some conclusions about which is the better design and why as well as how you might further improve your trusses.

6 Final design

After completing your preliminary design report, we will report to you the top designs in your section in terms of load, cost, and load-to-cost. You will then have a chance to redesign your truss. Keep in mind that since your grade is based in part on how your design stacks up against other designs in your section, it is worthwhile to spend some time trying to improve your design to be the best. Of course, your design will not likely be the best in all categories. Eventually, of course, you need to settle on a final design and provide a full analysis as in the preliminary design phase.

6.0.1 Final design report

Due on April 26 by 4 p.m.

The report is similar to the preliminary design report. The grading rubric can be found in Appendix D. It should include the following specific elements.

1. Introduction

   Describe your motivation and approach for your final design; did you focus on cost? on max load? on load-to-cost ratio? on a combination?

2. Procedure

   Describe any changes you made in the design procedure you came up with for the preliminary designs. (If you have not made any changes, you can simply note that.) Describe your plans for construction.

3. Analysis

   Note any changes from your analysis used in the preliminary designs. As before, if you have not made any changes then you can simply note that.

4. Data

   Include your final design drawing with all members and joints clearly labeled in a fashion consistent with the output of your software. Highlight the member that will buckle first. Include the same type of table as you did in your preliminary design report listing the output of your Matlab code.

   In addition, add columns to that table for the following.

   (a) Actual straw length for each member
   (b) Maximum supported load and uncertainty, using the actual straw length
   (c) An ”engineering intuition” adjustment to that buckling strength. This adjustment is intended to account for the quality of your construction, the quality of your particular materials, your past experience with the straws, previous lives as a builder of trusses, effects due to phase of the moon and the color of your best friend’s pet fish, and so on. Keep in mind that this adjustment is purely optional and could be up or down, but should definitely be *small*.
   (d) Force in the member for the predicted actual maximum truss load for the constructed truss.

Of course, to get some of those numbers you will need to at the very least have cut your actual straws and, preferably, have constructed your final truss.

5. Results

   Give the critical member, its length and buckling load, the theoretical maximum load, truss cost, and load-to-cost ratio and the actual maximum load, truss cost, and load-to-cost ratio and the adjusted maximum load. Include the uncertainty for all of the loads (but don't worry about factoring in a range for the load-to-cost ratios based on the uncertainty).

6. Discussion

   Discuss the rationale for your design, including how you optimized it. Show at least three valid alternate early truss designs with their design drawings and the corresponding computed results (critical member, theoretical max load, cost and load-to-cost ratio only). Note that two of those designs can by the ones used in your preliminary design report. (Yes- you understood that right. You need to do an additional preliminary design.) Describe how your design evolved and what design decisions you made along the way.

   For your final design, discuss your (intended) building technique.

   Give also a discussion of your adjusted estimate; how did you come to your adjustment? What is it capturing?

7. Appendix: Meeting minutes of the Hartford roof collapse discussion

   On the course web site you will find assigned reading on the Hartford roof collapse. Your team should have a meeting to discuss these readings. In your discussion, pay special attention to the use of computer programs in analysis and design. Discuss also an appropriate safety factor to be used on your own truss if it were to be used in a case where human life is at risk and report what maximum load you would claim for your design. Consider variability in materials and construction and any other factors you deem relevant. Be sure to keep in mind the Fundamental Canon No. 1 from the Code of Ethics of Engineers, National Society of Professional Engineers, 1997: "Engineers shall hold paramount the safety, health, and welfare of the public in performance of their professional duties."

   During this meeting you should assign someone to take minutes; those minutes should be submitted in an appendix to the final report. The minutes should adhere to the following guidelines.

   (a) The date, time, and place of the meeting should be recorded along with the names of the participants. The (acting) chair of the meeting and the recorder (minute taker) should be identified.
   (b) The planned agenda should be attached.
   (c) The important points should be summarized, along with who suggested each of them.
   (d) The conclusions should be recorded and any action items listed, with the responsible person identified.
   (e) The date, time, and place of the next meeting should be given, if schedule, or the disposition of the group require. For example, a date for when a decision as to a follow up meeting will be made or a decision that no further meetings of this group are needed. (Note that we fully expect that this last is the one most likely to be used.)

6.1 Matlab script

E-mail your Matlab script (one per group) to the designated GTF by the final report deadline so that your program and its output can be verified.

7 Construction and testing

This is arguably the most fun element of the project. I mean, analysis is great, design is interesting, but building something and then breaking it? Now that's fun!

The testing apparatus is illustrated in Fig. 7.1. The truss will be placed on the horizontal surface of a frame, elevated approximately 18 inches off the ground. A pin will be inserted into the center of the joints at each end of your truss. One of these pins will be placed in a 'v' groove, creating a pin joint. The other will rest on a smooth surface, creating a rocker joint. Adjustable vertically oriented support rods are provided to support the truss out-of-plane. (These are not shown in Fig. 7.1 but can be seen in the photographs on the cover page of the report.) Pins will be inserted through the center of the load joint and a loop of string will be attached. The weights will be hung on this string. The testing apparatus will be available for inspection during straw testing.

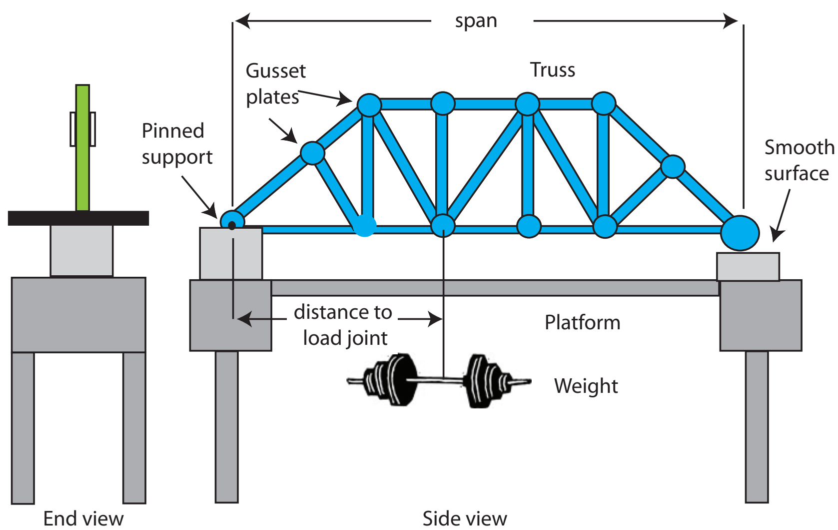


Figure 7.1: Cartoon of the testing apparatus

7.1 Construction

The accuracy of your prediction and the performance of your truss depends in no small part on the quality of its construction. Key points to keep in mind are for all straws at a joint to intersect at a common point, for gusset plates to be as small as possible, for the entire construction to be planar, and, of course, for the truss to conform to all specifications (locations of pins, lengths, cost, etc.). It is highly recommended that you consider carefully how you will build your truss so that it is as close as possible to your design.

There are two particular items that are unique to our testing setup. First, the distance between the pin support and the surface beneath it is only 1 cm. You therefore **must trim the gusset plate** at this joint to be as close to the joint as possible. If it extends too far below the pin, the pin will not rest properly on the support.

Second, these trusses can hold a surprising amount of weight. In fact, the weight can be enough for the pins supporting it to rip right through the gusset plate material before the truss itself fails! Therefore, at your loading joint you need to ensure extra strength. You must thus double up the gusset plates at the loading joint.

7.2 Testing

Testing will occur on April 27. Your entire team must be present for the actual testing. If you have a legitimate conflict on this day, please see your instructor as soon as possible in the semester to make alternative arrangements.

When you show up for testing, your truss will be inspected by a GTF or instructor. The design requirements (overall length, minimum straw length, etc.) will all be verified. Note that if these requirements are not met you will not be allowed to test your truss (and will thus receive a zero on this portion of the project). The overall quality of the build will be evaluated. The truss will then be loaded into the testing apparatus.

You will begin by adding the minimum weight. This weight must be successfully supported for a full minute. At that point, you may add additional weight in whatever increment you like. Each new weight must be held for 10 seconds. Failure is defined as either a member (or members) buckling or a sag of a portion of the truss by more than 6 cm below the end joint line. The buckling load is the last successfully supported load, not the one that actually causes failure. Since your final grade depends in part on how close your actual load is to your prediction (within the uncertainty bounds – this is why the uncertainty is so important!), you will want to go in small increments as you get close to your theoretical limit.

Trusses can hold either less or more weight than predicted (or, rarely, exactly as much as predicted). Once you reach your predicted load, the natural inclination is then to throw on as much additional weight as possible to force a failure. Unfortunately, this does not give a true representation of the strength of your truss. Thus, each additional increment after the first can be no larger than the previous one.

8 Grading

A numerical grade with a maximum of 100 points will be assigned via the following proportions.

1. Straw testing and report: 20%
2. Preliminary design report: 25%
3. Final design report: 25%
4. Calculated theoretical load, cost, and load-to-cost ratio: 15%
5. Accuracy of maximum load prediction and failure member: 15%

Your grade on the theoretical load, cost, load-to-cost ratio, and accuracy of your maximum load prediction will be determined **in comparison to the other teams in your section**. In each category, the team with the best result will get maximum credit with the other teams getting lower credit based on how close they are to that maximum (and yes, if you are very close to the maximum you will also get full credit. A one gram difference out of a 1 kg load, for example, is not significant). We will report the maximums in each category after the preliminary design phase so that you may choose to redesign your truss.

Note that your final design must meet all the specifications. Failure to come up with a design to meet those specifications will lead to a maximum grade of 60% on the project.

The different grading rubrics are given in the appendices.

Acknowledgements

This project was originally conceived and developed by M. Isaacson and S. Grace in 1996. Major revisions over the years have been done by, among others, S.B. Andersson, C. Farny, S. Grace, G. Holt, M. Isaacson, T. Melamed, T. Murray, J. Sullivan, A. Tomboulides, and D. Wroblewski. There have probably been others as well.

Date of this (the latest and greatest (?) revision): February 6, 2013

A Guidelines on writing reports

For all reports, proper format and proper English usage are required. All reports must be clear and user friendly. Each deliverable should be interpreted as one per design group. Be sure to include your section number on the title page, along with your team and member names. All of your reports for this course must be at least two pages long, though you should find that they are all much longer than that.

General guidelines to follow include the following.

1. Do not write in the first person.
2. Include all experimental data you collect.
3. Show all equations used and define all variables.
4. Typeset your equations (rather than writing them by hand).
5. In fact, typeset just about everything. The only exceptions are handwritten meeting notes or hand-drawn schematics.
6. Be consistent with your you name and number your plots, figures, and equations throughout the text.
7. Cite all references
8. Proofread for typos, spelling, grammar, formatting, and general writing flow. This is especially important when multiple authors are involved.

A comprehensive report should include the following. (Note that not every item is necessarily applicable to every report. That's why these are general guidelines.)

1. Cover page

   This should contain the title of the report, the name of the group, the names of the members of the group, the section, and the name of the professor of the section.

2. Table of contents

   A listing of the sections of the report and the pages on which those sections begin. (You have opened your textbooks, right? They have tables of contents that you can use as examples.)

3. Abstract

   This is a brief summary (6-10 sentences) that describes the purpose of the report and, where applicable, the main result.

4. Introduction

   This explains the purpose of the report/lab/testing that was done. Discuss what you intended to learn from the experiment/test/analysis/design and how you plan on using what you have learned.

5. Procedure

   This describes what you did to gather your data. You should describe any experimental apparatus in detail.

6. Data

   Present the data in tabular form. Do not forget to include units! Be sure to include a brief description that orients the reader to the source of the data.

7. Analysis

   Describe the analysis that you performed on the data. Show all equations with all symbols defined. Show an example for each unique calculation (e.g. sum of moments, standard deviation, mean buckling load, etc.). References any figures (such as FBDs), data tables, or tabular presentations of your results as needed.

8. Results

   Present your results in tabular and/or graphical form in a way that is easy for the reader to follow and interpret. Label and reference each table and graph.

9. Discussion

   Answer any questions that you have been asked to answer in the lab/project manual. Discuss your results. Do they make physical sense? Do they help you accomplish the goals you set out in your introduction? Discuss the uncertainty in your data and the sources of error.

10. Conclusion

    What did you learn? How will the results be used? What might you suggest doing differently next time?

11. Appendices

    Attach any hand calculations, Matlab code, extra data tables, alternative designs you considered but didn't use, and other relevant information that are important but did not make their way into the main report. Be sure to reference your appendices at some relevant point in your report. (Notice, for example, that this appendix was referenced earlier in this document.)

B Straw report grading rubric

Category	**Percentage**
Writing quality and overall presentation	15
Data presented in a clear manner (such as a table*)	7
All units specified	3
FBD drawing provided	10
Correct FBD analysis	15
Graph has axis labels, legend, etc.	5
All data points (your three, plus three others) drawn	5
Error bars drawn	5
Line fit drawn	5
Uncertainty estimate calculated	10
Error bars on plot	5
Dominant error sources identified	5
General discussion error given	5
Discussion of data and fitting given	5

* Just use a table, OK?

C Preliminary design report grading rubric

Category	Percentage
Writing quality and overall presentation	15
Rationale for using a computer program	10
Solution of assigned problem (by hand and with Matlab)	15
Design 1 diagram (consistent labels, legible diagram)	5
Design 1 max load calculation	5
Design 1 truss cost and load-to-cost ratio	5
Design 1 critical member identified with length and buckling strength	2
Design 1 error analysis	8
Design 2 diagram (consistent labels, legible diagram)	5
Design 2 max load calculation	5
Design 2 truss cost and load-to-cost ratio	5
Design 2 critical member identified with length and buckling strength	2
Design 2 error analysis	8
Discussion of the best truss	10

D Final report grading rubric

Category	Percentage
Writing quality and overall presentation	10
Cover page exists, lists team members with ID numbers, course section, and date	2
Introduction: explanation of motivation and approach	5
Final design drawing given with all members and joints labeled and all lengths and angles given	10
Matlab script e-mailed and is correct	8
Table of results with theoretical and actual calculations	20
All calculations correct	10
Uncertainty analysis given	5
Discussion of experience-adjusted estimate	2
Discussion of design rationale and optimization approach	10
Three valid design alternatives given and analyzed	13
Minutes of Hartford meeting (date, time, attendees, agenda, summary, conclusions, next meeting)	5