Session 1368

Design, Fabrication and Testing of Wooden Trusses for Undergraduate Mechanics

David Hall, Kelly Crittenden
College of Engineering and Science, Louisiana Tech University

Abstract

The sophomore engineering curriculum at Louisiana Tech University includes a mechanics course that integrates topics from statics and mechanics of materials. This three semester hour course, which is officially listed as 2/3 lecture and 1/3 laboratory, attempts to seamlessly integrate lecture, laboratory, and group problem solving. The laboratory component of the course focuses on the design, fabrication, and testing of a wooden truss made from 3/8 inch and/or ¼ inch wooden dowels supported at the joints by small wooden blocks. The truss span, which ranges from 30 inches to 50 inches, and the loading configuration are varied each term. Three potential modes of failure are evaluated, including dowel fracture due to excessive axial stress, dowel pull-out due to shear failure of the glued joint, and dowel buckling for members in compression. Over the past couple of years, we have developed experiments to quantify the tendency of a given member to fail in each of these three modes. Prior to initiating the truss design, students determine the strength and modulus of the dowels, the shearing strength of the glued joints and the buckling strength of the dowels as a function of length. Armed with this information, student teams evaluate potential truss designs and optimize their chosen configuration to support the maximum load or maximum load divided by truss weight. These trusses, which weigh less than 10 lbs and sometimes support over 3,000 lbs, are built using simple tools and require minimal faculty supervision during construction. This paper will describe all aspects of the project, including truss design rules, the method of fabrication, associated experiments, testing fixtures, testing equipment, and testing procedures.

I. Introduction

A constant challenge for engineering educators is to incorporate hands-on laboratory and design projects into their courses that appropriately reinforce engineering fundamentals. Busy instructors are often tempted to resort to a traditional lecture based delivery of course material even when laboratory resources are available. Unfortunately, outstanding projects and laboratory exercises are often dropped from courses due to the added effort required to purchase and prepare laboratory materials, develop assignments, check the testing equipment, answer questions, perform the experiments, and grade the resulting reports. To be sustainable, hands-on laboratory and design projects must be affordable and should seek to minimize the added workload imposed on the faculty and staff.

In 1999 the College of Engineering and Science implemented an introductory engineering mechanics course that successfully incorporates the design, fabrication, and testing of a wooden truss like the one shown in Figure 1. The truss design project is supported by laboratory exercises to determine material properties, pullout forces, and buckling response. This sequence of laboratory exercises and the design project have proven to be sustainable at our University, having been taught by eight different instructors over a period of four years. These course activities continue to improve with time. This paper will describe the ENGR 220 course, the truss design project, and the supporting laboratory exercises. Our aim is to provide sufficient detail to allow these activities to be incorporated into engineering mechanics courses at other institutions with minimal effort.

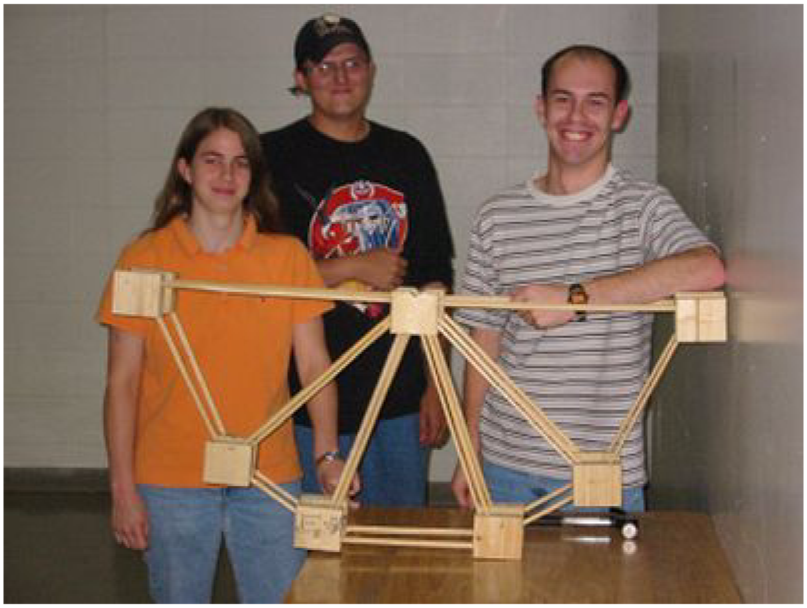

Figure 1 - A wooden truss typical of those built in our course.

II. Description of the ENGR 220 Course

Prior to the full implementation of the integrated engineering curriculum [1-4] in the 1999 - 2000 academic year, a traditional mechanics sequence of statics, mechanics of materials, dynamics and fluid mechanics was in-place for civil and mechanical engineering. One of the most significant problems associated with this traditional sequence is that students were taught to calculate forces in members, moments, centroids and moments of inertia in the statics course but were not shown how these quantities are used in engineering to analyze or design members until later courses. In ENGR 220 every concept of statics is followed by a description of its application in either analysis or design. By utilizing a "just-in-time" presentation of topics, students are motivated to learn by seeing how the concepts fit together within the context of engineering analysis and design.

ENGR 220 includes, in order of presentation, concurrent force systems; axial loads producing normal, shearing and bearing stresses at joints; axial deformations and strains; material properties; working stresses and factors of safety; moments; centroids; rigid body equilibrium; frames and machines; plane trusses; torsion; flexural loading, flexural stresses and shear stresses in beams for simple and composite cross sections; deflection in beams using superposition; stresses in thin walled pressure vessels; and stress concentrations. This course represents the final engineering mechanics course for most biomedical, chemical, industrial and electrical engineering students and the introductory course for civil and mechanical engineering students.

In an attempt to help students visualize the concepts covered in ENGR 220, the delivery format has shifted from lecture to an active learning environment which incorporates hands-on activities, laboratory experiments, and the truss design project[5]. The course is officially listed as 2/3 lecture and 1/3 laboratory, and we have attempted to seamlessly integrate the lecture and laboratory components of the course. With the exception of a benchtop universal testing machine (tensile testing machine), the equipment and supplies needed to support these projects involve inexpensive materials and parts that are readily available at hardware stores or industrial supply companies. The testing fixtures and all supplies required to support the truss design project and the associated laboratories are described in later in this paper. The truss assignment is detailed below.

III. The Truss Assignment

Teams of four students are asked to design and construct a truss to support the largest possible concentrated load at the center, as shown in Figure 2. Student teams are provided with wooden dowels for the members and blocks for the joints. A typical list of supplies for a truss that must span 42 inches is given below:

- 16 hardwood dowels 3/8 inch in diameter and 36 inches long; and
- 14 pieces of 3 inch by 1.5 inch pine boards for the joints.

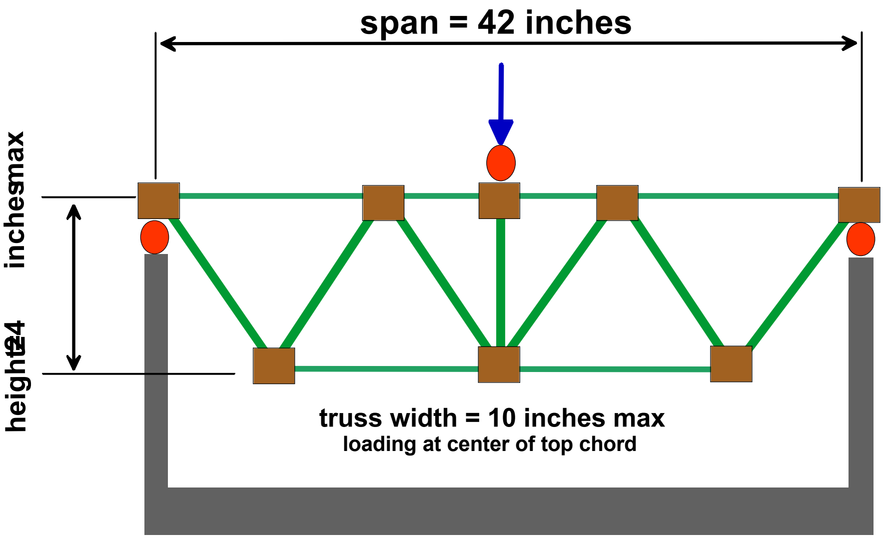

Figure 2 – Sketch given along with truss assignment.

Although the rules for the truss design vary from term to term, a typical set of rules is summarized below:

- the maximum height of the truss is limited to 24 inches;
- the maximum width of the truss is limited to 10 inches;
- the minimum height of the truss is 12 inches;
- only the blocks and dowels provided by the university may be used;
- the final design must be a truss that can be analyzed using the methods presented in class (no beams allowed);
- all contact between the truss and the loading fixture must occur at the joints;
- the blocks can not be cut to bring the total number of joints to above 14;
- no shaving, drilling, sawing, or sanding is allowed so that the weight of a block or dowel can be decreased;
- students must use the same glue used in the earlier joint strength experiments; and
- no other types of fasteners such as nails, screws, bolts, tape, bondo, or wire are allowed.

For trusses that must lie at or below the point of loading, students are cautioned to avoid any interference of the members with the loading supports, as shown in Figure 3. Students are also advised to saw a small wooden notch on each block that contacts the center loading bar to prevent the truss from sliding when loaded.

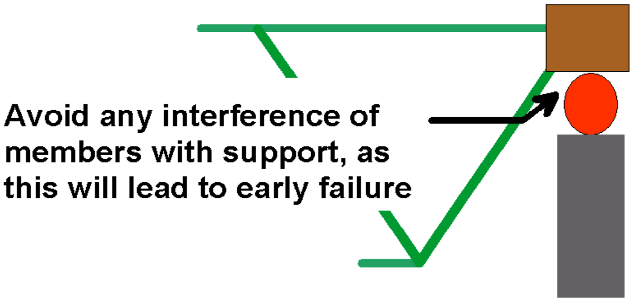

Figure 3 – Students are cautioned to avoid interference of the dowels with the supports.

The project has been designed to allow for variation in the assignment from term to term. The span, maximum and minimum truss height, glue type, number of dowels and blocks, dowel diameter, number of different dowel diameters, and truss configuration (upright or inverted) can easily be accommodated by the loading frame and testing machine. This term-to-term variation in the assignment is necessary for a meaningful and sustainable project, since the better designs and their supporting calculations could be easily “handed down” to teams in subsequent terms.

IV. Purchase and Preparation of the Supplies

Each term, the supplies required for all sections of ENGR 220 are purchased in one batch from a local lumberyard. A picture of the dowels and the wooden blocks ready to be distributed to the class is shown in Figure 4. The rectangular blocks used for the joints are constructed from 8 foot long 2 by 4s that have cross sectional dimensions of 1.5 inches by

3.5 inches. These 96 inch long boards are sawn into 3 inch pieces using a chop saw, resulting in about 31 usable pieces per board. The sawing process goes quickly, and the sawing for three sections of 40 students (120 students total) can be completed within 1 hour. Assuming 14 joints are required per team of 4 students, then a total of 420 blocks and 14 or 15 boards will be required for the truss project (some of the blocks are faulty and must be discarded). Additional 2 by 4s are also required for an additional laboratory exercise that determines the force required to pull a member out of a wooden block. This laboratory exercise is described later in this paper.

Figure 4 – Dowels and blocks ready to distribute to the class.

Wooden dowels must also be purchased. These dowels typically come in boxes of 100, and we receive a discount on the usual price since we are purchasing them in bulk. Truss designs may involve the use of two dowel diameters, or a single dowel diameter may be required. Considering both the dowels and the 2 by 4s blocks, the total cost per student for all of the expendable supplies in ENGR 220 typically runs less than $2 per student.

V. Truss Design and Analysis

This section shows the calculations required for the truss assignment given in section III. The first step in the design process is to determine the configuration of the truss. Students are given a handout with pictures of many different truss configurations, and they are required to consider and discuss at least one alternative design as part of their work. For the example whose calculations are shown in this section, the symmetric truss shown in Figure 5 is adopted.

After choosing the configuration, the force in each member must be determined using the method of joints. Most designs assume that the total external load is carried equally by two parallel trusses that are connected by cross members. Students are instructed to complete the calculations by assuming that one of the trusses carries a 1,000 lb. load. The forces shown in Figure 5 are based on this assumption. As part of the assignment, students are required to give a dimensioned sketch of their truss with tensile members colored red, compressive members colored blue, and zero-force members colored yellow.

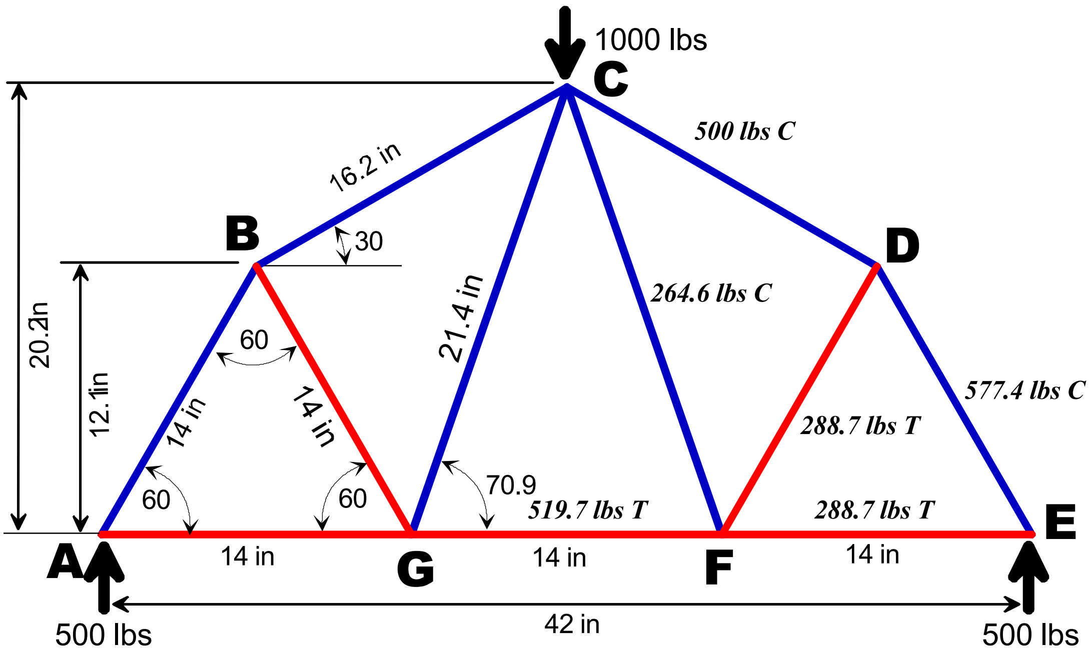

Figure 5 – Example truss design with dimensions and forces.

After calculating the forces, the students must evaluate the potential failure of each member. The failure modes considered include excessive axial stress, pull-out of a dowel from its joint for members in tension, and buckling of members in compression. Separate laboratory exercises are completed in class to quantify each of these failure modes prior to or shortly after the truss project is assigned. These three laboratory exercises are described in Appendices 1 through 3.

First, failure due to excessive axial stress is evaluated. Here, the flexural strength of the wooden dowel as determined from several three point bend tests (see Appendix 1) is used as the limiting stress. The normal stress in each member is computed as the force in the member divided by both the cross sectional area of a dowel and the number of dowels that make up the member. For the calculations presented here, we will assume that the material has a strength of 19,000 psi in both tension and compression.

Second, failure due to pull-out of a dowel from the wooden block is evaluated. An earlier laboratory evaluates the statistical variation of the pull-out strength (see Appendix 2), resulting in the shearing strength of the glue. Based on the glued contact area of the wooden dowel and the hole in the block, the force required to pull the dowel out of the joint is computed for each member in tension. If all of the holes have the same depth as the joints tested in the laboratory (the depth is typically 1.5 inches), then the pull-out force values can be used directly without the need to compute the glue stress. This method is typically adopted for simplicity. For the calculations presented here, we will assume that a dowel glued into a 1.5 inch deep hole will hold 1,090 lbs.

Third, failure due to buckling of the members in compression must be determined. Buckling experiments are carried out for the dowel size used in the truss design (see Appendix 3), resulting in the plot of buckling load versus member length shown in Figure 6. A curvefitting program called CurveExpert[6] is used to fit a curve to the data. The resulting equation for the data in Figure 6 is

$$P_{cr} = 14300 \cdot L^{-1.5} \tag{1}$$

where P_{cr} is the buckling load and L is taken as the length of the dowel between the wooden blocks (not the length shown earlier in Figure 5). Buckling is usually the most likely mode of failure for trusses, and students are cautioned to consider buckling before they choose their final truss configuration.

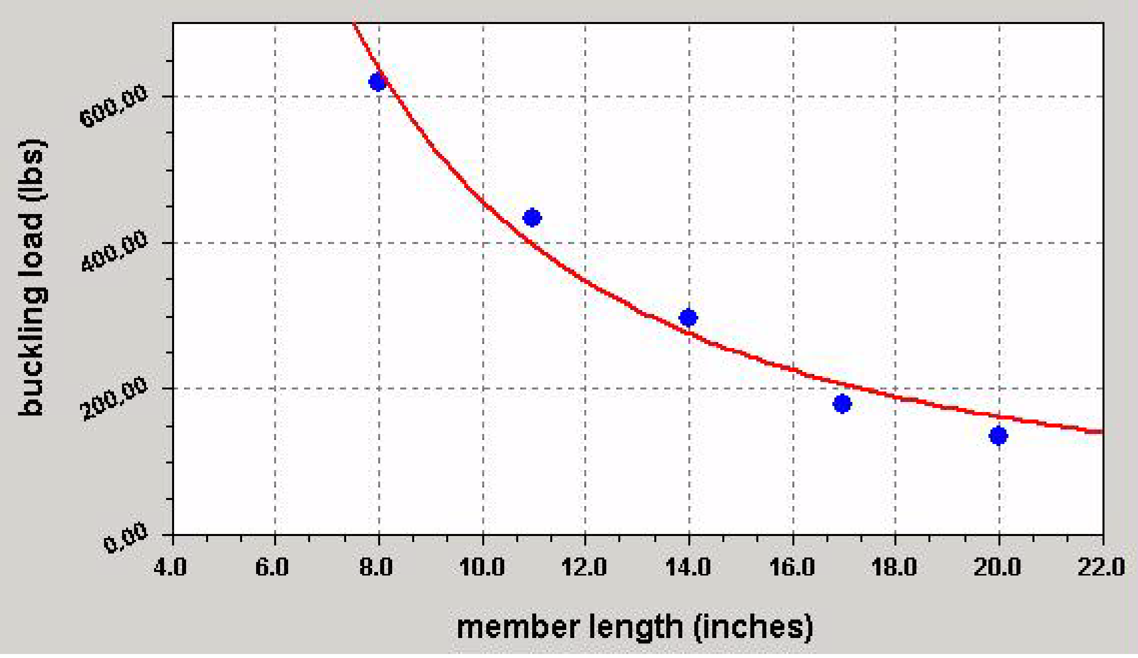

Figure 6 – Plot of buckling data and the corresponding curvefit.

After the force in each truss member is computed, the member loads, axial stresses, and buckling loads are calculated for the truss and are summarized in a single table, as shown in Table 1. Students are required to submit their results in this format, as it makes checking the results more convenient for the grader and forces the students to be complete in their analysis.

Next, students are required to complete a second table to help them arrive at the appropriate predicted failure load. The factor of safety corresponding to an applied load of 1,000 lbs on a single truss is computed for each member, and the most critical member is selected as the member with the lowest factor of safety. Table 2 summarizes these calculations.

Table 1 – Summary of forces, stresses, and buckling loads on members.

members	member diameter (in)	member length (in)*	number of dowels in member	total member force (lbs)	T or C	axial stress (psi)	buckling load (lbs)
AB, DE	0.375	11	2	577.4	C	2,620	392
AG, EF	0.375	11	1	288.7	T	2,620	--
BC, CD	0.375	13.2	1	500.0	C	4,530	298
BG, DF	0.375	11	1	288.7	T	2,620	--
CG, CF	0.375	18.4	1	264.6	C	2,400	181
FG	0.375	11	2	519.7	T	4,710	--

* This member length is the distance shown in Figure 5 minus 3.0 inches (holes are assumed to be 1.5 inches deep).

Table 2 – Evaluation of factors of safety for a load of 1,000 lbs. applied to one truss.

members	T or C	total member force (lbs)	force to cause pullout (lbs)	pullout FS	load to buckle a member (lbs)	buckling load FS	axial stress (psi)	dowel strength (psi)	axial stress FS
AB, DE	C	577.4	1,090	--	392	1.36	2,620	19,000	7.25
AG, EF	T	288.7	1,090	3.78	--	--	2,620	19,000	7.25
BC, CD	C	500.0	1,090	--	298	0.60	4,530	19,000	4.19
BG, DF	T	288.7	1,090	3.78	--	--	2,620	19,000	7.25
CG, CF	C	264.6	1,090	--	181	0.68	2,400	19,000	7.92
FG	T	519.7	1,090	4.19	--	--	4,710	19,000	4.03

In Table 2, the pullout factor of safety is computed as the force that will cause pullout (1,090 lbs) in a single dowel times the number of dowels that make up the member divided by the total force in the member. Similarly, the buckling factor of safety is computed as the load required to buckle a single member times the number of dowels making up the member divided by the total force in the member. Finally, the axial stress factor of safety is simply the dowel strength divided by the axial stress (the axial stress already accounts for the number of dowels making up the member).

After completing Table 2, the predicted failure load is calculated as 1000 times the smallest factor of safety in Table 2 times the number of parallel trusses. The smallest factor of safety occurs in members BC and CD and is approximately 0.60. Thus, for this design which employs two parallel trusses, the predicted failure load is 1200 lbs. (1,000 lbs. x 0.60 x 2). The expected failure mode for the truss is buckling in member BC or CD.

V. Truss Construction

The truss can be constructed using simple tools by students with little or no woodworking experience. A drill press and an angle vise are provided for drilling holes into the wood blocks to receive the dowels, as shown in Figure 7. A small handsaw or hacksaw is provided for sawing the dowels. The use of power tools other than a drill is discouraged, as injury could occur. Students are required to supply their own safety glasses and measuring devices when working in the University shop, and they must be given permission and safety instructions before operating any machinery in the shop. Student groups are encouraged to assemble their trusses prior to gluing to be sure that all of the parts fit properly and that the overall dimensions are correct. Figure 8 shows that some student groups discover that they have significant problems when they first assemble their truss. It is not uncommon for students to approach an instructor asking for a few more blocks and dowels. A large table covered with a cardboard sheet is provided near the shop for assembly and gluing.

Figure 7 – Students drilling holes in wooden blocks to receive the dowels.

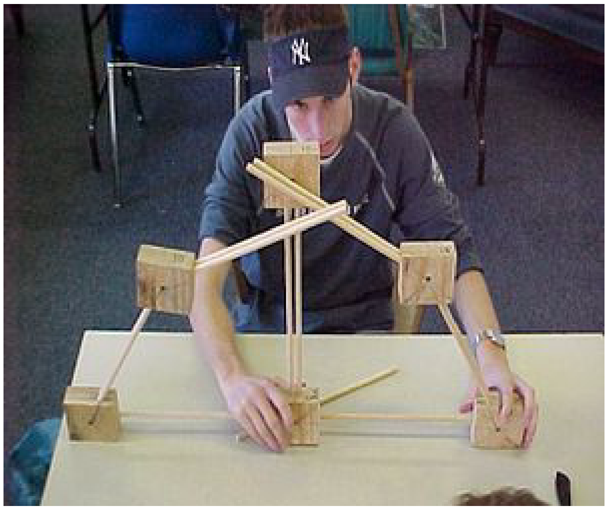

Figure 8 – A “small” problem is discovered as a student assembles his truss.

VI. Testing the Trusses to Failure

Before testing the trusses to failure, each team is required to deliver a six minute oral presentation where they predict the failure load, location and mode. Next, the truss is weighed on a digital scale (only in cases where the objective is to maximize the strength to weight ratio). The truss is then placed in a testing frame that can accommodate trusses 50 inches long, 10 inches wide, and 30 inches high. The testing frame is designed to support the truss at both ends and to apply a load in the center, although off-center loading is possible. Diagrams of the testing frame can be found in Appendix 4.

Prior to testing, the frame is mounted in a Tinius Olsen tabletop universal testing machine with a 5000 lb. capacity. A picture of the testing setup is shown in Figure 9. The cross-head speed of the machine is set to 2 to 3 inches per minute to allow students to get a clear visual image of the failure mode. The test is deemed to be complete when it is clear that the peak load has been reached. Upon failure, the maximum force applied to the truss is recorded from the LCD panel on the testing machine.

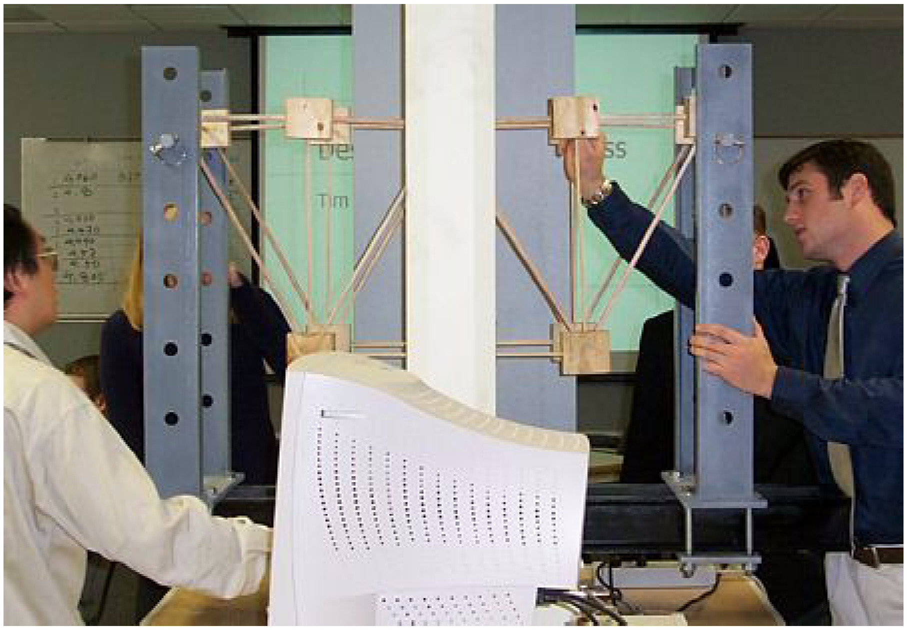

Figure 9 – Setup for testing the trusses.

The testing is often followed by a brief discussion of the failure mode and the proximity of the predicted failure load to the actual load. The predicted failure load of most trusses is larger than the actual failure load. Much of this difference is due to misalignment of the joint which induces moments in the compressive members resulting in significant reductions in the buckling load. We are considering adding eccentricity to the buckling experiment described in Appendix 3 so that predicted loads more closely match the actual failure loads.

VII. Project Grading

Grading of the truss projects is based on the design report (60%), the design presentation (30%), and on the performance of the truss (10%). The required format for the written design report is given in Appendix 5. For ease of grading and to help guide the students through the design process, the required calculations must be summarized in the format presented earlier in Tables 1 and 2, and detailed calculations must be given in the appendices of the report to allow for thorough checking.

The design presentation must be implemented in MS PowerPoint. Students are requested to dress professionally for the presentation, and all of the group members must speak. The truss performance score is based on the peak load or the maximum load to weight ratio carried by a given truss when compared to performance of the other trusses in the class. Students get 2% for participating, 6% for achieving the mean load of the class, and 10% (full credit) for having the strongest truss. The scores for groups between 2% and 10% are scaled linearly based on the minimum, mean, and maximum truss loads.

VIII. Student Assessment of the Truss Project

To evaluate student opinion of the truss design project, students who had recently completed the truss project were asked to comment on their experience. Of the 40 students surveyed, none were unhappy with the design project. Some of the comments received were:

> "[The truss project] gave us a feel of what problems can arise during design and fabrication of a project."
>
> "…we were able to actually use our calculations toward something tangible that we could see and build."
>
> " hands-on learning…practical application of what we learned in class." *This comment occurred in many forms.*
>
> "…allowed us to be truly involved in group work and to interact socially outside the classroom."
>
> "gave a better understanding of tension, compression and zero-force members (visual)."
>
> "…shows that calculations and predictions made are not always going to be exact…"
>
> "…first time in engineering that I actually go to build and test something…"
>
> "…good experience with [computer] programs such as SolidEdge and MDSolids…"

The only negative comments came from the grading scale used and the composition of some of the groups (one individual thought the groups were not well balanced). Overall, the comments showed an enthusiasm toward the truss design project and an excitement toward engineering.

IX. Conclusions

A truss design project and three supporting laboratory exercises have been presented. These projects reinforce many of the engineering fundamentals presented in our integrated statics and mechanics of materials course. The project and laboratory exercises lead to a significant amount of hands-on work and experimental analysis by the students taking the course. The design project is well-liked by the students and has proven to be sustainable over a four year period with eight different faculty members.

X. Acknowledgements

This research is partially based upon work supported by the National Science Foundation Action Agenda Grant 9972729.

Bibliography

1. Nelson, J.D. and B. Schroder. 2001. Establishing an Integrated Mathematics, Engineering, and Science Curriculum: Lessons Learned. Proceedings of the American Society of Engineering Education Meeting, Albuquerque, New Mexico.

2. Schroder, B. and J.D. Nelson. 2000. Institutionalization of An Integrated Engineering Curriculum at Louisiana Tech University. Presentation at the NSF Combined Research and Curriculum Development / Action Agenda Meeting. Washington, D.C.

3. Nelson, J. D. and S. A. Napper. 1999. Ramping Up an Integrated Engineering Curriculum to Full Implementation. Proceedings of the Frontiers in Education Conference, San Juan, PuertoRico.

4. Nelson, J.D., S. Napper, B. Elmore, J. Carpenter, B. Deese. 1998. An Integrated Freshman Engineering Curriculum. Frontiers in Education Conference, Phoenix, AZ.

5. Hall, D., P. Hadala, and F. Roberts. 2000. Laboratory Exercises for Statics and Mechanics of Materials on a Shoestring. Proceedings of the American Society of Engineering Education Meeting, St. Louis, Missouri.

6. Hyams, D.G. 1997. CurveExpert 1.3. **http://www.ebicom.net/~dhyams/cvxpt.htm**.

Biographical Information

Dr. David Hall is an Associate Professor of Mechanical Engineering at Louisiana Tech University. He earned his Ph.D. in mechanical engineering in 1995 from the Georgia Institute of Technology where he specialized in computational analysis of high temperature fracture. His research interests include trenchless technology, buckling of thin walled pipe liners, computer vision, and innovation in engineering education.

Dr. Kelly Crittenden is an Adjunct Professor of Engineering at Louisiana Tech University. He earned his Ph.D. in Biomedical Engineering from Louisiana Tech in 2001 where he used computational analysis to study the repair of femoral neck fractures. He is currently teaching a variety of freshman and sophomore level engineering courses, as well as upper level biomedical engineering courses.

Appendix 1: Determination of Flexural Strength and Flexural Modulus of Dowels

Purpose. The flexural strength and modulus of the wooden dowels are determined as an in-class laboratory experiment. The truss design project assumes that a member will fail when the axial stress in either tension or compression reaches the flexural strength of the material. The elastic modulus is not typically used for any calculations, although it can be used to estimate the buckling load of members when experimental buckling data is not available.

Materials and Equipment. At least three 12 inch long wooden dowels are required for this experiment. If time permits, the same experiment can be performed with dowels of a different diameter to reinforce the fact that dowel size does not influence flexural strength and modulus. Also, more than three samples can be used per experiment to produce more accurate results.

Testing Fixtures. A simple three point bending fixture made of wood is used for this experiment, as shown in Figure A1.1. The fixture consists of a base with a hole and two uprights. The uprights are spaced eight inches apart, and the base is bolted to the testing machine. The uprights have small notches cut in them to keep the dowels in place. The cross-head of the testing machine is fitted with the same loading bar used in testing the trusses.

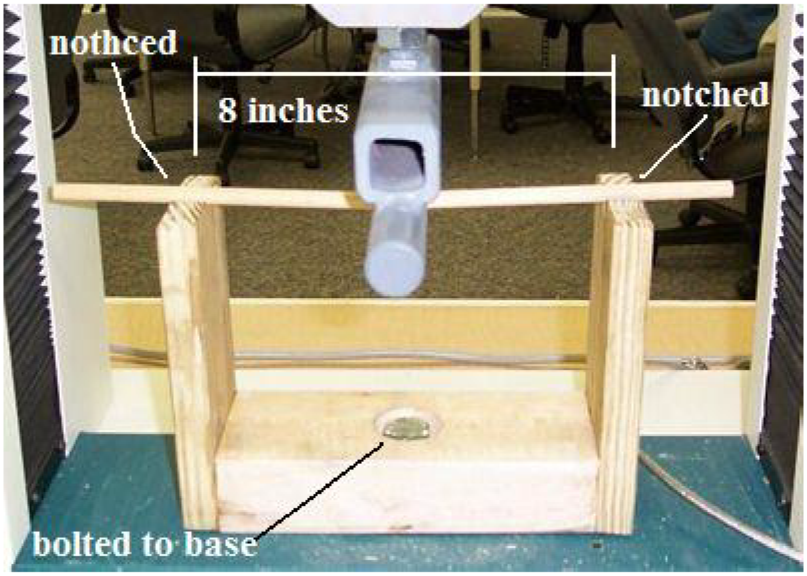

Figure A1.1 – The fixture used in the three-point bend tests.

Testing Procedure. Before testing begins, the speed of the cross-head is set to 0.5 inches per minute. A dowel is set in the notches of the uprights and centered in the testing fixture. Then, the cross-head is lowered until it comes in contact with the dowel, and the force and displacement readouts are zeroed.

If the force and displacement values are to be recorded manually, the cross-head is moved down in 0.05 inch intervals, and the corresponding force at each interval is recorded until the dowel breaks. After the data is recorded, the points are plotted (force versus displacement), and the slope of the linear portion of the graph is calculated and plugged into

$$E = slope \cdot \frac{L^3}{12 \cdot \pi \cdot r^4} \qquad \textbf{(A1.1)}$$

where L is the distance in inches between the supports (eight inches), r is the radius of the dowel, and E is the flexural modulus.

Next, the flexural strength of the dowel material is calculated using

$$\sigma_u = \frac{P_{\max} \cdot L}{\pi \cdot r^3} \qquad \textbf{(A1.2)}$$

where P_{max} is the peak force recorded during the test and σ_u is the ultimate flexural strength of the dowel material. If only σ_u is required for the analysis, which is the case when buckling data is available, then it is not necessary to record the load versus displacement data for calculating the flexural modulus. This greatly shortens the time required to conduct this experiment.

Appendix 2: Determination of Dowel Pull-Out Strength

Purpose. The purpose of the pull-out strength laboratory is threefold. First, the lab familiarizes the students with the shop environment where they will be building their trusses. Second, the lab requires each team member to submit an individual report summarizing the experiment, thereby improving the students' technical analysis and communication skills. Finally, the shear strength of the glue used to build the trusses is determined.

Materials and Equipment. Since statistical analysis is performed on the pull-out data, the number of samples should be relatively large (30 samples or more). Thus, the number of samples given to each group depends on the class size. A drill press fitted with an appropriate sized drill bit and a vise for holding the wooden blocks is required to prepare the samples, as shown earlier in Figure 7. It is recommended that an adjustable angle vise be used to hold the wooden blocks, as a vise of this type is required for the construction of the trusses. Students are given a lecture about shop safety prior to preparing their specimens.

The wooden joints produced by the teams are representative of a basic joint in a truss. Each joint is made from two wooden blocks, 3 inches by 3.5 inches and a single 3/8 inch diameter wooden dowel. The blocks and dowel are precut, so the only work to be done by the teams is to drill a hole in each wooden block to accept the dowel and then to glue the dowel in place. The glue is allowed to set for 24 hours, and the wooden joints are tested during the next available class period.

This experiment can be varied from term to term by changing the hole depth, the dowel size, or the glue type. Having multiple hole depths allows the teams to discover that the shearing strength at failure is roughly the same, regardless of hole depth.

Testing Fixtures. The fixtures used to hold the wooden joints in the Tinius Olsen testing machine are shown in Figure A2.1. These fixtures can be fabricated from 4 inch square tubing. The only fabrication work necessary is to cut the four inch square tubing into two four inch long pieces. Next, a hole is drilled in the center of one side of the square. A bolt will pass through this hole to mount the fixture to the testing machine. Finally, a slot is cut in the side opposite the hole so that a specimen can be slid into the fixtures.

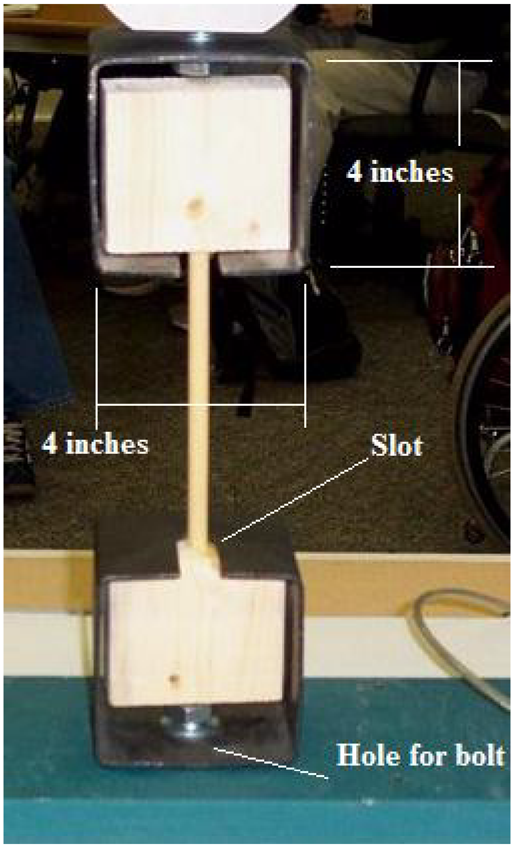

Figure A2.1 – Testing fixtures and wooden joint used for the dowel pull-out tests.

Testing Procedure. The fixtures are bolted to the testing machine, and the cross-head is set to move at a rate of 1 inch per minute, the jog (or return) speed is set to 10 inches per minute, and the machine is set to store the highest force measured during test. The initial force reading is zeroed and the testing is ready to begin.

The wooden joints are placed in the fixtures, and the loading is increased until the joint fails. The maximum force is recorded from the LCD panel of the testing machine for each sample. The mode of failure is also recorded. Although most samples fail by pull-out, it is not uncommon for a dowel or the wooden block to fracture, as shown in Figure A2.2. Only the specimens that fail due to pull-out should be used to compute the shearing strength of the glue.

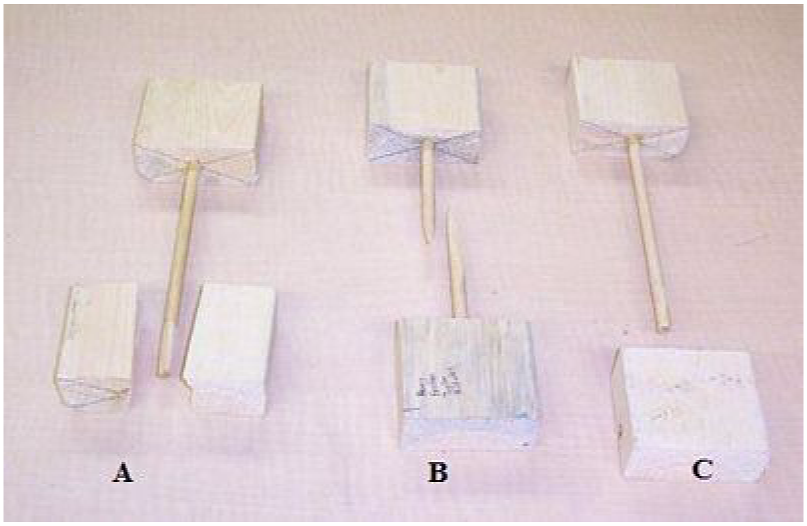

Figure A2.2 – Three of the common failure types for the wooden joints, A) broken block, B) broken dowel and C) pull-out.

Upon completion of the lab, the teams are asked to calculate the average shearing strength of the glue. First, they must calculate the strength of the glue in each sample as

$$\tau = \frac{V}{A} \qquad \textbf{(A2.1)}$$

where τ is the shearing strength for an individual sample and V is the maximum force applied to the sample. The surface area of the glue joint is computed as

$$A = \pi \cdot D \cdot h \qquad \textbf{(A2.2)}$$

where D is the diameter of the dowel and h is the hole depth. The average shearing strength of the glue is computed for all samples. This value of strength is used to estimate the pull-out load for a given depth of hole.

As an additional part to this lab, a report is required in which the teams are asked to perform standard statistical analysis on the data. Histograms of joint strength are created, and the standard deviation and mean of the pull-out force (or glue strength) are computed. More advanced statistics topics could easily be added, including confidence limits or computing the probability that a specimen subjected to a given load will fail. This experiment reinforces the importance of statistical analysis in engineering.

Appendix 3: Determination of the Buckling Resistance of the Dowels

Purpose. Dowels are loaded in compression to determine the relationship between buckling load and dowel length. This load versus length data is used to construct a plot such as the one shown earlier in Figure 6 so that the critical load of truss members in compression can be determined.

Materials and Equipment. Three sets of dowels with lengths of 11, 14, 17, 20, and 23 inches are cut for each diameter of dowel used to construct the trusses. Also, for safety concerns, a Plexiglas shield is placed around the testing machine to protect against projectiles from the buckling dowels.

Testing Fixtures. The fixtures used to hold the dowels in place are fabricated from 2 segments of 1 inch diameter round steel stock 2.5 inch long. Holes 1.5 inches deep with a diameter slightly larger than the dowel to be tested are drilled into the pieces to accept the dowel. The holes are chamfered to allow for easier insertion of the dowel that is being tested. Each of the pieces is welded to a bolt that can be screwed into the testing machine. Two fixtures are needed, one for the base and one for the cross-head of the testing machine, as seen in Figure A3.1.

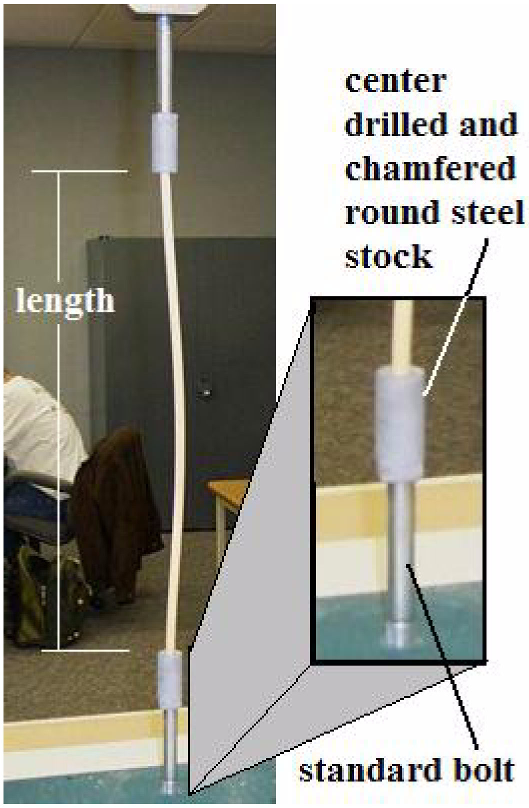

Figure A3.1 – Fixtures used to hold the dowel during the buckling experiment along with a close-up of one of the fixtures.

Testing Procedure. The dowels are placed in the fixtures, and the cross-head is lowered until the dowels are thoroughly seated in the fixtures. At this point, the exposed length of the dowels (as seen in Figure A3.1) is measured and recorded. The force readout on the testing machine is zeroed, and the Plexiglas shields are put in place. The cross-head is set to move at a rate of 0.5 inches per minute, and the machine is set to record the highest load encountered during the test. The cross-head is moved downward until the dowel buckles. After the tests are completed, the data for each dowel length is averaged, and the critical load versus dowel length is plotted. A mathematical relationship between buckling load and dowel length can be determined through fitting, resulting in an equation like the one shown earlier in Equation 1.

Appendix 4: Truss Testing Frame

The truss testing frame is designed to support a truss at both ends underneath a centered load. The truss can be either upright (as seen in Figure 5) or inverted (as seen in Figure 1). The testing frame can accommodate trusses up to 50 inches long, up to 10 inches wide and with a maximum height of 30 inches. The frame is constructed mostly from steel channel (C4 x 7.25). The truss support bars can be raised in six inch increments. It is necessary to be able to raise the supports in order to accommodate inverted trusses. The span of the truss supports is also adjustable so that trusses of different lengths can be testing using the same frame. Figure 9 in the body of this paper shows a picture of an inverted truss loaded in the testing frame.

The testing frame can be broken down into three main components: two adjustable uprights and one fixed base. The uprights, which are shown in Figure A4.1, consist of two steel channel beams that are welded to a ½ inch thick rectangular plate. The uprights are placed 12 inches apart to allow room for the truss to be placed in the frame. The upright channels are drilled to accept a support bar. The holes for the support bar are spaced six inches on center, and the support bar is held in place by snap pins on each end. The uprights are attached to the fixed base by four bolts that pass through the rectangular plate and a matching plate on the bottom of the base. As the nuts for each of the four bolts are tightened, the fixed base is sandwiched between the upper and lower rectangular plates.

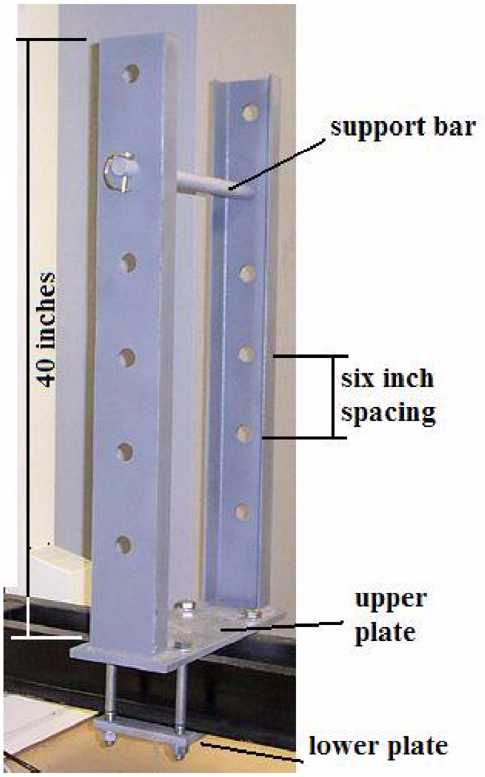

Figure A4.1 – One of the uprights that make up the truss testing fixture.

The other main component of the truss testing frame is the fixed base, as shown in Figure

A4.2. This base is bolted to the testing machine to ensure that the frame stays in place during testing. The base is constructed from two 60 inch pieces of channel connected by four 4 inch pieces of channel at the ends. The entire frame is shown in Figure A4.3.

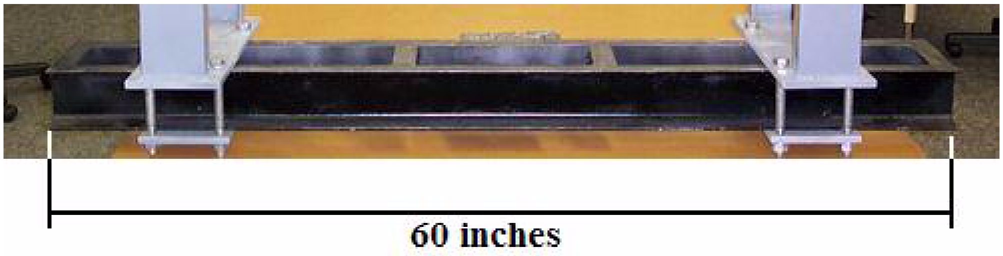

Figure A4.2 – The fixed base of the truss testing frame.

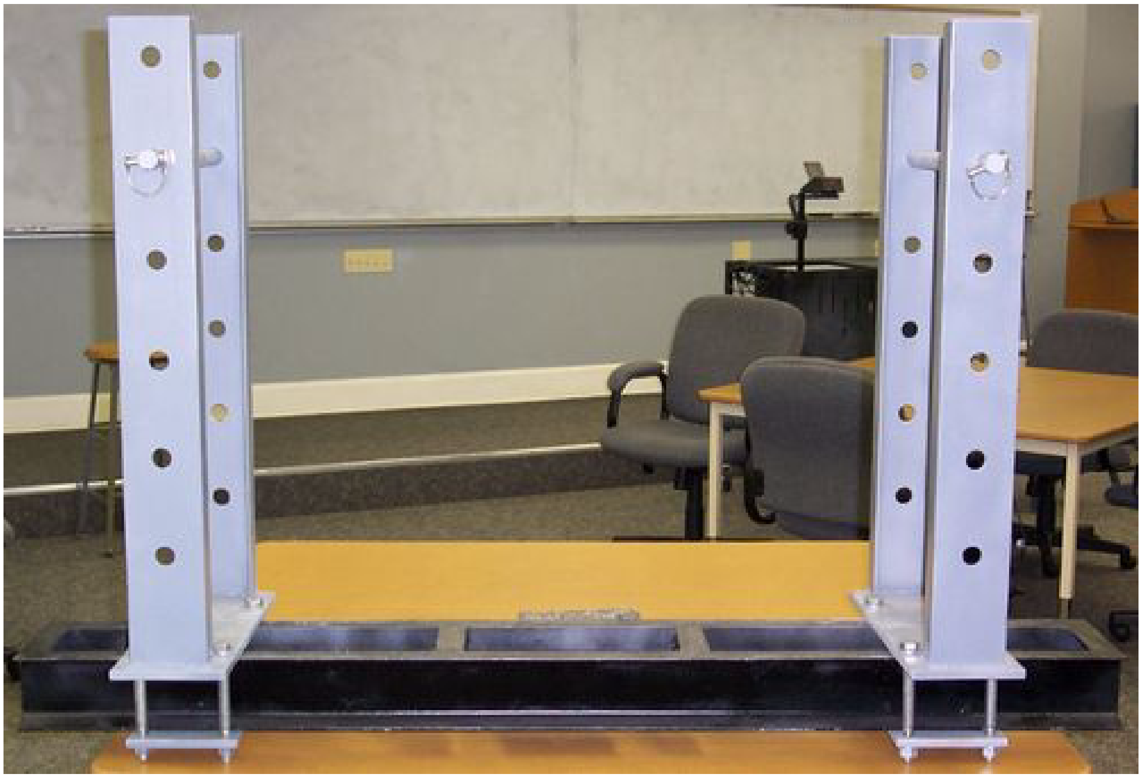

Figure A4.3 – The assembled truss testing frame.

Loading is applied at the top of the truss using a loading bar, as shown in Figure A4.4. This bar is made from 1 inch round stock cut to a length of 12 inches. The round stock is welded to 1.5 inch square tubing which is in turn welded to a bolt that is screwed into the load cell of the cross-head.

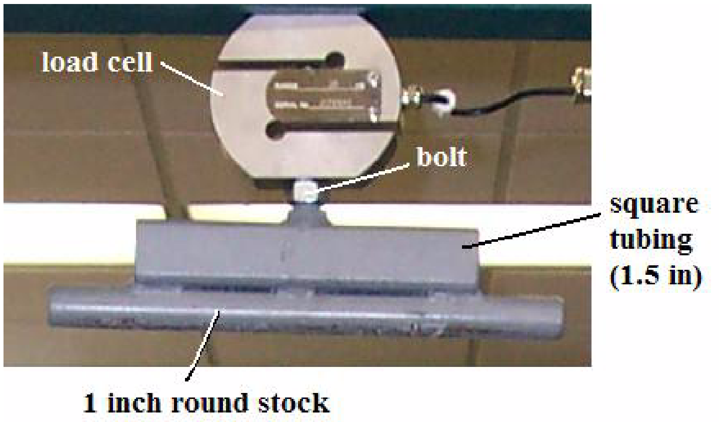

Figure A4.4 – The load application bar.

Appendix 5: Design Report Format

The required format for the report is summarized below. The reports are generally about ten pages in length excluding the appendices. The report must be computer generated (excluding the appendices), and only one report is required per team. All pages of the report must be numbered, and all figures and tables must have captions and be referred to from the body of the report.

Title Page. The Title Page must contain the project name, the names of the students submitting the report, the course number and section, the course title, the instructor's name, and the date.

Executive Summary. The Executive Summary should be a concise summary of the report which briefly describes the problem and highlights the most important conclusions. The executive summary should be as clear, specific, and quantitative as possible. No more than 1/2 to 1 page. For example, "A fifty pound load was applied to a cantilever beam in increments of five pounds resulting in deflections ranging from 0.05 inches to 0.5 inches. The measured deflection was linearly proportional to . . . ". The executive summary should be quantitative and direct, and should avoid references to the experiments as exercises that are required for ENGR 220.

Design Objectives. This section should introduce the design problem, state the constraints, and discuss the objectives to be achieved. This section should be no more than one page long.

Design Assumptions. The assumptions should be clearly stated in this section.

Material Properties. All material properties used in the design of the truss are listed in this section. Also, the sources of this information must be referenced. Most of the material properties will come from experiments performed in class.

Design Alternatives Considered. Computer generated sketches the design alternatives should be given in this section. The reasons for not adopting these alternative designs should be discussed.

Design Calculations. The design analysis should describe the calculations and refer to the relevant figures, plots, and tables. Sample calculations should be included for each type of analysis completed. A complete set of calculations should be available in the appendices. The calculations should be summarized as in Table 1 of this paper. This section should also include a dimensioned sketch of the truss, with tensile members colored red, compressive members blue, and zero-force members yellow. All joints should be labeled with letters (A, B, C . . .), and these letters should correspond to the member designations used in the discussion and in the tables.

Predicted Failure Load. This section should discuss the calculations leading to the predicted failure load. The results should be summarized as in Table 2 of this paper. The critical joints or members should be identified in this section.

Fabrication. The fabrication methods used to build the truss should be discussed in this section.

Estimated Cost of Design. Based on an hourly billing rate of $60/hr for engineering services and $35/hr for fabrication work, the total cost of the truss design should be estimated in this section.

References. List references in alphabetical order using the following format.

Hall, David E., "Course Notes for Engineering 220," Louisiana Tech University, College of Engineering and Science, Fall 2002.

Appendices. Appendix 1 should show all of the calculations required for the final design. Appendices should be listed in numerical order (Appendix 1, Appendix 2, etc.). Lengthy calculations, lengthy data sheets, raw data, or other supporting material is appropriate for the appendices. This information may be hand written.