Laboratory Exercises for Statics and Mechanics of Materials on a Shoestring

David Hall, Paul Hadala, Freddy Roberts
Louisiana Tech University

Abstract

This paper outlines the design, construction, and fabrication of seven laboratory exercises and a design project for a sophomore level integrated statics and mechanics of materials course. The academic setting in which the course was created is given along with an overview of the course content. Each laboratory and design project is described in detail, including photographs, drawings of the equipment, student work requirements, principles demonstrated, and equipment design and fabrication. The experiences of the authors and their students with these projects during the Fall 1999 offering of the course are presented, and other classroom activities to enrich student learning are suggested.

I. Introduction

There is a nationwide movement to restructure engineering curricula to provide integration between the subjects of engineering, English, mathematics and the sciences [1,2,3]. This integration, along with a strong emphasis on active learning, team activities and critical thinking, has been shown to significantly increase student retention and better prepare students for the situations they will face in the workplace. In response to this movement, The College of Engineering and Science at Louisiana Tech University has implemented a common, integrated curriculum for all engineering majors that spans the freshman and sophomore years[4,5]. The first of the three fundamental engineering courses taught in the sophomore year is ENGR 220, an introduction to engineering mechanics, which integrates selected topics from statics and mechanics of materials[6].

Prior to the full implementation of the integrated curriculum 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, bearing and tearout stresses at joints; axial deformations and strains; material properties, working stresses and factors of safety; moments; centroids and moments of inertia; rigid body equilibrium; plane trusses; frames and machines; friction; torsion; flexural loading, flexural stresses and shear stresses in beams; deflection in beams; stresses in thin walled pressure vessels; and combined loadings, stress tensors, and failure prediction. 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 a design project. These physically based activities allow for complex problems to be included in the course so that a deeper level of knowledge can be attained for selected engineering mechanics topics. With the exception of basic data acquisition equipment, these class projects involve inexpensive materials and parts that are readily available at hardware stores or industrial supply companies. The purpose of this paper is to provide sufficient information to allow the projects to be incorporated into engineering mechanics courses at other institutions with minimal effort.

II. Delivery Format of ENGR 220

Louisiana Tech University operates on a quarter system with semester hours. Over the span of the 10 week quarter, a 3 semester hour, lecture-based course will meet 30 times at 75 minutes per lecture, and a 1 hour laboratory course will meet approximately 10 times at 180 minutes per lab. ENGR 220 is set up as 2 semester hours of lecture and 1 semester hour of laboratory which results in three 110 minute class periods per week. These long class periods are intended to allow for seamless integration of lecture and lab in an active classroom setting.

The in-class active learning exercises can be broken into three distinct categories, as described below.

- Groups of two to four students solve problems to reinforce concepts presented earlier in the class period (as opposed to the instructor working out the problem on the board). This gives the instructor a chance to mingle with the class and provide one-on-one assistance as needed. Students are motivated to work hard on these exercises since their group work must often be submitted for grading. Many of these problems involve physical measurements of a body or device passed out in class.

- Groups of two or four students complete laboratory exercises which involves taking experimental data, comparing this data to analytical calculations, and preparing a technical report. The experimental portion of these laboratory exercises are completed by the student groups when possible. Otherwise, the laboratory data is taken in front of the class by the instructor or selected students. These required measurements introduce students to the concepts of precision and error.

- Groups of four students design, fabricate, and test a wooden truss in which their grade is based on a formal design report, truss performance, and an oral computer-based (PowerPoint) presentation.

The daily aim of the class is to mix things up, with some lecture, some hands-on activities and some group problem solving. ENGR 220 will continue to be developed to allow hands-on activities or laboratory experiences in most of the 110 minute class periods.

III. Laboratory Exercises

Since the University and COES have limited budgets for equipment purchases, funds are often not available to purchase specialized equipment or pre-packaged experiments, especially when some of the experiments must be replicated 10 times to allow student groups to perform the labs simultaneously. As a result, the preparation of equipment for laboratories for ENGR 220 must be limited to the purchase of key components, and fabrication has been accomplished in the COES machine shop using student and technician labor (and, sometimes faculty labor). In most cases, the design of the laboratory equipment has been performed by the faculty with fabrication suggestions from machine shop personnel. In other cases, senior level mechanical engineering students have designed or refined laboratory equipment as part of the requirements of special problems or capstone design courses (provided the problems are suitably complex).

The description of each laboratory project and the authors' experiences with these projects are given below. Additional details are given for most of the projects in the appendices.

Equilibrium of Concurrent Force Systems. A plywood box mounted on a laboratory cart, shown in Figure 1, and a few inexpensive battery operated fish scales are the key elements of the apparatus for this experiment. The sides of the box have U-shaped, fencing nails driven part way into the walls on two inch centers. These are attachment points for tension cords which support a weight pan and exercise weights. Although Figure 1 shows the set up of a two-dimensional problem, three-dimensional problems which require another support string are also set up. An assortment of cords, rings snaps, hooks and pulleys complete the apparatus.

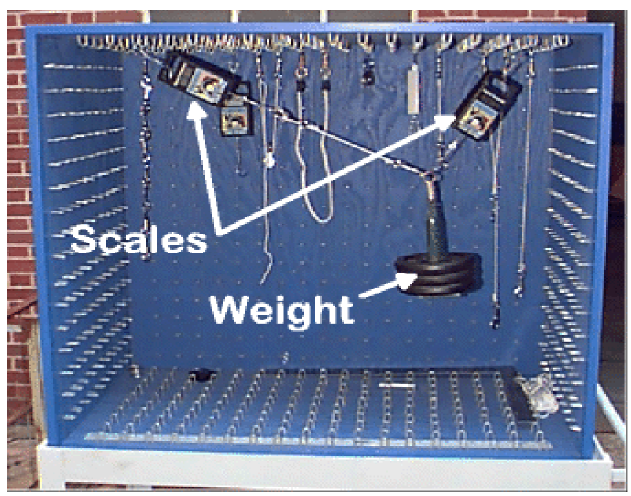


Figure 1 - Wooden box used to examine concurrent force systems.

After introducing the subject of concurrent force equilibrium using vector mechanics and teaching the students how to form a force vector in i,j,k notation given the magnitude and the coordinates of two points on the line of action, the instructor sets up a three string configuration in class. Students help with the measurement of the string coordinates and recording of string force magnitudes (from the fish scales which connect to the strings). The students are then given approximately 30 minutes to work through the solution of this problem in class, and they are instructed to compare their analytical answers to the experimental measurements from the fish scales.

Using the weight pan and a pulley, a more complex case involving two concurrent force systems is set up, where one force is common to both force systems. Groups of four students must analyze and report on this case plus two others of their choice that they set up outside of class (this takes about one-half hour for each group of students). For each case the students use the principles taught to calculate string forces and compare them to data from the fish scales. The teams prepare written reports describing the exercise, the computations performed, the differences between theory and experiment, and the sources of error. It is easy to show the students the magnitude of error resulting from poor coordinate measurement by simply moving the support point of a string from one support point to the next adjacent one. Accuracy of the experiment was generally good, and this proved to be an effective learning experience. When tested on concurrent forces later in the course, the students did quite well.

Analysis of Pinned Connections. Approximately 20 pinned connections were constructed from wood (Figure 2). Groups of four students were required to examine a connector and measure the dimensions of each member and the pin(s). Based on these dimensions and an assumed axial load applied to the members (such as 100 kg), the location and magnitude of the maximum axial normal stress, bearing stress, shearing stress in the pin(s), and shearing stress in the members due to tearout of the pin(s) were computed. By comparing these stresses with the strength of the members and pins in tension, compression and shear, the groups then determined the peak load that the connection could carry and the location and mode of probable failure.

Figure 2 - Wooden connector.

This project effectively demonstrated how stresses vary from point to point in a pinned connection and that it is the weakest point that limits the peak load carried. The instructors found that it is necessary to give the students a significant amount of guidance before allowing the students to analyze the joints independently. It is recommended that the instructor clearly

- present the concepts of normal axial stress, bearing stress, shearing stress in pins, and tearout stress;
- demonstrate for a sample connector how the maximum axial normal stress for an assumed load is calculated using the minimum cross sectional area;
- describe the material property which limits each of the stress quantities (for example, the axial normal stress is limited by the tensile strength of the material, the bearing stress is limited by the compressive strength of the material, etc.);
- compute the factor of safety for the assumed applied load and the peak load of the sample connector assuming that axial normal stress governs failure; and
- explain that the factor of safety and the peak load due to axial normal stress, bearing stress, shearing stress in the pin(s), and tearout stress must be calculated separately and that the smallest peak load determined from all calculations is the peak load of the connection.

Walking the students step by step through this process before turning them loose on the project will allow them to be more successful, thus reducing their frustration and building their confidence. However, to allow for initial exploratory learning, it is recommended that the student groups be allowed to examine their joints and discuss possible failure modes before the concepts of axial normal stress, bearing stress, shearing stress in pins, and tearout stress are presented. Refer to Appendix A for more information on this project.

Stress Concentrations. Students are introduced to stress concentrations through a numerical laboratory exercise that involves curvefitting[7] and the use of a scientific calculation software package[8]. The problem described here involves the stress concentration induced when holes of various sizes are drilled through the center of a plate which is subjected to axial loading, as shown in Figure 3. Students are required to plot the allowable load, P, as a function of hole diameter, d, for a given material when a factor of safety of 2.0 is employed.

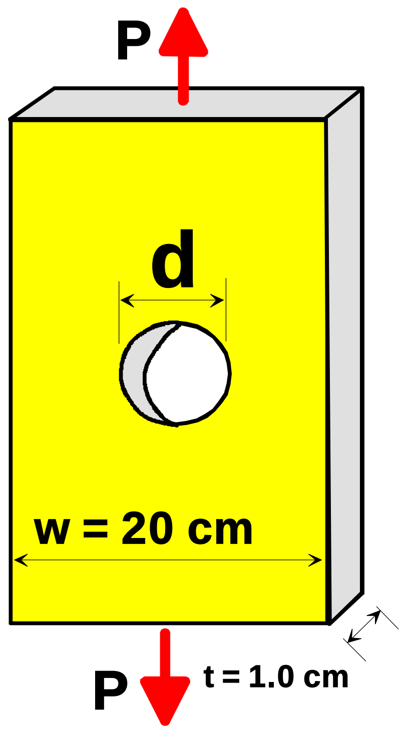


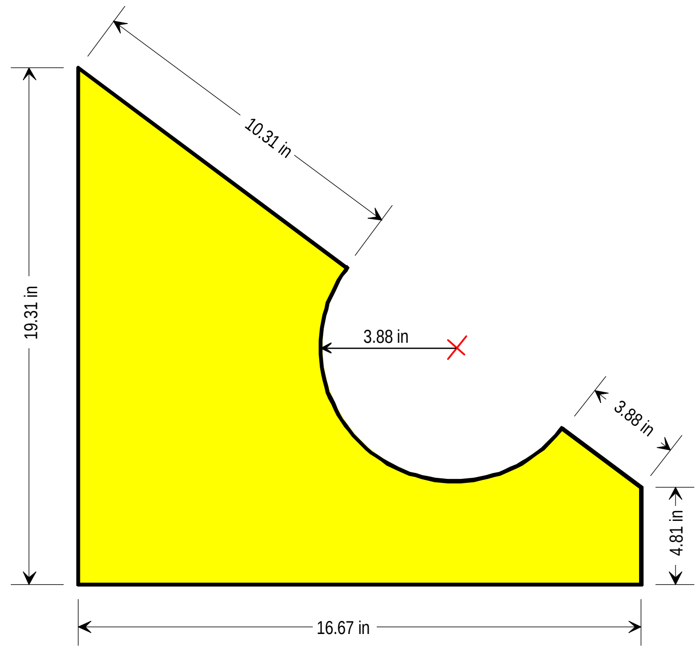
Figure 3 - Geometry and loading for stress raiser.

Students manually select points from a stress concentration factor plot (which is available in most elementary mechanics of materials books) and enter these points into a curvefitting package to determine an expression for the stress concentration factor, K, versus d/w, where d is the diameter of the hole and w is the width of the plate. By embedding this expression into a scientific calculation software package, students generate the required plot of load versus hole diameter.

The instructors found that it is helpful to give a 10 - 15 minute presentation on the effect of discontinuities on the stress distribution in bodies before introducing the laboratory project. The basics of curvefitting are then discussed and the use of the software packages which will be used for the analysis is briefly demonstrated. Most of the students had little trouble completing this exercise. Those students who did have trouble either incorrectly used the fitting variable, d/w, in the place of d or they somehow incorrectly solved for the allowable load P in terms of K, the material strength, and the dimensions.

Equal Support of a Wooden Body. A piece of 3/8 inch thick plywood cut as described in Figure 4 is to be supported at three locations such that the support reactions at each of the three locations are equal. The project requires the plywood shape and three support sticks along with three mechanical or digital scales to measure the magnitudes of the reactions (mechanical balances are shown in Figure 4). To complete the project, student groups of two are first required to compute the centroid of the body. Based on this centroid location, they then sum moments about their chosen x and y axes such that the body is balanced. If the coordinate system is chosen at the centroid, the problem solution reduces to the requirement that $x1+x2+x3 = 0$ and $y1 + y2 + y3 = 0$, since all of the forces must be equal.

Students should be taught to compute centroids and to determine reactions by summing moments before being assigned this project. It is helpful to discuss equilibrium in three dimensions, since



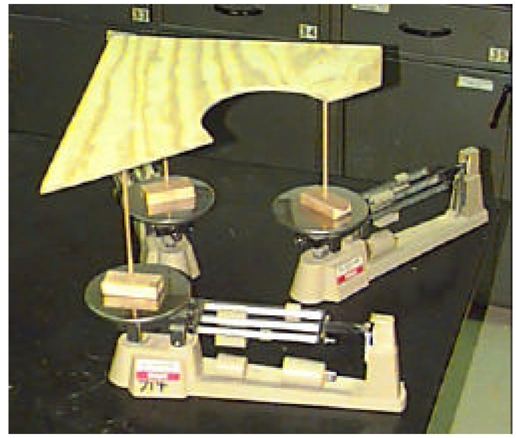


Figure 4 - Plywood shape being supported by three mechanical balances.

this is a problem that involves summing moments about two axes. The student groups are required to submit a report detailing the location of the centroid and their support reactions (the support reactions must be separated by a minimum distance to allow for force measurement). Following report submission, the student teams must then go to the laboratory to test the accuracy of their calculations. A portion of their grade is based on how close the three reactions are to being equal. Several groups quickly learned that their calculations must be incorrect when their plywood shape fell over when supported at their computed points, and a few groups actually computed support locations that did not lie on the body. However, the vast majority of the students did very well on the project.

Measurement of Flexural Strains and Stresses. A flexural testing setup was constructed primarily using steel channel, vises, and exercise weights, as shown in Figure 5. This setup can be used to support a cantilever beam, a simply supported beam, an overhanging beam, or a statically indeterminate beam. By attaching a strain gage to the beam, the strain level can be monitored as a function of the applied loading. Student groups are required to convert the voltage or resistance measurements taken from the strain gage to strains and the strains to stresses using Hooke's law. These experimentally determined stresses are then compared to the stresses predicted analytically, and the percent difference between the experimental and analytical results is determined. Note that no transformation of stress is required if a single element strain gage is bonded to the beam so that the strain is measured along the longitudinal axis of the beam. Strain gages can be also bonded at other locations to evaluate the stress state in other directions and at other locations on the beam.

This project yields a good comparison between experimental and analytical results for cantilever beams. No experiments have been run yet for simply supported beams. Although the lab was conducted primarily as an instructor demonstration, the strain gage raw data was posted to the web for the students to analyze. The instructor should explain the principles behind measurement using strain gages (stretching the strain gage causes its resistance to change which can be associated with a given level of strain) and give the appropriate relationships for converting the voltage or resistance measurements to strains. Additional information on this laboratory setup is given in Appendix B.

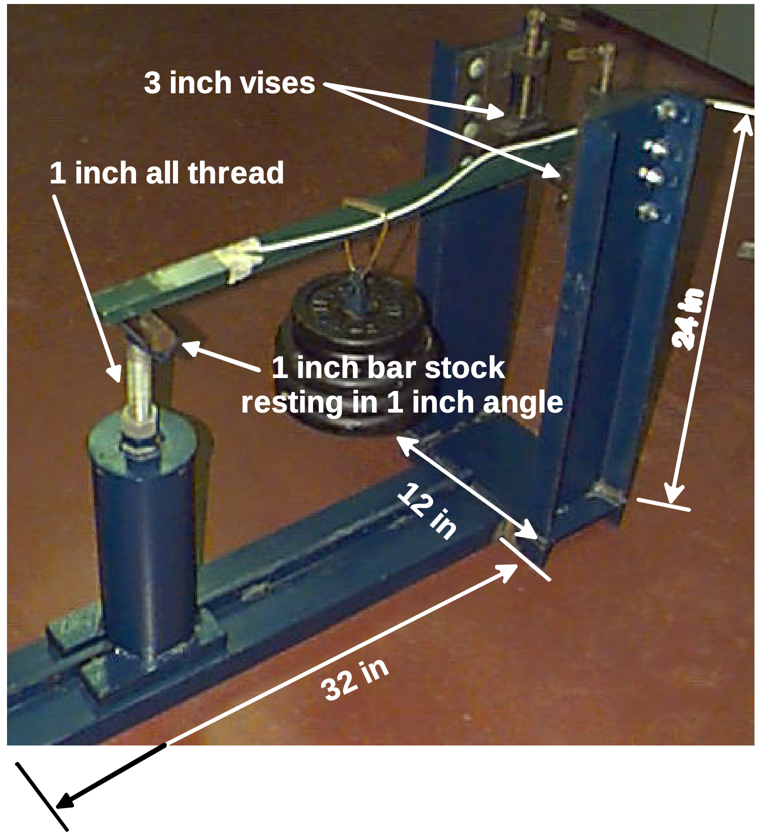


Figure 5 - Simply supported beam in test device.

Deflection of Beams Experiment. Students must learn to determine deflections and slopes of beams using the methods of integration (for simple configurations) and the method of superposition (for more complex loading conditions). To study this experimentally, the setup shown earlier in Figure 5 is used again.

Figure 6 shows a cantilever beam in the loading fixture with a distributed load and a point load. The distributed and point loads are each applied separately and then together. The deflections are measured with dial indicators on magnetic bases at two points for each loading case, and the students are able to experimentally verify that superposition works by comparing the sum of the deflections in the first two cases (distributed + point loads) with that from the third (both loads applied). The loading frame shown in the figure was built of scrap steel in the college's shop, and the weights used are from a weight lifting set. End fixity was attempted by using the jaws of two drill press vises.

Figure 6 - Cantilever beam with dial indicator.

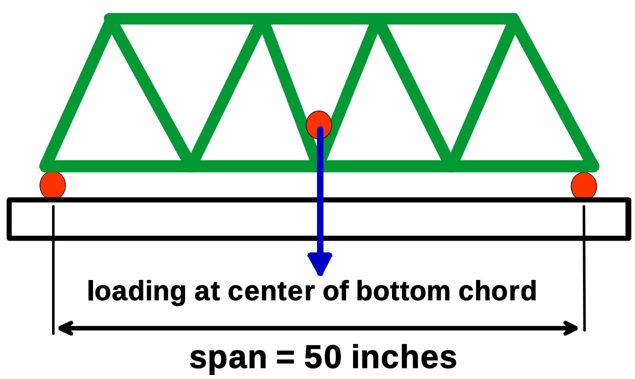
The students were required to calculate the deflections for all three cases and compare the calculations and the measurements. Because the vice did not closely approximate the zero slope condition assumed in the calculations, poor agreement was noted. This upset many of the students and damaged their confidence, but it gave the instructors a chance to help them understand an important practical lesson that it is difficult to achieve fixity in the real world. A simply supported beam, which was shown in Figure 5, will result in better comparison between the experimental and analytical results. Additional information on this laboratory setup is given in Appendix C.

Analysis of Thin Walled Cylindrical Pressure Vessels. A setup to study the relationship between the internal pressure and the stresses and strains in thin walled pressure vessels was constructed using a portable air tank, a large pressure gage, pipe fittings and a three element strain gage, as shown in Figure 7. The tank can be filled with air and taken to class along with a data acquisition system to monitor the strain level as air is released from the tank. Student groups can compute the strains from the voltage or resistance measurements from the data acquisition system, compute the normal and shear strain components in the tank from strain transformation relations, and compute the stresses in the tank using Hooke's law. Based on the measured stress change, students can analytically predict the pressure decrease which can then be compared to the actual pressure decrease in the tank. The experiment provides an excellent validation of analytical expressions for hoop and longitudinal stresses in cylindrical thin walled pressure vessels. Additional information on this experiment is given in Appendix D.

Figure 7 - Pressure vessel with pressure gage and strain gage.

IV. Design, Fabrication and Testing of a Wooden Truss

A major component of ENGR 220 involves the design, fabrication and testing to failure of a wooden truss. Teams of 4 students were asked to design and construct a minimum of two trusses with cross bracing to span 50 inches and support a concentrated load at the center of the bottom chord of the truss, as shown in Figure 8. Each team was given an identical amount of wood (sixteen 48 inch long construction stakes and twenty-five pieces of 3-in.x 3-in. x 3/8-in. plywood (used for gusset plates). The materials were brought into class on a cart, and the students were allowed to select their wood, as shown in Figure 9. The students were free to use glue or wood screws to make connections at the joints. Although facilities were provided in the college shop for constructing the trusses, most teams opted to build them with their own tools.



NOTE: The two supports and the loading yoke are one inch diameter bars

Figure 8 - Loading condition for trusses.

The students were required to prepare a project time schedule at the start of the project and a formal technical report and oral presentation summarizing their design at the end of the project. A portion of the overall grade was based on the amount of load that their truss carried relative to the truss that carried the maximum and minimum load. The strongest truss held 2,900 pounds, and the weakest truss held 340 pounds. The locations of the failures and the magnitudes of the failure loads were noted and discussed by the students. The teams whose trusses achieved the highest loads often contained one or more members with good woodworking

Figure 9 - Design materials.

skills and a better understanding of the mechanics of the problem. Most failures occurred in the joints. The students learned the importance of connection details in structural design the hard way.

The loading machine used to test these structures was a calibrated 5000-lb. hydraulic jack with a pressure gage mounted in a steel frame built from scrap in the college's shop. It is shown just before testing a truss in Figure 10. More details of the truss breaker are given in Appendix E.

As part of their reports and oral presentations, teams were asked to consider alternative designs, to compute the force and stress in each member, to estimate the failure load of the truss by considering failure due to excessive axial stress and failure due to buckling, to give a dimensioned drawing of their truss, and to determine the total cost to build their truss (given a rate for labor).

Figure 10 - Truss in the testing device with student team.

The truss project was assigned after introducing (1) analysis of plane trusses by the methods of joints and the method of sections, (2) the concept of axial stress, (3) brittle failure and ductile yielding in axial tension or compression and (4) factors of safety. A physical example of the buckling of a long wood member was demonstrated in class at the start of the project, and this was suggested to be a likely failure mode of some of the truss's compression members. Students were to told where to find more information on the subject. Only about half did in fact attempt to learn more on their own and apply it in their project. This attempt at introducing self-teaching and life-long learning was less than a success.

The project started approximately 1/3 of the way through the quarter, and the students were given two weeks to complete the work. In hindsight, the students should have been given at least three weeks to complete the project.

IV. Other Enrichment Ideas

In an effort to enhance the visualization of some of the basic properties of materials and geometric shapes and to give the students more measurement opportunities, a number of simple class exercises have been used with some success. Several of these ideas are described below:

! *Calculation of centroids of standard structural sections and comparison of calculated results with table values*. Short, 1- to- 2- inch, sections of angle iron (Figure 11), wide flange and I-beam sections have been cut from the machine shop scrap pile and passed to student groups along with a ruler. Students measure the various dimensions of the section, sketch the cross-section, and calculate the location of the centroid. Then using their measurements and the structural section tables of their textbook[6], they locate the section and compare their properties with those in the book.

Figure 11 - Angle iron.

! *Analysis of simple machines always involves bolt cutters, pruning shears, scissors, pliers, vice-grips and other simple machines.* When working machine problems, the authors brought enough of these devices from our own workshops to provide a simple machine for each student group to examine and make appropriate measurements sufficient to calculate the mechanical advantage of the machine. While most of these simple machines use compound leverage, even the simple machines demonstrate the concept. To perform this exercise each group needs only one simple machine and a ruler.

! *Axial deformation and calculation of strain.* The difference between displacement and strain is easily demonstrated with six rubber bands and two identical weights, as shown in Figure 12. Tie two sets of rubber bands together to make them roughly twice as long as a single rubber band. Then, hang undeformed and deformed rubber bands above the chalk board so that their initial lengths and displacements can be marked, as shown in the picture. Define the displacement of a rubber band as the distance that the bottom of the rubber band stretches due to the deformation caused by adding the weight. Show that the original length and displacement of the two rubber band system is approximately twice that of the single rubber band system. Ask the class which system has the higher stress (it is the same). Ask them which one has the most severe deformation - that is which deformation state is more likely to result in failure (they are equally severe). Tell them

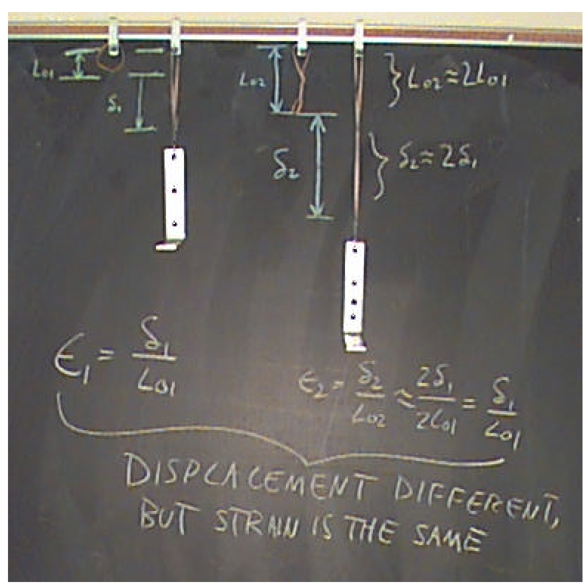


Figure 12 - Demonstration of displacement and strain.

that we need a quantity that can be used to quantify the severity of the displacement at a point in a material. Tell them that strain is this quantity.

- *Shear strain due to torsion.* Shear strains produced by torsional loading on a circular shaft can be easily demonstrated using a two foot section of a swimming pool noodle float. Use a magic marker to form a grid on part of the circumference of the noodle (make the marks about 1 inch apart) and twist the ends of the noodle to demonstrate that the squares become rhombuses as the torque is applied.

- *Torsional Failures.* Torsional failures for brittle and ductile materials can be demonstrated very effectively and easily using a long piece of chalk and a Tootsie Roll. The chalk can be twisted on the ends, it fails suddenly forming a typical conical brittle failure surface at 45° to the longitudinal axis. Each student group can be given a piece of chalk to produce their own failed specimen. Similarly by twisting on the ends of a Tootsie Roll, a ductile failure surface is produced (the Tootsie Roll breaks straight across). Again each group can produce a failed specimen for examination.

- *Torsional Loading.* The Trenchless Technology Center (TTC) is located at Louisiana Tech University. The TTC specializes in underground directional drilling techniques, and they have access to video footage which demonstrates the directional drilling technique which can be used when discussing torsional behavior of pipes. This video clip is shown, and a short section of drill pipe is brought to class and passed around to each group for inspection and measurements of inside and outside diameters of the pipe. Students are given typical lengths of bore paths and typically applied torques. By measuring the drill pipe (Figure 13), they then calculate the angle of twist of the long rod and the maximum torque that the pipe can resist. Students are usually amazed at the large amount of twist a long rod can endure (it twists around several times).

- *Combined Stresses.* To enhance the visualization of combined stress states and the formation of a stress tensor, the authors have developed a light plywood cube that is two feet on a side. The cube has holes drilled through the sides so dowels can be inserted to represent axial loads. Detachable arrows are placed on the dowels to represent tensile or comprehensive loads. Twelve inch strips of velcro base (the side with the loops) are glued to each surface to form a plus. Shear arrows have been cut from colored felt, and the other side of the pieces of velcro are attached to the arrows. Arrows come in three colors with four arrows per color. When using the stress cube, a legend of colors should be written on the board to keep the shear stress directions straight. The stress cube should also have a coordinate system noted so that the x, y, and z directions are always clearly evident. The axis directions markers are easily formed from corner molding which can be slid out and pressed or screwed into place with wood screws to which short handles have been attached. This device has been especially helpful when discussing the topics of combined stresses, principal stresses, construction of stress tensors and failure theories.

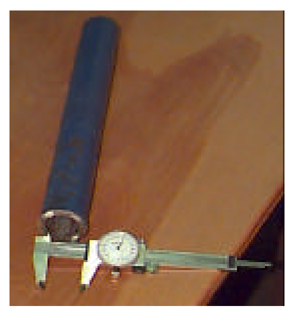


Figure 13 - Drill pipe measurement.

V. Conclusions and Recommendations

The experiments, demonstrations, and design project presented in this paper have all proven to be effective in reinforcing concepts of statics and mechanics of materials for students taking ENGR 220. Time does not permit using all of these tools and exercises every time the course is taught. It is important to provide a balance of lecture and laboratory based problem solving. Not every experiment should require a formal report, as three written exercises are usually enough to reinforce writing skills learned in earlier courses. The experimental devices presented can be constructed from inexpensive and readily available materials and can all be fabricated by someone with woodworking, machine shop, and welding experience.

Bibliography

1. Description of the Integrated Engineering Curriculum at Texas A&M available at: http://www.tamu.edu/coalition/, April 14, 1998.

2. Description of the Integrated Engineering Curriculum at Rose-Hulman Institute of Technology available at: http://fc.rose-hulman.edu, April 14, 1998.

3. Description of IMPEC, an integrated math, physics and engineering curriculum available at: http://www2.ncsu.edu/unity/lockers/users/f/felder/public/Impec.html, April 14, 1998.

4. Nelson, James, and Stan Napper, “Ramping up an Integrated Engineering Curriculum to Full Implementation”,

5. Schroeder, Bernd, S.W. and Jenna P. Carpenter, “Mathematical Support for an Integrated Curriculum”, Session 3565, Proceeding, American Society of Engineering Education,

6. Riley, W.F., L.D. Sturges and D.H. Morris, Statics and Mechanics of Materials - An Integrated Approach, John Wiley & Sons, Inc., New York, 1995.

7. Hyams, Daniel G., CurveExpert 1.3, http://www.ebicom.net/~dhyams/cvxpt.htm, 1997.

8. Mathsoft, Mathcad 7, http://www.mathsoft.com/, 1997.

Appendix A
Additional Information for Analysis of Pinned Connections

A variety of pinned connectors were constructed to allow students to explore the concepts of axial normal stress, bearing stress, shearing stress in pins, and tearout stress, as shown in Figure A1. The student work requirements, the principles demonstrated, and the equipment design and fabrication for this laboratory project are given below.

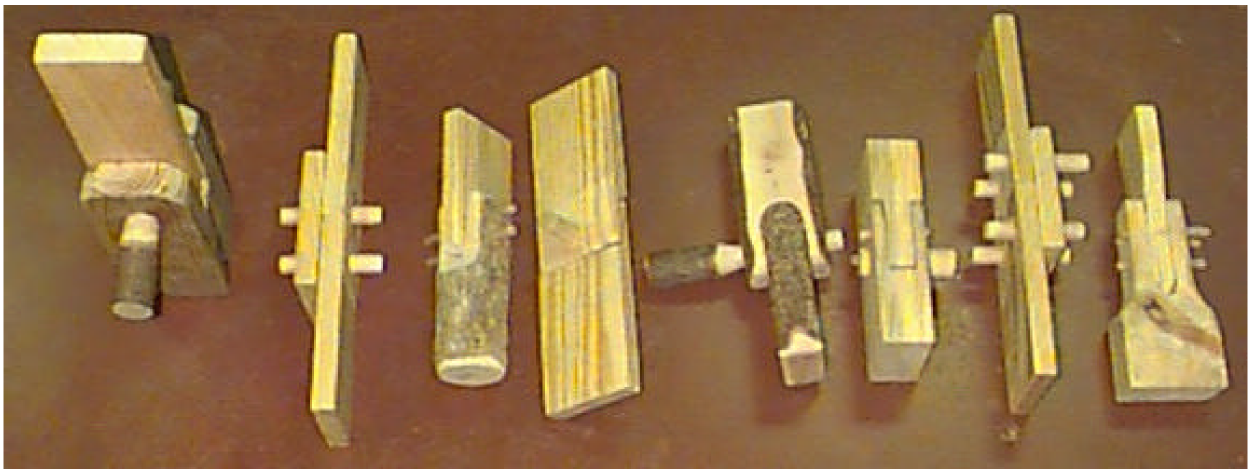


Figure A1 - Additional wooden connectors.

Student Work Requirements. The probable failure mode and peak load of a wooden connector is to be determined using the principles of mechanics of materials. Assuming a load of 100 kg is applied along the axis of the two members being connected, determine

- the maximum normal stress in the connector;
- the maximum bearing stress in the connector;
- the maximum shearing stress in the pin or pins; and
- the maximum tearout stress due to a pin trying to pull through the members of the connector.

Based on these stresses and the strength of the material in tension, compression, and shear, determine the factor of safety against failure for the 100 kN load and the peak load due to each type of stress. By examining each of these peak loads, determine the overall peak load of the connector. The analysis section of your report must contain a dimensioned sketch of your wooden connector with the critical points labeled as follows:

- A = location of maximum normal stress in the connector;
- B = location of maximum bearing stress in the connector;
- C = location of maximum shearing stress in the pin or pins;
- D = location of maximum tearout stress in the connector;

The dimensioned sketch must be followed by a table containing the following information:

Stress Term	Area		for an axial load of 100 kN		applicable material strength	peak load
	symbolic expression	value (m^2)	stress	safety factor		
axial normal						
bearing						
shearing of pins						
tearout						

Overall Peak Load = _______________

Note that the sketch showing the critical points and the table must be on the same page. Discuss possible design modifications which would allow the peak load of the joint to be increased (minimum of ½ page of text with accompanying sketches).

Principles Demonstrated. Consider the pinned connection in Figure A2 with a width of W, a thickness of t, a pin diameter of d, and a length between the edge of the pin and the end of a member of L. The pins are assumed to be symmetric with the center of the pin at W/2. The two members carry an external axial load of P.

The maximum average axial normal stress in the member is

$$\sigma_a = \frac{P}{(W-d)\cdot\frac{t}{2}}$$

The maximum average bearing stress between the pin and the member is

$$\sigma_b = \frac{P}{d\cdot\frac{t}{2}}$$

The maximum average shearing stress in the pin is

$$\tau_P = \frac{4P}{\pi d^2}$$

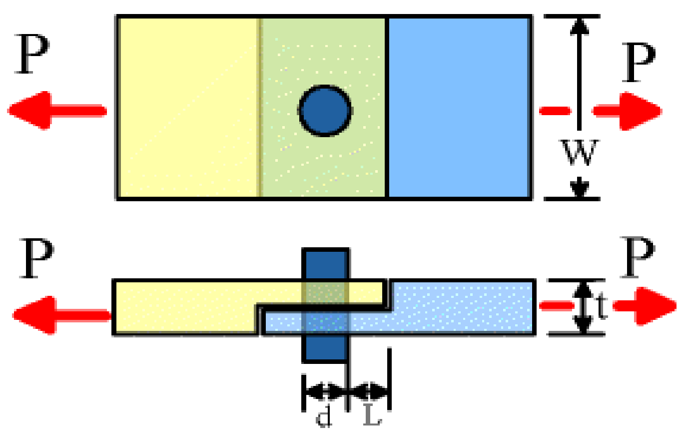


Figure A2 - Schematic of pinned connection.

Making the conservative assumption that the length L governs the tearout stress (as opposed to L + d/2), the maximum average tearout stress is

$$\tau_T = \frac{\frac{P}{2}}{L \cdot \frac{t}{2}}$$

It is assumed that failure will occur when the axial normal stress reaches the tensile strength of the member material, when the bearing stress reaches the compressive strength of the member or pin material, when the shearing stress in the pin reaches the shear strength of the pin material, and when the tearout stress reaches the shear strength of the member. Notice that for wood the problem is actually more complex since the strength in the grain direction is much different than the strength in the cross-grain direction. However, for the purposes of this project, students were allowed to assume that the material was homogeneous (which may be nonconservative depending on the properties chosen).

Experiment Design and Fabrication. The connector dimensions and materials chosen depend on the method that the joints will be incorporated into the class. For ENGR 220 at Louisiana Tech University, the instructors were required to transport a minimum of 10 connectors to class (1 connector per group of 4 students) along with rulers for the students to make their measurements. Consequently, the connectors were sized so that they could all fit in a standard size shopping bag, and they were constructed from wood to allow them to be lightweight. It is important that the size be large enough for the students to easily hold and discuss the connector in a group setting. Standard connectors involving swing bolts or rod ends and yoke ends that can be purchased from industrial supply companies would also be appropriate.

If wood is chosen as the material, a large variety of connectors can be easily constructed from a readily available lumber such as 1-by-4s (3/4 inches by 3 ½ inches) and 2-by-4s (1 ½ inches by 3 ½ inches). A single 1-by-4 or 2-by-4 with a length of 8 feet will go a long way. Dowel rods ranging from 1/4 inch diameter to 1 inch diameter are recommended.

Appendix B
Additional Information for Stress Concentrations

The student work requirements and principles demonstrated for the stress concentrations lab is given below.

Student Work Requirements. The student work requirements for this project can vary widely depending on the geometry and loading chosen and the context in which the problem is given. Example student requirements for the geometry and loading in Figure 3 are given here.

Holes with diameters ranging from 0 inches to 10 cm are to be drilled into the 20 cm wide and 1.0 cm thick plate shown in Figure 3. The plate is made of a relatively brittle cast aluminum 195-T6 alloy which has a yield strength of 160 MPa and a percent elongation of 5%. It is well known that holes and other discontinuities in bodies will result in elevated stress levels (stress concentrations) in the vicinity of the discontinuity. These stress concentrations will lead to elevated stresses which may lead to failure, particularly when the materials are brittle or when repeated loading is applied. A graph which shows the stress concentration factor, K, for various combinations of plate width to hole diameter ratios is shown in Figure B1.

For this laboratory project, determine the allowable load P which can be applied to the plate with a factor of safety of 2.0. The analysis should include the following steps:

! complete a curve fit of the stress concentration factor chart (x = d/w and y = K);

! give the equation of this curvefit;

! insert this equation and the given dimensions and properties into Mathcad and plot K (y axis) versus d (x axis);

! plot the allowable load, P, versus the hole diameter.

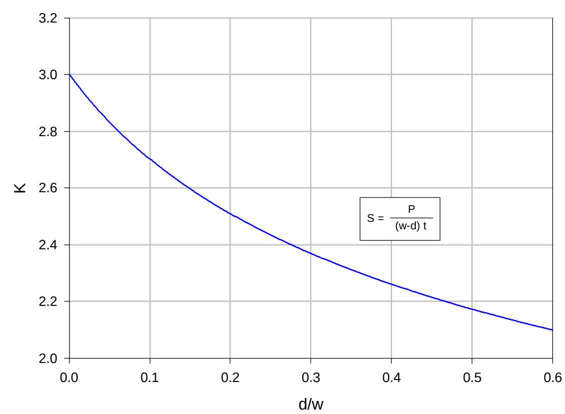


Figure B1 - Plot of the stress concentration factor versus d/w.

Principles Demonstrated. For the geometry shown in Figure 3, the maximum stress is computed by multiplying the stress concentration factor, K, by the nominal stress, S. Using the expression given for S in Figure B1, the maximum stress at the edge of the hole stress is

$$\sigma_{max} = K \frac{P}{(w - d) \cdot t}$$

where P is the load and w, d, and t are the dimensions of the body. Setting the maximum stress equal to the allowable stress which is assumed to be the yield strength of the material divided by the safety factor yields

$$K \frac{P}{(w-d)\cdot t} = \frac{yield\, strength}{SF}$$

where SF is the safety factor. Solving this expression for the allowable load P results in

$$P = \frac{(w-d)\cdot t}{K} \cdot \frac{yield\, strength}{SF}$$

where K will be a function of d/w. Generating the plot of P versus d is one of the primary objectives of the project. Another objective is to give students practice in using curve fitting and scientific calculation software packages.

Appendix C
Additional Information for Measurement of Flexural Strains and Stresses

The student work requirements and principles demonstrated for the flexural strains and stresses lab are given below.

Student Work Requirements. A beam with a rectangular cross section is subjected to a combination of distributed and point loading, as shown in Figure 6. The beam will be loaded incrementally and the strains are to be measured as a function of time using the strain gage attached to the beam along with a data acquisition system. The following elements must be completed as part of this project:

- a description of the experimental setup and how it works;
- a free body diagram of the beam;
- calculations showing how the strains are computed from the output of the data acquisition system;
- calculations showing the stress at the location of the strain gage for each loading increment;
- a plot of the experimental stress versus time curve (must be computer generated); and
- a table which compares the experimental and analytical stresses (with % error); and

Principles Demonstrated. This laboratory demonstrates how the elastic flecture formula is used to compute the stresses in beams. Single element strain gages inclined at 45° or three element strain gages on the edge of a beam could be used to examine the variation of normal and shear stress due to bending as a function of the distance from the neutral axis. Another major objective of this laboratory is to expose students to strain gages and to computer based data acquisition. The instructors are working toward creating a laboratory whereby all student groups actually mount and collect the data themselves.

Experiment Design and Fabrication. The laboratory setup shown in Figure 5 is intended to be used in situations where the instructor is performing the experiment in front of a class of 40 or more students. For this reason, the setup is relatively large and weighs approximately 360 N (80 lbs) not counting the exercise weights. If the experiment is to be replicated so that all student groups complete the lab independently, then a smaller beam and support fixture should be used.

The primary elements of the fixture, as shown in Figure 5, are given below:

- approximately 8 feet of standard C6 x 8.2 channel for the frame;
- 2 - 3 inch drill press vises;
- 16 1/2 inch carriage bolts with nuts and washers for attaching vise to frame;
- 12 inches of 1 inch diameter all thread with two 1 inch nuts;
- 12 inches of 4 inch diameter pipe for the moving support;
- 4 inches of 1 x 1 x 1/8 inch angle iron for moving support;
- 12 inches of 1 inch diameter bar stock for supports;
- 2 pieces of 3 x 1/4 inch flat bar approximately 7 inches long to hold beam when the vises are used as a cantilever support;

- 70 lbs. of exercise weights;
- 1 inch diameter tube with a small piece of flat bar welded to the bottom to hold the weights; and
- 1/8 inch diameter ductile wire to make a weight hanger.

The information listed above is meant to serve as a guide for constructing the flexural testing fixture. The specific sizes and amounts of the materials used to construct the fixture are not critical and in most cases was based on what materials were on-hand. The rib running along the top of the bottom piece of channel was originally incorporated to allow for other means of loading and is not needed when exercise weights are used as the loads.

The device can be simplified by eliminating the vises. However, this would eliminate the ability the device to handle cantilever beams and statically indeterminate beams with a clamped end. When cantilever beam loading is desired, the moving support is removed and the beam is clamped between two pieces of flat bar running between the drill press vises. Measuring the displacements from below the beam often results in interference of the dial indicators and the weights. A design that prevents this difficulty is shown in Figure C1.

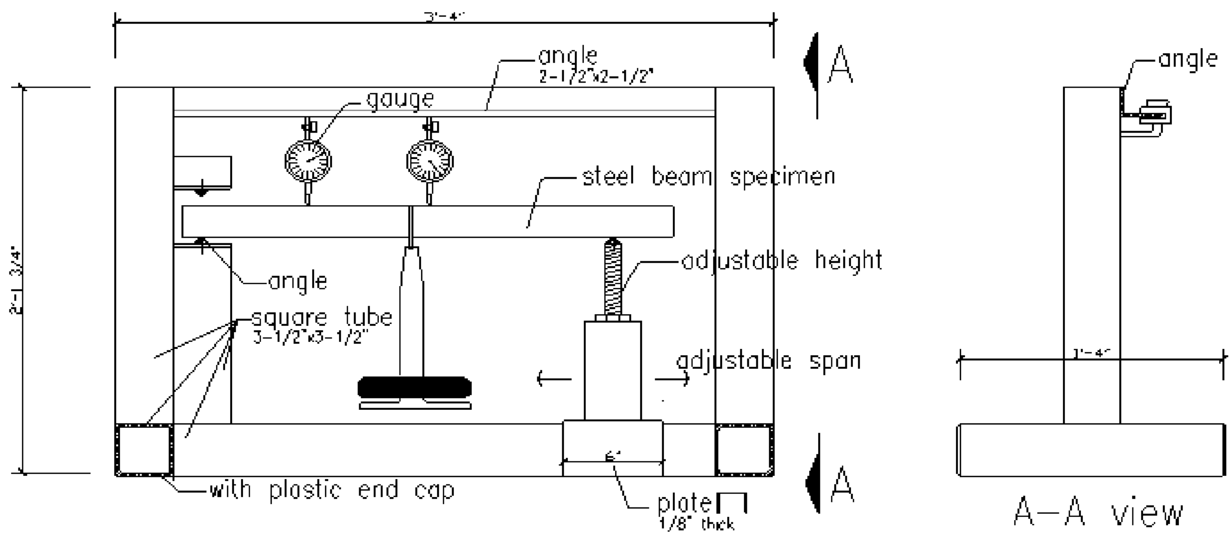


Figure C1 - Alternate setup for flexural testing device.

Appendix D
Additional Information for Analysis of Thin Walled Pressure Vessels

The student work requirements and principles demonstrated for the flexural strains and stresses lab are given below.

Student Work Requirements. The complexity of this laboratory can be varied depending on the orientation of the strain gage on the pressure vessel. The student work requirements given below assume that the orientation of the strain gage elements do not coincide with the x and y axes, thus complicating the problem. For the integrated statics and mechanics of materials course, the strain gage should be aligned with the x and y axes for simplicity since transformation of stress and strain are not covered. Also, for the problem described below, it is assumed that the thickness of the vessel is known. It is recommended at an additional pressure vessel be purchased and sectioned so that students can accurately measure the wall thickness and internal diameter.

The air tank shown in Figure 7 is equipped with a strain gage connected to a data acquisition system. As the pressure in the tank is decreased, the strains in the wall of the pressure vessel will also decrease. This decrease in strain and the corresponding decrease in stress is to be studied. Using the notation given in Figure D1, completed the following as part of this project:

! compute the strains å$_a$, å$_b$, and å$_c$ in the è$_a$, è$_b$, and è$_c$ directions at the peak pressure based on the output of the data acquisition system;

! compute the strains å$_x$, å$_y$,and ã$_{xy}$ at the peak pressure based on è$_a$, è$_b$,è$_c$, å$_a$, å$_b$, and å$_c$;

! compute the stresses ó$_x$, ó$_y$, and ô$_{xy}$ at the peak pressure from å$_x$, å$_y$,and ã$_{xy}$;

! compute the pressure change in the tank based on the changes in ó$_x$ and ó$_y$, and compare this value to the pressure decrease measured on the pressure gage; and

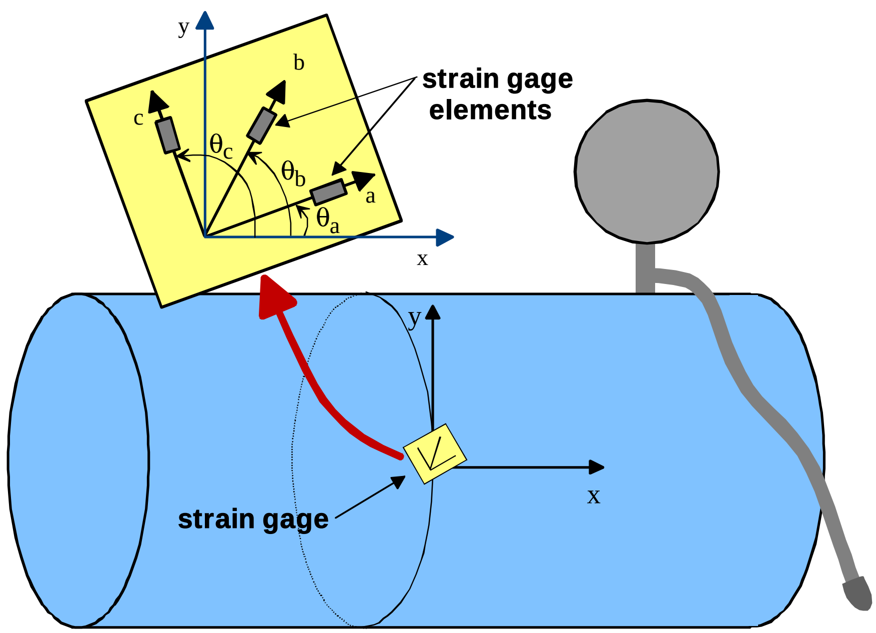


Figure D1 - Schematic showing the strain gage orientation.

! plot the experimentally determined stress change as a function of elapsed time.

Experiment Design and Fabrication. The equipment used consists of a portable air tank, a pressure gage, fittings used to connect the pressure gage to the tank, a strain gage and a data acquisition system. These portable air tanks can be purchased at auto parts stores, hardware stores or through industrial supply companies for less than $40. The tanks come with a small built in pressure gage. However, if the experiment is to be performed in front of a large class of students, a larger pressure gage will allow the students to watch the pressure fall as pressure is blead from the tank.

Appendix E
Additional Information for Truss Testing Device

Additional drawings and pictures of the device used to construct the truss are shown in Figures E1 through E4.

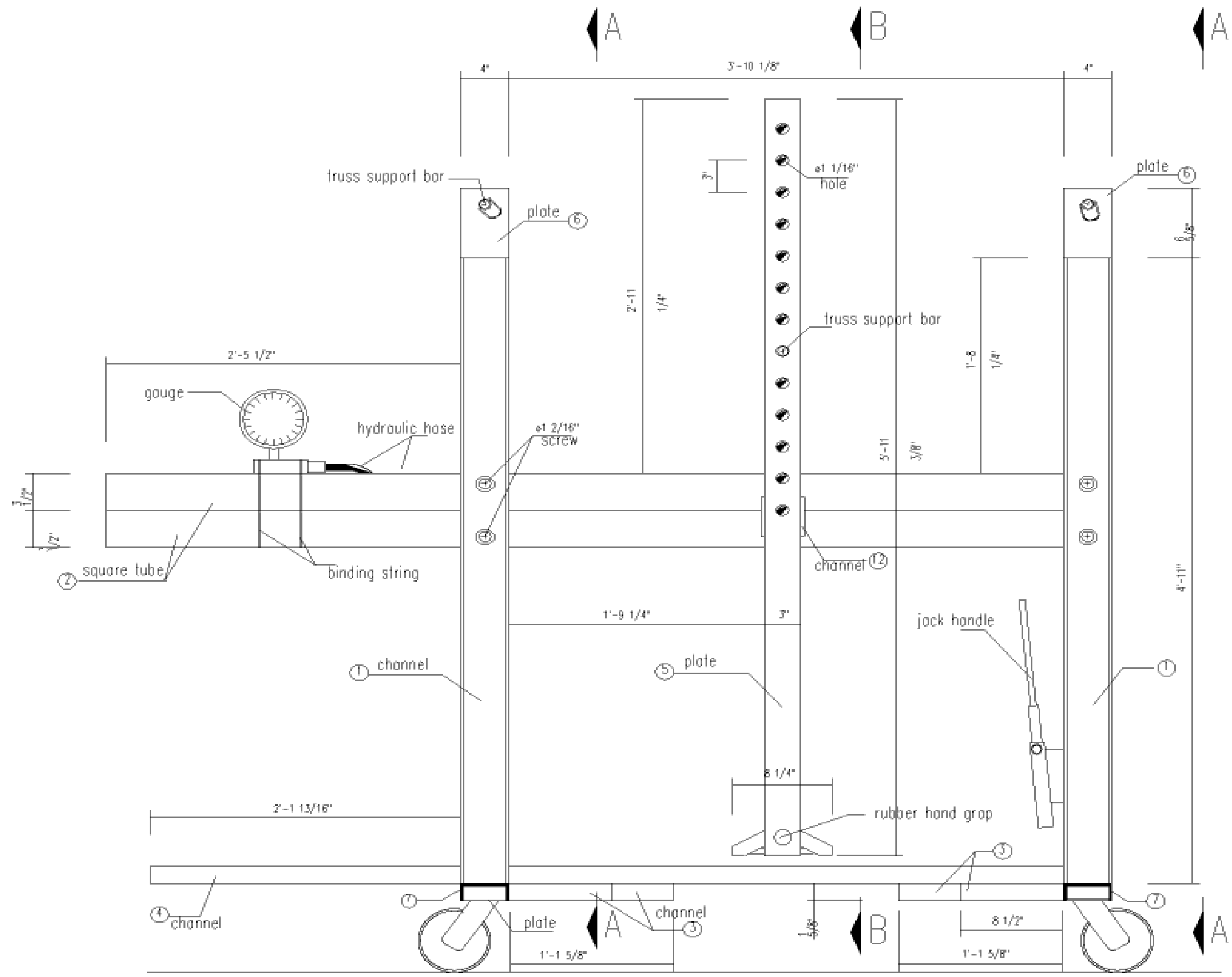


Figure E1 - Drawing of the truss testing device.

Figure E2 - Picture of truss testing device.

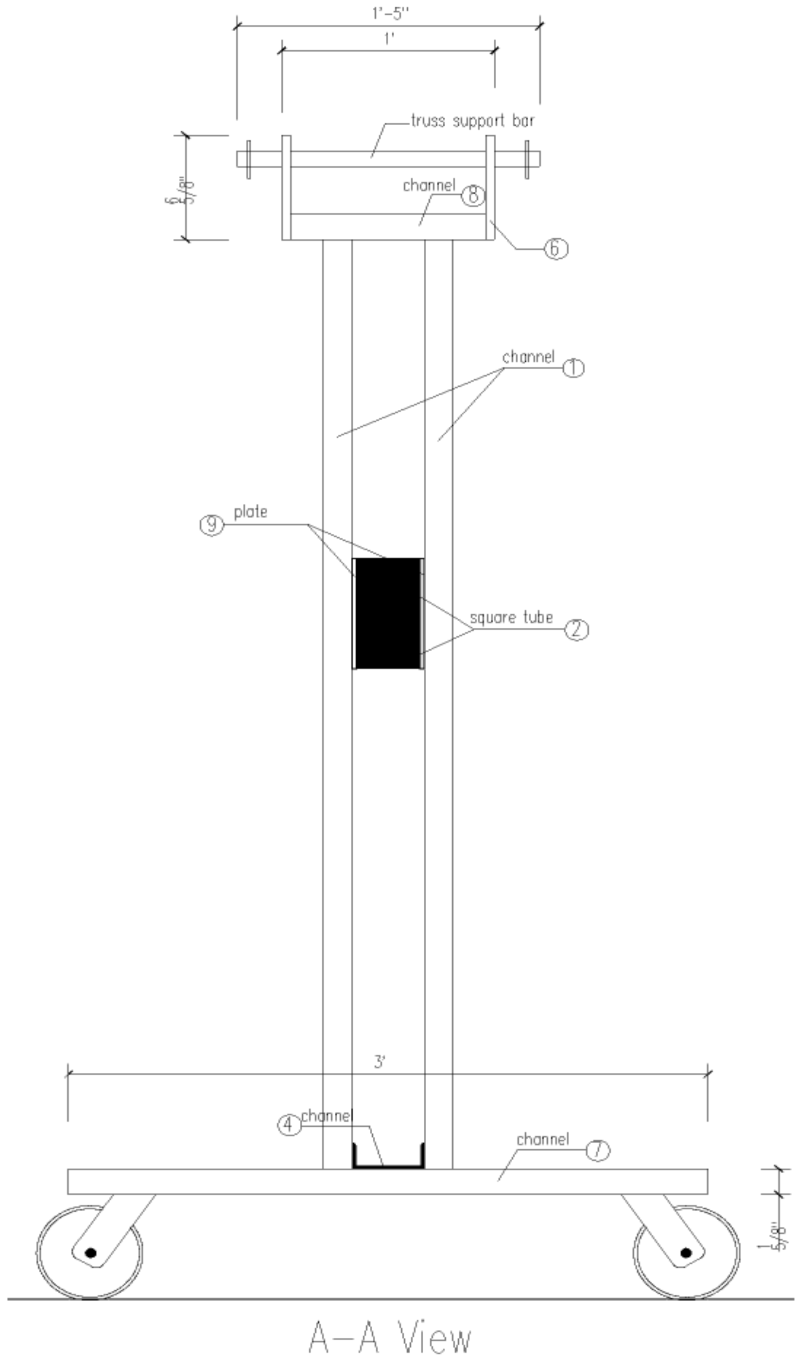


Figure E3 - Drawing of the truss testing device.

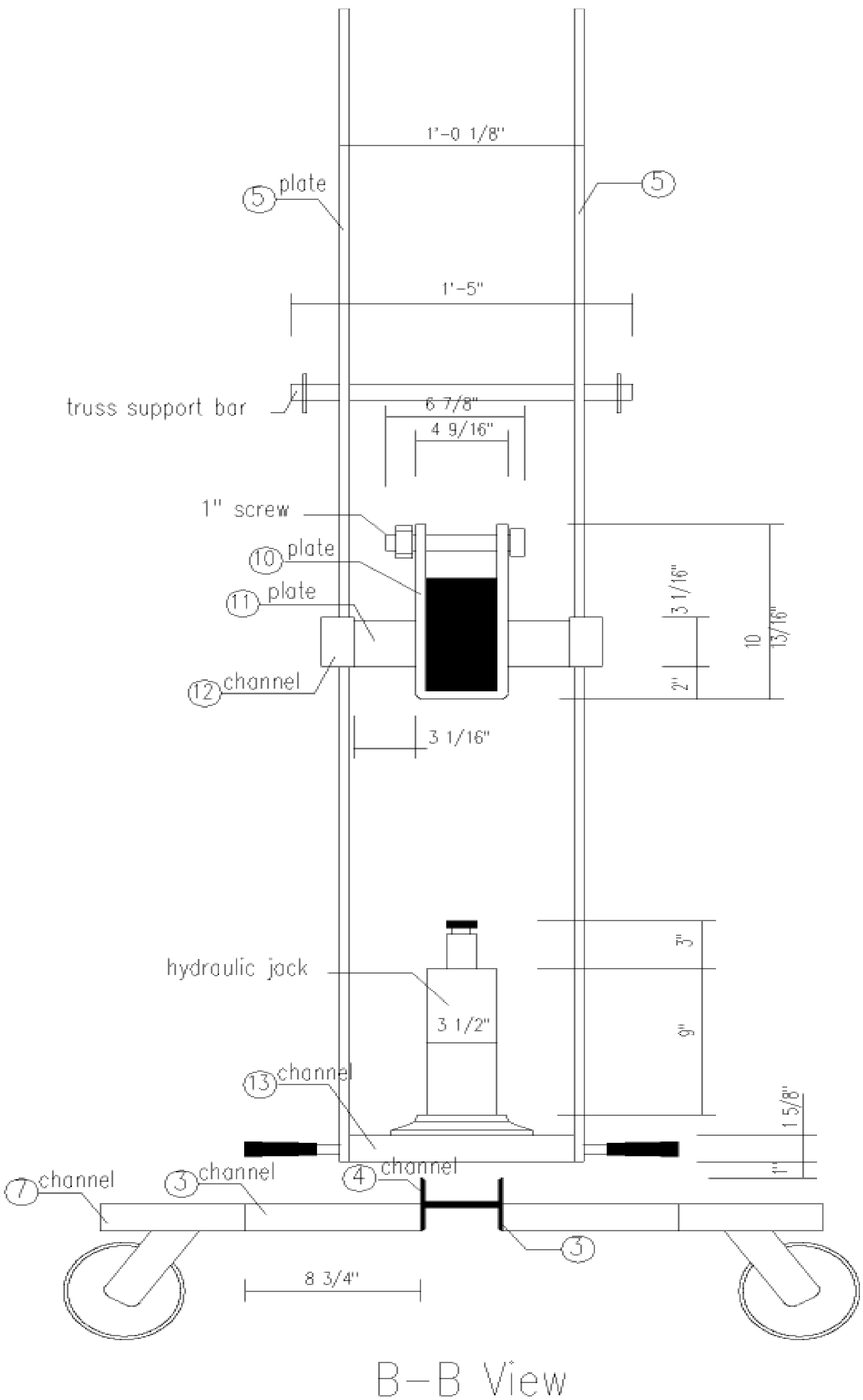


Figure E4 - Drawing of the truss testing device.