AC 2010-2146: TEACHING ENGINEERING REASONING USING A BEAM DEFLECTION LAB

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Teaching Engineering Reasoning using a Beam Deflection Lab

Abstract

Well crafted laboratories reinforce theoretical concepts presented in class, but also sharpen students' technical reasoning skills and provide practice in technical communication. This paper presents an introductory mechanics laboratory on beam deflection, suitable for freshmen engineering courses or as an opening week experiment for Strengths of Materials. The lab consists of 4 distinct experiments, each requiring students to measure maximum deflection of a simply supported beam. In each experiment, a single variable is adjusted (first load, then span, then cross-sectional geometry, and finally material). Although the procedure is likely similar to laboratories typically conducted in Mechanics courses *after* simple beam theory has been presented, the author suggests alternative objectives and student requirements targeted toward a less experienced audience. The primary goal of the exercise is to model engineering reasoning and begin a discussion on what makes for sound analysis. In conjunction with this goal, a standard for technical reporting also begins to form. To fulfill a secondary purpose, a simple addendum to the experiment is useful to show students the differences between the questions addressed by Statics (i.e. forces on rigid bodies) and those they will face in Strengths of Materials. The final objective is to demonstrate how stiffness is affected by both geometry and material, highlighting implications for design. The lab has been conducted in various forms in both an introductory design course and as a first lab in Strengths of Materials.

Introduction

Two vital skills for an engineering graduate are the abilities to reason and communicate effectively. ABET outcomes for baccalaureate engineering programs include abilities to "analyze and interpret data" as well as "to communicate effectively"[1]. The Boeing Corporation also lists these critical thinking and good communication as skill sets in their published "Desired Attributes for an Engineer."[2] Many have also argued that a harmony of these two skills is necessary to do either well. Cooney et al provide a review of critical thinking in engineering education which includes discussions on writing as a means to assess critical and reflective thinking for both open ended type activities as well as writing to articulate the design process.[3] Other organizations such as the Conceive, Design, Implement and Operate (CDIO) initiative and the Foundation for Critical Thinking provide resources for developing these abilities[4].

In addition to design projects (now being implemented in the earlier stages of curricula) laboratory work remains one of the principle ways in which students exercise critical thinking and effective professional communication. At the same time, lab exercises can help introduce or solidify engineering concepts presented in the classroom. Agrawal presents objectives for laboratory courses which include critical thinking in the planning and execution as well as for the evaluation of models and experimental data, in addition to effective communication[5]. These pedagogical purposes should be harmonious but may not be if students' attention is focused on learning too many new concepts at the expense of reasoning through the experiment itself. This is of particular concern for students new to standards of engineering reasoning and reporting.

In an introductory course for first year mechanical engineering students, laboratory experiments were included for two purposes: to set a standard for professional writing in follow on courses and to introduce a broad area of the discipline (e.g. thermo/fluids, mechanics, and materials). In earlier versions of these labs, priority was given to the latter purpose, and labs were used to introduce new concepts related to the discipline (e.g. energy conservation, stress and strain, crystal structure). Although most students could perform relevant calculations, produce suitable graphs, and even conform to the format of the report required, many struggled to effectively articulate the purpose, distill key results, or form appropriate conclusions. This began a frustrating endeavor to improve the students' reports (through feedback and multiple revisions). Eventually, it became clear that the student's difficulties were in part due to the nature of the design of the experiments. Each exercise introduced concepts (often several) which were new to the students, but did not necessary offer a single concise technical (or scientific) objective. Consequently, students' writing suffered. They provided reports intent relaying their understanding of the various concepts without any grasp of the experimental purpose; their writing lacked organization and evidence of critical thinking and as a result. Thus, in an effort to help students develop clear, concise, and convincing reports, modifications were explored for laboratories requiring written reports. With a renewed focus on setting a standard for professional writing, experiments were crafted with a straightforward technical objective in mind. Then, students were lead to think and write critically through their exploration of this objective.

This paper presents a beam deflection lab designed primarily for the purpose of introducing principles of sound engineering reasoning and establishing standards for professional reporting. The following section provides a procedure for a straightforward four part mechanics laboratory involving beam deflections. The exercises are designed specifically to engage students' engineering reasoning skills and form a standard for effective communication. Each part of the experiment is described in terms of the elements students are expected to ascertain and articulate in writing: (1) the technical objective, (2) background information leading to a theoretical prediction, (3) relevant procedural components, (4) key results including error assessment, and (5) implications and conclusions. This is followed by a discussion of experience in improving student skill through the grading process. Subsequently, an optional procedural addendum is discussed to highlight the difference in questions addressed in Statics and those of interest in Strengths of Materials courses. Conclusions are provided at the end of the report followed by a sample laboratory supplements provided as appendices.

Methodology for Baseline Experiment

Technical Objectives:

The technical objective is the foundational element to engineering reasoning. It is a single statement encompassing the 'purpose' and 'question' (see Paul's critical thinking model[6,7]). A laboratory handout provided to the student gives learning objectives but (purposefully) not the technical objective. Note that the supplementary laboratory handout in Appendix A provides pedagogical objectives: (1) examine differences in questions addressed by Strengths of Materials and Statics/Dynamics, and (2) provide standards and expectations for laboratory reporting, but that the engineering objective is to be determined as a class. A straightforward formula for determining the objective is proposed: "To determine the effect of ***what is changed*** on ***what is*** *measured* for *specific experimental circumstances*." Though simplistic, this 'recipe' for establishing the objective enables students to easily develop hypotheses and to defend conclusions they discern from the experiment. In the four parts of the experiment, **midspan deflection** is measured but a different variable is changed, thus each part has a distinct technical objective: (1) to determine the effect of **load** on deflection of a simply supported beam, (2) to determine the effect of **span** on deflection of a simply supported beam, (3) to determine the effect of **second moment of area** on deflection of a simply supported beam, and (4) to determine the effect of **elastic modulus** on deflection of a simply supported beam.

Prior versions of beam laboratory led students to incorporate the concept of stiffness (k = load/deflection) in the technical objectives, e.g. 'to determine the effect of *cross-sectional geometry/material* on *stiffness* for a simply supported beam.' However, the students' natural answer to the questions, "what is measured,' is 'deflection.' Though perhaps less sophisticated, the reasoning behind this answer and the technical objectives proposed is no less sound. So, in more recent iterations of the courses, a discussion of stiffness was left to other pedagogical activities while the beam lab was used primarily as a tool to teach critical thinking and writing.

Background & Hypotheses:
The necessary background information for the experiment is easy to find in any Strengths of Materials text along with deflection formulae for beams with various other loading conditions.[8]

$$\delta = \frac{PL^3}{48EI} \tag{1}$$

Equation (1) provides the midspan deflection (δ) of a simply supported beam with a point load at centerspan. P is load, L is span length, E is elastic modulus, and I is the second moment of area (or area moment of inertia) based on the assumptions of simple beam theory. Depending on their source, students may be required to derive equation (1) from a more generalized deflection formula for a simply supported beam with a point load at a specified location. Similar experiments are frequently conducted in conjunction with classroom lectures on simple beam theory, but students need not understand beam theory to intuitively understand the relationships between deflection and the first two variables (P and L). In fact, Matsumoto, et al suggests beam deflection experiments for pre-engineering curricula for high school students.[9] Nevertheless, definitions for elastic modulus and second moment of area are likely new concepts for first year engineering students.

The determination of second moment of area for various cross-section shapes is integral to the students understanding of part three of the experiment. It should also be noted that the second moment given in Equation (1) is that about the centroidal axis perpendicular to the load. If students have not been introduced to this concept (in a Statics course for example), the instructor will need to present the definition and discuss methods to calculate I for various cross-sectional shapes. A sample supplemental handout is provided in Appendix B. Though the concept of second moment of area may be new, however, most students could instinctively guess that certain cross-sections will deflect less than others (e.g. an I-beam deflects less than a square beam of the same cross-sectional area).

The definition for elastic modulus is usually given in terms of Hooke's Law between stress and strain for linear elastic material behavior, i.e. $\sigma = E\varepsilon$ where σ is stress and ε is strain. However, while stress and strain are absolutely fundamental concepts for the discipline of mechanics, they can easily become a distraction to students focused on the technical objective of part four of this experiment. It is enough rather that they understand that elastic modulus is a material property, independent of geometry (L or I) and load (P). Furthermore, they should be able to find literature values for elastic modulus for the materials used in the lab. For example, moduli for steel, aluminum, and wood(fir) are given in the Mechanics of Materials section of the FE Supplied-Reference Handbook.[10] Again, though modulus may be a new concept, most students could intuit that steel should deflect less than wood, all other factors being equal.

The role of the background information is to lead students to developing a theoretical answer or hypothesis for each of the four objectives. Students are encouraged to be as precise as the theory allows. For example, the first hypothesis could be stated as 'deflection is directly proportional to load with a positive coefficient of proportionality'. Thus it is clear that deflection increases with increasing load and that the relationship between the two is linear. Similarly, the hypotheses for the next three experiments are as follows: deflection is directly proportional to length cubed and inversely proportional to both second moment of area and elastic modulus (all with positive constants of proportionality.)

Finally, students are cautioned to understand the limitations of any theoretical model they use. Equation (1) is based on the assumptions associated with beam theory (e.g. straight long, narrow beam, uniform cross-section, homogeneous material properties, loaded perpendicular to beam axis, etc)[11]. It also assumes linear elastic behavior (generally true for ductile materials with small deformation.)

Procedure:

One of the advantages to the beam lab is that it requires modest resources (beams, a dial gage with a .001 x 0-1" range, 1/2 lb weights, simple supports, calipers, and a ruler or tape measure); it is also simple to perform. In fact, students, armed with the four objectives, should have no problems developing the experimental procedure themselves. The key is to vary only the relevant parameter during each of the four parts of the experiment. Students used an I-beam constructed from three 3/4"x 1/4" strips of basswood (the actual size is arbitrary) for the first two experiments. Although any span could be chosen, they set the beam on the supports with a 20" span for the first experiment, found the midspan and placed the dial gage under it, zeroed the gage with a 1 lb preload weight, and measured deflection as they added load in 1/2 lb increments up to 3 lbs. The purpose of the preload was to offset any natural bows in the beam and ensure the dial gage was in contact prior to adding the experimental loads. Students verified that the gage read zero after unloading all but the preload. If it did not, they repeated the experiment.

In part 2 of the experiment, the same basswood I-beam was used. In this case the experiment was repeated except that the span was adjusted in 2 inch increments from 12" to 24". The same 1 lb preload was used, but the experimental load was fixed at 2 lb for each span.

In part 3, the span was fixed at 20" and the experimental load at 2 lb, but two different beams were used: the I beam and a rectangular beam constructed from similar 3/4" x 1/4" basswood planks. Deflection was measured for each beam in both a horizontal and vertical configuration. Students used calipers to measure the cross-sectional dimensions of both beams and calculated second moment of area for each about the two centroidal axes (e.g. I_{xc} and I_{yc}). Note, though second moment of area accounts for the size as well as shape of the cross-section, beams of nearly equal cross-sectional area are used so that students don't focus on the more obvious factor.

In the final experiment, three 1/8" x 1" planks (one steel, one aluminum, one basswood) were tested with a 12" span and 2 lb experimental load. The planks were selected simply because they were available and the span was reduced to accommodate the smaller stiffness associated with the reduced second moment of area. For this experiment, students also had to beware of 'bottoming out' the dial gage which often required some adjustment of the zeroed location of the contact point.

In developing a clear and concise summary for their report, students needed to relate how the procedural steps contributed to the answering the questions posed by the four objective statements. This provided an excellent opportunity to discuss the quality of relevance with respect to professional writing. Not every observation or detail of the experiment needed to be included, only those that contributed (either positively or adversely) to addressing the technical objectives such as those which likely added to variability or error in the results. For example, students noticed in the fourth experiment that though the 3 planks shared the same nominal dimensions, their actual cross-sections varied somewhat. Thus changes in the second moment of area interfered with their ability to isolate elastic modulus as the sole variable changed in this experiment.

Distilling Key Results and Assessing Error:

Since the technical objectives are to assess the effects of four variables on deflection, and as the hypotheses provide specific predictions for each relationship, graphing each variable versus deflection with a theoretical curve fit is a natural way to represent the results. Note that although standard scientific practice would require the dependent variable (deflection) be plotted on the vertical axis, in this case students are taught to put deflection on the horizontal axis in keeping with engineering convention (i.e. load vs. deflection to parallel stress vs. strain plots from a tensile test). The first experiment is the most straight forward as the predicted relationship between load and deflection is linear. A line of best fit overlaid on the experimental data points provides a graphical representation of how well the data fits the hypothesis; in other words, whether deflection is in fact directly proportional to load. An example plot is shown in Fig. 1.

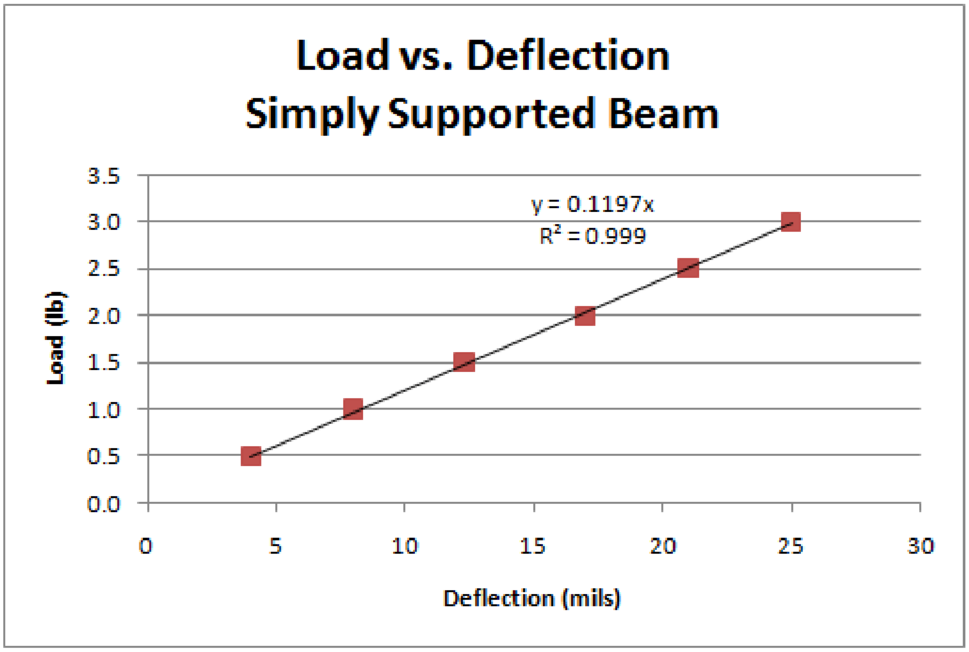

Figure 1: Sample Results for Load vs. Deflection (Part 1)

Students defend their assessment by some measurable *quantity* of the error, or the difference between their theoretical predictions (or hypotheses) and the experimental results. Then, they are expected to make some logical account for the *source* of the error. With the linear regression, the coefficient of variation (R^2) is an acceptable measure, where an R^2 of 1.0 indicates a perfect linear fit. However, students must be cautioned not to overstate their case. R^2 may near 1.0 because the relationship between deflection and load is in fact linear or because few data points beyond the minimum two required to define the line are available. The six data points available for part one of the experiment (corresponding to loads from 0-3 lb in 1/2 lb increments) should be sufficient. After quantifying the deviation between their predicted and experimental results, students use their reasoning to defend potential sources of the error. They should understand that the error could result from an inadequacy of their theoretical predictions, experimental variation, or a combination of both. If students infer limitations in their theory, they should provide evidence of poor assumptions. For example, if students repeatedly found that their dial gage did not return to zero upon unloading, or if the deflection increased at an increasing rate, they might conclude that the beam did not exhibit linear elastic behavior. A more likely source could be non-uniformity in the beam cross-section (recall that the I-beam was constructed from 3 strips of basswood.) At the same time, students will have found sources of error associated with their experimental procedure. The stronger reports discuss key observations that account for this in their synopsis of the procedure. Students with some laboratory experience often have 'at the ready' a number of stock sources for error and must be challenged to defend them for the experiment at hand. For example, many of their reports will mention "measurement error" which requires both clarification and a reasoned argument that it is a significant source of error for the experiment at hand. Given the tools used, a lack of measurement precision would probably only explain small differences in their theoretical predictions and experimental results.

Note that students could, armed with the cross-sectional dimensions of the I-beam, use the slope of the line of best fit to estimate the modulus of elasticity of the basswood. In fact, in a similar experiment with different pedagogical intentions, finding modulus may have been one of the technical objectives. However, 'determining modulus' does not have the same form as the technical objectives recommended here as there is can be no theoretical prediction with which to compare results. Students will frequently want to compare their result to a literature value which although prudent is not a measurement of error as these values are based on experiments themselves. There is one advantage to calculating elastic modulus at this stage. As grades of basswood can vary significantly, an experimental modulus found in part one could be used in part 4 which tests the effect of material (i.e. elastic modulus) on deflection in lieu of a value obtained from literature.

For the most part, even first year students bring some experience with using graphing software to perform linear regression, though they seldom consider how the analysis works. Consequently, the next three experiments provide slightly more of a challenge to their critical thinking skills. For example, the second hypothesis states that deflection is proportional to span cubed. Many students will want to plot span versus deflection; of these some may neglect to revisit their hypothesis and attempt a linear regression prior to cubing the span, others mindful of the hypothesis may fit a cubic curve to the data. In each case, students may be brought back to the objective and hypothesis to challenge the logic of their argument. In the former case, the question asked "how does span affect deflection?" is answered differently by the hypothesis "deflection is directly proportional to span cubed" than as inferred by the experiment "deflection is directional proportional to span" which begs for further analysis to evaluate and explain the disparity. Figure 2 depicts the latter fallacy. The cubic regression, if students display the best fit equation, has additional coefficients not present in Equation 1 (it will have the form $\delta = aL^3 + bL^2 + cL + d$). This provides trouble on two counts. First, it does not represent the predicted relationship (i.e. deflection is *directly proportional* to span cubed). Secondly, this regression requires a minimum of five data points; thus the 7 experimental points are inadequate to assess the quality of the fit (just as 3 points would be inadequate to conclude a linear fit). In this case, note that R^2 is 0.9995 despite being an incorrect curve because so few variables are needed to determine the fit. Consequently, students can see the benefit of plotting span cubed versus deflection and then performing a linear regression.

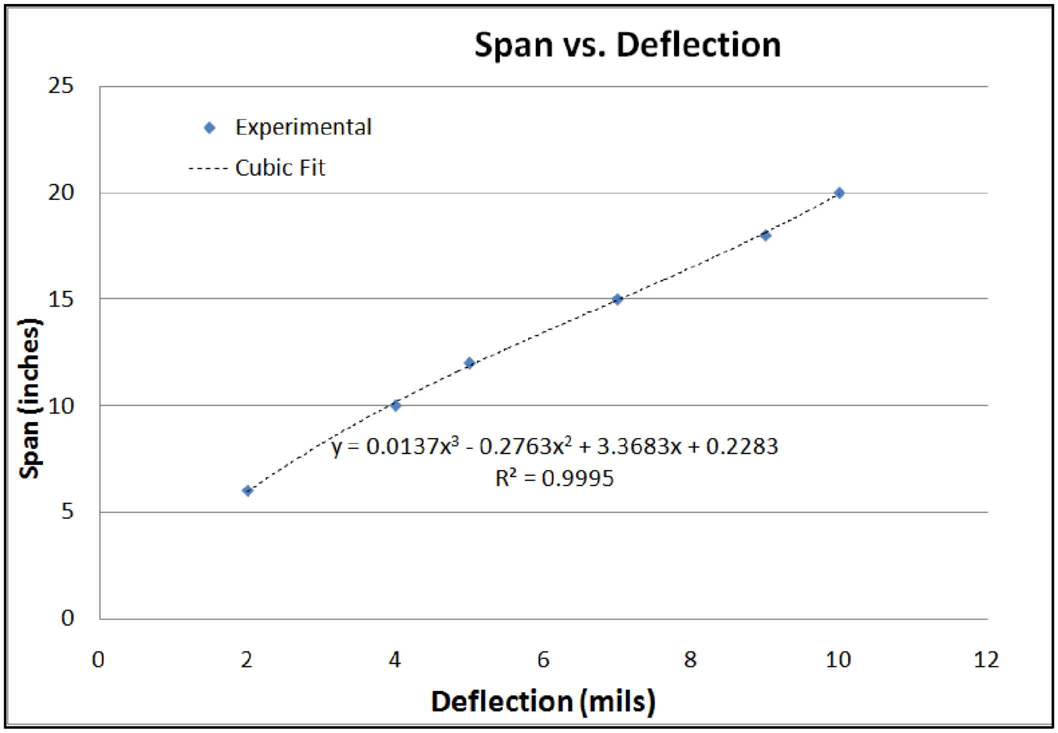

Figure 2: Incorrect Plot for Span vs. Deflection (Part 2)

Learning from the second part of the experiment, students quickly realize that they can also do linear regressions of 1/*I* and 1/*E* and deflection for parts 3 and 4 of the experiment. However, the number of data points is limited. There are only different 4 cross-sections (corresponding to horizontal and vertical orientations) for the deflection versus 1/I plot in the 3rd experiment, and only 3 materials for part 4. Thus, student reports should indicate that the R^2 is of limited value in supporting their argument that deflection is inversely proportional to second moment of area. For part 4, it is recommended that they not perform regression since the results are of no real value. However, they can draw a more general conclusion, i.e. "based on the theoretical relationship deflection should be inversely proportional to elastic modulus; the experiment shows that modulus increases, deflection decreases, but the evidence is insufficient to determine inverse proportionality."

Implications and Conclusions:

To complete their reports, students should be able to summarize their findings in one to two succinct sentences which answer the questions posed by the four objectives. Then they are encouraged to comment on implications for their findings with respect to design decisions. Finally, they make recommendations to improve the experimental process.

Evaluation

Grading criteria for laboratory reports abound for the sciences[12]. Lunsford and Melear provide a review and include an excellent sample rubric which correlates well with the report format presented herein (e.g. the technical objectives are "researchable question[s]," and "literature review" is conducted as part of background research).[13] Numerous resources are available for evaluating student critical thinking from the Open Practices website (http://openedpractices.org). In addition, the *Thinkers Guide to Engineering Reasoning* provides recommendations for grading student engineering work,[14] and Alfrey and Cooney suggest of rubric specifically for open-ended engineering assignments aimed at targeting critical thinking.[15] One common theme is that students are first evaluated on their ability to clearly state the objective (researchable question or problem statement). Thus, discovery of the technical objective is necessary to the students' success on the assignment. This is one reason why the formulaic objective (i.e. "to determine the effect of …") is advocated; it provides a model for a students understanding of what a technical objective might look. Given its importance, this criteria could be valued at anywhere from 10% - 30% of the entire report depending on both the level of assistance given and the degree of experience of the students. Other categories for evaluation followed the components of the report itself (i.e. background & hypothesis, procedure, results and analysis, and conclusion) along with issues such as proper formatting and grammar. Synthesis and analysis of results will generally take the most effort from students, and the grading rubric should reflect this.

The *Thinkers Guide to Engineering Reasoning* discusses qualities of good writing, many of which have particular relevance to laboratory reports. These include clarity, relevance, accuracy, precision, and logic among several others. The establishment of the objective improves the clarity of students writing significantly. Evaluation of the procedure section addresses clarity (does the student explain how the procedure accomplishes the technical objectives?), relevance (are details included which could affect results?), and precision (what are the specific beam load and support profiles which were tested?). Students' analysis of results should be evaluated with a number of these qualities in mind; they may be challenged on the logic of their inferences about experimental error for example. Finally, students are encouraged to draw relevant conclusions and design inferences that logically follow the experimental results.

Procedural Addendum

For students who have already taken Statics, the beam deflection lab can provide an introduction to a Strengths of Materials course which in addition to setting standards for student reporting, highlights differences in the assumptions and questions posed by the two courses. Equilibrium principles learned in Statics assume rigid bodies and attempts to find forces on those bodies while Strength is concerned with the response of deformable bodies to those forces. In Statics, students have limited concern for geometry (e.g. in calculating moments, to determine centers of gravity, etc.) and no concern for the material properties of the body. In Strengths, as obvious from Eq. (1), both geometry and material are of utmost concern.

As a simple addendum to the baseline experiment, support reactions may be determined for each beam in addition to the deflection measurements. Students used a fish scale to replace the support at one end of the beam for their measurements, but perhaps a better method would be to set the supports on flat scales. Since the point load is located at midspan, each support has a reaction equal to half total load. Of course, the beam has some dead weight of its own and that varies according to the material used. Nevertheless, the change in each support reaction should be half the added load. Since load varies only in part one of the experiment, the student can empirically verify that end reaction is independent of span, cross-section shape, and material.

Conclusion

Having a deep concern that engineering students learn effective written communication skills, a format of for a beam deflection lab was developed to provide students clear expectations for well-communicated reasoned thought within their reports. It is aimed toward students new to reporting with little to no prior knowledge of mechanics. The individual activities, as well as the report, are anchored upon simple objective statements of the form *'to determine the effect of* *what is changed* *on* *what is measured* for *specific experimental circumstances.'* Following a clear statement of the objective, students are taught to include background information required to develop a theoretical prediction, a summary of relevant procedural steps, key results with an assessment of both measures and source of error, conclusions and implications for design. The four distinct experiments in the beam lab give students practice repeating this pattern of analysis.

There several benefits to this approach. First, reports are more consistent and easier to evaluate. In the author's early experience with student writing, despite having a template, reports lacked a clear focus making it difficult to assess either the mechanics of their writing or the quality of their arguments. In essence, they had no reasoned argument to defend. A second advantage is that students clearly understand that sound reasoning is most important quality for effective communication. There is common ground between instructor and student with which to offer feedback and make improvements. As discussed above, the report is also ripe with opportunities to discuss qualities of sound reason, such as clarity of the objective, relevance of procedural details, precision of their theoretical predictions, the accuracy of experimental results, and the logic behind their assertions on sources of error. Finally, the simplicity of the technical objective statement makes it easily repeatable. Students will no doubt have reports with other kinds of objectives, but many of laboratories fit this form well, and the attempt to apply the formula at least proves that they are thinking about purpose.

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Appendix A - Sample Laboratory Handout

1.0 Materials and Equipment

- 1.1 24 in. basswood I-beam
- 1.2 24 x ½ x ¾ in. basswood beam
- 1.3 12 x 1 x $^1/_8$ in. steel plank
- 1.4 12 x 1 x $^1/_8$ in. aluminum plank
- 1.5 12 x 1 x $^1/_8$ in. basswood plank
- 1.6 two simple supports
- 1.7 Dial gage
- 1.8 22 in. ruler
- 1.9 Four ½ lb weights
- 1.10 Calipers

2.0 Objectives

- 2.1 As an introduction to the course, examine differences in questions addressed by Strengths of Materials and Statics/Dynamics.
- 2.2 Provide standards and expectations for laboratory reporting
- 2.3 Students will determine the "engineering" or "laboratory" objectives as a class.

3.0 Background information

- 3.1 Principles learned in STATICS
- 3.2 Beam theory will be discussed in class later on in the semester. However, students can develop hypotheses based on "Beam Deflection Formulas- Special Cases" from the FE Supplied Reference Handbook (FESRH).
- 3.3 Standards for lab reporting are provided as a separate handout.

4.0 Procedure

- 4.1 General procedure for Parts I-IV

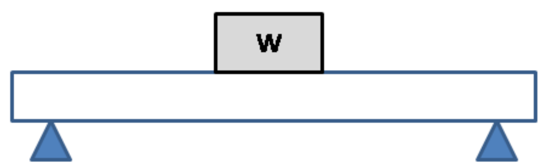


Figure 1: Depiction of loaded beam

- 4.1.1 Support beam with simple supports at designated span as shown in Fig. 1
- 4.1.2 Pre-load beam at midspan with two ½ lb weights. Place the dial gage at midspan under the beam and zero with the preload. (HINT. Make sure the gage is not at top center with the preload but provide at least ½ in clearance before hitting bottom center.) Measure deflection after designated weight is added.
- 4.1.3 Measure the end reaction ($\mathbf{R}_y$) using the fish scale to substitute for the one support.
- 4.1.4 Measure beam cross section. Sketch with dimensions. Calculate 2nd moment of area, *I*.
- 4.2 Divide into four groups. Each group will be responsible for performing one of the following four experiments.
  - 4.2.1 Part I: Using 20 in. span for the basswood I-beam, load in ½ lb increments up to 3 lb. Record deflections and end reactions.

4.2.2 Part II: Using the basswood I-beam and a 2 lb load, determine midspan deflection and end reaction for the following spans: 20", 18", 15", 12", 10", and 6".

4.2.3 Part III: Using a 12" span and a 2 lb load, determine midspan deflection and end reaction for the basswood beam in the 'I ' configuration and in an 'H' configuration and the rectangular basswood beam in both a vertical and horizontal configuration.

4.2.4 Part IV: Using a 12" span and 2 lb load, determine midspan deflection and end reaction for the steel, aluminum, and basswood plank beams.

4.3 Consolidate data on a single spreadsheet.

5.0 Analysis and Report

5.1 Provide a 4 paragraph lab report memo summarizing your findings.

5.2 Based on your knowledge of statics, what factors should affect the end reaction of the beam ($\mathbf{R_y}$)? Did the experimental data support this?

5.3 Take a look at the formula for maximum deflection provided in the FESRH. According to this, what should be the theoretical relationship between deflection and load?

5.3.1 Compare theory and experimental results graphically.

5.3.2 Provide a measure of how well the data supports this theory.

5.4 Using the same formula, what should be the relationship between deflection and span length? Again, compare graphically and provide a measure of how well the experiment agrees with the theory.

5.5 What should be the relationship between deflection and 2^{nd} moment of area?

5.5.1 Does the experiment support this?

5.5.2 What reservations might you have about drawing conclusions from part III the experiment?

5.6 In the deflection formula, there is one variable you may not be familiar with, ***E***.

5.6.1 Find the name and a definition for this formula. (Don't forget to cite your source.)

5.6.2 Find values of ***E*** relevant to this experiment.

5.6.3 Based on your experimental results, do the relative published values of ***E*** agree with the experimental results from Part IV?

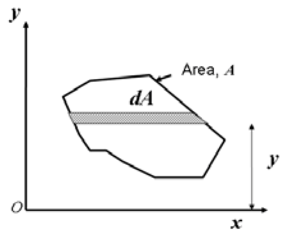
5.7 Address errors between theory and experimental results. Keep in mind that differences could result from experimental errors (e.g. measurement imprecision, procedural mistakes, etc.) and/or from errors associated with the theory (e.g. incorrect assumptions, etc.).

Appendix B - Finding the Area Moment of Inertia

The second moment of area (or area moment of inertia) is a parameter which describes the geometry of an object's cross-section.

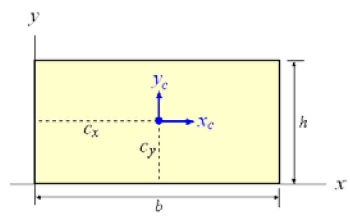
The second moment of area is defined as

$$I_x = \int_A y^2 dA$$



where y is the perpendicular distance between the axis of interest, x, and the element in the cross-section, dA. Second moments of area for common shapes are well known and many mechanics text books provide them in an appendix (see pg 940 of you text). For example, for a basic rectangular cross section like that of the beam in Fig 1, the second moment about the centroidal axis is

$$I_{xc} = \frac{bh^3}{12}$$



A more complex cross-section may often be decomposed into simple sections. The box beam in Fig. 1 may be decomposed into 4 numbered sections. Moments about the same axis may be added to one another. Since elements 1 and 3 have the same vertical centroid as the entire cross section, the equation above may be used to calculate their contribution to the second moment of area of the cross section as a whole:

$$I_{c1} = I_{c2} = \frac{B_1 H_1^3}{12}$$

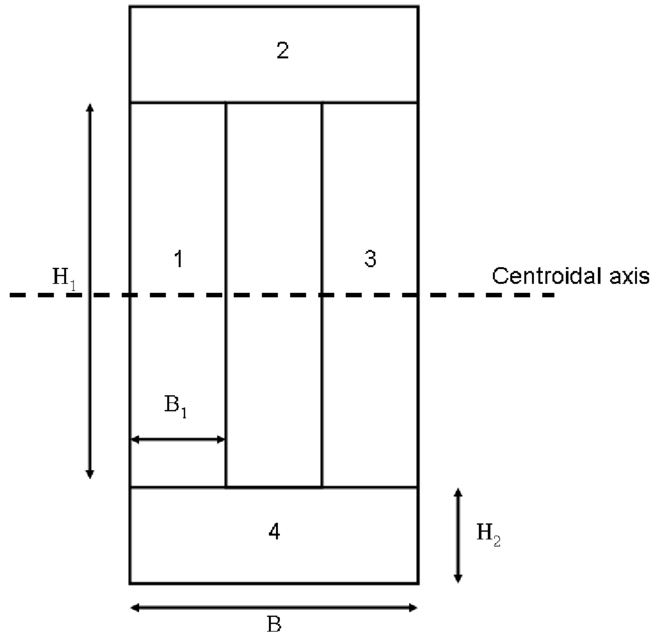


Figure 1: Box Beam

Elements 2 and 4, however, do not have the same centroid as the entire cross-section. Therefore the parallel axis theorem is needed to calculate their contribution:

$$I_x' = I_{xc} + d_x^2 A$$

Parallel axis theorem

In this theorem, I_{xc} is the moment about the element's own centroid; A is the area of the element; and d is the perpendicular distance between the element's centroid and the axis of interest (in this case the centroidal axis for the entire cross-section). Thus,

$$I_2' = I_4' = \underbrace{\frac{BH_2^3}{12}}_{I_{xc}} + \underbrace{BH_2}_{A}\underbrace{\left(\frac{H_1 + H_2}{2}\right)^2}_{d}$$

Now, all the moments about the centroidal axis are known, so they may be added to find the second moment of area for the entire cross section:

$$I_x = 2\frac{B_1 H_1^3}{12} + 2\left[\frac{BH_2^3}{12} + BH_2\left(\frac{H_1 + H_2}{2}\right)^2\right]$$