Work in Progress: Active Learning Activities to Improve Conceptual Understanding in an Undergraduate Mechanics of Materials Course

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WIP: Active Learning Activities to Improve Conceptual Understanding in an Undergraduate Mechanics of Materials Course

Abstract

This paper describes the development of a suite of active learning activities for an undergraduate course on mechanics of materials. One of the primary motivations for creating and implementing the new activities stemmed from the physical space in which the course was taught – a classroom specifically designed to encourage peer-to-peer collaboration. The round tables in the room and white-board-lined walls inspired a veteran, mechanical engineering faculty member to collaborate with an engineering education doctoral student to design a series of active learning activities for a mechanics of materials course. The goals of the activities were twofold: 1) to increase the student peer-to-peer collaboration during lectures, and 2) to increase the students' conceptual understanding of difficult, yet foundational, topics. Preliminary results indicated that the students found the activities helpful to their learning and felt comfortable with the concepts targeted. This work in progress manuscript briefly describes each of the active learning activities and illustrates the pedagogical benefits of interdepartmental collaboration.

Introduction

In Fall 2017, a new student-centered building opened on Purdue University's campus that houses many modern classrooms. The classrooms contain flexible furniture, white-board-lined walls, and ample technology to encourage instructors to use active learning pedagogies. This purposeful design of the classrooms motivated the authors to add more active learning activities to the curriculum of a mechanics of materials course that was taught in one of the new classrooms.

The incorporation of active learning techniques was not new for the instructor of record. Previously, he co-developed a learning environment called *Freeform* founded upon the research-based pedagogies of active, blended, and collaborative learning [1-3]. The mechanics of materials course utilized the *Freeform* framework, which included online video solutions for every example problem in a custom-written textbook, but most of the peer collaboration in the course consisted of periodic group quizzes. The instructor wanted to increase the frequency of student collaboration to capitalize on the unique learning space.

The goals of the new active learning exercises were both technical and social. The exercises were designed to enhance the students' conceptual understanding of fundamental topics in the course, and they encouraged students to practice their teamwork and communication skills. The course resources and assessments incorporated conceptual questions, so activities centering on conceptual understanding aligned well with overall structure and learning objectives of the course.

To help him brainstorm ideas for the new activities, the course instructor recruited an engineering education doctoral student who was researching the *Freeform* environment for assistance on the project. The brainstorming blossomed into a partnership with both the faculty member and the graduate student sharing in the design, development, and implementation of the activities. The partnership showcased the value of interdisciplinary and cross-level (faculty and graduate students) collaborations for pedagogical innovations. In total, the instructor and graduate student designed six active learning activities, targeting the concepts of: Poisson's ratio, shear strain, strain in indeterminate rods, beam deflection, states of stress for combined loading, and Mohr's circle.

Theoretical Foundations

All of the six new activities required the students to collaborate in pairs or small groups, and four of them incorporated a hands-on experiment. A plethora of research has established the benefits of active [e.g., 4], collaborative [5, 6], and hands-on (via physical or virtual manipulatives) [7-9] learning. Scholars also posit that learning and knowledge are situational, meaning that learning and knowledge depend on, and can be dictated by, the context (physical and social) of the environment [10-14]. One way the physical space can affect learning is through the influence of the pedagogical methods used by instructors [14-17]. Therefore, the use of active learning and peer collaboration in a classroom specifically designed for those pedagogies should positively impact student learning.

Additionally, the decision to focus the new activities on conceptual understanding theoretically enhances the students' problem-solving skills as well. The theoretical foundations of adaptive expertise posit that conceptual understanding, procedural knowledge, and the ability to transfer existing knowledge to new situations are all intrinsically linked [18-20]. To be a good problem solver, one must understand the underlying concepts [21]. Thus, prior work suggests that the deliberate design of the new activities to improve the students' conceptual understanding of difficult topics also increases the students' ability to solve traditional engineering problems.

Summary of the Activities

The new active learning activities targeted six fundamental topics of mechanics of materials that, based on the instructor's experience, students often struggled to master. The activities had to be low cost to accommodate approximately 40 groups. Students chose their own groups with group sizes ranging from two to four students, depending on the activity. The activities for each topic were implemented in two sections of the course (with 75 and 60 students each). The two sections of the course were taught on the same day but with a three-hour time gap separating the two sections. The time gap allowed the activities to be modified, if needed, based on the experience of the students in the first section. For example, the beam-deflection experiment (detailed later) was greatly simplified after the first section to improve its clarity and alignment with the learning objectives.

The addition of the activities did not require any elimination of content from the syllabus, but the activities did displace solving more example problems from the textbook during class. However, every example in the textbook had a solution video online, so the benefits of adding conceptual activities were deemed to outweigh the drawbacks of removing examples from lectures. The following sections briefly describe the current versions of the six active learning activities, and more details are presented in Appendixes A-E.

Poisson's Ratio and Stress-Strain Curves

The first part of this activity (Appendix A) consisted of a hands-on experiment to measure strain and calculate Poisson's ratio for an elastic material. The students measured the dimensions of the square strain element before and after stretching the nitrile rubber (cut from a nitrile glove to keep costs low) on which the element was drawn. After calculating Poisson's ratio from their measurements, the students commented on the appropriateness of the Poisson's ratio they calculated.

In the second part of this activity, students qualitatively drew the stress-strain curve for the nitrile material. To conclude the experiment, the instructional team discussed the students' values for Poisson's ratio and common shapes of the stress-strain curve.

Shear Strain

The shear strain experiment (Appendix B) was derived from the Poisson's ratio experiment and used the same nitrile rubber. However, for this experiment, the strain element was oriented at a 45-degree angle from the axis of the applied load. By marking the rotated strain element on the opposite side of the material but directly on top of the square used for the Poisson's ratio, students saw that the shear strain in a material depends on the plane of analysis. Students measured the deformation of the rotated strain element and calculated the shear strain. The experiment was designed to illustrate that shear strain is an angle evident in the change in the interior angles of the rotated stress element.

Stress, Strain, Elongation, and Geometry

This activity centered on the concept that the stiffness of a rod depends on its length and its cross-sectional area (Appendix C). Students measured the strain of two different sections of an indeterminate rod. Grids of lines represented the deformation of the rods in each section, as shown in the illustration of Appendix C. A series of questions then probed the students' understanding of the relationships between strain, force, cross-sectional area, modulus of elasticity, and rod length. This activity was completed at the beginning of the class, and at the end of the class period, common mistakes on the conceptual questions (as identified by the graduate student reviewing the students' work while the instructor lectured) were discussed with the class.

Beam Deflection

The fourth active learning activity focused on the relationship between the tip deflection and the length of the beam (Appendix D). Students worked in teams of four and investigated how the tip deflection of a beam under a uniformly distributed load changes when the length of the beam doubles. Two students in each group found an answer analytically by using the beam equations, and the other two students found an answer experimentally by measuring the deflection. For the experimental investigation, the students cantilevered a strip of thick paper off the edge of the table and measured its tip deflection for different overhanging lengths. The weight of the paper strip represented a uniformly-distributed load acting on the paper beam. At the end of the exercise, the two pairs of students compared their answers and developed hypotheses on why the answers differed.

Combined Loading

This activity represents a series of four exercises (Appendix E). During four distributed time periods over approximately three weeks, students completed exercises that identified the planar states of stress for an element in a beam under combined loadings of increasing complexities. For example, the cantilever beam in the first exercise experienced a single bending force, and in the last activity, a torque and two bending forces (along perpendicular dimensions) acted on the beam.

After the second of the four exercises, the instructors added the preliminary step of identifying the stress distributions on the cross-sectional area caused by each type of loading to the solution process. An example exercise that includes the step of drawing the stress distributions is included in Appendix E. The addition of this preparatory step when identifying the stresses at various locations of a cross section seemed to resonate with the students. One student expressed, "…drawing the distributions first finally caused [identifying the states of stress] to click. Now I feel like I know what I am doing."

To break the monotony of the four exercises, the third handout incorporated a suggested solution for the stress state at two points of the cross section. The students had to determine if the solution was correct, and, if it was incorrect, they needed to fix it. This alternative format benefitted the students in two ways: 1) it provided an example of how the solutions should be represented, and 2) it tested if the students understood the concept well enough to critique another person's work.

Mohr's Circle

Originally, the instructional team allotted an entire class period (50 minutes) for a Mohr's circle activity. However, based on the students' responses during the introductory lecture for the topic, the need for an activity spanning an entire class period became questionable. Therefore, a short pilot activity was used to judge the students' understanding of Mohr's circle before committing to a longer activity.

In the pilot activity (completed for both sections), the students raised different-colored flashcards to indicate their answers to multiple-choice questions from Timothy A. Philpot's *Mohr's Circle Game* [22]. This simple, short, and engaging activity revealed that students knew the concepts of Mohr's circle better than expected, so the original 50-minute activity was modified to be shorter. In the next class, the students answered eight more *Mohr's Circle Game* questions, but in addition to identifying the correct answer, they also had to briefly explain why the other two options were incorrect.

Student Feedback

At the end of the semester, the students completed a survey about the new active learning activities. Two of the questions and a summary of the students' responses are shown in Table 1. Overwhelmingly, the students felt comfortable with the topics targeted and found the associated activities helpful to their learning. (Mistakenly, only five of the six concepts and activities were included on this survey.) The students rated their comfort with identifying the states of stress in an element under combined loading the lowest of the topics, but they also rated the combined-loading exercises as the most beneficial. This pair of ratings highlights the difficulty students have with the concept of combined loading and the value of the new exercises.

Table 1. The students reported that the active learning activities helped them learn the concepts.

	Q1. How comfortable do you feel about the following concepts?			Q2. How beneficial were the following exercises for learning the associated concept?		
	Uncomfortable	Neither	Comfortable	Unbeneficial	Neither	Beneficial
Poisson's Ratio	13%	7%	80%	11%	4%	85%
Shear Strain	12%	3%	85%	10%	6%	85%
Beam Deflection	16%	2%	81%	9%	15%	76%
Combined Loading	16%	8%	76%	7%	7%	87%
Mohr's Circle	8%	1%	91%	11%	4%	85%

Note. Students were asked to answer each question on a 7-point scale ranging from Very Uncomfortable (or Very Unbeneficial) to Very Comfortable (or Very Beneficial). All uncomfortable (or unbeneficial) responses, with numeric values from 1-3, were aggregated for the percentages shown. Similarly, all comfortable (or beneficial) responses, with numeric values from 5-7, were aggregated.

The survey also included open-ended feedback questions and classroom-climate questions, but this data has yet to be fully analyzed. Preliminary results suggest that students appreciated the collaborative nature of the activities. For example, one student commented,

> "The most beneficial aspect of the activities was being able to work in a group so mistakes could be caught and explained between partners, which was helpful to me."

Another comment exemplified the technical benefit of the activities:

> "The exercises during which we were studying combined loading and drawing the stress state blocks was beneficial. Of this, the exercise during which we related the cross sectional [sic] depiction of each individual loading to its effect on the stress state block was incredibly helpful for me. I had been struggling to visualize this concept for a significant amount of time before we did that exercise."

This study did not incorporate a pre-/post-test design or compare exam scores across other sections that did not use the conceptual exercises because the focus was on the development of the activities. A more rigorous evaluation of student outcomes is planned for future semesters.

Conclusion and Future Work

This paper details six active learning exercises that resulted from an interdepartmental effort to increase the frequency of peer-to-peer collaboration in an undergraduate mechanics of materials class. Students reported that all of the activities were helpful in supporting their learning of the associated concepts. Furthermore, preliminary results from qualitative data suggest that students benefited from collaborating with their peers. Because of the apparent social and technical success of these activities, the instructor plans to permanently include these activities in the curriculum.

One challenge that must be addressed is the sustainability of the Poisson's ratio and shear-stress activities. The construction of the experimental apparatus for these two activities (nitrile rubber with wooden pieces at its ends and a strain element drawn in the center) required a significant amount of time, and the apparatuses could only be used for one semester as the rubber discolored after use. Future work will focus on the development of a robust experimental setup for these two activities that can be used for multiple semesters yet is still cost effective. Future work will also include a complete analysis of the survey data and a more extensive evaluation of the effects that the conceptual activities may have on the students' social and technical skills.

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References

[1] D. Evenhouse, N. Patel, M. Gerschutz, N. A. Stites, J. F. Rhoads, E. Berger, *et al.*, "Perspectives on pedagogical change: Instructor and student experiences of a newly implemented undergraduate engineering dynamics curriculum," *European Journal of Engineering Education,* 2017.

[2] J. F. Rhoads, E. Nauman, B. Holloway, and C. Krousgrill, "The Purdue Mechanics Freeform Classroom : A new approach to engineering mechanics education," presented at the ASEE Annual Conference and Exposition, Indianapolis, IN, 2014.

[3] N. A. Stites, C. Zywicki, E. Berger, C. Krousgrill, J. F. Rhoads, and J. DeBoer, "The impact of instructor experience on student success for a blended, undergraduate engineering class," presented at the AERA Annual Meeting, San Antonio, TX, 2017.

[4] S. Freeman, S. L. Eddy, M. McDonough, M. K. Smith, N. Okoroafor, H. Jordt, *et al.*, "Active learning increases student performance in science, engineering, and mathematics," *Proceedings of the National Academy of Sciences,* vol. 111, pp. 8410-8415, Jun 10 2014.

[5] D. W. Johnson, R. T. Johnson, and K. A. Smith, *Cooperative learning: Increasing college faculty instructional productivity. ASHE-ERIC Higher Education Report No. 4*.

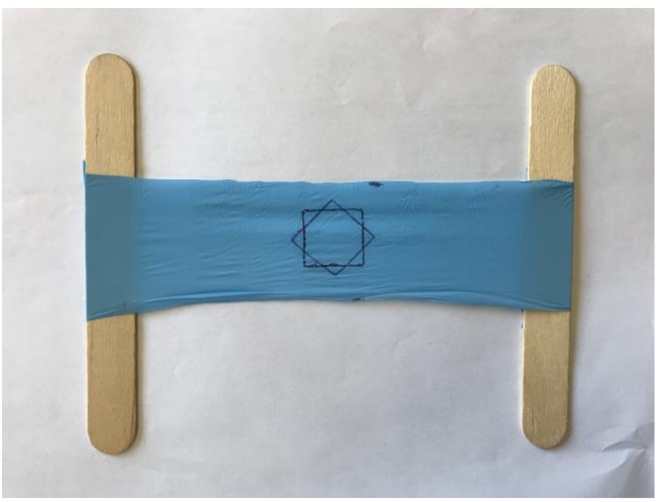
Washington, D.C.: The George Washington University, School of Education and Human Development, 1991.
[6] K. A. Smith, D. W. Johnson, and R. T. Johnson, "Structuring learning goals to meet the goals of engineering education," *Engineering Education,* vol. 72, pp. 221-226, 1981.
[7] A. Dollar and P. S. Steif, "Learning modules for statics," *International Journal of Engineering Education,* vol. 22, pp. 381-392, 2006.
[8] J. Sarama and D. H. Clements, "Physical and virtual manipulatives: What is "concrete"?," in *International Perspectives on Teaching and Learning Mathematics with Virtual Manipulatives*. vol. 7, P. S. Moyer-Packenham, Ed. Switzerland: Springer International Publishing, 2016, pp. 71-93.
[9] E. J. Sowell, "Effects of manipulative materials in mathematics instruction," *Journal for Research in Mathematics Education,* vol. 20, pp. 498-505, 1989.
[10] J. S. Brown, A. Collins, and P. Duguid, "Situated cognition and the culture of learning," *Educational Researcher,* vol. 18, pp. 32-42, 1989.
[11] A. Johri and B. M. Olds, "Situated engineering learning : Bridging engineering education research and the learning sciences," *Journal of Engineering Education,* vol. 100, pp. 151-185, 2011.
[12] J. Lave, "Situated learning in communities of practice," in *Perspectives on Socially Shared Cognition*, L. B. Resnick, J. M. Levine, and S. D. Teasley, Eds. Washington, DC: American Psychological Association, 1991, pp. 63-82.
[13] J. Pöysä, J. Lowyck, and P. Häkkinen, "Learning together “there”-hybrid “place” as a conceptual vantage point for understanding virtual learning communities in higher education context," *PsychNology,* vol. 3, pp. 162-180, 2005.
[14] P. Goodyear, "Flexible learning and the architechure of learning places," in *Handbook of Research on Eductational Communications and Technology*, J. M. Spector, Ed. New York, NY: Lawrence Erlbaum Associates, 2008, pp. 251-257.
[15] B. Cleveland and K. Fisher, "The evaluation of physical learning environments: A critical review of the literature," *Learning Environments Research,* vol. 17, pp. 1-28, 2013.
[16] K. A. Graetz and M. J. Goliber, "Designing collaborative learning places: Psychological foundations and new frontiers," *New Directions for Teaching and Learning,* vol. 2002, pp. 13–22, 2002.
[17] N. Van Note Chism, "A tale of two classrooms. New directions for teaching and learning," *New Directions for Teaching and Learning,* vol. 2002, pp. 5-12, 2002.
[18] G. Hatano and K. Inagaki, "Two courses of expertise," *Research and Clinical Center for Child Development Annual Report,* vol. 6, pp. 27-36, 1984.
[19] A. F. McKenna, "An investigation of adaptive expertise and transfer of design process knowledge," *Journal of Mechanical Design,* vol. 129, pp. 730-734, 2007.
[20] M. G. Pandy, A. J. Petrosino, B. A. Austin, and R. E. Barr, "Assessing adaptive expertise in undergraduate biomechanics," *Journal of Engineering Education,* vol. 93, pp. 211-222, 2004.
[21] R. Streveler, T. Litzinger, R. Miller, and P. Steif, "Learning conceptual knowledge in the engineering sciences: Overview and future research directions," *Journal of Engineering Education,* vol. 97, pp. 279-294, 2008.
[22] T. A. Philpot. (n.d.). *MecMovies: Mohr's circle game*. Available: https://web.mst.edu/~mecmovie/

Appendix A. Poisson's Ratio and Stress-Strain Curves

<u>Learning Objectives:</u>
By the end of this activity, you should be able to:
1. Experimentally estimate the Poisson's ratio for a material;
2. Sketch the stress-strain curve for a material.

<u>Instructions: (using the apparatus in Figure 1a)</u>
1. Measure L_{x0}, L_{y0}, L_x, L_y.
2. Calculate the Poisson's ratio for the material.
    a. Is this value reasonable?
    b. Why or why not?
3. Predict and sketch the general shape of the stress-strain curve for this material.

<u>Looking Ahead</u>: Provide evidence that the element does not experience shear strain. (Hint: see Chapter 3 in lecture notes)

a) 

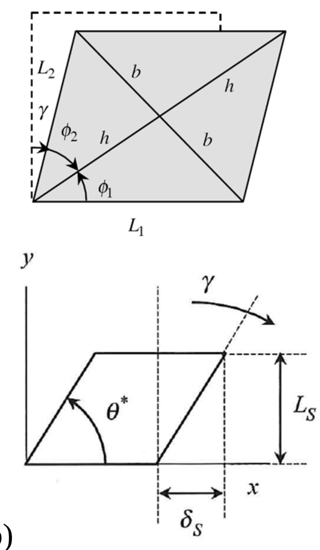
b) 

Figure 1. a) The apparatus used in the experiments regarding Poisson's ratio and shear strain; b) the diagram included in the handout for shear strain.

Appendix B. Shear Strain

Learning Objectives:
By the end of this activity, you should be able to:
1. Experimentally measure shear strain;
2. Explain and interpret shear strain.

Instructions:
1. Measure *h*, *b*, L_1, L_2, δ_s, L_s.
2. Calculate the shear strain of the element. [See Figure 1b.]

$$g = \frac{p}{2} - \left(f_1 + f_2\right) = \frac{p}{2} - \cos^{-1}\left(\frac{\left(2h\right)^2 - L_1^2 - L_2^2}{2L_1L_2}\right)$$

a. Is this value reasonable?
b. Why or why not?

3. Calculate the ratio δ_s/L_s. How does this compare to your measured shear strain?
4. Does the element experience other strains besides shear strain? Why or why not?

Appendix C. Stress, Strain, Elongation, and Geometry

As shown in Figure 2, a rod is made up of elements (1) (of Young's modulus E_1, cross-sectional area A_1 and length L_1) and (2) (with Young's modulus E_2, cross-sectional area A_2 and length L_2), with (1) and (2) being joined by rigid connector C, and with the other ends of the elements fixed to ground. A load P acts at connector C. A square grid pattern is painted on the surface of each rod element. Expanded figures of these square grid patterns after the application of the load P are provided on the following figure. Note that the drawing of the rod is generic; *please make no assumptions about the relative sizes of L_1 and L_2 based on the figure*.

a) From the figure, determine the e_x component of strain for each element (including the *sign*).

b) If $A_2 / A_1 = 1$ [or 2, depending on the group] and $E_2 / E_1 = 1$, determine the ratio F_2 / F_1 where F_1 and F_2 are the axial loads carried by elements (1) and (2), respectively. Based on this, which element is carrying the larger load?

What is the ratio L_2 / L_1 for this rod? Does the size of this ratio make sense based on the relative sizes of the "stiffnesses" of elements (1) and (2)?

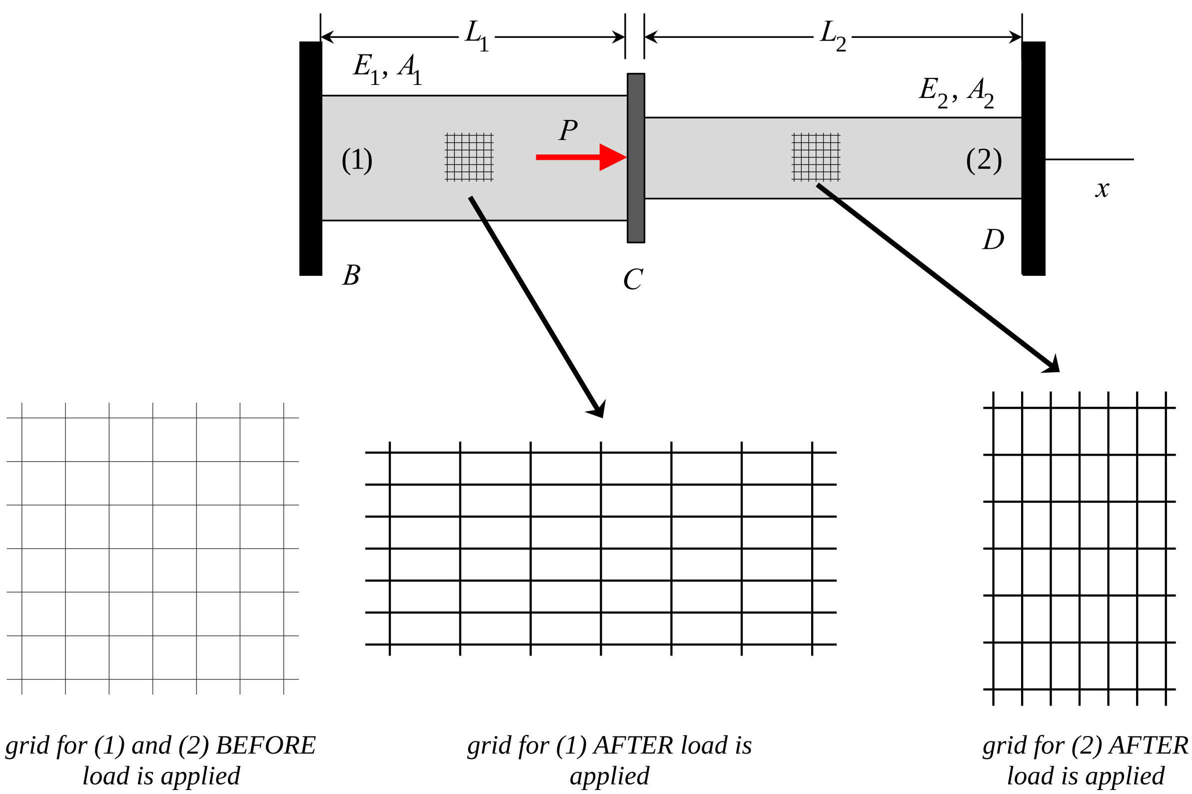
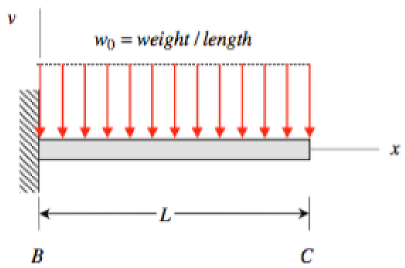


Figure 2. Simulated deformations of rod after a load is applied at the connector C. The students measured the strain in each section of the rod.

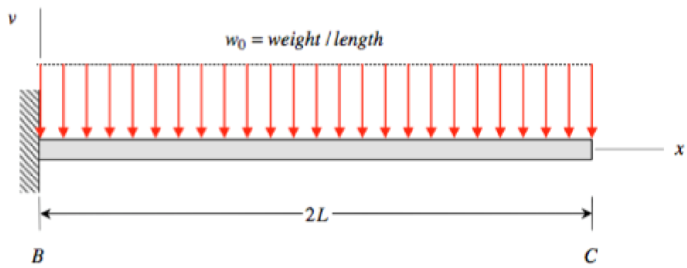
Appendix D. Beam Deflection

Goal:
To understand how the maximum deflection of a beam is related to the beam's length. In particular, we want to answer the question: "*If you double the length of a beam, how does that affect the maximum deflection of the beam*?"

Problem statement:
The cantilevered beam, ***Beam #1***, has a length L, has a cross section with a second area moment of *I*, and is made up of a material with a weight/length of w_0 and a Young's modulus of *E*. ***Beam #2*** has the same properties as Beam #1, except it has a length of 2*L*. Let δ_C represent the deflection of the beam at C.



Beam #1



Beam #2

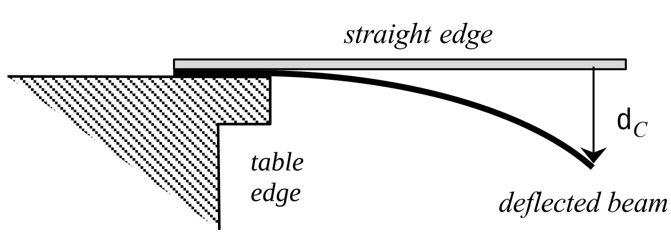
Task #1.1: ANALYTICS
Referencing either Example 11.1 or Appendix 5 of the lecturebook, find the tip deflection d_C.

Results:

- For ***Beam #1*** (of length *L*): $(d_C)_{1A} =$
- For***Beam#2*** (of length 2*L*): $(d_C)_{2A} =$

From the analytical equations, you have: $\dfrac{(d_C)_{2A}}{(d_C)_{1A}} =$

Task #1.2: EXPERIMENTS
Using beams and measuring devices provided, measure the tip deflection d_C for two beams: Beam #1 of length *L* and Beam #2 of length 2*L*.



Results:

- For Beam #1 (of length *L*): $(d_C)_{1E} =$

- For Beam #2 (of length 2L): $\left(d_C\right)_{2E} =$

Therefore, from experiment, you have:

$$\frac{\left(d_C\right)_{2E}}{\left(d_C\right)_{1E}} =$$

<u>Task #1.3: CONCLUSIONS</u>

How do the analytical and experimental results compare? If they differ, why? Think deeper than "measurement error" for possible explanations.

Appendix E. Combined Loading

This activity was repeated for times with loadings of increasing complexity. Below is a portion of the third exercise.

Goal:
Identify and draw the state of stress of a mass element in structural members with different applied forces.

Problem Statement:
A torque and axial force act at the end of a shaft with a cross-sectional area *A* and a polar moment of inertia I_p. The resultant torque and axial force are shown in the figure below. What are the states of stress at the points "*a*", "*b*", and "*c*" at a cross section located at a distance *L* from the end of the beam?

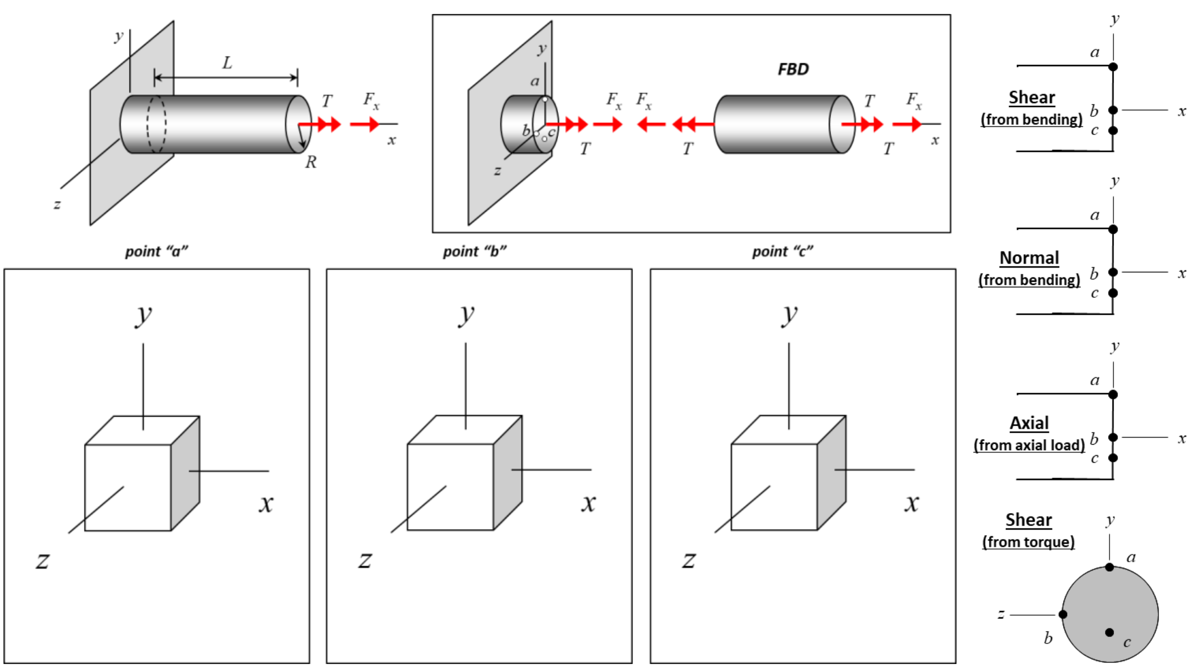


Figure 3. The process of having students draw the stress distributions on the right side seemed to significantly help the students be able to draw the stresses on the elements.