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A Hands-On Activity to Teach Students About Normal and Shear Failure Modes

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Abstract

Students entering a mechanics of materials course often have difficulty visualizing how a structure or assembly can fail in different ways due to normal and shear stresses. In particular, they can struggle to identify relevant combinations of load and area necessary to calculate potential critical stresses at different locations in a system.

To address this issue, an activity was designed to help students think through different ways simple assemblies can fail and identify the correct combinations of load and area needed to calculate the stress associated with each potential failure. This activity incorporates low-cost, easy-to-manufacture physical manipulatives along with questions designed to scaffold exploration of the topic. It can be completed by small groups of students in one 50-minute class period. In developing the activity, the hypothesis was that the active-learning, inquiry-based approach would improve student ability to calculate stresses associated with potential failure modes.

A pre- and post-test related to normal and shear failure was used to evaluate the effectiveness of the activity in promoting student learning. In addition, a survey was used to interrogate students' impressions of the activity and how they perceived it helped them learn. The activity was piloted in Fall 2025 in a mechanics of materials class with 30 students, who all provided pre/post testing and survey data. Examination of the pre/post test data reveals that the majority of students did improve their performance when analyzing a scenario involving shear and normal stress after the activity. Examination of the survey data indicates that students enjoyed the activity and that they felt it helped them better understand normal and shear stress failure. Students particularly praised the physical manipulatives and group discussion.

Introduction

Visualization and spatial reasoning skills have been shown to be important predictors of student performance on engineering exams and in workplace problem-solving [1,2]. For this reason, many interventions have been developed which aim to improve the spatial visualization skills of students, typically during engineering graphics courses aimed at freshman [3,4]. However, there is some criticism that tests designed to gage student visualization skills are not engineering specific [5]. Students entering an engineering science course later in the curriculum often still struggle with visualization, particularly in relation to how a structure or assembly interacts with loading.

To tackle this problem, researchers have begun to design hands-on learning activities for statics courses that are focused on helping student better understand vectors and free-body diagrams (FBDs) in 3D space. For example, Wodin-Schwartz et al developed a series of tactile experiences to help students feel loading as they construct FBDs [6]. Likewise, Davishahl developed a series of inquiry-based activities involving physical manipulatives [7,8] to help students develop FBD skills and build representational competence.

For courses that build off of statics, such as mechanics of materials, instructors have developed a wide-range of active learning experiences involving common tools [9], physical manipulatives [10], small group activities [11], and assemblies designed specifically for inquiry-based learning [12]. However, in reviewing the literature, few–if any–of these activities focused on the visualization skills associated with identifying possible failure modes in a structure or assembly. Students can struggle to determine these failure modes, often having particular difficulty determining combinations of loading and area relevant to various normal and shear failures. This paper outlines the development of an activity designed to help students think through different ways simple assemblies can fail and identify the correct combinations of load and area needed to calculate the stress associated with each potential failure. The activity involves students working through a set of inquiry-based, active learning tasks involving physical manipulatives in small groups.

Methods

The following subsections describe the in-class activity and associated physical manipulatives as well as the research assessment designed to determine how the activity impacted students.

Activity

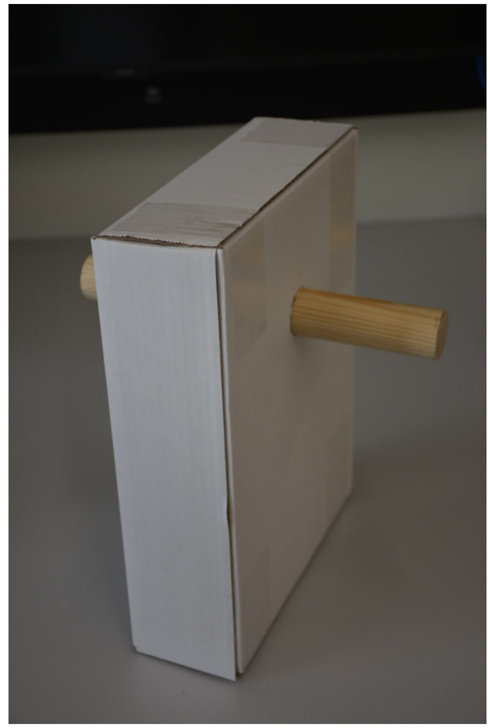
The educational intervention consists an activity designed for use in one 50-minute class period during which students interact with 4 low-cost, easy-to-implement physical manipulatives and associated guidance worksheets. The activity is designed to help students identify areas associated with different normal and shear failure modes in mechanical assemblies.

The 4 physical manipulatives are built using common, inexpensive materials that can be found at big-box hardware, craft, and retail stores. Each manipulative is designed to have several possible failure modes; which failure would occur depending on the relative material strengths of each part of the assembly. (The as-constructed materials are representative of any possible material.) Figure 1 shows photographs of the each of the 4 manipulatives. Table 1 provides a summary of the materials and costs associated with their construction. The total cost for a set of 4 manipulatives (appropriate for up to 8 students) is approximately $25. The simple nature of the manipulatives makes this activity easy to scale to larger classes.

Each of the physical manipulatives is accompanied by a worksheet that guide groups of students through an exploration of the stresses acting in the assembly. Figure 2 shows the worksheet associated with one of the physical manipulatives (the assembly shown in Figure 1 (b)).

To carry out the activity, students are divided into small groups of 3 or 4. Each group begins with one of the physical manipulatives and associated worksheet and is tasked with answering the questions provided on the sheet. After 5 minutes of working time, the group will swap manipulatives with another group and attempt to fill out a second worksheet. When the activity was implemented for the study, two physical manipulatives were available in the classroom at a particular time. This was done to ensure not all groups had the same manipulative to encourage groups to work independently but also ensure periods of review between group work. After students have attempted the second worksheet, a debriefing session where the instructor

(a)



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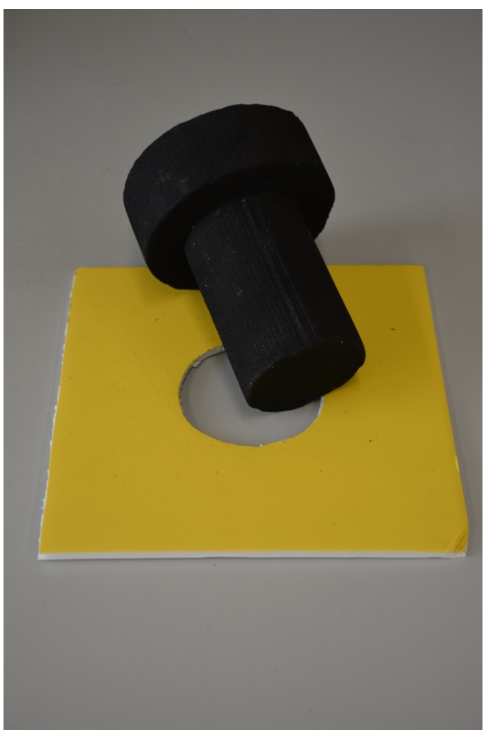


(c)

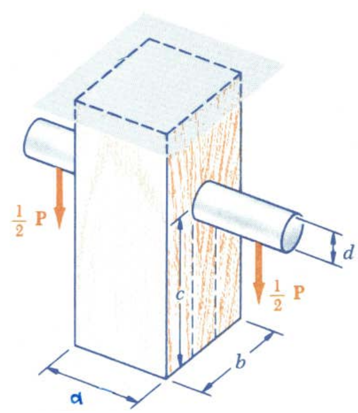
(d)

Figure 1: The four physical manipulatives used as part of the activity: (a) a pipe and rod joined by a pin and pulled apart by tensile forces, (b) a block fixed on one end with attached "handles" that experience a pulling force, (c) an oversized fastener which seats in a hole and is pulled downward, and (d) a set of glued lumber pieces that is pulled apart by tensile forces.

Table 1: Materials and costs associated with construction of each of the 4 physical manipulatives.

Assembly	Materials	Supplier	Cost
(a) Pipe and Rod	1" diameter dowel (8 in)	Lowes	$1.33 / ft
	1" ID PVC pipe (8 in)	Lowes	$0.81 / ft
	Clevis Pin	Lowes	$4.98 ea
(b) Block and Handles	1" diameter dowel (1 ft)	Lowes	$1.33 / ft
	9" x 12" x 3" box	Walmart	$1.13 ea
(c) Fastner and Hole	floral foam cylinder	Hobby Lobby	$4.99 ea
	floral foam disk	Hobby Lobby	$3.99 ea
	foam board	Hobby Lobby	$4.99 / sheet
	spray paint	Lowes	$6.98
	hot glue	-	-
(d) Glued Boards	1x4 pine board (5 ft)	Lowes	$1.07 / ft
	wood glue	-	-

A load P is supported as shown by a pin inserted through a hole in a post ($\frac{1}{2}P$ on either side of the post). The post hangs from a ceiling; the connection between the post and the ceiling is secure. The post has a cross-section of a by b and the pin is embedded a distance c from the lower end of the post. The diameter of the pin is d.



(a) There are two ways this combination of structure and load could fail due to shear stress. What are they? Explain each in words or using a sketch.

(b) For each possible shear failure identified in part (a), write a symbolic expression for the shear stress in terms of the forces and dimensions provided in the figure.

(c) This combination of structure and load could also fail due to normal stress. How could this happen? Explain in words or using a sketch.

(d) For the normal failure identified in part (c), write a symbolic expression for the normal stress in terms of the forces and dimensions provided in the figure.

Figure 2: The guidance worksheet associated with the “block with handles” physical manipulative. Groups of students attempt to answer the questions on the worksheet while interacting with the assembly in Figure 1 (b).

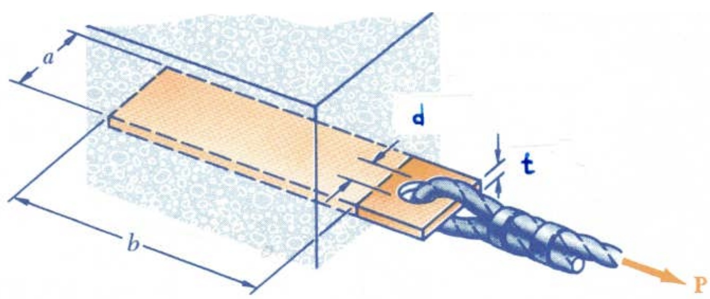
reviews solutions and answers questions on both manipulatives occurs for approximately 5 minutes. This concludes one round of the activity. Because there are 4 physical manipulatives, two separate rounds of the activity are possible for a total time commitment of 30-40 minutes.

For the purpose of this study, the concepts of normal and shear stress had been introduced in an earlier class session to allow class time before and after the activity to be used for research assessment. However, absent the need for this assessment, an instructor could use the time before the activity for a review of normal and shear stress failure modes.

Research Assessment

Two instruments were used to assess the impact and effectiveness of the activity. The first assessment was a pre- and post-activity test consisting of two questions asking about normal and shear failure of an assembly different from the physical manipulatives used in the activity. This pre/post test, shown in Figure 3, was used to assess the learning gains resulting from student participation in the activity. The second assessment was a post-activity survey designed to gauge student perceptions of the activity. This survey consists of 5-point Likert scale prompts (strongly disagree to strongly agree) and open-ended responses as shown in Figure 4.

A plate of thickness t is embedded in concrete to anchor a high-strength cable. The diameter of the hole in the plate is d, the the embedded part of the plate has dimensions $a \times b \times t$ as shown in the figure.



(a) Write a symbolic expression for the normal stress you would need to consider if failure was going to occur in the plate. Write your expression in terms of the forces and dimensions provided in the figure.

(b) Write a symbolic expression for the shear stress you would need to consider if failure was going to occur because the plate pulled out of the concrete. Write your expression in terms of the forces and dimensions provided in the figure.

Figure 3: The pre/post-activity test scenario and questions.

Please answer each question as it pertains to the normal and shear failure activity.

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
This activity helped me understand and visualize normal and shear stresses.					
This activity helped me understand different ways that assemblies could fail.					
The physical items used in this activity were beneficial to my understanding.					
The information provided by the instructor was sufficient for competing the activity.					
I enjoyed working on this activity.					

What part of the activity did you enjoy the most?

What aspect(s) of the activity could be improved? How would you make an improvement?

Other comments:

Figure 4: The post-activity survey used to collect student opinions of the activity.

Results

The following subsections summarize student perceptions of the learning activity as captured by the post-activity survey and the effectiveness of the activity in promoting learning as captured by the pre- and post-activity test questions.

Student Perceptions

Student perceptions of the activity and physical manipulatives was nearly universally positive, as indicated by student responses to the Likert-scale prompts on the post-activity survey. Figure 5 shows that nearly all students agreed the activity was helpful for developing their understanding of normal and shear stress and failure modes and that the physical manipulatives were beneficial. Furthermore, all students agreed that the information provided by the instructor was sufficient for completing the activity and that they enjoyed working on the activity. Taken together, these results indicate that students view the activity favorably through the lenses of both learning and fun.

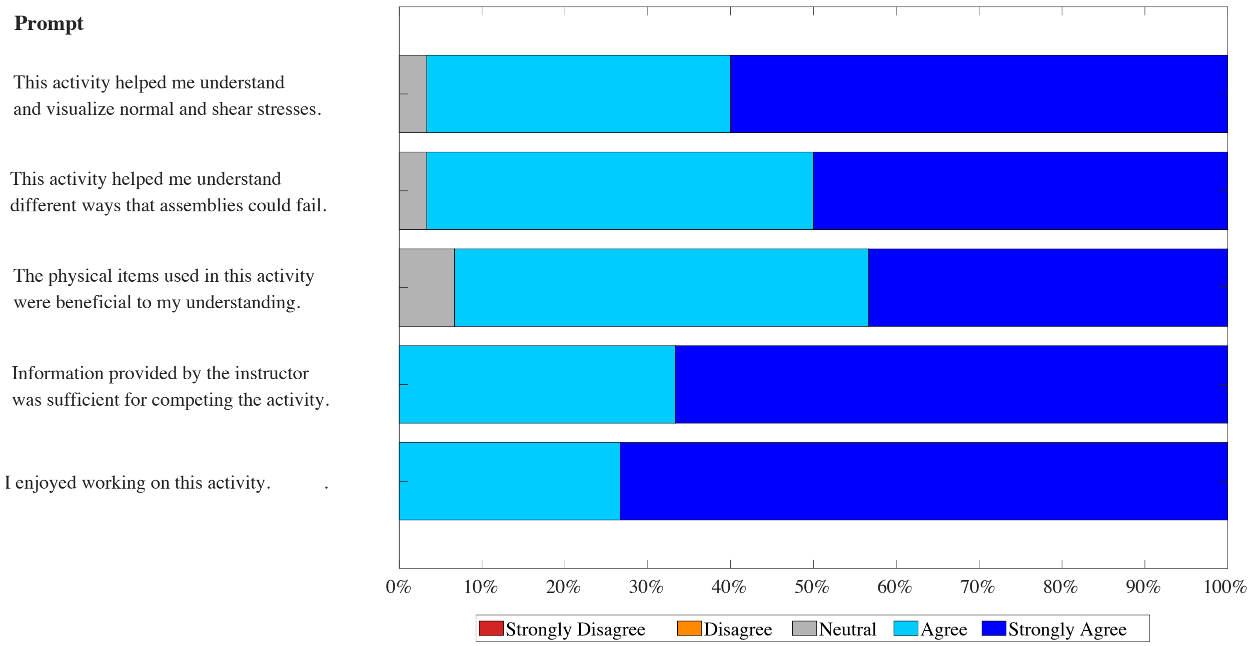


Figure 5: Student responses to the prompts on the post-activity survey. The amount each bar is filled by a particular color indicates the percentage of the student population making that selection. With Strongly Disagree = 1 and Strongly Agree = 5, the mean values of the responses from top to bottom are 4.57, 4.47, 4.37, 4.67, and 4.73.

Responding to the open-ended prompts on the post-activity survey, students highlighted the visualization / drawing aspect of the activity (12 responses – 40%), the physical models / hands-on nature of the activity (10 responses – 33%), and the ability to work in a group / collaborate (9 responses – 30%) as the parts of the activity they enjoyed most. These comments reflect student preferences for applied, cooperative learning and strongly support the active-learning and inquiry-based design of the activity. Regarding improvements, students most frequently listed a brief review of normal and shear stress before the activity (5 responses – 17%), a more detailed debrief about failure modes after the activity (4 responses – 13%), and examples of how the physical manipulatives would appear when failed (3 responses – 10%). Taken together, these responses indicate students found many aspects of the activity to be enjoyable, and had thoughtful reflections on how to make the activity better. Appendix 1 presents the unaggregated responses to the open-ended prompts for further review.

Effectiveness in Promoting Learning

In analyzing the pre- and post-activity test questions, student responses before and after the activity were compared to determine if students improved their performance after the activity. Each of the two questions on the test was scored for improvement. Students received a point for improvement if comparison of their post-activity answer to their pre-activity answer reflected an improvement in the type of area selected or in the actual symbolic answer provided. As an example, a student could receive an improvement point for the first question on the test if their post- vs pre-activity responses involved switching from an area parallel to the applied force (incorrect) to an area normal to the applied force (correct) or involved switching from an incorrect normal area (e.g. $a * t$ — not subtracting the hole's projected area) to a correct normal area (e.g. $(a - d) * t$ — the correct area). Table 2 summarizes the two ways of exhibiting improvement for each test question. Note that even if students made both possible changes, only one improvement point per question was ever awarded.

Table 2: Test question pre- to post-test amendments which scored improvement points.

Question	Ways of Scoring an Improvement Point
1	• switching from a parallel to normal area • improving algebraic correctness of response
2	• switching from a normal to parallel area • improving algebraic correctness of response

Using this scoring rubric, in no case did a student's answer on the post-test reflect poorer performance, whereby an answer became less correct after participating in the activity. This represents success regarding the low bar of "first, do no harm" for the activity. Breaking down opportunities for improvement, for the 30 students who participated in the activity there were 56 chances to improve (4 students answered the first question correctly during the pre-test, slightly reducing overall opportunities to see improvement). For 31 of these chances, students did show an improvement on the post-activity test for an overall improvement rate of 55.4%. Breaking down improvement by student, 7 students showed no improvement on either of the test questions, 15 students showed improvement on one of the test questions, and 8 students showed improvement on both test questions as shown in Figure 6.

Overall, this indicates that the activity helps students improve their ability to select appropriate combinations of load and area for calculations associated with normal and shear failures, supporting the initial hypothesis that the active-learning, inquiry-based approach of the activity would improve student ability to calculate stresses associated with potential failure modes.

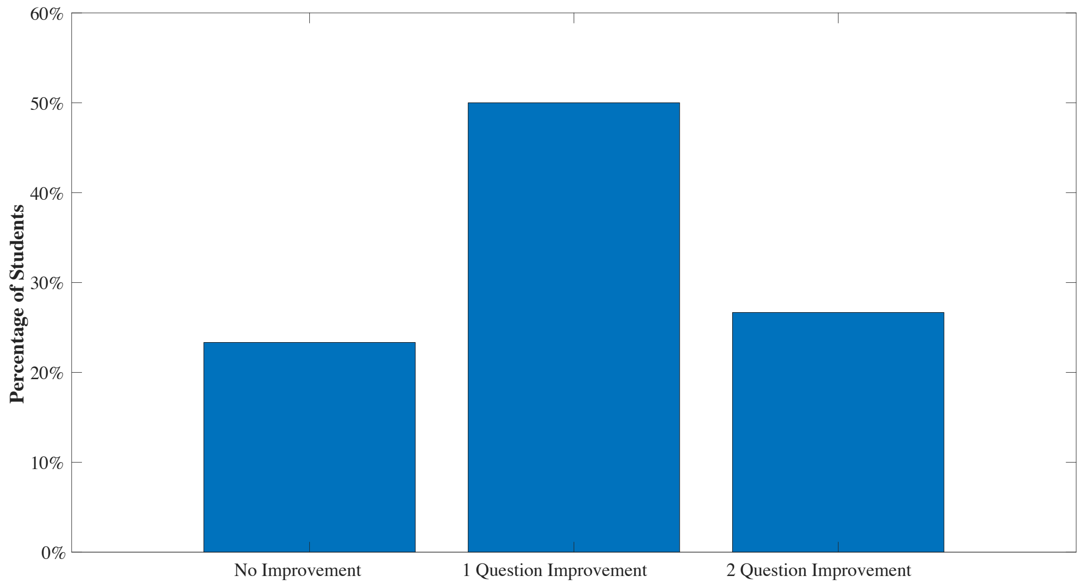


Figure 6: Percentages of students with different levels of improvement on the post-activity test. Overall, 73.3% of students showed improvement of their responses after the activity.

Discussion

The level of student learning resulting from the activity may appear moderate, since only 73.3% of students showed at least some improvement on the pre- and post-activity test and only 55.4% of overall opportunities for improvement were realized. However, because the test question involves a different assembly from the physical manipulatives used in the activity, it represents an opportunity for students to transfer knowledge to an entirely new scenario. Seen in this light, having 73.3% of students improve as a result of the intervention seems encouraging.

In terms of improvement score and overall correctness on the post-activity test, students performed better on the first question (which involved computing normal stress) than the second question (which involved computing shear stress). This is probably partially due to students generally struggling more with visualizing and computing shear stresses than normal stresses (as observed by the instructor), but may also point to the need to put more emphasis on the shear stress failure scenarios during the activity.

This study is limited by the fact that the sample size was relatively small at 30 students. It is also limited by the fact that there were only 2 pre/post test questions to assess potential learning gains, neither of which was psychometrically validated. Finally, this study had no control group, so it is unknown how learning gains might compare for students spending an equal amount of time engaged in another activity designed to provide instruction about normal and shear failure modes.

Conclusions and Future Improvements

Considering the survey data, it is clear that students find the activity and associated physical manipulatives a fun and useful method for becoming familiar with normal and shear failure modes in assemblies. The pre- and post-activity testing further reveals that students do improve their performance in pairing loads and areas related to calculating normal and shear stresses as a result of the activity. Taken together, these findings show that the activity and associated physical manipulatives are an effective way to help students to build skills related to shear and normal failure via an active-learning, inquiry-based process.

The activity could be further improved and refined in the future. The themes expressed by students in the post-activity survey are valid and worthy of consideration. The time for the activity is fairly tight for a 50-minute class period; the time used for the pre/post testing and post-activity survey during this initial offering might be best used for a brief review of normal and shear stress before the activity and a more detailed debrief about failure modes after the activity, particularly for shear stress failure. In addition, adding additional features to the physical manipulatives (e.g. force arrows) and creating "failed" manipulatives that show the affected areas for each failure mode, could further enhance the impact of the activity for students.

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Appendix 1: Opened Ended Survey Questions–Student Comments

Question 1: What part of the activity did you enjoy the most?

- Working with others on drawing the diagrams.
- Getting to work hands on.
- The hands on and working together.
- The physical models of each scenario helped me visualize better.
- I enjoyed drawing shear and normal stress diagrams. They helped me understand where and why objects tear in certain areas.
- Group discussion.
- The physical pieces.
- It was hands on and not just lecture.
- This activity really helped me understand it visually and learn how area is involved.
- Working in groups.
- Visualizing the different normal/shear forces with tangible items and different examples.
- Collaborating.
- Working with classmates (teamwork). Having something to visualize. Finally getting the answer right or at least I think I did.
- Drawing and understanding how the objects would fail.
- Being able to hold and see the physical parts.
- Being able to visualize with props.
- I liked the group aspect as I can ask my friends questions and receive answers/explanations pretty quickly.
- Trying to distinguish shear vs normal and coming up with ways to fail.
- I enjoyed being able to connect the equations to the visualization.
- I am a visual learner so I'm glad this catered to my learning needs.
- Group discussion.
- Playing with the physical item to wrap my head around it.
- See the physical objects and getting a visual understanding.
- Finding the expressions from the drawings.
- Stress equations.
- Talking through it with group.
- The last one because more complicated examples are the most beneficial.
- Drawing diagrams.
- Drawing and conceptualization.

Question 2: What aspect(s) of the activity could be improved? How would you make an improvement?

- Set a timer for each object.
- More going over the process to solving the problems after attempting them.
- I'm not sure this improved understanding about the equations specifically.
- There were a few places where the directions could have explained the physical situation a little better.
- Activity was good. Hard time visualizing what measurements belonged to parallel and perpendicular stresses.
- More descriptive problem.
- I think it's fine the way it is.
- Using items where forces were needed. See normal and shear force in action.
- I wish we talked more about how we know where something breaks.
- Less paper.
- Showing the right answer and explaining it more felt rushed.
- None.
- Five-minute review session before the activity.
- Using a bit more challenging objects and forces for the failure.
- A little more talk about normal vs shear forces before the activities.
- Explain difference between shear and normal and why they're different and which areas to use.
- Have more complex shapes as the ? maybe.
- More focus on equations (I don't get them).
- Label the dimensions on the physical piece.
- Maybe videos or simulations on how it might actually break.
- Maybe seeing one of the objects actually fail in anticipated manner.
- Personally, I think using the physical item on my own was more beneficial than being in a group, but I'm probably the minority in thinking so.
- I wouldn't have changed anything.
- Takes some time to do.
- N/A
- Explain normal vs shear more.
- More time and an image on both sides of the page.
- Have a set of broken models to show how they would break.
- Distinct definitions of normal and shear stress.