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Helping Students to Feel Mechanics

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Helping Students to Feel Mechanics

Abstract

This paper assesses the use of physical models as teaching tools in mechanics. These tools were used to introduce engineering theory as part of first and second year civil engineering mechanics courses.

The model kits were designed to cover: arches, Gothic cathedrals, suspension bridges, tanks and culverts, dams and retaining walls, point equilibrium, rigid body equilibrium, and beam statics. They were designed in a way to allow the students to feel forces and experience them targeting a deeper learning rather than surface comprehension of mechanics concepts.

The beam activity is discussed here, as an example of how the activities work. Students were given the opportunity to work with simply supported beams. The kits were comprised of two pin supports, a wooden beam, two scales, three wooden blocks intended to represent uniformly distributed loads, and a custom made torque tool. The goal of the activity was to provide the students with a sense of how forces act in a mechanically stable structure before being introduced to the mathematical rigor. From the activity, the students are expected to develop an intuition for how reactions are produced, the effect of uniformly distributed loads and their equivalent point loads, and the concept of moments (how they are produced, direct application and its independence of position). The activities were designed to challenge the students' intuition, target misconceptions and engage them more in critical thinking.

To assess the value gained by utilizing these models, the students were presented with questionnaires prior to participation in the activities. The questions are designed to gauge the students' understanding of core concepts with respect to their intuition, rather than mathematical rigor. An example of such a question from the Gothic Cathedral activity is: "Give an example of how assembly sequencing is important in building construction". The same questions were also presented to the students after participation in the activities to assess their gained knowledge.

This paper demonstrates the validity of inductive learning. In contrast to standard education, where students are presented with the theory first, the students are encouraged to make the connections between core concepts on their own via experimentation. Following this, the students are presented with the theory, with the expectation that they are able to understand the principles intuitively as they are presented with the relevant equations. Although all the students

experienced the hands-on mechanics activities in their first year, the theory was not explained until subsequent courses. The theory explained to the students builds from the intuition developed from these activities, reinforcing what they have learned. The goal of inductive learning is to guide the students away from memorization, where they are limited to only solving problems they have already seen, and shift towards a critical thinking framework, where they can abstract what they have learned to more complex problems.

Students expressed appreciation of these models. Some of the comments were: “It was nice to feel where the tension was”. “I learned how to apply it to real life rather than memorizing it for an exam”.

Introduction and Background

Conventional engineering lectures are structured to present students with theory pertaining to a specific scientific principle, followed by examples and practice problems. Once the students are presented with the theory, their knowledge is usually reinforced with a laboratory experiment on the material. This approach focuses on having students remember information for later application. The issue with this approach is that students begin to think in terms of set test cases. If they are presented with a problem, they attempt to relate it to an example they have seen before and approach the solution in the same manner; this approach can be problematic as the examples shown are not universal. In trying to solve problems by relating them to a few fundamental cases, the students sacrifice adaptability, and in turn forgo critical thinking.

The aim of this paper is to demonstrate a means of building intuition in students through experiential learning, so that they can have a gut feeling for how the system works. Experiential learning is often referred to as ”learning through reflection on doing”[1]. Felder and Silverman[2] state that “babies do not come into life with a set of general principles, but rather observe the world and define inferences”.

The learning models of Kurt Lewin[3], John Dewey[3], Jean Piaget[3,6], as well as Benjamin Bloom’s Taxonomy[4,5], will assist in providing context for discussing the proposed teaching tools.

Lewin proposed a four-stage cycle in which learning begins with concrete experience[3]; the learner interacts with the environment. Experience is then followed by observation and reflection, in which the learner collects data and forms connections. Reflection on the observations made leads to the formation of abstract concepts and generalizations, whose implications can be tested and verified in new situations.

Dewey proposed that learning transforms impulses, feelings, and desires of concrete experience into higher order, purposeful action[3]. Similar to the Lewin model, Dewey states that learning begins with observation, which when combined with knowledge of a past similar situation and judgement, forms insight into the significance of the material. This form of extrapolation is akin to the formation of abstract concepts and generalizations proposed in Lewin’s model.

Piaget states that experience and concept, reflection, and action form the basic continua for the development of adult thought[3]. His developmental process for cognition in children provides a learning cycle comparable to those of Lewin, and Dewey. The cycle begins with an action that has a measurable or observable effect on an object. The next stage consists of "reflecting abstraction"[6] in which the learner repeats the action, with variation, to build a database of causes and effects. From this database, the learner is able to extract properties of the object through the process of "empirical abstraction". By applying this process to a variety of objects, the learner enters a "cognitive stage" in which new knowledge is formed. Lastly, the learner uses the acquired knowledge to create more complex simulations and thus achieve elevated insight.

Bloom's Taxonomy is a set of models that classify learning objectives and acquired behaviours into three domains: Cognitive, Affective, and Sensory[4,5]. The Affective and Seonsory domains reflect more on acquired behaviours which are not the primary focus of this study. The Cognitive domain is broken down into six objectives: Remembering, Comprehending, Applying, Analyzing, Synthesizing, and Evaluating. The Remembering stage involves students remembering and recognizing basic facts. Following this, students enter the Comprehending stage, in which they begin to interpret the recalled facts. The students then use the acquired knowledge to solve new problems in the Applying stage. Next, the students disseminate the information and begin forming relationships in the Analyzing stage. Once understood, the students can form new patterns in the Synthesizing stage. Lastly, the students can begin making judgements about the information in the Evaluating stage. This paper proposes teaching tools to help combat the common issue of students stagnating in the Remembering stage.

The discussed learning models serve to demonstrate that learning is a process in which interaction is crucial. Active learning as a form of experiential learning therefore serves as the basis for discussion.

Active learning is defined as "any instructional method that engages students in the learning process"[7]. The purpose of this learning strategy is to instill a desire to investigate in students, so that the concepts learned are more ingrained. This contrasts the traditional learning style in which students are presented with copious amounts of theory and examples with the hope that they can extract the underlying principle; the governing code in this approach is that practice makes perfect. While practice can help students to achieve a decent grade in their courses, it creates a class of limited thinkers that may face challenges in solving real world problems.

This study attempts to show that good problem solvers are developed when students are able to come to a conclusion on their own. Inductive learning is a form of active learning in which the instructor provides the students with the guiding tools needed for students to understand the material, without explaining explicitly how it works[11,12]. When a student comes to the right conclusion through investigation, their understanding is solidified as they now have an intuitive understanding of the concept.

Abrahams and Miller[9] assert that "science involves an interplay between ideas and observation". To implement an effective inductive learning strategy, one must develop two key skills in students: observation, and critical thinking.

This study aims to accomplish this through the use of physical models in first and second year engineering mechanics courses. The students will perform experiments with the models prior to being exposed to the concept. These models are designed to clear misconceptions and illustrate certain concepts (torque, beam reactions, equilibrium) so that students can develop an instinct for how the principles work, leading to understanding of the theory as it is presented. The models attempt to move students past the preliminary stages of the discussed learning models and foster critical thinking. Student feedback was collected to determine the efficacy of the models and aid in refining them for future use.

Problem Statement and Activity Kits Descriptions

Test results from upper year engineering courses indicated that students had several misconceptions regarding elementary mechanics concepts. Primarily, students had difficulty translating these basic concepts into common engineering calculations (equilibrium, calculating reactions).

Some of the concepts students struggled with included proper foundation design, the transfer of forces in suspension bridges, the different ways torques can be generated, support reactions, construction order, hydrostatic loads, and vector operations in mechanics.

To mitigate problems in understanding in future courses, this paper intends to tackle the issues by providing students with a better foundation in elementary mechanics concepts. By illustrating the required concepts in their most basic forms, the hope is for students to use their gained insight to solve more complex problems.

The following physical models (made in house) were used as teaching tools for a first year mechanics course (CIVE 104) at the University of Waterloo. The course focuses on using Newtonian mechanics to analyze simple structures, as well as providing students with an introduction to hydrostatics.

Each of the aforementioned issues and misconceptions will be tackled through the use of these physical models, with the goal of preparing the students for subsequent courses.

While the goal of these activities is to help students build an intuition for mechanics, some gaps in content are intentionally left for subsequent courses to address.

Beam Statics

The Beam Reactions activity kit (Figure 1) is designed to help students better understand Newton's Third Law, and how it pertains to static beams subjected to simple loads. The kit contains 2 digital scales, two triangular plastic fulcrums (supports for the beam), 2 large matchsticks, 1 torque tool, 1 laser etched beam, 1 Rectangular wooden weight (uniformly distributed load), and 2 triangular wooden weights (triangular distributed loads).

The students are asked to investigate the different types of loading applied to a simply supported beam and observe the effect of the loading on the measured reactions. The students are expected to gain knowledge of how distributed loads act on a beam and how to find their equivalent point loads. This is accomplished by using the distributed loads in conjunction with the matchsticks to simulate a point load. The torque tool is helpful in demonstrating the effect a directly applied moment has on the reactions in a beam, and that the value of the moment does not depend on the location (in contrast to calculating a moment from a standard load).

Lastly, the students are also exposed to the concept of composite loads (combination of the triangular and rectangular weights) with the expectation that they intuitively discover that the equivalent point load acts at the centroid of the load geometry. The matchstick is expected to help clear misconceptions the students may have about the equivalence of point loads and composite loads.

The aim of this activity is to give the students a foundation in understanding the different types of loads that can act on a simple beam, and provide a transition into calculating reactions using Newton's second Law.

Figure 1: Beam Statics Activity Kit

2D Equilibrium

The Equilibrium kit (Figure 2) contains parts for two separate, but similar activities. The kit contains 1 metal ring (circular carabiner), 1 ruler, 1 protractor, 1 plywood rigid body (potato shaped) with 5 attachment points, 4 spring scales, and 3 large (24" x 35.5") sheets of paper.

The first activity conducted with this kit is Forces at a Point, which illustrates the concept of equilibrium at a single point. This effectively teaches students how to use 2D vector addition (through the spring scales) to show that the point is in equilibrium. The forces are applied using the spring scales and signify the magnitude of the vectors, while the protractors will be used to determine the angles. The students are asked to pull on a number of spring scales attached to the metal ring (the point) until the ring no longer moves. They then trace the magnitude and direction of the applied vectors onto the sheet of paper and show mathematically that it is in equilibrium. In addition to understanding that both magnitude and directon influence equilibrium, students are given physical context to vector addition.

The second activity conducted with this kit is Multi-Force Body. This activity follows the same concept as Forces at a Point, but also considers the effect of moments as the forces are no longer applied at a single point. Through this activity, the students learn that in addition to force equilibrium, the object must also be in moment equilibrium to remain static. The students use the different attachment points to learn how moments are produced from a force, what a fulcrum represents in rotation, and what a force couple is (and how it relates to moments). An important point to gain from this activity is that a moment can be produced with a net force of equal to zero.

Combined with the Beam Statics activity, the students are expected to understand the different ways of producing a moment, and the implications of each method in the context of equilibrium.

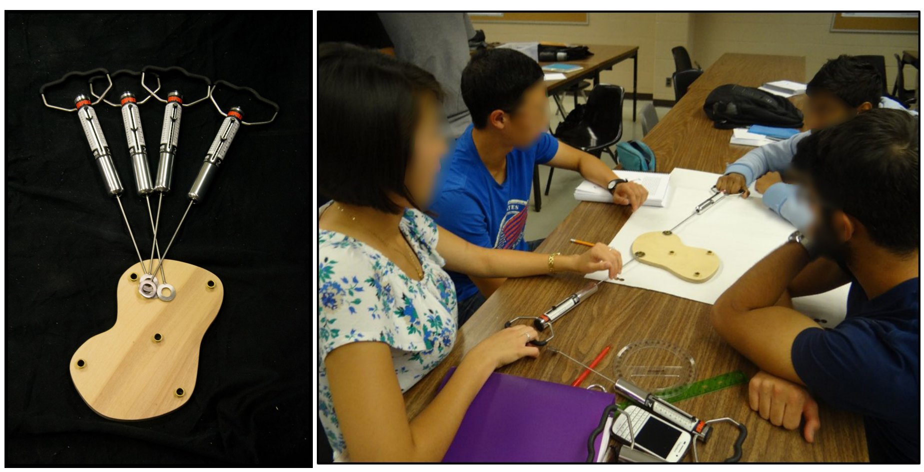

Figure 2: 2D Equilibrium Activity

Soil and Water

The Soil and Water kit (Figure 3) contains apparatus for two activities: Dams and Retaining Walls, and Tanks and Culverts. The kit consists of 1 Plexiglass box, 1 container full of marbles, 3 curved tank walls (3 length fragments of pipe), 1 grey circular disk (tank base), 6 rubber bands, 2 file folders, 1 pair of scissors, 1 roll of tape, 1 ruler, 1 rubber mat, 1 wooden short-legged retaining wall, 1 wooden double-legged retaining wall, and 1 metal L-shaped retaining wall.

The Dams and Retaining Walls activity aims to show students how granular media behaves when restrained laterally. The dam portion of the activity instructs students to build two dams out of the provided file folders, one that is curved towards the water (marbles), and one that is curved away. The students are to learn that when the dam is curved away from the water, the load is concentrated at the center of the dam, making it more likely to fail. This contrasts with having the dam curved towards water, where the load is distributed to the supports. The retaining wall activity aims to illustrate how the triangular lateral load is developed in granular media, as well as showcasing the two major failure modes in retaining walls (sliding, overturning). The students experiment with the different retaining wall designs, in addition to testing the specimens with and without the rubber mat (importance of friction).

The Tanks and Culverts activity demonstrates the effects that granular media have on pipe-like structures. In the tanks portion of the activity, the students are asked to construct the tank using the 3 pipe components, the small disk, and the rubber bands. They are asked to simulate static and dynamic loading with the marbles and then determine the optimal reinforcement layout (rubber bands) to keep the structure stable. In doing so, the aim is to have the students understand that the optimal reinforcement layout follows the lateral force distribution on the walls. They will recognize that the highest force is applied at the bottom, with the least applied at the top, and that this behaviour arises from how forces are transferred in granular media (producing lateral loads, with the highest at the bottom due to gravity). In performing the culverts portion of the activity, the students recognize that the optimal shape for a culvert is circular, so that the pressure is evenly distributed along the surface.

Feedback from subsequent mechanics courses suggested problems with this topic due to an incomplete understanding of forces in liquids/granular media. The activity is designed to give the students an introduction to hydrostatics, fostering an understanding of how hydrostatic loads arise, and clearing misconceptions related to vertical/lateral hydrostatic loads.

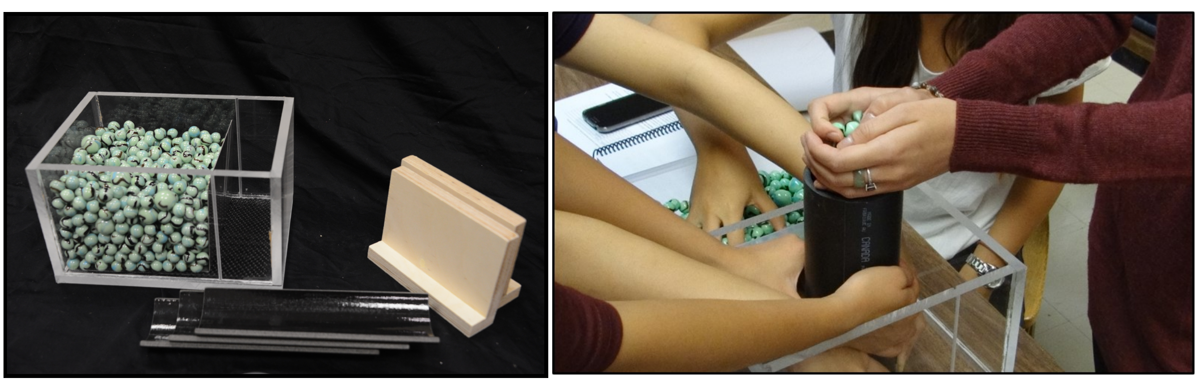

Figure 3: Soil and Water Activity

Arches

The Arches activity is designed to teach students how arches and cables carry/transfer forces. The kit (Figure 4) contains 1 rubber mat, 5 1.5 x 3 x 8.5” wooden blocks with end angles of 18degrees, 5 1.5 x 1.5 x 8” wooden blocks with end angles of 18degrees, 2 1.5 x 1.5 x 8.75” wooden blocks with end angles of 30degress and 6degrees, 2 1.5 x 1.5 x 5.5” wooden blocks with end angles of 8degrees, 2 1.5 x 1.5 x 5.25” wooden blocks with end angles of 45degrees and 11 degrees, 3 1.5 x 1.5 x 3.25” wooden blocks with end angles of 30degrees, 1 48” long piece of chain, and 2 24 x 35.5”sheets of paper.

The students are asked to build 5 different, specified arch models using the given blocks and must determine the different forces acting on the different members. The students are expected to learn that friction, as well as the inclination of the blocks play a major role in determining arch stability. The students also discover the importance of the keystone in holding an arch together. Lastly, the students trace their arch designs on the given sheets and attempt to match a hanging chain to their arch outlines. This simple test illustrates the property that a hanging chain will find its own equilibrium, and if flipped upside down, will provide the shape for a stable arch; the students learn that this optimal shape is a catenary curve.

The activity also aims to clear the common misconception that friction between the ground and the bottom blocks does not influence stability; it simulates a basic foundation through the use of a rubber mat. They also dispel the notion that heavier blocks lead to collapse, as the increased mass creates a larger friction force between the components.

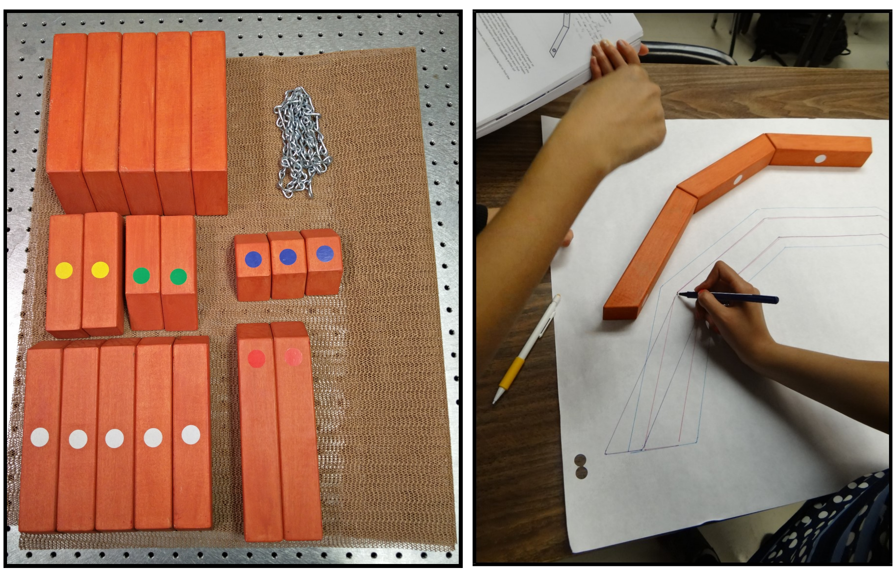

Figure 4: Arches Activity

Gothic Cathedral

The purpose of the Gothic Cathedral activity to introduce students to the forces in a traditional gothic cathedral, the role of flying buttresses, and the importance of the order in which the components are assembled.

The kit (Figure 5) consists of 6 vertical members (piers) with 2 notches, 4 flyers, 4 3" blocks (for walls/columns), 2 6" blocks (for walls/columns) , 2 9" blocks (for walls/columns/ceiling), 2 buttresses (large blocks with single notches), 2 vaulted ceiling segments, 1 roof assembly, 1 rubber mat, and 1 roll of tape.

The students are asked to construct a given design by building from one side to the other, from the outside in, from the inside out, and from the ground up. A common belief prior to the activity is that constructing the center of the cathedral first ensures stability. The students should observe that the construction order matters and that not all the methods will work. They are then asked to come up with their own designs/construction order to engage their critical thinking skills and understanding of how flyers and buttresses function.

Figure 5: Gothic Cathedral Activity

Suspension Bridge

The Suspension Bridge activity is designed to help students discover the guiding principles behind how suspension bridges work, and introducing them to the different components and construction methods.

The activity kit (Figure 6) consists of 2 bases with attached piers and towers, 7 short plywood deck sections with side pins, 3 short plywood deck sections with no side pins, 1 long plywood deck section, 2 thin plywood deck sections, 2 chains, 2 rubber mats, and 1 ruler.

The students are asked to construct the suspension bridge using different combinations of the deck pieces, investigating the different challenges associated with each combination as they progress. They are also encouraged to think about the different logistical issues that one deals with when constructing over bodies of water.

The activity aims to help students understand how the cables transfer the deck forces to the piers, the influence of deck rigidity, friction, accurate measurements for pier distance, swaying effects, and adequate support conditions.

The activity includes an investigation into deck stiffness to challenge the students' notion that a flexible deck allows for better load transfer. In conducting the activity, they also learn that a flexible deck is more prone to catastrophic wind loads, and overturning of the piers under significant deck loading.

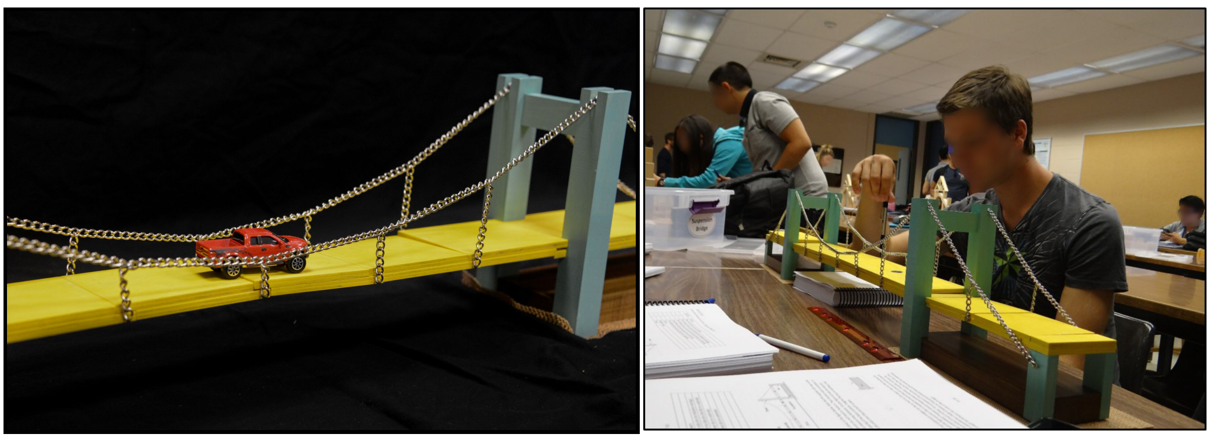

Figure 6: Suspension Bridge Activity

Results

To assess the effectiveness of the models as teaching tools, the students were asked to complete short surveys regarding the activities they completed; the data was collected over two offerings of the CIVE 104 course. Two surveys were conducted over the course offerings. The first survey was conducted after the first offering of the course and simply polled the students on the usefulness of the models. The second survey was conducted during the second offering of the course and assessed the students' knowledge immediately before, and after the activities. The activities were conducted in groups of four students, with one kit assigned to each group. The relevant concepts were presented to the students in the lectures following the activities.

The first survey gauged the students' interest in the activities, and whether they felt they better understood the relevant concepts afterwards. The results are organized into two categories: Activity Was Useful, and Activity Was Not Useful. A total of 154 responses to the survey were collected.

The first part of the second survey gauged the students' knowledge prior to conducting the activity, while the second part assessed their knowledge after completing the activity. Both parts consisted of the same three questions, specific to the performed activity. The surveys recorded data for the Tanks and Culverts, Dams and Retaining Walls, Arches, and Suspension Bridge activities. The responses were assessed for understanding and are grouped into two categories: Understand Concepts, and Do Not Understand Concepts. A total of 46 responses to the survey were collected.

Figure 7 suggests that students gained the most understanding from the Suspension Bridge, and Gothic Cathedral activities, with no negative comments. The popularity of these two activities may be attributed to the fact that various designs are explored in each experiment.

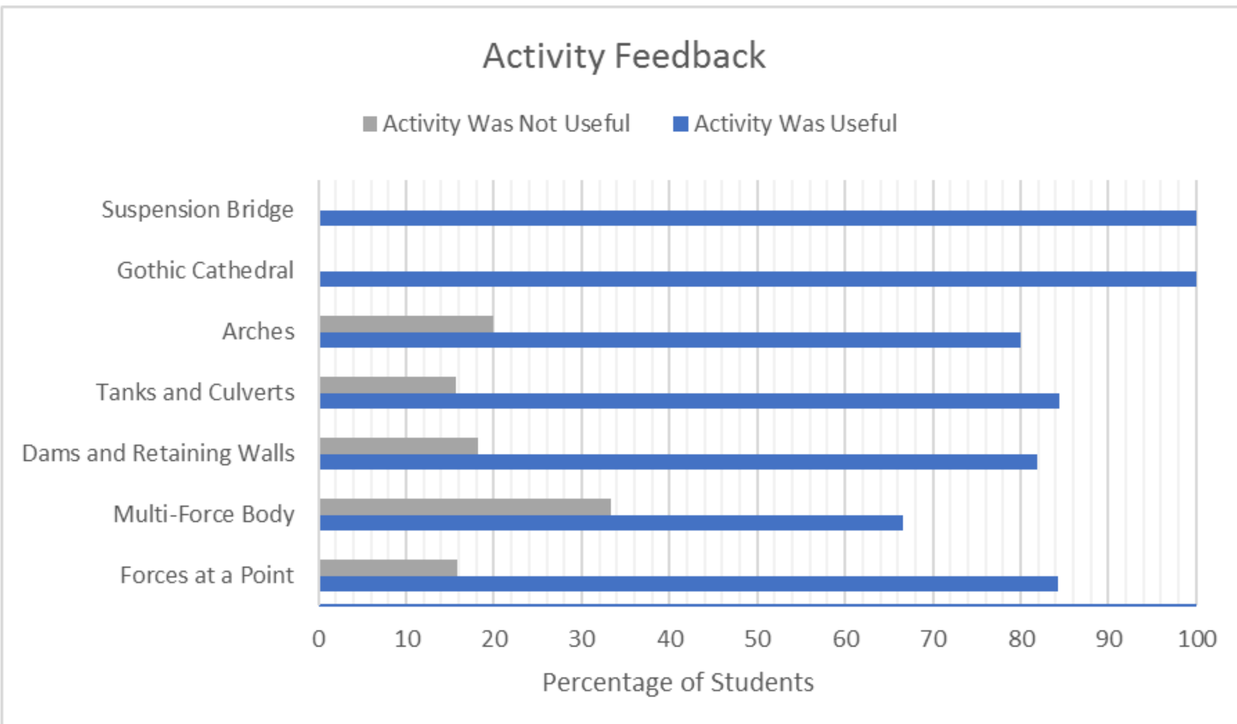

Figure 7: Student Feedback on Usefulness of Activities

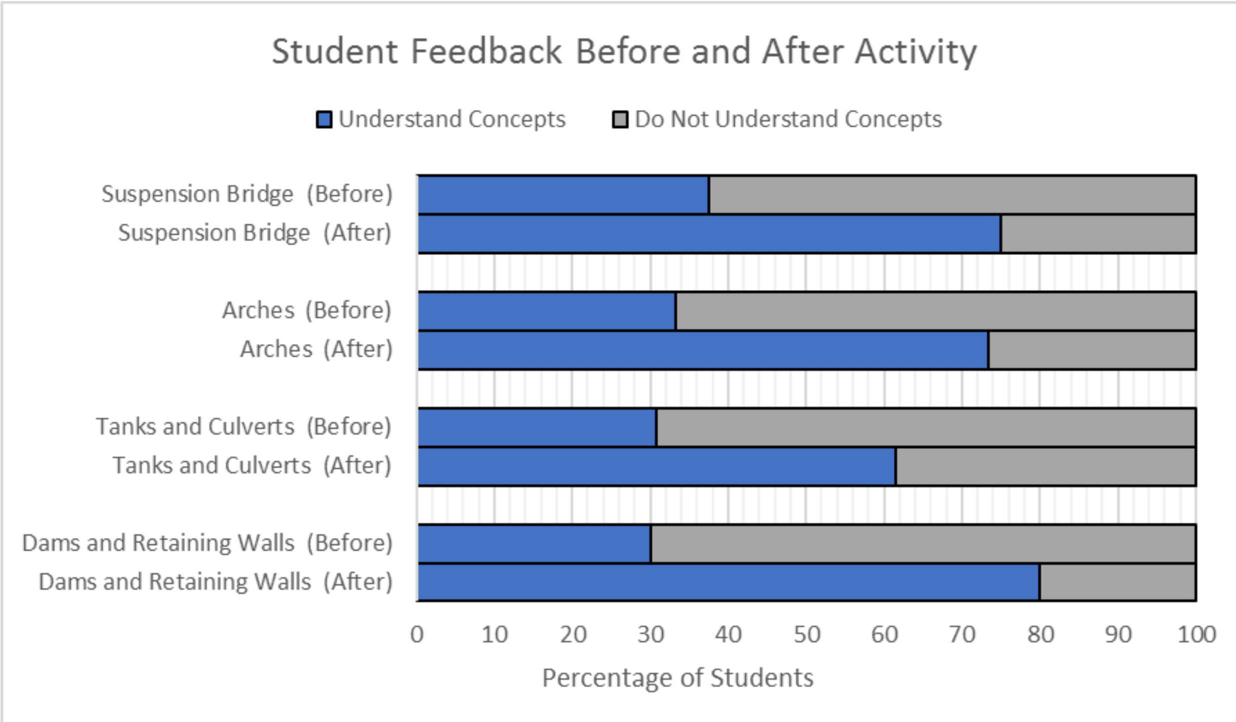

Figure 8: Feedback on Students' Understanding Before and After Conducting Activity

The Suspension Bridge activity allows students to experiment with many deck arrangements and load combinations. In experimenting with their own arrangements, they are able to witness and understand how different loads act on different components. Furthermore, through a variety of designs, the students are engaged in the "reflective abstraction" stage of Piaget's development cycle and are better equipped to make generalized statements about how suspension bridges work. Students mentioned that "[w]orking with a model gives one the freedom to experiment and obtain a 'feel' for the functionality of the various components". Allowing the students to directly gauge the effects of their actions helps them build an intuition for how the structure functions. Another student claimed they were "able to feel the tension in the cables and observe compression in the piers". Figure 8 illustrates the knowledge gained by the students after performing the activity.

Similar to the Suspension Bridge activity, the Gothic Cathedral activity allowed students to create different designs and experiment with different construction orders. The students were able to understand the function of each component by utilizing them in their designs, as opposed to reading a definition. One student commented that "[i]t is really hard to learn the names of all the structural components when learning from a book. By doing the activity [they] can repeat the names of every component [they] used."

Figure 8 suggests that students were able to grasp the core mechanics of arch stability after conducting the activity. Students claimed that understanding how a hanging chain's shape is determined from equilibrium helped solidify their understanding of how an arch is able to stand,

and that a catenary is the optimal shape for an arch. Students also commented on their understanding that the “[s]urface area of the blocks affects stability” and that “friction plays a crucial role in keeping the blocks together”.

The Tanks and Culverts activity displayed positive results for understanding how granular media behaves in pipe structures. Most students seemed to grasp how gravity, in conjunction with friction, produces the lateral pressure in stacked granular media/liquids. One student commented that “[they] got to feel the force of the marbles pushing against the tank walls. This helped [them] to see where the elastics should be placed”. Some students were unable to make the connection between the weight of the marbles and the lateral pressure distribution stating that “[they] do not understand why the lateral force at the bottom of the tank is greater”, thinking that “the force on the tank should be even everywhere”. In the context of culverts, students stated that “[they] now understand that pressure needs to be evenly spread for it not to fail”, and that “circular shapes work best” to achieve this.

The Dams and Retaining Walls, and Tanks and Culverts activities serve to complement each other in reinforcing students’ knowledge of hydrostatics. Figure 8 suggests that the Dams and Retaining walls activity had a more positive impact on the students’ understanding as a higher ratio of students understood the material after conducting the activity. As with the Suspension Bridge and Gothic Cathedral activities, the dams and retaining walls activity allowed students to experiment with different dam/wall designs. The success of this activity, in contrast to the Tanks and Culverts activity, can be attributed to the variety of designs used, with one student commenting that they “[o]bserved immediate consequences to design choices, allowing [them] to understand why they fail/work”. The variety of designs associated with this activity further suggests that Piaget’s “reflective abstraction” stage is vital to the preparation of these models, as it is a key factor in the students’ understanding.

Conclusions

The survey results demonstrate that the physical models benefited the first year engineering students. In each of the topics presented, the students gained a deeper understanding of the core mechanics involved, with some models performing better than others. The main observation noted from the surveys is that the students gained more knowledge from the models that presented them with variety in terms of design. The activities where students were able to create their own designs/ experiment with multiple designs aided them in grasping the intended concepts. In particular, the Suspension Bridge, Gothic Cathedral, and Arches activities achieved success in this regard. One conclusion that can be drawn from the success of these activities is that experimenting with multiple cases aids in clearing misconceptions. The students are able to see a certain concept acting in different situations, helping them to build an intuition for the mechanics, and clearing misconceptions in the process.

The feedback provided will be used to improve the activities for future iterations of the course. In particular, revisions to the Tanks and Culverts activity will be investigated to introduce more variety. Several different pipe designs would help solidify students' understanding of the forces involved and how best to design for them. In addition to this, adding a component that exemplifies the transfer of forces in granular media would be beneficial. The students would build a better intuition for force transfer in the structure if they had a more solid grasp on how the media inducing the forces operated.

Another revision to the process that might be considered for future iterations is explanation of the kits. To help improve the efficiency of the activities, since time is a constraint, short videos explaining the kits could be made prior to the activity. The goal of the videos would be to simply explain each of the different components, without giving too much detail about the activities themselves; the videos should not take away from the prime goal – investigation.

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