A Musical Twist on the Standard Bridge Project

Prof. Vicki V. May, Dartmouth College

Vicki V. May, Ph.D., P.E. is an Instructional Professor of Engineering at Dartmouth College. Her research focuses on engineering education and K-12 outreach. She teaches courses in solid mechanics, structural analysis, and design at Dartmouth. Prior to relocating to the east coast, Professor May was an Associate Professor of Architectural Engineering at the California Polytechnic State University in San Luis Obispo.

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Background
Students have traditionally designed, analyzed, built, and tested small-scale bridges as part of an introductory solid mechanics course. This past fall, however, students designed, analyzed, and built *sound-generating* or *musical* bridges in small groups. Fifty-two students, mainly sophomores, enrolled in and completed the course. The project was inspired by discussions with composer Molly Herron, who is writing an engineering-inspired piece to be performed in the spring of 2017 as part of a celebration for the 150th anniversary of the Thayer School of Engineering at Dartmouth. Molly requested that students build unique instruments that were interactive and symbolized engineering for the performance. The class agreed to take it on as a project. Composer Herron plans to incorporate the musical bridges designed by the students into her composition and performance.

Goals, Objectives, and Requirements
The main goal of the project was to have students apply the theory discussed in class to design, analyze, and build sound-generating or musical bridges in small groups. Additional goals for the project were: to engage a broader demographic of students (specifically women and underrepresented minorities), help students build connections between engineering and music, and encourage students to be creative.

In addition to designing and building bridges, students analyzed the forces, stresses, and deflections expected in their bridges for a given load and calculated stiffnesses and frequencies for the sound generating elements of the bridges. Further, they carefully selected materials based on acoustical properties such as impedance and sound radiation. Finally, they measured and adjusted the frequencies generated by their bridges. A public exhibition was held at the end of the term to display and interact with the bridges. Bridges are currently in storage and will again be exhibited publicly during the anniversary celebration and performance in the spring of 2017.

Students were required to focus on musical instruments that relied on beams, such as xylophones and kalimbas/thumb pianos, or stringed instruments like harps and guitars, since the behavior of beams and strings are concepts that are discussed in the course. Other instruments such as wind and percussion instruments were not allowed since their behavior does not rely on concepts related to solid mechanics. In addition to analyzing the structural behavior of the bridges, students calculated frequencies and explored the use of different materials thus extending their understanding beyond basic solid mechanics principles.

Requirements for the bridges were that they:
- Produce specific frequencies through mechanical means,
- Be interactive,
- Symbolize engineering,
- Be approximately 4ft x 2ft x 2ft in size, and
- Safely support a load of 150lb at least 1.5ft off the ground.

Each group was given a budget of $100 for supplies for their bridges. Funding was provided by the Thayer School of Engineering.

Cooperative Learning

A cooperative learning approach was used throughout the project to help ensure that the small groups functioned well and learned together. Cooperative learning is an instructional strategy through which small groups of students work toward a common goal to enhance their own learning as well as that of their group members (Johnson et al., 1988). Simply putting students into groups to work together does not necessarily create a cooperative learning environment (Oakley, 2004). The key elements of cooperative learning and how they were addressed through the project are as follows (Johnson et al., 1998):

1. *Positive Interdependence* – The project was complex enough that completion required contributions from all group members.
2. *Individual and Group Accountability* – For all phases, at least 50% of the project grade was assigned individually. Peer assessment was also included in the grading structure.
3. *Promotive Interaction* – To promote interaction, students were given time during class to work on the project as a group and to ask questions of the professor and teaching assistants.
4. *Social Skills* – In addition to feedback on content related to the course, group interactions were supported through individual meetings with the professor and readings related to group dynamics (Fujishin, 2013).
5. *Group Processing* – Groups were asked after each phase to think about and report on group dynamics. How is the group functioning? How could it function more effectively?

Meta studies have shown that when compared to more traditional learning approaches, cooperative learning results in higher test scores, higher levels of critical thinking, higher levels of transfer, and improved ability to work in groups (Johnson and Johnson, 1989). Students who learn in cooperative environments tend to be more actively engaged and motivated by the topic and have more frequent student-student as well as student-faculty interactions (Lord, 2001).

Project Phases

The project was separated into three phases: a conceptual design phase, a calculations and prototyping phase, and a construction and reflection phase. Rubrics for each phase of the project were distributed to the class and are included in the Appendix of this paper.

Phase 1: Conceptual Design. During the conceptual design phase students worked in groups of three or four to create drawings and a small prototype of a musical bridge. Students also researched musical instruments and bridges during this phase. Prototypes were created using easy to find materials like foam-core, tape and string and were meant simply to give a three-

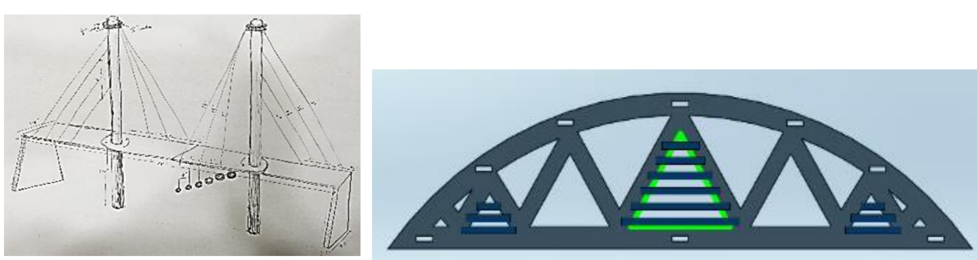


Figure 1. Phase 1 conceptual designs of musical bridges

dimensional idea of what the bridge would look like. Each group presented their conceptual design to the class and review board for feedback. Students were encouraged to be creative during this phase of the project and push the limits of ideas. How could they generate sound while visually representing engineering? Two of the conceptual designs that were submitted for phase 1 are shown in Figure 1: a rotating bridge with strings that was sketched by hand and a curved truss bridge with xylophone bars integrated into the design that was drawn using SolidWorks.

Phase 2: Calculations and Prototyping. After Phase 1, groups were re-formed, with slightly larger groups of students (six to eight students per group) pursuing eight of the ideas presented in the conceptual design phase. Proposals from the conceptual design phase that were similar were combined where possible. For example, several groups proposed building cable-stayed bridges with strings to generate music. Multiple groups were combined, with students shifting to different groups as interests changed.

The goal of this second phase of the project was to demonstrate that a full-scale version of the proposed musical bridge would be safe and would produce sound or music. Thus, each student was required to analyze their group's bridge and predict the forces and deflections expected for a specific load. In addition, each student conducted a parametric study to investigate how changes to their design would affect the forces and displacements expected as well as the frequencies generated. For the parametric study students were asked to vary one thing such as the height of the bridge or the orientation of diagonals to determine the impact of these changes on the forces and deflections. Students were allowed to use analysis software for the calculations including SAP2000, a structural analysis program, and SolidWorks Simulation. For most students this course was a first introduction to analysis software so they were far from experts. Students were required to verify the computer results by performing a set of calculations by hand to verify the computer results including checking overall equilibrium, making several cuts through the structure to verify internal forces, and approximating deflections to ensure that they were in the ballpark. Hand calculations proved to be the most difficult aspect of this phase as it required students to make approximations and estimations.

As a group, students were also required to build a prototype to test one portion of the sound generating aspect of their bridge. Prototypes for this phase were small, often a single string assembly or xylophone bar, with the goal of testing sound production and constructability of the connections. They also developed a construction plan and budget during this phase of the project including details of where they would work, costs of materials they would need, and how the work would be distributed among team members.

Students were encouraged to consider different materials both from a strength perspective and from a musical perspective during this phase. They were asked to consider how their material choice would affect the stresses and deflections in their bridge but also how their material choice would affect the sound quality of their musical bridge. Students were introduced to the acoustical properties of materials and materials selection through a lecture by a materials expert, Professor Ulrike Wegst; relevant papers were also distributed (Wegst, 2006; Wegst et al., 2007, and Wegst, 2008). The key acoustical properties that students considered when selecting materials for their musical bridges were: the *speed* at which sound travels through a material, c, as given by

Equation 1; the *impedance, z,* which affects how sound is transmitted between different materials and is given in Equation 2; and the *sound radiation coefficient, R,* which relates to how much the sound is damped out in different materials and is given in Equation 3 (Wegst, 2006).

- Equation 1: speed of sound through a material = $c = \sqrt{\frac{E}{\rho}}$;
- Equation 2: impedance = $z = c\rho = \sqrt{E\rho}$;
- Equation 3: sound radiation coefficient = $R = \frac{c}{\rho} = \sqrt{\frac{E}{\rho^3}}$;

where E = modulus of elasticity and ρ = density. As seen in Equations 1 through 3 the key acoustical properties for musical instruments are based on the modulus of elasticity and density of the materials, properties that are also useful in solid mechanics.

Students used the CES Material Selector software (https://www.grantadesign.com/products/ces/) to compare and better understand the benefits and limitations of different materials. Figure 2 shows a materials property chart that was created using the Natural Materials Selector (Wegst, 2008). Charts such as these allowed the students to quickly compare materials. Students experimented with a range of materials including bamboo, mahogany, padauk, and more.

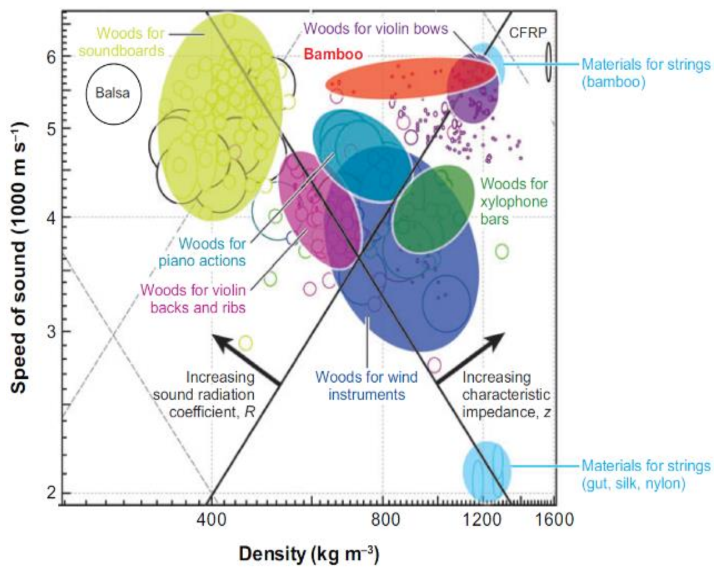


Figure 2. Materials property chart created using the Natural Materials Selector (Wegst, 2008)

Phase 3: Construction and Reflection. The focus of the final phase was on construction and reflection. Most of the students in the class used wood as their primary construction material and built their bridges using tools in the woodshop from basic saws and hammers to laser-cutters and the CNC routers or shopbots. The final bridges included chimes, a bridge that relied on a system of springs and bells, xylophone bars, and guitar strings. Rather than a final competition, the musical bridges were displayed as part of a public exhibition at the end of the class. The bridges remained on public display for two months after the course ended, with people stopping by frequently to play them as they walked through the engineering building. Figure 3 depicts several of the bridges that were constructed for the course. Students constructed bridges using a range of materials including metal tubes, guitar strings, and a range of different types of wood from pine to mahogany and padauk. The bridges will be used by composer Molly Herron for a performance at the Thayer School of Engineering at Dartmouth in May of 2017.

Figure 3. Final musical bridges

Observations and Results

As evidenced by end of the course evaluations, students seemed more engaged and reported learning more from the musical bridges project than with small-scale strength-tested bridge projects used in previous years. Course evaluations from this past fall (2016) were compared with those from the previous year (2015). Both courses were taught by the same professor, the author, with the only major difference being the project: the musical bridge project in the fall of 2016 and a more standard small-scale bridge project in the fall of 2015. Fifty-two students completed the course in 2016 and fifty-six completed the course in 2015. Table 1 shows students' responses to the question of how effective the project was in supporting their learning in the course. Students responded using a Likert scale from Extremely Effective to Not Effective. As seen in table 1, 55.3% of the students in 2016 rated the project Extremely Effective, while only 40% of those in the fall of 2015 rated it Extremely Effective. In both years, the students found the project to be effective with ~80% of the students rating the project as either Very or Extremely Effective in both years but a higher percentage rated the musical bridge project to be Extremely Effective.

Table 1. Comparison of student responses on project effectiveness by year

Year – project	How effective was the project in supporting your learning?:			
	Extremely Effective	Very Effective	Effective	Not Effective
2016 – musical bridge	**55.3**	**25.5**	**17.0**	**2.1**
2015 – standard bridge	**40.0**	**38.9**	**16.8**	**4.3**

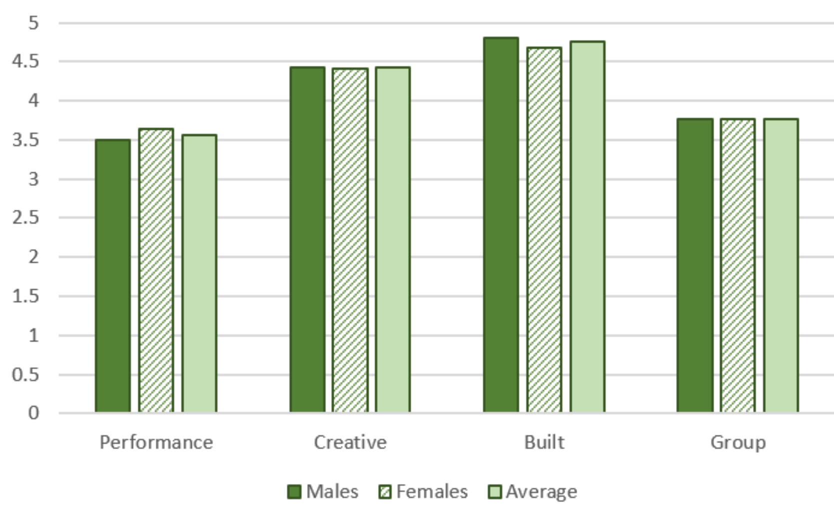
Students were also asked to estimate the amount of time that they spent on the bridge project as part of the end of course evaluation. Table 2 shows the results for the amount of time that students estimated they spent on the project in 2016 and 2015. As shown in Table 2, students in 2016 estimated spending more time on the musical bridge project than those in 2015 on the standard bridge project, with 34.8% reporting spending >15 hours/week on the musical bridge in 2016 and 21.8% reporting spending >15 hours/week on the standard bridge project in 2015. Students were told to focus on the time spent during phases 2 and 3, which took place during the final 4 weeks of the term

Table 2. Comparison of students estimates of the amount of time spent on the project by year

Year – project	% of students reporting spending different amounts of time each week on the project (during the 4 main weeks of the project)			
	>15 hours/week	10-15 hours/week	5-10 hours/week	1-5 hours/week
2016 – musical bridge	**34.8%**	**34.8%**	**23.9%**	**6.5%**
2015 – standard bridge	**21.8%**	**34.5%**	**38.2%**	**5.5%**

Students in the course this past fall (2016) were asked to rate the importance of different aspects of the musical bridge project on a Likert scale from 5 to 1, with 5 being Extremely Important and 1 being Not Important. Forty-eight of the fifty-two students in the class responded to the survey, twenty-six of whom were male and twenty-two of whom were female. Different aspects that they were asked to rate, as shown in Figure 4, included how important it was to them that 1) the bridge would be used for an actual **performance**, 2) they were able to be **creative** with their designs, 3) they actually **built** the bridge rather than just designing it, and 4) they were able to work in a **group** on the project. As seen in Figure 4, there was very little gender difference in the responses. The most important aspect to students was that they actually built musical bridges rather than just designed them, with male students rating the importance of this aspect slightly higher. Students also indicated that they enjoyed being creative with their designs. They were less concerned that the bridge would be used for a performance and with the opportunity to work in a group, though still positive on both of those aspects.

Figure 4. Likert scale reporting on the importance of different aspects of the musical bridge project



One gender difference emerged: when asked whether next year's class should build musical bridges or standard bridges, female students were more likely to vote for the musical bridges than male students. 77% of the females who completed the survey voted for the musical bridge project whereas only 55% of the males voted for the musical bridge project, with 45% voting for the standard bridge project. While there are many possible reasons for the preference by females for the musical bridge project, one theory is that the females preferred the interdisciplinary nature of the project; previous studies have found that women are drawn to interdisciplinary projects (Barnard et al., 2012 and Zastavker et al., 2006).

Conclusions

The musical bridge project was driven but the need for instruments for an upcoming performance but proved to be an engaging project. Students reported spending more time working on the musical bridges and seemed to be more engaged in the project than students in previous years. And females, in particular, seemed to prefer the musical bridges over a more traditional bridge project. The author plans to continue to use some variation on the musical bridge project for future solid mechanics courses. Questions, however, remain: did students find the musical aspect of the project more engaging or would another type of interdisciplinary project be just as engaging? Did the musical bridge project result is improved learning? Were students more creative? Did their critical thinking skills improve? Future projects will attempt to explore these questions and more.

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Appendix. Rubrics for each phase of the project.

Conceptual Design Phase Rubric – Musical Bridges
Solid Mechanics – Fall 2016

Name: ____

	Full points: simply completing each of these aspects does not mean you will get full points. High-quality, accurate, and easy to understand work will receive full points.	**Zero Points**	**Points**
Presentation	Each group will present their conceptual design ideas and plans for moving forward to the class and review board. These presentations will not be graded but hopefully you’ll receive lots of helpful feedback.		/0 group
Research and Design Philosophy	Evidence of research on existing structures and instruments: using the Internet is fine but cite your sources. What inspired your design? How does your bridge symbolize engineering? And how will it produce sound/music?	No research or design philosophy.	/25 individual
Individual Drawings	Drawings or sketches demonstrate that a range of ideas were explored – these sketches may be drawn by computer or by hand.	No drawings or sketches.	/25 individual
Group Drawings	Plan, elevation, and three-dimensional drawings of your proposed design concept are presented. Drawings may be done by computer or by hand but must be to scale, with dimensions and annotations included.	No drawings.	/25 group
Model	A high-quality small-scale model is built (foam core or cardboard is fine) to show how all the pieces will fit together. Overall size: <12”x12”x12”	No model.	/25 group

Calculations and Prototyping Phase Rubric – Musical Bridges
Solid Mechanics – Fall 2016

Name: ____

	Full points: simply completing each of these aspects does not mean you will get full points. High-quality, accurate, and easy to understand work will receive full points.	**Zero Points**	**Points**
Presentation	Each group will present their final design ideas, prototype and plans for moving forward to the class and review board. These presentations will not be graded but hopefully you'll receive lots of helpful feedback.		/0 group
Drawings	Each group should create drawings that are detailed and complete, with dimensions, by hand or by computer.	No drawings.	/40 group
Prototype	A prototype of one piece of your bridge should be built and tested: does it produce the frequency and loudness you expect?	No prototype.	/40 group
Construction Plan	How will you construct your musical bridge? What tools and equipment will you need? What materials will you use and why? What materials do you need to acquire for construction? What is the estimated cost of the materials and equipment required for you to complete musical bridge? Where will the construction take place: do you need space at Thayer? Will you use the woodshop in the Hop? Will you use the machine shop?	No plan.	/20 group
Parametric Study & Calculations	Each group member should design a study to compare at least three variations on your group's proposed design through calculations: which designs produce the correct frequencies, how much do the members deflect, which designs use the smallest amount of material, etc.? Variations may include member size, member type, member dimensions, member orientation, number of members, overall shape, etc. – explore lots of different ideas. Individual group members should explore different design variations. Your results should be supported with calculations. Your calculations must show that the bridge can support the required load and generate sound.	No parametric study nor calculations.	/100 individual

Construction and Reflection Phase Rubric – Musical Bridges
Solid Mechanics – Fall 2016

Name: ____

	Full points: simply completing each of these aspects does not mean you will get full points. High-quality, accurate, and easy to understand work will receive full points.	**Zero Points**	**Points**
Construction	Construction completed on time and of high quality.	Construction not completed on time or of poor quality.	/30 group
Aesthetics and Symbolism	Aesthetics and symbolism will be judged by the class and by the review board.		10/group
Creativity	Creativity will be judged by the class and by the review board.		10/group
Final Report	Each student should submit a final one-page reflection on the project: What worked? What didn't work? How did the project relate to the concepts from the course? What are the strengths of your musical bridge? What are the weaknesses of your musical bridge?	No final report.	/50 individual
Self and Peer Evaluations	Each student will evaluate their own level of commitment and contribution to the project as well as that of their group members.		/10 individual