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Starting from the End: Introducing a Final Exam Problem on the First-Class Meeting to Foster Curiosity and Engagement Throughout the Semester

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introduction

The Kern Entrepreneurial Engineering Network (KEEN) promotes an Entrepreneurial Mindset (EM) consisting of 3 Cs: curiosity, connections, and creating value [1]. It is claimed that instilling students with EM will improve their learning outcomes and career readiness [2], [3].

Recent research has shown that EM can be applied to Engineering Technology (ET) coursework, with promising results [4], [5], [6].

The motivation for this study was to examine whether activities based on EM would improve the perceived weak aspects of an existing junior-level mechanical engineering technology (MET) class on finite element analysis (FEA): student engagement and final exam performance.

research methods and procedures

This paper describes efforts in the fall semester of 2023 to implement facets of EM into a finite element analysis course in the MET program at Montana State University.

Reviewing the final exam from the previous fall semester, it was noted that the main problem from the exam could be introduced earlier in the semester, if not the very first class meeting, where it could be solved (though incompletely and incorrectly).

The problem itself received positive feedback from the students; specifically, they enjoyed the fact it was a real-world engineering project with important ramifications.

The inspiration for the problem had been a YouTube video [7] about the clever technology used to focus the mirrors of the James Webb Space Telescope. The presenter of the video (which has over 670,000 views in its first two years) demonstrates how a flexible metal mechanism is used to manipulate the 6 degrees of freedom of each mirror segment to a step size of 7.7 nm with a repeatability of 2 nm over a range of 10 µm [8]. The video clearly shows the result of a finite element analysis of the compound flexure used to achieve this performance. However, the video only shows the solution for small displacement of the output surface (roughly 10 µm) due to displacement of the input surface by 1 mm. It does not show the corresponding stresses that develop in the flexure during use or compare them to material strengths. A student in a junior-level FEA course can be expected to perform this analysis to solve for both displacement and stress, drawing conclusions about acceptability of performance (displacement) as well as factor of safety against static yielding and fatigue failure (stress).

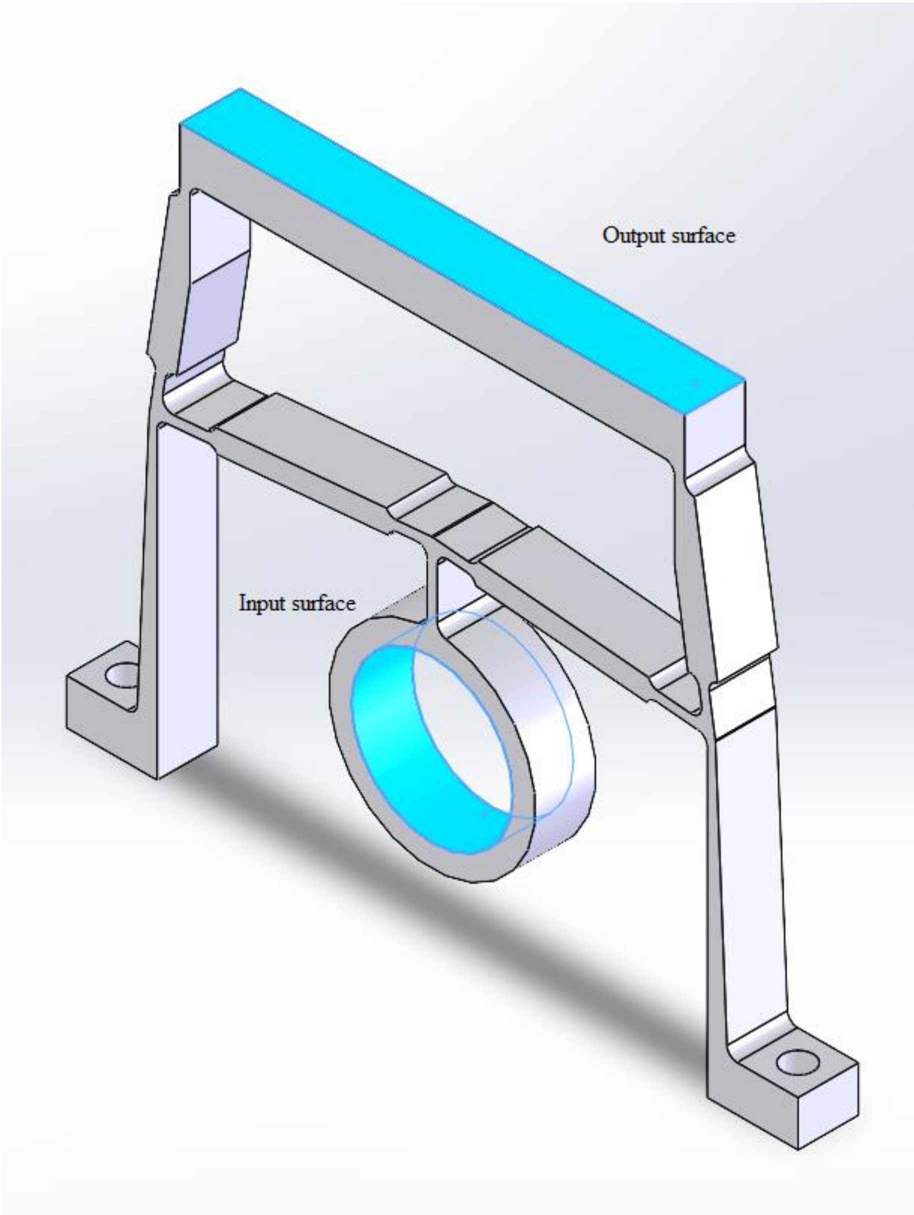

Figure 1: Computer model of the flexure showing input and output surfaces

To further hook the students into the problem, it was posed as a reverse-engineering project. The James Webb Space Telescope is now wildly successful with a long backlog of experiments to run, but it ran 15 years and $10 billion over budget [9], [10]. If it could be reverse-engineered and a second copy of it built, the builder could stand to both make a healthy profit as well as enhance the frontier of human scientific knowledge by doubling our deep space imaging capability. The students were prompted to think of themselves as engineers who were not just problem solvers, but value creators—creating economic value for themselves and their employer as well as societal value by increasing scientific experimentation capacity.

With this setup, the analysis of the flexure was introduced during the first lecture of the semester, as the students can grasp the need to solve the problem but lack the tools from pre-requisite classes to arrive at a useful conclusion. They were clearly residing in Vygotsky's Zone of Proximal Development [11], where curiosity should be high, and with some instruction, able to expand their engineering capabilities.

One goal of introducing the problem in the first lecture was to capitalize on the importance of the first lecture of the semester in engaging the students. A typical first lecture in an FEA course might introduce the syllabus, then cover solving the displacement of an abstract object that can be represented as a single spring with 2 nodes with 1 degree of freedom that reduces to set of linear equations with a 2x2 stiffness matrix. The object may then be represented as 2 connected springs with 3 total nodes (4x4 stiffness matrix) before further abstracting into the mathematics of solving for displacement of a node with 6 degrees of freedom in a mesh full of other similar nodes. This method of lecturing does not interest many junior-level students, especially in an MET program that does not require linear algebra courses. In fact, the only pre-requisites for the course are Applied Strength of Materials, Applied Thermodynamics, and two courses in a Computer-Aided Engineering sequence.

Instead of solving the problem individually, as had been done on the test with the previous cohort, it was presented as a group project. Collaborative assignments and projects are considered High-Impact Educational Practices at Montana State University. Small group collaboration has been shown to improve performance on cognitive learning outcomes and student attitude [12]. In-class collaboration is better for the latter [12]. This project was mainly done in-class for this, and other reasons. First, the class period is 110 minutes long and needs to be broken down into smaller modules to keep the students' focus and attention. Secondly, the physical activity of moving around the room to locate and work with a group was also targeted at breaking up the monotony of sitting still in front of a computer screen for 110 minutes. For this reason, groups were chosen at random instead of allowing the students to choose their own groups, where most would default to choosing adjacent students. Experience shows students in a class in a computer lab will sit at the same computer every period for reasons of both habit and ease of file management. Finally, the in-class setting provides for real-time interaction, one of the five tenets of cooperative learning identified by the National Effective Teaching Institute (NETI).

After the YouTube video was shown, random groups were announced, and the project was introduced. To reverse-engineer the space telescope, the first step was to reverse-engineer the mirror-actuating flexure. The video creator provides the geometry of the flexure [13] but those files were not directly used. Instead, an approximation was re-created from scratch so that the geometry would not be the same, and performance would vary from that reported for the JWST flexure and the video's replica flexure. The goal of the project was to determine the performance of the flexure in three scenarios. In the first scenario, the flexure input was to be moved 1 mm to verify that the output surface moves nearly 10 μm and to determine the maximum stress value of the part under those conditions. The part material and geometry were chosen to make the stress in this scenario exceed the material's yield strength. For the second scenario, the students need to determine the maximum input motion that can be used to keep the stress in the part lower than yield strength and what output displacement is produced by this input. In theory, this could be used to determine the flexure's performance characteristics for focusing the mirror. In the third scenario, fatigue life must be accounted for. Even if it were economically reasonable to send an astronaut to make repairs to the JWST (as has been done with the Hubble Space Telescope), the JWST is not located where astronauts can reach it. So, the students are asked to determine the maximum input motion that can be used to keep stress below a level that will produce infinite life of the part and what output displacement is produced by this input.

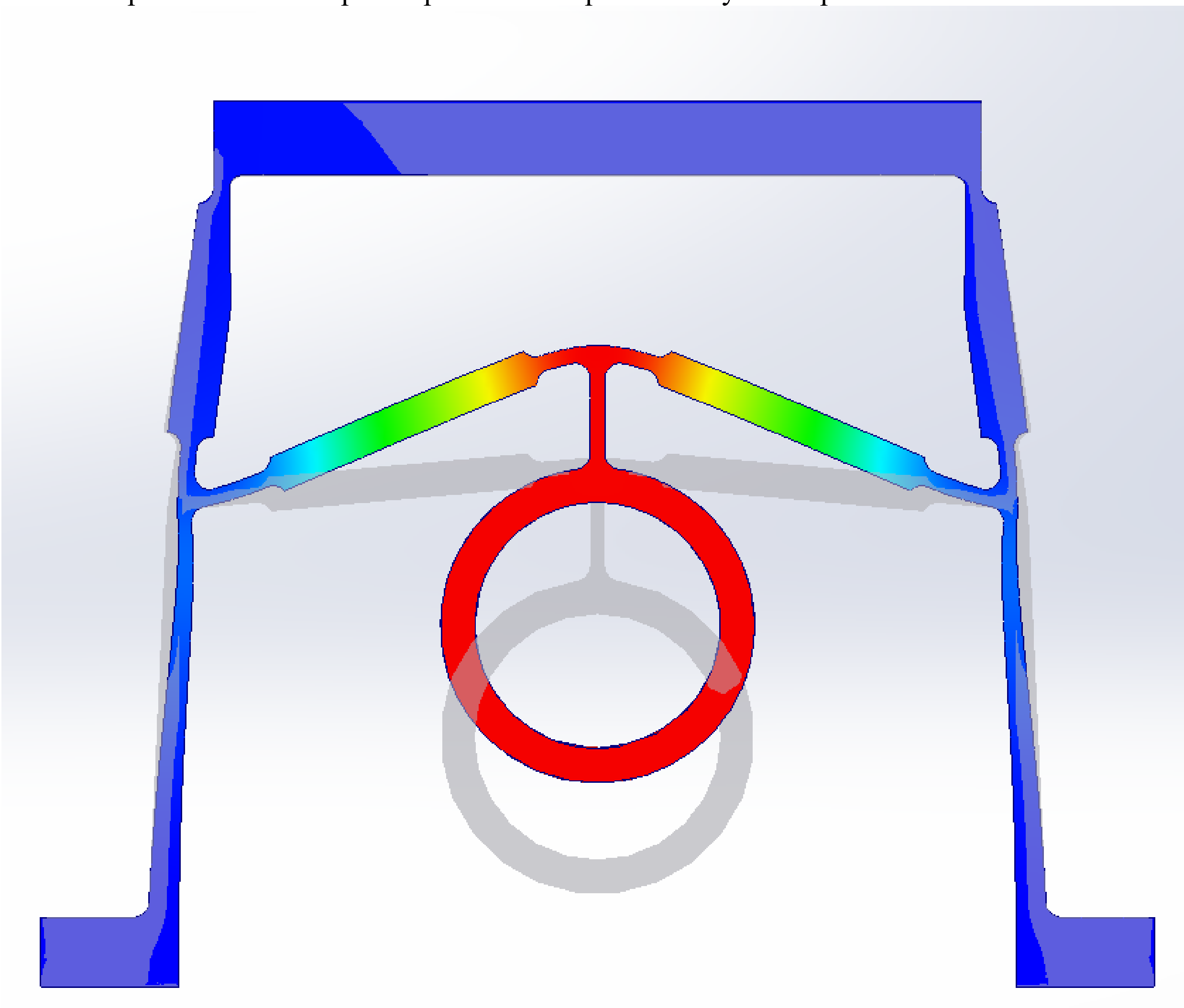

Figure 2: Example results of a simulation showing displacement of the flexure when the input surface is lifted 1 mm. The exaggerated deformed shape is shown superimposed on the original geometry.

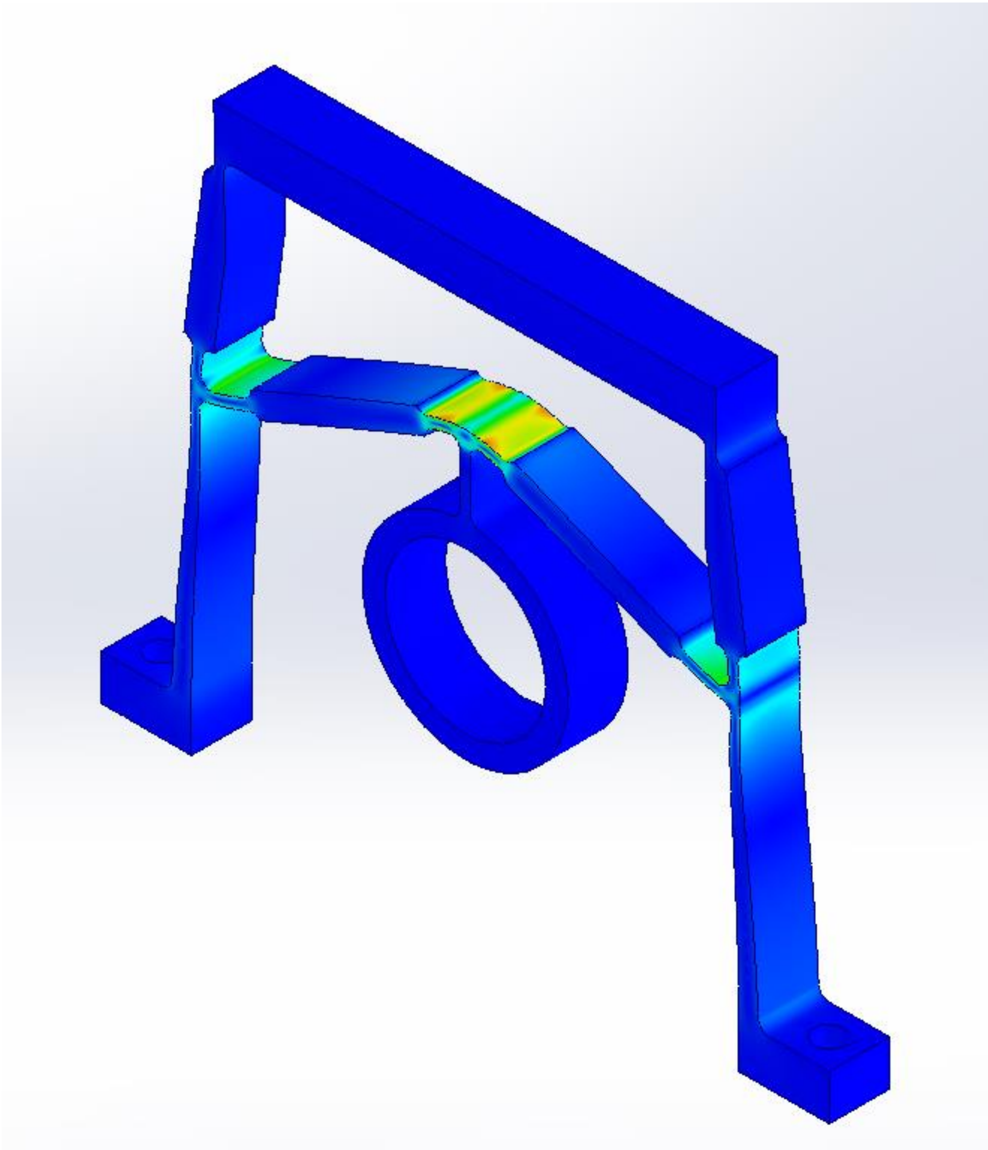

Figure 3: Example stress result plot

The groups of 2-3 students were instructed to find one another, and then were given their first assignment: an icebreaker, and a chance to discuss how they would attempt to solve this problem with the skills and knowledge they have at this point in their educational careers. The icebreaker was an attempt to help develop interpersonal and small group social skills, one of NETI’s five tenets of cooperative learning. A life size 3D-printed plastic model of the flexure was given to each group to help with brainstorming. Students were then informed that at the end of the given time for discussion, a student in the class would be randomly selected to present the findings of their group, and that this would be a common practice in the class—to improve their skills at communicating their ideas in a design review-type setting, they would need to practice. The student selected would receive extra credit points for presenting. This was designed to keep the stakes low, while still providing a reward and promoting individual accountability for the group’s output, one of NETI's five tenets of cooperative learning.

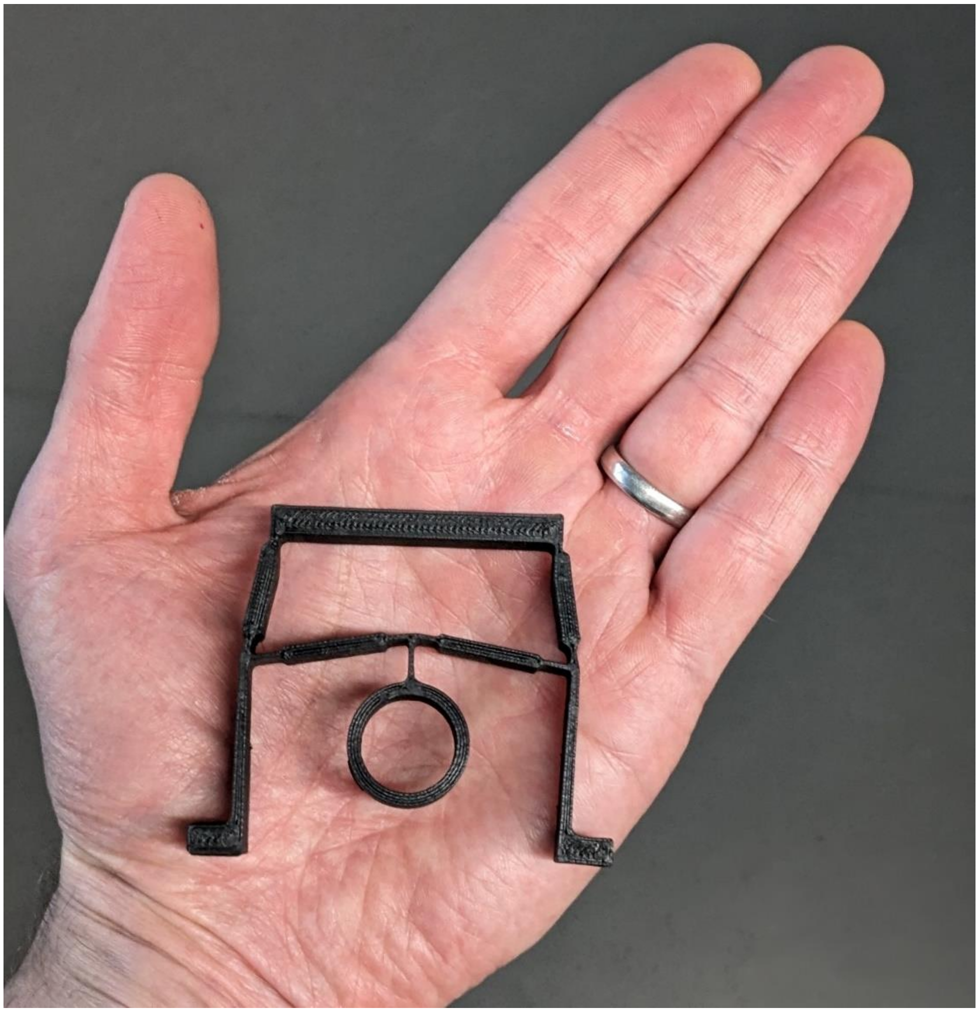

Figure 4: 3D-printed sample flexure used in class

Most groups were able to generate ideas on estimating stress by idealizing sections of the flexure as beams as they had seen in a statics class, and some that had taken classes in mechanisms were able to imagine the flexure as a multi-bar linkage with pin joints at the thinnest points. The consensus was that there was simply no way for them to arrive at an answer for stress and displacement working by hand. Some groups did propose building the part and testing it to measure the performance to bypass the difficulty of calculation; this segued directly into the explanation that computer-aided engineering is the way to avoid the costly and time-consuming process of iterative prototype testing. In fact, by the time they were to leave the first class period, they would be able to generate a first estimate of two of the three scenarios posed. The rest of the class period was then used to walk through the process of using FEA software to run a simple linear static study on the model of the flexure—applying a linear elastic material model, fixturing the feet, applying the 1 mm displacement to the input surface, creating a default standard mesh, and running the simulation to determine stress and displacement. It was then demonstrated that, due to the nature of linear static simulations with linear elastic material models, the input could be scaled to predict an input to produce exactly the stress level desired; for instance, if the 1 mm input produced 16 µm of output motion and 1,400 MPa of stress in a part with a yield strength of only 350 MPa, an input of 0.25 mm would produce 4 μm of output and 350 MPa of stress.

In subsequent class meetings, further FEA techniques were covered with textbook readings, homework assignments, and lectures. Topics included mesh refinement and convergence, simplification via symmetry, 2-dimensional simplification, geometric nonlinearity (stress stiffening), fixturing to virtual walls or an assembly using idealized bolt connections with varying tightening and friction parameters, nonlinear static studies, and nonlinear material properties (such as an elastic-plastic model). In each class period, the groups were given 20-30 minutes to debate whether and how the new technique learned could be used to update prior estimates for flexure performance. They were prompted to explore multiple solution paths and not accept the established solutions per KEEN's curiosity framework. At the end of the allotted time, a random student was selected to present their group's findings to the class as an informal design review. After the design review, students all returned to their original seats, where a quiz was delivered on the online learning management system (LMS). The quizzes were not traditional knowledge-testing quizzes; they were reflection exercises. The students were prompted to compare and contrast the methods used by the presenting group and their own. They were also prompted to reflect on how well their group functioned during the exercise, sometimes with follow-on questions about whether all voices were heard, whether multiple solution paths were considered and how one was selected among alternatives, and what the group could improve upon to work better in future class meetings. This type of self-assessment is another of NETI's five tenets of cooperative learning.

The final applicable topic in the course to this flexure performance scenario is fatigue life simulation. Instead of using this as a final 30-minute block of time to work in a group, it was decided to assign this as a final project to culminate the experience. One reason was to gain the benefits of outside-of-class collaboration that had not previously been realized [12]. Another reason was the much more varied array of acceptable solutions there are in a fatigue problem, as the analyst must use judgment in applying reliability demands, factor of safety, and many fatigue strength-modifying factors. Assessing and managing risk, a key learning outcome of KEEN's connections component of EM, took precedence in this project—students were reminded that the JWST has 18 mirror segments, each requiring 6 of these flexures to control a degree of freedom each. If any of the 108 flexure mechanisms were to fail during the lifetime of the space telescope, performance would be severely degraded, and there could be no possibility of sending astronauts to the telescope to make repairs. Due to the statistical nature of fatigue lifetime prediction, students cannot just come up with a single answer for how far the input surface can be actuated and how far the output surface moves with that input if stresses are kept at a low enough level for infinite life, they must be able to explain the assumptions that were made to arrive at their answer and what the justifications and consequences are for those choices.

It was desired to stage the presentation of the results of this final project as a design review—given the design and material for the flexure, how could it be operated to ensure infinite life? Unfortunately, having all 9 groups present during a 110-minute class period would prove highly repetitive and bore most students very quickly. Also, trouble has arisen in past final projects as Montana State Univesity has discouraged placing too high a weighting on final exams and projects to reduce the stress on students during finals. Many students have not given a respectable effort on a final in this class when the final cannot change their grade more than a single letter. The solution to both these problems was to have the final project design review submitted as a video posted to the class LMS site, as well as assigning each student to post constructive criticism to 2 other groups' videos that had been randomly assigned by the instructor. Each student was then aware that peers would be reviewing their work, and pride would prevent them from submitting low-level effort.

results and discussion

Two quantitative measurements were taken to compare the performance of the 2022 Fall cohort (who were presented with the flexure on the final exam) with the 2023 Fall cohort, who were presented with the flexure during the first class meeting and in subsequent group activities.

The first measurement was on performance against the relevant learning objective as stated in the course syllabus. This learning objective was inherited from a previous instructor and was stated as "Upon successful completion of this course, students will demonstrate an ability to apply the Finite Element Method (FEM) through selection of appropriate analysis methods and application of appropriate analysis tools to determine meaningful results and validate accuracy of results." Fall 2022 students received an average of 4.19 on a scale of 1-5; Fall 2023 students received 4.68 on average. Two students in the Fall of 2022 did not submit the final exam, one student in the Fall of 2023 refused to work with their assigned group on the assignment. Those results were not included in this analysis. It is hard to directly compare the results, as in Fall 2022, the measurement was taken on an individual assignment, while the Fall 2023 assignment was completed by groups of 2-3 students.

The second quantitative measurement was taken to measure student engagement. A simple record of class attendance was used. In each semester, the class meets nearly 30 times (depending on placement of holidays in any given year). In the two semesters analyzed, the last two class periods where attendance was taken both semesters were the 20^{th} and 21^{st} class meetings. In the Fall of 2022, unexcused absence at those two lectures averaged 34.2% and, in the Fall of 2023, it averaged 12%. Statistical significance was not investigated.

Several other goals of the implementation were measured qualitatively. The first lecture of the semester was observed to interest the students much more after implementation. Students did practice presenting in a design review setting. By the maxim 'you get better at what you practice,' it is expected that the practice improves the skill. However, it is unclear whether the practice was structured enough to produce meaningful results. Participation and effort in the final exam or project in the class were improved. As noted above, in the previous semester, not every student even submitted a final exam, and several submitted incomplete exams. For the final project in the semester in which this method was implemented, all students submitted a final project (though 1 submitted separately from their group), and all but one participated in providing constructive feedback in the peer review process, even though that had a minor weighting in their final project grade.

conclusion

KEEN's EM framework has been shown to provide a way to improve student engagement and performance in an FEA class in the MET curriculum. Active, collaborative learning in small groups on an interesting, complex engineering problem from day 1 of the class resulted in more engagement in the class measured on attendance and willingness to complete the final exam or project. Average student performance measured by the associated learning objective in the course syllabus also improved.

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