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Using FEA as a Pedagogical Tool for Teaching Machine Component Design

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Abstract

Over the last 50 years, Machine Design textbooks have been continually updated to include instruction on current technology and to include the latest standards. However, current technology has not been incorporated in the teaching of the material. Specifically, there is a chapter in most texts that addresses basic finite element analysis (FEA) theory. However, FEA is not used to teach the concepts of machine design. Conversely, the content of machine design is not used to enhance students' FEA skills. These two topics are natural partners and can be used to enhance the learning of both topics. The pedagogy presented in this paper seeks to bridge these gaps.

FEA has been applied to many aspects of machine design to better understand the interplay between machine elements. Very little of this research is currently incorporated in the teaching of machine design, even though FEA is commonly used in industry for machine element selection and design. Additionally, the tool itself is not used to explore complex interactions between machine elements in the classroom to allow students to better understand the interactions and have a better feel for implementing these elements in complex systems.

Although in many schools, students learn the theory behind FEA and how to use it, they get little opportunity to apply the knowledge gained to "real life" scenarios. Using FEA to teach machine design provides an ideal opportunity to expose students to interpretation of FEA results.

Five modules were developed to encourage exploration of machine elements using FEA: Modal Analysis of a Shaft, Stress and Deflection Analysis of a Shaft, Press Fit of a Component on a Shaft, Effect of Changing Pitch and Pressure Angle on Contact and Bending Stresses in a Spur Gear, and Gasketed vs. Non-gasketed Bolted Joints. Each module includes a theoretical background section, a model set-up section and a list of questions for the student to answer by exploring the results of their simulations. Additionally, the modules developed through this research are interactive and require student exploration. They, along with other learning activities could easily be used to encourage a more active classroom.

As Finite Element Analysis is taught concurrently with Machine Design II at University, students were learning to use ANSYS software and the FEA theory simultaneously with machine design content. Students stated that the FEA activities helped them understand the machine design content much better than just performing book problems. However, due to sequencing in the two courses, many students also found performing the FEA analyses to be beyond their abilities. Future plans for this research include sequencing the FEA and Machine Design courses to allow better synergy and reducing the amount of model generation required of the students to focus more on interpretation of the results and reinforcement of the Machine Design content.

Introduction

FEA has been incorporated by many in the teaching of engineering mechanics over the last twenty years. Papadopoulos [1] provides not only an excellent survey of the literature of courses in which FEA was used, but also points out that FEA can be used as an effective instructional and computational tool without in-depth knowledge of the theory behind the tool. In spite of this research and that of others, FEA adoption in courses to enhance student conceptual understanding is sporadic and considered novel. Current engineering education research and publications indicate a need to increase the FEA content of engineering programs [2]. At many schools, this task has proven quite difficult given curriculum credit hour restrictions [3]. The materials developed through this research aim to expose students to FEA without adding credits to their curriculum. Using FEA to teach machine design will allow schools that cannot incorporate a full course on FEA into their curriculum due to credit hour restrictions to teach FEA to their students while also increasing the depth of understanding students can obtain while studying machine design. An attempt has been made to do so in Lee [4].

Machine Design is taught today in much the same way as it has been taught many years. From the website for the Shigley [5] text comes the following quote, "The tenth edition maintains the well-designed approach that has made this book the standard in machine design for nearly 50 years." In those 50 years, machine design textbooks have been continually updated to include instruction on current technology and to include the latest standards. However, current technology has not been incorporated in the teaching of the material. Specifically, there is a chapter in each of the texts that addresses basic Finite Element Analysis (FEA) theory, however, the technology is not used to teach the concepts of machine design and the content of Machine Design is not used to enhance the students' FEA skills. These two topics are natural partners and can be used to enhance the learning of both topics [3].

FEA has been applied to many aspects of machine design to better understand the interplay between machine elements. This substantial body of knowledge is commonly used in industry and has, to some degree been incorporated in current engineering standards for machine element selection and design. However, very little of this research is currently incorporated in machine design textbooks and the teaching of machine design in general. Additionally, the tool itself is not used to explore complex interactions between machine elements in the classroom to allow students to better understand the interactions and have a better feel for implementing these elements in complex systems. Finally, as with all computer tools, FEA can be incorrectly used to create very incorrect results. [6]

There are two voids in the education of engineers. The first is that state of the art is well beyond the information being conveyed to students and students are not learning to explore engineering topics using modern engineering tools. This first void is evident when comparing current teaching practice and textbooks to the vast body of research that has been done on machine elements.

The second void is in fulfilling ABET (Accreditation Board for Engineering and Technology, Inc.) [7] student outcome (k) which states that students should have an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice. One of the most common and most effective of these tools is FEA. Although our students learn the theory behind FEA and how to use it in FEA courses, they get little opportunity to apply the knowledge gained to “real life” scenarios.

The research reported in this paper attempts to use FEA to teach Machine Design and, conversely, to use Machine Design to teach FEA.

Methodology

Instructional modules were created that included exercises and instructions to correctly model a given machine element in FEA. Probing questions were asked regarding element selection, boundary conditions, meshing and load application. Once the model was developed, it was modified to explore the effects of changing specific variables in the machine element to increase the students’ understanding of how design choices affect the stresses and deflections in the machine element. In some cases, in addition to the machine design content explored using the model, the model was also used to explore the effects of different boundary condition choices and load application methods on the results of the simulation.

These modules were given to students when a specific machine element was discussed in class. The class is formatted as a twice a week two hour and fifteen minute class allowing for some active learning to take place during class time. The exercises were introduced during class and completed outside of class. Students were required to submit a lab report detailing their choice of modeling strategy as well as answering a number of focused questions regarding their simulations and the machine element being explored. When the assignments were submitted the investigative questions were discussed in class.

In addition to these modules, traditional lecture/discussion was used to discuss the elements and a large design and build project was used to solidify the concepts. Also, the use of FEA modeling was introduced to students in a previous Strength of Materials laboratory.

Five modules were developed: Stress and Deflection Analysis of a Shaft, Modal Analysis of a Shaft, Press Fit of a Component on a Shaft, Effect of Changing Pitch and Pressure Angle on Contact and Bending Stresses in a Spur Gear, and Gasketed vs. Non-gasketed Bolted Joints. In addition to the written modules, seven instructional videos were created to assist students in creating and manipulating finite element models: Where to Find Things in ANSYS Workbench, Importing SolidWorks Files into ANSYS, Adding Material in Workbench, Formatting Results in

ANSYS Workbench, Output at Precise Locations in ANSYS Workbench, Using Adaptive Meshing to Ensure Convergence in ANSYS, and Slicing a Body in ANSYS.

Additional concepts, that would otherwise be difficult to explore, that were explored in class as a result of the FEA analysis, included the effects of different boundary conditions on the deflection results. Specifically, a bearing constraint versus a remote point displacement constraint were compared. In class, the fact that the bearing constraint (no displacements in the radial directions across the entire bearing surface) more accurately models a roller bearing and reduces the shaft deflections while increasing the stresses and the remote point displacement constraint more accurately models a ball bearing and yields larger shaft deflections and smaller stresses. This comparison both strengthened students' modeling skills and their understanding of bearing selection.

Modal Analysis of a Shaft allowed students to not only see the basic relationships between mass and length of a shaft and natural frequency, but also allowed them to visualize the natural frequency of complex shafts, something not possible using analytical methods.

Press Fit of a Component on a Shaft encouraged students to explore the relative advantages and disadvantages of using press fits vs. keys to secure shaft components. In addition, they were able to visualize the tradeoff between torque carrying capacity and stress in the shaft.

Effect of Changing Pitch and Pressure Angle on Contact and Bending Stresses in a Spur Gear allowed students to develop a sense of the effect of changing pressure angle on the bending stresses in a spur gear. Originally, this activity also was intended to explore the effects on contact stress, but this was eliminated due to difficulties in getting the models to converge.

Finally, Gasketed vs. Non-gasketed Bolted Joints allowed students to explore the effects of changing bolt size and spacing on both gasketed and non-gasketed joints. It also allowed them to see the dramatic effect of introducing an unconfined gasket on the stiffness of a joint.

Sample Exercise

Below is an example of the Stress and Deflection Analysis of a Shaft exercise.

Shaft Layout and Design Decision Making

Purpose: To explore the characteristics of shaft design and develop a feel for the required features and how to minimize stress in a shaft.

FEA Theoretical Modules to be Reviewed: The following modules should be thoroughly understood prior to attempting this exercise:

1) Basic FEA Modeling

CAD Modeling Questions: To ensure your model can be modified, you will need to think through the process of modeling the shaft and related components.

1) Given the diagrams below, in what order would perform the following operations to create the shaft?
   a) Add radii at all steps
   b) Determine all shaft diameters including fits for press-fit parts.
   c) Determine maximum step sizes at part interfaces.
   d) Determine keyway dimensions
   e) Draw shaft as cylinders
   f) Assign dimensions to all shaft cylinders
2) When drawing the shaft, is it best to start at one end and work from there or start in the middle?
3) Should intermediate reference planes be used when modeling the shaft to make future modification easier?

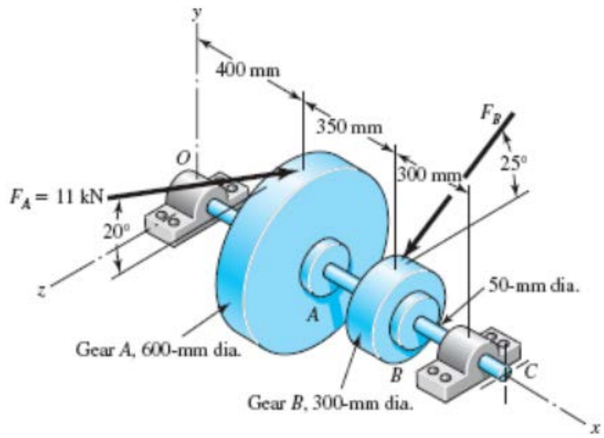
FEA Modeling Questions: To ensure loads and constraints are properly applied, you will need to think through the process of constraining the shaft and how loads should be applied.

1) With regard to stress, what points on the shaft are potentially critical?
2) In order to capture the critical stresses, what features/components must be accurately depicted and which may be simplified?
3) Can symmetry be used to reduce computational time?
4) Can the assembly be sectioned to reduce computational time?
5) Are there parts of the assembly that need a finer mesh than others?
6) How should contacts be modeled?
7) How should the press fit for the bearings be modeled?
8) What constraints should be used to most accurately model the shaft?
9) How will loads be applied?

Procedure:

1. For all steps in this exercise, document your results. For hand calculations, carefully perform the calculations and document all assumptions and your methods. For FEA, create a word file with screen shots of all of your boundary conditions and loads as well as an image of your completed model including the mesh and results.
2. Perform a hand-calculated stress analysis of the shaft at the critical points to determine the maximum stress. Determine the factor of safety with respect to the Gerber fatigue criterion for the shaft using this analysis. Also, pick a point that is remote from all stress risers and calculate the stresses at that point to validate your FEA model.
3. Create CAD models of the below shaft.

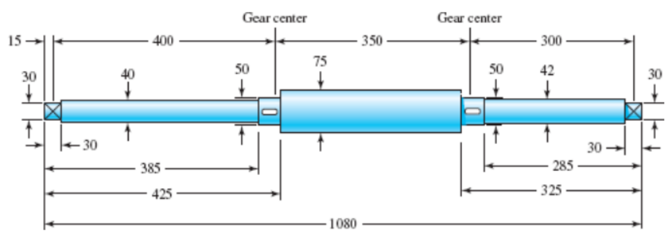
a) Loading diagram—You must solve for F_B prior to loading your FEA model



*Problem 3–73**

Taken from [5]

b) Initial Geometry



*Problem 7–21**
All fillets 2 mm. Dimensions in mm.

c) Size keyways using a square key. Consult Machinery's handbook for recommended dimensions.

d) Consult the SKF bearing selection manual to determine the maximum fillet radius at the step for axial bearing location. Override the note on the above figure to provide a radius on the shaft that is smaller than the bearing inner ring fillet. Also ensure that the step height is allowable. Reference http://www.skf.com/binary/30-121486/10000_3-EN-webb.pdf pg. 510 to start.

4. Model the assembly in FEA
   a) Import the shaft file. Make sure to select add material (as opposed to add frozen) under the operation selection. Also set your axes to your preferred orientation.
   b) There are a number of ways to provide a location for applying the forces to the gears. You can either 1) use remote force and scope the force to the appropriate journal on the shaft or 2) apply an equivalent force to the keyway and an appropriate moment to provide an equivalent system or 3) try your own equivalent method and see how it works.
   c) Make sure to modify the material definition to account for the actual material in the book.
   d) Validate the FEA model using the calculated values for the point from part 1). If the results don't match, fix your FEA model or hand calculations whichever is incorrect. Results should be within 5% for a simple analysis such as this one.
   e) Determine the factor of safety with respect to the Gerber fatigue criterion. Compare to hand results. If they don't match, why not? Be specific.

5. Modify the model to explore shaft design
   a) Perform the FEA if the right gear and the bearing are exchanged (remember you can't slide components over portions of the shaft that are larger than their ID). Exchange the two components retaining the gear loading and altering the location. Simply alter the location of the bearing (and change journal size to accommodate).
   b) Reduce the distance between the components in the original configuration by a factor of 2.

Analysis:

1. What did you learn about stress risers at bearings? Is the increased stress due to the step important to the overall shaft design? When would it be more critical? Think about locations of components on the shaft.
2. Based on your experimentation, when designing shafts based on stress and deflections, should components be cantilevered or simply supported?
3. Based on your experimentation, should shafts be as short or as long as possible?
4. What are the advantages of cantilevering components and when should it be considered? Give at least on example.

Documentation:

1. For each FEA Analysis, as a minimum, you must include documentation of your model per the Formatting Results in ANSYS Workbench video found under Documents>FEA Links. In addition, you must include the results for individual points used for comparison in a format that is easily read.
2. Answer all Analysis questions using documentation from your simulations in Workbench and reference those simulations.
3. Upload your ANSYS project to BB.

A sample of the student submission for this assignment is given below:

Shaft Layout and Design Decision Making

Analysis:

1. What did you learn about stress risers at bearings? Is the increased stress due to the step important to the overall shaft design? When would it be more critical? Think about locations of components on the shaft.

It is critical to have some sort of fillet at the step that constraints a bearing axially. The stress riser at a corner on a shaft is exponential going to infinity. Bearing catalogs typically give the dimensions for the shaft the user is mating the bearing to; in this case the minimum radius on the shaft should be <1 mm for a 30 mm bore bearing. The designer should always keep this in mind when locating a bearing axially on a shaft because the stress concentration can be detrimental to successful operation. When the ratio of the big diameter to the little diameter at the step becomes much greater than the fillet size, the stress concentration factor becomes critical. Figure 1 shows the von mises stress for the shaft from Problem 3-73; the stress concentration factor at the keyway and the step following it are 3.0 and 2.0, respectively. Another factor that increases stress concentration is the location of the components on the shaft. There should be as little cantilevering of components as possible; though the results for von mises stress in Figure 4 are extremely high (5x the original von mises stress), the stress rings show how the stress is multiplied significantly when a component is out a distance from the bearing.

2. Based on your experimentation, when designing shafts based on stress and deflections, should components be cantilevered or simply supported?

Components should have as little cantilevering as possible. Cantilevering is necessary for systems such as automotive engines for access (serpentine belt, alternator, etc.), but they are designed in such a way that they are nearly constrained up against the engine on the face of the pulley. Figure 4 shows how stress can be amplified (5x) when a component is engaging over a distance; an additional moment is created. Simple supports are much more reliable than a cantilever situation; when cantilevering, FEA analysis should always be performed.

3. Based on your experimentation, should shafts be as short or as long as possible?

Shafts should be as short as possible in most situations. Not only will critical speed be an issue on a longer shaft, but the deflections due to the rotation will cause components, namely gears, to contact outside of the line of action which can cause excessive wear on the gears and even system malfunction. Mentioned above is how to support a shaft; shafts should be short and simply supported.

4. What are the advantages of cantilevering components and when should it be considered? Give at least one example.

Cantilevering components allows for many advantages even though it can cause significant moments to be created. Cantilevering, as mentioned earlier, is used in automotive design to allow easy access to pulleys and many other smaller sub-systems that are belt driven. If a shaft is already supported on both ends then it would be impossible to get a gear or pulley onto the shaft! Cantilevering can be considered depending on the geometry and material properties of the shaft in question. If the diameter of the shaft is significant compared to the pitch diameter of a gear or pulley then little deflection (moment) can be transferred back to the support. If the designer is concerned about weight then they may consider using an aluminum shaft, but if there is going to be significant loading on the component, then steel or a material with a relatively higher stiffness should be used. Figure 4 shows the dangers of moving a component to the end of a significantly cantilevered shaft with a relatively small diameter.

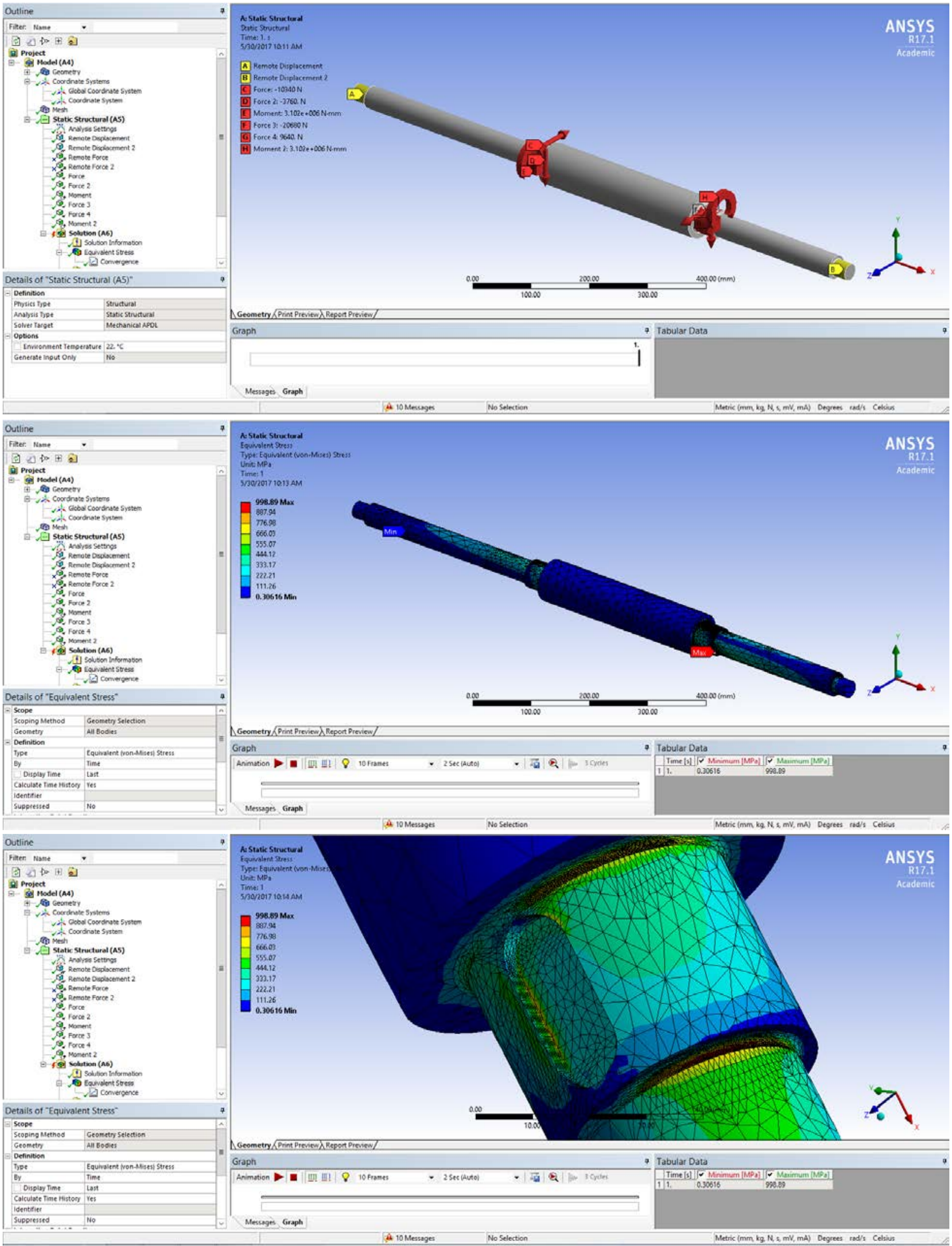


Figure 1: Problem 3-73 Shaft Max Von Mises - Constraints and Structural Analysis Results

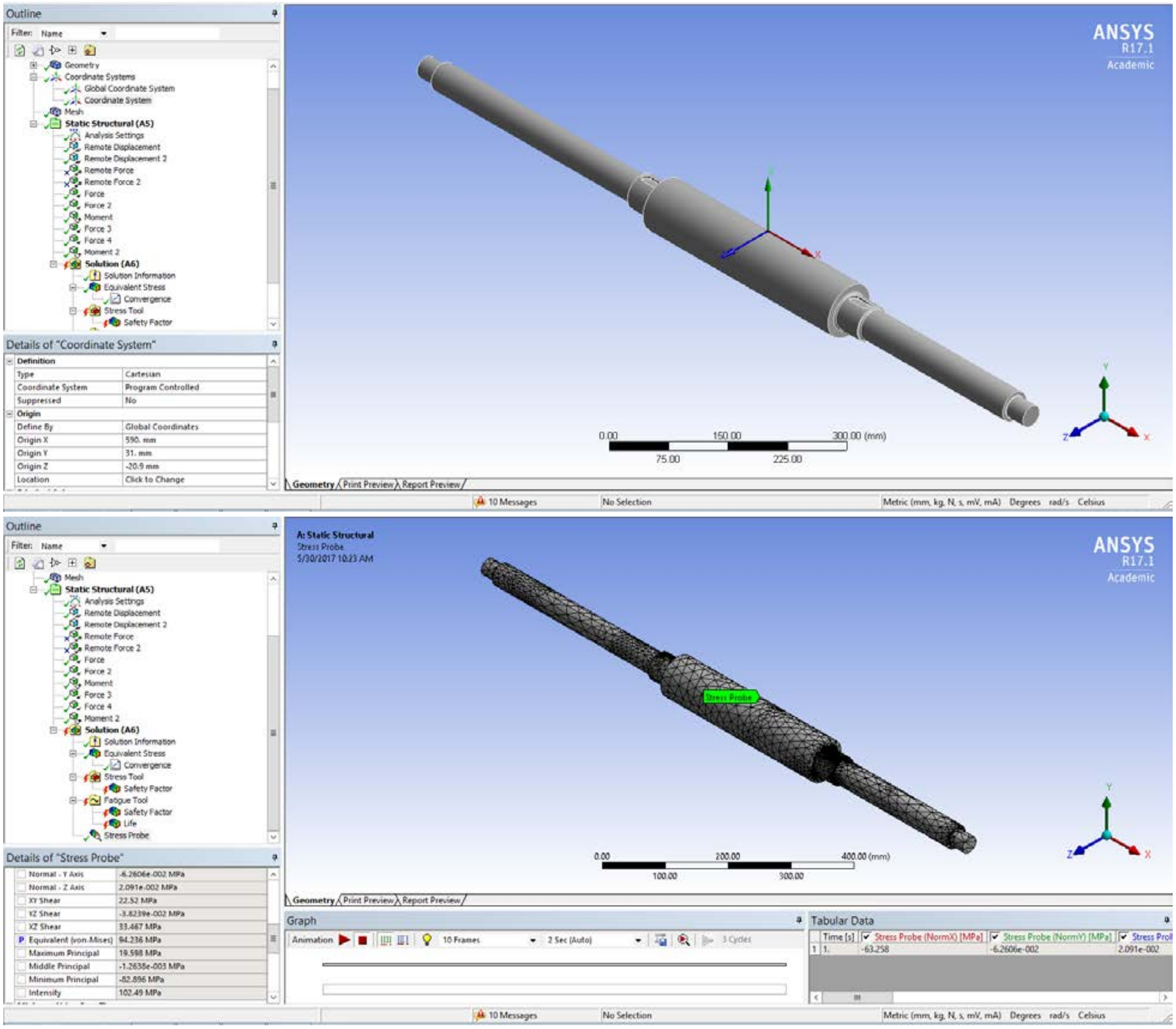


Figure 2: Problem 3-73 Shaft Safe Location - Constraints and Structural Analysis Results

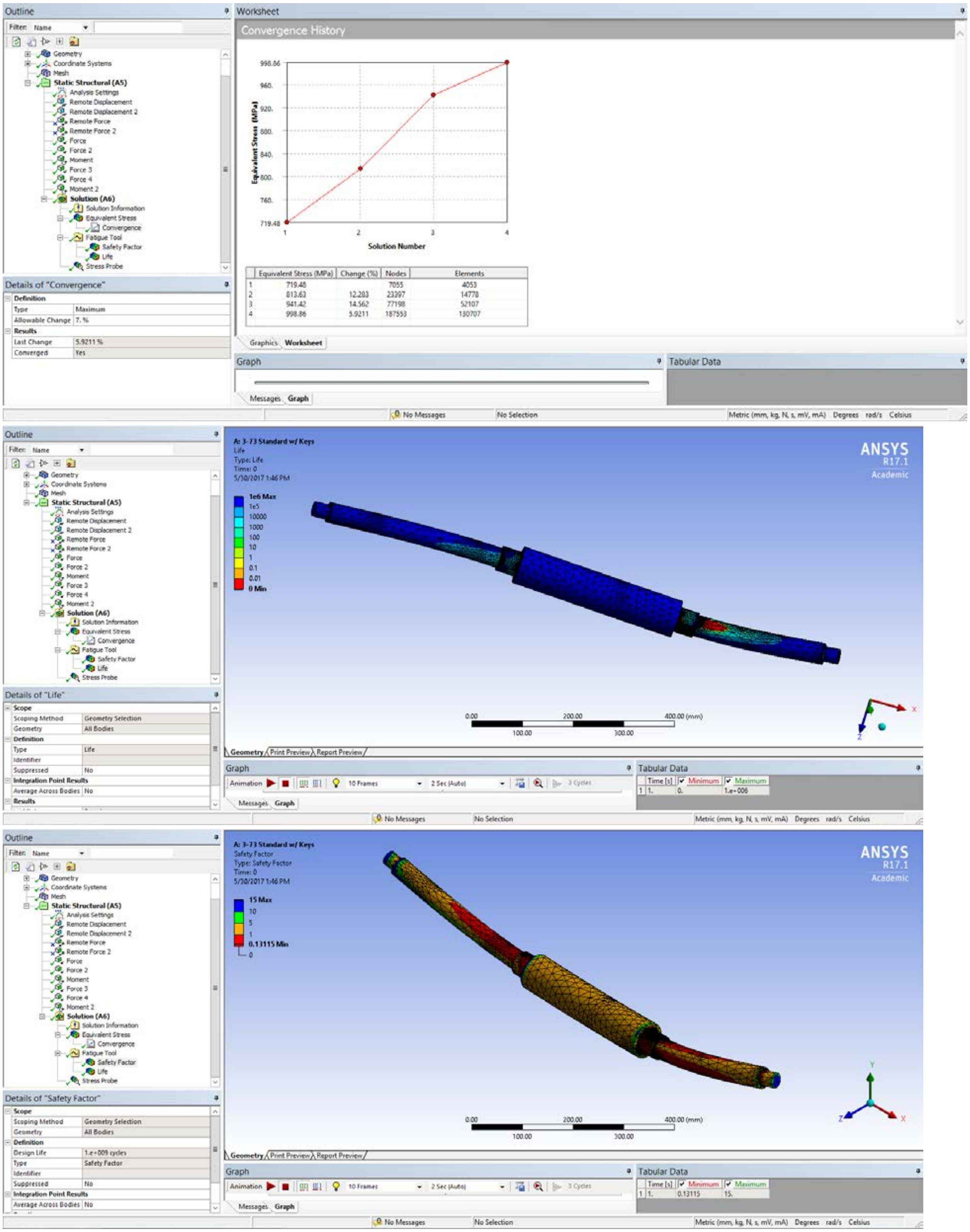


Figure 3: Problem 3-73 Shaft – Convergence, Life, and FOS Results

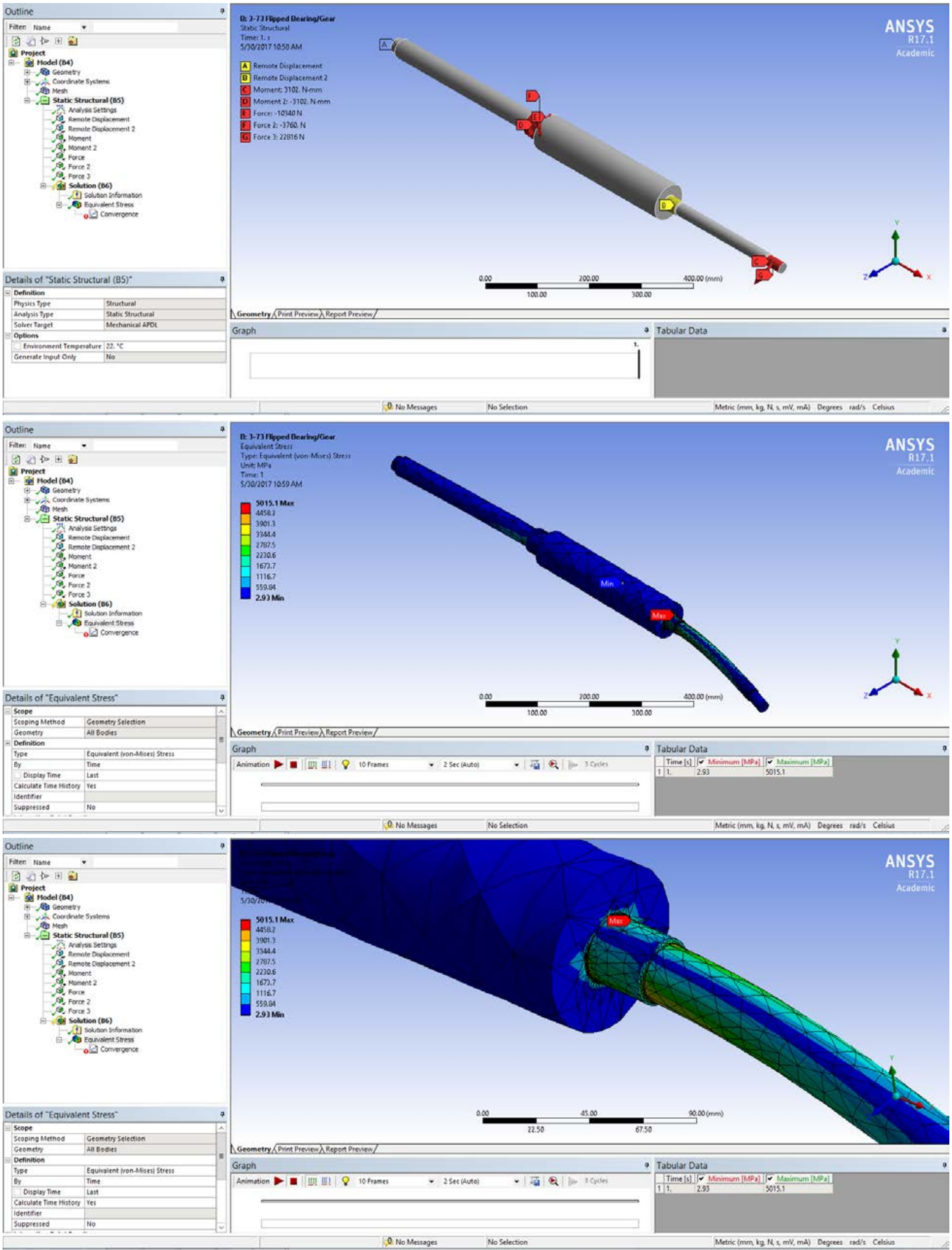


Figure 4: Problem 3-73 Bearing / Gear Flip - Constraints and Structural Analysis Results

The student results to the first question show that the student did place the information presented in class; bearing manufacturer requirements, stress concentration factors and design of steps, into context using the FEA results. In addition, subsequent results show that the student placed the FEA results into context to help visualize good design practices. For example, the student was able to develop overall rules of thumb regarding placement of machine elements on the shaft as well as controlling stress risers. Although this insight can also be gained using theoretical equations, visualization of the concepts allows students to more fully internalize the information.

Results

Overall, the exercises achieved the desired result—allowing students to visualize the stresses in machine components being studied and draw general conclusions about the effect of changing design variables on the effectiveness of an element. However, students were very dissatisfied by the amount of work required to obtain these results and the work required to develop the FEA models.

Student comments about the FEA modules were:

Was this class intellectually stimulating? Did it stretch your thinking? Why or why not?
It was intellectually stimulating. Combined FEA and Machine Design topics for a better full understanding.
What aspects of this class contributed most to your learning?
The FEA homework was helpful, some iteration of the problem statements will be necessary and it would be nice if the FEA assignments could be such that students were more eased into using the software, rather than hit with a freight train all at once.
What aspects of this class detracted from your learning?
Long homework assignments in FEA that I did not learn anything from.
I was not a fan of the original FEA projects. We had another class that we were taking simultaneously solely for learning about the subject so it wasn't fun spending over thirty hours of my memorial day weekend trying to figure out a software I hadn't really used yet. I thought the project was cool and worth-while, but would've been better suited for a little later in the semester. Just a couple weeks later so we'd warmed up on the software in EGR 329.
What suggestions do you have for improving the class?
Work through FEA assignments to make less of a demand on students.
Describe ways your instructor could be MORE effective
Only thing I can think of was lowering the work load. Specifically the FEA projects. It was hard to balance everything at the beginning of the semester.
Further explaining ANSYS before assigning FEA homework would also be very nice because we did not know very much about FEA early in the semester.
Describe ways this course could be improved
The FEA emphasis felt like it happened too early. We only started talking about modal analysis last week in “our FEA course” and had to do a report on it for the third week of class or something. The shafts homework would be okay paper-only and then later in the semester do more FEA.

Exam grades on the closed book, conceptual portion of the exams decreased from the previous year. On the same question set, the average in 2016 was 67.2% with a 10.7% standard deviation. In 2017, it was 59.4% with a 12.4% standard deviation.

Discussion

As can be seen from the drop in performance and the comments, work needs to be done to modify the exercises to make them more effective. The workload in the course with the addition of the modules was very overwhelming to many students. Exam grades decreased. This could either be due to not learning specific concepts as well, the test questions not addressing the topics that were learned or students being overwhelmed by the amount of work and, therefore, not having time to study for the exam. Given the comments in the student evaluations, the workload and time to study for the exam may be the dominant cause.

Modifications will be made to the modules to provide students with the FEA models to use to explore the Machine Design topics. This will substantially reduce the workload and allow students to focus on the machine design content. In a concurrent class on specifically the FEA method, students will learn to perform the modeling. This will both ensure the students are using correct models and not drawing incorrect conclusions due to poor modeling and a greater focus on concepts.

Incorporating the model building portions of the modules in the FEA course will encourage students see the concrete use of FEA in mechanical engineering.

Conclusions

Although results and student opinions on the effectiveness of the FEA modules described in this work were mixed, the pedagogy is sound. However, significant modifications to the delivery method are required to ensure that students are not overwhelmed by the workload and are able to fully absorb the content of the modules.

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