

Collaborating with Industry Partner within an Undergraduate Finite Element Course

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Abstract

One of the ABET outcomes for engineering students is that they have the ability to apply engineering principles to solve problems. In addition, students should have the ability to analyze and synthesize results that meet desired constraints within a problem. Early in a student's career, as they begin to acquire the analysis tools and methods, there may be few opportunities for application to real world projects with consideration for complex problems or situations. However, in the junior or senior level courses, students should be afforded more and more opportunities to incorporate engineering analysis, design and synthesis. An undergraduate finite element analysis (FEA) course provides an excellent opportunity to do so through project based learning. This experience is further enriched with industry collaboration to develop a project with real-world design objectives and constraints.

This paper discusses a semester finite element project developed by Accuride Corporation, in which students are asked to design and analyze an aluminum commercial truck wheel. The students were given a generic model that provides limits of the physical design space as well as guidance on boundary conditions to account for inflation pressure, tire interface loads, and vehicle loading. They had a goal to minimize vehicle weight given constraints on maximum stresses and deformation. In addition, they were encouraged to develop attractive styling as with hand hole geometry and placement. Students presented their final designs in writing and orally before a panel which included faculty members and Accuride engineers. They were evaluated on final weight, style, presentation, and analysis, with the latter making up the bulk of the score.

The project provided several opportunities for students to connect directly with real world design issues in a way that wouldn't have been possible without the industry partnership. For one, students felt the pressure of competition to achieve the lightest wheel, just as Accuride must keep pace with industry competitors to maintain or grow their market share. In addition, they were held accountable for weaknesses in their analysis process. For example, the industry panel quickly identified sharp corners and other unnecessary stress concentrations as design flaws when a student's finite element analysis failed to detect them. Students were pressed on how they validated their analyses. Finally, the project revealed areas for improvement for the finite element course itself, particularly to help students synthesize FEA with concepts and tools from earlier courses.

Introduction

Finite Element Analysis (FEA), a numerical method for solving complex problems in engineering, continues to gain traction as a valuable design tool within a variety of industries.¹⁻³ This trend lies in part due to advancements in the development of user friendly FEA software. As a case in point, Dassault Systemes, designer of SolidWorks Simulation, promises their software can help companies develop products “better, faster, cheaper” and that the intuitive process is such that a ‘specialist’ is not required.⁴ Consequently, several faculty have made the case that the transition from a research tool to a professional competency suggests engineering students gain some level of FEA literacy at the undergraduate level.^{5,6} At the same time, undergraduate students (and likely professional design engineers as well) find ways to misuse the tool, whether through poor modeling choices, by misinterpreting results, or failing to translate a computer aided design (CAD) model into an adequately defined FEA model.⁷⁻⁹

In a previous publication,¹⁰ the authors discuss experience with an undergraduate FEA course, focusing in particular on finding an appropriate balance between theory and practical application through software. Three objectives for the course were outlined: (1) enhancing students’ grasp of foundational topics in math, physics and engineering; (2) developing technical competency through using FEA software; and (3) improving engineering judgment and modeling skills. In this paper, a new development for the course: a ‘real world’ design project brought to us from Accuride Corporation, a local industry partner and employer of our graduates is presented. This project required students optimize an aluminum wheel for the commercial trucking industry with a specific objective and several design constraints. For one, we wanted to expand students’ experience in the practical application of software (part of the continuing effort to find the right balance with theory). A CAD file for a template design was provided to facilitate modeling in SolidWorks Simulation.¹¹ At the same time, students were given only general guidance about how to model boundary conditions, and essentially no direction in how to optimize their designs. Secondly, the course has always included a student project with the goal of improving judgment and requiring accountability for modeling choices. The selection of this specific design problem enhances this goal by requiring students compete with their classmates and defend their designs to industry professionals.

In the next sections, the evolution of a semester project and its role in meeting course objectives is discussed. Then specifics on how the project was executed are presented. This is followed by a discussion of assessment and recommendations for improvement. Finally, the paper concludes with an overview of the project challenges and benefits.

Course Background

The Introduction to Finite Element course is a mechanical engineering technical elective for undergraduates, brought to the program in 2013. The course format includes two hours of lecture and a two hour computational laboratory. The course begins by introducing students to one-dimensional single degree of freedom problems. We present theory for solving axial displacement & temperature problems. In addition, the course provides practice with two and three dimensional models,

incorporating SolidWorks software through tutorial-style lessons. Student assessment includes midterm exams, weekly homework exercises on theoretical content (e.g. stiffness matrix calculations), small programming assignments, comprehensive exercises which include physical experiments, and a semester-long modeling project which had, prior to 2016, been student-selected. The primary pedagogical objective for this project was to provide students with practical experience in modeling and analysis. They were encouraged to experiment with modeling choices (for boundary conditions, for example) and assess the consequences of those choices on the responses they were most interested in (usually stress and deformation). In many cases, students selected projects based on internships or co-operative experiences.

A consistent theme in student feedback regarding the project has been that they felt they needed more instruction and more time with the software. In part, this concern was addressed by adding tutorial-style practice assignments available from a SolidWorks focused text.¹² Even so, the transition from directed assignments to independent modeling of an unstructured problem requires significantly more skill. The project required students show initiative in learning the particular skills needed for their selected project. (For example, some problems required complex assembly connections, mixed meshing, or non-uniform loading.) This was something that we felt appropriate for an junior/senior level elective, but providing assistance and assessing the variety of projects was challenging. In addition, some students were likely to select projects that required skills they already had, rather than stretch to learn new ones. A common project would be easier to manage while ensuring all students were challenged.

Accuride Corporation is a leading producer of wheels and wheel-end components for the commercial vehicle market. Their research and design team continues to push the envelope in the design and manufacture of the wheel in order to maintain market relevance. Finite element analysis plays a significant role in this effort. At the same time, Accuride is a valuable partner with our engineering programs. They serve on the advisory board and hire both students and graduates. In addition, they frequently sponsor senior capstone projects, many of which depend on finite element analysis. Thus, it was natural to seek their counsel to aid the continuing development of an undergraduate FEA course. As it happened, they had a project which might benefit from the creativity of students, that fit the objectives of the course.

Accuride's project required a design optimization of an aluminum wheel for the commercial trucking industry. They provided a base solid model of a wheel with general loading descriptions as well as a handful of specifications and constraints. The project required students make consequential modeling decisions regarding some complex boundary conditions, use of symmetry, and element type. At the same time, students were accountable for the total weight of the wheel, as this is a top priority for customers. The details of the project and student deliverables are outlined in the next section.

Project Specifics

Accuride supplied a problem statement, motivation, loading conditions and basic solid model. This statement included assumptions to help students make design choice justifications based on cost, weight, performance and other criteria. Of particular interest were innovative design and/or

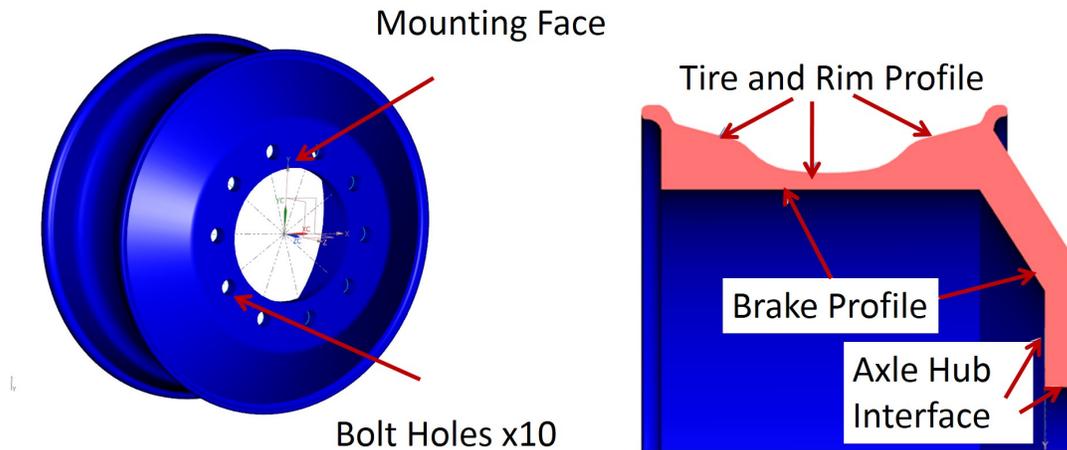


Figure 1: Whole wheel and section view of base model wheel.

analysis methodologies that students might bring to the project based on their experience.

The challenge is to design a typical commercial truck wheel that has a potential for being commercialized in the North American commercial truck market. It is assumed that this part will fall into the high volume production category and will represent a customer's vehicle brand. This assumption implies that styling and appearance are important. Since the selling price of the wheel is limited by what the customer will pay profits are controlled by minimizing cost. For this challenge we will assume that all of the cost is in the material that remains in the wheel. (i.e. 100% of the machined scrap is recycled into put back into production and manufacturing costs are not variable). The critical failure mode for wheels is material fatigue. However, it will be assumed that maximum deformation and principal stress limits will correlate sufficiently for a preliminary design.

The supplied parasolid model for a 22.5x8.25 aluminum commercial truck wheel was converted to a SolidWorks part file by the instructor before delivering to students. The base model provided the required outer contour of the wheel surface needed to interface with tire but the inner surface included a large design envelope. The whole wheel model with a section view is show in Fig. 1. Students were allowed to trim material from the base model subject to stress and deformation constraints.

Students were required to design and optimize the wheel to achieve the following objectives and constraints:

- Maximum Profit (business objective)
- Minimum Weight (marketability)
- Desirable Styling ("sell-abilty")
- Max Principal stresses below specified limits (material limits)
- Maximum deformation below specified limits (brake interference)
- Maintains geometric limitations (industry standards)

Students presented their final designs and defended their modeling choices to Accuride engineers and course instructors. Examples from a student presentation are shown in Figs. 2 through 4. Figure 2 shows the iterative process of refining the wheel geometry. Figure 3 demonstrates that the maximum stresses are below the material yield strength. And, Fig. 4 is an example of one student's the final design.

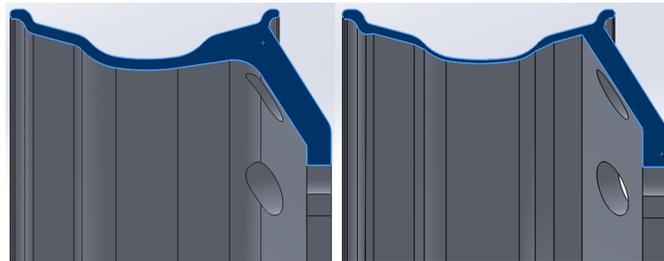


Figure 2: Example of student design iterations of wheel profile (shown in blue). Material is removed to save weight.

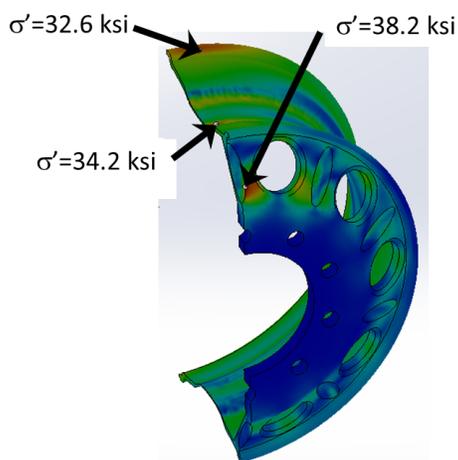


Figure 3: Resulting stress plot calling out three areas of high stress. The material yield strength is 39 ksi.



Figure 4: Example of Student Final Design: The final weight is 35.5 pounds. Note the student's creativity with the hole pattern on the wheel curb-side surface.

Students also provided a written design report. They were evaluated using the criteria below:

- Meets design criteria: Maximum points for lowest weight among peers while satisfying all constraints, 30%
- Styling: Includes creativity with hand hole designs 10%
- Design Method, 40%:
 - Good modeling practices to include mesh convergence analysis.
 - Optimization methodologies.
 - Validation of loading conditions.
- Documentation and Presentation, 20%

The project specifications met the desired objective to challenge students' engineering judgment and modeling skills. In addition, students needed to learn new terminology and expand their technical skills in using FEA software. For example, the boundary conditions for the wheel loading were quite complex. This included inflation pressure, loading from the tire-wheel interface, and a non-linear loading from the vehicle weight as transferred through the tire. In addition, some geometry modifications could have been used to improve meshing and application of boundary conditions. There were also various planes of symmetry in the part geometry that could have been used to model the wheel. Finally, students were accountable for their design and modeling choices. They had to defend these choices during the final presentation to include validation of loading, mesh refinement, and their optimization methodology.

Course Assessment and Discussion

Student project scores were based on evaluations from two instructors and four Accuride engineers. On average, students earned 83% on the project as a whole including 85% for meeting the design criteria, 83% for their design method, 84% for their design and presentation, and 76% for styling. Some consistent positive feedback from the Accuride engineers included that students demonstrated a clear understanding of the project objective and industry terminology. In addition, several students, were commended for unique designs including creativity in hand hole alterations, reinforcement in high stress areas, and using an offset of the tire interface. A few students was also recognized for grasping implications of their design on manufacturing processes, and for effective use of symmetry. Surprisingly, there were equal positive and negative comments in several areas emphasized in class. This included mesh refinement, clarity in presenting modeling choices such as loading boundary conditions, and describing attempts to optimize for weight. Finally of concern, some students introduced stress concentrations in their design without considering the effects on fatigue performance.

Student feedback for the course and the project was fairly positive overall. However, about half of the students left comments to the effect that they still needed more and earlier instruction in SolidWorks, particularly to help with the project. One student captured this sentiment as follows: "The Accuride project would be a great project if we had more knowledge of SolidWorks prior to receiving it. At first, it seemed as if we were blindly cutting to reduce weight based on the model alone and not by intuition." On one hand, students have a somewhat naive expectation that classroom instruction can provide the intuition that is only possible with practical experience. The mistakes they made during the project are part of the learning experience. As an example, a student who fielded tough questions about fatigue concerns for his design, will likely not forget about the effect of stress concentrations in the future. However, their recommendation is not entirely invalid in that we have been wrestling with the balance between theoretical and practical knowledge since the course's inception. To address this issue, topics in the course were reorganized to introduce students to the software (SolidWorks) and finite element modeling techniques (Mesh refinement & Stress Concentrations) starting in the second week. In addition, assignments and exam questions that assess students' understanding of modeling decisions were included.

A few changes were made in the Spring 2017 offering to improve the overall project experience. First, students were given simulation assignments early in the semester to help develop skills that

they would need for the project. This included assignments that illustrated the implications of stress concentrations, mesh convergence & symmetry. In addition, students were shown how to use split lines and cylindrical coordinate systems to apply non-uniform loads. We invited an Accuride engineer for an intermediate review of student simulation for the base model. This provided an opportunity for students to assess their boundary conditions. For example, students had to report reaction forces at the constraints and maximum stress and displacement at a key location. In particular, verifying the reaction forces revealed misunderstanding regarding how applied loads were interpreted by the software. This review allowed students the opportunity to make corrections before optimizing wheel geometry. The overall presentations improved as a result of these changes. Since almost all students had appropriate boundary conditions, reviewers could focus on the students unique approaches to the geometry optimization process.

Conclusions

Overall, the first iteration of the Accuride project has been successful. Students enjoyed the challenge and competition of designing and analyzing a real product for a real company. They gained experience in presenting their work and defending their decision making process. Our industry partners appreciated interacting with students, gained insight into the analysis processes and approaches that someone relatively new to the field might bring to their product design. Finally, the faculty developed ideas for improving the class to help students succeed in these projects - and eventually in their careers. The faculty also gained an understanding of what industry partners are looking for in graduates of the program; specifically the skills that students need coming out of the finite element class.

The project advances the overall pedagogical goals for the course, particularly in improving engineering judgment and modeling, and developing competency in using and interpreting results from software. The project also enhanced student's grasp of foundational topics in engineering. The major benefit of a project like this one is that it forces students to synthesize a variety of concepts in order to make sound engineering decisions. In addition, the project provided insight into the intersection of coursework with an real world industrial application. Finally, the opportunity for students and industry professionals to interact provided a mutually beneficial experience. Students gained practice in professional communication and design. Meanwhile, the industry professionals were able to contribute to the development of potential future employees.

Acknowledgments

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