Adding a Simulation Module to a Primarily Experimental Mechanical Engineering Course

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Abstract

This study reports on addition of a simulation module based on Finite Element Analysis (FEA) to Mechanical Engineering Materials and Laboratory course at University of Hartford. The study addresses two topics: (1) mastering different levels of knowledge with the help of simulations, and (2) honing new simulation skills. The course has a weekly lab session where students perform various materials testing such as tensile, shear, bending, and impact. The lecture portion deals with the theories behind materials' formation, bonding and how those relate to the material properties. In the recently added simulation module, students were assigned projects to simulate the mechanical testing procedures performed in the lab. The simulations were done using Abaqus Unified FEA software.

The main goal of this study was to assist students with the learning process. Students gained deeper understanding of the material properties and the materials' changes resulting from various testing procedures by simulating the influence of relevant parameters and using visualizations. The other goal was to familiarize students with modern computational tools for solving engineering problems. The importance and value of this approach is in the use of industrial software early in the curriculum, as well as helping fulfill ABET student outcome (k). Students were also required to compare their simulation results with the experimental data, and discuss the potential sources of variations. Objective was to improve students' analytical skills and decision making in design problems.

Students' achievement was assessed by the project deliverables: status report, oral presentation and final report. Additionally, a survey was conducted on effectiveness of the simulation project in developing students' simulation skills and learning mechanical engineering concepts.

I. Introduction

While use of advanced design tools and software is deemed imperative for engineers in both research and industry settings, acquiring these skills is not typically embedded in the undergraduate curriculum. Some students may choose relevant professional electives; however, for majority, a steep learning curve is required to grasp and master the skills required for engineering career or graduate school [1]. There also exists a gap between the concepts and theories students learn, and the real life applications of those concepts [2]. The use of modern computational tools can be effective in bridging that gap in engineering education. This study describes a finite element analysis (FEA) approach to teaching and learning concepts of solid mechanics.

FEA has been incorporated in teaching of solid mechanics subjects for over a decade. Choudhury *et al.* [3] reported on utilizing simulations for teaching beam deflection theories. They suggested that the visual input from the graphical simulation draws students' attention towards the underlying cause of deflection and eventually, a deeper understanding of the theory. Use of FEA in analysis of mechanics of materials concepts was also investigated by Navaee and Kang [4]. Some of the examples included analysis of axially loaded members, beam bending, combined loading, and pressurized vessels. In a recent study, FEA based simulations have been employed in a mechanical behavior of materials class to study the fatigue responses of materials [3]. Application of simulations has also been reported in materials science laboratory courses in support of understanding material macroscopic responses to atomic-level changes during tensile testing [4]. The need for increasing FEA content of engineering programs has also been indicated by other researchers in engineering education [5]. In fact, integration of advanced tools into classroom is recommended and endorsed by the National Research Council report, *How People Learn*, as a means to support student learning [6, 7].

The focus of this research is Mechanical Engineering Materials and Laboratory, which is a sophomore level course offered by the Department of Mechanical Engineering at University of Hartford. The course includes a lecture module where students learn about the theories behind materials' formation, bonding and how those relate to the material properties, and a lab module in which students perform various materials testing such as tensile, shear, bending, and impact. The current study reports on the impact of a recently added simulation module where students were assigned projects to simulate the mechanical testing procedures performed in the lab. The simulation project was done using FEA in Abaqus software. It was the first time at authors' institution that: (1) FEA was applied this early in the curriculum; and (2) theory, experiment, and simulation were coupled.

The goals of this FEA-based simulation project were to: (1) assist students with the learning process; (2) familiarize students with simulation tools that are highly relied on in industry and research centers; and (3) enhance students' analytical skills by requiring them to compare their simulation results with the experimental data, and discuss the potential sources of variations. Students gained deeper understanding of the material properties and the effect of various testing procedures on material behavior by simulating the effect of relevant parameters and visualizing the results. The project design was based on the following teaching strategies:

1- Team learning: Students formed groups of 4 as the simulation project collaborators. The role of instructor was mentoring the students to facilitate learning, rather than controlling the learning path. This resulted in a student-centered teaching environment, which according to the literature boosts students' self-confidence and helps them develop communication skills [8].

2- Scaffolding: Scaffolding in education refers to a variety of instructional techniques applied to progressively enhance students' understanding, and move them towards greater independence during the learning process. Scaffolding techniques have been implemented by educators for decades in various disciplines [9-14]. This pedagogical concept is rooted in learning theories of Vygotski which states that learning development is enabled by interaction with stronger members of the same culture, either stronger students, or the teacher. An important aspect of this theory is that assistance is only provided at times of encountering difficulty and where needed. Another fundamental component of the theory is that help must be eliminated when no longer needed. According to Vygotski, many times students will be at the verge of understanding a concept and a minute amount of help from peers can lead to a breakthrough, this is what he defines as the state of “proximal development” [15, 16]. This will gradually enhance students’ level of independency throughout the learning path.

The scaffolding strategy implemented in this study was breaking down the simulation assignment into smaller steps, from the sketch, to visualization, and checking on students’ progress at the end of each task. Upon facing difficulty students sought help from other members of the project team, or the instructor. Project deliverables were also turned in two steps, a mid-semester status report to demonstrate their modeling results at the end of accomplishing all subtasks, and end-of-the-semester group presentation and final report to elaborate on the modeling development from scratch, simulation results, and comparison of simulation results against those from the experiment.

II. FEA Modeling

Adopting simulations for design and manufacturing leads to optimized designs in shorter times with reduced costs. For this reason, companies and research centers are increasingly relying on simulations for their design and analysis. As a result, learning simulation skills better prepares students for job market requirements. In this study, students were assigned simulation projects that incorporated FEA.

Abaqus, a software suite for FEA and computer-aided engineering, was used for the simulation project. Model creation followed the typical guidelines: defining problem including simplifying assumptions, identifying global constants and expressions, constructing physical geometry including symmetries, specifying material properties and assigning those properties to the geometry, defining the involved interactions between components of the system, setting boundary conditions and the applied loads, meshing the physical structure into finite elements, initiating solver, and post-processing the results. Model verification was performed to ensure proper convergence, and validation was done against the experimental results [9].

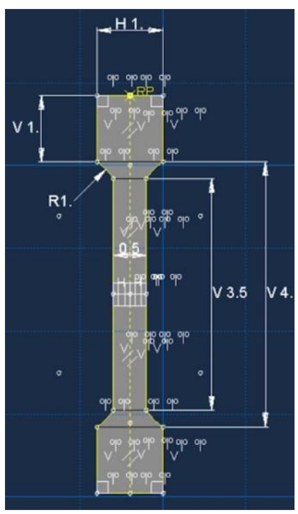
III. Implementation Process

Each student group was assigned a project to simulate one of the materials testing procedures previously done in the lab. Topics covered (1) tensile testing of ductile materials, (2) tensile testing of brittle materials, (3) torsional testing of ductile materials, and (4) torsional testing of brittle materials. Virtual test samples had the same geometry, dimensions, and material properties (including elastic and plastic mechanical properties) as their experimental counterparts. The boundary conditions were specified to match the experimental test setup.

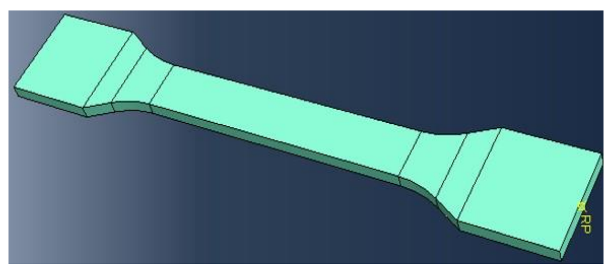
To facilitate skill-building while dealing with the new software interface, students were given: (1) an in-class demonstration of one simulation (cantilever beam bending test) to familiarize them with the software interface and functions, and (2) online resources on mechanical testing of structures such as videos by Abaqus Simulia. Students were checked in for successful modeling steps, otherwise support was only given when asked for as part of the scaffolding strategy.

Two deadlines were set for the project: (1) mid-semester status report, (2) end-of-the-semester group presentation and final report. The status report requirement was to demonstrate a working model with results. Students were provided with feedback if certain steps needed modifications. The requirements for final report were posted online, together with instructional videos on data visualization and export. Students were to record all necessary modeling steps and illustrate them with relevant screen snapshots, data visualizations, and lastly correlations between the simulation and experimental results. Before submission of the final report, student groups presented their projects and received feedback. The feedback had to be incorporated into the final report before an online submission.

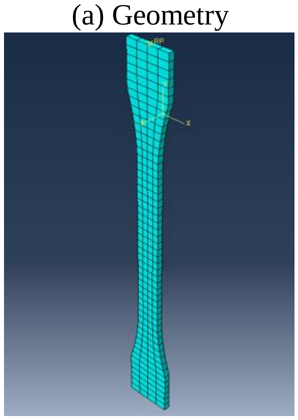
Samples of students' modeling work and comparison between simulation results and experiment are shown in Figs.1-3. Figures 1(a)-(d) illustrate modeling steps: geometry, material properties, mesh, and boundary condition. Prior to meshing, the part was partitioned to help facilitate a finer mesh, and ultimately a higher solution accuracy. Students were directed to perform mesh size analysis and mesh size convergence, and choose a balance between accuracy and computing time. Element quality verification was also performed using the element quality tool in Abaqus. Stress singularities such as stress at notch tips or corners were not relevant for this study. The boundary conditions were selected such that they best represent the experimental setup.



(a) Geometry



(b) Material Properties


(c) Mesh

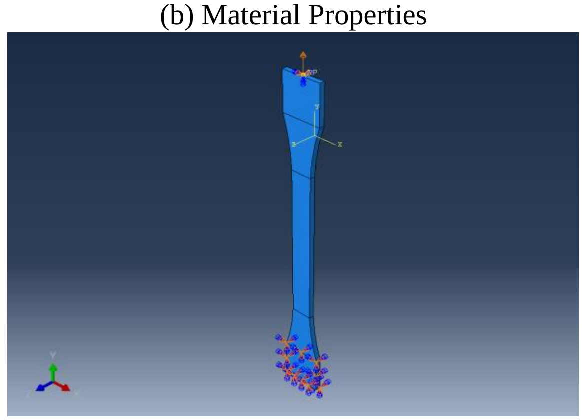
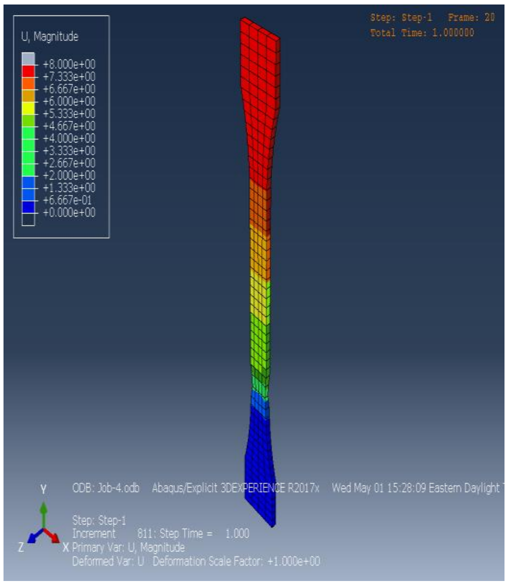
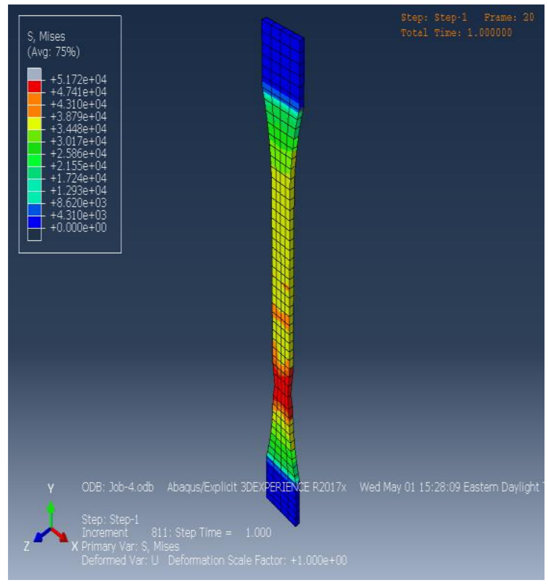

(d) Boundary Conditions

Figure 1. Tensile testing modeling steps

Figures 2(a)-(b) demonstrate the deformation and stress distribution results. Simulations allow finding the deformation and stress levels at every point in the material, whereas the experimental results indicate the bulk behavior of the material only. Students can explore various loading conditions and visualize their effects on the specimen, and develop deeper understanding of the theory. Such exposure to simulations in a specific project environment in an early fundamental course is shown to better prepare students for future course projects, research projects and engineering practice [17].



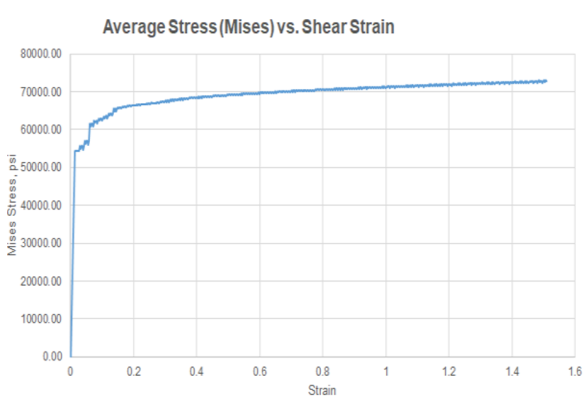
(a) Deformation contour plot



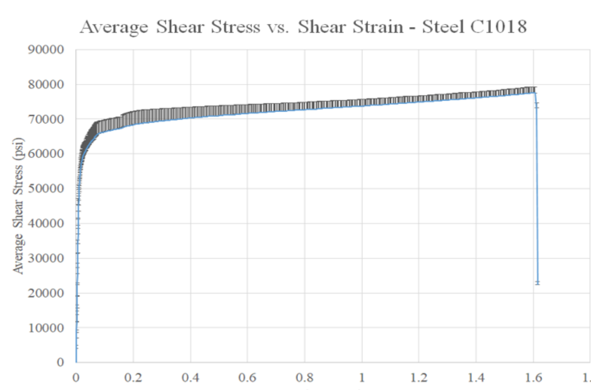
(b) Stress distribution contour plot

Figure 2. Tensile testing contour plots

Stress-strain diagrams of a steel torsional rod obtained from simulation and experiment are shown in Figs. 3(a) and (b), respectively. In stress-strain diagram of Fig. 3(a), Von Mises stress criterion was assumed to be a safe consideration for a ductile material's 3D stress elements. In Fig. 3(b) stress was calculated using the experimental force data and the shear stress equation on the surface of a circular shaft.



(a) Simulation stress – strain plot



(b) Experiment stress – strain plot

Figure 3. Torsional testing stress – strain plots

Excerpts from students' final report focusing on data analysis and synthesis are given below. They are followed by instructors' observations.

"Simulation vs. Experimental Similarities:

Some similarities of the experimental vs. simulation are as follows. For one, the main deformation modes and patterns of the rods were the same. The rods twisted and deformed along their rotation axis, but did not deform much outside of twisting until fracture. The similarities in the stress vs. strain graphs of the simulation and experimental results reside in its shape and the values extracted from the data….

Simulation vs. Experimental Differences:

Despite the simulation being an excellent representation of reality, there are some major differences between the simulation and the actual experimental results. One of the biggest differences between the experimental results and the actual results was that the load in the simulation was applied at a concentrated point in the middle of the end of the rod. This was done in order to simplify the simulation process, but was not the best representation of reality…."

Students discussed the similarities between the simulation results and experimental data, as well as input requirements allowing acceptable accuracy. They also noted the differences and explored the potential sources of variations. Analytical solutions were not required due to the complexity of material behavior beyond yield point. Additionally, for normal forces applied at the end of the member, the distribution of stress requires mathematical theory of elasticity which is beyond the scope of a sophomore level course.

Students' discussion clearly indicates that correlations of results between various approaches promote students' critical thinking and problem solving skills. These are essential skills to develop prior to entering the workforce or graduate school, where analyses of results from multiple approaches and decision making are highly demanded.

IV. Outcome Assessment

Project deliverables (status report, group presentation and final repot), each provide data on specific skill set areas summarized in Table 1. Status report and oral presentation of the final report were followed by qualitative feedback in the form of comments, and students were expected to incorporate the feedback and improve the quality of their work.

Table 1. Project deliverables and skill area

	Project Deliverables		
Skill Area	Status Report	Group Presentation	Final Report
Modeling Proficiency	✓		✓
Written Communication			✓
Oral Communication	✓	✓	
Teamwork	✓	✓	✓
Analytical Thinking			✓

Students were surveyed on the usefulness of the project in: (1) developing their simulation skills; and (2) learning mechanical engineering concepts. The fall 2019 survey results indicate that all of the students either agreed or strongly agreed with both statements. This project was also administered in Spring 2019 for the first time, and 85% of the participants either strongly agreed or agreed that applying simulation methods for understanding mechanical engineering concepts is useful. There have been 53 project participants in total. Following are some excerpts from students' comments in the simulation project survey: "Clear understanding of failure of materials in real life conditions, and visualizing the internal response that each section of material goes through before failure. It wasn't possible to know this by experiment, as only the overall material behavior is available in experiment."; "Good introduction into 3D material modeling and FEA, as modeling skills is extremely helpful for future jobs."; and "Experiencing trouble shooting process, and learning a new way of looking at the tests performed during the lab. Solving unexpected problems creatively."

Conclusion

This paper reports on addition of a FEA-based simulation module to a primarily experimental mechanical engineering course. Each student group was assigned a project to simulate one of the materials testing procedures previously done in the lab. Topics covered (1) tensile testing of ductile materials, (2) tensile testing of brittle materials, (3) torsional testing of ductile materials, and (4) torsional testing of brittle materials. The simulation module was designed to bridge the gap between the theoretical concepts, limitations of experimental testing, and the complexity of practical applications. In addition, it is familiarizing students with digital technology skills that are highly relied on in industry, as well as helping fulfill ABET student outcome (k). Team-based learning and scaffolding were integrated to this module as part of the teaching strategies.

Overall, adding simulations to a fundamental mechanical engineering course helps illustrate and explain some of the complex and important mechanics principles and concepts. The capability of simulations in demonstrating the internal response of each point in the material to loading and visualizing the influence of relevant parameters, assists students with more in depth understanding of failure mechanism of materials. Additionally, the visual attractiveness of the simulation results generates student interest in the subject matter. Other learning outcomes of the new course module include: building technical skills valuable for career preparation, exploring new avenues of problem solving once faced difficulties, and developing analytical thinking by connecting multiple learning approaches: theory, experiment and simulation.

Acknowledgement

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