



# **Work in Progress: Sustained Implementation of FEA in an Undergraduate Solid Mechanics Curriculum**

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While modeling and simulations are taught in upper-level and elective courses, a typical engineering undergraduate curriculum does not contain consistent integration of simulations. In a previous study, the author has advocated for early exposure of mechanical engineering students to FEA in a sophomore-level solid mechanics course to improve students' understanding of the subject matter. This study reports on the continued implementation of FEA in a junior-level Machine Design class to leverage the full potential of available advanced tools throughout the undergraduate curriculum. Simulations can be particularly useful where a physical lab does not accompany a theoretical course, as is the case for Machine Design course at University of Hartford. This is a valuable opportunity for students to build career preparation skills, specifically, since FEA is commonly used in industry for machine element design to understand the interplay between machine elements and how to implement them in complex systems. The simulation project of this study is assigned to students after the theoretical concept and practice problems have been covered on the deflection topic. Students will then perform model setup and analysis of deflection simulations. Later in the semester, when failure criteria for static loading for ductile and brittle materials are covered, students are asked to discuss their simulation results with respect to an accepted failure theory for the selected material. This facilitates the development of students' critical thinking skills by making connections between theory and simulation, and illustrates some of the fundamental mechanics principles and concepts.

### **1. Introduction**

Advanced computational tools provide a powerful resource to address the need for learning through real-world concepts. Computational simulations offer an interactive learning tool for students to explore various concepts, test ideas, and receive feedback [1]. The use of computer simulations as a learning aid in higher education is growing rapidly and has become a major trend in undergraduate engineering education [2]. On the subject of machine design, textbooks have been continually updated to include instructions on current technology and modern computational tools. Specifically, there is a chapter in most textbooks that address finite element analysis (FEA). However, FEA is not commonly incorporated in teaching machine design concepts. More recently, engineering educators argue that FEA can be applied to better understand the interplay between machine elements, and conversely, the content of machine design can be utilized to enhance students' FEA skills [3]. To this end, significant efforts have been made in incorporating FEA-based simulations into teaching solid mechanics and machine design concepts [3-5]. However, the need for increasing the FEA content of engineering programs has been indicated by researchers in engineering education [6].

In a previous study, the author has advocated for early exposure of mechanical engineering students to FEA in a sophomore-level solid mechanics course as an attempt to improve students' understanding of the subject matter. This study reports on the continued implementation of FEA in a junior-level Machine Design class. Simulations can be particularly useful where a physical lab does not accompany a theoretical course, as is the case for Machine Design course at

University of Hartford. This high-impact approach can be implemented without sacrificing the theoretical contents of the curriculum by taking advantage of online support materials.

The ultimate goal of this research is sustained integration of learning and discovery with modern computational skills. From a broad perspective, this study is aimed to promote the three distinctive learning objectives in Bloom's taxonomy: Cognitive, Affective, and Psychomotor, by leveraging simulations in teaching and learning.

The first and most significant impact of simulations is on the cognitive domain with emphasis on the key levels of thinking.

1. Remembering: In the first stage of Bloom's taxonomy, you might ask students to recite something you've taught them, quote information from memory based on previous lectures, read material and notes. In our case, instead of having students sit back and absorb information, they are asked to describe and explain what is happening in the simulation.

2. Understanding: Simulations facilitate visualization of the key concepts, which is directly associated with the 'Understanding' level in Bloom's taxonomy.

3. Applying: Simulation assignments enable students to engage in the solution process, observe changes, and observe the effect of the changes they make. This is directly associated with the application level in Bloom's taxonomy.

4. Analyzing: Along the simulation process, students will experience difficulties that lead them to explore different avenues while making decisions. This will require them to draw connections between ideas and utilize critical thinking, i.e., the key elements of the 'Analyzing' stage in Bloom's taxonomy.

5. Evaluating: Students receive immediate feedback, which helps them make judgments about the simulated phenomena, its validity, and the overall questions at hand.

6. Creating: In the final level of Bloom's taxonomy, the student demonstrates full knowledge by applying what they've learned, analyzed, and evaluated, and building something, either tangible or conceptual. That could include writing a manual or report on a particular topic, designing a piece of machinery, or revising a process to improve the results. In simulation assignments, students submit their simulation files along with a report that includes their process, analysis of results, and conclusion.

The affective and psychomotor domains are added benefits of simulations embedded into instructional delivery and assignments. An analytical approach to problem solving typically results in students having a hard time connecting abstract formulae and mathematical equations to the real world. Consequently, they may not be able to place a value on the covered material and have an adequate appreciation for its application [7]. The psychomotor domain is promoted by students exploring the software capabilities in order to: (1) learn the structure of the software, (2) investigate modeling the problem, and (3) gain simulation skills. Another advantage of embedding simulations in the curriculum is promoting the Accreditation Board for Engineering and Technology (ABET) learning outcome 3: Students should have the ability to use the techniques, skills, and engineering tools necessary for engineering practice.

## 2. FEA Modeling

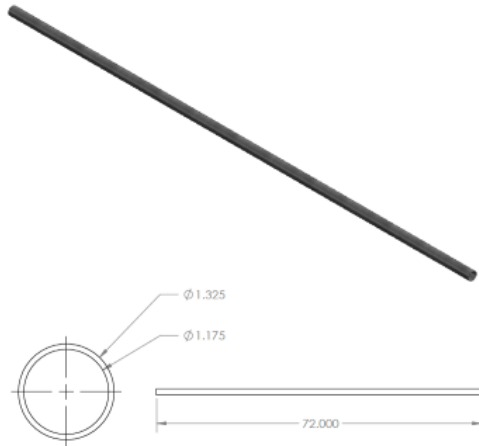
Model creation follows the typical guidelines: defining problems including simplifying assumptions, identifying global constants and expressions, constructing physical geometry including symmetries, specifying material properties and assigning those properties to the geometry, defining the involved interactions 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 is performed to ensure proper convergence. In this project, either Abaqus or SolidWorks, software suites for FEA and computer-aided engineering, is used for the simulation.

## 3. Pedagogical Approach

**Simulation Task:** The simulation assignment described in this paper is cantilever beam deflection under the application of distributed load and point load. The boundary condition for the cantilever beam is fixed support on one end. Each student determines the length of the beam and magnitude of the distributed and point loads based on an application of their choice. Students then select the material type and cross-sectional dimensions of the beam by verifying that the beam can withstand the applied forces. Each student will then finalize their assignment details (load, material, geometry) after discussing their selection procedure with the instructor.

**Instructional Material:** To facilitate skill-building while dealing with the software interface for those who had not had a prior experience of FEA simulation in earlier courses, students were given: (1) an in-class demonstration of one simulation to familiarize them with the software interface and functions, and (2) online resources on mechanical testing of structures by Simulia, (3) an instructor-recorded video to provide guidance on some of the challenging steps of modeling, and (4) YouTube videos to help students with exportation of the results.

**Assignment Delivery:** Before the deadline to deliver the completed simulation job and final report, students had separate due dates, two-three days apart from each other, for submitting the individual **modeling steps** as mini assignments: (1) Geometry, (2) Material Properties, (3) Load & Boundary Conditions, (4) Mesh. Figure 1 shows an example of modeling steps submitted as individual assignments at separate times. The goal here was to assist students with troubleshooting every step before progressing to the next one.



(a) Geometry

Properties	
Name:	Galvanized Steel
Model type:	Linear Elastic Isotropic
Default failure criterion:	Max von Mises Stress
Yield strength:	2.03943e+08 N/m <sup>2</sup>
Tensile strength:	3.56901e+08 N/m <sup>2</sup>
Elastic modulus:	2e+11 N/m <sup>2</sup>
Poisson's ratio:	0.29
Mass density:	7,870 kg/m <sup>3</sup>

(b) Material Properties

Loads and Fixtures

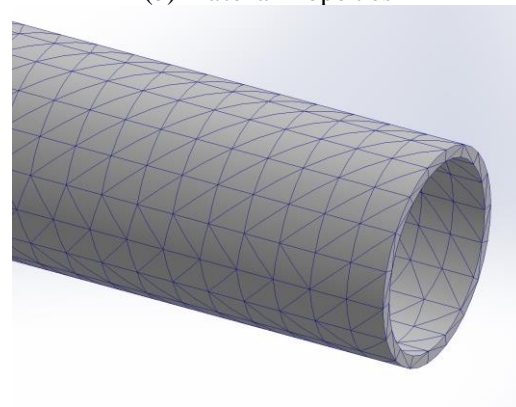
Fixture name	Fixture Image	Fixture Details
Fixed-1		Entities: 1 face(s) Type: Fixed Geometry

Resultant Forces				
Components	X	Y	Z	Resultant
Reaction force(N)	0.00120544	276.044	-0.0175114	276.044
Reaction Moment(N.m)	0	0	0	0

Load name	Load Image	Load Details
Force-1		Entities: 2 face(s) Type: Apply force Values: ..., ..., -6.02926 lbf
Force-2		Entities: 1 edge(s) Type: Apply force Values: ..., ..., -50 lbf

(c) Mesh



(d) Boundary Conditions

Figure 1. Model Information

Upon facing difficulty on any step, students could seek help from each other or the instructor. The instructor then evaluates and provides feedback on students' mini assignment submissions. At the final submission deadline, students submit the completed simulation job and a **final report** which includes the modeling steps (Geometry, Material Properties, Load & Boundary Conditions, and Mesh), with the instructor's feedback implemented, and the simulation results including the stress and deformation contour plots and animations, and stress-stress diagram. Sample simulation results are illustrated in Figures 2 (a)-(c). Then follows a class discussion on the comparison of simulation results and static failure theories. In the future implementation of the simulation assignments, students will also be asked to calculate the beam deflection using the moment area method, compare the results with those of the simulation, and incorporate this comparison in the final report.

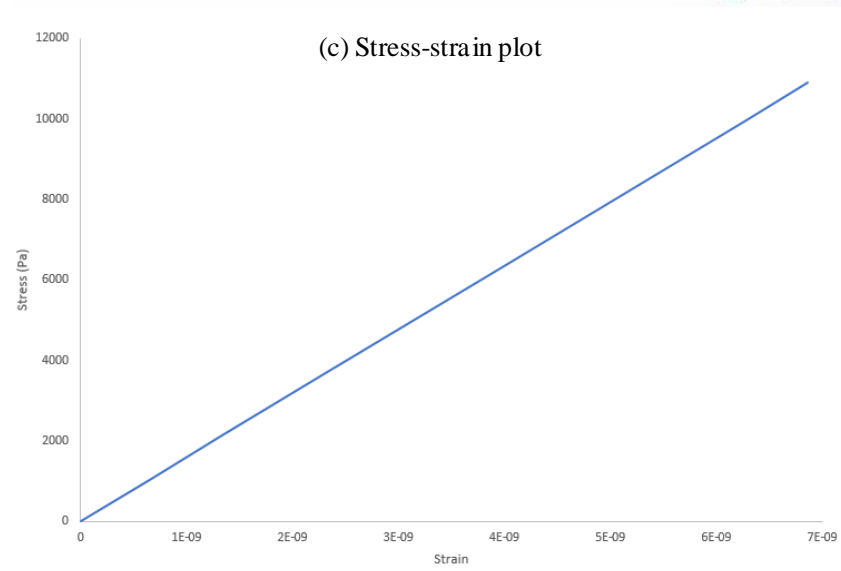
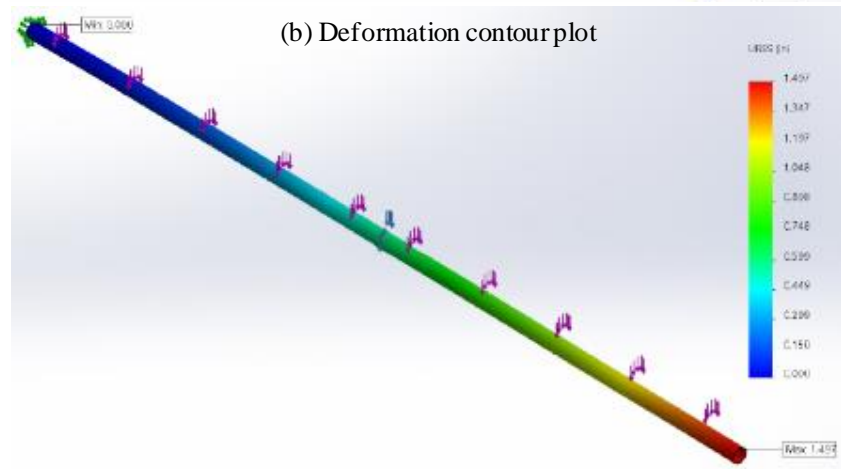
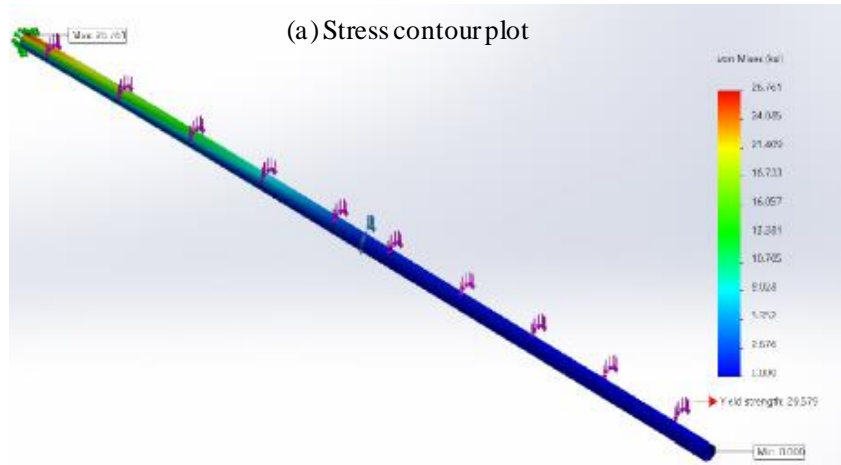


Figure 2. Simulation Results

#### 4. Outcome Assessment

Project deliverables are used to assess three skill areas: modeling proficiency, written communication skills, and critical thinking. Table 1 shows which skill areas each of the deliverables provide data on. Modeling steps submission is followed by qualitative feedback in the form of comments, and students are expected to incorporate the feedback into the final report submission. Final reports are graded by the instructor and used as quantitative measures of students' performance on simulation assignments. On the final report, students' average score was 89.5 out of 100 in Spring 2021, approximately 1% higher than the average in Fall 2020.

Table 1. Project deliverables and skill area

Skill Area	Project Deliverables	
	Modeling Steps	Final Report
Modeling Proficiency	✓	✓
Written Communication		✓
Critical Thinking		✓

Surveys were conducted with the goal of assessing the effectiveness of the simulation. The survey results for fall 2020 and spring 2021 are presented in Table 2. Survey statements addressed (1) learning theoretical concepts, (2) developing simulation skills, and (3) being provided with informative supporting materials. The responses were on a scale of 1 to 5, corresponding to 'strongly disagree' and 'strongly agree,' respectively.

Table 2. Survey Results

Survey Statement	Fall 2020 Average Score (n=9)	Spring 2021 Average Score (n=6)
The simulation project was useful in developing simulation skills	4	4.5
The simulation project was useful in learning mechanical engineering concepts	4.1	4.5
The Simulation project had informative supporting materials [Blog, YouTube, Other]	4.6	4.3

Students were also encouraged to share feedback on their experience with the simulation project. Presented in Table 3 are some excerpts from students' comments. In the right column, the outcome associated with each comment is specified.

Table 3. Open-ended Comments

Students' Comments	Outcome Area
Created a visual understanding of the problems solved in class.	Deeper understanding of the subject matter
What I found helpful about the simulation projects was getting an actual visualization to what stress can do to structures we use.	Deeper understanding of the subject matter
It was extremely helpful to have broken down into multiple assignments, it allowed me to understand the process of completing the simulation better.	Impact of breaking down the project into multiple assignments
Breaking down the project was helpful in directly addressing any issues in completing the entire assignment.	Impact of breaking down the project into multiple assignments
Recommend speaking with the lead instructors for ME 376 and ME 213 for an aligned, cohesive student experience.	Suggestions for improving the assignments

One of the issues observed by the instructor was that for the submission of the simulation results, students were not properly following the steps that were instructed in the online resources. An example is the exportation of simulation results for creating the stress-strain curve. This could be due to the fact that instruction for the exportation of simulation results is not typically included in the in-class demonstration of the simulation interface and modeling steps; thus, it only relies on the online materials. Including a short demonstration of data exportation and visualizations could perhaps result in enhanced quality of submissions.

One area of consideration for future assessment of students' simulation skills is that, after students perform a number of simulation assignments with complete instructional materials, assign them a simulation with a minimal tutorial, but one that can be performed having mastered the points covered in the prior assignments.

For the usefulness of simulation assignments in learning mechanical engineering concepts, one approach to consider in future assessments is giving students a pre-test before performing the simulation assignment on a given concept, and a post-test after the assignment has been completed and the feedback implemented.

## 5. Conclusion

This paper reports on the pedagogical approach and outcome assessment for a case study of embedding FEA in teaching machine design concepts. From a broad perspective, this study is aimed to promote the three distinctive learning objectives in Bloom's taxonomy: Cognitive, Affective, and Psychomotor, by leveraging simulations in teaching and learning. This is a valuable opportunity for students to build career preparation skills, specifically, since FEA is commonly used in industry for machine element design, to understand the interplay between machine elements and how to implement them in complex systems. The simulation project discussed in this study is assigned to students after the theoretical concept and practice problems have been covered on the deflection topic. Students will then perform model setup and analysis



of deflection simulations. Student survey data shows that simulations help illustrate and explain some of the complex and important mechanics principles and concepts, and facilitate building technical skills. Students also provided feedback on how to enhance the assignments for the future.

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