Using Solid Models to Visualize Concepts in Engineering Mechanics

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Abstract

Students often struggle to understand basic concepts in core engineering mechanics courses such as strength of materials, dynamics and kinematics. With professors from these courses acting as project clients, teams of two to four students in an advanced CAD course provided a suite of in- class demonstration tools using either finite element analysis or mechanism simulation. Topics in strength of materials included Saint Venant's principle, Poisson's ratio, beam bending and neutral axis, axial elongation of a tapered shaft, combined loading, superposition, and torsional loading. Kinematics and dynamics demonstrations were based on simulation of dwell mechanisms, cognates, Ferguson's paradox, spherical and spatial linkages, and a double pendulum. The advanced CAD students gained valuable experience in using CAD software simulation tools, but also reinforced their understanding of basic engineering concepts. The faculty teaching these topics will be able to use these new demonstration tools in their core engineering classes in the upcoming semester.

Introduction

Engineering educators have increasingly noted that students lack conceptual understanding of basic engineering mechanics. Students achieve passing grades in their basic engineering science courses by completing problem sets using algorithmic processes, but fail to understand the significance of their calculations, making it difficult for them to apply their knowledge to new situations (Montfort et al., 2009). Educators have developed concept inventory assessments to evaluate student misconceptions in basic mechanics courses such as statics, strength of materials and dynamics (Richardson, 2004), but little work has been done in upper level courses such as kinematics and dynamics of machinery (Canfield, Hill and Zuccaro, 2016). Misconceptions may arise from previous everyday experiences, and are difficult to overcome with traditional lecturing and textbook examples. Educators are currently developing computer simulations and/or hands-on active learning tools to help students overcome these misconceptions (Deliktas, 2011; Fraser et al., 2007; Newcomber, 2015;

Self et al., 2008). Most of this work is focused on introductory courses in physics and engineering science (statics, strength of materials and dynamics).

In spite of these efforts, students still retain deep-seated misconceptions that can hinder their success in upper level courses (Brown et al., 2018). Roman philosopher Seneca proclaimed that *docendo discimus* (“by teaching, we learn”) (Crispo, 2015). By partnering with engineering professors in the basic mechanics courses, students in an upper division CAD course were tasked with preparing visual representations to explain these basic mechanics concepts, thereby enhancing their own understanding of these basic concepts while also providing useful tools for the engineering instructors.

Methods

The Advanced CAD course at WPI is intended for upper division mechanical engineering students who have completed an introductory solid modeling course as well as the mechanics sequence. Many of the students have also taken the kinematics and machine design courses. The course objectives are to improve the students’ solid modeling skills and introduce them to various analysis tools such as dynamic simulation and finite element modeling. Although students use SolidWorks in the introductory CAD course at WPI, the Advanced CAD course is taught using Creo due to its more robust analysis capabilities.

Structural analysis using the FEA simulation application in Creo uses wither part or assembly models from the standard modeling application. Loads, constraints and materials are applied in the simulation application; mesh generation is automatic. Students do not need to understand details of the numerical solution methods or mesh generation to use the package, although some guidance from the instructor is necessary when questions arise or models fail due to problems with selection of constraints and interpretation of results.

Kinematic and dynamic modeling in Creo is relatively straightforward. Assembly models are created in the standard modeling application, but utilize pre-defined kinematic joints. The assembled linkages are then opened in the mechanisms application to apply loads, driver motors, springs, dampers, and other dynamic elements, as well as special constraints such as cams, slots and gears. Interference or collision detection within the analysis is optional, but requires significantly more computation time. The application is capable of analyzing either fully determinate (0 DoF) models, or forward dynamic solutions based on the equations of motion.

Topics suitable for simulation using finite element analysis included simple loading conditions (axial, bending), torsion, combined loads and superposition, St. Venant’s principle, Poisson’s ratio, and stress concentrations. For example, students in strength of materials courses have difficulty understanding the concept of the stress tensor as exhibited by the distribution of forces in bending beams. Typical homework problems involve calculation of bending stresses and displacements, but the scalar values calculated do not provide students with a more holistic view of the tensor qualities of the stresses and the distribution of stress and displacement throughout the beam. Instructors in these courses requested visual images to demonstrate these concepts.

Instructors also asked for dynamic simulations of dwell mechanisms, cognates, Ferguson's paradox, double pendulum and planetary gears. For example, cognate linkages are presented using static images in many kinematics texts (Norton, 2011; Waldron, Kinzel and Agrawal, 2016). Any fourbar linkage has two cognate linkages which generate identical coupler curves, as shown in Figure 1. These cognate linkages can be used in design applications requiring motion along a specific path. The cognate linkage may provide more convenient ground pivot locations, but because the link lengths and driving link are different, the cognate may not satisfy the Grashof condition and/or the velocity of the coupler point along the identical coupler curves differs even though the cognates may be Grashof crank-rocker linkage. Dynamic simulations would enable the students to grasp these differences in linkage behavior.

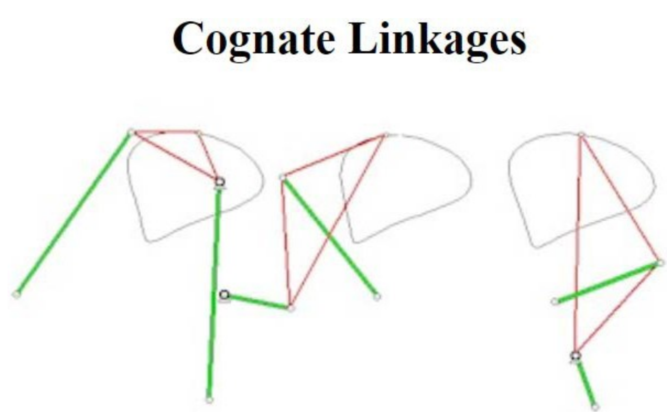


Figure 1. Cognate fourbar linkages with identical coupler curves (blue). The linkage on the left is a non-Grashof linkage. The linkages in the center and on the right are both Grashof crank-rocker linkages wherein the shortest green link can be motor-driven, but have different velocity profiles along the coupler curve (adapted from Ampofo, 2018).

Students were provided with a list of various topics that had been proposed by instructors in the strength of materials, kinematics and machine design courses. Teams of 2-4 students selected one of these topics, consulted with the sponsoring instructor regarding the desired content, reviewed their modeling strategies for the simulation with the CAD course instructor, and prepared a demonstration and course handout materials for use by the sponsoring instructor during the two- week project time frame.

Results – Stress Problems

Five teams each produced multiple FEA simulations to illustrate various classical stress analysis problems which could be found in standard textbooks, and that the instructors had identified as representative of difficult problems for their students.

Even a simple axial loading problem, as shown in Figure 2, holds the potential for significant learning. The CAD students were challenged to identify the proper boundary and loading conditions that would simulate the textbook problem. Whereas the textbook shows a fixed base and point load, when these boundary conditions are applied, the model does not show the uniform stress distribution one would expect from the textbook example. St. Venant's principle is evident in the higher, non-uniform stresses at both the load and base. The simulation requires a combination of partial constraints and free motion in the x, y, and z directions at the ends and a distributed load along a region at the center of the beam. Under these conditions, the model is able to duplicate the textbook example and also shows lateral displacements caused by the Poisson effect. A similar analysis is conducted as a lab exercise earlier in the course, with a compressive axial load at the end of the beam. Results of the lab exercise are shown in Figure 3.

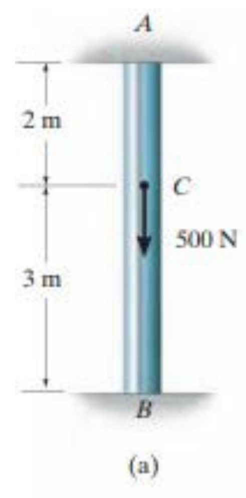


Figure 2. Textbook problem for statically indeterminate axial load (Hibbler, 2003).

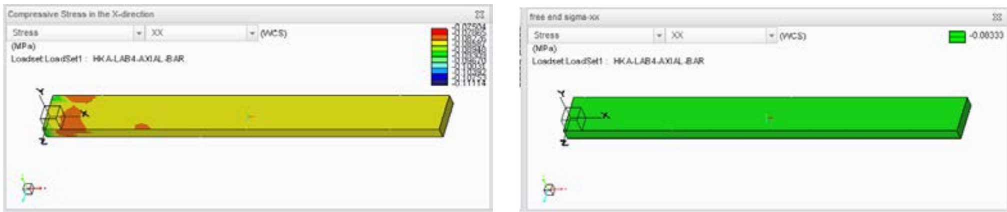


Figure 3. FEA analysis of simple axial loaded beam with fully constrained end (left) and partially constrained end (right). Note that the more complex constraint set is needed to simulate the uniform stress distribution of the textbook example.

More complicated models were used to demonstrate stress concentrations in notched beams (Figure 4). These simulations were intended to accompany physical models made from acrylic that could exhibit the stress bands using a polariscope (photoelasticity).

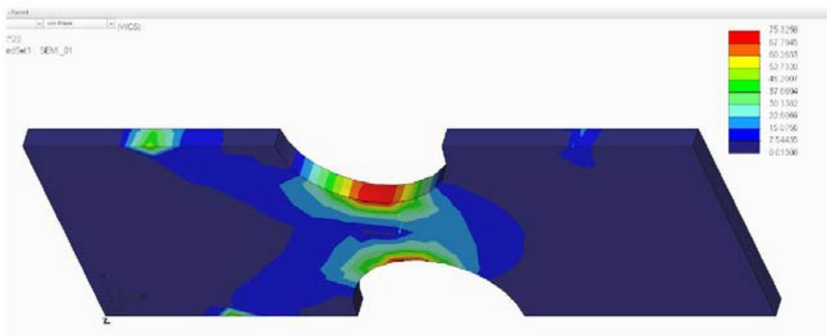


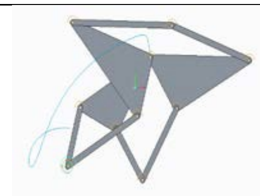
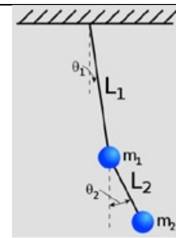
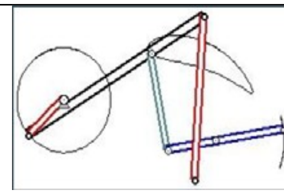
Figure 4. FEA model of beam showing stress concentrations at a notch

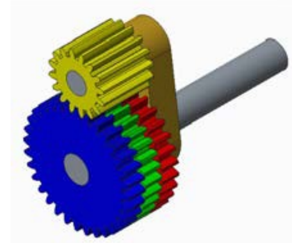
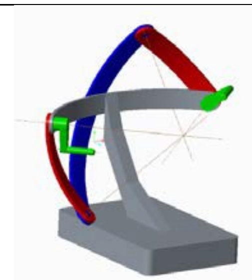
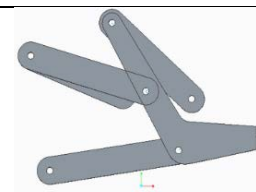
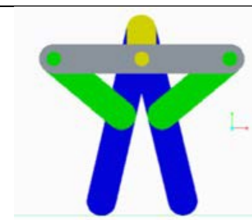
Other student teams studied torsion and superposition. All of the FEA teams prepared a class handout with visuals from the stress analysis for instructor use. Two of these teams also provided animations of the deformed models.

Results – Dynamics Problems

Nine teams elected to create dynamic simulations using the mechanism modeling application in the CAD system. Challenges faced by the students included selection of proper constraints at the connections (joints) between the parts in the assembly, designing Grashof mechanisms that could demonstrate the desired principles, and working with 3D linkages. Table 1 lists student models of linkage and gear mechanisms and materials provided to the instructors. Note that the simulations were used to create videos demonstrating the motions within the mechanism; class handouts also included plots of the kinematic properties such as linear and angular position, velocity and acceleration of various points and bodies.

Table 1. Mechanism models created by student teams in Advanced CAD course

Topic	Deliverables	Thumbnail Image
Cognates	Class handout with Roberts diagrams, two .mpg videos	
Double Pendulum	Class handout, .avi file, working mechanism model for student and instructor use	
Dwell Mechanisms	Class handout, two working mechanism models for instructor demonstrations	

Ferguson's Paradox	Class handout, working demonstration model, video	
Spatial Six-bar Mechanisms (2 teams)	Working models, videos	
Spherical Fourbar	Working model, video	
Stamping Mechanism	Working model, video	
Walking Tribot	Working model, video. This model was created as a research tool for robotics faculty, not for classroom demonstration.	

Discussion

Student response to the selected projects were overwhelmingly positive. Although several teams expressed some frustration with the challenge of duplicating the textbook examples and designing functioning mechanism models, they felt that this was a valuable learning experience. The course objectives do *not* include strengthening their understanding of basic mechanics and machine design concepts. This project enhanced their understanding of the basic principles in mechanics and kinematics, while also providing an opportunity to deepen their knowledge of the simulation applications in the solid modeling system. Some representative comments from their final reports include:

- *This project gave the team valuable experience in conducting finite element analyses as well as provided a useful review in topics of stress analysis.*
- *In this projected we learned an extensive amount about FEA modeling as well as axial loading calculations.*
- *Through this project we were able to practice our finite element analysis skills as well as further improve our understanding of basic stress analysis principles. Visualizing what direction certain components of stress act in is something that is extremely confusing even for students who have already taken (strength of materials). In each loading scenario we had to be mindful of what types of stresses were acting on the beam and what the best way to display them would be.*
- *Overall, our team very much enjoyed this project. All four of our team members became much more proficient using the simulation application.*
- *We come away from this project with a better understanding of how to build, constrain, and analyze mechanisms to accomplish specific tasks.*
- *Overall the project was an interesting way of applying what we had learned in the course and taking it one step further.*

Conclusions

These student comments demonstrate that the use of carefully selected FEA simulations enhances student understanding of concepts in stress analysis. Dynamic simulations of textbook linkage and gear kinematics problems are challenging modeling exercises for CAD students and can be used to demonstrate the behavior of mechanical systems in an engaging manner. Students in the CAD course strengthened their understanding of basic concepts in engineering mechanics and machine design through using the CAD simulation applications. Instructors for the courses in strength of materials, kinematics and machine design will be using the simulations, animations and graphical displays during the upcoming semester.

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