Using Solid Modeling to Enhance Learning in Mechanics of Materials and Machine Component Design

Dr. Edwin M. Odom, University of Idaho, Moscow

Dr. Odom teaches introductory CAD courses, advanced CAD courses, mechanics of materials, manufacturing technical electives and machine component design within the Mechanical Engineering program. He is involved with the inter-disciplinary capstone design program, experimental mechanics, and has participated in several NSF grants one of which formalized the Mindworks learning resource. Professor Odom is a co-leader of the Idaho Engineering Works (IEW).

Dr. Steven W. Beyerlein, University of Idaho, Moscow

Dr. Beyerlein has taught at the University of Idaho for the last 28 years. He is coordinator of the college of engineering inter-disciplinary capstone design course and currently serves as the Department Chair for Mechanical Engineering. Dr. Beyerlein has been active in research projects involving engine testing, engine heat release modeling, design of curricula for active , design pedagogy, and assessment of professional skills.

Using Solid Modeling to Enhance Learning in Mechanics of Materials and Machine Component Design

Abstract

This article reports on a classroom research study about the use of solid modeling as a visualization tool for deep learning of engineering mechanics principles. There is a need for deep understanding of technical content in courses such as Mechanics of Materials and Machine Component Design in order to lay the foundation for robust prototypes in Capstone Design. A typical classroom experience in mid-program engineering science courses involves lecture followed by assigning problems from the text. Associated lecture notes and explanations along with assigned problems and their solutions are in a two dimensional form, i.e., presented as printed output or handwriting on a page. The equations used are also in two dimensional in form, reducing physical behavior to analytical expressions and cross sectional properties to a single value. It is not easy for the beginning learner to visually connect the course content and problems to the three dimensional world. Instead of the desired outcome of interpreting the assigned problem from the world around them, students look to pattern match the figure in the assigned problem to figures or location in the chapter. To provide an opportunity to more fully engage in their learning experience, a series of assignments has been developed where students use skills from their 3-D solid modeling course to conceptualize and even solve mechanics problems. These exercises begin by using a fully defined 2-D sketch to graphically solve static problems. Next, the 2-D sketch is used to determine cross sectional properties, e.g. cross sectional areas, second moments of area, product of inertia, and principal moments of inertia and centroid locations. These results are then compared to the results that were calculated manually. Later 3-D solid modeling is used to model 3-D stress states in support of 3-D Mohr's circle exercises, stress distributions of compound stress states, shapes of optimized beams, and frustrom measurements needed in a bolted connection analysis. The effectiveness of these visualization enhanced assignments has been assessed through pre-course surveys, quality of homework submissions, post homework visitations and post-course surveys.

Introduction

To begin taking classes in the junior year, our students need to be certified, meaning that students need to have substantially finished the first two years earning no more that three grades of D or F while earning better than a grade of C in five courses. Once certified, students can begin the junior year with its emphasis on Mechanical Engineering courses. One thread of the junior year, is a two-semester sequence, taught once a year, on the topics of intermediate mechanics of materials (fall semester) and machine component design (spring semester). The text used is a custom printing of the Shigley and Mischke 5th edition Mechanical Engineering Design[1] (many students find the original online). The first semester covers analytical mechanics while the second semester covers applied mechanics. A result of teaching a junior level 2-semester sequence once a year, is that it substantially defines our senior class one year in advance, allowing for planning of technical electives and recruitment of senior capstone design projects. The educational setting is 2/3 flipped classroom environment where students prepare by reading and working problems outside of class and then work on problems during class and 1/3 lecture for introduction of new subjects and delving into more difficult topics. Class is held twice weekly (M-W 1 hour 15 minutes) with a homework assignment due on Friday.

Sometime ago when class sizes began increasing, we began to assign students, alphabetically, numbers starting at 1 to the number of students in the class. This number is placed in the upper left hand corner of all assignments. This facilitates ordering of papers which are handed in, graded, and recorded individually. This manner of grade entry, provides for a very large data set ($\approx$8,000 entries per semester) which is useful for assessment. After grading, papers are sorted, for each student, for return. The return of papers is at the beginning of class, where the instructor calls out the student numbers, sequentially, with the expectation students will be physically present for transfer. The goal is to return assignments in under 2 minutes. Approximately 5 minutes are then allotted for students to discuss and compare grading while the solutions are put up on the overhead.

Historically, assessment of the efficacy of these courses has included student grades, results from the FE exam, and comparison of a student survey given on the first and last day of class. These measurements have been positive. However, student questions and responses to questions have been troubling. For example, during office hours a student would come in with their book and their question would begin with " I found this equation." Querying students with questions such as "Why would that equation apply to the problem?", "Are there any limitations to this equation?", and " Can you sketch on the blackboard the situation this equation applies to?" resulted in less than satisfactory responses. These experiences lead to an introspection of "What mental image does a student see?" [2,3] Hence, the exploration of using solid modeling to increase student engagement in mechanics of materials and machine component content.

Solid Modeling Enhanced Assignments

The following assignments, outlined in Table 1, have been developed over the last few years for inclusion in the first semester. The first column of the table gives the topic and the solid modeling objective, visualization and/or realization. Visualization is used to communicate the result of the analysis whereas realization indicates solid modeling is integral to the analytical solution. The initial assignments are meant to begin to create a visual link between the foundational concepts in statics/mechanics of materials to solid modeling. Later assignments use solid modeling to directly support the completion of a mechanics of materials solution as well as visualize/add meaning to the solution. The second and third columns indicate the student learning objectives for mechanics of materials and solid modeling respectively. The assignments were harvested from a number of references. Specific details of the analytical solution are not included as each reader may have different approaches.

Seven problems are presented, each becoming more difficult, beginning with statics and ending with unsymmetrical bending and principal stresses and their direction cosines. For each problem there is a brief problem description and a student solution. This is followed by observations about the solution route and the solution.

Table 1
Mechanics of Materials and Solid Modeling Learning Objectives

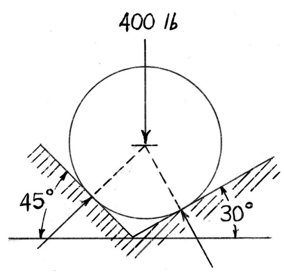
Topic Objective	Mechanics of Materials Learning Objectives: Students will	Solid Modeling Learning Objectives: Students will
1: Statics Realization	draw FBD, use equations of equilibrium, find unknown forces	create a fully defined sketch, define a length to force scale, graphically create a parallelogram of forces, find the unknown forces
2: Area Properties Realization	determine the location of the centroid, calculate moments and product of inertia, principal moments of inertia and angle to principal axis system	create a sketch of the cross section, use the Section Properties Tool to obtain properties calculated using MOM, identify variable name differences and sign conventions
3: Beam optimization Visualization	write a continuous moment equation, determine optimum offset to minimize moment, design beam cross sections	use results from MOM analysis to visualize the design
4: Combined stress state Visualization	determine the bending moments about the x and y axes, calculate the bending stress at the corners of the beam, and calculate a combined bending stress	use results from MOM analysis to visually realize the design
5: Curved Beams Visualization	calculate the bending stress on the inner and outer surface of a curved and the location of the centroid and neutral axis	use results from MOM analysis to visually realize the design
6: Unsymmetrical bending Realization and visualization	use the cross sectional properties and distances to calculate stress at points of interest, define a stress to length scale for visualization	find the centroid, moments of inertia, principal axes, distance from the principal axes system for use in MOM analysis, visually realize the solution
7: Principal stresses Realization and visualization	calculate invariants, find the roots of the characteristic cubic equation and direction cosines	use results from MOM analysis to visually realize the design

Assignment 1: Concurrent forces in a plane: Graphical Statics [4]

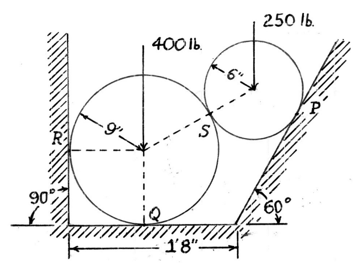
a) A cylinder rests in a right-angled trough, as shown in Figure 1-a. Determine the forces exerted on the sides of the trough at if all surfaces are perfectly smooth.

b) Two cylinders rest in a trough, as shown in Figure 1-b. Determine the forces acting at points *P, Q, R,* and *S.*

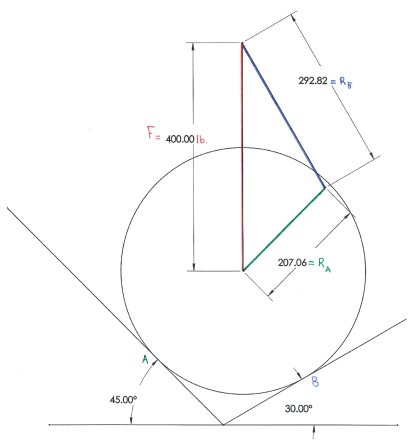
Solve both problems analytically and graphically (solid modeling), using one method to verify the other.



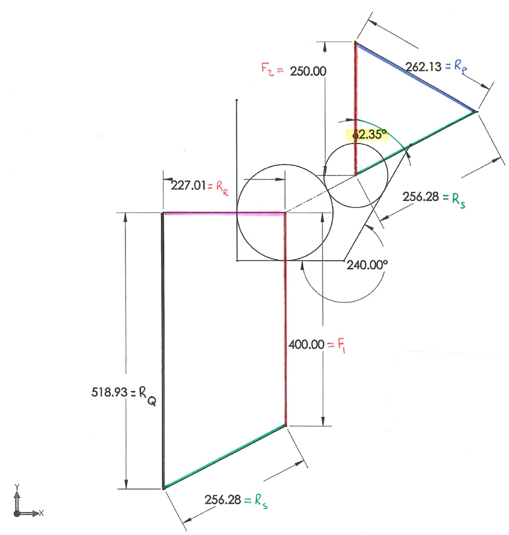
a)



b)



c)

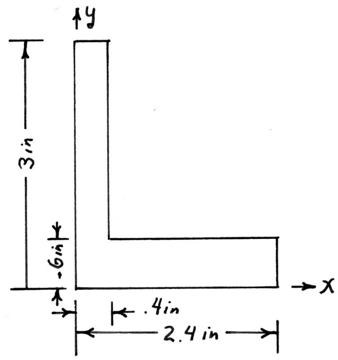


d)

Figure 1 Graphical solution. (Upper figures a) and b) present the problem, lower figures c) and d) show a students solution)

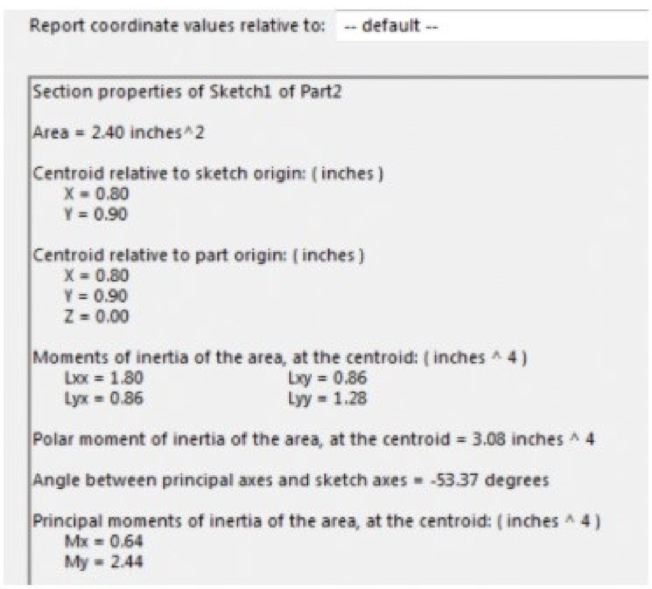
Observations: The problem depicted in Figure 1 a) was assigned first and there was some student questioning of the value of solving the problem graphically. When the problem shown in Figure 1 b) was assigned, the questions changed to is the analytical solution necessary? The analytical solution requires some insightful trigonometry to find the angle of contact between the two cylinders.

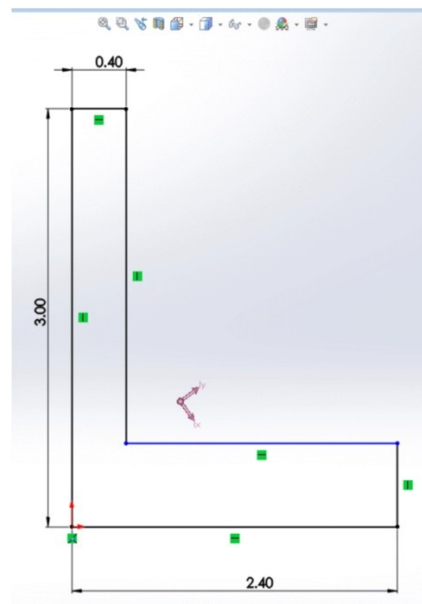
Assignment 2: Cross section properties



For the L-shaped cross section shown, determine analytically and graphically (solid modeling) the location of the centroid, second moments of area (moments of inertia) about the centroid and the product of inertia. Determine the angle to the principal axis system and the principal moments of inertia.

a)





b) c)

Figure 2: Upper figure a) is the geometry of the cross section, lower figures b) and c) are student work.

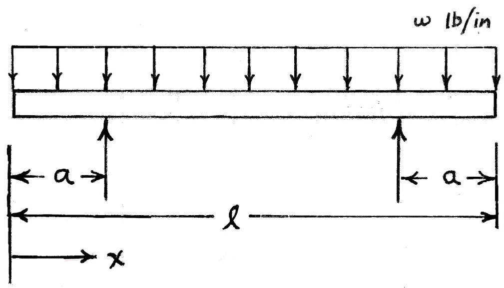
Observations: This is a very straight forward geometry to sketch and the program will calculate the section properties. Students need to interpret the variables. For example the solid modeling program uses L_{xx}, L_{yy}, and L_{xy}, for the moments and products of inertia whereas mechanics of materials typically uses I_x, I_y, and I_{xy}. The solid modeling program reports a product of inertia with a positive sign when it should be a negative. Finally, the solid modeling program reports a -53.37 ° angle between principal axes and sketch axis whereas in mechanics of materials the angle between x-axis and the principal axis X would be the complement to that angle, 36.63°.

Assignment 3: Visualization of Solution (team assignment)

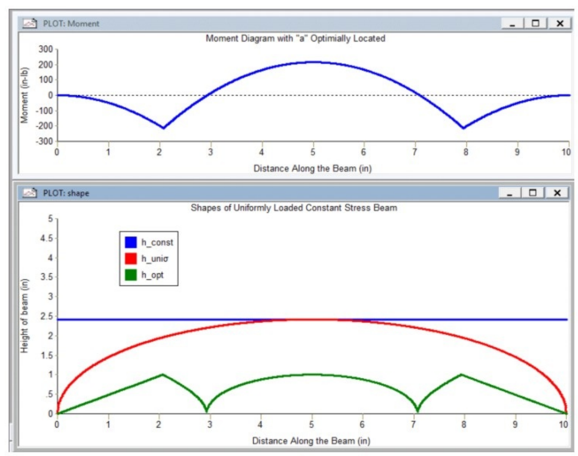
For a uniformly loaded *w* simply supported beam of length *l*, where the supports are offset from the end of the beam by a distance *a*, find the offset distance *a* which minimizes the bending moment. Then with l =10 in, and w =100 lb/in, base of the beam b =.1 in., and a design stress of 12,840 lb/in^2 design three beams,

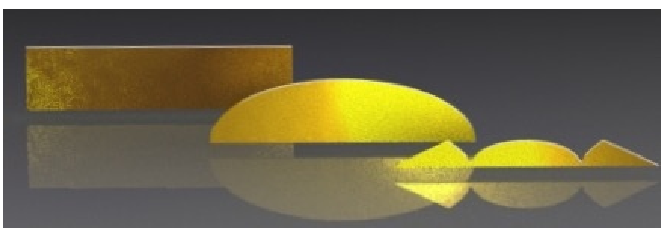
a) simply supported (*a*=0) constant cross section height *h* along the length,
b) simply supported (*a*=0) constant stress, varying height *h* along the beam, and
c) simply supported (*a*= optimum setback) constant stress, varying height *h*

Graphically, show the three designs in a manner that allows for a visual comparison.



a)





b)

c)

Figures 3: Upper figure a) is the beam geometry and loading, b) moment diagram for optimum setback and heights of constant strength beams, and c) visualization of three equal strength beams

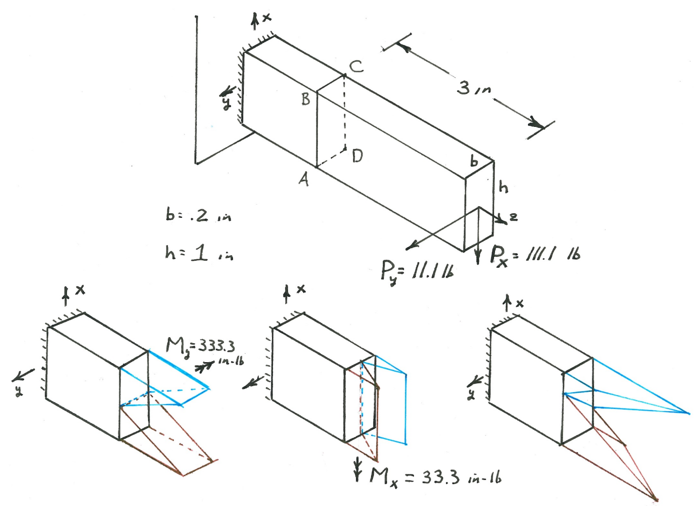
Observations: Using Heaviside step functions the moment equation can be written as:

$$M = -\frac{wx^2}{2} + \frac{wl}{2}(x-a)H(x,\mathrm{a}) + \frac{wl}{2}(x-(l-a))H(x,(l-a))$$

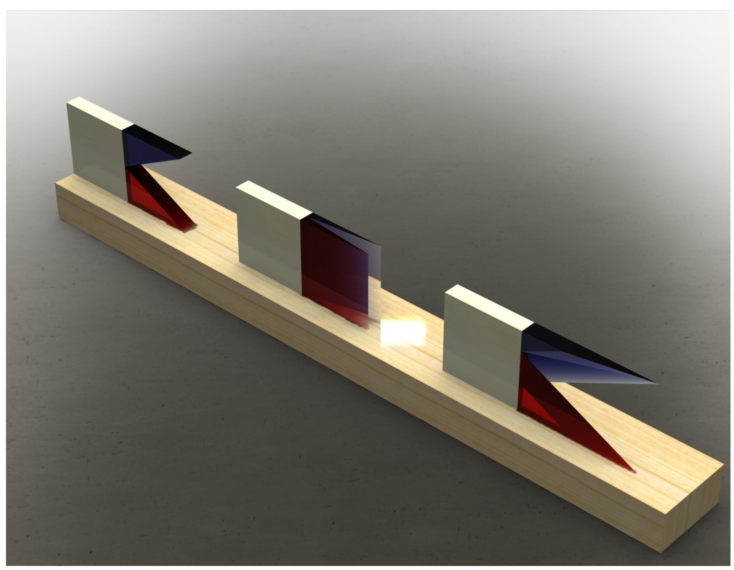
programming. The Heaviside step function *H(x, a)* is equal to zero if $x < a$ and one if $x \geq a$. Once coded students can explore the magnitude of the moment at the supports and the center of the beam for various values of *a* by guess and check, equation solver or by optimization. After finding the optimum setback *a*, beam heights can be calculated for the three designs. (Problem from Shigley and Mischke,[1])

Assignment 4: Visualization of Combined Stress Distributions (team assignment)[5]

For the rectangular cross section beam loaded with a moment M_x about the x-axis and a M_y about the y-axis calculate the maximum bending stresses and their locations for each moment. Sketch these stress distributions. Write an expression for the combined bending stress, verifying it is correct at the four corners of the beam, and then use that expression to determine the angle where the combined bending stresses are zero (the neutral axis).



a)



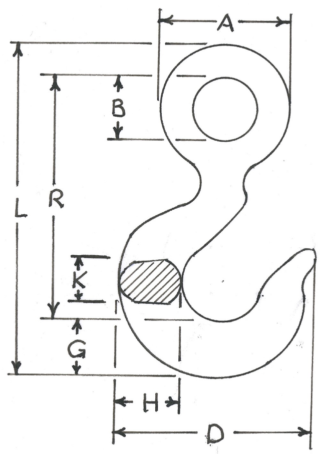
b)

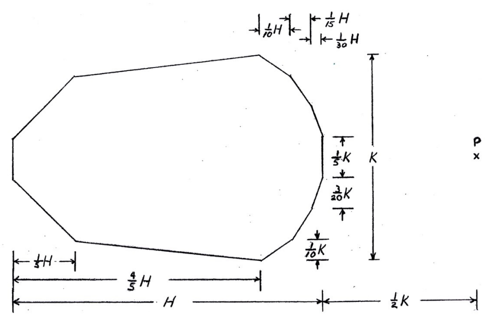
Figure 4: a) Stress distribution hand out and b) students work

Observations: The handout for the class did not include the red and blue lines. These were added in a class activity/lecture. The cross sectional dimensions, moment arm and load were selected for ease of sketching the problem statement and bending stress calculations. The bending stress caused by bending about the y-axis is 10 ksi (scaled as 1in. in the isometric views) and about the x-axis is 5 ksi (scaled as ½ inch.) The blue (tension) and red (compression) lines were added to the problem statement in a class activity/lecture. The combined stress distribution is sufficiently difficult that many students couldn't quite follow along. This set the state for having students use their solid modeling skills to visualize the stress distributions. (Popov [5])

Assignment 5: Flexure of Curved Beam (team assignment)

A practical application of curved beam bending theory is the chain hook. Below is a sketch of a eye hook from the MSC catalogue [6]. A numerically friendly cross section is also provided for determining the location of the centroid and flexural neutral axis. Calculate the minimum and maximum bending stress and plot the stress distribution. By way of solid modeling, visualize your understanding of your solution. (P=15 tons, A=5.34, B=2.84, D=8.37, G=2.59, H=2.94, K=2.19, L=14.05, R=10.21 (in))





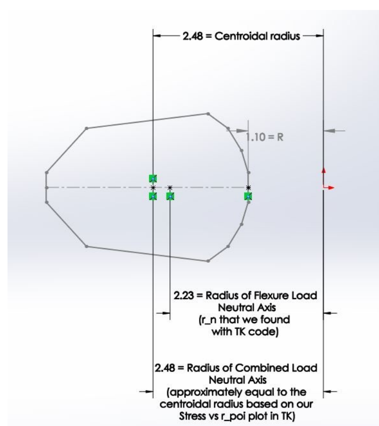
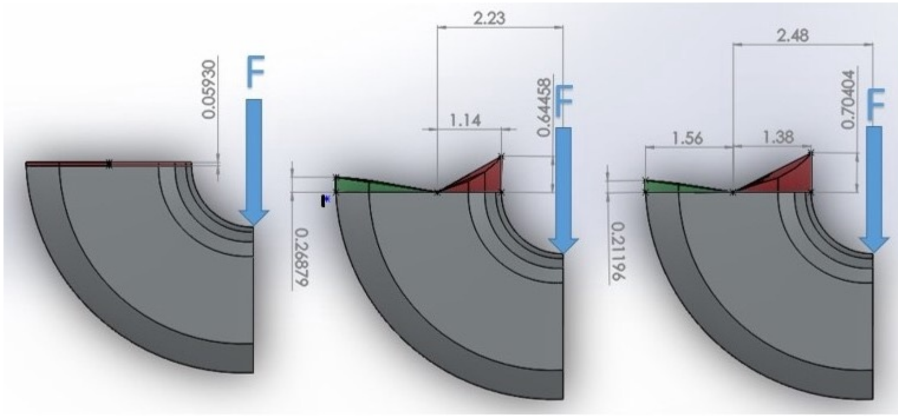


Figure 5 a): Upper figures show the problem geometry while lower figures show one teams visualization of the solution.



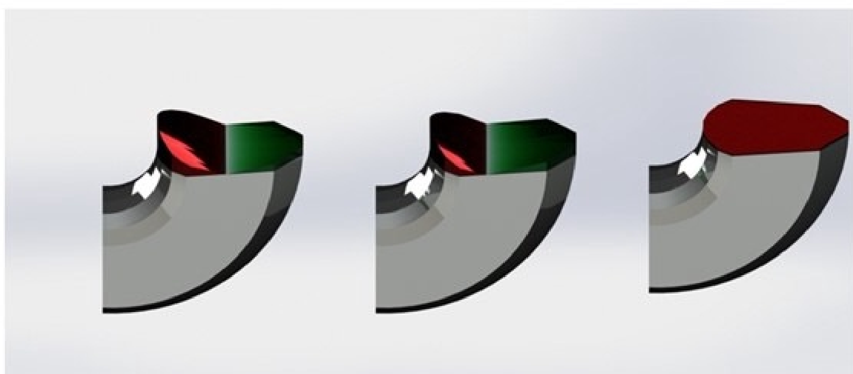
Axial Stress Bending Stress Combined Stress

(Height Dimensions on red and green stress sections X 10000 = Maximum stress created for each case)

(Dimensions from center curve to point of 0 stress = r distance in code for 0 stress)

The Bending Stress seems to be zero at the neutral axis, and the Combined stresses seem to be zero at the Centroid

Stresses created in the hook by the force (Red is in tension and green is in compression)



Total Stress (F/A+MY/(AE(rn-y)) Moment Stress Axial Stress

Figure 5 b) Student team's visualization of the solution. (Note the observation of the location of the neutral axes)

Observation: Calculating the bending stress distribution follows the solution given in Shigley and Mischke [1] which was originally developed by E. Winkler. To calculate the location of the neutral axis *R,* the integral $\int dA/r$ as well as the cross sectional area *A* were determined numerically using Simpson's integration method. The simplified cross section dimensions could be put into a List function in TKSolver. For pure bending, the neutral axis is moved from the centroid inward towards the center of curvature. However, when the axial stress was combined with the bending stress, the neutral axis shifted back to the centroid. This interesting observation was made by multiple student groups. The author had never made that observation before.

Assignment 6: Unsymmetrical Bending (team assignment) [7]

A cantilever beam with a of Z-shaped cross section is loaded at the end by a vertical load *P*= 724 lb. Determine bending stress distribution on a cross section. Compare hand calculations for the moments and product of inertia, principal moments of inertia, angle to the principal moments of inertia, and decomposition of the applied moment into moments along principal axes. Create images showing distances from the principal axes system to the points of interest, stress distributions about individual *X, Y* principal axes and a combined stress distribution.

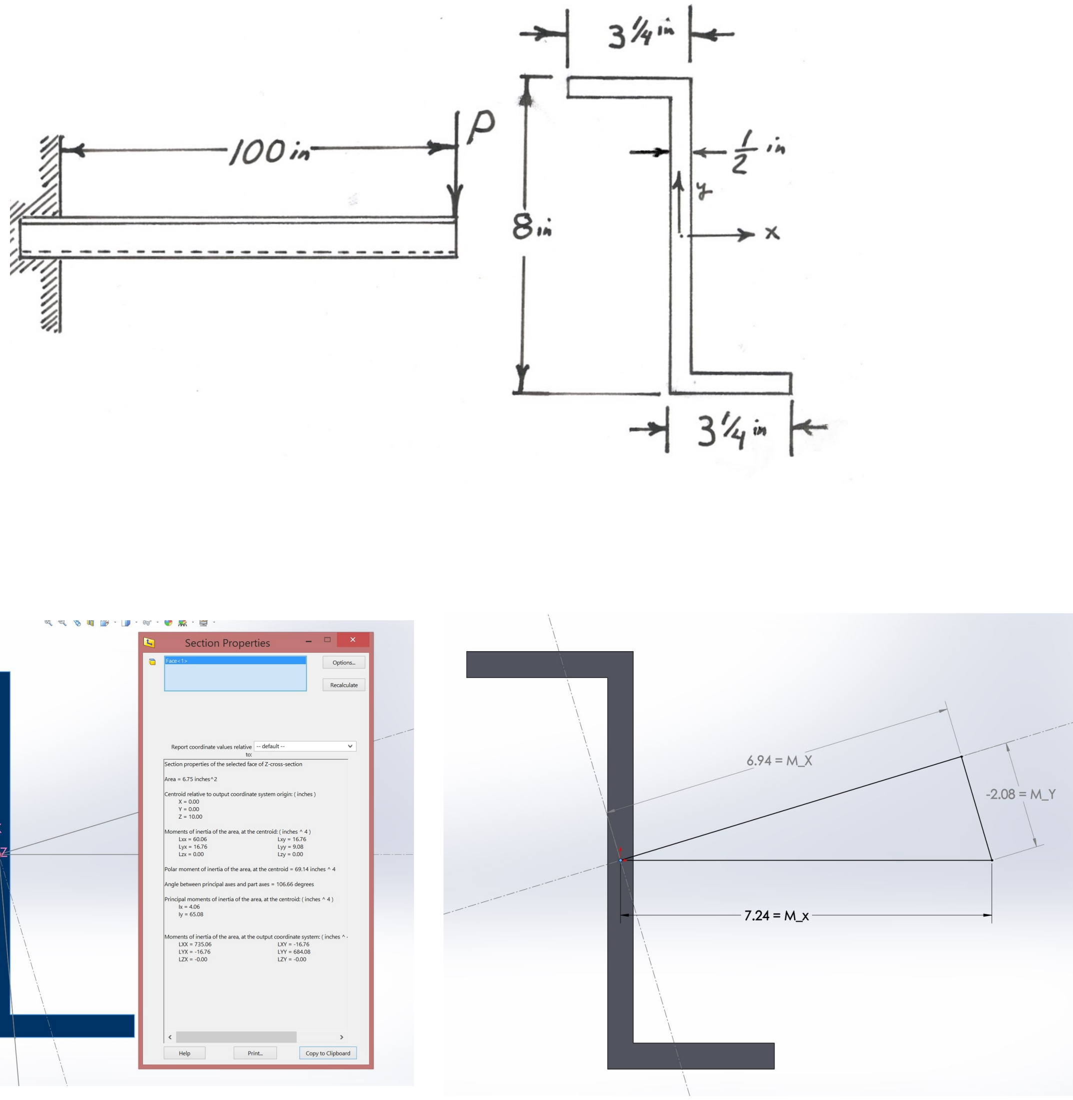
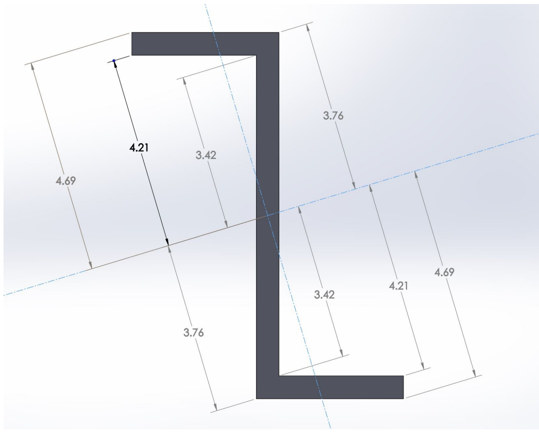
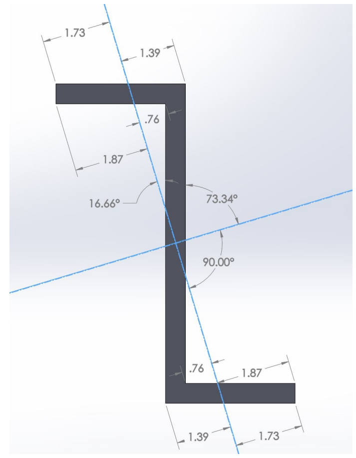


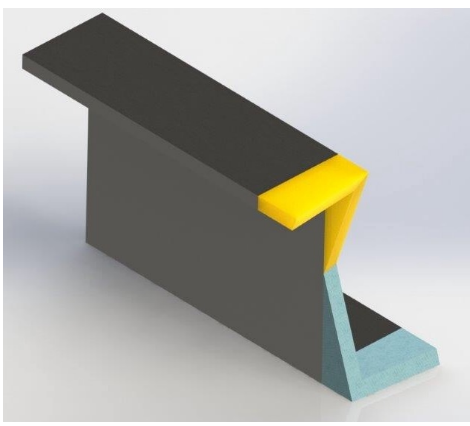
Figure 6 a) Upper figure is the problem while the lower figures are student work to find the cross sectional properties and visually show the moment components acting along principal axes.

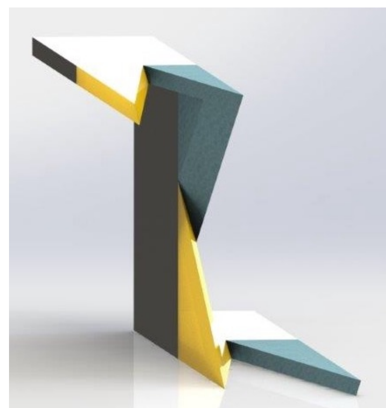




$$\sigma_Z = \frac{M_X Y}{I_X}$$

$$\sigma_Z = \frac{M_Y X}{I_Y}$$





$$\sigma_Z = \frac{M_X Y}{I_X} - \frac{M_Y X}{I_Y}$$

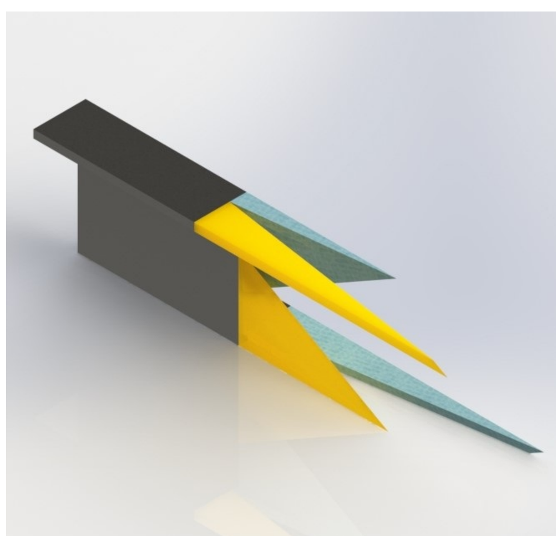
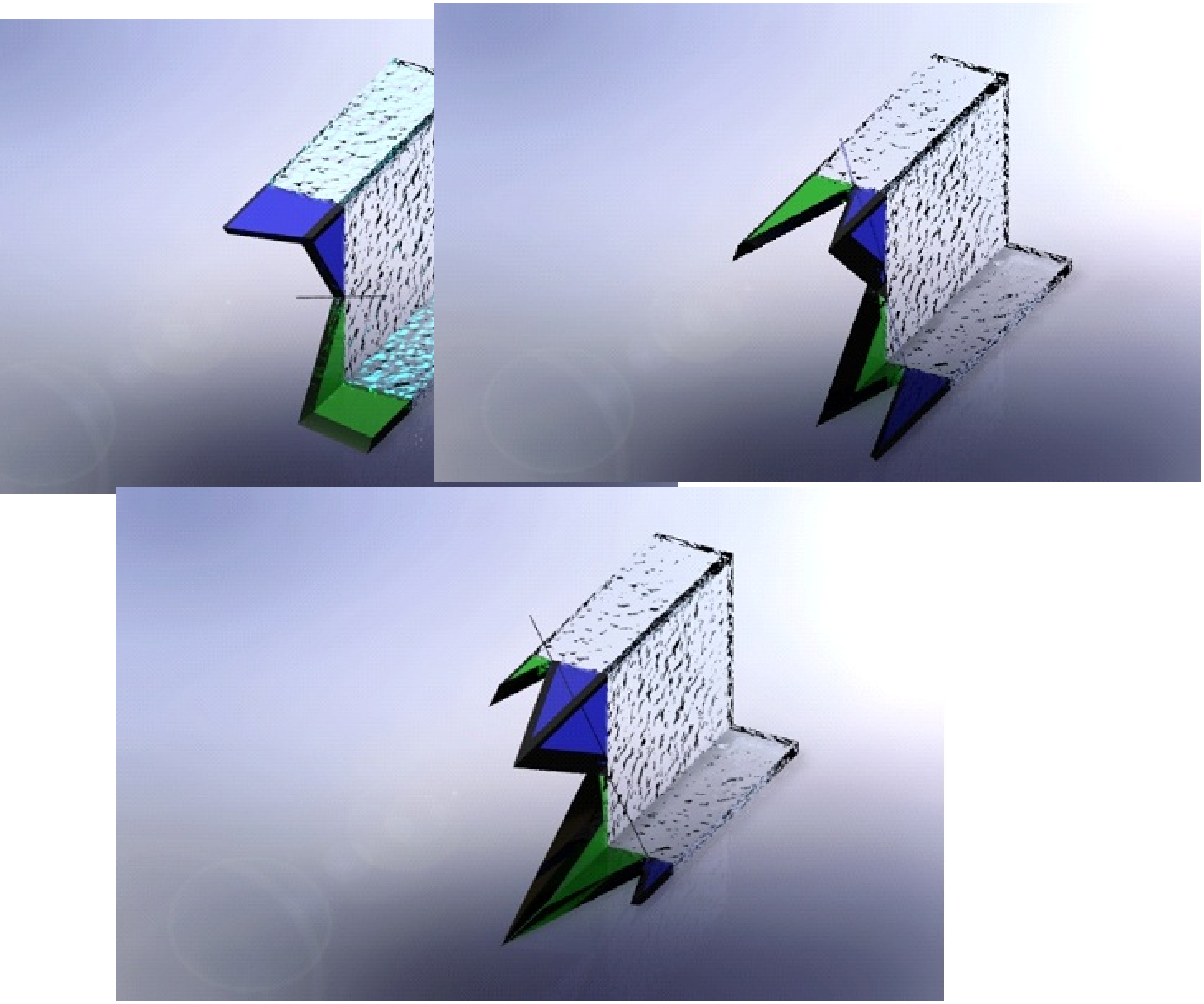


Figure 6 b) Top figures show distance from principal axes, middle figures visualize cross section stress distribution, and the bottom figure shows the combined stress distribution.



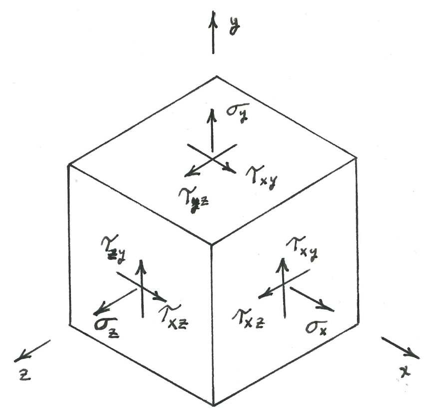
Observations: Using only an analytical approach (graduate level) to find the normal stress distribution results in a relationship:

$$\sigma_z = -\left(\frac{M_y I_x + M_x I_{xy}}{I_x I_y - I_{xy}^2}\right)x + \left(\frac{M_x I_y + M_y I_{xy}}{I_x I_y - I_{xy}^2}\right)y$$

which does not lend itself to visualization of the bending behavior [8]. This relationship could be made numerically straightforward to use by using solid modeling to find the moments and product of inertia (I_x,I_y, I_{xy}) Figure 6 a) followed by the x ,y coordinates of the point of interest from a dimensioned sketch. Visualizing how the bending about two principal axes would still be difficult. By solving the problem with respect to the principal axes, a student can stay visually connected to the solution, visualizing the solution along the way. One final point is that the approach outlined here makes all cross sections equal in terms of difficulty.

Assignment 7: Principal Stresses and Direction Cosines (team assignment) [1, 9]

Given the following stress state, (σ_x=10, σ_y=10, σ_z=15, τ_{xy}=5, τ_{yz}=4, τ_{xz}=3 ksi) determine the principal stresses and direction cosines of the angles between the original axes system and the principal stress axes system. Late in the design, it was determined that an oil galley needed to be added. After studying the stress state, select the path least disruptive to the component's strength. Using your solid modeling skills and **full artistic freedom** show this path in the original stress element and the principal axis system .



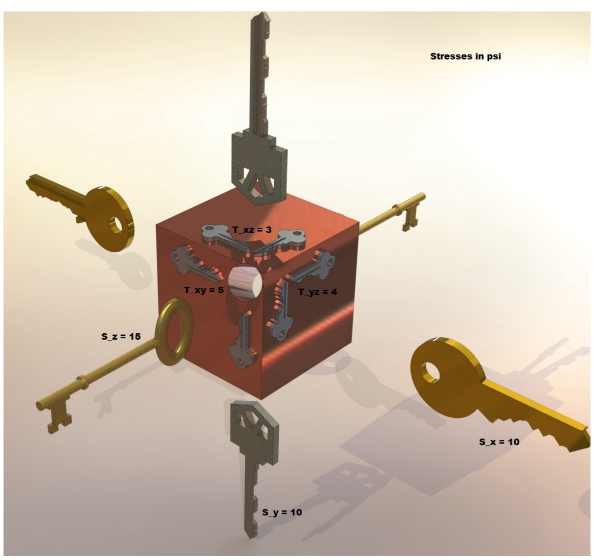
σ_1=19.96 σ_2=10.09 σ_3=4.93

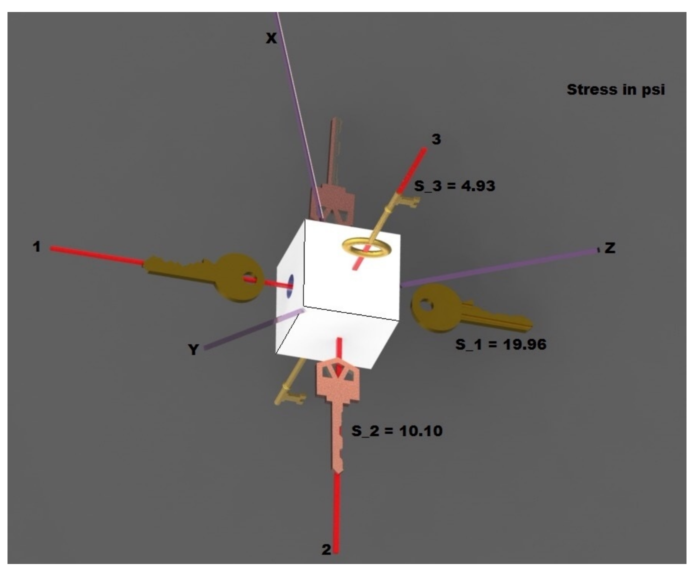
Direction Cosines

	x	*y*	*z*
X	.48	.52	.71
Y	-.57	-.43	.70
Z	.67	-.73	.09

a) b)

Figure 7 a) and b): a) Sketch of 3-D state of stress and b) classical manner of reporting the solution.





c) d)

Figure 7 c) and d): An example student visualizing a state of stress in the original and the principal coordinate systems.

Figure 7 e): Student submission of principal stresses.

Observation: In our curriculum, students will have taken or be enrolled in a junior level linear algebra class and have been introduced to eigenvalues and eigenvectors when this problem is assigned. Theoretical explanations are reviewed but only briefly. The analytical portion of the assignment is to create a program that calculates the three invariants for the characteristic equation and then solve for the roots and their directions. The programming exercise begins by studying the logic of a legacy TK-Solver program from Bhonsle and Weinmann [9] (Appendix A). Students then freshen up this code by including the use of Greek characters and the use of functions for organization. Heavy program commenting is expected. After the solution is obtained, students are asked to verify by way of cross product that the three sets of direction cosines do form a right-hand coordinate system. As indicated in the problem statement, students are free (actually asked) to use their full artistic expression to show the original state of stress as well as the principal state of stress. Adding an oil galley has the goal of helping students tie the two visual expressions of the stress state together.

Assessment

The assessment of the efficacy of this course is explored from three aspects. The first, shown in Figure 8, was to explore how prior educational experiences and their assessments predict the initial four-week performance in this course. The second assessment was to compare student initial four-week averages in the course to the final averages which is shown in Figure 9. Finally, an attempt was made to determine how students construct and retain knowledge over time, this is shown in Figure 10.

a)

b)

c)

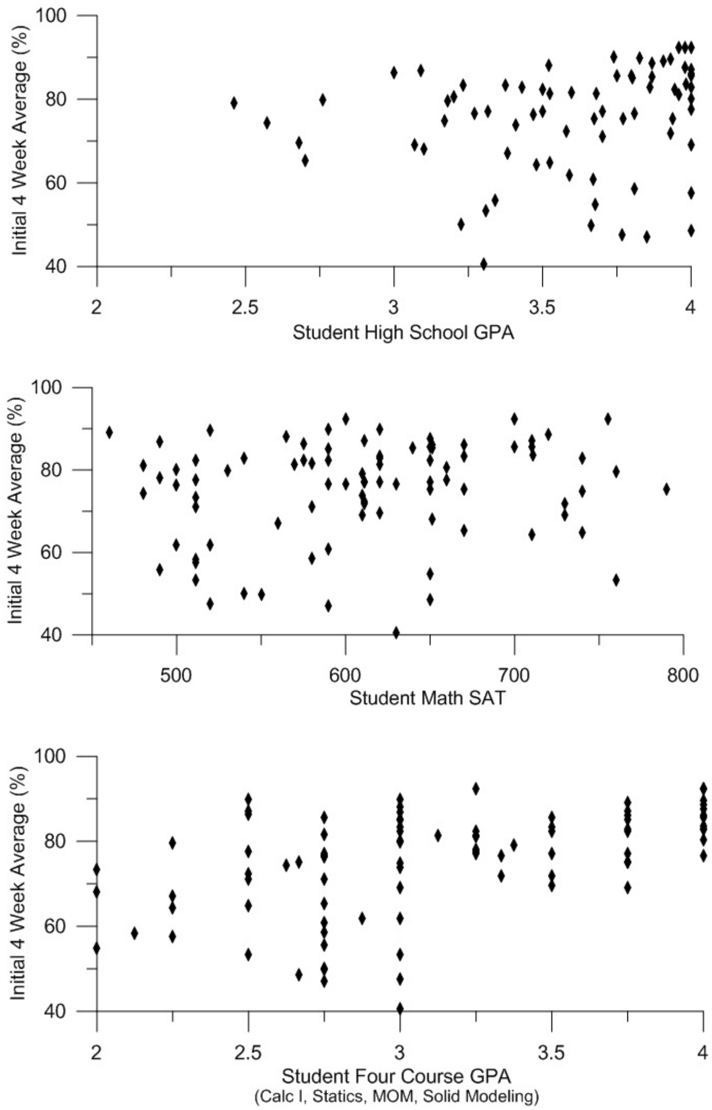
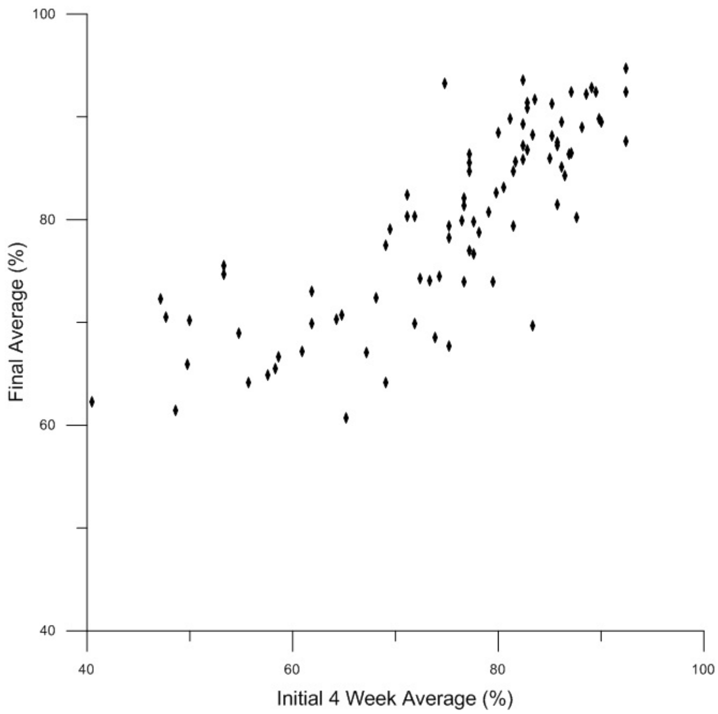


Figure 8: Initial four week average versus three possible causative variables, high school GPA, Math SAT, and four course GPA

Prior Educational Experience, Figure 8: The assessment of the present course (dependant variable) thought to be most relevant to previous experience was the student grade average for the first quarter of the semester (4 weeks.) This portion of the class focuses on review and assessment of topics from statics and mechanics of materials courses (23 separate problems were assigned during this time period) as well as a self assessment of these topics by the students. The only new material was a computer analysis program, TkSolver, as it is used throughout the year. Possible causative (independent variables) events considered was high school GPA, SAT math score, and the GPA of four prerequisite classes, one from each semester of the freshman and sophomore years, the first calculus course, statics, mechanics of materials, and solid modeling. These comparisons are shown in Figures 8 a), b), and c) respectively. There appears to be little if any dependence between high school GPA or Math SAT and the student average for the initial 4 weeks of the course. There appears to be a trend between the four course average and the initial four-week average as shown in Figure 8 c).

a)



b)

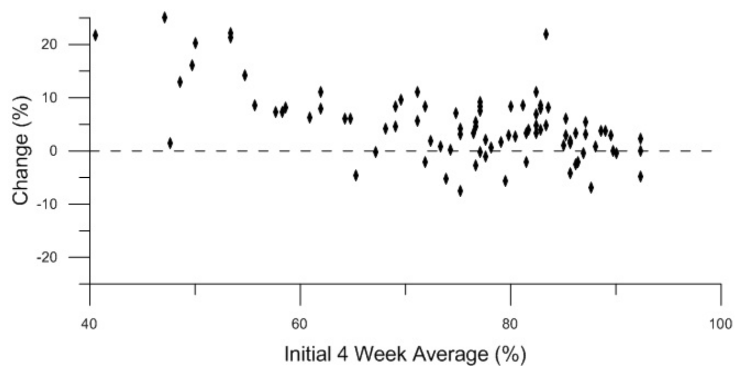


Figure 9: Final class GPA a) and change in GPA b) versus the initial four week average.

Initial four-week versus final average: In Figure 9 a) there appears to be a trend between the class average at four weeks and the final class average. Students that start well in the course tend to finish well. Focusing on the students that have a lower initial four-week average indicates that something else may be in play. Figure 9 b) indicates the change in student average between the initial four-week and final average. Of the 88 students in the class, the class average decreased for about 11 students, stayed approximately the same for 12 and increased for the remainder. Importantly, this occurred while covering the more difficult topics in the course, i.e., unsymmetrical bending, bending of curved beams, energy methods, and three-dimensional stress states. Additionally, the largest gains in average were for students that had lower initial 4 week averages. Perhaps this is due to having more possibility for improvement but even if that is accepted, they improved their performance while covering more difficult topics. This improvement in student performance occurred concurrently with the visualization assignments.

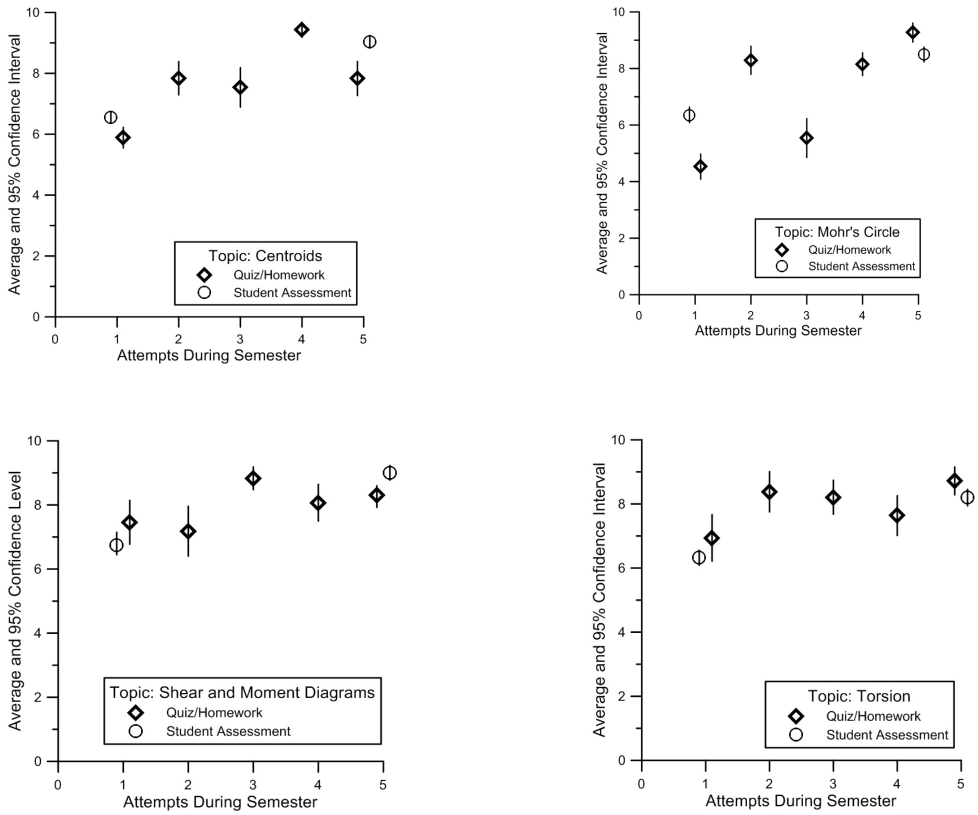


Figure 10: Student performance over the course of a semester on four mechanics of materials topics

Student knowledge construction and retention: The third assessment was to look at how students construct knowledge over time and how they retain it. During the initial 4 week portion of the class, the topics of calculating a centroid, Mohr's circle of plane stress, shear and moment diagrams, and torsion of circular cross section shafts were reviewed. Additionally, on the first day of class, students completed an assessment of their knowledge of various topics using a Likert rating scale. Subsequently, at about 3- week intervals throughout the semester, these topics were assessed by way of in class quizzes. The students then performed a self assessment at the end of the semester. The results of these assessments are shown in Figure 10. Generally, for all four topics, student performance improved throughout the semester. There does seem to be a drop off around the second or third attempts but the averages rebound after that.

Discussion

Four years ago, the first experiment (Assignment 3) with using solid modeling to supplement a mechanics of material solution was piloted. During grading of that assignment, several student groups turned in visuals that were quite striking. The visuals were such that, grading was suspended, while ascertaining who did this work. Early in a semester, in a larger class (60 students) a data point an instructor has is the present grade average in the class. These striking visuals were turned in by students that were struggling with the theoretical and analytical aspects of the class. The time spent on that assignment must have been disproportionate to the normal time spent on an assignment. While this was an anecdotal observation then, it has been repeatedly made. The time students are willing to spend on these assignments is such that assignments are spaced out over the semester because other classes need to have access to the computer lab. For our resources and curriculum about seven assignments as presented here are possible.

The data in Figure 9 b) strongly suggests a student's performance, as measured by class average, improved during the last 12 weeks of the semester as compared to the first four weeks. The first four weeks are review of previous materials with little new material, while the following twelve weeks include the introduction of curved beam theory, energy methods, shear flow, shear centers, unsymmetrical bending, 3-dimensional stress states and failure theory. It was during the twelve weeks that the assignments that included solid modeling were completed. Student performance improved while covering more difficult material.

After completing the fall semester covering intermediate mechanics of materials, the spring semester covers machine component design. Due to the nature of our curriculum it is the same student population allowing an assumption that students are comfortable with the solid modeling -mechanics of materials connection. This connection can be carried forward. For example, Figure 11 shows student work on the bolted connection. The figure shows the assumed geometry of material that is involved in the analysis. Solid modeling can be used to determine dimension of the frustroms used in the spring constant analysis [1]. The second figure illustrates the difference in bolt shapes that can improve the fatigue performance of the bolted connection [10].

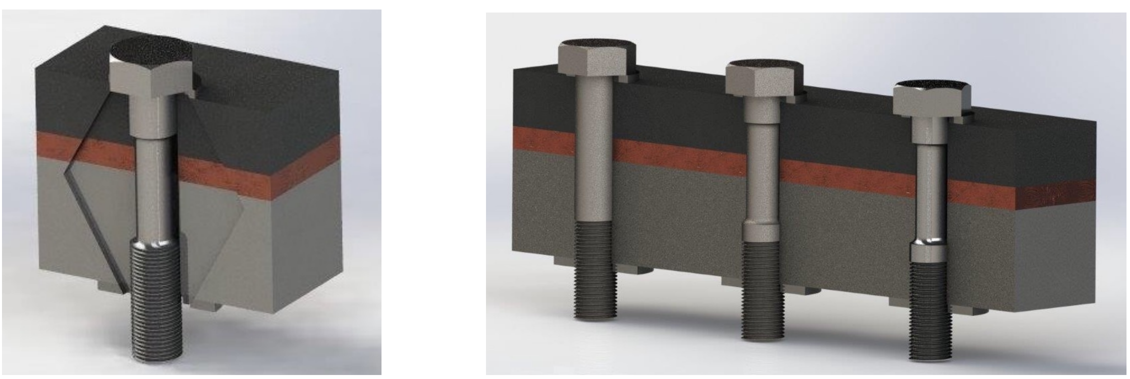


Figure 11: Solid models from a bolted connection assignment where the fatigue safety factor is increased first by shape and then improved materials.

Determining the effectiveness of including visualization into the course content is difficult since the class room is a dynamic environment. Therefore, holding one variable constant while changing another to get a clear cause and effect is not straightforward. The data suggests an improvement in student performance from beginning to the end, shown in Figure 9, is similar to the findings shown by a comparison between interactive-engagement versus traditional methods [11]. In this case the engagement is creative active visualization.

Conclusion

This study began by connecting metrics from prior engineering learning experiences (in pre-college courses, in college placement exams, and in selected pre-engineering course work) to initial performance in a mid-level Mechanics class. Not surprisingly, performance that was temporally closer to this course (i.e. grades in selected pre-engineering course work) was found to be the strongest indicator of course preparation. The paper outlines a sequence of homework assignments that integrate active, creative visualization with mechanic's course content. Seven diverse examples of progressively greater conceptual difficulty are presented. The impact of this teaching method was studied using periodic topic-specific quizzes as well as self-reported confidence in solving different types of mechanics problems. Quiz performance and problem solving confidence grew in all areas that were examined. The overall impact of this intervention on students with different academic backgrounds was interrogated using a method suggested by Hake [11] that traces gain in performance throughout a course versus performance during an early 4-week trial period within the course. Results showed that students of all academic backgrounds benefitted from the intervention, with proportionateley great impact on students who were lower performers. The conclusion is that appropriately framed solidmodeling exercises, within a meaningful mechanic's framework, stimulates engagement of a broad range of students in a mid-level Mechanics course that has a traditional reputation of heavy and lengthy homework assignments that primarily challenge just analytical skills. The assessment data presented here suggest that a visualization component along with a flipped classroom environment shows promise to be a powerful tool for knowledge/skill acquisition as well as student engagement in mid-level mechanical engineering courses.

References

1. Shigley, J. E. and Mischke C. R., *Mechanical Engineering Design*, Fifth Edition, McGraw Hill, Inc. New York, NewYork 1989.

2. Ferguson E. E., *Engineering and the Mind's Eye*, 2nd Printing, The MIT Press, 1992

3. Ward J., Why can I see memories, *Scientific American Mind,* January/February 2016.

4. Timoshenko S. and Young D. H., *Engineering Mechanics*: Statics, Preprint Copy, McGraw Hill, Inc., New York, New York, 1956

5. Popov P. P., *Introduction to mechanics of materials,* Prentice-Hall, Inc., Englewood Cliff's, NJ, 1968

6. *MSC Industrial Supply Co.* Catalogue, 2010.

7. Timoshenko S., and MacCullough G. H., *Elements of Strength of Materials*, D. Van Nostrand Company, Princeton New Jersey, 1949.

8. Boresi A. P. and Schmidt R. J., *Advanced Mechanics of Materials,* John Wiley & Sons. Inc., New York New York, 20003

9. Bhonsle S. R. And Weinmann K. J., *Mathematical Modeling for the Design of Machine Components*, Prentice-Hall, Inc., Upper Saddle River, NJ, 1999

10. Faires V. M. *Design of Machine Elements*, Macmillian Coll Div; 4th edition, 1965

11. Hake, R. R., Interactive-engagement vs traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses, American Journal of Physics, 66, 1998

Appendix A

Assignment 7 Principal stress and direction cosines

The following is legacy code from Bhonsle and Weinmann that is provided to students. The assignment is to study the code and understand the logic of a trigonometric solution to finding the roots of a cubic equation.

```
;TK Lead Model By DR. S.R. Bhonsle & DR. K.J. Weinmann
;                of
;Michigan Technological University Houghton Mi. 49931.

; Characterestic Equations ;
Sp^3-I1*Sp^2+I2*Sp-I3=ERR

;Following are the equations derived in this chapter
; to solve problems related to 3-d stresses

I2=Sx*Sy+Sx*Sz+Sy*Sz-Txy^2-Tyz^2-Txz^2
I1=Sx+Sy+Sz
I3=Sx*Sy*Sz+2*Txy*Tyz*Txz-Sx*Tyz^2-Sy*Txz^2-Sz*Txy^2
Sa=2*S*((cosd(l/3)))+1/3*I1
Sb=2*S*((cosd((l/3+120))))+1/3*I1
Sc=2*S*(((cosd(l/3+240))))+1/3*I1
S=(1/3*R)^.5
l=acosd(-Q/(2*T))
R=1/3*I1^2-I2
Q=1/3*I1*I2-I3-(2/27)*I1^3
T=((1/27)*R^3)^.5
a=(Sy-Sp)*(Sz-Sp)-Tyz*Tyz
b=-((Sz-Sp)*Txy-Txz*Tyz)
c=Txy*Tyz-Txz*(Sy-Sp)
k=1/(a^2+b^2+c^2)^.5
li=a*k
mi=b*k
ni=c*k
S1=max(Sa,Sb,Sc)
S3=min(Sa,Sb,Sc)
Taumax=(S1-S3)/2
I1=S1+S2+S3
```

The above code can be reorganized and coded using user defined TK Solver functions in to a very brief code that shows the logic of the solution.

```
call invariants(;I1,I2,I3)
call constants(;R,Q,S,T,α)
call roots(;Root_1,Root_2,Root_3)
σ_1=max(Root_1,Root_2,Root_3)
σ_3=min(Root_1,Root_2,Root_3)
σ_1+σ_2+σ_3=I1
call Cosines(σ_1;l_1,m_1,n_1)
call Cosines(σ_2;l_2,m_2,n_2)
call Cosines(σ_3;l_3,m_3,n_3)
```

This is the solution to Assignment 7 from Bhonsle and Weinmann

Status	Input	Name	Output	Unit	Comment
	19.9664796	Sp			Princ. stress (psi, ksi, Pa, or MPa)
		I1	35		Matrix Solving Constant
		I2	350		Matrix Solving Constant
		I3	995		Matrix Solving Constant
	10	Sx			Stress in x-dir (psi, ksi, Pa, MPa)
	10	Sy			Stress in y-dir (psi, ksi, Pa, MPa)
	15	Sz			Stress in z-dir (psi, ksi, Pa, MPa)
	5	Txy			Shear stress (psi, ksi, Pa, MPa)
	4	Tyz			Shear stress (psi, ksi, Pa, MPa)
	3	Txz			Shear stress (psi, ksi, Pa, MPa)
		li	.47522675		Direction Cosine of Sp (deg, rad)
		mi	.522525959		Direction Cosine of Sp (deg, rad)
		ni	.707902647		Direction Cosine of Sp (deg, rad)
		Sa	19.9664796		Principal stress (psi, ksi, Pa, MPa)
		Sb	4.93448179		Principal stress (psi, ksi, Pa, MPa)
		Sc	10.0990386		Principal stress (psi, ksi, Pa, MPa)
		S	4.40958552		Constant
		I	59.2834019		Constant
		R	58.3333333		Constant
		Q	-87.592593		Constant
		T	85.7419406		Constant
		ERR			Error term
		a	33.4983183		Constant
		b	36.8323982		Constant
		c	49.8994389		Constant
		k	.014186585		Constant
		S1	19.9664796		Max. Prin. stress (psi, ksi, Pa, MPa)
		S2	10.0990386		Intermidiate Prin. stress (psi, ksi, Pa, MPa)
		S3	4.93448179		Min. Prin. stress (psi, ksi, Pa, MPa)
		Taumax	7.51599893		The max. Shear stress (psi, ksi, Pa, MPa)

The students are asked in Assignment 7 to improve on the organization of the output..