Connecting Rod Design Competition–Solid Mechanics Multiple Failure Mode Design and Testing Project

Wendy Reffeor, Ph.D., David Blekhman, Ph.D.
Seymour and Esther Padnos School of Engineering
Grand Valley State University
Grand Rapids, MI 49504

Abstract

Students in Solid Mechanics courses commonly struggle with balancing multiple failure modes in a single part. To improve their understanding of failure modes, stress risers and design, students in the Solid Mechanics course are required to compete in a connecting rod design competition. As an added benefit of the project, students have an opportunity to reinforce their CAD/CAM and dimensioning skills learned in a first-year CAD/CAM design course.

Working in teams of two, students designed, machined and tested a connecting rod. The pin connections in the rod were represented by two 3/8” holes 3” apart. Students were to design the geometry of the part around and between two holes. The part was to have a maximum width of 1”. Students documented their designs through design calculations and a dimensioned CAD model, generated machine codes using CAM software, machined their parts, measured their parts to ensure accuracy and tested the rods to failure using a tensile tester. Grading was based on the strength-to-weight ratio of the connecting rod, accuracy of their failure force estimate, documentation of anticipated failure forces in all possible modes of failure, dimensioned CAD drawings, quality of manufacturing and the poster used to present their designs.

In the first year of the competition, the rods were machined from plastic, chosen for ease of machining. However, using plastic caused inaccuracies in determining the failure load as the stress risers reacted differently than in a less ductile material. Aluminum was chosen as the material for the second year of the project.

More than 30 teams participated in the contest the first year and 29 in the second. Testing results for the failure load were within 45% plastic and 21% for aluminum rods. Student comments were very positive both about the design experience and their understanding of the concepts incorporated in the project. The project quite effectively achieved the primary goal of helping students understand multiple failure modes and stress risers in axially loaded members. It also reinforced student design, CAD/CAM, dimensioning and machining skills.

Introduction

The old saying, "A picture is worth a thousand words," is a contemporary pedagogical reality. While looking at a picture is passive, an experiment would be an active learning exercise worth many times more. According to Jenkins[1], retention of information by students who only look at pictures is about 30%, which is 3 times more than retention of reading material. On the other hand, when learning exercises are conducted with an active learning content, retention increases to 70% for talks, discussions and presentations, and to 90% for demonstrations, lab experiments and written reports.

The benefits of active learning have long been recognized in engineering. Mahendran[2] describes two projects adopted at Queensland University of Technology in Engineering Mechanics and Steel Structures courses. Engineering Mechanics was taught to freshman students, and their project was to design and construct a straw bridge over a river subject to static loading by a train and dynamic loading by a truck. Both the building materials (drinking straw, paddle pop sticks and balsa wood) and loading (different truck weights) were periodically changed to provide a variety of challenges. Sophomore students in Steel Structures, in groups of four, were designing and testing in axial compression open, unwelded, cold-formed thin-walled 1 m long steel columns with simply supported end conditions using different cross-sectional geometries, grades and thicknesses of steel. Both projects were evaluated in judged competitions and both have about one third of the total grade allocated to the efficiency of the design *i.e.* the greatest carrying capacity per unit weight. Students' responses were overwhelmingly supportive of both projects. Students found the projects provided better understanding of the theory, 87% and 95% for the bridge and the steel column projects, respectively. Students also supported (95%) the idea of making the projects a regular feature of the respective courses. Through these projects the author found strong evidence of students' developing self-sufficient learning skills early in the engineering program. In addition to better comprehension of the material required to succeed in the projects, students enhanced their library research, drafting and technical report writing skills.

Based on the Bicycle Dissection Exercise, Regan and Sheppard[3] demonstrate the effectiveness of "rolling-up the sleeves" in student learning of machines and mechanisms in their surroundings. The authors emphasize the role of supporting multimedia in enhancing student experiences. They also discuss the iterative nature of engineering exercises based on student input from evaluations. It should be noted that iteration is a normal procedure in engineering design and so is natural for engineering educators striving for the best learning approaches for their students.

"Can you reinvent the wheel?" For engineering students this well known question can be paraphrased as, "Can you reinvent the bicycle?" so popular projects involving bicycles have become. Jenkins and Arola[4] introduce a bicycle frame study as a "do-and-say" exercise developed to help students to overcome difficulties of absorbing the simple truss vs. frame concepts. To an observer a bicycle frame is a spatial combination of triangular elements; to a mechanics course student that immediately constitutes a truss. However, the experiment and theoretical analyses help the student to realize that the working loadings in the bicycle violate the truss assumptions. Using this experiment as an example, the authors follow to emphasize that the perceived need for reforms of the undergraduate education in mechanical engineering is not necessary; rather the teaching tools and methods used should become more proactive and student oriented.

Statics and Solid Mechanics at Grand Valley State University is a four-credit sophomore level course combining classical statics with a vigorous introduction to the mechanics of materials.

This is achieved by adding topics on tension, compression, shear, axial loading, torsion and columns to the standard set of topics in statics. Student learning is supplemented by two semester projects. Both are completed in teams of two. The first is designing a bridge over a river. The initial design is selected with the help of the West Point Bridge Designer software[5] with the goal of building the cheapest bridge possible and then, using the method of joints, students analytically verify various loading cases and safety factors. The deliverables include a thorough report and an in-class Power Point presentation.

The Connecting Rod Design and Competition is the second course project. A detailed project description follows later in the paper.

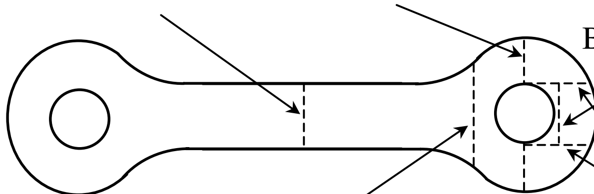

Figure 1. Typical Dog Bone connecting rod and possible failure modes in tension.

This project serves multiple goals. It is introduced after several failure modes in bars have been covered in lecture. These include axial loading in bars, stress concentrations due to stepped designs and holes, failure through bearing stress and hole shearing by a pin. A connecting rod, an example of which is given in Figure 1, can experience any of those failure modes. There are two main objectives students are to meet in their design: the rod should attain the largest load-to-weight carrying capacity and the load and the failure mode at which the rod fails should be properly predicted. Thus, students have to negotiate the competing failure mechanisms subject to axial loading in the rod. Additional goals include the polishing of CAD/CAM skills and an introduction to tensile testing. The design and generation of the machining codes are accomplished utilizing the Pro/ENGINEER software and the actual machining is done on a Pro-light CNC mill. Initially, students acquire these skills in Engineering Principles I, a course teaching students design fundamentals and CNC machining. The course is taught to students in all engineering disciplines. Students in each discipline complete a number of advanced projects throughout the engineering program and the Connecting Rod is one of the first in the lineup. Moreover, the students' machining and tensile testing skills are often called upon during their Co-op employment.

Assignment

For this project, students were asked to design a connecting rod for an automotive engine, which will have the highest strength-to-weight ratio. The material used was a 2" x 5" x 1/4" block of 6061-T6511 aluminum. To encourage careful and savvy work from the start, teams got a maximum of two pieces of aluminum only after the instructor approved final drawings. The final width of the connecting rod was limited to 1" and the two 3/8" holes were spaced 3" apart. The minimum applied force-to-weight ratio was required to be 50,000 and the predicted failure load was to be within 15% of the actual value.

A few weeks later, on the day of the competition teams submitted the connecting rods and the posters. The information included on the 20" x 28" poster was explanation of the design choices made, calculations performed and drawing with design and actual dimensions shown. The lower right corner of the poster contained a box with the predicted values of maximum load and force-to-weight ratio as well as labeled blanks for the actual values obtained during the competition. The box provided clear results for the team and the other students in the competition. It helped them to evaluate whether the predicted strength values and locations were correct for a given design.

Grading facilitated quality design and calculations and was as follows:

> 30% strength-to-weight ratio (Grades are based upon winning entry being 100% and the 50,000 minimum as a C.)
> 30% predicted versus actual strength
> 20% drawings including dimensioning and actual measurements
> 20% calculations and explanation

In addition to creating a communication mechanism for the contest, the posters were also a part of the grade. However, rather than a percentage, they were graded as a multiplier of the grade. This conveyed the message that in "real-life" engineering, not only the content, but also the vessel in which it is delivered counts. It is important for students to hone communication skills as they are being emphasized more and more in industy. Each poster receives a multiplier of 0.9 – 1.1. A 1.1 required a better than expected poster quality: all information was displayed very well and the team went above the project requirements to communicate effectively. A grade of 1.0 was received for meeting the project requirements with a neat, professional poster. Grades of less than 1.0 were assigned to those posters that either did not meet the project requirements or were not professional in appearance.

Failure modes

In planning their rod, students had to take into account the possible modes of failure summarized above as well as shown in Figure 1 with their respective location on the rod. Figure 2 shows the dimensions to be used in the calculations, which are outlined below with their corresponding samples of failure that occurred during the competition.

Axial loading is calculated as follows:

$$P = \sigma_U \, t \, c$$

where P is the load at which failure occurs and σ_U is ultimate stress. Most of the designs were geared toward this mode of failure by making the center of the rod the weakest point (see Figure 3).

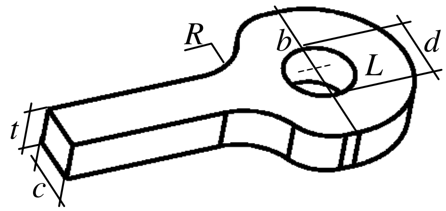

Figure 2. A half of a dog-bone connecting rod with the dimensions used in calculations.

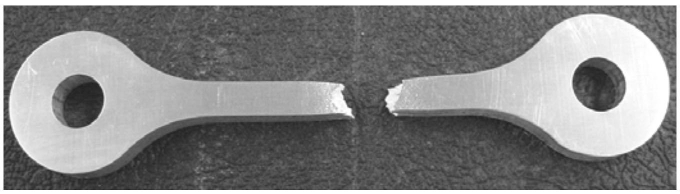

Figure 3. Connecting rod fracture due to axial loading.

Holes act as stress risers due to a dramatic change in cross-sectional area (see Figure 4 for a failure example). In practical calculations, this is accounted for by evaluating the stress concentration factor defined as:

$$K = \frac{\sigma_{max}}{\sigma_{nom}}$$

For a bar in tension, σ_{nom} is the average stress based upon the net cross-sectional area. In these particular calculations, the maximum allowable stress σ_U is substituted for σ_{max} as the rod was tested to failure. The value of K can be found by applying the ratio of d/b in graphs found in Strength of Materials texts, for example Gere[6] used in our course. Thus the load causing such a failure can be calculated as follows:

$$P = \frac{\sigma_U t \left(b-d\right)}{K}$$

Figure 4. Failure due to stress concentration for flat bars with circular holes

Stress concentration in stepped flat bars with shoulder fillets is similar to that of holes (see Figure 5). The value of K this time depends on two ratios R/c and b/c. In cases when the graph (Gere[6]) was not sufficient, students used Roark's[7] formulas covering all possible ranges of those ratios. And the load is:

$$P = \frac{\sigma_U t c}{K}$$

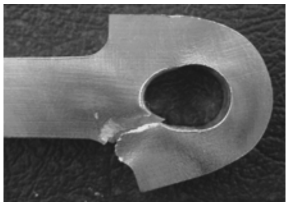

Figure 5. Small fillet radius resulted in a high stress concentration and a failure.

Bearing stress occurs because pins press against the bearing area, which is defined as the projection of the contact surfaces. According to Newton's third law, the forces act on both the pin and the hole surfaces. However, the pins used in testing were hardened steel versus the aluminum rod, causing the softer aluminum to yield. While bearing-stress failure never occurred in the rods due to dimensions (see Figure 6), the holes were significantly affected by the bearing stress, lengthening and pinching the rod, and making the removal of the specimen a challenge. In the connecting rod case, the load based on the ultimate bearing stress is evaluated as:

$$P = \sigma_b t d$$

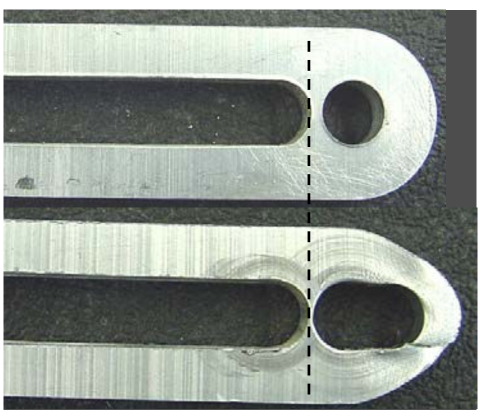

Figure 6. Failure by shear stress. The top pictures is the undeformed rod for comparison. Significant distortion of the material is visible due to the bearing and shear stress.

In addition to introducing a bearing stress, the pin action also produces a shear stress on the hole. Figure 6 demonstrates the shear type failure occurring in destructive testing. The maximum load is calculated based on the value of the ultimate shear stress τ_U :

$$P = 2 \tau_U t L$$

where the doubling of the area accounts for two planes of shear.

Results

This year 29 teams participated in the competition. The rod designs demonstrated a multitude of shapes and technical solutions. In the assignment, students were encouraged to evaluate existing designs for various types of connecting rods. As a result, the most common shape is of a dog bone (see Figure 7). However, such designs as the modified dog bone (see Figure 8) and the ribbon (see Figure 9) were also frequent, though it was required to have the shaft holes fully surrounded by the material so the load could be transmitted in both tension and compression applications. Both latter designs required some modifications to the calculations and rethinking of the failure modes.

Figure 7. Dog Bone type connecting rod.

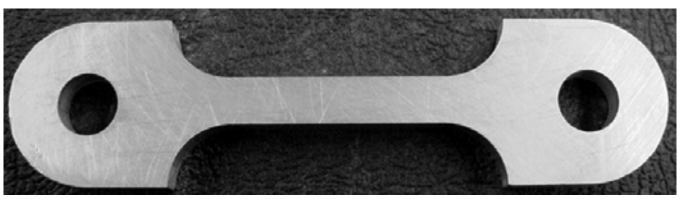

Figure 8. Modified Dog Bone type connecting rod.

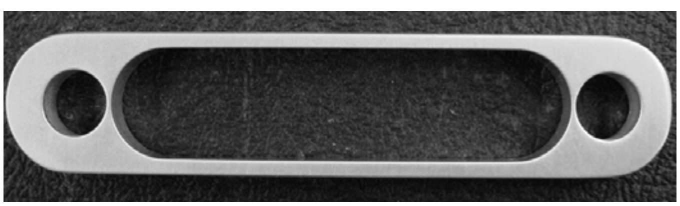

Figure 9. Ribbon type connecting rod.

It was interesting to note that certain designs were prevalent in individual course sections. Both the modified dog bone and the rubber band design were found in only one section and the majority of dog bones were in the remaining section. This is most likely due to students discussing the problem with their classmates. Although the basic design within a class was similar, each team produced a unique design.

Projects were graded on both accuracy of failure load prediction and failure load to weight ratio. When using plastic last year, students had difficulty predicting the failure load, yielding an average of 45% error between predicted and actual values. This was primarily due to plasticity relieving the stress risers. Therefore, this year aluminum was used for the designs. The only change between last year and this year was the material and the average error was reduced to 21% as can be seen in Figure 10.

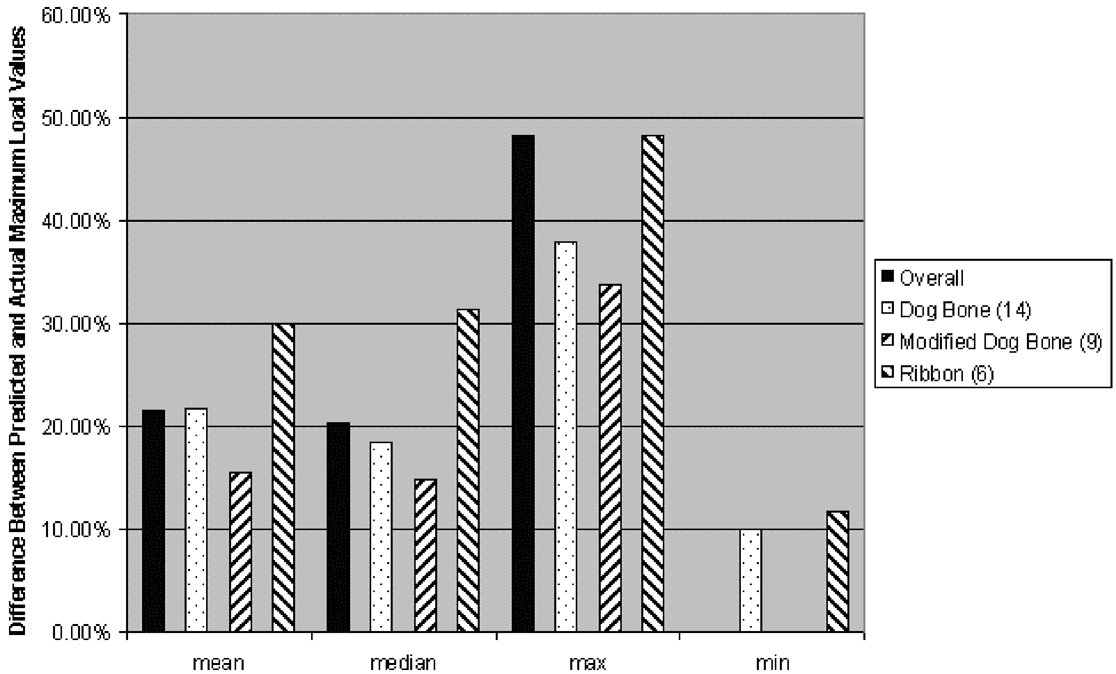

Figure 10. Comparison of Percent Error for Different Design Geometries

It is interesting to note that the different design concepts yielded significantly different results. The most accurate predictions, across all four statistical indicators, were achieved when students chose to design the modified dog bone. This design conforms most accurately to stress concentration factor charts such as those found in Strength of Materials texts and Roark's Formulas for Stress and Strain[7] and therefore gave exceedingly accurate results with the average error being only 15.6%.

The average error in predicted load for dog bones was 22% and 30% for ribbons. These errors reflect the increasing difficulty in accounting for interactions between multiple stress risers. The trends in errors were in agreement for all statistical indicators examined. Note also that one student group actually predicted their failure load to within one pound.

Seventy-five percent of the students under estimated their failure load. This is to be expected as, in general, engineering design is conservative.

Figure 11 shows the statistics for strength-to-weight ratio. Although the modified dog bone style was the most accurate, it also had the lowest average strength-to-weight ratio. As would be expected, the strongest geometry was the dog bone with its smooth curves and resulting low stress concentration factors. The average strength-to-weight ratio for the dog bone was 18% higher than that for the modified dog bone. The ribbon design was slightly weaker than the dog bone (2.5%), but still much stronger than the modified dog bone (15%).

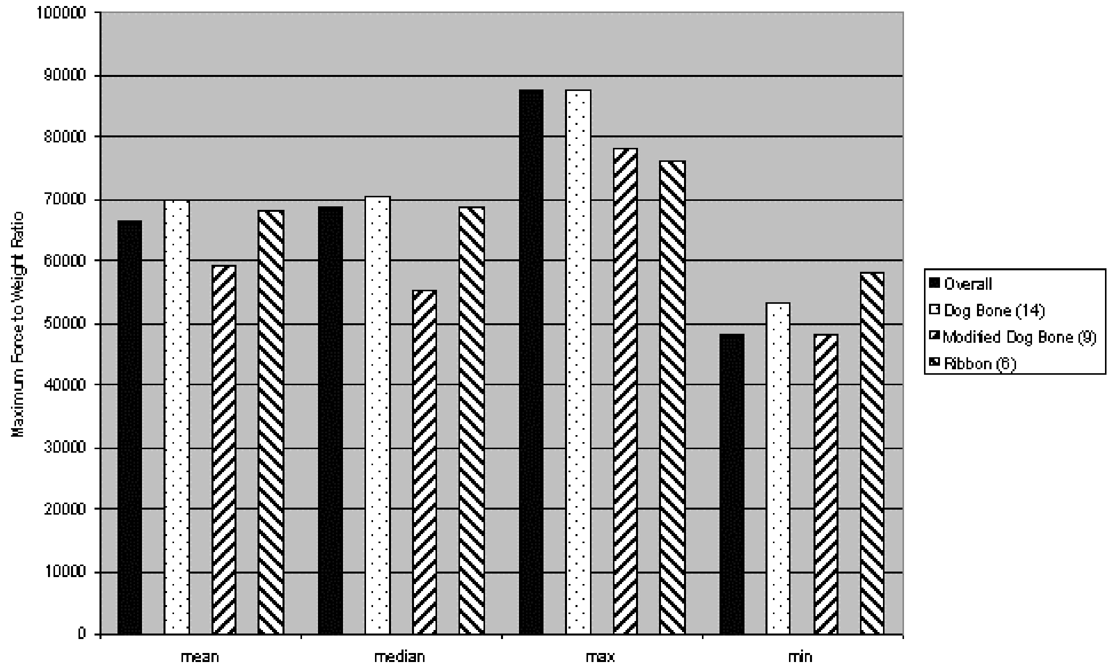

Figure 11. Comparison of Maximum Force to Weight Ratio for Different Geometries

It is interesting to note that the ribbon design yielded a smaller range of strength-to-weight ratios than the other two. This may be caused by the smaller number of specimens. It may also be due to the lack of opportunities for optimization in this design.

It is clear that some groups chose accuracy of calculations over highest strength-to-weight ratio when designing their rods. Those who chose the modified dog bone were attempting to make their design fit theory while those who chose the dog bone were maximizing their strength-to-weight ratio. There was no clear reason to choose the ribbon design other than, perhaps, it seemed intriguing to the students.

Discussion

The connecting rod contest was deliberately designed to bring students to the sixth level of Bloom's Cognitive Taxonomy[8], evaluation. The problem was open-ended, only specifying material, size envelope, and goals. Design criterion included ability to generate highest strength-to-weight ratio, ease of machining and ease of accurate load prediction. To choose the best design, students first prioritized these design objectives and then evaluated each proposed design to them. As a result, there were many solutions to the same problem. Student designs fit into three general types with varying levels of optimization completed once the basic shape was chosen.

To balance the five possible failure modes, students iterated their designs, removing material from areas of lowest stress and increasing material in areas of low stress. Most of this optimization was performed assuming that the stress risers acted independently and conformed to the basic forms in stress-concentration tables—hole in an axially loaded member and change in cross-section of an axially loaded member. In many cases, students did additional research to determine the effects of multiple stress risers and transitions in the geometry of the specimen. This generally resulted in more accurate results and those students learned the value of research. Students also became aware that bearing stress and shear stress are unaffected by stress risers.

Many students quickly realized that a limiting factor would be the ability to machine the shape they chose to design. This was a very valuable lesson since machinability is a major influence in product design. It is interesting to note that machining errors accounted for less than an approximately 5% error in failure load when calculations were redone using actual machined dimensions.

One difficulty in this type of experience is the students' inability to account for interactions between stress risers. This could be resolved somewhat by allowing students to use an FEA program to verify their predictions. One difficulty with this approach is giving students a false sense of their ability to use FEA software. In addition, the extra workload introduced for students to learn a new software program was deemed unnecessary.

A definite advantage of this project is its relationship to other courses in the curriculum. Students use their CAD/CAM skills acquired in their freshman CAD/CAM course and are exposed to tensile testing which is more fully covered in their Materials Science Course. In addition, students begin to learn time management and interpersonal skills which will be helpful to them in all future courses.

Students were required to create posters that were displayed during the testing of the rods. Creating these posters gave students an opportunity to exercise their critical thinking skills as they needed to decide what should be included on the poster. In addition, and more importantly, the posters allowed all groups to see the results of others and thus, to draw their own conclusions as to which designs were best.

Student Feedback

Last year, students were asked to answer the following questions:

1. Did you feel the connecting rod project helped you to integrate the concepts you had learned in the course?
2. What did you feel was the most beneficial aspect of the connecting rod project?
3. What did you feel was the least beneficial aspect of the connecting rod project?
4. How would you change the connecting rod project to make it better?

The responses to Question 1 were 32 positive, 3 mixed and 1 negative. One of the most interesting comments came from one of the students with a mixed response. He said "We had to use what we learned to determine the stress in the rod, but the stress risers were closer together so we had to guess on parts of it." For students to realize that this educated "guessing" is a part of design was one of the unwritten and secondary goals of the project. Unfortunately, this student didn't make the connection or was still, like most students, uncomfortable with it. One of the most positive concepts was “This was a great way to experience Statics in engineering (and) making logical assumptions and seeking out material to help in the design.”

All students commented on Question 2. Representative comments included:

> “Finally the topic of stresses really clicked for me while designing it.”
> “Using various tools to make, measure, and test our parts along with applying our knowledge to a real life situation.”
> “Seeing our calculations actually worked out by testing.”
> “Stress concentrations are one of the more abstract concepts in the class. Seeing how the plastic flowed and broke made the concepts easier to realize.”

These comments show fairly clearly that the main goals of the project are, in the students' opinion, are being met.

Fewer than half of the students responded to Question 3. However, the majority of those who did commented that the least beneficial aspect was difficulties in milling. This, unfortunately is a very “real life" problem. It was minimized in the second year by using a single, more capable mill and scheduling machining times. One very interesting comment was, “We never went over designs after testing and explained what worked and what didn’t.” This comment was definitely taken seriously and the posters were implemented this year as well as the photographs of the rods before and after the testing were taken for future discussions.

Again, fewer than half of the students responded to Question 4. Most responses referred to difficulty in milling. Once again there was a comment on reviewing designs after the project was complete.

Conclusions

This project will continue to evolve through time. There are already a number of changes to be implemented for next year. A class period following the competition will be allowed for discussion of the results. This discussion will include the statistics given in this paper as well as conceptual support for the findings.

If at all possible, next year a less ductile material will be used. The limitation in implementing this is the ability of the mills to machine harder, stronger materials. However, brittle materials tend to give a more consistent response to stress risers since there is little deformation to relieve the risers. This will result in more accurate failure load predictions and a more rewarding experience for the students.

Finally, next year the project will be made more realistic by introducing both tension and compression performance of the parts in addition to a taper in the rod. This will complicate the project and when this is implemented, the connecting rod project will be the only course project. The consequence of this is more time will be allowed for project management and documentation will be increased to include a written report.

Overall, this project has been a great success. Students are identifying major project objectives as the most useful aspect of the project without being prompted which indicates the effectiveness. Some modifications will be pursued in future iterations to improve the project even more.

Biblioghraphy

1. Jenkins, M. G., "Standards and Codes in Mechanical Engineering Education: Confounding Constraints or Helpful Hindrances?," *Standardization News*, Vol 27, No 9, 1999.

2. Mahendran, M., "Project-Based Civil Engineering Courses," *Journal of Engineering Education*, Jan, 1995.

3.Regan, M., Sheppard, S., "Interactive Multimedia Courseware and the Hands-on Learning Experience: An Assessment Study," *Journal of Engineering Education*, Apr, 1996.

4. Jenkins, M. G., Arola, D. D., " When Is a Truss not a Truss: A 'Do-Say' Pedagogical Laboratory Exercise," *Session 2526, Proceedings of the 2001 American Society for Engineering Education Annual Conference & Exposition,*" Albuquerque, New Mexico, June 24 - 27, 2001.

5. http://bridgecontest.usma.edu/

6. Gere, J. M.,"Mechanics of Materials," 5th ed., Brooks/Cole, Thomson Learning, 2001

7. Young, W. C., Budynas, Richard G., "Roark's Formulas for Stress and Strain," 7th ed., McGraw-Hill, New York, 2002.

8. Bloom, B. S., "Taxonomy of Educational Objectives: The Classification of Educational Goals: Handbook I, Cognitive Domain. "Taxonomy of Educational Objectives (Cognitive Domain)," Longman, New York,1956.

Biographical

WENDY REFFEOR, Ph.D. is an Assistant Professor in the Padnos School of Engineering at Grand Valley State University. She holds a BS in Mechanical Engineering from GMI Engineering & Management Institute, an MS in Mechanical Engineering from Purdue University and a Ph.D. from Michigan State University. Since joining GVSU, she has focused on introducing design in traditionally analytical courses in the Mechanics sequence.

DAVID BLEKHMAN received his Ph. D. in Mechanical Engineering from the State University of New York at Buffalo and his B.S. and M.S. in Thermal Physics from the St. Petersburg State Technical University in Russia. While his teaching interests are associated with the fluid and thermal sciences, he has enjoyed teaching Statics and Solid Mechanics course for two years since joining Grand Valley State University in 2002.