AC 2012-3128: DESIGN OPTIMIZATION PROBLEM IN A MATERIALS ENGINEERING COURSE

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Design Optimization Problem

in a Materials Engineering Course

Introduction

Many applications in mechanical design require engineers to optimize the design of parts that have been in use for some time. This paper will discuss a design project that is given to senior Mechanical Engineering Technology students in an upper-level Materials Engineering course. The uniqueness of the project is that it not only requires the student to optimize the geometry of a part, but also to determine an optimal material such that a design index is maximized (the design objective). A high design index requires product stiffness and strength to be maximized at minimal weight so both material selection and geometry play important roles. A typical design approach taught to the students prior to enrolling in the course might have been to assume a material (steel) then use strength of material concepts to determine geometry to meet a strength or stiffness requirement with little regard to weight, cost, or optimization. The purpose of this design project is not only to utilize the above methods for determining ideal geometry but also to utilize Cambridge Engineering Selector (CES) software to determine the optimal material. In addition to discussing a specific example used in the design project, this paper will discuss the grading rubric, examples of work performed by students, student feedback, and how this project could be used in other courses to enhance the student's education.

Problem Definition

The student is to design and optimize the C-shaped link shown in Figure 1 for static loading. Figure 2 shows a 3D view of an optimized C-shaped link. The geometry of the link cannot exceed the package size defined in Figure 1. The goal is to determine geometry and material such that the link is as strong as possible, as stiff as possible, and as light as possible while not exceeding the space constraints. The objective in choosing a material is to optimize a number of metrics of performance in the product in which it is used.[1] The student should present designs with three different families of materials: optimal composite design, optimal plastic design, and optimal metal design. NOTE, the geometry for these three cases should be similar! The design index, D, that they are trying to maximize is as follows:

$$D = \frac{K^{1/3} F_y^{1/2}}{W}$$

Where: Fy = max load for yield, K = stiffness of part, W = weight of part

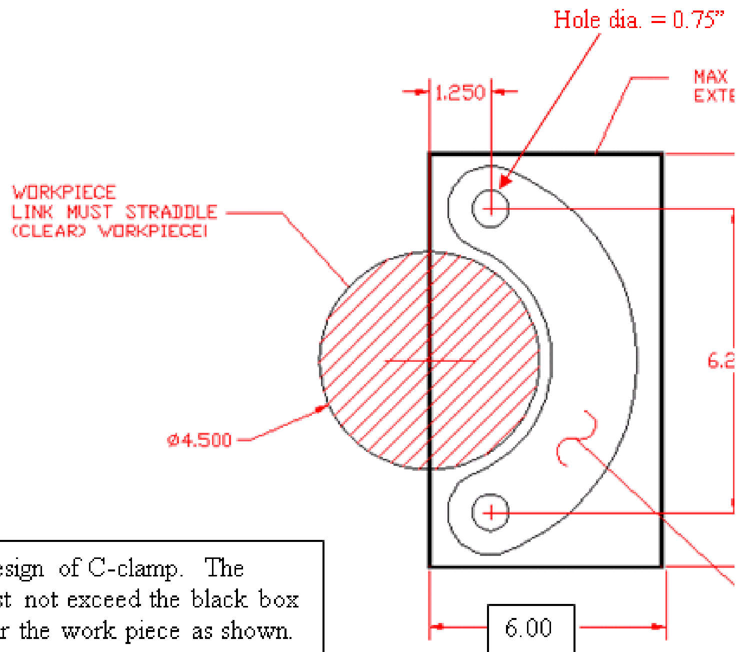


Figure 1 – Design of C-clamp. The geometry must not exceed the black box and must clear the work piece as shown. Depth (into paper) 2” max

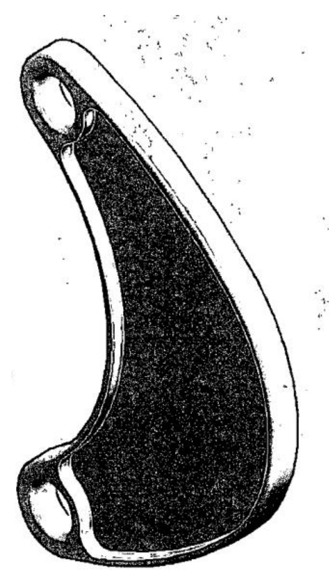
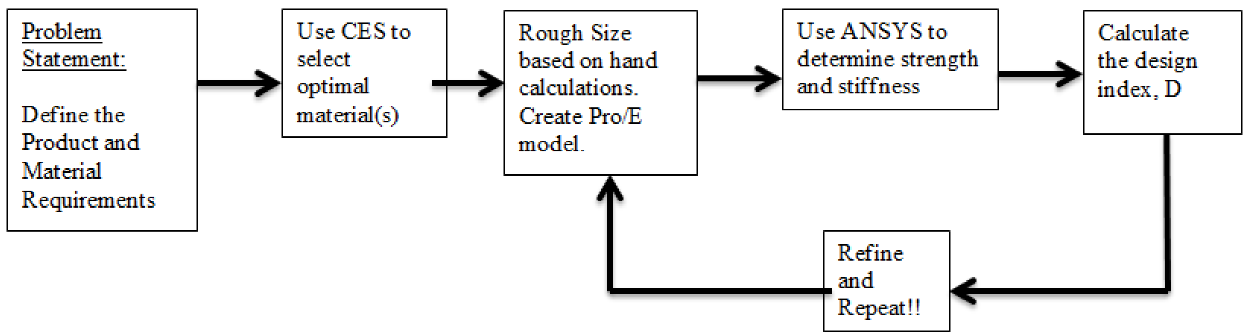


Figure 2
3D View of C-shaped link

Design Approach

The selection of a material for a specific application is a thorough, lengthy and expensive process. Almost always, more than one material is suited to an application and the final selection is a compromise that brings some advantages as well as disadvantages.[2] The student should start by optimizing either geometry or material selection. Students are to employ CES to select the optimal material. Patton states that when a designer selects a material, the designer should consider three basic requirements: service requirements, fabrication requirements, and economic requirements.[3] The C-clamp can be modeled as a cantilever beam with free height for the purposes of determining material performance indices.[4] The appropriate material indices can be found in CES help files or lecture notes and are summarized below:

CES Approach for Material Selection:



Stiffness constraint at minimal mass for beam with free height: $M_1 = \frac{E^{1/3}}{\rho}$

Stiffness constraint at minimal mass for beam with free height: $M_2 = \frac{\sigma_y^{1/2}}{\rho}$

Students are required to find optimal material for three families of materials: composites, thermoplastics and metals. The CES approach is as follows:

1. Insert tree stage and add family of materials of interest (i.e. thermoplastics)
2. Insert a limit stage and filter out materials with percent elongation less than 5%. This will eliminate brittle materials which are inappropriate for this application. Also, insert a maximum price of $100/lb to eliminate any "exotic" materials.
3. Insert a graph stage of modulus vs density. Insert a line with slope = 3.
4. Insert another graph stage of strength vs. density. Insert a line with slope = 2.
5. Go back and forth between the two graph stages raising the line and filtering out materials. Continue to do this until there are 2 – 5 materials left. Select the "best" material – this will be the optimal material for this sample. Print out and save the material record. These are the properties used in the FE (finite element) analysis.

Geometry Approach

Students should use basic strength of material concepts for curved beams to get some insight as to how the c-clamp should be designed. Then, create a design in Pro/E (Pro Engineer) and import it into ANSYS. In ANSYS, they apply a 1 lb load to the inside surface of one hole and use a *frictionless* support at the inside surface of the other hole. Instead of frictionless support the student may also use a cylindrical support with radial and axial fixed and tangential free (note this is the same as frictionless support but more stable since the axial dof is eliminated). The yield load, Fy, can be determined by scaling the stress at 1 lb to the yield stress then multiplying by 1 lb. The stiffness, K, can be determined by taking 1 lb divided by the average total deformation of the hole only at 1 lb. The student should continue to iterate in Pro/E and ANSYS until the student feels they have optimal geometry! The design index, D, should be calculated for each iteration and should be maximized as much as possible. This will help guarantee that the student has maximized the geometry as well as the material.

Report Requirements

Students work in groups of two and are required to submit a formal report. The report must contain the following:

1. Title Page – project title, instructor name, screen capture of the final design.
2. Table of contents w/ page numbers.
3. Introduction – clearly state the objective of the project (what it is they are trying to do). Briefly discuss the engineering tools used.
4. Summary – summarize important results only. Include the below table in the summary section:

DESIGN	ITERATION	MATERIAL	Yield Strength (ksi)	Modulus (E6 psi)	Density (lb/in^3)	Material Index M1	Material Index M2	Stiffness, K (lb/in)	Yield Load, Fy (lb)	Weight (lb)	Design Index D
1. Thermoplastic											
2. Metal	1							64,672	7,405.80	0.91695	**3765.755117**
	2							7,030	1,384.80	0.83372	**854.789934**
3. Composite											

Table 1 – Summary of results for final designs of all three materials.

5. Discussion – discuss results.

- What design is the best (1, 2 or 3)? How did they select the optimal material? How did they optimize the geometry?
- The designs are strictly performance based but what if cost was an issue? How would the material selection change? The student should redo the CES part by replacing density with cost index (\$/lbs.) times density (lbs./in^3) which yields units of \$/in^3. This method allows students to rank materials based on a fixed volume associated with their design.
- The geometry for all three designs was the same which assumes that material selection has no impact on design. Is this entirely true? How might the designs change based on the material (hint: think contact stress with the plastic design, the BC applied does not consider this)? Are all materials isotropic? Large Deformation?
- The design of the c-clamp was really optimized for static loading. What if the loading was different (i.e. shock loading, fatigue loading, etc…) how would the approach differ? What additional material properties would be important? For static analysis, does the approach above capture every possible design issue which might impact material selection (hint: again think plastic!!)?
- The student is to add anything they feel is important. The student should do some independent research to verify material properties.

6. Appendix – include FE plots showing several iterations, including model refinement to determine optimal geometry. Include CES graph showing final materials left. Include material records for the three materials selected. Include hand calculations using curved beam theory for at least one case. The student should include a detailed, dimensioned drawing of the final design. Show isometric view, show section views as appropriate, follow dimensioning rules.

Grading Rubric

Below shows the grading rubric for the project paper.

- Cover Page … 2.5 points
- Table of Contents … 2.5 points
- Introduction … 4 points
- Summary … 20 points

- Discussion/Technical Content … 40 points
- Drawing … 15 points
- Grammar/Spelling … 7 points
- Format (Figures labeled properly, legible and easy to read page #, etc.) … 5 points
- Proper use of CES, hand calculations, and other courses to support claims/references … 4 points
- Total … 100 points

Student Feedback

At the completion of the project, the students were given a survey to gain insight on their thoughts about the project. There were 30 students that completed the survey. As with most student surveys, some student feedback was not helpful or not pertinent to this deisgn optimization problem so they were ommitted. The following shows the survey questions and a summation of the student's most often stated responses:

1. Which engineering course was the most beneficial to complete the project? The students responded that FE Analysis course and this Materials Engineering course were the most important.
2. What portion of the project challenged them the most? The students responded Pro/E modeling, finding the optimal design geometry, and stress analysis.
3. Rank the engineering topics mostly used (most to least):
    a. FE Analysis
    b. Design / Pro E
    c. Material Science
    d. Strength of Materials
    e. Graphics / Drawing
    f. Manufacturing
4. What did the student enjoy most? The students responded that they enjoyed the competition and freedom to make their own decisions with the design.
5. What did the student enjoy least? The students responded the the time involved with developing the report and nothing.

6. What could be improved on the project to make a more valuable learning experience? The students responded again, nothing, and also to have the weight of the part be more important and more time to do the project.

Although not included as a survey question, students have verbally responded that the most important lesson learned from this Design Optimization Problem was the importance of material selection as well as the geometry. In other words, they understand that an optimal product includes both the optimal geometry and optimal material. Also, through many engineering deisgn iterations they come to realize that engineering a product in the real world is time consuming but the reward is greatly satisfying. Finally, they realize the importance of "engineering coupling" (i.e. how changing a part feature size may have a negative impact on weight but an overriding postitive impact on strength and stiffness).

Use of this Project in Other Courses

This project along with student results are used in other courses. For example, in Advanced Strength of Materials, curved beam theory is discussed and various student solutions are used to illustrate good (and poor) curved beam designs. Also, design optimization is discussed in a junior level Machine Design course to emphasize the importance of design iterations and brainstorming. Finally, the project is used in a senior level Finite Element Analysis course for Plastic Engineers. In this course, shape optimization analsyis (i.e. shape finder in ANSYS) is used to find the best use of a thermoplastic material for a body.

Conclusions and ABET

This design project clearly demonstrates the need for proper material selection, design iterations and refinement. Once the optimal materials are found, students typically iterate 20 – 30 times changing geometry in Pro/E and importing this geometry into ANSYS for analysis to determine stress and stiffness. The student must calculate the performance (design) index for each of these design iterations. Students further refine the design to try to maximize this index. This project provides students with a strong foundation in design iterations and creates an atmosphere of friendly competition! The best student design had a design index, D, of 12,100 which resulted in first place for this student group. Finally, this design project has been used as a direct assessment tool for ABET accreditation for the following objectives:

Outcome A: The MET program must demonstrate that graduates have an appropriate mastery of the knowledge, techniques, skills, and modern tools of mechanical engineering technology

Sub-outcomes:

a1	Mastery of knowledge current to each student's year of study.	*Students are required to use high end analysis tools (FEA) and verify stress results with hand calculations. Curved beam theory is used to calculate stresses in c-clamp and compare these stresses to ANSYS results. Von Mises stress and various failure theories are used to make sure safety requirements are met. Students are required to use material indices to maximize strength to weight ratio and stiffness to weight ratio for 3 classifications of materials: composite, metal and thermoplastic. Finally, an overall design index is calculated and used as a means to benchmark and optimize designs. An optimal design is determined for all 3 families of materials: metals, composite and thermoplastic. Advanced graphics are used to produce a detailed drawing for the final optimized design.*
a2	Mastery of techniques and skills	*This design project clearly demonstrates the need for design iterations and refinement. Students typically iterate 20 – 30 times changing geometry in ProE and importing into ANSYS for analysis. The student must calculate the performance (design) index for each design iteration. Students further refine the design to maximize the index. This project provides students with a strong foundation in design iterations.*
a3	Mastery of modern tools	*Students are required to use CES (material selection software by Granta) to filter, screen, and rank and then select optimal materials. Students are required to use Pro/Engineer to create and modify numerous designs. ProE is used to create*

		detailed drawings. Students use an FEA package, ANSYS to analyze their designs for stress. Finally, students use ShapeFinder function in ANSYS to optimize their designs.

Summary & Conclusions:
Class average score 84% exceeds Program target of 70%
Conclusion: students exhibit the expected performance in mastery of the knowledge, techniques, skills, and modern tools of mechanical engineering technology.

Outcome B: The MET program must demonstrate that graduates have an ability to apply current knowledge and adapt to emerging applications of mathematics, science, engineering, and technology

Sub-outcomes:

b3	Applications of engineering and technology	This project clearly captures the need for students to adapt to emerging applications of engineering. The latest engineering software packages are used to complete the project. A full search on latest engineering materials is used in conjunction with state of the art software to find the "best" engineering material. This material changes from year to year due to advances in thermoplastics and composites.

Summary & Conclusions:
Class average score 84% exceeds Program target of 70%
Conclusion: students exhibit the expected performance in applying current knowledge and adapt to emerging applications of mathematics, science, engineering, and technology.

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