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The Integration of Cost into Mechanical Engineering Design Curricula

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Abstract

The integration of cost into design courses in engineering and engineering technology programs is necessary to provide graduating engineers the skills to become immediate contributors to the goals and profits of their chosen companies. There are many methods that can be used, including sophisticated decision science techniques. One example of a teaching and analysis technique developed for use in a strength of materials course is described. In this example, a simple selection model, called a decision matrix, is used to decide what combination of factors provided a cost-effective design. This type of technique will allow teaching professionals to introduce and reinforce the concept of cost into basic mechanical engineering design courses. Decision matrices are extensively used in many fields of science, health care, electronics, and manufacturing. Obviously, more sophisticated decision science processes using complex analysis and modeling techniques can also be used. The purpose of this paper is to introduce the concepts of cost and optimization of design to engineering students early in their educational careers. The more sophisticated decision science models can be incorporated into advanced engineering design courses. Techniques such as this can also be applied in many other courses and disciplines including project management. The cost of oil and gasoline has tripled in the last few years. The concept of cost-effective design has suddenly reached new heights and now affects almost everyone in the world in which we live.

Introduction

In a long career of interaction and work with engineers, designers, and architects, it has been observed that many have difficulty determining the proper combination of factors, such as material, shape, safety, reliability, efficiency, and cost, necessary to satisfy customers' requirements. There are a number of recognized methods available to evaluate the structural rigidity or integrity of design components. However, many design professionals lack the ability to incorporate cost effectiveness and optimization into their design. How do you get the most rigidity for the least cost and, in many cases, at the lowest weight? To quote an old expression, how do you get "the most bang for your buck?" In our extremely competitive international world, how do we remain efficient and win competitive bidding in the design arena? Graduating engineering and engineering technology students do not have a good grasp of this concept, and it is suggested that faculty have the responsibility to introduce and nurture cost-effective design. The purpose of this paper is to demonstrate one method of introducing this concept to mechanical engineering students in typical strength of materials courses. Rigidity will be defined by considering both the material and the shape of the cross section. Different combinations of materials and shapes will be evaluated. A simple decision matrix will be shown as one method of comparison, and this entire process will be pulled together. This concept should be incorporated into a variety of other engineering and engineering technology courses to demonstrate and reinforce its application.

Definitions

The rigidity (or stiffness) of a material is simply a measure of the amount of deflection, δ, that occurs when a simple cantilevered beam is exposed to some applied load as shown in Figure 1.

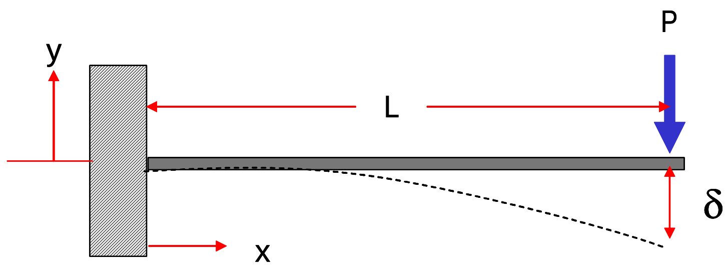

Figure 1: A simple cantilevered beam showing an applied load at the end of the beam and depicting the amount of deflection [1]

The amount of deflection, δ, is a function of both a material property and the cross-sectional shape of the beam. The material property is the modulus of elasticity, E, of the material being used and can be determined by a simple tension test or found in published literature. Normally, the modulus of elasticity is a constant for each specific metal but can vary by molecular weight in polymers. The shape property is the moment of inertia, I, of the cross-sectional shape, which can be determined by using a number of mathematical and graphical methods or found in published literature.

The modulus of elasticity is simply the slope of the elastic portion of the stress strain curve from a tension test, as shown in Figure 2.

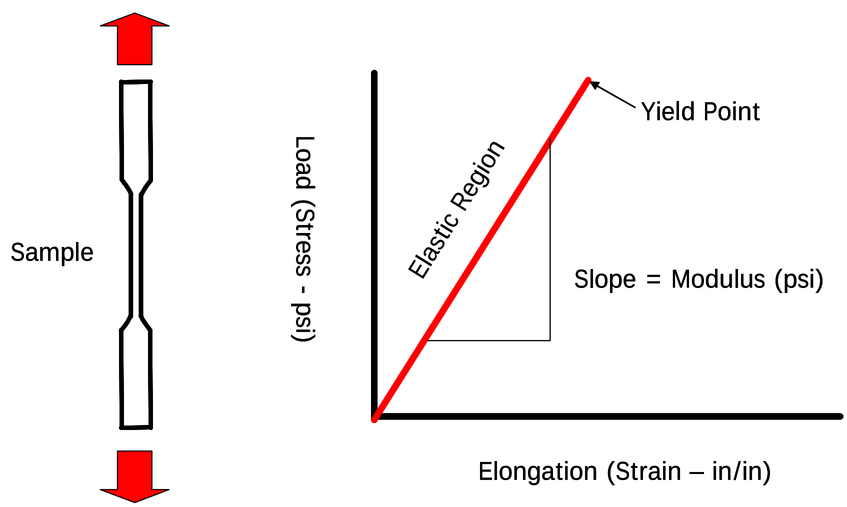

Figure 2: Determination of the modulus of elasticity from a simple tension test

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The modulus, E, is a material property and varies for different materials; however, E is normally constant for alloys of the same material. For example, all iron and steel alloys have essentially the same modulus. Examples for three materials are shown in Figure 3.

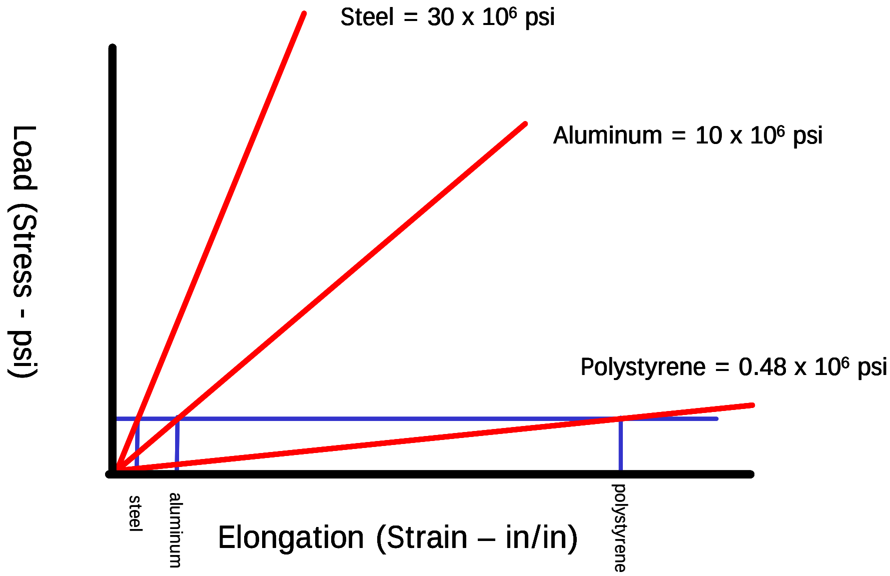

Figure 3: A comparison of the slope of the elastic portion of the stress strain curve for steel, aluminum, and polystyrene

Intuitively, looking at the slopes in Figure 3, it can be observed that for a given stress level, each material will deflect differently based on the modulus of elasticity because it is a material property. In looking at the deflection of cantilevered beams made from the three different materials, the following can be seen (see Figure 4).

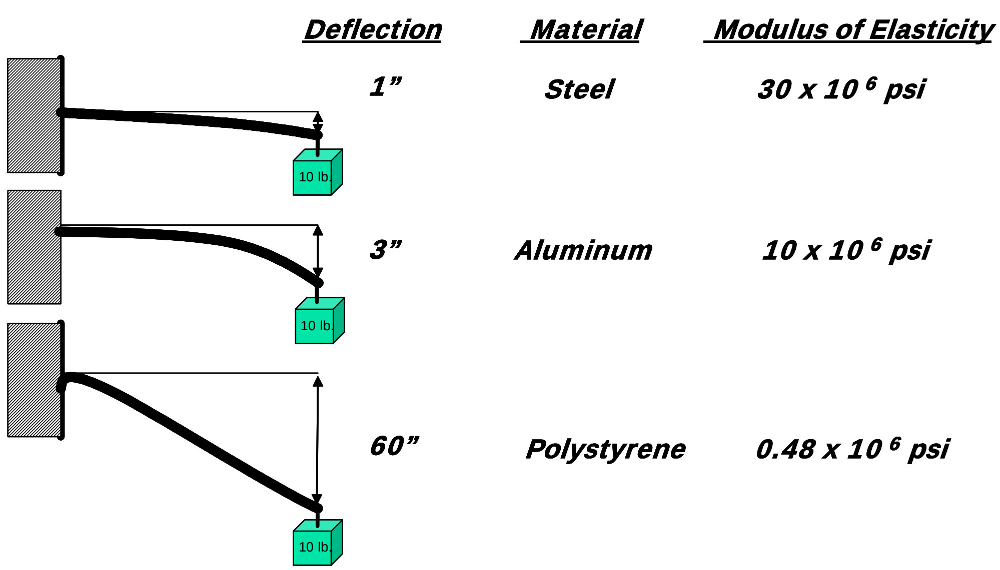

Figure 4: A comparison of modulus materials with the deflection of a simple cantilevered beam, assuming all pieces are equivalent size and shape and neglecting the weight of each member [2, 9]

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The material rigidity and density can be compared using the specific stiffness ratio [2], which is the ratio of the modulus of elasticity to the density.

$$\text{Specific Stiffness} = S_p = E/\rho$$

For example, when comparing steel to aluminum, the following is observed [3, 8]:

Steel [6] = 30×10^6 psi / 0.28 lbs/in^3
Aluminum [7] = 10×10^6 psi / 0.10 lbs/in^3

This gives an equivalent ratio for each material. Thus, steel and aluminum are very similar when looking only at the amount of stiffness per pound of weight and not considering the shape of the cross-section. The ratio for polystyrene is significantly lower, demonstrating that polymers are much less rigid than most metals.

As will be discussed, the shape effect must always be considered and can be expressed as the moment of inertia, I [1]. This is the capacity of a cross-section to resist bending. It is always considered with respect to a reference axis, such as x–x or y–y. It is a mathematical property of a section concerned with the cross-sectional area and how that area is distributed about the reference axis. This reference axis is usually a centroidal axis. This moment of inertia is an important value, which is used to determine the state of stress in a section, to calculate the resistance to buckling, and to determine the amount of deflection of a member.

The following is an example. Consider the two 1"x 4" solid bars shown in Figure 5 and determine which will deflect more and why.

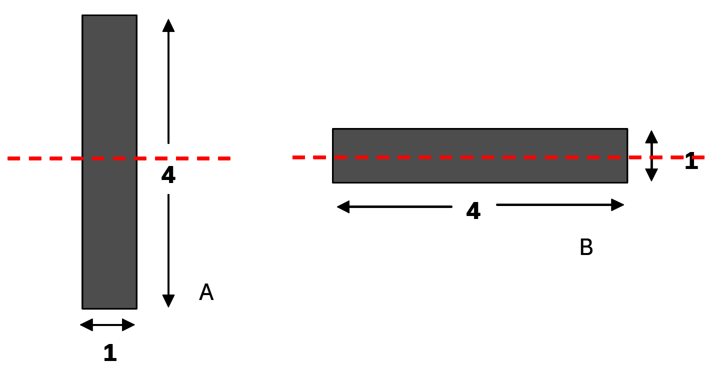

Figure 5: Example depicting the variation of the moment of inertia of the same cross section oriented relative the horizontal axis

Bar A has its 1" dimension parallel to the horizontal axis, while bar B has its 4" dimension parallel to the horizontal axis. The moment of inertia for a rectangular cross-section in relation to the horizontal centroidal axis can be calculated using the following equation [1, 4]:

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$$I_x = \frac{bh^3}{12}$$

Equation 1: Moment of inertia for a rectangular cross section

In Equation 1, b is the length of the base, and h is the height of the cross-section. Other shaped cross-sections require different equations to calculate their moments.

Using this equation and substituting values for the respective base and height dimensions, it is seen that bar A has a moment value of 5.33 in^4, while bar B has a value of 0.33 in^4. Both bars are the same size and shape; however, they are oriented differently. Bar A is significantly more rigid (16 times) than bar B. Although the cross-sectional area of both bars is the same, it is distributed differently above and below the horizontal axis, which results in a greater stiffness for bar A. Intuitively, envision a 2" x 8" piece of dimension lumber. It is clear that its rigidity when oriented with the 2" dimension parallel to the horizontal axis (like a floor joist) is significantly greater than with 8" dimension parallel to the horizontal axis.

Deflection Analysis

Combining the material property, E, and the shape property, I, into one equation gives the total deflection, δ, of the cantilevered beam, as shown in Figure 6 and Equation 2.

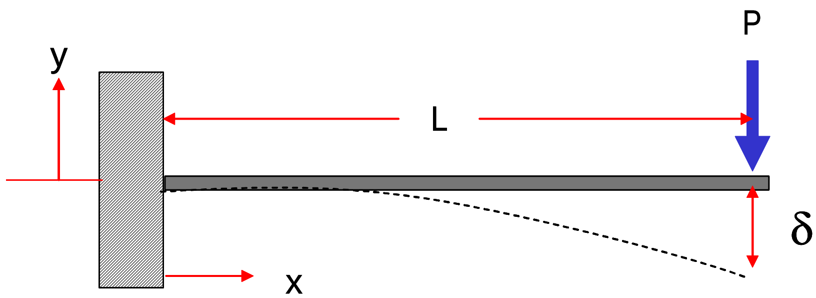

Figure 6: A cantilevered beam used in the determination of the deflection of the end relative to the applied load [1, 4]

$$\delta = \frac{-PL^3}{3EI}$$

δ = Deflection at the end
P = Load
L = Length
E = Modulus of Elasticity (material property)
I = Moment of Inertia (shape factor)

Equation 2: Equation to predict the deflection of the end of a cantilevered beam related to the modulus of elasticity, the moment of inertia, and the applied load [1, 4]

δ is the total deflection for the cantilevered structure pictured in Figure 6. Look again at the 1" x 4" steel, aluminum, and polystyrene bars to see that the total deflection of each can be

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calculated. Assume that the applied load, P, is 500 lbs., the length of the cantilevered bar is 36", and that the bar has the 1" dimension parallel to the horizontal axis. Substituting these values into the equation above gives the following results for each beam:

$$\delta_{steel} = -(500 \text{ lbs})(36 \text{ in.})^3 / 3(30 \times 10^6 \text{ psi})(5.3 \text{ in}^4) = -0.0489 \text{ in.}$$

$$\delta_{aluminum} = -(500 \text{ lbs})(36 \text{ in.})^3 / 3(10 \times 10^6 \text{ psi})(5.3 \text{ in}^4) = -0.1467 \text{ in.}$$

$$\delta_{polystyrene} = -(500 \text{ lbs})(36 \text{ in.})^3 / 3(0.48 \times 10^6 \text{ psi})(5.3 \text{ in}^4) = -3.0560 \text{ in.}$$

This reveals that the aluminum bar deflects three times as much as the steel bar of the same shape. This also demonstrates that polystyrene has a huge deflection (60 times greater) and is probably not a consideration in most designs.

Consider only the steel and aluminum bars. How can the deflection of the aluminum bar be made the same as, or similar to, the steel bar? The answer can be determined by rearranging Equation 2 and solving for I to obtain Equation 3.

$$I = -PL^3 / \delta(3)(E)$$

Equation 3: Rearrangement of Equation 2

Substitute in the value of E for aluminum, 10×10^6 psi. Use a load of 500 lbs and a length of 36" (same as before), and set the deflection, δ, of the aluminum bar to -0.0498 in. The result is 15.61 in^4.

Thus, to get a deflection of the aluminum bar equal to the deflection of the steel bar (- 0.0498"), an aluminum bar must have a moment of inertia, I, equal to 15.61 in^4. Look at the various cross-sectional shapes available for aluminum and determine which shape has a moment of inertia equal to or greater than 15.61 in^4. One example of a shape that meets this criteria is a 4" x 6" aluminum I-beam which has an I value of 21.99 in^4. This would give a total deflection of - 0.0354, which is 0.0139 less than the steel bar.

Using this method, equation, and E and I values, we can also look at other combinations of materials and cross-sectional shapes to arrive at the lowest deflection characteristics for the lowest density. In the above comparison, the 1"x 4"x 36" steel bar would weigh 40.32 lbs, and the 2"x 6"x 36" aluminum I-beam would weigh only 12.09 lbs. Thus, an aluminum I-beam has greater rigidity than the steel bar and weighs 28.23 lbs. less. This evaluation practice is common in the aerospace and transportation industries but can be used in most situations. Obviously, for differently supported beams and parts, the deflection equations are different and can be found in any strength of materials text or reference book [1, 5].

Cost

Cost must be introduced in almost all comparative design processes. This is the part that is missed in many typical courses. There are many methods that can be used to evaluate the cost factor. One simple process is to look at the material cost per pound in the above example. This yields the following:

The cost of common low carbon steel is approximately $0.25 per pound, and for a typical aluminum product it is approximately $1.00 per pound.

> 1"x 4" x 36" x 0.28 lbs /in^3 = 40.32 lbs
> $0.25 / lb x 40.32 lbs = $10.08 for the steel bar
>
> 4" x 6" x 36" aluminum I-beam weighs 4.03 lbs / ft = 12.09 lbs
> $1.00 / lb x 12.09 lbs = $12.09 for the aluminum I-beam

Therefore, the aluminum I-beam gives less deflection and costs only $2.01 more than the steel bar base on typical market prices.

Another process is to consider the actual costs per foot of the above bar and I-beam. The quoted price for 1"x 4" 1020 cold rolled steel bar is $16.60 per foot, and the 4"x 6" aluminum I-beam is $16.14 per foot [10]. The cost for a 36" section of each is $49.80 for the steel bar and $48.42 for the aluminum I-beam. On an actual cost basis, the aluminum I-beam is less expensive and significantly lighter weight and more rigid. This demonstrates an example of cost-effective design. In an aircraft, automobile, or boat, this weight difference is significant because the weight factor is one of the most important design criteria. Ultimately, cost is almost always the major consideration in the real world and should be well-understood by students. With the dramatic increase in fuel prices, the need for cost-effective design has cast its shadow on nearly everyone. The focus on high effeminacy and cost effectiveness is part of the solution to this problem.

Decision Matrix

To evaluate the above factors and integrate cost into the equation, a simple selection model, such as a decision matrix (Table 2), can be used. To create a decision matrix, the following steps should be followed.

- Establish the design criteria. In our example, the design criteria might include deflection, weight, cost, size, and safety. Many other criteria can also be included.
- Assign a weighting factor to each of the design criteria based upon the relative importance of each. Since there are five design criteria in this example, a five point scale (1–5) could be used. A weighting factor of 1 would be the least important, and 5 would be the most important.
- Develop a list of design alternatives or, in our case, material and shape combination options. This list may include the following: 1"x 4" steel bar, 1"x 4" aluminum bar, 1"x 4" polystyrene bar, and 2"x 6" aluminum I-beam.
- Establish a Rating Factor that indicates the performance of the design alternative with respect to each design criteria. These could be as listed in Table 1.

Table 1: Rating factors

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Rating Factor	Definition
1	Failure
2	Low Performance
3	Average Performance
4	High Performance
5	Outstanding Performance

- Use the above five rating factors to rate each design criteria for each of the design alternatives.
- Multiply each rating factor by each of the weighting factors and obtain a value for each design alternative.
- Determine the best design alternative by summing the respective value columns within the decision matrix. The column with the highest sum is the best choice

Table 2: Decision matrix [5]

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		1" x 4" Steel Bar		1" x 4" Aluminum Bar		1" x 4" Polystyrene Bar		2" x 6" Aluminum I-beam	
Design Criteria	Weight Factor	Rating	Value	Rating	Value	Rating	Value	Rating	Value
Deflection	**5**	5	25	4	20	1	5	5	25
Weight	**4**	1	4	5	8	5	20	5	20
Cost	**5**	4	20	3	25	2	10	5	25
Size	**2**	4	8	4	8	3	6	3	8
Safety	**3**	4	12	4	12	1	3	4	12
Totals			**69**		**73**		**44**		**90**

Clearly the aluminum I-beam is the best option. The aluminum bar has the second highest total, so it might be an alternative if the deflection meets the design standard.

Summary and Conclusions

- We as educators have the responsibility to teach engineering and engineering technology students all aspects of design, which includes cost effectiveness. They will be more effective engineers and will be immediate contributors to their company of choice.
- Based on my years of experience in industrial design and manufacturing, we fall short of the cost-effective design goal because we do not introduce or emphasize the economics in traditional engineering design courses.
- Many students graduate, begin a job, and are surprised to learn that the design they are asked to create for their company is not always the best mechanical design. It is the acceptable design that is the lowest cost or the lightest weight. In some situations, it is possible to do both, as shown in the example above.
- A decision matrix is a simple tool that can be used to distinguish among several design alternatives. Cost should be included and highly weighted in a design alternative analysis.

- Advanced decision science models and algorithms can be used for more complex designs and factors. These should be included in advanced or graduate level courses.
- With the rapid rise in energy costs and the finite supply of fossil fuels, the concept of cost-effective design has been thrust into the spotlight by consumers and manufacturers.
- Astronaut John Glenn, when asked what he felt as he sat in the Apollo capsule awaiting launch of the first manned flight to the moon, is reported to have said, "I felt exactly how you would feel if you were getting ready to launch and knew you were sitting on top of two million parts, all built by the lowest bidder on a government contract."

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Biographical Sketch

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