# *One Mechanical Design Teacher's Challenge*

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## ABSTRACT

Engineers are problem solvers. Graduating engineers leave school with a diploma and a set of "tools". Combined with the tools of societal knowledge[1] and principles that will enable them to become contributing members of their communities, these tools include basic science, mathematics, engineering science, and some practice[2] at exercising these principles. A challenge to the engineering teacher is not only to introduce these technical tools in a classroom setting, but to offer reasonable experience in their use to solve realistic problems. Unfortunately, too many students tend to accept an "answer" from a computer-based tool simply because it was an answer without interpreting or validating it. It may or may not be an answer.

This paper looks at two examples used by one mechanical design teacher in his response to this challenge, namely, a student being too quick to accept the output from a computer simulation. Two analytical models and two finite element models of the same structural objects under the same load and boundary conditions are exercised and the results compared and discussed.

The conclusion of this paper is that a person using finite element analysis software to estimate the structural response of an object should first have an idea of the magnitude of the expected response using basic engineering science before using more advanced computer simulation and, then compare the two estimates to support taking a position with respect to the acceptability of the predicted response.

## INTRODUCTION

One of the challenges of introducing advanced analysis tools, such as finite element analysis ("FEA"), is that too many engineering students are too willing to accept the output of a computer program without questioning its validity or reasonableness. The challenge to teaching the use of a computer tool is to establish the value in questioning the results of any computer simulation. This challenge is illustrated in this paper by

[1] Derived from the university's "core courses" plus their personal experiences.
[2] As in homework, labs, assignments. etc.

comparative assessment of the results of using different computer software systems to estimate the performance of two structural objects to load and boundary conditions. The performance of the objects, as measured by stress, of a cantilevered beam and a triangular bracket are estimated using two analytical methods (Strength of Materials and Theory of Elasticity) and two finite element analysis programs (Nastran and ProMechanica) to perform numerical estimates of the specified structural response.

## THE DESIGN PROCESS

The question is asked: *What is the difference between a scientist and an engineer?* One response is that a scientist discovers new knowledge while an engineer puts that knowledge to work. "The essence of engineering is the utilization of the resources and laws of nature to benefit humanity."[3] The "tools" engineers use to perform their service to society include basic science, mathematics, engineering science, and engineering principles. Undergraduate university education attempts to provide the exposure to and experience with these tools to provide a reasonably rounded person capable of being productive in society. This educational process provides a framework to which the student can add additional capabilities or skills to enhance his/her own engineering success potential.

All undergraduate mechanical engineering students at Lamar University take MEEN 3320, Mechanical Design I and MEEN 4323, Mechanical Design II. The mechanical design texts introduce the Design Process in their first chapter in a variety of ways. The Design Process can be summarized as follows:

1) Recognition of Societal Need,
2) Definition of the Problem,
3) Synthesis of Solution(s),
4) Analysis (&/or Optimization),
5) Evaluation, and
6) Presentation.

An illustration of this Process is that in the mid-1800s there was a need to expand westward to help the growing country to reach its potential (Phase 1). The problem was that the nation's transportation system was not up to the task (Phase 2). Some people said more and faster ships were needed to go from the east coast to California around the tip of South America while others said sturdier wagons were needed to travel across the undeveloped country. Groups of people would form and evolve their favored solutions (Phase 3). The most promising would then be developed in greater detail, made, tested, and revised (Phase 4). The final solution would be evaluated to see if it were a practical solution to the original problem (Phase 5). If it could be implemented or sold to the public, the product would be produced and marketed (Phase 6).

It has been the author's observation that the typical American university education stresses Phase 4 in providing engineers-to-be with the math, science, engineering tools

[3] R.C. Juvinall and K.M. Marsek, Fundamentals of Machine Component Design, 3rd ed., John Wiley, p. 3.

they need to do their work.[4] Lectures introduce the theory and principals while homework and other assignments provide practice in exercising those principals. Equations defining mathematical models simply manipulate the numbers inserted into them, incorrect units and all! Therein lies one of the major challenges in teaching mechanical design, namely, getting students to check, or interpret, their work.

## THE PROBLEM

Too many students, and unfortunately some practicing engineers as well, are too willing to accept the output of an FEA computer program without questioning the validity of the output. The classic example that comes to the author's mind is when in the early 1990s the mechanical design assignment of estimating how much the flagpole in the quadrangle in front of the Setzer Student Center at Lamar would have deflected had Hurricane Alicia come through Beaumont in 1983 rather than through Houston. The class members had to first determine the best estimates for the physical and material properties of the flagpole, such as, height (about 30 feet), wall thicknesses of the several telescoping sections, and material's stiffness and strength. They then used MSC.Nastran to make an FEA model[5] to estimate the horizontal deflection at the tip of the flagpole. This was to be reported in a word-processed memo report as a semester project. Most of the students did a credible job, but one student stood out, not for doing his work, but for the work he didn't do. He confidently handed in his report, with the extensive computer printout attached, predicting a deflection of *400* inches! This deflection had obviously violated the assumption of small deflection theory inherent in linear finite element analysis programs. When questioned about the size of the predicted deflection and the fact that the wind would have to bend the flagpole and stretch it to get the estimated 400 inches at the tip, he looked puzzled and responded, *"But there were no error messages."*[6] This situation provided an opportunity to discuss how that the absence of error messages in a computer printout has nothing to do with accuracy of the solution, but just its numerical stability. The numerical stability of a mathematical calculation is a necessary condition for an accurate prediction, but not a sufficient one.

## THE CHALLENGE

An engineer has three basic ways of estimating the response of an object under load, namely, the Experimental, the Analytical, and the Numerical. The Experimental approach builds and breaks the object and then revises the design until it doesn't fail[7]. The Analytical approach uses mathematical modeling to produce closed-form equations

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[4] It is the author's opinion that the last phase of design is the most important. And it has nothing to do with engineering, but without it, why should an engineer spend any time developing a unique (and potentially very useful) solution if s/he can't "sell" it to her/his management or client? The salesmanship associated with the Presentation Phase is so very important. The ability to read/write/speak/spell proper English is critical to a person's success as an engineer.
[5] Geometry, Elements, Element Properties, Material Properties, Loads, and Boundary Conditions.
[6] Nastran tags coding errors, either as simply "Warnings" and as the more serious "Fatal" error. This student had neither of these error messages in his printout.
[7] What constitutes failure is another one of those "tools" that are taught in the Lamar curriculum.

that "calculate"[8] the response. The Numerical approach is a mathematical approximation of the object and its deflection and/or stress response[9]. An example of this last approach is the increasingly popular *finite element method*.

This paper combines the latter two approaches above to illustrate the point of the paper, namely, that finite element model results must always be interpreted. All FEA response predictions must be interpreted before they are accepted. The challenge to teaching the use of a computer-based tool, such as finite element analysis, is to establish the value in questioning the results of any FEA simulation.

**Examples of the Challenge**

This teaching challenge is addressed in this paper through comparative assessment of the results of using different FEA software to estimate the performance of objects to the same load and boundary conditions. The two objects chosen were a cantilevered beam and a triangular bracket.

Consider first the cantilevered beam shown in Figure 1.

Example 1: Cantilevered Beam, Transversely Loaded at its Free End

For this steel beam example, a = 1", b = 2", c = 1" and L = 12". A 1,000 $lb_f$ load is applied as an end load downward. The four stress response estimates, two analytical and two FEA, are expected to be close to each other. How close is "close enough" is the challenge for the student.

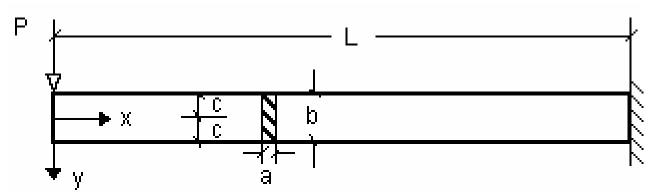


**Figure 1: Cantilevered Beam**

Two analytical approaches for estimating the stress response are the commonly used Strength of Materials ("SoM") approach[10] and the more advanced Theory of Elasticity ("ToE") approach[11]. In the bending stress equations below for any point (x, y) in the beam, P is the end load, E is the Young's modulus, ν is Poisson's ratio, and I is the moment of inertia of the cross-section.

Strength of Materials: $$\sigma_b = -\frac{My}{I} = -\frac{(Px)y}{I}$$

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[8] Calculation is a mechanism only and does not imply "correctness". Correctness is a judgment.
[9] "Approximation" is the key word.
[10] The basics introduced in the sophomore year at Lamar University in CVEN 2372, Mechanics of Solids, and amplified in MEEN 3320, Mechanical Design I.
[11] At Lamar this is a graduate course, ENGR 5315, Theory of Elasticity.

Theory of Elasticity: $\sigma_b = -\dfrac{Pxy}{I}$

These two stress equations estimate the same level of stress in this particular object. The results are summarized in Table 1 where the positive signs indicate tensile stresses and the minus signs indicate compressive stresses. In other objects these stresses most likely will be different, as demonstrated with the triangular bracket in Example 2.

The Numerical approach was implemented using two different FEA programs[12]. A three-dimensional ("3-D") geometric model of this beam was made in ProEngineer ("ProE"), the parametric solids modeling part of Parametric Technology Corporation's software system. The ProE model was then taken into ProMechanica ("Mechanica"), the analysis part of the software system, where the type of material used was assigned, the load defined, and boundary conditions applied. After being analyzed in Mechanica and the results recorded, the ProE model was converted in Mechanica to an input data file for use in MSC.Nastran ("Nastran"), the software system provided by the MacNeal-Schwendler Corporation. Nastran analyzed the response using the same material, load[13] and boundary conditions.

The initial stress results are summarized in Table 1. The differences in the values are addressed and discussed in the next section. The effect of mesh controls to illustrate the challenge in using FEA in the classroom are summarized in Tables 2 and 3.

Example 2: Triangular Bracket, Uniformly Loaded

The 12"x12"x1" steel bracket has a 1,000 $lb_f$ load applied as a load per unit length, w. The bracket is shown in Figure 2.

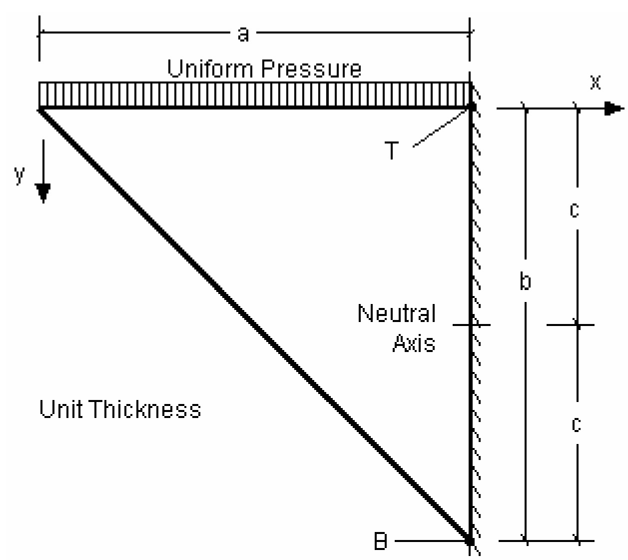


**Figure 2: Triangular Bracket**

[12] MSC.Nastran, a linear, h-element formulation approach and ProMechancia, a p-element formulation of polynomial order up to $9^{th}$ order.
[13] Gravity was not considered in either model of either example.

The SoM stress equation used to calculate the stress at the wall is taken from the machine design text[14] currently used in Mechanical Design I and II. The expanded equation is

$$\sigma_b = -\frac{My}{I} = \pm \frac{[(wa)(\frac{a}{2})]c}{I}.$$

The ToE equation for the same $\sigma_{xx}$ stress, or bending stress $\sigma_b$, at any point (x, y) for a uniformly distributed load per unit length w is derived from Timoshenko[15]. The normal stress in the x-direction is

$$\sigma_b = \sigma_{xx} = \left[\frac{4w}{(4-\pi)}\right]\left\{\frac{\pi}{4} - \frac{xy}{(x^2+y^2)} - \arctan\left(\frac{y}{x}\right)\right\}$$

A 3-D model of the bracket was constructed in ProE and used in both Mechanica and Nastran to generate the FEA models. The data of Table 4 below resulted from the use of the default values for the FEA model parameters, such as, element size. This example did not warrant a sensitivity study relating to mesh controls.

It is reiterated that the paper simulates a new user who initially takes the built-in defaults of the software, using it somewhat as a "black box".

## SUMMARY AND DISCUSSION OF RESULTS

The trend that one would expect in the bending stress results when using analytical calculations and FEA simulation of the same object is for the Analytical approach to predict a lower stress than the Numerical, or FEA, approach since the FEA model is a mathematical approximation of the stiffness of the object being modeled.

Consider first the results for the end-loaded cantilevered beam.

### Cantilevered Beam

The initial summary of the stress estimates using the four approaches for the cantilevered beam is given in Table 1.

**Table 1: Stress Response of End-Loaded Cantilevered Beam**

| | Analytical Approach | | Numerical (FEA) Approach | |
|---|---|---|---|---|
| **Response Parameter** | **Strength of Materials** | **Theory of Elasticity** | **MSC.Nastran Center / Corner** | **ProMechanica Center / Corner** |
| $\sigma_{xx}$, psi, (Top) | 17,990 | 17,990 | 5,802 / 9,089 | 19,659 / 20,680 |
| $\sigma_{xx}$, psi, (Bottom) | -17,990 | -17,990 | -4,642 / -4,921 | -16,750 / -19,630 |

[14] Juvinall & Marshek, 3rd edition, p. 186.

[15] S.P. Timoshenko and J.N. Goodier, Theory of Elasticity, 3rd edition and applied in the author's ENGR 5315 class notes.

These initial stresses predicted for the cantilevered beam using default values for the FEA parameters show significant variations in the predictions, especially for the Nastran model. Does this say Nastran is no good as an FEA tool. Absolutely not! It just means the results need to be investigated.

As a first step in this investigation of the differences in the FEA estimates, consider averaging the corner and center estimates of the stresses in the Nastran and Mechanica models. These average stresses at the top and the bottom of the cross-section are better estimates for comparison with the analytical estimates if no further investigation were done. These averages are given in Table 2.

**Table 2: Summary of Averaged Stress Estimates, Cantilevered Beam**

| | **Analytical Equations** | | **FEA Approach** | |
|---|---|---|---|---|
| **Response Parameter** | **Strength of Materials** | **Theory of Elasticity** | **Nastran Average** | **Mechanica Average** |
| $\sigma_{xx}$, psi, (Top) | 17,990 | 17,990 | 7,414 | 20,170 |
| $\sigma_{xx}$, psi, (Bottom) | -17,990 | -17,990 | -6,968 | -19,315 |

The relative magnitudes are still an issue since the FEA models are expected to estimate higher stress values than the Analytical approaches. Mechanica seems to be there, but not Nastran. This variation in the Nastran results was further investigated in a sensitivity study of the results to changes in mesh size, something that most students don’t do unless specifically directed.

Mechanica simulates a finer mesh (i.e., smaller elements) through increasing its polynomial order in areas of rapidly changing stress, such as at the wall. To get the equivalent effect in Nastran, a user would need to specify smaller elements in regions of expected high stress gradients. The FEM mode of Mechanica produces the Nastran input deck from the ProE solids model using a default mesh size, in this case, 1”. Thus, it uses two CTETRA solid elements[16] to model the 2” vertical dimension of the bar. For this object, Table 2 shows this number of elements to be inadequate.

Using only two large elements through the thickness of the beam in the area of the maximum bending stress is not good modeling because the results calculated for the CTETRA element are keyed to the centroid of the element. In this case the centroid is relatively well away from the top (or bottom) edge and one would get significantly less stress due to the shorter moment arm (y) from the neutral axis of the cross-section at the wall. The centroid can be simulated closer to the top and bottom edges by using smaller elements, thus driving the moment arm farther from the neutral axis and closer to the top and bottom surfaces. A finer, or smaller, mesh by Nastran should produce results closer to, or exceeding, the Mechanica estimates. A variation in mesh size was done to illustrate this expectation.

Element size in the FEM mode of Mechanica that produces a Nastran input file is controlled by a “mesh size” parameter. If that parameter is set to produce a CTETRA

[16] These elements are acknowledged to be stiffer than the more commonly used CHEXA “brick”, but it allows more efficient automatic generation of the 3-D element mesh in Mechanica’s FEM mode.

element no larger than 0.125" on the surface at the wall as opposed to the 1" defaulted element size in this case, the stresses predicted change dramatically, as seen in Table 3.

**Table 3: Summary of Stress Estimates for Smaller Nastran Elements**

| | Analytical Equations | | FEA Approach | |
|---|---|---|---|---|
| **Response Parameter** | **Strength of Materials** | **Theory of Elasticity** | **Nastran Average** | **Mechanica Average** |
| $\sigma_{xx}$, psi, (Top) | 17,990 | 17,990 | 25,191 | 20,185 |
| $\sigma_{xx}$, psi, (Bottom) | -17,990 | -17,990 | -19,896 | -19,315 |

This trend between the predictions is more like that expected. Note that both FEA models predict different values for the top and bottom edges at the wall unlike the two analytical estimates. These top and bottom estimates are even more dramatic in the case of the triangular bracket as is seen in the data of Table 4 below.

It was not the objective of this paper to find an optimum mesh for the cantilevered beam for these two FEA approaches to demonstrate the expected trend, but rather to illustrate what one gets by using an FEA program without fully understanding the nature of the assumptions implicit in the programs. This unexpected trend in Tables 1 and 2 for the Nastran data can be confusing to a "plug-and-grind" user who may have his/her attention on another pressing assignment. But that is an excuse, not a reason.

A real problem would exist if the Nastran model with the default-sized elements produced in the FEM mode of Mechanica had been the only estimate made of the stresses. One must be cautious when using FEA blindly.

Consider now the results for the triangular steel bracket.

**Triangular Bracket**

The expected trends for the stresses between the Analytical and FEA approaches have been stated previously. These trends are observed in the stress results in Table 4. This would be comforting to a student having had an introduction to the Strength of Materials approach and now just beginning to use FEA, until another anomaly is recognized, namely, that none of the methods outside of SoM predict equality between the tensile (top) and compressive (bottom) stresses as does the SoM equations first taught sophomore engineering students. This is a challenge to the mechanical design teacher who will build on this strength of materials foundation.

**Table 4: Stress Response of a Triangular Bracket with Uniform In-Plane Loading**

| | Analytical Approach | | Numerical (FEA) Approach | |
|---|---|---|---|---|
| **Response Parameter** | **Strength of Materials** | **Theory of Elasticity** | **Nastran (Default)** | **Mechanica (Default)** |
| $\sigma_{xx}$, psi, (Top) | 250 | 305 | 605 | 743 |
| $\sigma_{xx}$, psi, (Bottom) | -250 | -194 | -85 | -43 |

Variation in stress predictions in the bracket is definitely a dilemma for a new user of FEA. Not only is the variation between the Analytical and Numerical approaches in Table 4, but between the top and bottom of the cross-section at the wall in all approaches except with the SoM. The variation between FEA approaches can be expected, but there is now a variation in the ToE estimate between the top and bottom. With respect to the Strength of Materials approach, the Theory of Elasticity is the more accurate because it incorporates fewer assumptions made during the derivation of the two sets of equations.

The two Analytical stress estimates for the bracket are both lower than predicted by FEA models, as expected. The same top-to-bottom trend seen in the beam example is observed in both the Mechanica and Nastran FEA results for the bracket. The bracket's Nastran model incorporated the default settings programmed in the Mechanica FEM module that generated it from the ProE model. However, it had less an effect on the number, and size, of the finite elements because the bracket is thin relative to its other dimensions. In the case of the beam, the thickness was on the same order as the other beam dimensions. Conveying this type of modeling sensitivity to a student using FEA is a challenge.

**Discussion**

The following points reflect this mechanical design teacher's experience with someone who does calculations and FEA studies without due consideration of the reasonableness of the estimated stress response.

1) A person should always interpret the results of calculations or simulations for reasonableness. It is not unusual to find engineering students substitute numbers into equations without questioning the reasonableness of the "solution". One common characteristic of this situation is inconsistency in the units of the numbers used in the simulations[17]. Unless one substitutes the units along with the numerical values in equations at the beginning of the calculation, it is easy to automatically assume that everything is okay when the "answer" falls out of the calculator or computer. Results calculated with inconsistent units are useless. Another example is where units are mixed, such as using "mm" and "inch" parameters in the same equation without converting one of them.

2) Computers may only get you a bad answer quicker. Many use FEA programs almost as "black boxes" not understanding what was being calculated. Before computers came along the simple equations of the Strength of Materials were the "way to go". As microcomputers replaced the slide rule, developers programmed them to automate the solution of matrix methods of structural analysis giving rise to the FEA phenomenon of today. For the unwary, computers can simply get wrong answers quicker!

3) A challenge to a teacher is to introduce the more advanced and capable finite element analysis method as a tool that when used must be used with extreme caution. Just because there are no "error messages" does not mean that the results are acceptable. Results must be consistent with what basic engineering principals would predict. Such reasonableness is influenced by engineering judgment of the user.

[17] This is not reserved just for students as evident in the recent loss of a NASA probe to Mars caused by one design group using "mm" units while another used "inches".

4) One guards against unreliable answers from finite element analysis studies by having a Strength of Materials estimate available for comparison. One recent Lamar ME graduate told me that his current assignment was to find a way to get a SoM estimate of the sophisticated FEA structural model others at the time were preparing. The company wanted an independently made and manually-generated (analytical) estimate as a gauge for comparing with the FEA (numerical) response when it became available.

5) Stress is not a function of the material used, but only of geometry. Many find it hard to grasp that a cantilevered beam made out of plastic will have the same stress as a steel beam under the same conditions. Note that the three stress equations given in the paper do not contain the material parameter, E, or Modulus of Elasticity. Only the deflection is a function of the material used.

7) Calculations predict, they do not specify. The mechanical design of objects relies heavily on *calculations*, or the Analytical approach, and *simulations*, the Numerical approach as given in the finite element analysis method. In no case is a calculation or simulation absolute or final. Calculations and simulations are both approximations and must be interpreted as such. To use them without applying judgment is to invite disaster.

## CONCLUSIONS

The conclusions supported by this paper include:

1) A person should always interpret the results of computer simulations.

2) Computers may only get you a bad answer quicker.

3) A challenge to a teacher is to introduce the finite element analysis method as a tool that when used must be used with extreme caution.

4) One guards against unreliable answers from finite element analysis studies by having a Strength of Materials estimate available for comparison.

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Professor Corder received his B.S., M.S., and Ph.D. ('68) in Mechanical Engineering from Texas A&M University. He then spent nineteen years in industry including the defense industry, mobile jackup platforms, fixed offshore platforms, and gravity-based drilling and production platforms for use all year in the Arctic Ocean. The last eighteen years have been spent teaching mechanical design in the Mechanical Engineerng Department at Lamar University in Beaumont, Texas and holds a professional engineer license in the state of Texas.