One Mechanical Design Teacher's FEA Challenge

Paul R. Corder

Mechanical Engineering Department
Lamar University
Beaumont, Texas

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 error-free response without interpreting or validating the results. The results may or may not be an "answer".

This paper looks at two examples used by this 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 principles 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 computer-based 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 comparative assessment of the results of using different computer software systems to

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

estimate the performance of two structural objects to load and boundary conditions. The performance of a cantilevered beam and a triangular bracket are evaluated using two analytical methods (Strength of Materials and Theory of Elasticity) and two finite element analysis programs (Nastran and Mechanica) to perform numerical estimates of their stress response under similar loads.

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 a Societal Need,
2) Definition of the Problem (associated with that Need),
3) Synthesis of Possible Solution(s),
4) Analysis (of the "best" one),
5) Evaluation (with respect to it solving the Problem), and
6) Presentation (of the solution).

An illustration of this Process is that in the mid-1800s there was a societal 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 yet 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 cargo wagons were needed for people to travel across the undeveloped middle of the 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 modified (Phase 4). The final solution would be implemented and, thus, evaluated to see if it were a practical solution to the original problem (Phase 5). If the solution was acceptable and could be 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, 4th ed., John Wiley, p. 3.

they need to do their work[4]. Lectures introduce the theory and principles while homework and other assignments provide practice in exercising those principles. Equations defining mathematical models simply manipulate the numbers inserted into them, incorrect units and all! Therein lays 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 with its 125^+ mph winds rather than through Houston near where the author lived at the time. 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 the material's stiffness and strength. They then used MSC.Nastran ("Nastran") to make an FEA model[5] to estimate the horizontal deflection at the tip of the flagpole. This estimate was to be submitted 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 fan-folded computer printout attached, predicting a horizontal deflection of <u>*400*</u> inches! This deflection had obviously violated the assumption of small deflection theory inherent in linear finite element analysis. When questioned about the magnitude of the predicted deflection and the fact that the wind would have to bend the flagpole and <u>stretch</u> 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 a "teaching moment" to discuss how the absence of error messages in a computer printout has nothing to do with the <u>accuracy</u> of the solution, but just its <u>numerical stability</u>[7]. 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. They are the EXPERIMENTAL, the ANALYTICAL, and the NUMERICAL. The Experimental approach builds and breaks the object and then revises the design until it

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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" or as the more serious "Fatal" error. This student had neither of these error messages in his printout.

[7] Assuming there was a small epsilon.

doesn't fail[8]. The Analytical approach uses mathematical modeling to produce closed-form equations that "calculate"[9] the response. The Numerical approach is a mathematical approximation of the stiffness of the object and its deflection and/or stress response[10]. An example of this last approach is the increasingly popular *finite element method*.

This paper combines the latter two approaches to illustrate the point of the paper, namely, that finite element model results must always be interpreted. All FEA response predictions must be <u>interpreted</u> before they can be accepted. The challenge to teaching the use of a computer-based tool, such as finite element analysis, is to establish the value of the extra "work" needed 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 such as used for a storage shelf.

Consider first the cantilevered beam shown in Figure 1.

<u>Example 1: Cantilevered Beam, Transversely Loaded at its Free End</u>

For the steel beam shown below, 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 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. The stress component is the stress normal to the wall, σ_{xx}.

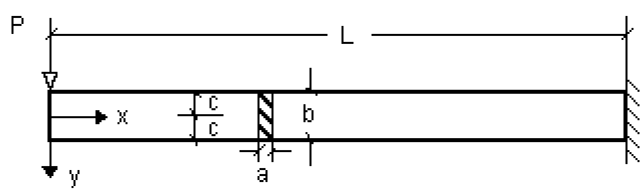

Figure 1: Cantilevered Beam

Two analytical approaches for estimating the stress response are the commonly used Strength of Materials approach[11] and the more advanced Theory of Elasticity approach[12]. 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] What constitutes failure is another one of those "tools" that are taught in the Lamar curriculum.
[9] Calculation is a mechanism only and does not imply "correctness". Correctness is a judgment.
[10] "Approximation" is the key word.
[11] The basics introduced in the sophomore year at Lamar University in CVEN 2372, Mechanics of Solids, and amplified in MEEN 3320, Mechanical Design I.
[12] At Lamar this is a graduate course, ENGR 5315, Theory of Elasticity.

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

In this case, the two equations estimate the same level of stress in the identified 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 is demonstrated with the triangular bracket in Example 2.

The Numerical approach was implemented using two different FEA programs[13]. 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 Mechanica, the structural 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 Nastran, the software system provided by the MacNeal-Schwendler Corporation. Nastran analyzed the response using the same material, load[14] 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 effects 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 In-Plane

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

The strength of materials equation used to calculate the stress normal to the wall is taken from the machine design text[15] 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 theory of elasticity equation for the same σ_{xx} stress, or bending stress σ_b, at any point (x, y) for a uniformly distributed load per unit length w is derived from Timoshenko[16]. The normal stress in the x-direction at any point (x,y) is

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

[13] MSC.Nastran, a linear, h-element formulation approach and Mechanica, a p-element polynomial formulation of up to 9th order.

[14] Gravity was not considered in either model of either example.

[15] Juvinall & Marshek, 4th edition, p. 123.

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

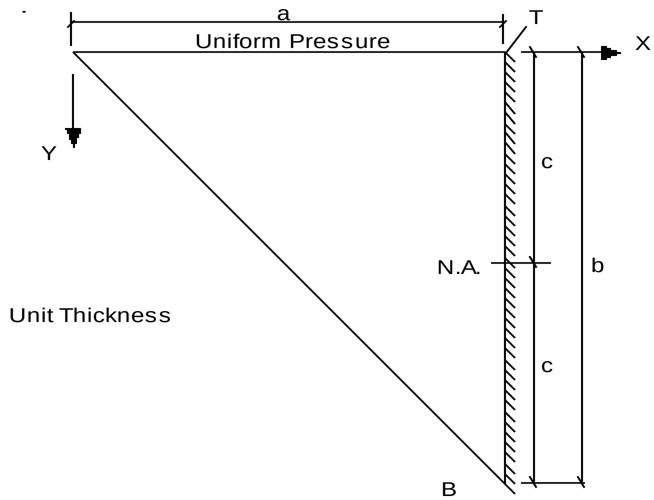

Figure 2: Triangular Bracket

A 3-D model of the bracket was constructed in ProE and used in both Mechanica and Nastran to generate the FEA model results. 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 to get an optimal solution. The study simulates a user new to FEA who initially takes the built-in defaults of software, using it somewhat as a "black box".

SUMMARY AND DISCUSSION OF RESULTS

The trend that one would expect in 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 analysis 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**	**Nastran Center / Corner**	**Mechanica Center / Corner**
σ_{xx}, psi, (Top)	17,990	17,990	5,802 / 9,089	19,659 / 20,680
σ_{xx}, psi, (Bottom)	-17,990	-17,990	-4,642 / -4,921	-16,750 / -19,630

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 model and its results need to be investigate further.

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, End-Loaded Cantilevered Beam

	Analytical Equations		**FEA Approach**	
Response Parameter	**Strength of Materials**	**Theory of Elasticity**	**Nastran Average**	**Mechanica Average**
σ_{xx} , psi, (Top)	17,990	17,990	7,446	20,170
σ_{xx} , psi, (Bottom)	-17,990	-17,990	-4,782	-18,190

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 investigated in a study of the sensitivity of the results to changes in mesh size, something that most students don't do unless specifically directed by their instructor.

Mechanica simulates a finer mesh 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 file from the ProE solids model using a default mesh size, in this case, 1". Thus, it uses two CTETRA solid elements[17] to model the 2" vertical dimension of the bar. For this object, the Nastran results of Table 2 show this number of through-thickness 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 practice 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 the Mechanica estimates. A variation in Nastran 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

[17] 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**
σ_{xx}, psi, (Top)	17,990	17,990	25,191	20,185
σ_{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 that have equal magnitudes for the top and the bottom.

It was not the objective of this paper to find an optimum mesh for the cantilevered beam for these two FEA approaches, 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 some other un-related course. 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 triangular steel bracket of Figure 2.

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 strength of materials predict equality between the tensile (top) and compressive (bottom) stresses as does the strength of materials equations first taught sophomore engineering students. This is a challenge to the mechanical design teacher who intends to 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 Mesh)**	**Mechanica (Default Mesh)**
σ_{xx}, psi, (Top)	250	305	605	743
σ_{xx}, psi, (Bottom)	-250	-194	-85	-43

Variation in stress predictions in the bracket is definitely a dilemma for a new user of FEA who stops to think about it. 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 strength of materials. The variation between FEA approaches can be expected, but there is now a variation in the theory of elasticity estimate between the top and bottom. With respect to the strength of materials approach, the theory of elasticity is considered the more accurate because it incorporates fewer assumptions made during the derivation of the two 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 and small through-thickness elements automatically result. In the case of the beam, the thickness was on the same order as the other beam cross-sectional dimension. 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) <u>A person should always interpret the results of calculations or simulations for reasonableness.</u> 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[18]. 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 and units are attached. Results calculated with inconsistent units are useless. Another example is where units are mixed, such as using "mm" and "inch" units in the same equation without converting one of them.

2) <u>Computers may only get you a bad answer quicker.</u> 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) <u>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.</u> Just because there are no "error messages" does not mean that the results are acceptable. Results must be consistent with what basic engineering principles would predict. Such reasonableness is influenced by engineering judgment of the user.

[18] This is not reserved just for students as evident in the early 1990s 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, or similar, estimate available for comparison. Recently one Lamar M.E. graduate told the author that his current assignment was to produce a strength of materials, or hand calculation, estimate of the performance of a new down-hole drilling tool for comparison with a sophisticated FEA model of the tool that others in the company were preparing. His supervisor wanted an independently made and manually-generated (analytical) estimate to use as a gauge for comparing with the FEA (numerical) response when that 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 wood will have the same stress as a same-size steel beam under the same conditions. Note that the three stress equations given in the paper do not contain the material stiffness parameter, E, or modulus of elasticity, but only geometry. 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 an independent Strength of Materials, or equivalent, estimate available for comparison.

PAUL R. CORDER

Professor Corder received his B.S. ('63), M.S. ('65), 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, gravity-based drilling and production platforms for use all year in the Arctic Ocean, and the space program. The last twenty-two 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.