AC 2011-2300: A PHILOSOPHY OF INTEGRATING FEA PRACTICE THROUGHOUT THE UNDERGRADUATE CE/ME CURRICULUM

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A Philosophy of Integrating FEA Practice throughout the Undergraduate CE/ME Curriculum

Abstract

The availability and accessibility of professional-quality Finite Element Analysis (FEA) software, bundled with solid modeling CAD tools, presents the opportunity to enhance ME and CE engineering instruction. In part this would be by illustrating and reinforcing class materials, and in part by enabling novice students to study problems of deeper complexity and design orientation. Although some freshmen design courses are beginning to incorporate FEA as a modeling and simulation tool, it appears that attempts to incorporate FEA in subsequent mechanics courses like Statics and Mechanics of Materials are often mired in top-down theory-first pedagogy. We argue that a theory-first approach is neither necessary nor even sufficient to leverage the full potential of the available tools throughout all of the formative phases of the curriculum. Based on evidence from experience, we advocate for a new, consistent approach of early and continued exposure to FEA, beginning with the freshmen year, and continuing with subsequent mechanics courses, in which students can learn and interpret results of FEA, without requiring deep instruction in the underlying FE theory. We further argue that this concurrent FEA usage will improve students' understanding of mechanics theory and practice. We hope that this paper may provide a foundation and justification for considering the use of professional software in engineering education.

1. Introduction

Professional quality software for Finite Element Analysis is now routinely bundled with solid modeling CAD tools, and formerly-complex tasks have been streamlined into a few standard mouse picks (with options to refine as desired). Therefore novices can potentially begin modeling and running simple problems after just a few minutes of instruction. This raises questions of how such a powerful tool should be used in the undergraduate ME and CE curricula, where it may both bolster the learning process, and develop competence in a valuable professional skill. In addition, the idea of integrating sophisticated software into most mechanics-based classes highlights some perennial questions about engineering, and about learning.

To address these questions, in Section 2 we provide a literature review of attempts to integrate FEA into courses from the ME or CE curricula. Several attempts to use FEA with *freshman design courses* have been made, with a tendency to deemphasize FE theory, and use FEA as a tool to investigate problems of analysis and design. In contrast, it appears that the dominant trend in prior efforts to integrate FEA into the *basic mechanics courses* (Statics, and Mechanics of Materials) involved top-down theory-first approaches incorporating at least a reduced version of FE theory (e.g., derivation of simple elements). As we discuss, our proposal is to emphasize the use of FE as a tool, not only in the freshman courses, but throughout subsequent courses in mechanics, although surely with progressively increasing sophistication. We did not discover an articulation of such an overall philosophy in the literature.

In Section 3, we acknowledge and respond to some common objections to early or non-theory based uses of FEA in undergraduate courses, including matters such as ‘principles vs. tools’, accessibility, technological obsolescence, and computation errors. While we generally discount many of these objections, they perhaps explain the cautionary ‘theory-first’ approach of the examples from the literature review. In Section 4, we respond to concerns about the risk of foregoing mathematical skills development.

In Section 5, we enumerate and discuss the kinds of intellectual foundations and skills that appear to be important for successful use of FEA. These should not be considered to be necessary *a priori*, and thus barriers to the early incorporation of FEA; rather, they are to be developed and reinforced throughout the curriculum as the student advances. These skills include creating sensible models, generating meaningful solutions, and interpreting them within a framework of evolving sophistication. Most of these rely on mechanics concepts such as an appreciation of linearity, the mechanics of single or multiple load paths, the tensorial nature of stress (not to be confused with teaching tensor theory *per se*), the mechanics of long uniform members, and the interpretation of stress results for plastic collapse, fatigue initiation, or brittle failure. Other skills, such as the implementation of a desired boundary condition, or mesh refinement to achieve convergence, are tied more closely to the nature or limitations of the software. Especially, the very iterative nature of modeling a complex situation simply, in order to approximate the results of interest, needs to be approached in a way that encourages critical exploration, once students are less stymied by hand-calculation difficulties.

With that foundation, in Section 6 we suggest a path forward for the integration of FEA into the ME and CE curricula. Of course we advocate expanding the practice of early exposure in freshman design courses, in which mechanics understanding need not *precede* FEA usage. But whether or not this has been possible, we recommend that FEA should be used synergistically within subsequent classes such as Statics, Mechanics of Materials, Design of Machinery, and Structures, where increasing conceptual and procedural knowledge of mechanics fundamentals will aid in correctly using FE software, and conversely, increasing skill using the FE software will simultaneously enable students to explore more deeply the main concepts of those subjects. In this integrated approach, students will repeatedly be engaged in matching theory (mechanics) to simulation, which should be a powerful reinforcement of both.

For these and other reasons, we argue that it is desirable to strategically incorporate FEA, emphasizing its use as a tool, into any class where it can be applied. A useful amount of coverage might be roughly equivalent to one week of lectures, and two weeks of homework, within each of three or four courses (preferably spread out through the term). A few specific ideas are provided for using this sophisticated modern tool in various engineering classes. This has been done on a trial basis, using the SolidWorks Simulation platform, in classes ranging from Introduction to Engineering, up through Advanced Strength of Materials. Informal student feedback was always enthusiastic.

2. Literature Review

Using modern CAD-integrated FEA it is easy to create a 3D model of a complex solid object, apply boundary conditions, mesh, and solve. Within about an hour, anyone who is familiar with

Microsoft Windows and understands the component description of a force can learn how to do this for a diverse range of shapes and loadings. And the graphical portrayal of input and output quantities makes it easy to detect many user errors. But what are educators doing to incorporate this ubiquitous, increasingly inexpensive tool into basic engineering classes?

The practice of embedding or integrating FEA into freshman design courses seems to have made an appearance in the 1990's, coincident with the movement to develop integrated freshman curricula that include or emphasize design. Barr et al. (1998; 2005)[1,2] describe their work to include FEA as part of a larger focus on solid modeling in an engineering design graphics course. Cole (1999)[3] articulated a similar strategy to include FEA as part of a philosophy of integrating CAD into the Mechanical Engineering Technology curriculum. Ural & Yost (2010)[4] report developing a freshman level project to investigate the behavior of a SMARTBEAM®, in which the FEA and experimental measurements are conducted simultaneously and compared. In each of these cases, use of FEA as a practical tool is emphasized, and none appeared to require students to learn the underlying FE theory or to know principles of mechanics of materials *a priori*. Numerous other examples, not cited here, appear to exist in introductory freshman design courses.

In contrast to the situation with freshman courses, attempts to incorporate FE into the basic mechanics courses, Statics and Mechanics of Materials, seem to be more isolated. This is not surprising since such courses are largely focused on by pencil & paper problems involving closed form solutions amenable to hand calculation. Furthermore, any such efforts seem to have been dominated by top-down, theory-first approaches in which direct instruction of basic FE theory is presented. Brinson et al. (1997)[5] advanced the idea of teaching a matrix approach to understanding 1-D beam elements and 2-D triangular elements. Several other attempts to integrate FEA into early mechanics courses appear to focus on FE theory equally intensively, e.g., Earley (1998)[6]; Zhao (2004)[7]; and Chaphalkar & Blekhman, (2007)[8]. However, we did find two examples of insertions of FEA into mechanics courses that appear to deemphasize FE theory, although the level of detail in each is perhaps insufficient to be conclusive. Boronkay & Dave (1997)[9] introduce FE into Mechanics of Materials as part of a revised ME Technology curriculum, and Pike (2001)[10] introduces FE into a design project as part of Statics. In summary, we conclude that the occasional use of FEA in undergraduate mechanics courses is almost always top-down, theory-first.

We do acknowledge some attempts to emphasize the use of FEA as a working tool within undergraduate FEA courses, e.g., Coyle & Keel (2001)[11]; Jolley, Rencis & Grandin (2003)[12]; and Prantil & Howard (2008)[13]. This is welcome, but impels us to emphasize that we are not talking primarily about FE courses, but rather the application of FEA within several prior undergraduate courses. Based on this review, we are encouraged by the developments of integrating FEA as a hands-on tool in the freshman design courses, and advocate for this approach to continue in subsequent courses in Statics, Mechanics of Materials, and beyond. To our knowledge, a philosophy for integrating FE as a tool *throughout* the undergraduate engineering curriculum has not been articulated. It is thus the objective of this paper to propose one: effectively an amplification of Papadopoulos (2004)[14].

3. Discussion of Conventional Objections to Using FEA in Traditional Classes

We open with an analogy, meant to caricature typical justifications for not teaching FEA practice within the core disciplinary courses:

One can imagine a complicated and expensive mechanical calculator (ca. 1950) being advertised as a major advance in engineering. Structural calculations could be performed via relaxation methods by filling out a series of tables according to precise rules. But students would need many hours of training to learn to operate the calculator, lay out a particular type of calculation, and arrive at a result. And they probably wouldn't have access to such an expensive tool in their careers if their eventual employer did not provide it. So if presented with an either-or choice, anyone would surely conclude that learning the fundamentals of structural mechanics principles and calculations is preferable to learning to use the complex equipment. Learning the fundamentals would equip students to understand any new generation of calculator and technique; whereas, studying the previous decade's best method without the fundamentals would soon leave the students professionally obsolete.

In addition, these original calculating machines and methods had an unfortunate abstract aspect: there were many detailed, error-susceptible steps to work through before arriving at a result that could be interpreted in concrete terms. So, the chance of an error was increased, while the detection of that error required an independent method of getting the result.

Are such concerns relevant to modern FEA? We tend to think not. It's quick for a typical student to learn enough to get started, so we needn't posit an exclusive choice between fundamental understanding, *versus* ability to use the software – both should be possible! Also, the software is almost universally available. Upgrades mainly involve minor interface reorganizations, leaving the process flow basically unchanged. Furthermore, input and output are both very visual, which substantially increases the likelihood of correctly specifying the intended model and boundary conditions. Finally, FEA is here to stay, and its use in engineering practice will continue to become more and more important.

Other frequently-offered arguments seem similarly off-target:

Engineers must know the principles behind a tool before using it. We clearly don't apply this criterion consistently, since most of us don't know how to design the circuits or write the software for our calculators. Many of us can't even derive the inverse Laplace transforms given in tables. Perhaps this argument is a legacy of the traditional top-down, analysis-first approach with which engineering, and mechanics in particular, have been taught for decades.

Computers cannot be trusted. In our experience the main errors are due to the user (faulty input, poor modeling decisions, and ignorance of the software) – most of which can occur in hand analyses as well as on computers. Many of these errors are outlined in Prantil & Howard (2008)[13] and Jeremić et al. (2009)[15]. Like any use of idealized models and calculations, critical exploration of results is needed to maximize their validity.

We embrace the importance of teaching principles and fundamentals, but feel that those should overwhelmingly represent the basic *mechanics* that is already the province of the standard classes. FEA tools, treated as black boxes, can potentially serve this goal in at least three ways: (1) reducing the drudgery and potential errors of computation, allowing students to focus more on the underlying mechanics; (2) allowing students to explore more complicated, yet extremely relevant, problems that are normally intractable when confined to idealized solutions with analytic solutions; and (3) providing convenient whole-field visualization of results.

Although this has been the briefest possible enumeration and critiquing of ideas, one hypothesis can be advanced with some confidence: reflexive dismissal of student use of FEA is not intellectually honest or convincing. Opponents need to present specific reasoning as to how a modest reallocation of class time and focus could significantly undercut important aspects of engineering education.

4. Another Educational Concern

Although we mostly discount the straw-man arguments enumerated above, there are certainly real concerns that demand consideration by educators. Foremost among these is the development of mathematical fluency.

Traditional classes rely on learning and practicing the language of mathematics, which may be understood not so much as the way that students will solve future complex problems (though some may), but rather as a method of fully defining problems, of making statements precise, or of deepening conceptual understanding. It could well be argued that a student being told of, or visually observing, the proportionality of circular-shaft torsional stress to radius may never appreciate this as well as the student who is forced to make and support that statement mathematically. And, it may be considered that students attain too little mathematical mastery as it is. In that case, any diminution of that practice, and perhaps a shift to the visual and qualitative, potentially leaves students handicapped.

Concern for mathematical ability is compelling. However the following points seem *apropos*:

- First, many somewhat sophisticated mathematical procedures are of very narrow utility (for example conformal mapping or inversion of transforms by residues) and do not find frequent use. So at the very least, we can restrict the mathematical priorities to relatively straightforward topics (algebra, trigonometry, analytic geometry, calculus, and elementary ODE).
- Second, in the experience of the first author during two decades in industry, most graduated working engineers rarely use mathematical tools in their careers. This does not itself prove that the mathematical approach did not help them learn, but we have seen no clear evidence that it did. Our perception is that both the workplace and the schools have already partially conceded the abandonment of mathematical skill (except for graduate studies).

Thus, mathematics-related concerns focused on FEA could be misplaced. There are already substantial problems with students not becoming mathematically fluent, that cannot be laid at the feet of advanced software.

Here is how we view the question of tradeoffs: would a student become a better engineer by having a tool that can solve complex problems, and an education that includes many important qualitative illustrations and a heightened focus on critical thinking? Or would they be better off striving to maintain the current level of basic mathematics, which can be a matchless technique for thinking and deriving general conclusions?

To us the answer depends primarily on the amount of reduction (in class time and focus) that is envisioned. Our perspective is that a less-than 10% re-allocation of class attention toward the use and interpretation of FEA offers a large return in conceptual visualization and problem-solving capacity, with little erosion of what is currently being taught. In other words, using FEA might well improve the understanding of mechanics, without actually being responsible much of the slide in mathematics. (An example is the torsion of open structural sections when warpage is either permitted or suppressed. Mechanics of Materials students commonly learn about circular tubes, after which the slit tube with warpage allowed is treated with the rectangle chart. The enrichment possible by using FEA, without any diminution in the ordinary mathematical treatment, is to plot slit-tube angle of twist versus length, when warpage is suppressed at the held end. Local torsional compliance changes from the un-slit tube value to the slit warpage-allowed value, beyond a characteristic decay length.)

5. Mechanics Background and Software Limitations that should be Learned in order to Use FEA Effectively

Here we outline the kind of knowledge that seems important for using FEA effectively. But for clarity, note that the particulars should not be considered to be necessary *a priori* (and thus barriers to the early incorporation of FEA); rather, they are meant to be developed throughout the curriculum as the student advances.

We mechanics educators and practitioners have absorbed some concepts so well that it is easy to forget the initial ignorance of students. In fact, many technical ideas must be learned in order to interpret FEA results, catch modeling errors, and guide design. One essential kind of knowledge is therefore comprised of concepts, assumptions, and critical thinking that should already be part of the normal curriculum. Rather than proposing that students can learn *less* mechanics than presently if they are to use FEA, we specifically advocate that they should learn *as much if not more*. But what we're recommending relates mainly to a holistic understanding of mechanics principles, a qualitative understanding of 'what affects something else', and an expanded grasp of definitions. It includes additional structural design principles. The usual adjuration to 'calculate problems first by hand' is re-interpreted as 'take steps to validate and benchmark your FEA approach'.

Of course the feeling that students need to master mechanics concepts in order to use FEA effectively is not unusual. What distinguishes our perspective is the idea that FEA use needn't be deferred until after the mechanics classes – introducing it early in the curriculum and using it to illustrate principles and validate hand calculations may better meet those classes' objectives, while simultaneously helping students to develop expertise in solving more-complex problems.

Other needed prerequisite knowledge involves FEA-specific understanding about such matters as the mesh, the boundary conditions, and deciding which aspects of the solution are likely to be valid. (Secondarily, issues of solver and element type may occasionally be useful.)

A third essential class of knowledge and skills is not so easy to present as a list. It is that of developing an appropriate model for determining the results of interest. Systems are generally studied in an unreal isolation, with simplified geometry and properties, in the hope that the missing aspects were not significant to the information being sought. But such ‘truncation’ may indeed alter the results, and it is up to the user to perform some kind of validation. Of course, exactly the same problem is present with hand calculations or laboratory experiments. Fortunately, the critical thinking skills required to address model validity, instead of being an afterthought, can take center stage when FEA is available. That is because the effects of incorporating geometric details, or more-realistic boundary conditions, can be assessed quantitatively without undue effort. So an early introduction to the use of FEA can play an important role in developing modeling skills.

We now expand on the mechanics background and FE know-how needed to perform competent FE analyses.

Mechanics background needed to make reasonable models and understand results: Following are some of the specific mechanics idealizations and notions that should be understood for effective, intentional use of FEA:

- Linearity for small displacements, and fixed contact regions. Ability to superpose basic solutions, or to scale any solution in load or overall size.
- The ability to interpret a result in terms of basic ideas or elementary asymptotic solutions. For example, the bending moment transmitted by a cross section; the force and moment equilibrium of loads plus reactions; the maximum bending or twisting strain at an outer fiber; rigid-body degrees of freedom of body or system.
- Stress is a tensor, a directional specification of tractions across variously oriented surfaces. Principal directions. No tractions at a free surface, so principal directions are parallel to the surface, and sometimes predictable from symmetry.
- For isotropic material failure, we can ignore stress orientation and use a scalar invariant. For failure across a seam, we must determine normal and shear tractions across it.
- Multiplicative stress concentrations based on geometry (re-entrant corner or cavity).
- For a single load path (determinate), the resultants are known from the load. For a multiple (indeterminate) load path, springs in parallel share the load. Adding material generally increases the load carried by a support, and perhaps even its peak stress. [Example: an axial torque supported by two structurally parallel torsional load paths to ground: 10”L X 2”D and 2”L X .625”D. The slender shaft has higher shear stress, but increasing its diameter raises rather than reduces the stress.]
- The concept of a pinned support: modest moments idealized as no moments. Modeling other classic localized boundary conditions such as built-in, or compliant.
- Understanding torsion and bending (moment proportional to angle change per length) and the quantities governing stress. Large cross sections transmit a given bending load with small stress; small cross sections permit a bending angle with small stress. (Ditto torsion.)

- Stored elastic strain energy from boundary work done.
- Understanding that the world is not rigid, and particularly that prevention of warpage and lateral strain is not realistic. But when calculating stress, it may be possible to ignore non-reality of a far-away rigid end support, if there is no other load path.
- St. Venant concepts and their breakdown – what constitutes a 'sufficient distance away' for loading details to become unimportant?

Specific considerations in using FEA effectively: We now turn to some important specific FEA-related ideas and skills. There is little doubt that FEA applied to an accurately modeled object with accurately defined and sufficiently smooth equilibrium body forces and surface tractions will yield meaningful results, if the mesh can be refined sufficiently. But most analyses fall outside of that limited scope, for the following reasons.

- Load impedance: many loading agencies do not have zero impedance. The pull of a cable, for example, alters its direction when the structure deforms. And the force of a stretched spring is also altered by deformation. A contact force is almost never distributed in a known fashion.
- Connections: Most objects are connected to other objects, or to 'the outside world'; and some of the loads are reactions that must be found, or could be displacement-dependent. As soon as we depart from the situation of specified loads, the opportunities for error increase. Probably connections constitute the main difficulty -- anything short of a full-penetration weld has un-joined areas that either start with a gap (non-conforming), or can open up like a crack (varying contact area) at high load, thus altering compliance and stress. They may even involve frictional slip, bolts moving around in their holes, etc.
- Supports / Foundation: The ultimate foundation considered to support a machine under study is not necessarily idealized well by rigidity. A supporting slab or typical floor may become concave due to downward load, whereas a cantilevered balcony may become convex. If the system connection to the floor is overdetermined, these different support deformations will cause very different machine stresses. Prantil and Howard (2008[5]). Therefore the first concern in performing FEA is to determine whether the joints and constraints affect the analysis, and if so whether they are correctly specified. For some problems (e.g., a cantilevered body supported in a relatively compact area) the overall displacement could be affected by details at the support – for example, the suppression or allowance of torsional warpage affects overall torsional stiffness. (Ditto, bolt preload.) But this has little bearing on stresses in a region sufficiently far from a single support. St. Venant's principle is an invaluable part of any hand or computational analysis; the concurrent use of FEA allows it to be examined and understood more clearly and concretely.
- Geometric imperfections: Bodies do not have perfectly flat surfaces, and generally contain various flaws or threaded holes, re-entrant corners etc. Usually a small feature in a massive cross section has only a slight effect on entire-body stiffness, and it a very local effect on stress. Therefore the appropriate approach is to ignore such small features (leading to a simpler overall part) for global results; then to recognize the stress-concentrating effects of a small feature and either study it in isolation, or simply apply an already-determined asymptotic behavior (i.e., stress concentration factor). If the feature is carelessly left in place, the user may properly ignore its careful meshing and assume that the computed stress

will be inaccurate. (Of course, the role of imperfections in the buckling of thin-wall structures is another matter altogether.)

- Redundant load paths: If there is more than one load path, the relative stiffnesses become an essential part of the stress calculations. These are determined by the geometric accuracy in major respects, the joint conditions, and even the mesh – if mesh is too coarse it can artificially increase stiffness.
- Non-ideal boundary conditions: We all freely use the idea of a pinned boundary condition as a shorthand representation of a small region of support with modest angular stiffness. A true frictionless pin is rare in practice. And it's not always easy to implement a pinned boundary condition in FEA – sometimes resort must be had to a flexure to approximate it. This all has to do with the somewhat unreal task of studying an idealization that never occurs in reality.
- End and edge effects: steps in surface tractions lead to singularities (for example at the edges of loaded surface areas), but this is suppressed by a coarse mesh. If one elects to be imprecise about details of loadings and supports, the results must be discounted in that region.
- Mesh: A not-too-coarse mesh is needed to capture stiffness of a load path. And, a sufficiently fine mesh (in comparison to small geometric features) is needed to converge to the high localized stress at a concentration. If a displayed stress result shows the patchiness of the underlying mesh, obviously it is too coarse. If an element is misshaped or has a high aspect ratio, accuracy could suffer.

Most of the foregoing ideas (as well as many others) don't need to be presented as dry abstractions – each concept can conveniently and memorably be illustrated via a simple FEA exercise or in-class example.

In summary, our perspective is that modern FEA software reliably produces determinate results from the user-selected inputs and mesh. So only a few potential problems need to be considered:

- Are we accurately specifying our problem in a way that should give the needed information?
- Have we avoided sign or magnitude errors in our input?
- Have we chosen mesh to deliver sufficient accuracy?
- Are we examining the proper output variable?

It should go without saying that reviewing the input, and thinking critically about the model idealizations and the mesh, is always desirable. When a sufficiently similar problem has already been studied (numerically, experimentally, or analytically), then comparing the results can aid in the detection of problems. Doing this routinely in early classes ought to pay dividends, not only if students take an advanced FEA class, but also for critical assessment of any engineering modeling.

6. Proposed Path to Embed Modern FEA within the Engineering Curriculum

The conventional path to teaching FEA is to make it an upper-division elective or requirement after students have had statics, mechanics of materials, machine design, and a class in linear algebra. It is common for that elective class to focus on the theory of FEA, rather than skill in applying FEA to useful problems.

Our alternative vision is that every student can learn to do something exciting and useful with FEA, starting at the earliest stages of their education. It's easy to show freshmen how to do simple things, while of course adding a warning about potential inaccuracy. As further classes present important concepts and methods, it is not hard to 'keep up' with a few more FEA skills and better understanding of its capabilities and limitations. FEA can then be used to illustrate class concepts and demonstrate the effectiveness of hand (strength of materials) calculations. By the time they are seniors, students can have the mechanics-based ability to apply FEA intelligently, interpret the results, and think critically about their choices. We feel such a path can provide all students with a tremendously useful tool, can cement their understanding of mechanics, and can increase their confidence and enjoyment as budding engineers.

Use of FEA in the following classes has been tried, with positive student response:

<u>Introduction to Engineering</u>: FEA can easily be introduced in Introduction to Engineering, or in Engineering Graphics (where solid modeling is taught). The literature already contains examples of this, some of which we highlighted in Section 2. To summarize our view, in one or two hours students can learn to define a 3D body, apply constraints and loads, generate a mesh, and solve. Displacement components, and von Mises stress are useful outputs. In very simple ways, the relation of von Mises stress to yield or fatigue can be explained. The need for mesh refinement at a notch can be demonstrated. A simple truss can be modeled and investigated for bar yield or buckling, with explanation of the value of truss depth and bar EI. Lastly the difference between a beam with simply supported ends and built-in ends can be demonstrated. In effect, this would serve as an early introduction to several important concepts about mechanics and structures.

<u>Statics</u>: Statically determinate force balance problems can be modeled with either idealized constraints (rollers, cables, pins) or with flexures that do the same thing – of course the ideas of tensile and compressive stress would be needed. The force on each support can be determined numerically and compared to hand calculations. And quite complex truss problems can be studied approximately (without necessarily introducing pinned connections). The initial idea of a beam bending moment is intuitive and made visible by stress, so the idea of a force being equivalent to an offset force plus a moment is made concrete. The distinction between underdetermined, overdetermined, and statically determinate supports can easily be examined, and basic spring mechanics (series and parallel, locked-in stress, linear and angular equilibrium of a spring-supported body) can be explored.

<u>Mechanics of Materials</u>: Stress components can be illustrated in all kinds of bending, torsion, or membrane (pressure vessel) problems. By changing the initial system orientation, the cartesian stress components change according to Mohr's circle. Torsion problems (for example a flat bar or W section) can match tables, and clearly exhibit the role of warpage. Beam problems can match hand calculations. Column buckling and simple stress concentrations are easy to model. The synergy of using FEA in this class is that a wide array of introduced phenomena and quantities can be demonstrated, and used to check hand calculations, while simultaneously building skill and judgment at using the software. The significance of boundary conditions belongs here, where rigidly held ends differ from slope-allowed or warping-allowed ends. Other topics include St. Venant's principle, stored energy, reciprocity, center of twist, stress concentrations, parallel load paths, determinate and indeterminate beam supports, principal axes

of beam section, yield, and fatigue. Warnings can be given (and illustrated) for contact problems, including altered compliance, and nonlinearity. We envision that a few FEA concepts would be taught in classroom demonstrations, as part of showing important concepts. Others could be mentioned in assigning homework problems.

Machine Design: At this juncture, students could be facile users of FEA, able to pick up tips and principles easily. In this class they can reproduce textbook tables of stress concentrations once they learn how to refine the mesh for convergence; furthermore they can test stress concentration amelioration. They can consider and illustrate different material failure theories (yield, fatigue initiation, brittle tensile failure). Contact stresses (in bearings, gear teeth, and bolted joints) can be modeled. Deformation of complex machine bases becomes straightforward to estimate. Assemblies can be studied with full connection nonlinearity. Elastic matching of shaft slope to bearing slope can be demonstrated.

7. Conclusions

Modern FEA tools are not immune to user errors. But neither are hand calculations or experimental measurements. Each approach to answering engineering questions requires some sophistication and fundamental understanding to be effective.

What is different about FEA software today is that it is extremely easy to get started, and the visual interface makes it relatively easy to detect many input errors. And, default settings do a good job with ordinary problems. Therefore we don’t see a need to precede FEA usage with linear algebra lectures, any more than we demand that students understand the algorithms used in hand-calculators that evaluate the arctangent.

Thus we see a major pedagogical opportunity to introduce beginning engineers to FEA, and then link their growing mechanics sophistication to more capable use of FEA. This should enhance and reinforce the understanding of mechanics concepts, at the same time that it builds competence and judgment in the use of a powerful software capability. The greatest benefit with least effort might be achieved by devoting time equivalent to two or three full lectures, spread throughout the semester, in each of several courses (a freshman course, then Statics, Mechanics of Materials, and Machine Design). This would not mean two lectures lost, since all FEA demonstrations would be devoted to topics normally covered in each class.

In summary, we have attempted to steer a course between two opposite propositions: (1) that Mechanics of Materials and matrix methods must be a pre-requisite for learning FEA; or (2) that modern FEA can be used effectively with essentially no background. We feel that FEA can and should be usefully introduced at the beginning of an ME or CE engineering education. (Fortunately, a movement is underway to introduce FEA into freshman design courses or freshman introductory courses in engineering.) But we particularly urge the further insertion of FEA into immediate successor courses in mechanics, particularly Statics and Mechanics of Materials. Crucially, in these courses as well, we advocate use of FEA as a tool, without the need to delve deeply into the underlying FE theory or algorithms. The reason is that the mechanics learning can operate synergistically with the software facility: enhanced mechanics understanding will mean better use of the software, and more-sophisticated software use will illustrate and motivate the mechanics concepts and modeling skills being taught. Beyond these basic mechanics courses, we also recommend incorporation into intermediate courses such as Machine Design and Structural Analysis. Under such a unified approach, both in the commitment to expose students continually, and in the treatment of FEA primarily as a tool, students' mastery will increase as they learn more mechanics principles, classical structural solutions, design ideas, modeling skills, and FEA limitations. Such a path will also provide the further benefit of making any future FE-specific course more meaningful. In any event, to gain most of the benefits of commercial FE software, it does not appear necessary to study the underlying algorithms. The result of this approach, we believe, will be better mechanics education, a valuable problem-solving capability, and greater student satisfaction.

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