Uses and Abuses of Finite-Element Analysis

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The use of finite-element modeling for structural analysis has been well established for decades and is used pervasively worldwide. It is now used for not only linear statics, but also for nonlinear, dynamic, and sometimes coupled (thermal-structural, fluid-structural) analyses of structures. Complex structural models are now analyzed routinely, where this was not possible 30 or 40 years ago. Instead of a few hundred degrees-of-freedom (DOFs), current models can typically be in the millions of DOFs.

When I started my professional career with what was then known as the Westinghouse Bettis Atomic Power Laboratory in the early 1970s, finite-element analysis (FEA) was just starting to emerge as a structural analysis tool. When "out-of-plane" bending became possible, it was a big deal at the laboratory. Meshes were built by hand with the analyst being the one who kept track of the nodes and elements manually, usually with the assistance of a large sketch of the model on a sheet of layout paper and a stubby pencil.

The input deck (when it really was a physical deck of cards) was created manually on a key-punch machine usually by the analyst. And at Bettis, we walked the deck of cards across the runway (Bettis was built on an old airport) to the computer building and deposited our input deck to be run when it was your turn on the computer. If you had a comma in the wrong column of one card in the deck, you would have to find the error, correct it and start the process all over again. And frequently on weekends, all the structural analysts were kicked off the computer so the nuclear physicists could run the dreaded nuclear reaction program PDQ (pretty damned quick) that would take all weekend to model the nuclear reaction for the life of a reactor.

However, it now seems the pendulum may have swung too far in the other direction in a sense. Modern FEA programs are capable of analyzing nearly any complex structural problem, which is a wonderful capability. We now use finite-element tools to model nonlinear behavior, dynamic structures and loads, determine natural frequencies and mode shapes, estimate structural response from spectral inputs and so forth. And the modeling tools have kept pace with the FEA solvers. Complex meshes can now be constructed directly from solid models in most cases, often with only a few key strokes, which is again a wonderful capability. However, in the hands of inexperienced engineers, or designers in some cases, the results can be disastrous.

The finite-element modelers are now so user friendly that nearly anyone can create a finite-element mesh and get answers. But the old saying, "garbage in, garbage out" (GIGO) still holds. Inexperienced engineers and sometimes designers who do not have adequate knowledge are now capable of building a mesh from a solid model and getting "answers" with little knowledge of what they are doing. The software is so "user friendly" that the process can be almost described as push-button engineering.

With these powerful tools, it is possible to go directly to a stress contour plot without even displaying the mesh. When I once questioned a senior mechanical engineering student about skipping this step in the analysis of a senior design engineering project, his response was, "why would you ever want to see the mesh?" Turning an inexperienced engineer loose with these powerful modeling tools is akin of turning a student, who just finished driver training, loose with a Formula 1 race car.

As I recall my days back at Bettis designing and analyzing reactor core structural components, I had to dig through texts of Roark's *Formulas for Stress & Strain*, Peterson's *Stress Concentrations Factors*, Den Hartog's *Advanced Strength of Materials*, and Timoshenko and Goodier's *Theory of Elasticity* to develop reasonable approximations from classical solutions, (affectionately known as "hand-calculations") to estimate loads and stresses from closed formulas for sometimes complex structures and loading conditions.

This process, while certainly not as accurate as valid FEA results, helped me develop sensitivity for how the stresses are distributed in a structure and how the structure will respond to various types of loadings. Entry-level engineers do not necessarily go through this experience building process and instead may start building complex FEA models immediately "out-of-the-box," generating answers without adequate training, experience or supervision. I offer a couple of illustrative examples of this issue that I have recently encountered.

I received a call from a customer who could not understand why a shock-isolated electrical cabinet was experiencing such high displacements due to base input shock accelerations. The displacements seemed too high for the magnitude of the input accelerations, and the model results showed that the cabinets could impact each other as well as the surrounding structure. The design engineer continued to add restraints in the design to reduce the cabinet displacements predicted by the FEA results in an attempt to meet the available space envelope.

When I reviewed the model, boundary conditions and acceleration loading, I realized that the analyst had used the peak value of a transient base acceleration and applied the peak value as a static base acceleration field over the entire model. This of course obviated the benefit of the shock isolators and resulted in displacements of the cabinet, which were an order of magnitude too high. When the model was rerun with a transient base acceleration-time history applied to the base shock isolator mounting surface, the cabinet displacements were negligible.

Other examples relate to the FEA guidance, or lack thereof, that engineering students received from advising university professors. I have been active during the last decade with corporate sponsorship of senior engineering design projects at several major universities across the country. Nearly every project that involved a structure had a corresponding finite-element analysis that the students present, beaming with pride. However, many of these models had major flaws that neither the student team nor the advising professor realized.

One memorable example represented a significant safety risk. The structure in this case was that of a torque restraint fixture designed and analyzed with FEA by the students and subsequently blessed by the advising professor. The structure was designed to react to the torque applied to large bolts by a hydraulic torque machine. In this case, the input torque was in the range of 6,000 ft-lbs. The fixture was designed with 1-1/2-inch and 1-5/8-inch steel plates connected by fillet welds. The student's finite-element model treated the fixture as one continuous structure, as if it had been machined out of a large solid block of steel with no welds at all. But in reality, the only features joining the thick plates were the relatively small 1/4-inch welds.

Since the project involved the students using the fixture to do bolt torque testing, I felt compelled to analyze the structure myself at least with hand calculation to ensure safety. As expected, the weld joints were seriously overstressed in many areas, and I asked the student to make a number of design changes to the fixture before using it. I also insisted that they place a scatter shield between them and the test fixture when applying the very high torques.

The software companies that develop finite-element modeling software also have some degree of culpability, in my opinion. The software is now so user friendly that designers who are usually quite proficient at computer-based mechanical design can automatically create FEA models from solid design models. Just push the button, and get impressive looking stress plots.

Generally, however, they do not have the education, background or analysis experience for what at times are complex structures. There is generally little or no understanding of what a stiffness matrix is, mesh convergence, or the difference between static and dynamic loads. The term "mesh monkeys" comes to mind. Of course, there are some exceptions, but based on my observations, inexperienced users remain a systemic problem. Software tools now allow a designer to transform a solid model directly to a finite-element model, apply loads and generate stress plots. As noted before, they might not even view the mesh. Designers outnumber specialized structural analysts by an order of magnitude, and therefore represent a lucrative market for software vendors.

So what are the lessons learned? Before turning inexperienced engineers or designers loose with finite-element software, proper training in the uses and abuses of the tools should occur. The major suppliers of structural finite-element packages typically will have training classes offered at periodic intervals in different locations. The classes that I have attended are usually quite good and well worth the investment in time and money.

Additionally, my advice is that senior supervision and guidance for entry-level structural engineers and analysts is critical. This sounds obvious, but I continue to witness cases where it simply does not happen. We all learn by our mistakes, but in these cases mistakes cannot only be costly but may also pose a safety risk. Mistakes will be made, but as long as an experienced set of eyes reviews the model, assumptions, boundary conditions, loadings and results, this risk can be significantly reduced. S/V

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