Using Finite Element Analysis for Continued Product Improvement

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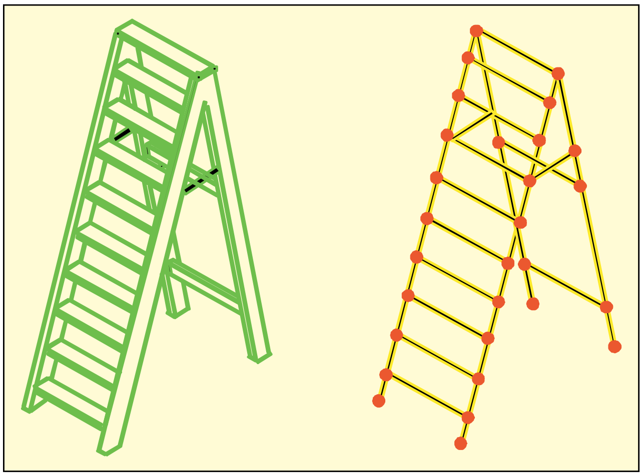
Take a look around. Much of what you see has, in some small or large way, been simulated on a computer prior to production. Numerical simulation helps build safe bridges, improve gas mileage, and guide the manufacture of plastic parts. It ensures that hand tools will not break, that computers will not overheat and that knee joint replacement components will not fail.

Numerical simulation comes in many forms. It ranges from the analysis of an individual part, such as a bolt, to the simulation of an entire system, such as a chemical processing plant. It can involve structural analysis, electromagnetic analysis, heat transfer, or fluid dynamics. Structural analyses, including predictions of mechanical stress, deformation, and vibration, make use of a technique called Finite Element Analysis, or FEA. This technique has served as the cornerstone for Computer-Aided Engineering (CAE) for decades.

An Overview of Finite Element Analysis

In 1943, Richard Courant began to develop structural simulation tools to study vibration. His work was quickly followed by broader development work in the aerospace and automotive industries. Over the years, the application of FEA has grown to include the study of loading, failure limits, material response, thermal applications, and more, in industries that range from nuclear power to healthcare. As an example, FEA can be used during the design of a bridge by civil engineers who need to know how the bridge will respond when it is filled with cars. For a given set of loading conditions, the analysis would indicate how much the bridge structure would deform and whether or not any of the components would break under the imposed load. Cost-cutting measures, in the form of fewer supports or less expensive materials, could also be analyzed.

The first step in performing an FEA simulation is the creation of a geometric model on the computer. There are many computer-aided design (CAD) packages on the market today that can be used for this purpose. Typically, CAD models are 2D or 3D representations of the system of interest. However, in some cases, beam or shell models are used. The next step is the creation of a mesh. This process breaks up the model into smaller finite regions, called elements, where the local response (be it deformation or some other result) under all possible deformations are computed and stored. The points where the elements connect are called nodes. For example, if the response of a ladder to a person standing on it were under analysis, the ladders' rungs and legs may be separated into individual elements for study. The weight of a person would be applied to the rungs of the ladder, that is to say to the specific elements of the analysis that are being loaded, on which the person is assumed to be standing. The analysis then computes how the rest of the ladder, the legs and other rungs, would respond to and distribute that person's weight. Element shape varies based on the type of problem being solved. For a 2D problem, triangles and quadrilateral elements are typically used. For 3D problems, the options are 4-sided tetrahedra, 6-sided hexahedra, prisms, or pyramids. During the meshing process, the element attributes are also defined. The attributes include behavioral factors, material properties, and section properties. This information is used to govern the physics and guiding equations to be used in the analysis. In general, the element type is selected based on the type of loading and geometry under examination. For example, line elements of the "beam type" might be used to model bolts, while those of the "3D type" are used to model more complicated structures that cannot be modeled with simpler elements. Once the element types are chosen, the model's geometry is filled with those elements, creating a mesh. During the analysis process, the governing equations are solved for each node where the elements connect.

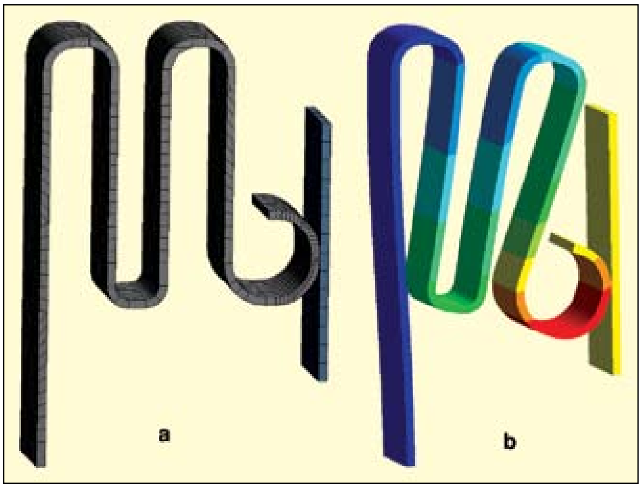


Model of a ladder (left) and (right) ladder rungs and legs broken down into individuol elements and nodes

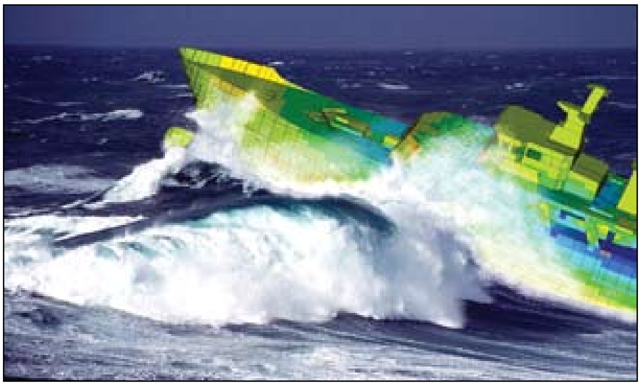
This simulation reflects the effect of loading a building roof with snow. The image on the left is the original mesh, with red arrows that depict the loading direction. The contour plot on the right depicts the simulation's displacement results.

The accuracy of the solution depends, in part, on the mesh density, or number of elements used to fill a given volume. Up to a point, greater solution accuracy can be achieved with higher mesh density. The benefits of higher mesh density must be weighed, however, against the cost of the increased computational resources needed to solve the problem. If *N* governing equations are solved for each node in a particular model, the total number of equations solved will be *N* multiplied by the number of nodes. If a particular part is meshed with 10 nodes, and if 6 equations are solved for each node, then a total of 60 equations would be solved overall. While this is not unmanageable on a basic computer, mesh sizes today can grow to include millions of nodes and elements, so that many millions of equations need to be solved for a single analysis.

The calculation itself begins with prescribed load conditions, such as the mechanical or thermal loading on each element. During the solution, the stiffness matrix for each element is calculated by solving the governing equations and combined to produce the total stiffness matrix for the entire structure. For the ladder case, the mesh elements for the rung of the ladder on which a person is assumed to be standing would have the weight of the person as well as the rung's weight applied to them. These loads are referred to as the structure load vector. The simulation calculates a force balance in the overall system, i.e. all the ladder's nodes and elements, by solving the total system of equations. This may be a direct or iterative solution. As one can imagine, this type of example can be scaled to something larger as well, for example a bridge's structural analysis. For a thermal analysis, the elements would have load vectors in the form of heat fluxes or constraints in terms of nodal temperatures, and an overall energy balance would be sought. In this manner, the FEA calculation allows the engineer



FEA is used to analyze structural problems, such as this spring plate example. Such simulations take into account factors such as contact between components and loading in order to predict displacement. (a) The initial mesh and configuration of the spring plate assembly is comprised of two components: a vertical plate on the right side of the mesh which, when pressed, compresses the spring, which is on the left side of the mesh. (b) This contour plot reflects displacement results calculated by FEA for each of the components.



ANSYS is used to simulate the structural response of details like welded connections on offshore patrol vessels when subjected to cyclic loading and environmental conditions. (Image courtesy of Howaldtswerke-Deutsche Wert AG.)

to examine a system's response to mechanical or thermal inputs and thereby assess the associated capabilities and limitations of the system to those conditions.

The Growth of FEA with Computational Power

Historically, enhancements to FEA capabilities have been driven by consumer needs and ongoing advances in computer technology. Consumer needs have driven the development of physical models. Increased computational speed and power have allowed model development to enter the realm of increasingly complex analysis. In addition, the falling cost of computational resources coupled with user-friendly interfaces has resulted in a rapid growth in the number of people who use FEA software. As a result, FEA is now playing a larger role in the product design cycle, where the scope of problems analyzed is continuing to expand. Indeed, the relationship between the evolution in software engineering and the evolution in computational capacity has been one of interdependence, where each has played a role of driving and being driven by the other.

Advances in computational resources include those in hardware capabilities, operating systems, software development, and graphics capabilities. High performance computing has evolved from large mainframes to desktop mini-computers and workstations, to personal computers, and more recently, to networks of shared- and distributed-memory computers and supercomputers. During this evolution the speed of computing has increased dramatically, cutting the time required to solve a typical FEA problem from days in 1980 to minutes today. Graphical user interface (GUI) advances

ANSYS Mechanical is used to optimize design solutions such as lightweight, high integrity helicopter landing grids. (Image courtesy of Weir Strachan & Henshaw and NATO Pictures.)

have made it possible to use FEA software to reference large quantities of printed documentation

In conjunction with these technological developments, FEA usage has advanced as well. In particular, there have been shifts in the demographics of those who run structural simulations and in the types of analyses they tend to perform. The increased ease of use has attracted a broader consumer base. Whereas the early adopters of simulation technology were highly-trained specialists, generalists and even non-engineers use FEA today. As the group of end users has grown, so has the demand for new analysis capabilities, tools and models. The scope of simulation has matured from single-component analyses to multiple-component assemblies, and to entire systems analyzed for cost, reliability and performance. The role that FEA has played in the product design cycle has expanded from simple failure analysis to design verification, to design guidance and optimization. Today's FEA is a tool that plays a key role in engineering design and follows a product through its entire life cycle.

The ANSYS Story

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An effective FEA software company must be able to meet the changing needs of the engineering community while incorporating the expanding technology of the day. These goals must be met in an environment where effective business practices prevail. The ability to change course as external factors change is also critical. One company that has demonstrated a leadership role in the FEA business world is ANSYS, Inc. of Canonsburg, PA.

The ANSYS story parallels many of the entrepreneurial successes that dot the American business landscape. Like many before him, Dr. John Swanson, company founder and chief technologist, had a dream – that one day, all products would be designed, tested, and manufactured using the computer. During the 1960s, Swanson served as manager of structural design at Westinghouse Astro-Nuclear Laboratories. There, he used FEA to solve structural problems for the nuclear industry. He reasoned that if he could integrate the mathematical equations he used at work with emerging computer technology, his dream would be fulfilled. Dr. Swanson envisioned the time when the computer would replace the engineer's handbook, just as calculators had supplanted slide rules. Using computers, engineers could predict the effects of stress, temperature, pressure, and motion on a design, instead of investing in expensive prototypes and testing. He foresaw these developments not only because of the technology promises of the day, but because this technology could serve to slash design costs, shorten

Dr. John A. Swanson.

The first headquarters of Swanson Analysis Systems, Inc. (SASI).

design cycles, and, most importantly, produce higher quality products. Like all visionaries with a dream, Dr. Swanson embarked on a mission to provide rigorous engineering analysis capabilities on the computer. That mission began in 1970 in a small farmhouse in Elizabeth, PA with a single employee – himself.

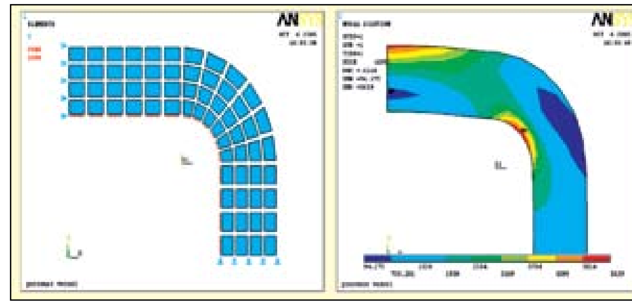
The Birth of a Company

The fledgling company was named Swanson Analysis Systems, Inc. (SASI). Its mission was to develop and market finite element analysis software that could simulate static (stationary), dynamic (moving), and heat transfer (thermal) problems. Swanson recognized that this type of product could benefit not only the nuclear industry, but many other industries as well.

In 1970, computers were just becoming available to the engineering community. Even so, engineers who encountered problems that could benefit from computer simulation did not have readily available software to use. Thus, the timing of John Swanson's company couldn't have been better. SASI's business grew alongside the growth in both computer technology and engineering needs. SASI had yearly growth rates between 10 and 20 percent, and to date, has never had a losing quarter or year. In 1994, SASI was sold and its leading product, ANSYS, became the new company's (ANSYS, Inc.) flagship product.

Under Swanson's guidance, SASI's development and business strategies focused on choices that allowed customers' problems to be solved, encouraged professional growth and job satisfaction for employees, and provided the broadest opportunity for company growth while simultaneously minimizing risk. With regard to ANSYS software development, there was an ongoing internal push to develop faster, better, simpler technology. As new computing platforms became available, ANSYS was ported to them once it was certain that they were sound. As new numerical methodologies were developed, they were assessed and if deemed appropriate, implemented. Focus remained on developing better products, even if it called for the re-writing of certain code. SASI involved their customers in decisions about the future directions of software development. Initial exchanges with potential and existing customers eventually grew to become biannual conferences and then regional or worldwide conferences to discuss new technology and solicit feedback. The involvement of the customers resulted in numerous benefits – the customers felt that their opinions were valued, they were happy to know that their problems were being solved in a rigorous manner, and by responding to the customers, the software developers got great personal satisfaction. As a result, the customers would often use or buy more software.

While SASI engineers involved the customers in their product planning, it did not make a habit of creating customized products for them. It was not unusual for a customer to request that a special capability be incorporated in ANSYS to meet their particular need. Often the customer would be willing to pay for such a capability, and it was tempting to engage in the practice. However, customized releases have a number of potential problems associated with them. First, there are often questions about who owns the customized code. Second, the customized software, like standard software, would require maintenance. Third, any software should be thoroughly tested and verified prior to release, and this important step might be skipped in the interest of time and cost. The SASI



Early example of an ANSYS training seminar problem.

approach was to collect the various needs of several customers, distill them into a common general capability, and incorporate that capability in the standard ANSYS package at no charge to any customer. For cases that cannot be handled in this manner, ANSYS allows user-defined programming in the ANSYS environment via APDL (ANSYS Parametric Design Language), UPF (User Programmable Features), and UIDL (User Interface Design Language).

Software Testing and Verification

For a product as complex as ANSYS, a thorough understanding of the product is essential. Techniques for gaining product knowledge include performance testing, benchmark testing, the study of very large (and very small) problems, and the testing of alternative formulations and coding techniques. Benchmark tests, for example, have been widely used to compare computer performance by measuring the time it takes to complete a calculation on a set problem. The benchmark tests often involved competitor software. By comparing similar products from different software providers, the engineers could determine if the competition had more efficient solvers. Tests such as these helped to ensure that the technology was well understood and that the most productive changes required for new software could be developed.

From time to time, technology was obtained from external vendors rather than developed in-house. When this occurred, tests were performed on the purchased or licensed software and if possible, the source code was acquired so that it could be reviewed in depth, ported to new platforms, improved and maintained. If certain technology was licensed, a paid-up license was obtained so that the pricing to the customer was not constrained by license terms. This allowed educational versions with full functionality to be offered at attractive prices.

The Growth of Business Services

SASI received its revenues from the use of the ANSYS product. All other activities were directed toward increasing the product usage. Items such as training, documentation, conferences, interfaces with other software packages and translators for files in different formats were recognized as tools that all help the customer use the product. Thus, these items were supplied free or at a minimal cost. Engineers always want to do the best possible job, so the expectation, which has been accurate so far, was that the product usage will always expand to meet the computer or budget constraints.

The rewards for a successful business are many. For John Swanson the most important was the opportunity to be of service to the engineering profession, and the profession has honored him in many ways. In 2004 he received the John Fritz Medal, the highest award in the engineering profession and presented each year for scientific or industrial achievement in any field of pure or applied science by the American Association of Engineering Societies. In 2006 he received the ASME Presidents Award. The lesson he passes on is a simple one: seek a new concept, usually arising from an intimate knowledge of a problem needing to be solved, and develop a solution (and product) in close cooperation with the customers. Follow where the customers want to go. Do not try to force the customers into a pre-defined mold; they usually have strong opinions and you can be more successful by listening to them and following their advice. S&V

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