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# Rapid Modeling and Analysis Tools

## *Evolution, Status, Needs and Directions*

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# Rapid Modeling and Analysis Tools[†]
## *Evolution, Status, Needs and Directions*


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## ABSTRACT

The design process is rapidly evolving as the twenty-first century begins. Advanced aerospace systems are becoming increasingly more complex, and customers are demanding lower cost, higher performance, and high reliability. Increased demands are placed on the design engineers to collaborate and integrate design needs and objectives early in the design process to minimize risks that may occur later in the design development stage. The Mars Sample Return/Earth Entry Vehicle has stringent design requirements imposed due to mission objectives. These requirements in turn necessitate the mitigation of uncertainties and risk associated with the system design and mission. Characterization of material response accounting for damage, delaminations, and manufacturing flaws, and understanding their influence on structural integrity to meet mission objectives are critical. Extreme environment loading conditions due to re-entry and impact on the earth's surface using a passive impact energy management system require detailed mathematical models and advanced analysis tools based on verified constitutive models.

The design process becomes a balancing process between risk and consequences. High-performance systems require better understanding of system sensitivities much earlier in the design process to meet these goals. This understanding is developed through enhanced concept selections, reduced uncertainty, and enhanced analytical tools. However, the cornerstone of the design process is the design engineer. The knowledge, skills, intuition, and experience of an individual design engineer will need to be extended significantly for the next generation of aerospace system designs. Then a collaborative effort involving the designer, rapid and reliable analysis tools and virtual experts representing the knowledge capture of technical disciplines, manufacturing processes, mission profile, and/or system performance will result in advanced aerospace systems that are safe, reliable, and efficient.

This paper discusses the evolution, status, needs and directions for rapid modeling and analysis tools for structural analysis. First, the evolution of computerized design and analysis tools is briefly described. Next, the status of representative design and analysis tools is described along with a brief statement on their functionality. Then technology advancements to achieve rapid modeling and analysis are identified. Finally, potential future directions including possible prototype configurations are proposed.



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# INTRODUCTION

The design of advanced aerospace systems demands a full understanding of system functionality, system interdependencies, system risks and possible failure scenarios [1-6]. This understanding cannot be attained from a single discipline view, irrespective of the depth of understanding in that discipline. However, a systems engineering perspective with in-depth understanding in at least one discipline is critical to the design process and contributes to understanding and mitigating risks [1]. The design process has been and remains very much a "engineer-in-the-loop" process that taps human creativity and invention. Design and analysis tools free the engineer to perform detailed simulations earlier in the design process, to assess off-nominal conditions readily, and to explore the design space fully. Risk-based design makes the process more robust provided the systems-level understanding is incorporated and detailed knowledge of a specific discipline is utilized – having rapid modeling and analysis tools alone will not result in successful designs. As such, the focus of this paper is technology needs for engineering design and analysis that maximize capturing the physics accurately, that question modeling and analysis assumptions, and that provide error assessment and adaptivity.

In the years before computers and advanced numerical methods such as the finite element method, engineers developed mathematical models that captured the physics of the response using mass-spring-damper models or a few differential equations. The engineer understood the system response, developed the mathematical model, calibrated it with test results, and solved the problem. Complicated systems were designed and flown using this approach. Today's aerospace systems are just as complex and then some due to the use of advanced materials and increased performance requirements. While faster computers and better analysis tools are available, increased responsibilities are being placed on the users of these tools. In Ref. [7], Cook, Malkus, and Plesha comment on this point:

> *"... Although the finite element method can make a good engineer better, it can make a poor engineer more dangerous.*
>
> *In years past, when an analysis was done by hand, the analyst was required to invent a mathematical model before undertaking its analysis. Invention of a good model required sound physical understanding of the problem. Understanding can now be replaced by activation of a computer program. Having had little need to sharpen intuitions by devising simple models, the computer user may lack the physical understanding needed to prepare a good model and to check computed results. Or, what the user perceives as understanding may instead be familiarity with previous computer output.*
>
> *Computed results must in some way be judged or compared with expectations. ...*
>
> *... a competent analyst must have sound engineering judgment and experience, ...doubts raised in the course of the analysis should be taken seriously."*

Guidelines for analysts on the use of advanced analysis systems are generally problem specific as few global guidelines are valid. Software developments, researchers, and analysts form user groups and organize user forums to share experiences, needs, and directions. The process involves lifelong-learning skills from the elementary topics taught in college through advanced topics. Specialized application areas have their own "rules of thumb." Papers by Zukas and Scheffler [8-10] in impact and penetration, papers by Bushnell [11, 12] and Starnes, Hilburger, and Nemeth [13] on shell stability, and a paper by Young and Rankin [14] on analysis of a launch vehicle are representative examples.

For many years the design process has changed little. Tools used in the design process, however, have evolved substantially. Collectively the computer-aided design, manufacturing, and engineering tools are referred to as *CAx* tools. In addition to the traditional roles of such *CAx* tools, new roles associated with overall product development, product management, and reporting are becoming increasingly important as reducing design-cycle time and cost are also goals to be met. Risk management and treatment of design uncertainties are incorporated to mitigate failure and to understand system sensitivities. These factors have direct impact on the design process.

The design process typically involves a concept phase, a preliminary design phase, and a detail design phase. Verification parallels development by way of an integrated test program that verifies analyses and confirms integrity and reliability. Each phase involves modeling and analysis at a level of detail commensurate with the design stage. Recently, more attention has been focused on issues such as operation, maintenance, and repairs with a view to operational cost reduction and possible extensions to the design life. In the current process, the designer/engineer makes decisions based on intuition and historical knowledge of the system and mission. Ryan and his colleagues have documented examples of aerospace vehicle design challenges, problems, and lessons learned [1-6]. They concluded that design is a careful balance between risk and consequences and understanding the system sensitivities is critical for mission success. Hales [15] identified ten critical factors in design and emphasizes the combination of human activities and their potential consequences in reviewing the design process. Using "the right tool, the right way" is one the factors – the computer is still a tool and not an engineer. The development of new design paradigms will provide the next generation of design and analysis tools the capability to maintain a competitive edge in the global marketplace.

Cultural changes are necessary for such paradigm shifts in engineering design. Incorporating additional engineering analysis into the early stages of the design process typically causes a delay in getting preliminary design concepts to the next level [16]. However, these designs are better designs incorporating more knowledge of the system and have a higher chance of success with fewer design changes later on in the process. Engineering managers need to change their mindset in that increased engineering effort invested up-front is more than offset by saving in the long term. Management also needs to invest in the continual training of designers and engineers in the use of advanced engineering tools and computing systems. Engineers and designers need to recognize that familiarity with the engineering tools does not generate a good designer or analyst – individual abilities, creativity, insight and understanding of the system and its function are mandatory.

Over the past decade, computing hardware, software, human interfaces, and network connectivity have evolved tremendously. The integration of design and analysis tools together with scientific visualization tools offers new and exciting opportunities provided they include the necessary underpinnings of engineering mechanics, inclusion of uncertainties, and *a priori* assessment of manufacturability and cost. These tools must allow concepts to be developed in the context of current material capabilities, limits of analytical tools, manufacturing capabilities, and/or acceptable lifecycle costs. These underpinnings should be transparent to the next generation of designers and analysts who will expect a design environment that permits an immersive experience to explore new creative conceptual alternatives fully. Such tools will be the "*Tools of the Future*" according to Mr. Daniel S. Goldin, NASA Administrator [17]. Deliberate careful integration of engineering mechanics and mathematical rigor coupled with robust systems engineering integration methodologies must be provided by the *CAx* infrastructure in order for it to be successful.

Changes to the design environment have generally resulted from the automation of many design and manufacturing tasks such as the use of numerically controlled tooling systems, robotic assembly systems, computer-aided drafting, and rapid prototyping of selected parts. While very important, these aspects of the overall product development cycle are not part of the present study. Herein aspects of automating the simulation process with increased robustness and reliability are the focus. Tworzydlo and Oden [18, 19] have presented the fundamental issues needed to achieve a high degree of automation within the computational mechanics arena. Hierarchies of models and analysis effort are advocated coupled with knowledge-based expert systems (KBES) to meet future needs. Such KBES are described relative to the analysis tools themselves to guide (and protect) the designer. These KBES will become increasingly important as advanced mechanics tools are folded into the design cycle earlier, and higher requirements are placed on the designer as high-performance engineering systems are developed exploiting new materials on new concepts and operating at extreme limits and in extreme environments. Combining design and analysis intelligence with the design and analysis tools has the potential of offering an intelligent design synthesis environment.

The concept of an Intelligent Synthesis Environment (or ISE) for the design and analysis of new NASA aerospace systems has been proposed [20-28]. Deployment of ISE-like concepts has the potential to accelerate the aerospace industry's move from the present design environment to well beyond the concurrent engineering design concept of just a few years ago. Already virtual product development tools are beginning to appear, and design and analysis tools are merging together (*e.g.*, [29-33]). The design process needs to encompass the entire lifecycle of the system, not just its initial production off the assembly line. Simulation-based design provides a virtual design environment for new aerospace systems such as a tailless military aircraft, multifunctional adaptive structures, inflatable deployable structures, transatmospheric vehicles, and reusable launch vehicles [34]. In addition, the paperwork associated with a given design can be all consuming because of the need to provide a document trail for design changes, manufacturing issues, maintenance changes, suppliers database, materials database, and so forth. Such design process documentation then provides historical information and heritage data for subsequent designs provided it is readily accessible.

In 1999, the National Research Council performed an assessment of advanced engineering environments (AEE) and the requirements for achieving them [35]. The study examined current practices, barriers, and requirements for AEE. It focused primarily on NASA objectives but is relevant to other organizations and product designs. The process definition and implementation strategy are often dictated by the product itself and its production volume – design strategy for a one-of-a-kind system is much different than one for thousands or millions of units. Small savings (weight or cost or time) per system can have an enormous impact on overall product success depending on production volume. However, access to and utilization of rapid modeling and analysis tools in the design process are integral parts of the design of any engineering system.

This paper discusses the evolution, status, needs and directions for rapid modeling and analysis tools for structural analysis. First, the evolution of computerized design and analysis tools is briefly described (*i.e.*, where did we come from and how did we get here?). Next, the status of representative design and analysis tools is described along with a brief statement on their functionality (*i.e.*, where are we now?). Then technology advancements to achieve rapid modeling and analysis are identified (*i.e.*, what roadblocks and potholes have to be overcome?). Finally, potential future directions including possible prototype configurations are proposed (*i.e.*, where are we going and how can we get there?).

## RAPID MODELING AND ANALYSIS TOOLS

Before beginning, an understanding of four key words (rapid, modeling, analysis, and tools) should be clear. The first word "rapid" is perhaps the more difficult word to define in the present context. "Rapid" implies speed and herein will be balanced by some conditional statements. Given a legacy design that has been evolved over years with minimal re-engineering of the product, "rapid" can be defined based on available time. For example, an answer is needed within two days. Such a challenge for legacy designs are difficult to meet unless the corporate memory of the systems and related analysis models is still in place. Then "rapid" refers to the speed of the analysis tools themselves and the turn-around time required for various parametric studies and off-nominal evaluations. On the other hand, "rapid" can be defined as the time required for getting a new product from inception to market. It can also refer to the computational speed of the tools; however, the time bottleneck is typically the designer/engineer rather than the computing systems. Thus, "rapid" will herein refer to the speed of completing a new product design and the ability of the tools to provide the necessary information on an as needed basis so that no delays are evident.

"Modeling" refers to several aspects of the problem. Typically it refers to geometry and to spatial discretization of that geometry. It also refers to idealization – decision making related to dimensional reduction (*e.g.*, solid representation to a thin shell or beam representation) and related to feature removal (*e.g.*, elimination of assembly details for the analysis model). It can also refer to the basic equations used to describe the deformation process; that is, the mathematical or analytical model of the system. "Modeling" will herein refer to the mathematical description of the product geometry and a hierarchical definition of product design features.

"Analysis" is multi-facetted. Early in a design process, the "analysis" typically takes the form of closed-form solutions for an approximation to the design implemented perhaps using an engineering spreadsheet software tool. Later on in the design process, more complete descriptions of the design are available and discrete models are created and analyzed using finite element methods, finite volume methods, or boundary element methods. As the design proceeds, more detail about the design is generally incorporated into these discrete models and solved using the same analysis methods – perhaps including nonlinearities, contact, manufacturing and assembly simulations. "Analysis" will herein refer to the computational engines used to solve the engineering science and mechanics aspects of the design.

The word "tools" is, of course, fairly straightforward and means an implement used or employed to achieve a given task. For the most part, the word "tool" will be used herein to refer to a software system or collection of software systems tightly integrated together with the ability to communicate (or transfer) information and knowledge of the design in a collaborative manner. A common set of tools in structural analysis is the finite element mesh generator, the finite element analysis solver, and a post-processor to visualize the computed results.

Hence, the phrase "rapid modeling and analysis tools" refers to software systems that collaborate on solving the engineering science and mechanics aspects of a mathematical description of a product in a timely manner. This process is coupled with modeling tools for geometry definition, idealization, and spatial discretization that mathematically define the product to a set of analysis tools for engineering design, performance evaluation, risk mitigation, and lifecycle assessment. Several efforts have made progress in reducing the overall design cycle time by exploiting commercial-off-the-shelf design and analysis tools and various legacy analysis tools. The development of a virtual design environment with fully integrated *CAx* tools and complete associativity between geometry and analysis models using ASTROS is described by Blair and Reich [36]. Typically these efforts involve significant focus on the information transfer and interfacing. The new design tools are based on object-oriented programming concepts using CORBA software wrappers or JAVA-based analysis and display tools. The effort at Boeing in their DMAPS program and the Smart Product Model have been described [37, 38]. Phillips and Frey [39] demonstrated the use of solid geometry modeling using a prototype aircraft forebody. All disciplines used a common solid geometry model to obtain geometric data for their application. Significant savings were reported for many steps in the design/build process. Efforts at NASA Langley have resulted in the FIDO system [40, 41] for interdisciplinary design and optimization and the NextGRADE system [42] for assembling different stock objects with associated solid models and finite element models for developing analysis models. The goal of NextGRADE was to define the next generation revolutionary analysis and design environment. These efforts are indicative of the interest and need for improved communication between modeling tools and analysis tools and between various engineering disciplines involved in the design process. However, while better information transfer is needed (as opposed to better data communication) [43], it alone will not result in highly reliable aerospace systems for the future.

The design of new systems will need to integrate multiple disciplines, exploit new multifunctional materials and address realistic loading cases including loads in extreme environments. The designers of these systems are most likely middle school or high school students today. These students are the *point-and-click generation* accustomed to rapid response, sensory input, and stock piling extra *lives*. Engineering colleges are not adapting to these anticipated changes as rapidly as is needed to educate this next generation of design engineers to deal with this increase in breath and depth of responsibilities. Students will need to make the transition from playing a virtual reality game to doing engineering design with virtual reality tools. Hence, the infrastructure of the next generation design environment or advanced engineering environment must provide a safety net for the designer. This safety net must have sufficient computational intelligence, experience knowledge base, and engineering mechanics underpinnings to mentor and guide the design process.

## EVOLUTION OF DESIGN AND ANALYSIS TOOLS

It is important to keep the evolutionary process in perspective as visionary concepts are developed depicting the next generation design environment for future designers – for both needs and capabilities. Engineering design and analysis have always relied on mathematical models of the physical system to understand and thereby utilize the knowledge gained from those models to provide for mankind's needs and benefit. With the advent of the digital electronic computer, the development of finite element analysis techniques and computer programs provided the first general-purpose design and analysis tools. Some of the early development work is summarized by Carrabine [44]. Methods and tools are the products of that early work; however, people provided the innovation and the creativity needed to leverage the new digital computers and the new finite element techniques. Modern computational structural mechanics technology owes much to those who went before us – a heritage that present day researchers should strive to follow. The next generation of designers and analysts will have increased responsibilities and also opportunities because of these advancements.

Multiple aspects of rapid modeling and analysis tools may be considered; however for the present purposes, consider just four aspects: analysis methods; computing hardware; computing software; and materials and manufacturing.

### ANALYSIS METHODS

The underpinnings of engineering mechanics have steadily evolved over the past several centuries. Coupled field problems have been the subject of much research over the past several decades but typically address only two, or possibly three, strongly coupled disciplines interacting at a time. Numerical methods such as the finite difference approach, finite element approach, boundary element approach and so forth have matured dramatically over the past 30 to 40 years with the primary impetus being the availability of high-speed electronic digital computers. These structural analysis methods, numerical procedures, and computational algorithms provide the basis for Computational Structures Technology (CST). CST research work and future directions were identified in a series of *Aerospace America* articles in 1993 [45-51].

The finite element method continues to be the primary analysis tool in structural design. Hundreds of textbooks are available on finite element analysis, and tens of thousands of papers are published each year on new formulations, new computational procedures, or application of finite elements to solve an engineering problem. MacNeal [52], one of the pioneers in finite elements, has described the development of many finite element formulations being used in commercial finite element codes today. The evolution of the finite element method for structures generally has resulted in the development of families of elements with different polynomial approximation order (*e.g.*, bilinear and biquadratic quadrilateral plane stress elements). In these cases, a new finite element mesh is required for each element type.

Alternatively a single element with hierarchical shape functions can be developed [53, 54]. Here a single mesh is used for various polynomial orders. Early work in developing a commercial *p*-version finite element code, called PROBE [55-58], was led by a company named Noetics Technologies. In 1990, MSC acquired Noetics and launched development of *p*-version technology for MSC.Nastran. Some of the attractive features of PROBE included: the geometric definition using blending functions to describe accurately local structural details, the use of hierarchical shape functions within the element, and a hierarchical solution process that automatically recovers, given a user-specified maximum *p* value, the solutions for lower values of *p* thereby establishing convergence trends and error bounds. Flowers [58] illustrated the advantages of a hierarchical *p*-version finite element approach for a stress analysis of a splicing fixture ("bathtub fitting") using PROBE. Generation of a single spatial discretization and automatic recovery of solutions for lower *p* values are two key advantages that contribute to rapid modeling and robustness of the solution. Stone and Babuška [59] illustrated these features using StressCheck [60] for a crack propagation problem in a two-dimensional plane stress membrane. Fracture mechanics problems require accurate prediction of stress quantities, which is a natural application of *p*-version finite element technology. Babuška and Miller [61-63] describe procedures for accurate extraction of quantities of interest (*e.g.*, displacements, gradients, stresses, stress intensity factors). However, migration of *p*-version technology to large-scale, general-purpose finite element codes required some concessions. For example, uniform *p*-refinement had to give way to selective *p*-refinement and the hierarchical solution process yielded to an iterative or cyclic process.

The displacement-based finite element method for the analysis of structures is by far the most common formulation used in commercial finite element software systems. Mixed variational principles and hybrid models are used and do offer advantages over displacement-based methods; however, limited commercial implementations are available. For the most part, developers have focused on single-field, low-order finite element formulations that are good performers (accurate, reliable, fast, and efficient). Increased accuracy and resolution is left to the analyst through refinement of the finite element mesh, "mesh quality checks", heritage information for related analyses, and hand calculations.

Adaptivity associated with finite element modeling can be described in terms of the type of elements, the size of the elements, the order of the approximating polynomials within the elements, and the distribution of the nodes and elements in the finite element model. Typically the element geometry is described using shape functions consistent with the number of element nodes (*e.g.*, a 4-node element will use bilinear Lagrangian shape functions) regardless of the field variable approximations. A subdomain can be modeled with a given distribution of nodes and elements. If the nodes are re-located to improve the results, and no changes in connectivity occur, then the only changes are to the nodal coordinates – *r*-refinement. If the mesh is recreated by increasing the number of elements and thereby decreasing the element size, then a new finite element model results that generally requires a complete new solution – *h*-refinement. If the original mesh is used and the order of the approximating functions (usually polynomials) within the elements is increased, then an improved solution should be obtained for the given geometric representation – *p*-refinement. These polynomials are generally hierarchical polynomials that offer computational advantages. The overall implementation may also be hierarchical in that once the solution for a given *p* level is obtained, solutions for lower values of *p* are also available thereby allowing ready extraction of error estimates. Some may refer to replacing 4-node quadrilateral elements with 9-node quadrilateral elements (same number of elements but with more nodes) as *p*-refinement. However, it is not in the true spirit of *p*-refinement since remeshing of the geometry and creation of a new model is required – not just changing the specified level of *p*. If results are generated for a specified order of *p* and the software automatically *extracts* the solutions for lower values of *p*, then error estimates and solution trends can be readily observed – this is also *p*-refinement but in a hierarchical manner. One can also combine types of refinement. For example, in *h-p* refinement, both the number of elements and the order of the approximating functions are increased (though not necessarily on the same part of the model).

In every approach to adaptivity, effective application requires the use of selective refinement rather than uniform refinement. Uniform refinement, for example, would subdivide every element in the mesh in *h*-refinement or would increase the order of the approximating polynomials in every element and in all directions for *p*-refinement. Selective refinement performs an analysis and assesses an error measure. Then the mesh is refined or the polynomial order increased in selected elements (or both, that is *hp*-refinement) and potentially certain directions based on the element error estimate.

Finite element technology has evolved to a level where linear elastic stress analysis functions are reasonably automated and robust regardless of which analysis system is used – assuming that the physical problem is adequately modeled. Solid modeling and mesh generation software systems serve as pre-processors for the analysis tools and generally offer "quality check" options to the analyst for the spatial discretization. These checks are very helpful in verifying a finite element model. Ensuring shell surface normal vectors are aligned properly, no internal edges exist, no unexpected duplicate elements and other element checks on aspect ratio, taper, warping and distortion are critical basic tests that should be applied to every finite element model. However, linear structural dynamics problems (normal modes and transient response predictions) require a more sophisticated analyst and special modeling considerations are necessary (*i.e.*, inertia characteristics as well as stiffness characteristics) than typically required for a linear stress analysis.

Nonlinear simulations increase the complexities of the analysis by several orders of magnitude and also increase the need for high-fidelity physical data (*e.g.*, characterization of nonlinear materials; general imperfection data for stability and collapse problems; friction data for sliding contact problems associated with assembly modeling or impact simulations). Nonlinear transient problems (*e.g.*, crashworthiness, manufacturing process simulations) are perhaps some of more challenging mechanics problems and computationally intensive problems facing structural analysts today. Within the present design setting, nonlinear simulations are not routinely performed in the early phases of the design – partly because of their need for detailed information of the design and partly because of the effort required to perform them. However, nonlinear simulations are an integral part of the final design steps – in particular, for certification and for assessment of extreme loading conditions. They are also heavily relied upon as part of failure investigations and subsequent re-design efforts. The increased use of nonlinear simulation results is also driven by the need for highly reliable designs with stringent requirements for mission success. In these cases, nonlinear simulations are used to understand structural behavior and verify structural performance as input to a probabilistic risk assessment.

Future considerations of strongly coupled, multiple physics problems are perhaps the next steps that designers and analysts will be required to take as part of a routine design task. However, even today, the integration of computational fluid dynamics models with computational structural mechanics models is the subject of much research with little resolution on how to interface these two disciplines which use different numerical methods and have dissimilar spatial discretizations. Coupling of acoustic models and heat transfer models with structural analysis models is probably closer to being a reality even though it is not a routine process. Interfacing various aspects of the system design (control systems, optics, power systems) is being done in a loosely coupled manner using mathematical modeling tools.

Design optimization involves the automated search of the design space in order to minimize weight and cost and to maximize system performance (*e.g.*, see [64-70]). Some of the design variables are often discrete variables rather than continuous variables, which poses additional approximations on the design process. Multiple objective functions are also common (*e.g.*, weight, cost, performance) for a single design. In addition, multiple load cases need to be considered to account for as many mission configurations and full lifecycle environment as possible. As part of some optimization procedures, derivatives of the objective functions with respect to the design variables are computed. This information provides sensitivity information used to identify key design parameters. Often this is done using analytical models that capture the basic physics but perhaps not specific details. Gradient-based optimization procedures limit the type of problems that can be solved because of the need for design variable derivative information. Combinatorial methods such as those based on a genetic algorithm or simulated annealing methods provide ways of addressing the discrete optimization problem. Genetic algorithms provide a way to more fully explore the design space and for a given amount of computing effort will always have a "family" of acceptable designs from which to choose. The drawback is that a large number of function evaluations (complete analyses) are needed for each iteration or generation in order to evaluate and rank the members of that generation's population.

## COMPUTING HARDWARE

From a historical perspective, the digital computer has only been generally available since the 1960's and then in a limited manner. The first Cray supercomputer was not delivered until 1976. The first IBM PC was introduced in 1981 – only two decades ago. UNIX workstations with color graphics displays became available in the middle to late 1980's. Wide-area networking became reliable and widespread in the late 1980's – less than two decades ago. Now at the dawn of the twenty-first century, it is common to have a desktop PC with multiple 1-GHz processors, 1 GB of real memory, 100 GB of secondary disk storage, a fast Ethernet connection, a high-resolution color graphics display, and stereo surrounding sound. Dramatic changes in computing hardware and system software have taken place in less than five years – perhaps driven more by the entertainment industry than engineering design needs. This rapid increase in computing capacity is providing the necessary computational power to unleash the designer's creativity provided the design and analysis tools, the network bandwidth, and the graphics power are available [71]. Use of multiple CPUs for a single analysis task is becoming commonplace for several of the commercial finite element software systems. Capabilities to exploit massively parallel processing (MPP) systems are also becoming evident – primarily with the explicit solvers. New computing technology such as field-programmable gate arrays or FPGAs are appearing. Substantial investment of resources will be required to assess their potential and then to determine how they may partner with commercial software vendors in defining their potential role in engineering software. Consideration of such rapid evolutionary changes in computing hardware should be included in the planning and development of next generation design and analysis systems.

## COMPUTING SOFTWARE

Programming languages by which instructions are given to the computing hardware are also rapidly evolving. Early days of toggle switches loading binary-coded instructions evolved to FORTRAN programming and then to graphical user interfaces (GUI) with the "point and click; drag and drop" features. Soon visual and audio interfaces will be available as part of the human-computer interface options. Tied with these capabilities are the immersive technologies that permit users to have a "design experience" as they explore the vehicle, experience simulation results, perform mock-up assembly for tolerance checks and interference checking, and verify manufacturability in a virtual reality design environment.

Engineering software has also evolved from simply computing algorithms to include visualization. Early on simple *x-y* plotting routines were developed along with plotting routines to display undeformed and deformed geometry data as well as contours of response parameters on the geometry. Over the past decade significant advancements have taken place in surface representation, solid modeling and automatic meshing. Parametric approaches tie design component features together and thereby provide rapid methods for updating engineering drawings and analysis models at the same time.

Concurrent engineering concepts began to appear during this same period for vehicles like the B-2, the Joint Strike Fighter, and the Boeing 777 (*e.g.*, see [72-80]). Teaming aerodynamicists, structures analysts, designers, cost analysts, materials specialists, propulsion engineers, and manufacturing engineers together caused many problems to be resolved before they became problems. This approach led to a *paperless* design in some situations wherein even the assembly process was simulated to minimize the possibility of interference on assembly. As such, the need for mock-up assemblies was minimized in many cases and eliminated in some. JPL's Product Design Center is an example of applying concurrent engineering to space missions [81]. They noted that the benefits accrued from their approach were primarily due to changes in team process (integrated product teams) rather than from incorporating new tools.

Product Data Management (PDM) techniques have also been developed and implemented at several large companies, and PDM systems developers are now targeting smaller companies. PDM provides the tools for handling large amounts of data (requirements, drawings, part counts, material availability, analysis and design results, business data, technical reports, etc.). Miller

[82] reported that "computer-aided-design/computer-aided-manufacturing (CAD/CAM), simulation/analysis, and enterprise-resource-planning/materials-requirements-planning (ERP/MRP) systems will be tightly integrated, and inexpensive remote data access will be provided through a Web interface that supports multiple languages around the world". This ambitious goal is being addressed by *CAx* software vendors (*e.g.*, i-Man system from UniGraphics Systems[1], Windchill from PTC[2], and Enovia from IBM[3]), and the marketplace is continuously changing.

Some *CAx* tools provide for interfaces between CAD tools within the present heterogeneous CAD data environment. PTC's Pro/COLLABORATE allows engineering groups to share Pro/ENGINEER data on selected parts design and manufacturing as a result of outsourcing and still maintain compatibility with the overall system design and its evolution.[4] Product lifecycle management tools provide a collaborative environment for overall product development [83]. However, true interoperability between these *CAx* systems remains an ongoing challenge as the technology of geometric modeling, feature definition and product data definition continues to evolve. Providing an open architecture is also important, as individual companies need to couple the *CAx* tools with other add-on applications or proprietary analysis tools. The current trend of *CAx* tool developers is to provide an open, interoperable capability [84]. Until then, companies specializing in data format translation between various *CAx* software systems or formats will continue to thrive.

NASA Langley activities related to computer-aided engineering, such as NASTRAN, IPAD, PRIDE, IMAT, CSM and NextGRADE, also had goals aimed at improving the design and analysis process. NASTRAN was the first general-purpose finite element code developed, and it was released for general use in 1970 [85]. MacNeal-Schwendler Corporation (MSC), now MSC.Software Corporation, successfully commercialized this code and continually improves and expands its capabilities. IPAD [86-88] focused on database management techniques (*e.g.*, RIM) needed for large-scale systems and initiated some embryonic work on MIMD computing hardware (Finite Element Machine) and software. PRIDE [89-91] was a spin-off activity from IPAD and attempted to integrate different analysis codes, methods, and CAD systems – all on different computer types – through a shared database. IMAT [92] focused more on Space Station design issues using a PRIDE approach and based on MSC/NASTRAN and SDRC/I-DEAS as the primary tools. The CSM activity, initiated in 1984, focused more on the engineering mechanics aspects and computational mechanics issues associated with the rapid change in computing systems [93-95]. A framework for methods research called the CSM Testbed was developed to provide a path for timely integration of new methods and procedures developed by government, industry and university researchers into a large-scale analysis system [96]. This program, later named COMET-AR, provides some of the analysis foundations on which NextGRADE was built. NextGRADE [42, 97, 98] provides a graphical-user interface (GUI) for assembly modeling from a library of pre-existing spatially discretized subcomponents and primitives and served as a rapid modeling and analysis prototype system for ISE within

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[1] http://www.ugs.com/products/iman/ accessed on 08.16.01
[2] http://www.ptc.com/products/windchill/index.htm accessed on 08.16.01
[3] http://www.ibm.com/solutions/engineering accessed on 08.16.01
or http://www-3.ibm.com/solutions/plm/pub2/05256965005a58c0/1/26d7dec17577e5688525686600681a5f.jsp
[4] http://www.ptc.com/company/mail/express200108/lets_collaborate.htm accessed on 08.16.01

NASA. These objects can be manipulated and stretched; however, the associated spatial discretization was fixed and never changed.

NASA Glenn (formerly NASA Lewis) activities related to computer-aided engineering focussed primarily on high-temperature applications related to propulsion systems. Over the last several decades, Chamis *et al.* [99-104] have developed a number of computer codes for analyzing advanced composite structures such as CODSTRAN, METCAN, CEMCAN, HITCAN and IPACS. In addition, Chamis has championed the development of probabilistic structural mechanics methods and software for space propulsion systems that have applicability to other aerospace structural component design. One product of this effort is the NESSUS code. The establishment of non-deterministic methods as a research thrust area within computational mechanics discipline is due in a large part to Chamis' efforts.

## MATERIALS AND MANUFACTURING

Available materials are presently one of the limiting factors in advanced vehicle design. High-temperature applications, radiation exposure, and long-duration space flights all contribute limiting factors to our current set of materials available for design. Another aspect of the design and analysis process and those items that impact it involves materials and manufacturing. Incorporating computationally developed materials will become a part of the design process in that as the operation environment is defined (thermal conditions, moisture, durability, fatigue, radiation exposure, vacuum conditions) new advanced material systems can be tailored to these requirements [105]. Given a set of conditions, computational models of new materials will be developed to meet these new design requirements.

Advanced material systems from new alloys to composite materials continue to appear. Composite systems with either organic, metallic or ceramic matrix material and often their combination within a given structure are common today, and each system offers unique capabilities for specific applications. However, the manufacturing techniques required to use these new material systems can be as challenging as developing the material system itself. Composite panels, once built by hand-layup methods, are now built using automated tooling. Construction of complex shape parts is readily performed using advanced manufacturing tools developed to reduce costs associated with incorporating composites into a design.

Advanced composite materials provide designers options to tailor the structure for specific loading cases. Advanced manufacturing processes enable this tailoring and the fabrication of geometrically complex composite parts with varying fiber orientations. Incorporating these intricacies into the *CAx* models is necessary to understand and design the structure. FiberSIM[5] integrates with a CAD system to define the fiber path and flat patterns for manufacturing. Binder [106] reported substantial savings by end users of FiberSIM in terms of reduced time to design and analyze, reduced number of change orders, and improved structural performance.

Emerging material systems include smart materials, shape memory alloys, and self healing materials proposed for structural health monitoring, active structural control, and vehicle morphing. These materials pose great challenges. In addition to traditional mechanical loading,

[5] http://www.vistagy.com accessed on 08.23.01

the behavior of these multi-functional materials are influenced by thermal, electrical, and magnetic effects and their operating environment. Continuum mechanics models that define the material constitutive relations including small and large strain response, strain rate effects, and damage accumulation need to be developed for these biomimetic multi-functional material systems to ensure safe and reliable utilization.

Simulation of manufacturing processes is an on-going area of research and encompasses numerous mechanics issues. Metal-forming simulations must address large elastic-plastic deformations coupled with contact and including the thermodynamic effects of the deformation process. Adaptive analysis techniques are required as a result of the severe changes in geometry and potentially high mesh distortion. Thick components may evolve to thin components requiring different analytical techniques and kinematics models. Thin laminates may evolve to thick laminates wherein through-the-thickness effects cannot be ignored and residual stresses must also be accounted for in the simulation.

Because of the evolutionary aspects of materials development and manufacturing process design, cost estimates for new vehicles exploiting the state of the art can be very difficult to make and hard to swallow. Since the cost of development and possible re-tooling need to be factored into the estimate and since perhaps only a small number of these systems may actually be built, and only very limited historically data may be available, so extrapolation of cost estimates may need to be used. For large production volumes, this would be different as the development costs may be spread over more units.

## STATUS OF EXISTING DESIGN AND ANALYSIS TOOLS

This section gives an overview of capabilities, availability and direction of *selected* design and analysis tools currently being widely used or developed. It is not intended to be an exhaustive list of tools nor of their features. Its intent is to provide a foundation and basis for the discussion of the needs and challenges that should be addressed to support future rapid modeling and analysis tools. Many special-purpose tools and in-house proprietary tools are available but are beyond the scope of the present paper. The information presented is based on information from the vendor's web site and from the cited references.

### SPREADSHEETS

Electronic spreadsheets, such as Microsoft Excel, are widely used in the engineering design and analysis process. Many companies are doing "spreadsheet-level" systems engineering with much success within Concurrent Design Centers (or CDCs). These spreadsheets provide the "tracibility" needed for requirements and decision making. Detailed requirements flow provides the drivers for the design and hence the design tools.

### MATH MODELING TOOLS

Mathematical modeling tools (*e.g.*, MATLAB[6], Mathematica[7], MAPLE[8], MathCAD[9], and TK Solver[10]) are also frequently used in the design and analysis process. These tools have many

[6] http://www.mathworks.com/ accessed on 06.22.01
[7] http://www.wolfram.com/ accessed on 06.22.01

features that allow convenient *symbolic* as well as *numerical* mathematical analysis. They can be used as a pre- or post-processor for other analysis tools or as a stand-alone analysis engine. Some of the many features include convenient matrix and vector manipulation, ability to find and work with closed-form solutions, and excellent plotting and graphing capabilities. These tools also contain many toolboxes or packages for dynamical systems, control systems, partial differential equations, optimization, and many others. These tools typically allow interfacing with programming languages like C, C++, and FORTRAN. In addition, due to the popularity of these mathematical modeling tools, many specialized libraries are available for download from various sites on the Internet.

Software systems such as these will need to be interfaced with the structural analyzer at some level to provide access to system-level aspects of the design. Control systems for vehicles typically require normal modes of the vehicle to perform the transient dynamic simulations needed in order to design the control systems. MATLAB and SIMULINK are commonly used in this capacity today. Similar situations most likely exist for other specific aspects of the vehicle (*e.g.*, thermal, optics, power management, and orbital mechanics). The integration of such software systems will need to be included within any future design and analysis system as well as the data management and access aspects of these loosely coupled simulations.

## FINITE ELEMENT MODELING TOOLS

Modeling refers to the mathematical description of the product geometry and a hierarchical definition of product design features. These tools are used to create the design's geometry, create "flat" drawings, create solid models, and perform spatial discretization functions. Geometry data exchange between different *CAx* systems is not automatic. At present, some geometric modeling tools interact with analysis tools if they are from the same vendor (*i.e.*, Pro/Engineer and Pro/Mechanica). MSC.Patran is tightly coupled with MSC.Nastran; however, once the geometry is discretized, actual geometry information is not readily accessible by the analysis code. Standardization of geometry information in an object-oriented format with hierarchical attributes is needed. Standardized formats such as IGES and STEP provide a degree of compatibility; however, solid modeling technology is still evolving itself. IGES format represents a current standard but does not contain even today's definition of most solid geometry modeling tools. STEP format is the next level but even then some information is lost or not available. Companies such as PlanetCAD[11] and CAD-Translate[12] specialize in geometry-file translation. LaCourse's *Handbook of Solid Modeling* [107] presents a detailed description of various techniques, standards, and status of solid modeling technology. It covers integration of solid modeling technology with finite element analysis, knowledge-based engineering, product data exchange, manufacturing, and concurrent engineering. An overview of leading *CAx* products is given in Ref. [108], and representative geometry modeling and meshing software systems are now described.

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[8] http://www.maplesoft.com/ accessed on 06.22.01
[9] http://www.mathcad.com/ accessed on 06.22.01
[10] http://www.uts.com/ accessed on 08.29.01
[11] http://www.planetcad.com/ accessed on 08.30.01
[12] http://www.cad-translate.com/ accessed on 08.30.01

**MSC.Software Corp.** [13] **MSC.Patran**
MSC.Patran is a commercially available pre- and post-processing software system with solid modeling, finite element discretization techniques, and options to generate user input for selected analysis codes (*i.e.*, so called Patran preferences). Originally developed by PDA long before being acquired by MSC, MSC.Patran is tightly integrated with MSC.Nastran in terms of supporting current MSC.Nastran capabilities and features as well as direct access to the MSC.Nastran results database. Translators via neutral-file format or specific "preferences" are available for many other finite element systems. MSC.Patran is perhaps the most popular modeling tool for finite element analysis and is widely used in industry, government, and academia.

**Structural Dynamics Research Corp.** [14] **I-DEAS**
SDRC I-DEAS is another design and modeling software system that includes integrated drafting, solid modeling, meshing, analysis and post-processing. It features automatic mesh generation for two- and three-dimensional models and internal analysis tools for linear stress, eigenvalue and heat transfer analysis. Interfaces to external finite element codes are provided through a universal file format for finite element models and results.

**Parametric Technology Corp.** [15] **Pro/ENGINEER**
PTC's Pro/ENGINEER is a CAD/CAM product with a full-featured geometry capability integrated together with a set of product development tools for drafting, manufacturing and modeling. PTC success is a result, in large part, to their featured-based, associative solid modeling kernels. Add on modules, such as ModelCHECK are also available to enhance the process. ModelCHECK helps designers use correct modeling practices by letting them constantly monitor the Pro/ENGINEER model as design features are added, much as they would use a spell checker for a word processing application. An Application Programming Toolkit allows analysts to extend, automate, and customize a wide range of ProENGINEER design-through-manufacturing functionality using an application-programming interface (API) written in the C programming language. These functions typically provide programmatic access for creating, interrogating, and manipulating almost every aspect of the engineering model and its data management.

**Dassault Systems**[16] **CATIA**
Dassault Systems offer CATIA as a *CAx* tool for designers and suppliers. CATIA is marketed and distributed in the United States by IBM. It offers computer-aided three-dimensional interactive applications. It can be used to generate flat drawings, three-dimensional renderings and solid models used to determine component interferences. Boeing's selection of CATIA as the modeling system for the Boeing 777 was significant indicator to the *CAx* industry that CATIA is able to handle large-scale, full-vehicle design requirements [72].

[13] http://www.mscsoftware.com/ accessed on 07.26.01
[14] http://www.sdrc.com/ accessed on 07.26.01
[15] http://www.ptc.com/ accessed on 06.22.01
[16] http://www.catia.com/ accessed on 07.26.01

### Other Finite Element Modeling Tools

Other finite element modeling tools that are available and in use include Solid Edge, FEMAP, SolidWorks, AutoCAD, CADKEY, TrueGrid, and FEMB.

## FINITE ELEMENT ANALYSIS TOOLS

Analysis refers to the computational engine used to solve the engineering science and mechanics aspects of the design. These tools are used for the detailed structural analysis aspects of the design. Multi-physics capabilities are beginning to emerge in commercial software systems; however, the present effort of this paper focuses on structural analysis. Representative software systems for finite element analysis are now described.

### MSC.Software Corp. [17] MSC.Nastran, MSC.Marc, MSC.Dytran

MSC.Nastran is a general-purpose finite element analysis code from MSC.Software Corp. – perhaps *the* standard tool for finite element analysis and design. It has a long rich legacy of development beginning in the late 1960's as the NASA STRuctural ANalysis program [85]. It is often the specified analysis code to be used on many critical aerospace programs. Historically, its basis is a displacement formulation, and accuracy is achieved through mesh refinement (*h*-refinement). Over the past decade, *p*-refinement was incorporated allowing the user to use a specific mesh of elements and simply change the order of the approximating polynomial (*p* order). Their implementation is based on hierarchical shape functions for the primary field variables with a cubic definition used for element geometric shape. The process starts with a given order of interpolation in all elements and computes a solution. Error measures are evaluated and localized changes (selected elements and selected directions) in the element polynomial order are made. The solution is then re-computed (perform another iteration) until all error estimates are smaller than a user-specified value. Under a cooperative agreement [109] with NASA Langley Research Center, the interface element capability developed at NASA Langley has been implemented into MSC.Nastran. MSC's implementation of the interface technology exploits their new *p*-version element capability implying that some level of adaptivity should exist [110-112].

MSC.Marc is another general-purpose finite element code from MSC.Software Corp. that is known for its nonlinear capabilities. MSC.Software acquired MARC from the original founders in 2000. MARC is recognized for its large problem solution capability using the domain decomposition technique and parallel processing. Also, it is known for its solution procedures, material models, and element technology. Many of its features were exploited as part of the MHOST activity at NASA Lewis Research Center (now Glenn Research Center).

MSC.Dytran is a general-purpose finite element code for nonlinear transient dynamic response prediction from MSC.Software Corp. It is an explicit code with its origin tied to the 1988 public-domain version of DYNA3D from the Lawrence Livermore National Laboratories. MSC.Software integrated the DYNA3D code with PISCES (an Euler flow solver) to create MSC.Dytran. MSC.Dytran has the capability to solve structures, fluids, and fluid-structure interaction problems. It has several constitutive models (many inherited from the early DYNA3D code), contact models, and a family of single-integration-point finite elements.

[17] http://www.mscsoftware.com/ accessed on 07.26.01

However, these elements and material models are not necessarily consistent with those available in MSC.Nastran – input records are compatible; however, the underlying formulations are different (*e.g.*, the QUAD4 in MSC.Nastran is not the QUAD4 in MSC.Dytran).

**ANSYS, Inc.**[18] **ANSYS, DesignSpace**

ANSYS is a general-purpose finite element code known for its nonlinear capability and is widely used in the automotive and power industry. Swanson Analysis Systems, Inc. (now ANSYS, Inc.) developed ANSYS during the same time period as NASA developed NASTRAN (in the late 1960's and early 1970's) as an outgrowth of finite element research at the Westinghouse Company in Pittsburgh, PA. It is a full-featured nonlinear analysis code with newly developed multi-physics and probabilistic features.

A related product from ANSYS, Inc., named DesignSpace, provides up-front simulation of the design using three-dimensional geometry from a CAD definition (see Thilmany [16]). It can be used to test assemblies and simulation model development. DesignSpace is aimed at the design engineer that knows the product and component interaction thereby allowing them to iterate the design quickly to resolve design issues before they become problems. As such, the more experienced analysts have the charter of solving more detailed problems requiring advanced knowledge and understanding of computational mechanics methods. Up-front CAE solutions have high potential for reducing product development time. A comparative study [113] involving ten assembly analysis benchmarks and three design and analysis tools indicated the advantages offer by DesignSpace.

**Hibbitt, Karlsson and Sorenson, Inc.**[19] **ABAQUS Standard and Explicit**

HKS ABAQUS Standard is a general-purpose finite element code that has gained substantial popularity and users over the last decade. It has a full suite of capabilities from linear stress analysis, eigenvalue analysis (buckling and vibration), to highly nonlinear analysis including a large-strain formulation and progressive failure capability. The ability to incorporate user-defined elements and constitutive models provides an attractive feature for researchers to test new formulations.

HKS also provides ABAQUS Explicit, a nonlinear explicit transient dynamics finite element solver. This code has similar capabilities and functions as other explicit transient dynamics codes. However, it does appear to be consistent with the element technology, constitutive modeling technology and contact modeling available within ABAQUS Standard. This aspect contributes to validation and verification of the finite element model for quasi-static, eigenvalue, and transient response predictions.

**Parametric Technology Corp.**[20] **Pro/Mechanica**

PTC's Pro/Mechanica is a CAE tool developed for use by design engineers early in the design process. In 1995, PTC acquired it from Rasna, Inc. Pro/Mechanica shares the same user interface as Pro/Engineer and uses a *p*-version finite element formulation for the analysis. It

[18] http://www.ansys.com/ accessed on 07.26.01
[19] http://www.hks.com/ accessed on 07.26.01
[20] http://www.ptc.com/ accessed on 06.22.01

uses a precise representation of CAD geometry and uses either a multi-pass adaptivity algorithm or a single-pass adaptivity algorithm to increase the polynomial degree on parts of the model where user-specified accuracy has not been obtained (see Short [114]). The model can use design variables so that changes to the analysis can be minimized due to design changes and so that sensitivity studies can be executed. Pro/Mechanica can also function as a pre- and post-processor for other analysis tools.

**Engineering Software Research and Development[21] StressCheck**

StressCheck [60] is a general-purpose finite element code from ESRD utilizing a state of the art *p*-version finite element analysis technology. ESRD was formed in 1989 with the mission to "create and market software tools for the advancement of the quality, reliability and timeliness of information that serves the engineering decision-making process." StressCheck uses hierarchic shape functions for its *p*-version finite elements and gives error and convergence estimates for all quantities of interest. StressCheck supports linear and non-linear elasticity, modal analysis, buckling, steady-state thermal analysis including convection and radiation. The composites research team from the aeronautics industry, known as the Composites Affordability Initiative (CAI), has just completed an extensive study of current capabilities in the area of failure analysis tools for composite bonded joints. This study led the CAI team to unanimously choose StressCheck as the software tool to replace, as well as radically improve, existing industry standard software currently used for sizing bonded joints. StressCheck supports parametric models and has a handbook library of parts models. Models from the handbook can be loaded, and after setting values for the appropriate parameters, runs and reports can be executed and generated. Models can be generated from within StressCheck or they can be imported from other sources (*e.g.,* IGES geometry or NASTRAN bulk data decks). The post-processing is built in and includes global error estimation, pointwise or pathwise extraction, minimum or maximum value extraction, force resultants and moments, and fracture mechanics parameters (*e.g.,* stress intensity factors). StressCheck also includes a full featured plotting and report generating capability.

**Livermore Software Technology Corp.[22] LS-DYNA**

LSTC/LS-DYNA is a relatively new commercial general-purpose finite element code for nonlinear transient response problems. LS-DYNA also has its origins with DYNA3D from Lawrence Livermore National Labs; however, one of its originators, Dr. John Hallquist, is the president of LSTC and quite active in its on-going development. It is based on an explicit solver for transient dynamic response problems; however, an implicit solver for quasi-static response problems is also available. It has a wide-range of constitutive models and finite element types – even fully integrated elements. LS-DYNA is available on a wide-range of computers, operating systems and even for multi-processor and MPP systems. LS-DYNA offers an implicit solver capability for quasi-static analysis based on the same finite element technology used for the transient analysis. LS-OPT provides a new capability for design optimization. LS-POST provides processing features explicitly developed to support nonlinear transient dynamic simulations.

[21] http://www.esrd.com/ accessed on 06.22.01
[22] http://www.lstc.com/ accessed on 07.26.01

**Alpha STAR Corp.[23] GENOA**

Alpha STAR/GENOA is a relatively new analysis code recognized in 1999 as one of NASA's software-of-the-year winners [115]. GENOA [116] is an integrated structural analysis and design system used to model aging and failure in structural materials. It features the composite mechanics and probabilistic analysis technologies developed at the NASA Glenn Research Center such as those described by Chamis [101-103]. It also features a parallel processing capability, adaptive mesh refinement, and progressive failure analysis with element extinction.

**NASA LaRC NextGRADE and COMET-AR**

NASA Langley Research Center initiated the Computational Structural Mechanics (or CSM) activity [93] in 1984 using the concept of a "testbed" for methods research. The "testbed" had its origins as a combination of the NICE data manager and command language developed at Lockheed-Martin and the SPAR finite element code developed under contract to NASA. In 1990, the CSM testbed was formally named COMET. Government, industry and university researchers worked within this common framework for methods development. This system evolved into COMET-AR in the early 1990's and included some *h*-refinement mesh adaptivity. The key feature of COMET-AR is the implementation of the interface element technology that enables subdomains of different spatial discretization to be joined together along a common boundary. This feature provided an enabling capability used in advocating the next generation revolutionary analysis and design environment – NextGRADE. The NextGRADE system is a GUI-based *assembly-modeling* and analysis tool [42]. Assembly modeling implies that component geometry, structural idealizations, and spatial discretization are performed by a modeling tool such as MSC.Patran and then transferred to the NextGRADE system as "stock objects". A library of stock objects can be created thereby allowing a user to select different stock objects, drag-and-drop them on to a "scene" and then interconnect the stock objects using the interface element technology. Structural analysis is then performed using COMET-AR or MSC.Nastran. Significant work has been done on the NextGRADE GUI interface and immersive visualization features.

**STAGS**

STAGS is a general-purpose shell finite element analysis code with increasing capabilities in three-dimensional solid elements. It is perhaps the premier nonlinear shell finite element code for analyzing thin shell structures for buckling and collapse. It is a small strain, large-deformation, large rotation code. It has been developed primarily under government and internal Lockheed-Martin sponsorship. Some of the unique features from STAGS include the element-independent corotational procedures, advanced arc-length control strategies, crack growth analysis procedures for pressurized shells, shell-to-solid transition elements, unique sandwich element, progressive failure analysis for laminated composite structures, and hybrid static-transient solution procedures.

**Other Finite Element Analysis Tools**

Other finite element analysis tools include COSMOS, ALGOR, ME/NASTRAN, NE/NASTRAN, SAS/NASTRAN, ADINA, NISA, EAL, and ASTROS.

[23] http://www.alphastarcorp.com/ accessed on 07.26.01

# NEEDS FOR FUTURE AEROSPACE PROGRAMS

The design and analysis needs to support anticipated NASA aerospace programs are the key drivers to the research directions identified herein. These programs are broadly classified into several main types. First, vehicles for planetary missions are anticipated. For the next decade, these vehicles will most likely be unmanned but highly intelligent and self-adaptive. Second, space telescopes looking into deep space and looking back towards earth will be developed and deployed. Third, but perhaps directly tied to the previous two types, gossamer structures will be used with both planetary missions and telescopes (*e.g.*, solar sails, sun shields, and inflatable structures). Finally, space launch vehicles for access to space will provide additional impetus for the development of rapid design and analysis methods and procedures. These vehicles include reusable launch vehicles, a space shuttle replacement vehicle, space station crew escape vehicles, and so forth. These aerospace programs have some unique requirements, and some requirements are shared among programs. The key challenges for structural analysis and design are described next. These challenges are grouped into four areas: mechanics, computations, risk management, and decision-making.

## MECHANICS CHALLENGES

Mechanics challenges relate to the fundamental engineering mechanics underpinnings required for accurate, robust, physics-based simulations for the given design. For the most part, the basic partial differential equations governing the system response to any loading system or environment are well known. However, solving those equations when applied to complex structural systems with complex constraints, complex geometry definitions, and advanced materials pushes the current analysis tools to and beyond the limit of their capabilities. The challenges in this area include constitutive modeling, Gossamer structural mechanics, finite element technology, solution algorithm technology, and interface technology.

### Constitutive Modeling

New materials are continually being engineered using a combination of experimental procedures and computational chemistry. Advances in manufacturing techniques for current materials provide cost-effective usage of advanced materials (*e.g.*, textile composites) or that mitigate material system deficiencies (*e.g.*, stitching to improve transverse properties). To take full advantage of a given material system, an understanding and characterization of its failure modes and damage propagation process are needed. Specific topics related to material characterization include:

- Constitutive models for biomimetic materials are needed. The revolutionary nature of such material systems will require a new paradigm in constitutive modeling. A complete thermodynamical model accounting for strain-rate effects and chemical changes will be needed.
- Constitutive models for multifunctional materials used in structural health monitoring (embedded fiber optics), active structural control (piezoelectric materials and shape-memory alloys), and possible structural morphing are required.
- Development of validated and verified failure criteria and damage propagation models is lagging behind the development, availability and usage of advanced

composite materials of different architectures (unidirectional laminae; textile composites; polymer, ceramic, metal matrix composites; hybrid composites).

- Simulation tools for sandwich structures with different core materials (honeycomb, foam, truss) need to be developed for very thick components including damage models. Typically the core materials behave differently in tension and in compression – elastically and after failure initiation. Sandwich structures include structures that exploit hybrid fabrication concepts for special applications such as crash energy management systems.

**Gossamer Structural Mechanics**

Gossamer structural mechanics refers to mechanics associated with the design and analysis of ultra-thin, ultra-large membrane structures primarily for space applications. Jenkins [117] provides a thorough treatment of the state-of-the-art of these types of structures. An illustrative example question that might be asked in a gossamer structural mechanics context is: how do you package a membrane that when unfolded is the size of an aircraft carrier deck and a thickness of a sheet of thin plastic wrap? These issues are embodied in three areas: wrinkling mechanics, packaging simulations, and deployment simulations.

- Wrinkling mechanics deals with simulating the wrinkling behavior in thin membrane structures using a variety of techniques. Currently an effective approach based on effective material modeling [118, 119] has been demonstrated. This approach captures much of the physics but not all the physics. In some applications (*i.e.*, sun shields), a precise simulation of the wrinkling behavior may not be needed; however, for large telescopes, it may be the enabling analysis technology.

- Packaging simulations for these gossamer structures are also enabling technologies that need to be developed, validated, and verified. Modeling techniques from airbag simulations can be utilized and perhaps extended to large gossamer structures. However, new approaches developed specifically for these structures are needed. Parametric studies of different packaging concepts, different folding patterns, and different final sizes will be required in order to engineer and deploy such structures.

- Deployment simulations for folded gossamer structures (*i.e.*, single sheet of thin film) and for large inflatable structures (*e.g.*, Inflatable Antenna Experiment or IAE[24] [120]) are currently beyond the computational capabilities of the design and analysis tools. The deployment process is typically assumed with minimal analysis of the actual process itself. The initial phase of the deployment is highly nonlinear involving large deflections, large rotations, and surface-to-surface contact, while the final phase involves the full pressurization and rigidization process. Hybrid transient solution procedures are needed for such simulations (i.e., explicit procedures for early transient response and implicit procedures for final stages).

**Finite Element Technology**

The finite element method is in its fifth decade of development for engineering analysis. Often times it is said that finite element technology is mature and nothing remains to be done. However, nearly any analyst that has applied the finite element method to an engineering

[24] http://www.lgarde.com/programs/iae.html accessed on 07.12.21

system will disagree with that statement. Granted the finite element method has evolved significantly and rapidly. It is routinely used to solve complex engineering design problems, and the finite element method is by far the analysis tool of choice for structural analysis problems. The element technology available in most commercial codes is quite good and improvements in element formulations will be slow to come. However, with the seemingly ever-increasing CPU speed and memory sizes of current computer workstations, the types of elements that are computationally feasible will grow. Issues related to element technology that need to be addressed include progressive damage and strain softening, contact modeling, error estimation and adaptivity, and meshless methods.

- Element technology focused on progressive damage is a current area of much research especially in the area of strain softening. Topics include failure detection and material degradation procedures along with specialty elements such as decohesion or interface elements [121-126]. Associated with damage progression is the need for element extinction once the element stops contributing to the physics of the simulation. Such a capability exists in explicit transient dynamics codes for modeling penetration and is called element erosion or adaptive contact. Maintaining equilibrium for a structure exhibiting progressive damage is critical to insure valid solutions are obtained.

- Contact modeling is often the single most computational phase of a nonlinear simulation. Improvements in algorithm performance and ease of modeling have been made over the past few years; however, further improvements in computational efficiency, contact surface evolution, and modeling are still needed.

- Error estimation techniques have been proposed and many are in use. For the most part, general-purpose finite element codes do not have error estimators in place or integrated with the overall solution process. Error estimates generally relate to variations in secondary (or derived) quantities such as stress within certain regions of the domain. However, local changes in stiffness due to thickness changes, material changes or material degradation due to damage defeats this approach. Strain energy density is another measure used for identifying regions with localized large gradients. Adaptivity refers to the process of refining the spatial discretization to improve the solution accuracy. Many error indicators and quality measures have been proposed (*e.g.*, see [127-134]). Some are simple to implement such as the one by Zienkiewicz and Zhu [127]. Most have only been tested on linear problems due to the complexities associated with adaptive refinement for nonlinear problems. McCleary [133] evaluated several error estimators for *h*-refinement nonlinear shell analysis by exploiting an iterative equation solver to extend the nonlinear solution on one mesh to a more refined mesh. Limited use of *h*-refinement is available in the commercial codes (*e.g.*, LS-DYNA uses the element "fission" model, see [131, 133]). The use of *p*-refinement appears to be somewhat restricted. Several codes claim to offer *p*-version capability to the extent that the same finite element discretization is used to solve the problem sequentially for user specified values of $p$. They do not appear to be hierarchical *p*-version implementations wherein the solution for a given value of $p$ also provides, automatically, the solution for the lower $p$ values thereby enabling an assessment of accuracy and convergence of the solution.

- Meshless methods [135-142] refer to a class of methods where the discrete model of the problem does not depend on the availability of a well-defined mesh. Meshless methods typically cover the geometry of the structure with a collection of overlapping open sets. Each set can be described in terms of a node and a "window function" or "patch" or "cloud" around the node. Normally no connectivity information is given for the patches or nodes, and the patches can be of any shape and size. Reviews of some of the different *meshless* methods are given in Refs. [135] and [136]. Some of these different methods include Moving Least Squares (MLS) approximations; Belytschko's element free Galerkin (EFG) method [137-139]; Melenk and Babuška's partition of unity finite element method (PUFEM) [140]; and Oden and Duarte's *h-p* clouds [141, 142]. These methods are relatively new and appear to have several benefits for some problems. For example, since the method is *meshless*, inserting new nodes (*h*-refinement) is relatively easy. Nodes can be inserted at will (and the size of the patches can be decreased if desired), without any transition regions. Also when doing a *p*-refinement, the polynomial order on each patch can be increased completely independently of other patches. The methods are ideally suited for including *a priori* knowledge about the solution in the approximation space [140]. This can significantly reduce the number of degrees of freedom required for a given solution accuracy. Methods like these are ideal for fracture problems. Oden and Duarte [142] enrich the finite element space with special crack tip functions in the clouds containing crack tips. Fleming *et al.* [138] use a similar approach using their EFG method. Both of these approaches allow for trivial extraction of the stress intensity factors and allow for easy simulation of crack propagation without expensive remeshing or refinement [139]. Approximations of any regularity (smoothness) can be obtained and these methods are ideally suited for adaptive refinement – *h*, *p*, or *hp*. Depending on the approach, there are some issues with boundary conditions (particularly essential (displacement) boundary conditions), and there are integration issues to be considered when forming the linear systems. Much more work needs to be done on these elements and these methods need to be made available in the standard codes.

**Solution Algorithm Technology**

Solution algorithm technology refers to the procedures used to solve a given problem. It can refer to the use of hybrid solvers for linear stress analysis problems, to hybrid explicit/implicit methods for transient analysis problems, to hybrid quasi-static/transient procedures for mode jumping problems, and to integrated procedures for optimization and sensitivity analysis.

- Hybrid equation solvers have the potential to exploit emerging computing systems and may be required to meet the needs of adaptivity, hybrid modeling, and collaborative methods. Direct solvers such as LU decomposition and its various data structures (*e.g.*, banded, skyline, sparse, symmetric) have well-defined performance factors in terms of obtaining a solution after a given number of operations. Iterative solvers such as preconditioned-conjugate-gradient (PCG) methods have low storage requirements and at times offer the only solution alternative. Application of these solvers to finite element solution procedures and problems are described and their performance evaluated in Refs. [143-145]. Hybrid equation solvers that exploit the advantages of both need to be developed and exploited as a new paradigm of solvers to new algorithms.

- Hybrid solution procedures for quasi-static and transient response problems are now appearing (*e.g.,* [146]). Having access to these methods is of increasing importance as structural designs are optimized thereby driving critical response modes together (*i.e.,* closely spaced buckling eigenvalues) and as extreme environments and loading conditions are considered (*i.e.,* long duration crush simulations). Hybrid explicit/implicit time marching procedures are needed for many applications including space structure deployment simulations to access off-nominal conditions.
- Design optimization procedures for multiple objective functions using traditional gradient-based algorithms and evolutionary-based algorithms (genetic algorithms) are needed to deal with the complete life-cycle design. Cost, performance, operation, manufacturability, and maintenance often define competing requirements. Sensitivity derivatives need to be an integral part of the solution procedure so that key design parameters are readily identified and understood – in particular for high-performance systems.
- Hybrid modeling and collaborative methods refer to the use of the best appropriate modeling procedure for various aspects of the problem, their integration with each other and their collaborative work to solve the design problem.
- Techniques to exploit specific computing infrastructures (homogeneous or heterogeneous, co-located or dispersed, single- or multi-processor, conventional or configurable logic gates) need to be harnessed as an integral part of these procedures.

**Interface Technology**

Interface technology, in a broad sense, involves the coupling of independently modeled and analyzed subdomains of a given system. Different aspects of interface technology include the coupling of two or more disciplines, coupling of multiple types of analysis methods for a single discipline, and coupling of different spatial discretizations within a single discipline using the same analysis method. Collaborative problem solving involves the application of multiple methods, multiple models, and/or multiple computational procedures to solve an engineering analysis problem that potentially involves multiple disciplines [147]. A multiple-methods approach exploits the best attributes of a method to solve a problem – perhaps determining a local response. Coupling of finite elements, finite differences, boundary elements, exact solutions, analytical solutions and other methods are needed. A multiple-models approach frees the analyst to specify different spatial discretization levels in different subdomains without the burden of maintaining discretization compatibility on a point-wise basis. A multiple-computational-procedures approach exploits hybrid solutions strategies or hybrid computational models to assess the response characteristics and choose either a quasi-static or transient solution strategy or even combines local exact solutions with global discrete solutions.

Interfacing or coupling between different disciplines to form a multidisciplinary analysis tool is an active research area in many industries – especially in the aerospace industry. For example, unsteady aeroelastic analyses with active or passive controls are under development at a number of companies, government labs, and universities. Methods for coupling between acoustics and structures are another example receiving much attention. Perhaps the primary difficulty in such analyses is the information transfer between the disciplines across geometric boundaries that are discretized differently. A wing surface mesh may require one level of discretization for structures and quite another for aerodynamics. The interaction of these models and the physics being represented continues to pose challenges to the analyst.

Interfacing or coupling different methods of analysis together is also an active research area related to collaborative multifunctional procedures. This is perhaps more evident in multidisciplinary problems wherein a different method is used in each discipline. For example, structural acoustics problems generally use a boundary element approach or an asymptotic analysis approach for the acoustic problem while the finite element approach is used for the structural problem. Coupling between finite element and boundary element methods has also been demonstrated on selected problems. Another example using multiple methods is the alternating method used in linear elastic fracture mechanics where the solution based on a finite element model of an uncracked body interacts with an exact solution for the cracked body. The local stress state near the crack is transferred between the two analyses in an iterative or alternating manner until a converged solution is achieved.

Interface technology for coupling dissimilar finite element structural analysis models together along an edge or surface has been the subject of much research sponsored by NASA Langley's Computational Structures Branch (*e.g.*, see [147-156]). The interface element is derived based on a hybrid variational model of the assembled system and enforces displacement continuity and equilibrium of surface tractions along the interface in a variational or weak sense. As a result, different levels of spatial discretization can be treated in each subdomain. Rose [155] developed a strategy to connect two subdomains with different boundaries by computing a common interface geometry rather than requiring the interface boundary of each subdomain to be coincident. A computational disadvantage of the interface technology is that the resulting global assembled generalized stiffness matrix, while still sparse and symmetric, loses positive definiteness. Alternative formulations based on multi-point constraints have been developed and implemented as a pre-processor [156]. Under a cooperative agreement with NASA Langley [109], MSC implemented the interface element capability into MSC.Nastran. The MSC implementation exploits their *p*-version element capability implying that some level of adaptivity should exist in the MSC version of the interface technology [111, 112]. On the other hand, the COMET-AR implementation of the interface technology is strictly based on *h*-version elements.

A fundamental aspect of interface technology is the coupling and integration of various tools, models, methods and disciplines together. Data organizational challenges, data sharing challenges and various protection and access rights for the shared data as well as other issues need to be addressed. Some capabilities exist for determining detailed response characteristics using separate analysis models. Here the global model provides the boundary conditions for the local model that is typically more refined. Such approaches are referred to as submodeling, global/local, 2D/3D, hierarchical modeling, and various other names. Interface technology for both methods and modeling will be needed in an advanced assembly modeling and analysis tool. Various models having different levels of analysis fidelity and/or geometric detail will be needed in order to simulate the design process from concept through manufacturing. Definition of mechanical interfaces as required by the assembly of connected components (*e.g.*, solid rocket motor tang and clevis assembly joints) are needed as well as the appropriate analytical and computational procedures to simulate their response. These interface problems are multi-body contact problems, which pose their own challenges.

## COMPUTATIONAL CHALLENGES

Computational challenges relate to the computational infrastructure, computational software, and knowledge acquisition from the simulation. To a certain extent, these challenges are more difficult to address than the mechanics challenges. Here the computational infrastructure is very dynamic and often advances are made before the previous ones are fully exploited – sometimes this is a good thing. The Ultrafast Computing Team at NASA Langley found that significant changes in computational engineering are needed to address design and analysis challenges posed by future aerospace systems [157]. Redevelopment of existing tools will be required to exploit fully the emerging high-performance, high-throughput computing systems.

### Computational Infrastructure

The computational infrastructure refers to the computing system itself in terms of the type and number of CPUs, amount of physical memory, amount of secondary storage, its graphics capabilities and its network access. It is common for engineers to have a multiprocessor computer with gigabytes of random access memory and tens of gigabytes of secondary disk space sitting on their desktop. Access via a high-speed, high-bandwidth network to other computing systems enables some degree of a collaborative working environment. Hence a heterogeneous computing environment is available to the designer and engineer provided system software can take advantage of the available CPU cycles. Load-sharing software tools such as LSF[25] and high-throughput computing tools such as CONDOR[26] from University of Wisconsin-Madison [158, 159] are available and offer ways to harvest unused CPU cycles for engineering analysis tasks. Kaplan and Nelson [160] presented a comparative study of different approaches to exploit distributed heterogeneous computing systems including LSF and CONDOR. Both CONDOR and LSF operate on heterogeneous collections of workstations. The workstations in CONDOR clusters are loosely coupled. That is, the clusters are able to span multiple networks. Jobs can be farmed out to various workstations on the network and the user need not have accounts on all workstations in the cluster. Workstations in LSF clusters tend to be more tightly coupled than in CONDOR clusters, since usually LSF clusters are set up on a single network. Another type of cluster is the Beowulf[27] cluster [161-164] originally developed by Sterling and Becker in 1994 at the Center of Excellence in Space Data and Information Sciences (CESDIS). CESDIS was located at NASA Goddard Space Flight Center. A Beowulf is a kind of high-performance massively parallel computer made up of a cluster of PCs or workstations. Unlike CONDOR or LSF clusters, the nodes in a Beowulf are tightly coupled. They are dedicated to the cluster and only run the cluster jobs. A Beowulf cluster is connected to the outside world through only a single node. The nodes typically are running a free-software operating system like Linux. Depending on the type of problem, one is often able

[25] http://www.platform.com/products/LSF/ accessed on 08.23.01
[26] http://www.cs.wisc.edu/condor accessed on 08.06.01
[27] http://www.beowulf.org/ accessed on 09.04.01

to obtain supercomputer performance for a fraction of the price of a conventional supercomputer. Depending on the granularity of the parallelism desired, one can use one of these clustering systems. Large granularity parallelism can be used to exploit a heterogeneous computational infrastructure using CONDOR or LSF, while medium to fine granularity parallelism can be used to exploit a Beowulf cluster. Fine granularity parallelism can also be used to exploit massively parallel processing (or MPP) systems.

Immersive visualization methods and hardware (graphics rendering, processor speed, network bandwidth, real-time display) are coming on-line at various installations but are very expensive in terms of initial cost and maintenance and also for the infrastructure to support them. However, the ability to "walk-through" a design layout to examine assembly details and interference problems as well as to improve the comprehension and understanding of the simulation results from large-scale models is desperately needed today even without other features. Current utilization of this technology is essentially as a "big screen TV." Sensory input will need to include touch as well as visual and audio input. CyberGlove[28] offers such a capability coupled with *CAx* tools for digital prototype evaluations. CFD researchers are leading some of this activity, and have for years. The structures community needs to define the immersive functions that will enhance their abilities to design and analyze complex systems (*i.e.*, Is visual information enough? Should audio output be included to simulate breaking? Should touch or feeling output be included? How is the output defined?).

**Computational Intelligence and Soft Computing**

With the onset of new computing systems and alternative computing strategies and techniques, new paradigms for optimal design and analysis are being proposed. Evolving ideas associated with neuro-computing, genetic algorithms, intelligent computational engines, and knowledge-based solution strategies with self-learning and self-healing features are on the horizon (*e.g.*, see [17, 165-173]). One theme of soft computing is to develop an intelligent design evolution and analysis system with hybrid analysis strategies, multiple objective functions, and a knowledge basis. Such an evolutionary system will be based on modern analysis tools utilizing the evolving computing systems and based on a genetic algorithm to obtain a *family* of "good" designs after a given amount of time (*i.e.*, CPU time or number of design *generations*). The system will be hierarchical in nature with respect to analysis level, model fidelity, and process granularity for parallel computing. It will provide a rich design environment for engineers and will provide intelligent interfaces between the engineer, the designer, design and analysis tools, and computing and visualization systems. Since the system may be based in part on a genetic algorithm, design variables can be discrete as well as semi-continuous over a range. This feature provides a novel approach to design wherein a design variable can be stiffener type or stiffener pattern or different material systems or perhaps even a different component supplier. In addition, this approach readily lends itself to multiple objective functions and hence can include performance, cost and manufacturing objective functions and/or constraints concurrently if desired and available. A genetic algorithm establishes a "family" of acceptable designs after each iteration (or generation) and therefore the design process is more evolutionary (*i.e.*, let the design process execute for more time and the design may improve, but

[28] http://www.immersion.com/products/3d/interaction/cyberglove.shtml accessed on 08.28.01

a good design is always available). Having options available is becoming increasingly important as trade-offs between optimum performance and cost-effectiveness are made.

The analysis modules of the new system will vary in complexity and fidelity from simple analysis methods to detailed finite element analyses. The finite element analyses may involve finite element models of different fidelity (coarse or refined). The fidelity of the analysis procedure will be part of the genetic parameters used in the design evolution as a result of using a genetic algorithm. That is, a design parameter may now be the analysis level or type or even the level of mesh refinement in a portion of the finite element model. In such a case, results obtained from models of different fidelity may be used to establish confidence bounds or adaptively define and improve response surface characteristics. As results from high-fidelity simulations become available, the response surface definition would be appropriately updated.

Design parameters may also include discrete variables such as the type of solar panel or stiffener configuration or material selection option in addition to the usual design parameters of thickness, length, widths, etc. A genetic algorithm is used to sample the design space randomly, and then to evolve the design based on genetic operations on the binary strings (*i.e.*, crossover, mutations, and permutations) to rank and to generate children for the next design generation. Weighting functions will be used in the ranking of designs based on model fidelity and analysis robustness.

The computing infrastructure will involve a host computer networked to a heterogeneous computing system network. Based on a genetic algorithm, the system requires the evaluation of objective/performance functions for each design configuration in each generation. This task can involve hundreds of analyses of various computational complexities. First, an assessment of the computational effort required for each design configuration is needed. This estimate would be based on the number of nodes or elements or degrees of freedom, and solver features (bandwidth or operation count) and will be determined for a given type of analysis (*e.g.*, linear or nonlinear stress analysis, vibration, buckling, heat transfer, and so forth). Then the computational task will either execute some analysis tasks concurrently on many processors (essentially no communication between processors), or sequentially perform many analyses in parallel.

The parallel computations would use all available processors (massively parallel processing or MPP-type application wherein each analysis is a large computational problem). Or the computational task may launch many sets of computing tasks on a heterogeneous computing framework. Some tasks may be started on a fast single CPU computer, some on a MPP platform, some on a simulated parallel virtual machine or PVM environment depending upon the ranking of the computational effort to complete each analysis task. Early work on the parallel virtual machine or PVM environment [174, 175] represents a step towards creating a heterogeneous computing environment that could also include non-local (but networked) systems. Such a computing paradigm will be needed that can address concurrent computing needs (*e.g.*, rapid assessment of multiple load cases or multiple design configurations) and parallel computing needs (*e.g.*, parallel equation solvers for very large-scale problems, MPP implementations for transient dynamics). System software design and control of such computational tasks which read from and write to a shared database or even display results in real-time will need to be designed and developed.

In addition to PVM, the Message Passing Interface (MPI) will be useful for large-scale problems. MPI[29] is designed for high performance on both MPP platforms and on (homogeneous) workstation groups. MPI's goal is to provide a standard for message passing amongst processors that is practical, portable, and efficient. Software written for one MPP architecture using MPI is portable in the sense that the same code can be used on a different MPP architecture. That is, the software for inter-processor communication is standard even if the processor connectivity (*e.g.*, n-dimensional Cartesian or general topologies) is different. Even though they can be used for many of the same purposes, there are several differences between PVM and MPI. The main difference stems from the reason for their existence – PVM was designed to create a virtual machine – to connect a set of heterogeneous hosts that appear to the user as a single machine. MPI was created because each MPP vendor was creating their own proprietary application program interface (API) for message passing among processors. MPI was an attempt to standardize inter-processor communication (*i.e.*, the vendor implements the MPI API so the user can use it to write software that is portable across different computer architectures). MPI is therefore expected to be faster than PVM on MPP hosts.

New design and analysis systems will exhibit several new facets. One facet is the ranking of the computational effort and distribution of the computational tasks among available computational resources. Several other facets are associated with a genetic algorithm including the use of dynamic population sizes during the design evolution and the use of genealogies for historical input in generating "children" for the next generation. Another facet is related to the use of different discretization models as part of the design evolution. Starting with coarse finite element models, those designs which are ranked "good" are then re-analyzed using refined analysis models or methods to insure the overall robustness of the design evaluation process.

**Knowledge Acquisition**

The data management for the existing design and analysis models and simulations appears to be driven by GUI-named objects pointing to specific solid renderings and their finite element models (PATRAN neutral files). Data management of large shared databases stored on remote computer systems will pose significant challenges and advantages. Designers and analysts would share a common definition of the design as it evolves during the design cycle. However, issues associated with ownership, security, and access need to be addressed. Part of the problem is related to controlling access to update data or to access data. With regard to computed results from various simulations, data mining methods may be useful in relation to the intelligence part of the system by being able to search the results databases and extract search directions for the evolutionary design procedures.

Experience capture of the so-called "gray beards" on the design team is becoming increasingly critical for space systems. Developing methodologies to capture their knowledge into an intelligent system with rules and inference features will provide for added robustness and

[29] http://www-unix.mcs.anl.gov/mpi accessed on 08.28.01

reduce the design cycle time by being able to exploit "lessons learned" from past projects. The idea of accumulating and preserving a company's technical know-how and expertise has been explored (*e.g.*, Kühn and Höfling [176]). Invention Machine Corporation[30] offers several commercial systems for knowledge retrieval including CoBrain, Knowledgist, and TechOptimizer[31]. CoBrain is a tool that uses semantic processing technology to capture technical knowledge from a wide variety of sources. Knowledgist is a personal knowledge analysis system that actually searches documents by concept – data mining approach. TechOptimizer is a comprehensive suite of knowledge-based innovation tools designed for research. Web-based browsers with natural language or linguistic capabilities as well as keyword search capabilities have the potential for keeping the designer and engineer up-to-date with technology developments related to their design as they are posted to the web [177].

## RISK MANAGEMENT CHALLENGES

Risk-management challenges relate to understanding the uncertainties associated with the system and the related consequences of them. Using the overall design process, Saunders *et al.* [178] discuss the evolution of a small satellite design from the perspective of risk mitigation and mission success. The design process, tools and synthesis techniques that lead to mission success are described. There are at least three aspects of the design affected by risk assessment. First, a system level understanding of the design is needed to determine as completely as possible a list of operating conditions, environments and objectives. Second, a critical assessment of mission goals and metrics for success are needed. Third, an evolutionary process for continual improvement in the design is required in order to understand and reduce risk and thereby mitigate failure modes and improve robustness. Risk management attempts to quantify the level of risk taken for all known and perceived failure modes. Hence, using risk mitigation, the design is better understood and more reliable.

Risk management procedures for space systems are critical. Often times production is limited to one or two vehicles requiring perhaps a decade of planning and preparation. Uncertainties exist in two forms: the *unknown* and the *vaguely known*. The *vaguely known* refers to events, environments, loadings, or accumulated tolerances. Precise values for these variables are unknown, uncertain, fuzzy or vague. Range of values may be known and can be used to define bounds. The *unknown* refers to events, loadings, environments, and so forth that the designer and engineer cannot, or does not, foresee. For example, some early computer systems engineers and programmers apparently did not even consider the potential problems associated with Y2K. Thus the challenges here are associated with understanding system sensitivities, identifying high-risk issues, and the mitigation and management of those risks. Two areas are considered: non-deterministic analysis (NDA) procedures and probabilistic risk assessments (PRA).

### Non-Deterministic Analysis Procedures

Non-deterministic analysis procedures have several basic forms. One form exploits deterministic analysis tools, while the another requires the development of new tools. The former is discussed herein. Understanding the impact of changes in design parameters has been very much a part of the design process. Early efforts generally used a Monte Carlo approach to

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[30] http://www.invention-machine.com accessed on 07.19.01
[31] http://www.techoptimizer.com accessed on 07.12.01

assess uncertainties. In a Monte Carlo approach, a large number of deterministic analyses are performed for a random set of design parameters within a set range. Then using the results, a statistical analysis is performed to assess the design.

Optimization procedures for large engineering systems provided some of the impetus for sensitivity derivatives. Sensitivity derivatives are not free and are not always easy to generate. Typically, they are computed for different design parameters using finite difference operators and hence multiple deterministic analyses. In some cases, analytic expressions for these derivatives have been developed for a specific application and specific code. Having these derivatives, the designer is able to identify dominant design parameters and may exploit this information within an uncertainty analysis.

More likely, front-end software, such as NESSUS [179-185] or ProFES [186], is used to define and control a series of deterministic analyses and then to collect the results for a probabilistic analysis. This approach allows the features and capabilities of the deterministic codes to be exploited and gives the designer/engineer control over the probabilistic aspects of the design. Again the process involves many deterministic analyses that could vary in fidelity (*i.e.*, closed form solution to an approximate problem, curve fit to heritage data, detailed finite element analysis). Front-end software systems offer flexibility in terms of the fidelity of the model used in the computations. Detailed finite element models are at one end; analytical solutions to approximate problems are at another, and response surface modeling may serve as a bridging function between them. However, some efficiency is lost and direct access to internal features may not be possible unless an integrated NDA software system is utilized.

Hence NDA procedures pose at least two challenges. The first challenge is the basic definition of the probabilistic design (*i.e.*, identifying random input variables and systems response or performance parameters, and their range of values). This challenge will require a long-term solution beginning in the engineering educational process and will require certain cultural changes within the engineering profession. The second challenge is the computational issues associated with such NDA tasks. Essentially NDA tasks have large granularity and are well posed for distributed heterogeneous computing systems wherein an intelligent controller *farms out* analysis tasks to available computers on the network.

Applying NDA to aerospace vehicle design necessitates a system perspective even though only a single discipline analysis is performed. Response parameters should be tied to system performance that in turn is affected by structural performance. Local structural failures, while important to identify and understand, may not propagate sufficiently to cause system failure. Random variable selection along with response variable definitions may then be utilized with a factorial design process. Selected deterministic analyses are performed and provide the basis for defining response surfaces. These response surfaces then function as "pseudo" deterministic analyses for the probabilistic assessment.

**Probabilistic Risk Assessment**

Probabilistic risk assessment (PRA) is more involved than the NDA tasks just described. NDA tasks often provide probabilistic measures for a given event. PRA procedures can take different forms. One commonly used is the event-sequence diagram that seeks to capture all known key events, the sequence required for success, and the consequences of a failure. These procedures can be applied to complete life cycle models or specific missions, to complete functional systems or specific components. PRA models require a holistic view of the design from concept through operation and retirement. They generally require a systems-level understanding and out-of-the-box thinking with regards to what the design might experience. The goal of a PRA is to mitigate the unknowns associated with a design and its function. By anticipation of as many events as possible and thorough assessment of those events using robust analysis methods, the probability of mission success increases and known risk is minimized.

## DECISION MAKING CHALLENGES

Decision-making challenges relate to modeling and analysis not just to management issues. In the design process, countless decisions are made regarding the selection of materials, analysis tools, modeling fidelity, interpretation of results, and so forth. Often times these decision are made on an ad hoc basis or perhaps based on heritage information or even company best practices. Decisions early in the design process are known to commit the largest amount of resources in an effort to reduce the time to market. Providing rapid modeling and analysis tools for use early in the design process has the potential to reduce the design cost significantly. Exploiting the corporate memory and heritage data associated with a given design system and given analysis tools can also contribute to substantial savings – cost and time.

Much work has been done in the past couple decades laying the foundation and developing the necessary tools for using artificial intelligence and expert systems in the design and analysis process (*e.g.*, survey by Kokkinaki *et al.* [187]). Much of the effort has been applied in the finite element modeling aspect of the design process. Fenves [188] discusses the applicability of expert systems technology to the finite element domain and potential problems that will arise in any implementation of such an analysis assistant. He made the following comment related to the level of effort needed to develop such an assistant:

> *"The development of a modeling and interpretation assistant for the full range of physical problem types encountered in FEA work and applicable to a wide range of FEA programs is clearly an effort of the order of 10 or more [person]-years, requiring the cooperative effort of many domain experts and a large group of knowledge engineers."* [188]

The level of effort for even a modest task probably remains an order of ten; however, the real questions are whether there is an exponent on the ten and what is its value? Most likely the exponent is not one! Rank and Babuška [189] suggest and demonstrate a simple expert system for optimal mesh design in the *hp*-version of the finite element method. The expert system can give the status of the computations, give advice as to what the steps are, and answer questions like "why?" A "buckling expert" prototype was created by Zumsteg and Flaggs [190].

Knowledge-based systems have been used quite often in the prototypes and tools that provided expert finite element analysis assistance. Fenves [191] expands upon his earlier article with a similar article. In this article, he discusses some of the history and gives a framework and an overall architecture of a knowledge-based expert system for a finite element modeling assistant. Taig [192] describes a prototype stand-alone system called FEASA to support the non-specialist when performing a finite element analysis using a simple question/answer mode. Having even a stand-alone simple question and answer consultant would provide another level of checks that are much needed today. Labrie *et al.* [193] develop a prototype expert assistant to monitor a full finite element simulation. The expert is able to advise the user on issues such as meshing and boundary conditions as well as interpretation of selected numerical results. It was also able to detect errors and inconsistencies. These capabilities and tools will need to be refined, improved, and made more widely available in standard analysis tools.

## DIRECTIONS FOR A RAPID MODELING AND ANALYSIS FRAMEWORK

The evolution and status of structural design and analysis tools have been described. Technology needs associated with future aerospace programs have been identified. Challenges in engineering mechanics, computational systems, risk management, and decision making have been delineated. Now research directions for a future rapid modeling and analysis framework are described. These modeling and analysis tools will enable a more thorough exploration of the design space, an evaluation of the risk assessment for the new system concept, and a cost estimate for raw materials, manufacturing, and routine service and maintenance during the intended service life of the vehicle. Integration of these features together with manufacturing-technique simulations and costing methods will provide robust engineering designs with manufacturability and economic viability based on a known or specified risk.

This section will describe an evolving design framework to meet these needs. A conceptual framework for a new paradigm in analysis and design tools should be able to embrace the novel ideas of future research and be capable of achieving them in an evolutionary process. The concept will feature integration of engineering expertise, which is non-localized, using shared, interlinked data systems. Shooter *et al.* [194] describes the flow of design information in a product development environment by using shared semantics for data exchange. A collaborative engineering environment is needed for a systems-engineering approach involving multiple organizations in different geographical settings and should include a telepresence capability. Peña-Mora *et al.* [195] describes an integrated telepresence environment for civil engineering construction projects. They developed a set of requirements, a system architecture, and a system prototype. The power and versatility of a heterogeneous computing environment coupled with immersive visualization techniques for simulation and design will be exploited.

Five main areas need to be addressed as part of any future structural design and analysis software system. These areas are identified and then expanded on in subsequent sections. First, a graphical-user interface or GUI provides the primary interface with the designer. The designer can then "point-and-click, drag-and-drop" design primitives for the selected application and "group" these primitives together to form a system. This may be achieved using voice activation or even telepathy in the future. The GUIs of the future will be "intelligent" so that one can easily select the options one wants. For example, the user can tell the software that feature "X" should be activated and not have to search through a dozen pull-down menus or dialog boxes to find the appropriate check box. Visualization of the design concept through inception to manufacturing and on to its final design configuration is needed as the designer and analyst "walk-through" the system as the system experiences service loads and extreme environments, and as repair and maintenance tasks are performed. Second, data management techniques for providing and controlling access to large, shared design databases will need to be developed. Third, a computational intelligence system that includes an experience capture feature advises the designer on the "as-built" system and suggests analyses to perform (pull-down menus or pop-up assistants). In fact, this computational intelligence system will be able to control some of the analysis. For example, the engineer can ask for the stress distribution in a region and the system will pick the appropriate analysis to perform. Design loads, tolerances, and design criteria are obtained from a master shared database. Fourth, full development and implementation of a generalized interface technology expanded to include multiple methods and multiple physics will be needed. This point can not be emphasized enough. Without interfaces between multiple methods and tools and different disciplines, the design and analysis process will never achieve its full potential. Fifth, computational mechanics algorithms and evolutionary design optimization procedures will need to be developed to meet anticipated analysis needs to address new materials, new configurations, new computing technologies, and extreme environment simulations. This step will result is spawning multiple sequential analyses running concurrently or in parallel on multiple computer systems in possibly multiple geographical sites.

Coupled with these simulation tools will be a rapid-prototyping system to generate components not just "print" the image. For example, such a system may be envisioned for space exploration and colonization of planets or undersea wherein the inhabitants design and fabricate the tools and hardware as needed. This system would perform the design, analysis, and other simulations. Then a robotic device could scoop up some nearby surface material, process the minerals and create the part thereby minimizing payload and maximizing vehicle performance.

Such a design and analysis system may be available for the next generation of designers and engineers (perhaps by 2020). Today the requirements and mechanics advances need to be guided to support these future tools. A framework for rapid modeling and analysis is now proposed along with specific attributes that need to be included.

## STRUCTURAL DESIGN DRIVERS

Aerospace vehicle design is indeed a multidisciplinary task requiring system integration at many levels [1]. Structural design drivers are related to specific criteria imposed on geometry, weight, environmental effects, materials, loads, endurance/performance, system integration, constraints, schedule, cost, manufacturing, repair, and availability. Solutions to design challenges in these areas are developed by the engineers through careful application and interpretation of heritage design data, subcomponent and component testing, and analysis.

## FRAMEWORK ATTRIBUTES

The framework attributes are defined by considering the structural analysis drivers. The key drivers in most engineering design problems are geometry, materials, and structural analysis methods and tools. Manufacturability and cost also need to be incorporated early into the design process.

Manufacturability needs include the simulation of the manufacturing process itself, assembly modeling (primarily a connection problem), and process control. Simulations of sheet metal forming and mold flow analysis of plastics are currently possible for selected configurations and assumptions. Extensions to advanced materials, structural tailoring, and advanced manufacturing processes are needed – particularly for textile-based composite material structures.

Costing models are quite elusive. Certainly raw material costs can be modeled and even estimates for manufacturing cost can be made based on heritage manufacturing procedures. However, the construction of a single or just a few units requiring new tooling and new facilities are not easily amortized without production volume. Indeed this aspect, combined with high risk for mission success, contribute to the high cost for access to space. The design of such systems, from a cost perspective, should examine design alternatives that exploit existing manufacturing technology or facilities. This would require at least a facilities and capabilities database for different manufacturing techniques tied potentially to an availability scheduler and a review of environmental regulations that potentially may eliminate a fabrication process at some point in time.

To address the primary structural design drivers, functional requirements in *modeling and analysis*, *robustness and reliability*, and *computational infrastructure* must be considered. Any new framework for design and analysis needs to be coupled to (or integrated with) tools from other discipline areas as well. Specific aspects of each requirement related to structural design and analysis are described in the subsequent sections. Enabling thrust areas are also defined and include those aspects of the framework that enable rapid modeling and analysis and contribute to establishing confidence bounds for simulation results.

**Modeling and Analysis**

*Three-Dimensional Geometry*

Three-dimensional geometry needs must address full associativity between component parts and local details and provide for interconnection with analysis tools to reference geometry features. The geometry definition should include the functionality of STEP files with new attributes to define dimensional reduction (idealization) options, feature removal options, and hierarchical geometry definitions. Dimensional reduction provides an automated mechanism to transform a solid geometry definition of a part to either a surface or a curve. That is, the solid representation is needed to assess assembly modeling whereas the part may be accurately analyzed using one-dimensional beam theory with a solid model being collapsed to a curve with appropriate geometric properties (areas, centroid, shear centers, moments of inertia and so forth). In addition, a multi-level option for feature removal should be available for holes, rivets, joints, fillets, and other local stress risers. Providing a hierarchical set of interfaced models would insure accurate simulation of critical regions. General imperfections such as surface regularity, smoothness, thickness variation, edge variations as well as uncertainties associated with boundary conditions and load application need to be addressed. A geometry definition having cross compatibility with and accessibility from a variety of analysis tools will require extensive development and standardization in geometry definition and data format. This aspect is particularly challenging as geometric modeling is still evolving.

*Software/Data Structure Interfaces*

Software/data structure interfaces are needed since there is no one tool that models and solves all problems. Standard definitions for solid modeling functions and their representation are under development – but so is solid modeling technology. In addition compatibility and availability of simulation results for viewing, report generation, and immersive sensory utilization need to be guided in their development to support structural design.

*Multi-Level Idealizations*

Multi-level refers to having a capability such as the interface technology, submodeling, substructuring or local zooming to interrogate quickly, easily, and accurately different regions of the structural model. These methods will contribute to reliability of the solution and multiple solutions with a strong emphasis on adaptivity. It is proposed that this capability function like a magnifying glass. The user would move a *magnifying glass* over different regions of the structure, select one or more regions for closer study, and automatically detailed models would be generated, analysis tasks would be spawned, and results generated. Several key developments are needed to provide such functionality. First, response metrics to aid in identifying critical regions are needed. Metrics such as gradient sensors for primary and secondary variables are candidates as well as more global measures based on energy. Next, coupled geometry, and modeling tools that capture the true geometry within the discrete model of the structure and embed local geometry detail would provide a *telescoping* effect on response prediction. Third, effective computational procedures for the solution of large systems of equations exhibiting a hierarchical approximation structure are needed. These procedures would exploit networked, heterogeneous computing systems as well as massively parallel, homogenous computing systems.

*Multi-Fidelity Discretizations*

Multi-fidelity refers to the synergistic coupling of different approximations to solve a specific problem. Multi-fidelity also refers to the choice of analysis – that is, linear or nonlinear, transient or quasi-static. Heuristic models need to be defined to guide the analyst to the correct analysis type and to provide guidance to verify that choice. One rule to determine the extent of geometric nonlinearity is to examine the buckling loads for compression loaded structures. Another is to perform a geometrically nonlinear simulation using the full design loads and observe the convergence rate. The key in using multi-fidelity solutions for design is the understanding of the limits of the different levels of fidelity. This phase will require the use of an intelligent agent with expert heritage knowledge pertaining to the system or related system design as well as to the analysis tools and procedures. One scenario is illustrated by PANDA2 [196-198]. PANDA2 uses analytical closed-form shell solutions in the design optimization procedure with results contributing to the definition of an axisymmetric shell analysis. The final design is subsequently analyzed using STAGS, a general two-dimensional shell finite element analysis procedure. Another scenario involves different levels of assumption in solving the shell equations as demonstrated in DISDECO [199, 200].

*Hybrid Methods and Analysis*

Hybrid methods and analysis refer to the need for combining analysis methods and procedures to solve a complex problem. Further research is needed that exploits the best features of several analysis methods and integrates them together in some fashion to solve an engineering analysis problem. One example would be a hybrid solver feature that utilized a high-throughput computing system to spawn the task of matrix solution using different techniques.

Direct sparse solvers are generally the better solvers; however, iterative solvers with appropriate pre-conditioning (*e.g.*, previous solutions) may be competitive for reanalysis procedures or even incremental-iterative procedures in some cases. Hybrid procedures that couple explicit and implicit time integrators are needed for long-duration transient response problems (*e.g.*, crush and deployment simulations). In addition hybrid quasi-static/transient procedures for collapse and mode-jumping problems need to be automated and control sensors provided.

*Collaborative Multifunctional Procedures*

Collaborative multifunctional procedures will be developed to solve multidisciplinary design problems and to provide automated multi-level, multi-fidelity solutions to complex aerospace design problems. These procedures will make all engineering computations consequential as they provide the basis to assess analysis confidence bounds.

**Robustness and Reliability**

*Constitutive Modeling*

Materials available now and in the future serve as a key driver for the structural analysis framework. Constitutive modeling for current material systems – especially composite structures and hybrid/sandwich structures – are desperately needed today for designing aerospace systems where mitigating risk is critical. The need for having validated and verified constitutive models for elastic response, failure initiation and damage propagation is growing. This need will increase as biomimetic materials are incorporated into aerospace vehicle design. Material definitions should provide with interconnects to material property databases from material suppliers, independent laboratory testing, and material certification programs. Electronic formats for standardized tests results and their pedigree would provide access to a materials library for mechanical (stiffness and strength) and thermal characteristics. These material modelers would also exhibit a multilevel functionality tied to the problem statement and the geometry definition. That is, are data for three-dimensional analyses needed or is classical lamination theory adequate? Techniques such as the *telescoping composite modeling* approach of Chamis *et al.* [201] should be explored and potentially coupled with the analysis tools. In addition, advances in material science, achieved in part through the use of computational materials developments, should be accessible as a reverse engineering feature. An engineering problem would be defined in terms of material performance requirements (stiffness, strength, mass, thermal conductivity), and the computational engine searches the material database for candidate materials, candidate fabrication types, or potentially designs a new material exploiting nano-technology and computational chemistry.

*Adaptivity*

Adaptivity of the modeling and solution process seems to be the key element in performing reliable, robust structural analysis simulations. Different types of adaptivity are needed at each of level of modeling and each level of fidelity. Potentially these indicators could be in conflict with one another. Modeling adaptivity refers to *hp*-refinement of the finite element model to reduce some error indicator. Changes to the structural idealization can be viewed as a form of adaptivity as well (*i.e.*, go from Kirchhoff plate theory to Reissner-Mindlin plate model to higher order plate models to a full 3D model). Coupling of this process with a multi-level procedure would ensure that design features eliminated by one analyst are assessed at a different level and their assumption validated. It also verifies the discrete modeling for the current level. Solution adaptivity refers to the sensors and controls associated with different solution algorithms that depend on response predictions such as the simulation of large-displacement, large-rotation problems, progressive failure simulations, and contact simulations. Interplay between the response prediction and the geometry modeling impose a significant challenge for software developers that impacts the design and analysis effort. Changes in the geometry model have the potential to affect the solution prediction (*i.e.*, facetted approximations of a curved surface influence the contact/penetration simulation or the shell buckling simulation).

*Knowledge Acquisition*

Knowledge acquisition refers to four classes of knowledge capture and integration. The first class is experience capture of the "gray beards" either by discipline, analysis tool, modeling tools, materials, loading, or other aspect of the modeling and analysis process. The second class is corporate memory for a given system or vehicle class, for related systems, or for guidelines based on heritage data. The third class is expert opinion, which may be combinations of the first two classes. The expert opinion knowledge database would serve as virtual mentors or intelligent agents for the designer and analyst and may potentially initiate independent crosscheck analyses to confirm or refute assumptions defined for the simulation. The final class involves a continual search of internet-accessible documents and products for information and knowledge related to a particular problem. Keyword searching and semantics processing would be incorporated.

This thrust focuses on access to heritage design data, "gray beard" expertise, and internet-accessible information. Such a capability will provide the reliability and robustness needed for advanced aerospace vehicle development. Experience capture of individual experts and collectively as the corporate memory on large, long-term development projects will provide a safety net and cost-effective way to ensure mission success. Knowledge acquisition process is a key challenge today. Rule-based heuristics have been used in the past and provide some level of knowledge capture. Each company could develop knowledge repositories of modeling and analysis guidelines that are automatically queried and examined. These guidelines may be company protected or shared. They may be developed by the analysis/modeling tool developers themselves or by user groups. Data mining techniques are needed to search the voluminous sets of computed results and to search the knowledge repositories for selected information and patterns. In addition to acquiring and archiving relevant knowledge, tools for utilizing this knowledge are needed. Expert systems technology needs to be applied. These expert systems need to be enhanced so that they are capable of giving *appropriate* advice when needed (and being silent when not). They should have the ability to guide the analysis on their own and perform self-initiated verification computations as needed.

*Self-Initiated Crosschecks*

Leveraging off the knowledge acquisition effort, the framework would exploit the knowledge extracted from the current simulation, assess the behavior based on the knowledge repository, and, as needed, initiate independent analyses to verify assumptions, sensitivities to modeling or solution parameters (*e.g.*, convergence criteria, material failure model, or analysis tool). This attribute collaborates with nearly all other aspects of the framework. It also provides a safety net for novice users or as a mentor within an engineering education environment. For example, it can check if all known failure modes have been checked or considered.

*System Sensitivities*

Understanding system sensitivities is critical to arriving at a reliable design to meet mission objectives. Sensitivity derivative calculations provide indicators to key design parameters. Computation of sensitivity derivatives can be facilitated by using finite differencing or automatic differentiation tools (*e.g.*, ADIFOR[32,33]). However, actual numerical evaluation of these derivatives and the choice of the independent variables require system-level insight or component-specific expertise that may reside in a knowledge repository.

*Probabilistic Risk Assessment*

Probabilistic risk assessment (PRA) involves fully considering all system failure modes and their effects. Development of event-sequence diagrams for aerospace systems is becoming more and more common as understanding the role of risk mitigation on mission success and mission cost increases. However, establishing the confidence bounds on the analytical results that directly feed into the design PRA has largely been ignored. A modeling/analysis based PRA strategy is needed that provides a confidence bound on the response parameters in a design PRA. The question "how do you know the analysis is correct?" can be answered based on the use of self-initiated crosschecks, adaptivity in modeling and analysis, and testing.

**Computational Infrastructure**

*High-Throughput, High-Performance Computing*

High-throughput, high-performance computing systems include the emerging computing systems with large numbers of powerful processors, high-capacity, fast secondary storage media, and high-speed, high-bandwidth communication network. To achieve the high-throughput anticipated for this framework, innovative computing configurations such as Condor will be needed as well as a controller with a graphical-user interface.

High-throughput, high-performance computing systems will provide the computational resources necessary first to predict the structural response and second to interrogate that predicted response. In addition, these resources will contribute to establishing the confidence bounds on the predicted results. These confidence bounds may be established through the use of adaptivity in the modeling, through correlated cross-checks of the results using independent structural analysis codes and available testing data, and through evaluation of off-nominal conditions as identified in a probabilistic risk assessment.

*Sensory-Based Interrogation Techniques*

Sensory-based interrogation techniques began with the first rudimentary plotting capabilities. Since then significant advances in scientific visualization techniques, computing capability and graphical displays have occurred. Present immersive technology provides a three-dimensional virtual reality display of the design and possible simulation results; however, the technology has not yet reached sufficient maturity to see widespread use due in part to the cost. The technology is continuing to mature and incorporate more than just visual representation of the data. Development of sensory output metrics from a simulation needs to be undertaken and integrated with future releases of the immersive technology.

[32] http://www.mcs.anl.gov/adifor accessed on 08.28.01
[33] http://www.cs.rice.edu/~adifor/AdiforDocs.html accessed on 08.28.01

Immersive sensory technology involves the next step towards complete three-dimensional virtual reality, immersive display of a design and its response to loads. Future techniques will include other sensory input and require that sensory output metrics be defined as they might relate to design evaluation. For example, on assembly should part interference generate a noise? Or on sliding should frictional heating result? Requirements for such metrics contribute to defining the analysis needs to support these new simulation interrogation features.

*Distributed, Shared Databases*

Global enterprise systems continue to emerge in engineering design and analysis arena. To facilitate the global expansion, databases for the design will need to be accessible from remote, geographically dispersed groups that are perhaps using a heterogeneous mix of computing systems and software. This thrust focuses on access to design data (*e.g.,* geometry, materials, loads, and processes) by the analysis tools for endurance/performance assessments, for evaluation of system sensitivities, for system integration, and manufacturing. Designers need to archive the geometry data including local details, material specifications, and assembly procedures. Structural analysts need to retrieve this information and extract appropriate design details needed for various analysis tasks. Sharing these databases, controlling access, maintaining their integrity, and protecting proprietary data are issues that must be addressed. Some of these issues can be addressed internal to a company – perhaps by edict. However, research in data protection, data sharing and data consistency is needed.

## RECOMMENDATIONS

The results of this study on rapid modeling and analysis tools for structural design are summarized in this section with several specific recommendations. Perhaps some of these topics are already under development by *CAx* tool developers. The recommendations are as followed.

The first recommendation is ***to develop a multi-level modeling and analysis capability***. This capability will encompass solid modeling, discretization, and analysis tools. The tools should use full associativity between geometric entities and their local details and discretizations to provide accurate geometry data. A geometry definition having cross compatibility with and accessibility from a variety of analysis tools should be developed and utilized. Automated dimensional reduction features with capability for selected local dimensional transitioning should be included. This feature would provide a seamless interface between the solid model representation and the analysis model representation to depict shell and beam structures in three-dimensional space. Generalized interface technology should be developed and implemented. Without interfaces between multiple methods and tools and different disciplines, the design and analysis process will never achieve its full potential. Once appropriate interfaces are established, a formal structural mechanics assessment procedure using a building-block approach with full upward coupling to the global simulation model should be developed, demonstrated, and deployed.

The second recommendation is ***to develop a multi-fidelity modeling and analysis capability***. This capability will encompass methodologies needed to verify the robustness of the solution. Error estimation techniques should be developed and implemented. All computed values of interest should be presented with some estimate of the error bounds. The tools should utilize hierarchical methods with adaptivity including *hp*- and *p*-adaptivity. Meshless methods may also be of use to this area. Self-adaptive, automated hybrid analysis procedures are included under the multi-fidelity analysis umbrella. Procedures such as combined explicit/implicit time integration procedures and quasi-static/transient solution procedures need to be refined and automated by exploiting knowledge databases and expert system technology.

The third recommendation is ***to develop a PRA-based approach to design and analysis tools***. This approach would contribute to the overall risk-based design process by establishing confidence bounds for any required analysis task. Event sequence diagrams for modeling and analysis can be developed that identify risks and consequences associated with various assumptions incorporated into any analysis. Classification of users based on experience and training can contribute to user certification. Uncertainty assessment will provide added reliability and robustness to the development of computational models, to the execution of analysis procedures, and to the overall aerospace system design for mission success.

The fourth recommendation is ***to develop and integrate a high-throughput computing infrastructure with the design and analysis tools***. Computing models such as CONDOR harvest unused computing cycles from networked, heterogeneous computers to solve an analysis problem. Control of such a computational infrastructure using a GUI-based designer/analyst front-end having immersive and telepresence capabilities is needed. High-performance computational tools (solvers, graphics, search engines) are also required for performing the simulation, visualization, and knowledge acquisition.

The fifth recommendation is ***to develop and verify constitutive models for biomimetic materials and structures***. These systems tend to mimic biological systems in form and function. Multifunctional material models (embedded sensors, active structures, self-healing materials, structural thermal protection systems) will be an integral part of advanced aerospace vehicle design. *Telescoping* multi-scale material models are required to exploit material capabilities fully and to understand and characterize failure initiation and its propagation. Damage mechanics associated with existing and emerging fabrication technology and associated progressive damage models need to be developed. Crack-growth and delamination models continue to be weak links in analysis capabilities.

The sixth recommendation is ***to develop knowledge-capture technology***. Acquisition and archival of the knowledge base is becoming increasing important to preserve corporate memory and experience capture (designer, developers, users). Many of the original developers of our existing tools are now retired and the mechanisms to preserve their knowledge, insight, and understanding is critical. Utilization and integration of these knowledge bases in terms of intelligent agents or virtual mentors within *CAx* tools must also occur. Techniques for searching and data-mining of Internet-accessible information need to be developed and implemented as a process to address globalization. Full sensory immersion within a virtual design space and associated simulation features guided by computational intelligent systems will promote increased awareness of the structural response to given loads, boundary conditions, and other input variables.

The seventh recommendation is ***to develop, implement and verify data management procedures for large, shared databases across networked systems***. Guidelines to insure data consistency and accuracy need to be developed and incorporated in a non-adversarial, non-restrictive manner. Data accessibility, integrity, and security need to be assured.

To begin to address some of these needs, selected computational structural mechanics efforts need to be emphasized in the near term. These include:

- Enhance, extend, and/or develop new finite element technologies and related computational methods technologies needed to enable NASA aerospace programs. Develop tools that utilize these technologies or integrate these technologies into existing tools. These technologies include: progressive damage mechanics with strain softening constitutive models; improvements are needed in computational efficiency, contact surface evolution, and modeling; and develop advanced nonlinear solution algorithms.

- Develop and implement a collection of error estimators for primary and secondary variables. Robust, reliable error estimates are needed. All computed values of interest should be presented with error bounds or an estimate of the error. Error estimates need to be integrated with the overall solution process. Specific efforts in *h*-, *p*-, and *hp*-adaptivity need to be incorporated in the appropriate parts of the model to reduce the error and their value added to design robustness demonstrated, to provide knowledge for the knowledge database to support automated adaptive refinement of the models and solution procedures, and to provide a hierarchy of coupled analysis procedures to examine local regions within an overall analysis model.

- Generalize the existing interface technology and promote its utilization in new and existing tools. Explore existing commercial capabilities to model and analyze subdomains independently. Formulate a collaborative methods and disciplines approach using partitioned analysis procedures for multiple methods.

- Develop and implement risk-based design capabilities with uncertainty assessment for reliability and robustness. Computation of sensitivity derivatives should be an integral part of new tools. Exploit computational infrastructure to obtained these values and computational intelligence techniques to guide the results. Computational mechanics algorithms and evolutionary design optimization procedures need to be developed and utilized to meet anticipated analysis needs of new materials, new configurations, new computing technologies, and extreme environments.

- Assess high-throughput, high-performance computing models and develop innovative computational structural mechanics procedures to exploit them.

This paper has described various challenges related to mechanics, computations, decision making, and risk management. In addition, cultural changes are necessary in that more analysis effort will be done up-front thereby increasing the time and cost of the preliminary design phase but resulting in overall savings later on as a result of a better process (*e.g.*, fewer design change orders). Also the cultural change to do design a "new" way needs to be bridged by training, demonstrating the benefits, and proving the value added to the company and the individual (e.g., more analysis capability available up-front to better explore design innovation and creativity). Specific research programs and their technology development needs have been identified and include:

- Gossamer Spacecraft
  - Packaging simulation technology
  - Deployment simulation technology
  - Membrane wrinkling simulation tools
  - Damage (tears) mechanics
  - Anomaly assessment simulation tools
  - Uncertainty analysis; risk-based designs

- Re-usable Launch Vehicles
  - Multifunctional materials
  - Multidisciplinary analysis
  - Damage mechanics and strain softening
  - Generalized imperfection characterization
  - Multi-level, multi-fidelity shell analysis tools
  - Uncertainty analysis; risk-based designs

- Aviation Safety
  - Constitutive models for large strain, high strain-rate behavior
  - Failure mechanism models for energy dissipation
  - Hybrid adaptive solution procedures
  - Penetration and damage mechanics
  - Damage containment simulations (fuel tanks, luggage compartments)
  - Occupant modeling and dynamics
  - Biomechanics simulation tools for high –acceleration loadings

- Micro-Electromechanical Systems (MEMS)
  - Multifunctional materials
  - Multidisciplinary analysis
  - Micro-dynamics
  - Impact of miniaturization on numerical computations
  - Computational intelligence

## SUMMARY

Modeling and analysis tools of the past, present and future have been described. The evolution of these tools and their basic status have been described. Some of the structural analysis requirements to support potential aerospace design challenges of the future have been presented as well as specific technology development needs. Research directions to meet these needs have been recommended. The recommendations deal in part with developing the technology and methods needed by the infrastructure and the tools, developing and implementing the infrastructure needed by the tools, and integrating and using the technology, methods, and infrastructure in the design and analysis tools. Certainly much of the work will involve advanced computing systems, new engineering design and analysis environments, and perhaps a culture shock at times. However, there is much work to be done in the area of computational structural mechanics technology and a greater responsibility to insure its proper use. Knowledge acquisition, retrieval, integration, and utilization will help insure that the next generation of design engineers benefit from our efforts (*i.e.*, lessons learned). The framework proposed in this paper should give the design and analysis tools of the future the power and flexibility to tackle the toughest structural design problems in a rapid and robust manner.

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# APPENDIX

This appendix contains the charts used in the final oral presentation of this task. It was given at NASA Langley Research Center on September 26, 2001. These charts represent a limited summary of the final report and by themselves give an incomplete summary. Only selected findings and directions were covered in the final oral presentation. The final report should be referred to for a complete discussion of status and direction along with key reference citations.

# *Rapid Modeling and Analysis Tools*

## *Evolution, Status, Needs, and Directions*

**Norman F. Knight, Jr. and Thomas J. Stone**
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*Sponsored under GSA Contract - Task 1735*
*(March 1,2001 through September 30, 2001)*

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1

## *Outline*

- Objectives and approach
- Evolution of structural design and analysis tools
- Structural modeling and analysis tools
- Challenges for rapid modeling and analysis tools
- Framework for rapid modeling and analysis
- Recommendations
- Computational structural mechanics directions
- Summary

2

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## *Objectives*

- Review existing structural modeling and analysis procedures and tools
- Identify structural modeling and analysis needs for aerospace vehicle design
- Propose candidate framework for rapid modeling and design
- Prepare a white paper on rapid modeling and analysis for detailed structural analysis and design
  - *draft version delivered early September 2001 for review*

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## *Approach*

- Step back and see where we came from, where we are, and where we want to go
- Review existing structural modeling and analysis tools
- Identify technology challenges, needs and directions
- Identify attributes of candidate framework to meet these challenges

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## *Evolution of Design and Analysis Tools*

- A great deal can be learned from the history of design and analysis tools
- Analysis Methods
  - Rely on physical or mathematical models
  - Finite Element Method is the primary tool
    - Tens of thousands of papers on finite element analysis each year
    - h-version, p-version, error estimates, adaptivity, physical modeling
  - Lessons Learned:
    - Tools need to advance along with the theory
    - There are many different tools, so open architectures for interoperability is important
    - Investment in life-long learning skills is critical to advance the technology, use the technology, and lead its development



## *Evolution of Design and Analysis Tools*
*continued*

- Computing Hardware
  - Availability of high speed computers, large internal and external storage, high speed networks, and high speed graphics has greatly helped the development of tools
  - The available computing resources have continued to increase
  - The scope and size of the problems that are being solved are growing along with the resources
  - Lessons Learned:
    - Consideration of the rapid evolutionary changes in computing hardware (and the sizes of the problems one wishes to solve) should be considered in the planning and development stages of next generation design and analysis systems
    - Need to continually assess and update analysis models used in design verification; keep models updated with available tools

## *Evolution of Design and Analysis Tools*

*continued*

- Computing Software
  - Advanced mechanics features
  - GUI's and visualization
  - Product Data Management (PDM) for life-cycle modeling
  - Lessons Learned:
    - Evolving computing software capabilities and needs of industry and government drive the capabilities of the tools
    - Advanced mechanics features may out run general analyst's skill level
- Materials and Manufacturing
  - Hybrid material systems and innovative fabrication methods
  - Limited characterization of emerging materials
  - Lessons Learned:
    - Companion experimental and constitutive model research effort needed
    - Designing highly reliable aerospace systems place increased demands for accurate, verified constitutive models

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## *Selected Structural Modeling Tools*

- Some Capabilities
  - Create flat drawings
  - Create solid models
  - Associativity of parts/components
  - Perform spatial discretization
  - Interfaces & translators available for many FE solvers
  - Pre- and post-processing capabilities for analysis package
  - Internal analysis for some types of problems
- Some Tools
  - MSC.Patran
  - SDRC I-DEAS
  - Pro/ENGINEER
  - CATIA
  - FEMAP

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## *Selected Structural Analysis Tools*

- Some Capabilities
  - Nonlinear capabilities
  - Multi-physics capabilities
  - *p*- and *hp*- version capabilities
  - Error estimation
  - Adaptive refinement
  - Interaction with modeling tools
  - Multi-processor capabilities
  - User-developed features
  - Increasing capabilities
- Some Tools
  - MSC.NASTRAN, DYTRAN, MARC
  - ANSYS & DesignSpace
  - ABAQUS Standard & Explicit
  - Pro/Mechanica
  - StressCheck
  - LS-DYNA
  - GENOA
  - COMET-AR/NextGRADE
  - STAGS



## *Challenges in FE Modeling and Analysis*

- Mechanics challenges
- Computational challenges
- Risk management
- Decision making

***Future Rapid Modeling and Analysis Tools***
based on hierarchical and high-fidelity models that evolve with the design

**Establish *confidence bounds* on simulation results for robustness & reliability**

## *Mechanics - Constitutive Models*

- Constitutive modeling for modern and emerging material systems need to be developed ***and experimentally validated***
  - Different composite architectures
  - Hybrid material systems including sandwich structures
  - Multifunctional materials
  - Damage detection and propagation
  - Embedded health-monitoring systems
  - Self-healing materials
  - Energy-absorbing systems for impact energy management

***Biomimetic Material Systems***

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## *Mechanics - Gossamer Structures*

- Gossamer structural mechanics for ultra-thin, ultra-large membranes
  - Very large space structures
  - Limitations of ground-based testing
  - Packaging simulations
  - Folding pattern effects
  - Inflation rates
  - Influence of local wrinkling
  - Long deployment times
  - Assessment of off-nominal conditions

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## *Mechanics - FE Technology*

- Extend modeling paradigm beyond only low-order FE
- Extend analysis paradigm beyond linear stress and normal modes analyses
- Fully understand the FE modeling approximations and what it will (***and will not***) predict; what are the limits of the approximations within the model
- Incorporate multiple fidelity analyses (handbook/hand calculations, analytical solutions, different idealizations, different discretizations, multiple methods, multiple tools)
- Error estimation and adaptive mesh refinement tied to solid geometry models

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## *Mechanics - Solution Technology*

- Growing need for hybridized solution procedures for quasi-static and transient dynamic simulations
  - Quasi-static/transient procedures for collapse and mode-jumping problems
  - Explicit/implicit transient procedures for long duration transient simulations
  - Hybrid direct/iterative solvers for systems of algebraic equations
- Hierarchical modeling and analysis procedures leading to high-fidelity simulations
  - *p*-version technology; shell-solid transitioning
  - homogeneous-to-heterogeneous material modeling
  - multiple scales

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## Computational Challenges

- Computer hardware (CPUs, memory, storage) is faster than ever and getting even faster
- Solver technology for large systems of equations continues to improve; other aspects need attention
- Adaptivity at the model level and at the solution procedure level provides measure of robustness
- Harvesting unused networked CPUs provides source for distributed concurrent computing
- Immersive technology for visual and auditory senses place increased demands on computing infrastructure

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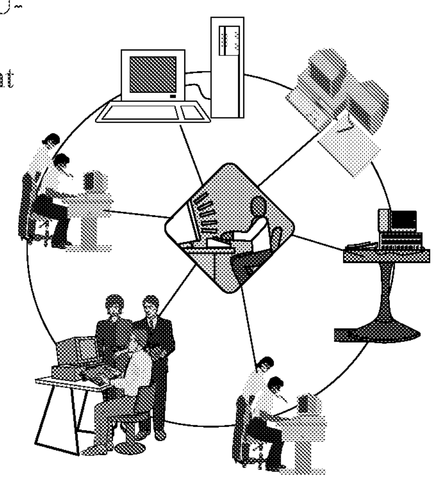
## Emerging Paradigm for Computing

- Systems such as Condor for CPU-cycle scavenging for high-throughput resource management
- GUI-based interfaces for parametric studies coupled with uncertainty models and/or optimization procedures (e.g., ILAB/Ames)
- Typically co-located but potentially geographically dispersed using heterogeneous computing systems



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## Risk-Based Design Challenges

- Deterministic methods to assess uncertainties through probabilistic procedures, fuzzy logic models, Monte Carlo simulations
- Non-deterministic methods
- Scenario-based probabilistic risk assessment for the mission, vehicle, component, or subcomponent
  - Event-sequence diagrams, event-tree models, and linked-fault-tree models to estimate probability of mission success and to identify most significant failure sequences
  - Requires system-level knowledge, heritage data, quantifiable bounds for design trade-offs

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## Decision Making

- Advancements in design and analysis tool capabilities tend to run ahead of analyst in terms of:
  - Underlying mechanics principles
  - Enormity of computed results
  - Speed of generating results
- Integration and interrogation of vast amounts of information necessitate the need for methodologies to “mine” data or to guide the simulation
- Intelligent agents within an evolving knowledge basis are needed to augment the engineer in the loop and to guide/insure robust solutions

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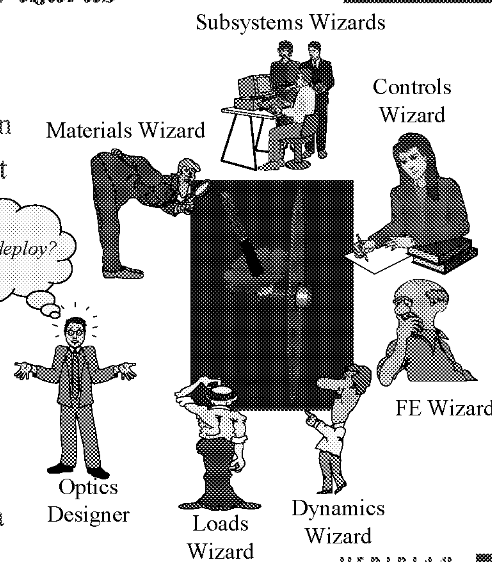
## Intelligent Agents - "Wizards"

- Virtual corporate history for modeling and analysis; system and subsystem design
- Different agents for different disciplines, different methods, different systems/subsystems
- Collaborative interaction as virtual colleague, virtual mentor, virtual reviewer, virtual critic
- Provides access to in-depth knowledge and heritage data








## Knowledge Acquisition and Integration

- Automated keyword and semantic processing of web-accessible documents and reports
- Experience capture of "gray-beard" experts
  - System, discipline, method, tool, life cycle, etc.
- Archival of corporate memory for project
- Tied to self-inquisitive approach for consistency, accuracy
- Establish *confidence bounds* on analysis models and their results for risk management tools
  - "How good is that number?"

## *Potential Features of Future Rapid Modeling and Analysis Tools*

- Solid-geometry-based with idealization attributes
- Automated spatial discretization with interfaces to multiple methods
- Constitutive modeling for advanced materials accounting for damage in a hierarchical manner
- Generalized imperfection definitions
- Uncertainty measures and sensitivity derivatives
- Advanced computational tools and related interfaces for concurrent and parallel computations
- Advanced interrogation tools including “wizards”



## *Framework Attributes*

**Structural Design Drivers**

•Geometry
•Weight
•Environment
•Materials
•Loads
•Endurance/Performance
•Constraints
•System Integration
•Schedule
•Cost
•Availability
•Manufacturability
•Maintainability

**Modeling & Analysis**

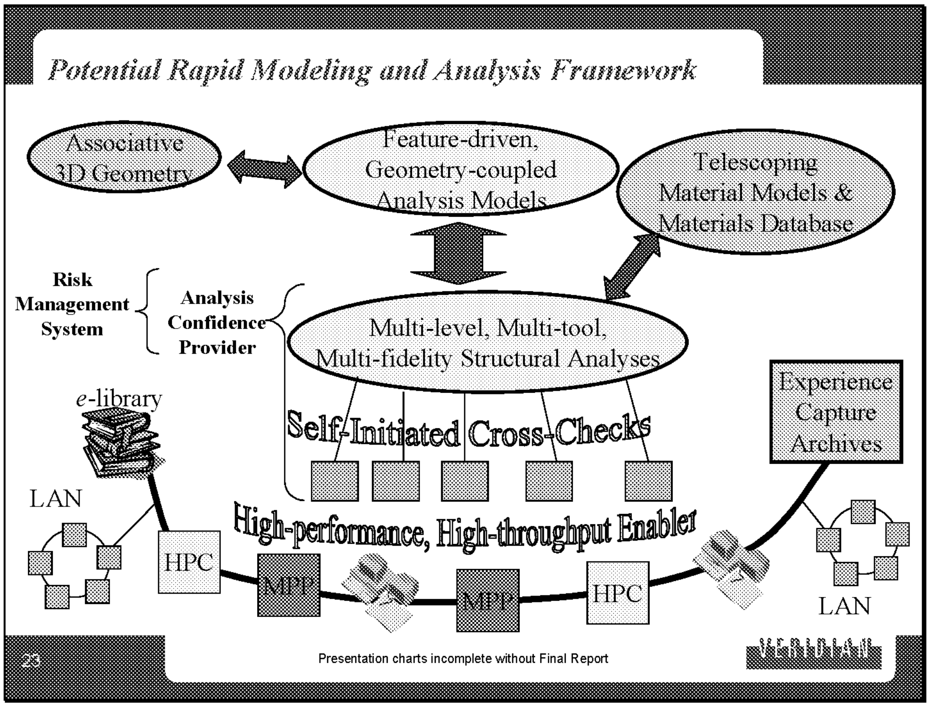
•3D Geometry
•Software/Data Structure Interfaces
•Multi-Level Idealizations
•Multi-Fidelity Discretizations
•Hybrid Methods & Analyses
•Collaborative Multifunctional Procedures

**Robustness & Reliability**

•Knowledge Acquisition
•Self-Initiated Crosschecks & Assessments
•Adaptivity (Modeling & Procedures)
•System Sensitivities
•Probabilistic Risk Assessment

**Computational Infrastructure**

•High-Throughput Computing
•High-Performance Computing
•Sensory-based Interrogation
•Distributed, Shared Databases



Potential Rapid Modeling and Analysis Framework
Associative 3D Geometry
Feature-driven, Geometry-coupled Analysis Models
Telescoping Material Models & Materials Database
Risk Management System
Analysis Confidence Provider
Multi-level, Multi-tool, Multi-fidelity Structural Analyses
e-library
Self-Initiated Cross-Checks
Experience Capture Archives
LAN
HPC
MPP
High-performance, High-throughput Enabler
MPP
HPC
LAN
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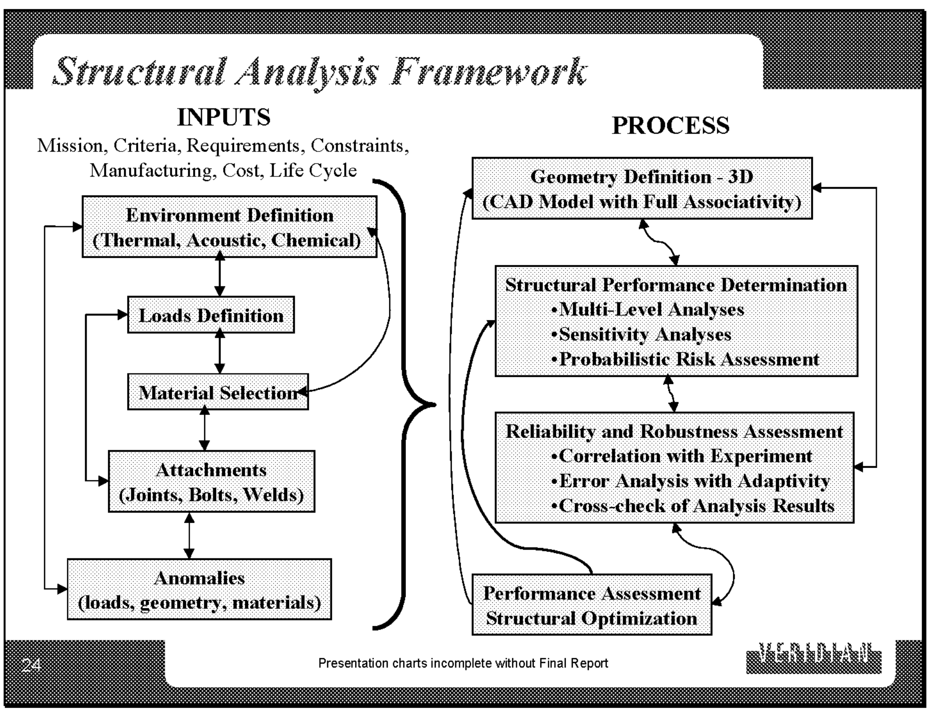

Structural Analysis Framework
INPUTS
Mission, Criteria, Requirements, Constraints, Manufacturing, Cost, Life Cycle
Environment Definition (Thermal, Acoustic, Chemical)
Loads Definition
Material Selection
Attachments (Joints, Bolts, Welds)
Anomalies (loads, geometry, materials)
PROCESS
Geometry Definition - 3D (CAD Model with Full Associativity)
Structural Performance Determination
•Multi-Level Analyses
•Sensitivity Analyses
•Probabilistic Risk Assessment
Reliability and Robustness Assessment
•Correlation with Experiment
•Error Analysis with Adaptivity
•Cross-check of Analysis Results
Performance Assessment Structural Optimization
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## *Structural Analysis Modeling Features*

### 3D Geometry
- Local details
- Parts
- Full associativity
- Accessibility

### Interfaces
- Direct geometry access
- Translators
- Accurate geometry
- Selectable detail level

### Structural Idealization
- 3D to 2D
- 2D to 1D
- 3D to 1D
- $C^1$ to $C^0$
- Symmetry

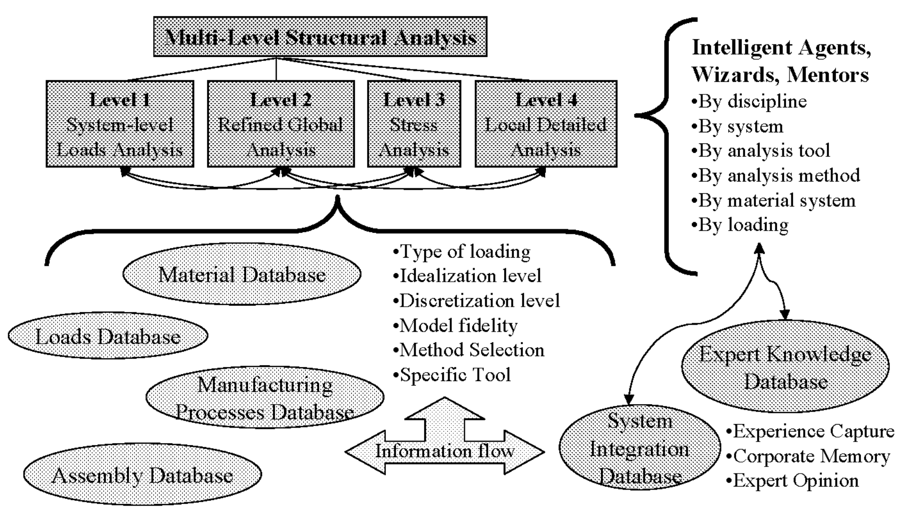
### Material Idealization
- Micro to macro
- Laminate to lamina
- Continuum models
- Hierarchical models
- Multiple scales

### Global-Local Modeling
- Multi-level substructuring
- Interface element
- Submodeling
- Mesh transitioning

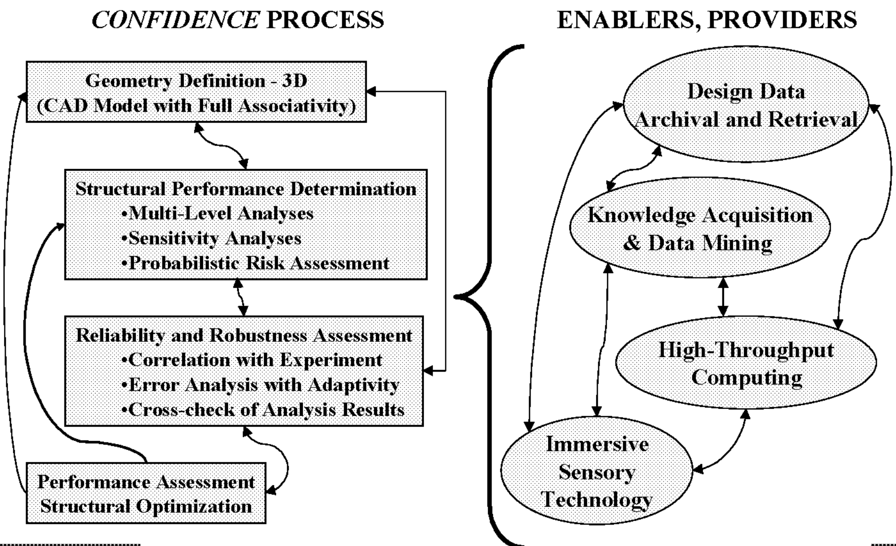
### Spatial Discretization
- Number of elements
- Types of elements
- Approximation order
- Method selection
- Error metrics



## *Structural Performance Determination*



## Computational Infrastructure






## Recommendations

- Develop a multi-level modeling and analysis capability
  - Encompass solid modeling, discretization, and analysis tools
  - Provide full associativity between geometric entities and their models
  - Generalized interface technology
- Develop a multi-fidelity modeling and analysis capability
  - Error estimation techniques
  - Hierarchical methods with adaptivity
  - Meshless methods
  - Self-adaptive, automated hybrid analysis procedures
- Develop a PRA-based approach to design and analysis tools
  - Define confidence bounds for any required analysis task
  - Event sequence diagrams for modeling and analysis
  - Classification of users based on experience and training

## Recommendations, *continued*

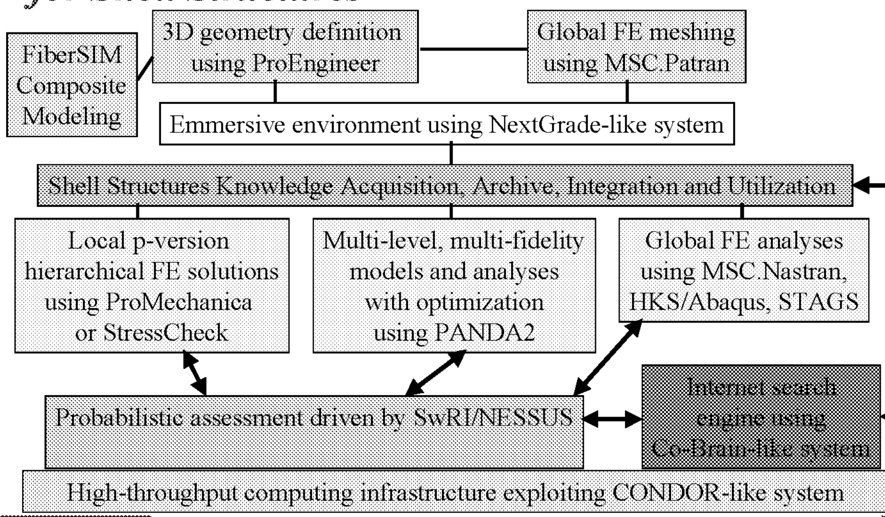
- Develop and integrate a high-throughput computing infrastructure with the design and analysis tools
  - Harvest unused computing cycles from networked, heterogeneous computers (*e.g.*, CONDOR)
  - GUI-based computational infrastructure controllers
  - High-performance computational tools
- Develop and ***verify*** constitutive models for biomimetic materials and structures
  - Multifunctional material models
  - *Telescoping* multi-scale material models
  - Damage mechanics, crack-growth and delamination models



## Recommendations, *continued*

- Develop knowledge-capture technology
  - Acquisition and archival of the knowledge base
  - Utilization and integration of these knowledge bases
  - Searching and data-mining of Internet-accessible information
  - Full sensory immersion
- Develop, implement and verify data management procedures for large, shared databases across networked systems
  - Data consistency, accessibility, integrity, and security
  - Fast access of distributed data

## *Candidate Framework Architecture for Shell Structures*

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## *Needs Identified for NASA Programs*

- Gossamer Spacecraft
  - Packaging/deployment simulation technology
  - Membrane wrinkling simulation tools
  - Damage (tears) mechanics
  - Anomaly assessment simulation tools
  - Uncertainty analysis; risk-based designs
- Re-usable Launch Vehicles
  - Multi-level, multi-fidelity analysis tools
  - Multifunctional materials
  - Multidisciplinary analysis
  - Damage mechanics and strain softening
  - Generalized imperfection characterization
  - Uncertainty analysis; risk-based designs

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## *Needs Identified for NASA Programs*

- Aviation Safety
  - Constitutive models for large strain, high strain-rate behavior
  - Failure mechanism models for energy dissipation; penetration and damage mechanics
  - Hybrid adaptive solution procedures
  - Damage containment simulations (fuel tanks, luggage compartments)
  - Occupant modeling and dynamics; biomechanics simulation tools for high–acceleration loadings
- Micro-Electromechanical Systems (MEMS)
  - Multifunctional materials
  - Multidisciplinary analysis
  - Micro-dynamics
  - Impact of miniaturization on numerical computations
  - Computational intelligence



## *Computational Structural Mechanics Directions*

- Enhance, extend, and/or develop new finite element technologies and related computational methods technologies needed to enable NASA aerospace programs
- Develop and implement a collection of error estimators for primary and secondary variables
- Generalize the existing interface technology and promote their utilization in new and existing tools
- Develop and implement risk-based design capabilities with uncertainty assessment for reliability and robustness
- Assess high-throughput, high-performance computing models and develop innovative computational structural mechanics procedures to exploit them

## *Summary*

- Many technical challenges remain
- Advances in computing infrastructure provide enormous potential to simulate structural behavior
- Advances in computing infrastructure provide enormous pitfalls for the unprepared analyst
- Increasing responsibility on analyst to insure the physics are captured accurately by the simulation
- Capturing corporate knowledge and providing system-level knowledge base is critical to risk mitigation

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**13. ABSTRACT** *(Maximum 200 words)*
Advanced aerospace systems are becoming increasingly more complex, and customers are demanding lower cost, higher performance, and high reliability. Increased demands are placed on the design engineers to collaborate and integrate design needs and objectives early in the design process to minimize risks that may occur later in the design development stage. High performance systems require better understanding of system sensitivities much earlier in the design process to meet these goals. The knowledge, skills, intuition, and experience of an individual design engineer will need to be extended significantly for the next generation of aerospace system designs. Then a collaborative effort involving the designer, rapid and reliable analysis tools and virtual experts will result in advanced aerospace systems that are safe, reliable, and efficient.

This paper discusses the evolution, status, needs and directions for rapid modeling and analysis tools for structural analysis. First, the evolution of computerized design and analysis tools is briefly described. Next, the status of representative design and analysis tools is described along with a brief statement on their functionality. Then technology advancements to achieve rapid modeling and analysis are identified. Finally, potential future directions including possible prototype configurations are proposed.

**14. SUBJECT TERMS**
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