201 Moody's Run
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Mail Stop 126
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Gentlemen:

Enclosed please find the final report entitled "Cyber Technology for Materials and Structures in Aeronautics and Aerospace," under NASA Grant, NAG 1- 2117 and administered by the College of William and Mary during October 1, 1998 to September 30, 1999.

Sincerely,

R. Byron Pipes, PhD
Principal Investigator
Visiting Distinguished Scholar
College of William and Mary

Copies to:
NASA Langley Research Center
Mail Stop 226
Hampton, VA 23681-0001
ATT: Terry L. St. Clair

NASA Center for Aerospace Information (CASI)
ATTN: Accessioning Department
7121 Standard Drive
Hanover, MD 21076-1320

Office of Grants and Research Administration
College of William and Mary
Williamsburg, VA 23187

Cyber Technology for Materials and Structures
In
Aeronautics and Aerospace

Final Report

R. Byron Pipes, PhD
Distinguished Visiting Scholar

October 1, 1998-November 30, 1999

Department of Applied Science
College of William and Mary
Williamsburg, VA 23185

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Cyber Technology for Materials and Structures in Aeronautics and Aerospace

1.0 Executive Summary

This report summarizes efforts undertaken during the 1998-99 program year and includes a survey of the field of computational mechanics, a discussion of biomimetics and intelligent simulation, a survey of the field of biomimetics, an illustration of biomimetics and computational mechanics through the example of the high performance composite tensile structure. In addition, the preliminary results of a state-of-the art survey of composite materials technology is presented.

2.0 Introduction

Scientists and engineers have long anticipated the time when the models that have been developed over the past 150 years in independent disciplines could be linked together to form a continuous analytical path from the atomic scale to the macro scale. Such a "linked" chain of mathematical models would allow the prediction of macroscopic phenomena resulting from descriptions at the atomic-scale. At least six and perhaps as many as nine orders of magnitude in physical scale must be bridged for this goal to become a reality. Today the world is witnessing extraordinary advances in understanding of physical, chemical and biological phenomena at the atomic and molecular scales. Pharmaceuticals are being designed through computer simulation that result in significant savings in clinical trials and yield extraordinary medicinal value to society. New methods for materials processing and for the creation nano-materials that possess properties impossible in conventional, monolithic materials have been first developed through simulation.

The invention of high strength fibers in the 1960's and the development of advanced fiber-reinforced composite materials during the 1970's focused the attention of the scientific community on a class of heterogeneous material systems wherein phenomena at the scale of the fiber, 5-10 microns (10^{-6}m), controlled behavior of structural systems manufactured from these materials to an unusual degree. What was different about these materials systems was the range in properties that could be achieved by changes in microstructural geometry. Very high levels of anisotropy are developed by the combination of high strength and high modulus fibers with a polymer, ceramic or metal matrix. Efforts to create models do describe these phenomena led to the development of micromechanical models for the prediction of the effective properties of such a collimated fiber composite or laminae (10^{-4}m), given its constituents and their volume fractions. Next, lamination theory was developed to describe the properties of the multi-axial laminate made up multiple lamina with given orientations (10^{-2}m). These models were linked to models for the prediction of deformation, strength, vibration and instability of structural sub-elements such as plate or shell geometries
(10^{-1}m). And finally, overall structural behavior was modeled through the linking of these models to modern finite-element programs (10^{+2}m).

While the development and linking of models over eight orders of magnitude has proved to be extraordinarily successful for advanced composite materials, there were significant gaps in the understanding of important phenomena. For example, the influence of processing and manufacturing conditions were not well understood and significant new efforts were undertaken to develop new models for these as well. Here the molecular scale

(10^{-8}m) of the fiber and especially the matrix phase became important. Significant efforts in this area continue under development today.

The progress in modeling of the behavior of advanced materials and the aeronautics and aerospace structures made from them has been extraordinary over the past thirty years. Yet many models remain isolated at a given level in scale and therefore unlinked to the models at both higher and lower scales. In addition, new understanding has been developed recently of important new phenomena that when linked to other models will provide new pathways to understanding that can yield new configurations, new materials systems and new understanding of the limitations of conventional materials and structures. Thus the inter-scale study, like interdisciplinary research, offers opportunities to advance the state of the art at an unprecedented rate. It can provide a road map for the essential research of the future.

3.0 Review of the Field in Computational Mechanics

Professor Michael Ortiz of California Institute of Technology has made significant contributions to the field of computational mechanics and has addressed multi-scale issues.[1] With Tadmor and Phillips, he also examined mixed atomistic and continuum models. [2] Examples considered included nano-indention and the brittle-to-ductile transition. Dislocation-based constitutive relations for pure metallic crystals and intermetallic compounds were also studied. In the latter paper two different length scales are dealt with – a characteristic dimension at the nanoscale due to extended defects and a second scale, larger by two orders of magnitude, that describes the crack tip. Direct atomistic

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[1] Ortiz, M. "Computational Micromechanics," Computational Mechanics, Vol. 18, No. 5, (1996), pp. 321-338.

[2] Tadmor, E.B., Phillips, R. and Ortiz, M., "Mixed Atomistic and Continuum Models for the Deformation of Solids," Langmuir, Vol. 1, No. 19, (1996), pp. 4529-4534.

calculations form the basis for the constitutive relations used in a finite-element continuum model. The approach is illustrated for the case of single dislocation structure and energetics. In a third paper[3] the treatment of the simultaneous resolution of continuum and atomistic scales is treated for deformation processes in a unified manner. The method developed differs from traditional finite element methods because the interatomic calculations are incorporated into the model through crystal calculations based on the local state of deformation.

Professor Wayne Mattice has studied the properties of dense polymers wherein the Angstrom scale is important, but where coarse-grained models are required. He has successfully spanned the length scales between the fully atomistic and course grained models with reversible scale steps.[4] While reversibility is not considered important by many, Mattice argues that it gives a high degree of robustness to this approach that is not present in many other models.

Geometric decomposition of a silicon slab into five different dynamic regions in a unified macroscopic, atomistic, *ab initio,* dynamics (MAAD) description is the subject of a recent paper by Abraham, Broughton, Bernstein and Kaxiras.[5] The work is characterized as a *tour de force* of computational physics in the sequential coupling of length and time scales. The unified dynamical treatment is exercised in the study of the brittle fracture of silicon. It links quantum, atomistic and continuum descriptions in five distinct dynamic regions: continuum finite-element region, molecular-dynamics region, quantum tight-binding region, finite element-molecular dynamics handshaking region and the

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[3] Tadmor, E.B., Ortiz, M., and Phillips, R., "Quasi-Continuum Analysis of Defects in Solids," Philosophical Magazine, Vol. 73, No. 6, (1996), pp. 1529-1563.
[4] Doruker, P. and Mattice, W.L., "A Second generation of Mapping/Reverse Mapping of Course-Grained and Fully Atomistic Models of Polymer Melts," Macromolecular Theory and Simulations, accepted for publication (1999).
[5] Abraham, F.F., Broughton, J.Q., Bernstein, N., and Kaxiras, E., "Spanning the Length Scales in Dynamic Simulation," Computers in Physics, Vol. 12, No. 6, (1998), pp 538-546.

molecular dynamics-tight binding hand shaking region. The overarching theme of the work is that a Hamiltonian is defined for the entire system. Its degrees of freedom are atomic positions and their velocities, displacement and their rates of change. Equations of motion are derived from the overall Hamiltonian in the manner of classical mechanics. The hand-shaking regions provide for continuity between the models at different scales and involve variations in mesh geometry and scale. The simulation involved 258,048 mesh points in the finite-element model, 1,032,192 atoms in the molecular dynamics region of length equal to 10.9 Angstroms. The size of the silicon sample simulated was 3649 by 521 Angstroms.

Dr. Kenneth Chong of the National Science Foundation has suggested that model-based simulation, based on robust numerical methods and addressing scalability from the atomic scale (micro level) to microns (meso-scale) to meters (macro-level) to kilometers (systems scale), can provide the foundation for virtual testing and reliability.[6]

Dr. Leslie Smith of the National Institute of Standards and Technology has described the NIST Center for Theoretical and Computational Materials Science that focuses on materials theory and performance in the development of powerful new computational tools. A conference entitled, "Hybrid Computational Methods for Multiscale Modeling of Materials was held during May 12-14, 1999. Specific focus of the NIST program has been micromagnetics and liquid crystalline polymers.

The National Science Foundation has initiated a program for exploratory research on biosystems at the nanoscale.[7] The NSF motivation stems from the fact that many biological molecules and

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[6] Chong, K. P., "Smart Structures Research in the U.S.," Smart Structures, edited by J. Holnicki-Szulc and J. Rodellar, Kluwer Academic Publishers, (1999), pp.37-44.

[7] "Exploratory Research on Biosystems at the Nanoscale," National Science Foundation, NSF 99-109

bimimetic systems exist on the size scale of 10^{-9} to 10^{-7} meters. It is suggested that these systems may possess unique functionality because of the size of their individual particles, clusters, or micelles. By assuming specific conformations or bonding with specific congeners, these systems may offer solutions in such problem areas as medical sensing, drug and gene delivery, tissue engineering, dispersions and coatings, and separations.

4.0 Biomimetics and Intelligent Simulation

At the beginning of the new millenium there are several disciplines that will provide revolutionary advances in technology for the benefit of society. As stated earlier, the power of today's computational and software systems have the potential to integrate through simulation many disciplines and concepts that have evolved independently over the past 150 years.

The "Grand Challenge" in materials science is the linking of understanding and models at multiple scales to form continuous analytical paths from the atomic to the macro scale. Such a "linked" chain of mathematical models would allow the prediction of macroscopic phenomena resulting from changes at the atomic scale.

At the same time the field of biological sciences has continued to provide new insights into the ways organisms have successfully adapted to the environment around them. These adaptations can provide significant insights into the efficiencies of nature and the potential for application of these ideas to man-made products and services. The field of "Biomimetics," or technology imitating nature, developed during the latter quarter of the 20^{th} century and as such is a new field. Yet the early results suggest a powerful potential for the future.

Advances in computation and simulation during the past three decades have also been extraordinary. Artificial intelligence, expert systems, data mining, neural networks and advanced software systems provide the vehicles for integration of advanced materials and structures simulation with the field of biomimetics. Fully integrated, biomimetics could illustrate new and revolutionary material and structural formulations that promise enhanced efficiencies or long-term durability in hostile environments. Materials science and structural/aeronautical simulations could then model these concepts over a range in scale from atomistic to macroscopic.

In order to accomplish the integration of the fields of biomimetics, materials science and aero/structural engineering, there is much to do. First, it will be increasingly necessary to form research teams focused on achieving specific goals for aeronautics and aerospace, but being made up of team members from the disciplines of biological science, biomimetics, materials science, aerostructures, computational fluid dynamics and computer science.

Potential goals could include the development of ultra lightweight aerostructures at greatly reduced costs over conventional systems. Pillar Three of NASA's Aeronautics and Space Transportation Technology Plan calls for the low cost access to space. The combination of significant weight reduction and enhanced performance in hostile environments of potential systems should provide powerful incentive to undertake this new paradigm for aerostructure development.

Many mistake biomimetics to be a field in which man-made products are direct imitations of the living organisms. The flight of the bird is used as an example for redesign of aeronautical vehicles. Yet the propulsion systems and mechanics of flight are quite dissimilar. No doubt the control surface behavior for the two has much in common, but the "airframe" and propulsion systems could not be more different. Indeed, the modern propulsion systems offer the potential for active control of lift and drag of the airfoil, while the airframe of the bird must account for wing motion quite in excess of that of the man-made aircraft.

The primary point of this discussion is that successful use of biomimetics for the benefit of aerospace vehicle technology will require the integration of robust materials and structures simulations with revolutionary ideas provided by the lessons of nature. The modern aeroengineer/scientist has as much to teach the biologist as they have to learn from biomimetics.

Let us understand the wonderful potential for the new and revolutionary ideas that biomimetics offers to the fields of aeronautics and aerospace, but let us remain committed to the development of a strong foundation in science and engineering that will allow us to fully realize those benefits.

5.0 Survey of the Field of Biomimetics

The Centre for Biomimetics was founded in 1991 at the University of Reading in the United Kingdom. Led by Professors George Jeronimidis and Julian Vincent, the research program focuses at the intersection of biomimetics,[8] intelligent materials, food texture,[9] composites and ceramics,[10] and horticultural science. [11,12]

Vincent suggests that all biological materials that perform mechanical functions are composites with fibrous structures consisting of protein macromolecules and with matrix materials consisting of a variety of materials such as protein, polysaccharide and water. He states that the mechanical properties of grass can be determined by a unidirectional composite model. The main fibrous tissue in grass is sclerenchyma which occurs in distinct bundles of

[8] Vincent, JFV and Jeronimidis, G., "Biomimetics of Flexible Composites: Towards the Development of New Materials," Biomimetics, Vol. 1, No. 4, (1992), pp. 297-307.
[9] Kahn, AA and Vincent, JFV, "Anisotropy in the Fracture Properties of Apple Flesh as Investigated by Crack-Opening Tests," Jor. Of Materials Science, Vol. 28, (1993), pp. 45-51.
[10] Vincent, JFV and Wyeth, P., "Characterization of a Hardened Biocomposite, Zinc-Impregnated Cuticle, Jor. Inorg. Biochem., Vol. 43, (1991), p. 675.
[11] Vincent, JFV, and Jeronimidis, G. "The Mechanical Design of Fossil Plants," Biomechanics and Evolution, edited by JMV Rayner and RJ Wootton, Cambridge University Press, (1991), pp. 21-36.
[12] Jeronimidis, G. and Atkins, AG, Mechanics of Biological Materials and Structures: Nature's Lessons for the Engineer," Oroc. Inst. of Mechanical Engineers, Vol. 209, (1995), pp.221-235.

fibers. Volume fraction of the reinforcement is determined by leaf section. Results reported show that the fiber phase at 4.5% volume fraction is responsible for 90-95% of the longitudinal stiffness of the grass leaf. By using a similar approach Vincent also measured the fracture toughness of the grass leaf.

Robin Eisner in The Scientist [13] describes the work of Mehmet Sarikaya of the University of Washington in the study of the mollusk, the abalone shell in order to develop impact resistant synthetic materials. Following a study of the micro architecture to determine the structural configuration of the abalone, Sarikaya and colleague, Aksay have developed a synthetic prototype material that mimics the shell's laminar structure. Although the authors have not achieved a ten-fold increase in fracture toughness, their results have been promising to date.

Professor Eric Baer[14] et al has developed a description of biological materials that reveals a hierarchical organization that can serve as a model for high performance composite materials. The authors argue that biological materials are "designed" to withstand complex stresses and are optimized on all scales from molecular to macroscopic.

Three rules of complex assembly are postulated. The first rule states that the structure is organized in discrete levels or scales where fibrils, consisting of micro and nano fibrils, exist. The fibrils are arranged in a manner necessary to successfully carry out the desired function.

The second rule states that the levels are held together by specific interactions between the components. Strong surface-to-surface

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[13] Eisner, R., "Biomimetics: Creating Materials from Nature's Blue Prints," The Scientist, Vol. 5, No. 14 (1991), p. 14.

[14] Baer, E., Hiltner, A. and Morgan, R.J., "Biological and Synthetic Hierarchical Composites," Physics Today, October (1992), pp. 60-67.

interactions are achieved by intermolecular covalent bonds at specific active sites and by van der Waals forces.

The third rule is that the highly interacting elements such as layers and fibers are organized into an oriented hierarchical system that is designed to meet a complex spectrum of functional requirements.

Baer illustrates these rules with examples of the tendon and the intervertebral disc. The tendon, which connects muscle to bone, is shown to be subjected exclusively to uniaxial tensile stresses. The Baer six discrete levels of organization of the tendon structure: triple-helical tropocollagen macromolecule, microfibril, fibril, fascicle, fascicular membrane and reticular membrane. This multilevel organization is responsible for tendon toughness and nonlinear, reversible tensile properties. Overstressing the tendon results in progressive failure of the sub elements in an energy absorbing process that assures toughness.

The invertebral disc is described as being made up of collagen fibrils that are organized into lamellae sheets in the annulus fibrosis, which surrounds the gelatinous nucleus pulposis. The geometry of the fibrils is shown to be arranged for to withstand compressive stresses by transforming these into radial and tangential tensile stresses in the lamellae of the annulus. In this way, it is suggested that the disc behaves as a cylinder filled with an incompressible fluid.

The search for new materials from biology is described as promising by Covault at Wright-Patterson AFB[15]. Microscopic infrared detectors of snakes that can detect 0.001 degree Centigrade temperature differences are being studied.

[15] Covault, C. "Materials Technology Leads AFRL Space Initiative," Aviation Week, April 5, (1999), pp. 44-45.

6.0 High performance Composite Tensile Structures

The structure of the biological tendon and the advanced carbon fiber can be observed to guide the development of optimum architectures, conformational forms and manufacturing methods for the high performance composite tether. The synthesis of tethers from advanced organic fibers offers the potential for significantly enhanced performance over conventional steel cables when specific tensile strength and stiffness dominate performance requirements.

The resulting tether architecture not only spans the scales of nano, micro, mini and macro, but also offers the potential for self-similar geometry at all these scales. As such, the tether may be unique in providing a structural element architecture where separation and linking of the important phenomena at each scale is possible. Certainly, the examination of issues at one scale will have much to teach us about phenomenon at the next higher order scale.

It is also instructive to combine both innovations in structural form and manufacturing methods with a fundamental understanding of both. The new tendon architectures will spring from the nano and macro architectures of biological tendon and advanced synthetic fibers. The resulting manufacturing methods can be drawn from the integration of advanced textile processes and polymer processing techniques such as pultrusion.

The results of the biomimetic analysis of biological tendon and carbon fiber structure can significantly advance the fundamental understanding of the static and time-dependent behavior of the high performance tendon. It also offers a unique opportunity to link important mechanisms and phenomena across multiple scales. Further, the fundamental understanding of the relationship between manufacturing and tendon architecture can provide for economic considerations, while revealing new more nearly optimum tendon architectures.

6.1 The Advanced Composite Tether

The advanced composite tether composed of carbon or aramid synthetic fiber systems shown in Figure 1 offers the potential for significantly enhanced performance over the conventional steel cable in applications where specific strength and stiffness dominate performance requirements.[16]

The conventional manufacturing of the tether involves four primary steps. In the first step the small diameter "wire" element is fabricated by the method of pultrusion wherein the dry fiber tow consisting of up to 80,000 individual fibers is impregnated with a thermoset or thermoplastic polymer and the cross-sectional geometry of the "wire" element is established. The diameter of the circular geometry "wire" made up of multiple tow is typically 3-5 mm. Next the "wire" elements are combined in a process known as " rope stranding" by twisting up to 300 "wires" to produce the strand. As many as 30 strands are combined to produce the tether. It is noteworthy to observe that a given tether cross-section may contain up one billion individual fibers.

In the final step the termination or joint for the tether is constructed in order to provide for load transfer between the tether and its support. Metal and polymeric end fittings must be designed to accomplish load transfer without loss in structural.efficiency.

Given the "rope like" geometry of the conventional tether, each of the scale elements contain helical twist that provides for the load

[16] Salama, M.M., Conoco, private communication, (1999).

transfer between the elements. Hearle [17] and Chou [18] have described the mechanics of several textile geometries including the rope or yarn. The opportunity to choose new wire cross-sectional geometries and to utilize advanced textile techniques in constructing the tether architecture provides the potential for revolutionary new tether geometries modeled after their microscopic counterparts.

6.2 Biomimetics for the Composite Tendon

Evaluation of the heirarchical structure of biological tendon following the work of Baer and examination of the morphology of synthetic carbon fiber as discussed by Oberlin[19] and Edie[20] can provide significant insights into the description of candidate tendon architectures to achieve optimum performance.

The determination of methodologies to control characteristics of fiber yarns as a precursor to developing the impregnated strand such as controlled fiber length distribution can provide for conformability of the yarn after impregnation. The mechanics of stretch breaking can be modeled and yarn bundle geometry examined for fiber alignment, distribution and spacing.

Multiple wire cross-sectional geometries must be assesses in light of the biological tendon. The impregnation process for production

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[17] Hearle, JVS, Thwaites, JJ, Amirbayat, J., Mechanics of Flexible Fiber Assemblies, Sijthoff and Noordhoff, The Netherlands, (1980).
[18] Chou, TW, Textile Structural Composites, Elsevier Science Publishers, B.V. Amsterdam (1991).
[19] Oberlin, A. and Gignon, M., "The Structure of carbon Fibers," Fiber Reinforcements for Composite Materials, (ed. A.R. Bunsell), Vol. 2, Composite Materials, Series Editor, R.B. Pipes, Elsevier, Amsterdam, (1988).
[20] Edie, D., "The Effect of Processing on the Properties of Carbon Fibers," Carbon, Vol. 3, No. 36, (1998), pp. 13-34.

of the impregnated strand or "wire" with thermoplastic and thermoset polymers would follow that described in the author's earlier work[21] [22]and that of Chandler et al[23] and Kim et al[24].

Textile processes that can produce the first element strand architecture include braiding, rope stranding and knitting techniques. Given the conformability of the impregnated strand at elevated temperature, these methodologies can be carried out at the post pultrusion station before the polymer is cooled. As many as 300 impregnated strands can be combined at this stage for the first strand element. Next, up to 30 first element strands can be combined to produce the complete tether architecture.

Models for the prediction of tether performance are, of course, necessary. Tensile strength and stiffness as well as tensile creep and relaxation can be modeled. The approach to this work should follow that of Chou et al[25] and begin with the properties of the synthetic fiber and the polymer to predict the properties of the impregnated strand or "wire" element. Next, models must be constructed of the first element strand geometry using the approaches of Chou[18] and Hearle[17] for the simple geometries. New models can be developed for the innovative architectures.

Development of models for the behavior of joints for the assembled tether geometries is essential. Contemporary joining

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[21] Astrom, T., and Pipes, R.B., "A Modeling Approach to Thermoplastic Pultrusion I – Formulation and Models," Polymer Composites, Vol. 14, No. 3, (1992).

[22] Astrom, T., Pipes, R.B., "A Modeling Approach to Thermoplastic Piltrusion II – Verification of Models," Polymer Composites, Vol. 14, No. 3, (1992).

[23] Chandler, H.W., et al, "A Model for the Continuous Impregnation of Fibre Tows in Resin Baths with Pins," Plastics, Rubber and Composites Processing and Applications , Vol. 18, (1992), pp. 215-220.

[24] Kim, T.W, "Effect of pressure on the Impregnation of Thermoplastic Resin into a Unidirectional Fiber Bundle," Advances in Polymer Technology, Vol. 9, No. 4, (1989), pp. 275-79.

[25] Chou, T.W., and Ishikawa, T., "Stiffness and Strength Behavior of Woven Fabric Composites," Jor. Of Materials Science, Vol. 17, (1982), pp. 3211.

methodologies must be evaluated in light of the new conformational architectures.

7.0 State of the Art Review of Composite materials and Structures Technology

The primary questions addressed in this assessment were as follows:

What is the status of the technology today?

What are the key technology issues that must be addressed to assure safety, reliability and reusability?

What needs to be done to advance the state-of-the art to assure safety, reliability and reusability?

What are the key benefits that accrue from advancing the stat- of-the art of composites technology?

The list of questions was used to survey the industrial composites community and those organizations surveyed are found in Appendix I.

7.1 Preliminary Assessment Results

The preliminary results from the survey can be summarized in the following list of critical issues

Materials and Processes
Ultra-Large Scale Design Concepts and Technologies
Improved Design Confidence and Reduced Factors of Safety
Systematic Codification of the Knowledge Base

Materials Standardization and Cost Reduction
Uniform Materials Property Data Base
Materials Innovations to Meet Advanced Requirements
Manufacturing Innovations for Ultra-Large Scale Structures
Robust Joining Technology
Manufacturing and Design Methods for Cost Reduction
Reliability, Durability and Safety

7.2 Materials and Processes

The materials and processes issues focus on the need for revolutionary out-of-the autoclave fabrication processes required for cost-effective composite structures, particularly ultra-large scale, unitized structures. New polymeric resin systems are required to accommodate these new manufacturing technologies. Ultra-low viscosity systems for resin transfer processes, chemistries appropriate for non-thermal curing and enhanced performance characteristics are desired new properties. The cost of qualification of new materials is seen as the primary barrier to the entry of new materials systems and the primary issue is to develop methodologies that remove the heuristics from the process and thereby allow for rapid and robust implementation of new developments as they occur.

The process for incorporation of materials synthesis and performance issues with the design/build process development requires further development. Target properties must be established to guide the materials synthesis efforts if new materials are to meet design specifications. Uniform test standardization for acceptance tests of materials systems can lead to cost reductions and must be further evaluated. Economic models for the prediction of the costs associated with the competitive manufacturing methods must receive further development. There is a concern that many of the starting materials used in the development of contemporary polymeric matrix materials my not be available in the future and replacement chemistries must be developed.

7.3 Ultra-Large Scale Design Concepts and Technology

The industry design trend is away from "black aluminum" design concepts and toward integrated structural concepts. This design trend is helping to reduce the cost of composite structure – thereby, making them more affordable and competitive with conventional materials and designs. This is an emerging trend that is still largely based in empirical methods. Manufacturing scale-up remains a high-risk endeavor with variability and reproducibility the major issues.

The state-of-the art for scale-up of manufactured parts and components is limited by the available autoclave dimensions. Out-of-the autoclave manufacturing methods are key to the success of ultra-large scale, integrated composite structures. However, the scale-up to large-scale integrated components remains largely an empirical process. Variability in geometry and performance remain issues.

There is the need for ongoing programs for the design and build of prototype components of ultra-large scale. In parallel a physics-based approach to structural design and analysis must be further developed to address performance variability and repeatability. Verified design and analysis methodologies to support large-scale integrated components should be an outcome of the programs proposed.

7.4 Improved Design Confidence and Reduced Factors of Safety

Although there have been many outstanding successes in application of composite materials in aerospace vehicles over the past 30 years, composite materials and structures technology remains an immature when compared to conventional materials and structures concepts. Overly conservative design factors have resulted in less than optimum configurations and unexpected failures during ground test have occurred. Manufacturing scale-up to large-scale, integrated structures remains empirical and design for manufacturing imperfections is in its infancy.

The industry standard for design factor of safety for composite structure is 1.5 and is based on Design Limit Load. Additional design factors are added to address uncertainties and incomplete understanding of local design detail features and damage tolerance issues. In many cases empirical methods are used where appropriate analyses are absent. The "building block approach," that consists of building and testing of subcomponents to evaluate most of the design details, is the predominate process used to eliminate performance and manufacturing uncertainties. It is expensive and time consuming.

There is a clear need to develop a process for the scale-up from simple materials tests to large-scale structure and to avoid the many intermediate steps. The "virtual building block" process is clearly called for. This will require scientifically based analyses to replace the empirical design methods that employ multiple factors of safety to accommodate multiple uncertainties. These analytical methods must be hierarchical and accommodate multiple dimensional scales. Further, they must incorporate manufacturing and service defects.

High-fidelity analysis and design procedures must be developed for the local detail features that will treat multiple dimensional scales and allow reduction in conservatism due to uncertainty. The relationship between weight and reliability may provide significant new insight into optimum design.

7.5 Systematic Codification of Knowledge Base

The knowledge base in composite materials and structures design, manufacture and testing is in jeopardy due to the aging of the technical work force, the fragmentation of the technology and the heterogeneous level and character of multiple proprietary codifications. The age distribution of the technical expertise in composite materials and structures is bimodal. A large fraction of the personnel are approaching or at retirement age. Two-thirds of the engineering work force may be under-experienced within three years.

The codification of the knowledge base is heterogeneous. Much is in proprietary, inaccessible vehicles. Except for Mil Handbook 17, no knowledge vehicle based in modern Information Technology is being developed. Knowledge level is not uniform and there are "pockets" of excellence distributed worldwide. The use of modern Information Technology for codification and dissemination of composites technology is minimal.

It is recommended to use Information Technology and Expert Systems to capture and codify the current state-of-the art. The use of codified information jointly by the aerospace and aeronautics communities would accelerate its adoption and use for the benefit of all future aerospace systems. The best practices and design protocols would emerge.

7.6 Materials Standardization and Cost Reduction

Uniform materials tests are required to reduce the initial cost of composite materials and the costs of qualification of new are modified materials systems. The materials supplier industry is made up of small to intermediate size organizations where only modest materials development costs can be absorbed.

In the contemporary composite materials industry, materials supplier, sub-fabricator and end user have different tests to qualify and re-qualify specific products. This results in excessive development costs.

Standardization of materials to allow prepreg, dry performs and adhesives to be ordered to a common specification is recommended. The establishment of an industry/government/university consortium to develop a system for national materials standardization is called for.

7.7 Uniform Materials Property Database

Standardized materials test methods are required to reduce costs of composite materials and structures. The current state-of-the art is based on a disintegrated database.

Different test methods are promoted by SACMA, ASTM and multiple industrial organizations. It is recommended that all users and suppliers use the same standardized test methods and materials forms and that a national materials database be developed from the standardized results.

7.8 Materials Innovations to Meet Advanced Requirements

New and improved polymeric matrices, adhesives and materials forms are required to enable low cost fabrication of ultra-large, optimum composite structures and vehicles. Extreme temperature performance and out-of-autoclave manufacturing requirements present significant challenges. Current incentives do not promote industrial investment in the development of new polymeric systems. The starting materials for many conventional polymeric materials may not be available in the near future.

New performance requirements for optimum materials systems include microcrack resistance, toughness and damage tolerance at cryogenic conditions. New polymeric materials must be developed with the appropriate combination of properties to meet both performance and manufacturing requirements. The most promising polymers must be evaluated for scale-up through a comprehensive evaluation. New materials forms must be developed including barrier films and prepregs. Coupon-level composites and adhesives databases must be developed for the new materials systems and forms.

7.9 Manufacturing Innovations for Ultra-Large Structures

Revolutionary techniques are required for the cost-effective fabrication of ultra-large optimum composite structures. Valid cost estimation models are required since cost will be the primary driver for use of these materials in future ultra-large scale systems.

There are currently no processes available to fabricate ultra-large scale, optimum composite structure in excess of the dimensions of the largest autoclave available, 26 feet in diameter by 90 feet in length. Recent experience with the X33 composite liquid hydrogen tanks suggests a need for better scale-up methodologies because non-autoclave processes have not received comprehensive development or evaluation.

It is recommended that aggressive programs be undertaken to support ultra-large scale composite structure manufacturing:

Develop non-autoclave fabrication processes.

Develop new or improved low and high temperature polymers for non-autoclave manufacturing.

Develop bonding processes involving thermal and room temperature electron-beam curing.

Develop fabrication models to improve performance and reduce cost.

Develop new lightweight tooling materials and fabrication processes.

Develop new interleafing materials and processes for improved cryo-barrier properties, microcrack resistance and damage tolerance.

Develop high speed, economic materials deposition rate methods.

Design for lean manufacturing and assembly with unitized structure and parts consolidation.

7.10 Robust Joining Technology

One of the major advantages of composite materials and structures is the potential for the economic consolidation of multiple parts into net-shaped components possessing increased geometric and materials complexity. However, this increases the economic risks due to the chance loss of large complex systems during the processing steps. Further, the current state of the art of manufacturing is limited by the available autoclave size as mentioned earlier. Hence, the need for robust joining technology cannot be overstated for both bolted and bonded joining. The structural and manufacturing efficiencies achieved through robust joing technology demand its emphasis.

Joining of composites is not commensurate with that of welding or bolting of metallic materials and structures. Of primary concern is the ability to discern, nondestructively, the strength and integrity of the adhesive joint. To date, this has not been achieved. Like the manufacture of large, net-shaped structural components, large adhesive joints put the fabricator at risk for component loss during the curing cycle. Reliable joint strength analyses are not available for bonded joints of complex geometry.

Three-dimensional analyses for bonded joints that include interlaminar and adhesive stresses and a robust bond strength analysis methodology are needed. Joining technology will have such a pervasive impact on the future of aerospace systems that a national resource for development and dissemination of knowledge for efficient joining of composite structure and materials is called for. The Edison Welding Institute is an example of the level and character of the effort required.

7.11 Manufacturing and Design Methods for Cost Reduction

While reliability, safety and reusability have been the primary focus of this study, the survey respondents overwhelmingly stated that "cost" was their number one goal in the development of composite materials and structures.

Composite materials offer performance advantages over contemporary materials and structures in spite of the fact that this technology is only 30 years of age. Extraordinary cost advantages have been demonstrated during that period. For example, the price of carbon fiber has changed little over the past 30 years – inflation was absorbed through productivity gains. Recently, the general aviation and rotorcraft industries have demonstrated new, cost competitive structural concepts.

Significant unrealized potential exists for innovation in materials and structural concepts in order to gain significant cost reduction and yield highly competitive composite structure. The time is right now to fully demonstrate the broad potential of this technology to provide, performance, reliability, safety and cost. Partnerships and increased understanding developed from a major NASA program were called for.

7.12 Reliability, Durability and Safety

Reliability is currently accounted for by design factor based on empirical design allowables and limited failure analysis capabilities. Uncertainty, variability and tolerance issues are either not addressed or are represented by conservative empirical factors.

Failure analysis is still limited to simple two-dimensional inplane models that do not always represent the physics. Damage tolerance design criteria for low speed impact have been accepted by the community for thick-skin wing structures based on impact energy and dent depth. Designs are usually based on coupon or small element test data.

The development of physics-based failure analyses, that account for local three-dimensional effects, are recommended. The relationship between weight and reliability deserves further study. An equivalent level-of-safety criterion for composite structures should be developed. The development of a physics based failure analysis procedure that represents the competing mechanisms of failure including local three-dimensional effects and three-dimensional stress gradients for all loading conditions is recommended.

In addition, there are several other developments required:

> Physics-based failure interaction criterion for multiple loadings
>
> Progressive failure analyses that include changing local damage state
>
> Procedures to account for uncertainties, imperfections and variability
>
> Damage tolerance design criteria for thin-wall fuselage structures
>
> Damage tolerance design criteria for sandwich structures

Damage containment concepts

Residual strength analyses and design procedures for composite structures subjected to combined internal pressure and mechanical loads

Equivalent level-of-safety criterion for composite structure

Appendix I : Survey Questions

1.2 Survey Questions

Analytical Methods

- Where are the gaps in the analytical pathways from micro to macro?
- Are analytic modeling and computational power sufficient?
- Are there issues in numerical methods for stress, deformation & vibration analyses?
- What is the state of the art of instability analysis?
- What is the state of the art on nonlinear analysis?
- What is the state of the art of failure analysis?
- Are analytical models for adhesive and bolted joining sufficient?
- Are analytical models for ultimate behavior adequate?
- Have imperfections been properly modeled and can critical imperfections be determined?
- Are three-dimensional, local effects properly analyzed?

Characterization Methodologies

- What is the state of the art of materials characterization?
- How are materials property variations characterized?
- What is the methodology for design allowable determination?
- Are test method standards adequate?
- What is the role of accelerated testing?

1.2 Survey Questions (continued)

Design Methodologies

- Are analytical and characterization methods sufficient foundations for design?
- Can multi-mode behavior be properly considered?
- Are “fail safe” and “safe life” approaches consistent?
- Are design tools robust?
- How is reliability ensured in design?
- What is the essential “building block” approach in design?
- How have conventional design approaches been adapted for composite materials and structures?

Manufacturing Methodologies

- What are the limits to conventional manufacturing methodologies and materials?
- What advances are required for large scale manufacturing?
- What are the revolutionary advances in manufacturing technology?
- How can manufacturing control reduce variability and costs?
- Have manufacturing defects been fully characterized?
- What is the resolution of modern methods of NDE?
- How can manufactured cost be systemically reduced?
- What are the effects of manufacturing variability on performance?

Materials Supply

- Are current materials supplies sufficient to meet the needs of the aerospace and aeronautics industries?
- Are unified materials specifications required?
- What effect has industry consolidation had on materials supply and cost?
- How can materials property variability be reduced?

1.2 Survey Questions (continued)

Service Life

- What is the state of repair technology?
- How is aging of the fleet considered?
- Are there unexplored issues in long term performance?
- What is our experience since 1970?

Flight Certification

- Flight certification for general aviation issues?
- Flight certification for commercial aviation issues?
- Flight certification issues for leisure aviation?
- Flight certification methodologies for space transportation vehicles?

Human Resources

- What is the level of maturity of the human resources in composites technology?
- How have the recent mergers influenced the available human resources?
- How are the programs of higher education influencing human talent availability?
- How are the federal laboratories developing human talent?
- What is the global availability of human talent?
- What role do internal education programs play?
- Institutionalized Knowledge and Technology Structure
- What are the primary repositories of knowledge?
- How are the federal laboratories playing a role?
- How is the technology knowledge base sustained?
- What role is Information Technology playing?
- Are technical societies important?
- Are the university/industry/government programs robust?
- What is the status of technology transfer?

1.2 Survey Questions (continued)

Thirty Years of Experience

- What are the lessons from the military programs?
- What are the lessons learned from commercial programs?
- What are the lessons learned from the space programs?
- What are the lessons learned from automotive programs?
- What are the lessons learned from marine applications?
- What are the lessons learned from leisure products?

Appendix II: Organizations and Personnel Surveyed

1.3 Organizations and Personnel Surveyed

The Boeing Company

- Jim Renton, Director for Structures Technology, Phantom Works
- John Quinlivan, Vice President, 767 Program
- Eric Cregger, HSR Fuselage Structures Team Lead, Seattle
- Charley Saff, Structures Technology, Phantom Works, St. Louis
- Jason Hatakeyama, Structures Tech., Phantom Works, Long Beach
- John Pulley, RLV, Downey
- Jeff Fukushima, Structures Tech., Phantom Works, Huntington Beach
- Tom Tobey, Director, MR&D, Phantom Works, Seattle
- Jerry Dickson, Senior Mgr, MR&D, Phantom Works, Seattle
- Ray Grove, BMT, Seattle

FAA

- Larry Ilcewicz, National Resource Specialist for Composites
- Peter Shyprykevich, FAA Technical Center

Lockheed Martin Skunk Works

- Robert Goetz, Vice President, Engineering
- Don Watson, Mgr, Structures Technology
- Don Sidwell, R&D Engineer
- Walter Franklin, Lead Structures Engineer, X37
- Glenn Grimes, Composite Structures Specialist
- Mark Miller, Deputy VP, Engineering

1.3 Organizations and Personnel Surveyed (continued)

Lockheed Martin Aeronautical Systems

Tony Jackson, Program Manager-NASA Programs, Technical Fellow
Steve Engelstad, Senior Engineer Specialist, Adv. Structures & Mtls.

Bell Helicopter Textron

Carl Rousseau, Structures

Northrop-Grumman Company

Ravi Deo, HSR TMT Member, Structures & Materials Technology
Bob Ley, Structures R&D, Military Aircraft Systems Div.
Steve Russell, Mgr, Commercial Structures Tech. Integration, Dallas
Tod Palm, Mgr., Str. Integration & Test, Military Aircraft Systems Div.

Hexcel Composite Materials

William (Will) McCarvill, Mgr., R&T
Roger Stirling, Sales Development Mgr.
Shaw Ming Lee, Director, Materials Science
Bruno Boursier, Prototype Lab Mgr., R&T

YLA

Gary Patz, President
Susan Robitaille, Director, R&D, Material Forms