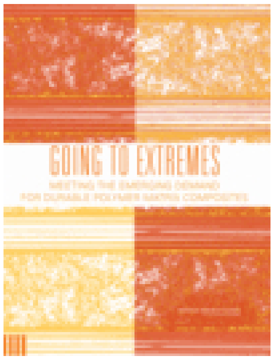

Going to Extremes: Meeting the Emerging Demand for Durable Polymer Matrix Composites

Committee on Durability and Life Prediction of Polymer Matrix Composites in Extreme Environments, National Research Council

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THE NATIONAL ACADEMIES
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Going to Extremes

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Committee on Durability and Life Prediction of Polymer Matrix Composites in Extreme Environments
National Materials Advisory Board
Division on Engineering and Physical Sciences

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Preface

The Department of Defense (DOD) Reliance Panel on Materials and Processes requested that the National Materials Advisory Board conduct a study to identify the barriers and current limitations on the use of polymer composites in extreme environments and recommend thoughtful strategies to enable increased reliable insertion and use of these materials in future critical applications. The emphasis was on issues surrounding methodologies for predicting the long-term performance of polymers in aggressive environments.

This is not a new question. In a previous study by the National Materials Advisory Board,[1] the government was encouraged to

- Support development and facilitate implementation of advanced analysis and computational methods to predict residual strength as a function of time; and
- Support programs to better understand basic failure mechanisms in advanced materials and their structures. Include the interactions at the various length scales of a material, from the microstructural to the macrostructural.

The committee set out to address both recommendations with increased specificity. It was charged with conducting a workshop to assess the current scope of the scientific and technical challenges associated with the use of polymer matrix composites (PMCs) in extreme environments and to assess the advances necessary to predict their behavior with greater precision than is now possible. The committee was charged expressly to carry out the following tasks:

- Assess the limitations of current durability design practices for use of PMCs in extreme environments.
- Identify future durability and life prediction needs that would permit the expanded use of PMCs in extreme environments.
- Identify novel or recent advancements for life prediction of PMCs not yet adopted or accepted by industry and develop any lessons learned.
- Identify approaches and candidate tool sets that could accelerate the development of robust scientific methods to accurately predict the state of PMCs as they are exposed to their operating environment during their service life.
- Prepare a workshop report with recommendations for advancing the ability to predict the behavior of PMCs in extreme environments.

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[1] National Research Council. 1996. New Materials for Next-Generation Commercial Transports. Washington, D.C.: National Academy Press. p. 75. Available at <http://books.nap.edu/catalog/5070.html>. Accessed February 2005.

A workshop was held on July 26-27, 2004, that included committee members, experts, and DOD representatives; the committee also met on that occasion. Technical topics were presented and then discussed. The topics covered the design considerations, the suitability of current modeling practice, the influence of processing and materials, and accelerated testing. The DOD representatives also provided a useful overview and rationale to set the stage for the discussions. Formal presentations were brief to allow committee members and guests to interact and focus on the answers to the questions raised by the above tasks. By the conclusion of the meeting, the committee had agreed on several overarching recommendations. It remained for the committee to assign individuals to gather additional information and then to summarize their findings through e-mail exchanges and regular teleconferences. The recommendations and supporting information that resulted from this process are presented in the body of the report.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Scott W. Case, Virginia Tech,
Thomas S. Gates, NASA Langley Research Center,
Gail Hahn, The Boeing Company,
John L. Kardos, Washington University,
Frederick J. Lisy, Orbital Research, Inc.,
Hugh L. McManus, Metis Design,
Richard Stein, University of Massachusetts, and
John Thesken, NASA Glenn Research Center.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by William G. Agnew, General Motors Corporation (retired). Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

The committee acknowledges the speakers from the government and from industry who took the time to share their ideas and experiences. The following individuals also greatly assisted the work of the committee through their participation in many of the committee's activities: Linda Schadler, liaison to the National Materials Advisory Board, and Tia Benson-Tolle and Ozden Ochoa of the Air Force Research Laboratory. Finally, the committee acknowledges the contributions to this report by the staff of the National Academies, including Rachel Fezzie, Laura Toth, and Toni Marechaux, and by Carol Schutte, a consultant to the committee.

L. Catherine Brinson, *Chair*
Committee on Durability and Lifetime Prediction
of Polymer Matrix Composites in Extreme Environments

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Executive Summary

Polymer matrix composites (PMCs) have been manufactured for over 50 years in the United States. The composites industry utilizes various resins (typically epoxies, vinyl esters, or polyesters), curing agents, and fiber reinforcements (typically, glass fibers). It produces a wide spectrum of industrial components and consumer goods, ranging from boats, bathtubs, and auto bodies to a variety of other parts and components.

Advanced PMCs are a sector of the composites industry that is characterized by the use of expensive, high-performance resin systems and high-strength, high-stiffness fiber reinforcement. While the aerospace industry, including military and commercial aircraft of all types, is the largest customer for advanced PMCs, these materials have also been adopted by sporting goods manufacturers, which sell high-performance equipment to the golf, tennis, fishing, and skiing and boarding markets.

Advanced PMCs have been extolled for their many advantages, including light weight, high specific strength and stiffness, property tailorability, and increased flexibility of design. However, in environmental conditions differing greatly from the ambient—that is, in extreme environments—the inherently complex material response of PMCs over time and the resulting evolution of their structural and functional properties have limited their effectiveness.

In particular, because of the complex nonequilibrium thermodynamic state of the polymer matrix, enormous uncertainties exist when predicting changes in the properties of PMCs as they are exposed over their lifetime to complex stress, moisture, and temperature conditions. Because such exposures can be coupled with exposure to chemical corrosives, ultraviolet radiation, or other degrading environments, the development and validation of predictive tools becomes ever more challenging. The inability to predict material performance under severe operating conditions is brought about by an inadequate understanding of the underlying physical mechanisms for material degradation, damage evolution, and failure in the hierarchical and highly heterogeneous material/structure. Taken together, these limitations on understanding have caused the design of composite components to be based on a relatively crude knockdown factor[1] or similar approaches in an attempt to account for the long-term evolution of the material's properties.

This inability to predict the long-term durability of PMCs—and the consequent overdesign of structures necessitated by this uncertainty—has limited their use. In some cases, PMCs are not used because the overdesigned part does not result in any design advantage. These issues are most serious for PMCs used in aggressive environments, where the stresses on the materials are high and numerous, leading to even larger uncertainties in polymer response over time. At the same time, it is in many such extreme environment applications that the advantages of lightweight, tailorable materials would be most beneficial.

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[1] A simple way to proportionally adjust all properties of a material at an elevated temperature is to multiply them by a factor based on the ratio of one property (yield strength, for example) at that temperature to the same property at ambient conditions.

For example, the combination of light weight and stiffness offered by PMCs makes them attractive candidates for structural components in both military and civilian applications. In aerospace applications, where thin structures and complex shapes are needed to save weight, the ability to create a unitized structure complete with integral stiffeners and skin significantly reduces the number of parts and fasteners in an aircraft structure. Potentially more important than specific strength, though, is the ability to make polymer composites multifunctional. In addition to providing structure, multifunctional materials may provide sensing, moving, analyzing, communicating, and acting capabilities. The flexibility in processing composite materials could enable many of these advances. A number of innovative designs planned for deployment in extreme environments may only be possible with the use of advanced PMCs.

In mission-critical applications, however, these new materials cannot be used without knowing their reliability. The current use of PMCs could increase dramatically if methods could be developed to reliably predict long-term durability and performance of polymer composites subjected to aggressive environmental conditions. To improve this situation, several factors must be considered, including the current state of predictive modeling and design practice for PMC components, the variety of accelerated testing techniques used to qualify material components, the influence of processing parameters, existing long-term databases, and target applications. To significantly advance the predictive capability, which will in turn enable reliable and tighter design of PMCs and dramatically increase insertion opportunities, the following recommendations are offered.

Recommendation: To successfully address the complexities of predicting the performance of PMCs, organizations should assemble interdisciplinary teams with experience in chemistry, polymer physics, materials, processing, mechanics, testing, component and system design, and application of PMCs in extreme environments.

While “interdisciplinary” has long since become a buzzword in scientific circles, actual interdisciplinary research is rare. Truly integrated interdisciplinary research is characterized by the synergistic fundamental contributions of researchers in different disciplines leading to advances that would not be possible otherwise. One reason for the lack of follow-through in many joint projects is that working across disciplines is difficult. It takes much more time and effort to communicate across disciplines and to focus on the connection between data and theories that originate from different length scales and different physics. Another reason for the failure to integrate research is that an individual researcher can be very successful while staying in one field, acquiring funding and publishing papers. However, the challenges of PMCs are too great for this situation to be allowed to persist. To enable design of PMCs to their potential for use in extreme environments, simplistic empirical approaches (such as knockdown factors) must be replaced by mechanism-based models for a range of behaviors, from chemical kinetics to delamination, which can predict long-term durability and performance. Researchers and organizations must team along nontraditional lines and form sustained collaborations to develop the models that are needed. Nowadays, teams are generally assembled by commercial technology integrators, so this recommendation is in many ways aimed at those teams. However, there are other ways to ensure the required teaming, including (1) wording federal program solicitations such that only sufficiently integrated teams will be able to compete successfully and (2) populating review panels for academic proposals with multidisciplinary experts.

Recommendation: A steering committee should be created across the PMC community, initiated and supported across a number of federal organizations, to oversee the development and maintenance of a roadmap (or roadmaps) for PMCs in extreme environments.

Technology roadmaps provide an effective framework for focused product development by highlighting the technology gaps that limit the transition of concepts to production. The preparation of a useful technology roadmap requires an understanding of a range of technical and nontechnical issues, including the current science and technology, future performance targets, technical, institutional, and market barriers, and R&D needs. While individuals, companies, and government agencies could all draft their own roadmaps, a team effort with an effective oversight mechanism is needed for success. The implementation of such a roadmap will require sustained attention, frequent updating, and effective integration of responsibilities and results.

The relevant PMC community includes the agencies interested in the efficacious use of PMCs to accomplish their missions—for example, National Aeronautics and Space Administration (NASA) for aeronautics and space exploration; Department of Defense (DOD) for defense systems; Federal Aviation Administration (FAA) for civil aviation; and National Oceanic and Atmospheric Administration (NOAA) for undersea exploration. As critical are the prime contractors responsible for designing and building the vehicles and structures that will operate in the extreme environments. The industrial technology companies are the main developers of the components, and the vehicle operators (the commercial airlines) are also stakeholders. Finally, the academic community that strives to understand and model the behavior of these advanced materials is also an essential element. Any oversight mechanism for roadmap stewardship must include members from all of these communities, but it should be initiated by the mission agencies.

Recommendation: Mission agencies should offer sustained support to develop and maintain comprehensive information on PMC properties in a new materials informatics initiative. A steering committee on the needs of the PMC community should be formed to ensure that this effort is effectively targeted. This committee should be responsible for developing guidelines and overseeing operations for a national PMC informatics initiative.

With one eye on the fine example set by the bioinformatics field, a materials informatics effort for PMCs should be pursued. Informatics has evolved in recent years as a branch of computer science and information technology that is concerned with the structure, creation, management, storage, retrieval, verification, validation, dissemination, and transfer of information. Informatics also innovates and optimizes the ways people generate, use, and find information.[2]

A number of official databases in bioinformatics and other fields are actively operating. The types of data sought for materials could be established from roadmaps and from lists of critical material properties. Data could be acquired automatically or through a manual curation process, or a combination of these. For instance, papers are added as they are published by automatic abstraction from a central journal database, and tools to visualize, extract, and analyze the data are constantly being updated. Such a model would be ideal for implementation of a database structure for PMCs. The materials database(s) will need to house critical data ranging from chemical structure and microstructural lay-up, to processing conditions and environmental profiles, to data utilization in designs, macroscopic properties over time, and failure modes and images. Curators and programmers will be essential to collect and add verified data, maintain and distribute data, and generate extraction, visualization, and analysis tools. The need for the centralized database is overwhelming given the vastness of the problem—namely, to systematically relate PMC response mechanistically by examining behaviors from chemical kinetics through microcracking. Readily available detailed, complex data are essential for researchers to develop reliable performance models for coupled response that can be validated and then incorporated into structure design.

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[2] The definitions and discussions of informatics in the Wikipedia are recommended. Available at <http://en.wikipedia.org/wiki/Informatics>. Accessed May 2005.

1

Background and Overview

Polymers are complex materials with flexible forms, widely varied compositions, and properties that change as the polymers interact with their environment over time. Structurally, polymers are large molecules built from many small molecules and can consist of many thousands of atoms in chains or networks of repeating units. Composites are complex—they are hierarchical designs of matrices, fibers, and other components that are both materials and structures. Combining polymers into composites, polymer matrix composites (PMCs) challenge the community to develop history-based durability models that will enable composite developers and component designers to tailor the properties of the matrix resin and the interstitial phases between matrices and fibers to the intended use environment, just as they tailor the direction of the fibers to the principle direction of loading. As use environments go to extremes of stress, temperature, chemical compositions, and other factors, this challenge becomes both more important and more difficult.

DEFINING THE CHALLENGE

The endless variety of polymer matrix composites is matched only by the variety of words used to describe their application.

Polymer Matrix Composites

A composite is a material made up of more than one component or phase. In a PMC, one component is a polymer matrix. The primary property of a PMC is generally structural, but a number of other functional properties may also be built into it. A multitude of layered, continuous-fiber-reinforced, particulate-reinforced, and nanoparticle-filled materials can be called PMCs.

For the purposes of this study, composite materials consist of micron-diameter fibers bound in a polymer matrix and used for high-performance structural applications. In many cases, these are continuous carbon fibers in a high-temperature (thermoset) resin material, but they can also be other fiber forms and resin systems. Table 1-1 shows some of the characteristics inherent in the combination of high-performance fibers and polymer matrices.

As the size of a dispersed phase becomes much smaller than a micron, the distinction between a composite and a blend blurs, and so does the boundary between continuum and molecular mechanics. Study in the area of nanoscale fillers and molecular dispersions in both fibers and resins is just emerging, and the modeling of these materials is inconsistent. As these technologies mature, the durability and life prediction methodology envisioned in this report will need to embrace the additional complexities wrought by inclusions at the nanometer scale throughout the composite. Nanosize inclusions fundamentally affect

TABLE 1-1 Characteristics and Applications of High-Performance Fibers in Polymer Matrix Composite Materials

Characteristic	Applications
Physical strength, specific toughness, light weight	Aerospace, construction, sporting goods
High dimensional stability, low coefficient of thermal expansion, and low abrasion	Printed circuit boards, missile structures, aircraft brakes, aerospace antennas and support structures, large telescopes, optical benches, waveguides for stable high-frequency (gigahertz) precision measurement frames
Vibration damping, strength, and toughness	Audio equipment, including microphones and speakers; robotic arms
Electrical conductivity	Airframes and aircraft skin materials, novel tooling, casings and bases for electronic equipment, electromagnetic interference (EMI) and radio frequency (RF) shielding, brushes
Low biological reactivity and permeability by x-rays	Medical prostheses, surgery and x-ray equipment, implants, tendon/ligament repair
Fatigue resistance and self-lubrication	General engineering applications with moving parts, such as automobiles
Low chemical reactivity, high corrosion resistance	Chemical exposure; radiation fields; valves, seals, and pump components
Electromagnetic properties	Electronic devices; motor and generator parts; radiological equipment

polymer mobility, allowing the mechanical and thermal properties of a composite to be dramatically altered even with very small volume fractions.[1,2]

Extreme Environments

An extreme environment for a PMC can mean different things to different people and can depend strongly on their science or engineering background. In the broadest sense, an extreme environment can be any application where the ambient conditions compromise a material's durability. This study focuses on advanced commercial, military, and space applications because these have been, and will likely continue to be, the most demanding.

Extreme conditions may be those encountered in the air, on the land, under the sea, or in space, each with its unique set of requirements:

- Extreme temperatures: high and low;
- Extreme chemical exposures: corrosive environments, including salt water and salt spray, or changing aqueous environments;
- Extreme loadings: high stresses, fatigue, or multiaxial loading; and
- Extreme temporal exposures: from long-term exposure to rapid gradients.

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[1] B.J. Ash, R.W. Siegel, and L.S. Schadler. 2004. Glass-transition temperature behavior of alumina/PMMA nanocomposites. *J. Polymer Science Part B: Polymer Physics* (42):4371-4383.

[2] B.J. Ash, A. Eitan, and L.S. Schadler. 2004. Polymer nanocomposites with particle and carbon nanotube fillers. In *Dekker Encyclopedia of Nanoscience and Nanotechnology*, 1st ed., J.A. Schwarz, C.I. Contescu, and K. Putyera, eds. New York: Marcel Dekker, pp. 2917-2930.

While any of these extreme conditions will affect the durability of a PMC, it is the combination of more than one that may have the most drastic effects.

Applications for PMCs are usually categorized based on operating temperature. A number of applications are at ambient temperatures—for instance, those that confer resistance to battlefield damage. Examples of nontraditional usage of PMCs are shown in Table 1-2. This table is not intended to be complete, but shows some examples of the various extreme environments where use of PMCs is being considered.

Air and Land

Applications in aeronautical vehicles are probably the best described, most widely studied, and well understood applications for PMCs in extreme environments. Extreme temperatures encountered in these applications may range from cryogenic to elevated (−250ºF to 1000ºF, or −150ºC to 550ºC). PMCs may be subjected to thermal cycles, erosion from weather, particulate matter such as sand, dust, hail, and ice, and lightning strikes. Under rapid heating conditions, entrapped water bound to the polymer chain may be released and may debond the structure as a result of hydrostatic pressure. This can result in blistering and steam-induced delamination. Because air vehicles are sometimes stored outside, the resins can age as a result of solar radiation or pollutants in the environment.

While many land-based applications rarely see extreme conditions, those that do offer some unique environmental considerations. Army unmanned robotic vehicles, for instance, may have to withstand rapid heating induced by bomb damage or impacts from rocks and other terrain impediments. They may also have to survive in rapidly changing weather, including sun, sand, ice, rain, and lightning strikes.

Ocean

Submarines and deep submersibles are typically made of steel- or nickel-based alloys. Because they are magnetic, these vessels can be tracked as they intersect Earth's magnetic field lines. Polymer composites are inherently nonmagnetic and may offer an advantage in both weight and cost because protective measures to prevent such detection are not required. Because ocean pressures are high, these structures may be centimeters thick and will experience severe cyclic loading, which can lead to microcracking and rupture. Because marine applications are in a salty environment, consideration must be given to avoiding dissimilar material combinations, which can lead to galvanic corrosion.

The use of polymer composite materials in the offshore oil industry is driven by their lighter weight and better resistance to corrosion compared to steel. Lighter weight is an important driver for deepwater applications because it can reduce the system cost for a deepwater structure such as a tension leg platform or spar. For such applications, the system's heave period must differ from the predominant wave frequency. Steel wire or tendons provide sufficient stiffness to accomplish this in shallow and intermediate-depth water. However, in very deep water, steel tendons are not stiff enough to avoid resonance with waves. PMCs can provide the necessary stiffness while meeting weight criteria, and the benefit of lighter weight increases with depth.[3]

In recent years, the offshore oil industry has increased the depths to which it drills. Deepwater reserves were once at less than 1,000 feet and are now at more than 10,000 feet. Composite applications for the offshore oil market include drilling and production risers, drill pipes, spoolable pipes, pipelines, tendons, and mooring lines. The environments under which these systems must operate include high pressure and load, high temperature, ocean conditions such loop currents, hundred-year hurricanes such as occur in the Gulf of Mexico, and constant exposure to salt water.

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[3] J.F. Flory, H.A. McKenna, and M.R. Parsey. 1992. Fiber ropes for ocean engineering in the 21st century. *Proceedings of Civil Engineering in the Oceans.* Vol. 5. New York, N.Y.: American Society of Civil Engineers, pp. 934-947.

TABLE 1-2 Capabilities and Limitations of Some PMC Applications in a Variety of Extreme Conditions

Candidate Application	Current Material	Critical Conditions	Current Limitations	Motivation for Change	Challenges/Barriers to Move to New Materials
Aircraft					
Aeroshell	Aluminum, titanium, or superalloy	350 to >700°F	Fatigue, weight, loads, thermal efficiency	Increase functionality, weight, reduced part count via unitized structure	Material and fabrication costs, temperature capability, strength and reliability, repairability
Conformal fuel tank	Titanium	−350 to −70°F	Cyclic stress, cracking, permeability	Reduced size and lighter than welded metallic system	Thermal stress, microcracking, delamination, fabrication costs, fatigue life, repairability
Engine duct	Titanium or superalloy	400 to 800°F	Fatigue, erosion, thermal stress	Cost, weight, stability	Liner integration, special performance, stability
Control surfaces, leading edges	Titanium, superalloy, or ceramic matrix composites (CMCs)	350 to 1200°F	Erosion and thermal stress. Failure due to impact.	Lower weight, unitized structures, reduced erosion, improved impact resistance	Fitting integration, thermal capability, erosion resistance, impact resistance, repairability
Nacelles (inner wall)	Aluminum	450 to 800°F	Fatigue, maintenance damage, corrosion	Weight, unitized structure, and corrosion resistance. Reduced maintenance costs.	Thermal resistance, fatigue strength, compatibility with hydraulic fluids, and cost to manufacture and repair
Radomes	SiN	600 to 900°F	Erosion and loss of transmission; fracture damage	Reduce erosion, improve impact resistance, reduce cost, improve transmission	RCS vs. structural performance, attachment to primary structure
Land					
Robotic vehicles	Ceramic	−80 to 250°F	Ballistic events, flammability	Weight, impact resistance, cost, repairability	Performance vs. rolled homogenous steel (RHS), toughness, flammability
Ocean					
Submersible vehicles	Steel or nickel base	−32 to 300°F	Corrosion, fatigue damage	Weight, fatigue strength, magnetic properties	Corrosion resistance, fabrication cost, stiffness, fatigue strength, compression, interlaminar strength
Oil and gas drilling risers, platform tethers	Steel	1.5 million lb axial tension; 3,000 psi internal pressure	Validation of design and prototype manufacturing and meeting regulatory requirements	Reduced life-cycle costs, reduced weight, corrosion resistance, tolerance to fatigue, extended reach	Tools to enable design, validation, accurate prediction of long-term performance, defining appropriate safety factors
Oil and gas pipes	Steel	Tension 250,000 lb; compression 20,000 lb	Validation of design and prototype and meeting regulatory requirements	Reduce weight, avoid corrosion, cost effective	Tools to enable design, validation, accurate prediction of long-term performance, defining appropriate safety factors
Space					
Satellites and space exploration vehicles (SEVs)	Aluminum, titanium, and PMC	−250 to +250°F >500°F (SEV)	Microcracking, strength degradation	Improved directional properties, thermal stability, weight, cost	Outgassing, dimensional stability, end-of-life properties, flammability, fabrication cost

Under these gruelling conditions, PMCs must perform as well as or better than metals with respect to gas and liquid permeability, corrosion resistance, and compressive strength. For example, a difference in the properties of the various components of a composite may result in unintended swelling, liquid-induced crazing, or catastrophic delamination. Confidence in performance is particularly important because the location of these applications makes inspection challenging. In some cases, reliability and durability might have to be certifiable without testing of full-scale prototypes.

In addition to facing technical challenges of material and system performance under highly demanding conditions, the oil market is highly regulated. Safety and environmental issues are top priorities and drivers, because the failure of one of these systems could cause catastrophic damage and loss of life. Regulatory agencies that are key stakeholders in the oil and gas industry include the Minerals Management Service of the Department of the Interior, the Coast Guard, and the Environmental Protection Agency.

Technical challenges and barriers for introducing these new materials into such systems include design, testing, and certification. To address these, the community has started developing integrated design methodologies to analyze and optimize a given structure so that it will meet the performance and durability demands of the entire value chain, from regulators, operators, and manufacturers to material suppliers. Once the development team decides on a technical approach for the new system, the materials or composites are tested at different levels of complexity. Approval by the regulatory agencies involves, among other things, performance and durability testing of the system and subsystems.

Modeling capabilities that could make the initial design and optimization of performance and durability easier would be beneficial. Although performance and durability testing must be done to satisfy key stakeholders, it would be valuable to have a modeling tool that could link manufacturing design to system performance and durability. Such a tool could enable understanding of fundamental limitations and failure modes and mechanisms for a given design and could optimize the design approach.[4]

Space

Space is equally challenging. There, materials can be exposed to thermal fatigue, atomic oxygen, ultraviolet degradation, and electrostatic discharge (ESD), among others. Satellites orbiting Earth can experience temperature swings from −250°F to 250°F, while some exploration spacecraft can see localized peak temperatures of almost 1000°F. Surfaces are exposed to atomic oxygen and ESD at low Earth orbit. PMCs must be chemically stable and have low levels of outgassing contaminates; generally, they must meet SP-R-022 outgassing requirements or better—less than 1 percent total mass loss or less than 0.1 percent collected volatile condensable materials. Outgassed material can condense on critical components or on windows of a spacecraft.

Because PMCs can be used in such dimensionally critical applications as antennas, they must be dimensionally stable over a range of temperatures. The material must retain mechanical properties from the beginning to the end of its life and must be able to withstand the microcracking that results from temperature cycling and outgassing. If used in inhabited structures like the International Space Station, it must be nonflammable, must not release toxic fumes, and must be able to withstand some debris strikes. Finally, the Sun produces ionizing radiation during solar flares, which over time (with dose dependence) can break the covalent bonding; chemically bound water can be released within the composite, causing expansion and debonding, as happens in high-temperature exposure.

For satellites and space exploration vehicles, weight and dimensional stability are key parameters in material selection. Large space structures, while weightless, remain massive, and this mass determines the need for stiffness and damping. Dimensional stability is important to maintain alignment during solar heating of the optics and antennas. Key concerns are microcracking that results from temperature cycling and outgassing. In addition, solar flares can result in significant property degradation when the total dose over time is high enough to destroy the covalent bonding in the polymer.

Moreover, objects for use in space must be lifted into space. Extra structural weight has no benefit and is detrimental in that it limits fuel or extra components that could enhance the performance of the

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[4] W.F. Andersen, J.J. Andersen, C.S. Mickelson, and T.F. Sweeney. 1997. The application of advanced composite technology to marine drilling riser systems: Design, manufacturing and test. Paper presented at Offshore Technology Conference, Richardson, Tex., pp. 29-38.

satellite or vehicle. For every unit of mass on the space vehicle and the payload, many units of fuel are needed. The fraction of the space vehicle structure allowed for fuel is the primary limiting factor in new launch vehicle designs. For example, it is estimated that to achieve practical single-stage-to-orbit capabilities, the structural mass must be reduced to a level that is not feasible given the capability of current materials.

Material selection can play an important role in radiation resistance. PMCs used in satellites and exploration spacecraft are structural and must maintain their design properties from the beginning of life—launch—to end of life. Today there are a number of adequate composite materials successfully operating in space, but there is always a need to improve directional specific properties by using materials that are stronger yet lighter. The introduction of nanoparticles into resins might offer potential in this direction.

The President's call for increased exploration of the moon and Mars puts more pressure on—and reveals more opportunity for—PMCs to perform in a variety of ways to save both weight and costs. In many cases, PMCs actually may be enabling. Improved durability and lifetime prediction would aid immensely in this new national effort.

Durability and Lifetime Prediction

Durability can be defined as the degree to which a material retains its physical properties while subjected to stress, such as heavy use, or adverse environmental conditions. Durability is definied in MIL-HNDBK-17 as a prediction of the time it takes for flaws to begin to initiate in nominal structure. To say a material is durable suggests that it has high initial strength, and that it will last a long time under normal conditions of use. The evolution of microstructure and macrostructure during actual use conditions, however extreme, is the real measure of what is generally called durability.

In practical terms, durability is primarily an economic issue affecting the inspection intervals, repair costs, and service life of a structure. Durability depends on the damage tolerance of a material. This is defined in MIL-HNDBK-17 as primarily a flight safety consideration. Damage tolerance ensures the structure can continue to carry the agreed-upon regulation loads despite any damage or degradation from sources such as growing fatigue damage (already initiated), impacts, or in-service discrete damage events (e.g., engine bursts).

To predict the lifetime of a component, it is necessary to define the properties at the beginning of life, and also to realize that these properties will begin to change almost as soon as the part is put in service, with some changes occurring as soon as the part is fabricated if it is exposed to air or moisture. How these microstructural changes affect macrostructural properties is important, as is the degree to which macrostructural changes can be tolerated and useful structural and other properties maintained.

Many factors play a role in selecting materials for applications with specific durability requirements. Consideration must be given to such factors as the extent of the existing database, coolant compatibility, expected time in service, and resistance to microcracking. All these factors vary with the environment. It is important to note that most experiments to establish a material's properties are usually done under ambient conditions. The variety of nonambient conditions tend to make testing in the many possible combinations unreasonably expensive. For this reason, experimental approaches are not viewed as a good way to establish reliability in every possible combination of conditions. Instead, sophisticated modeling approaches, verified and validated through the judicious use of a small amount of intelligently designed data collection, are more likely to succeed.

While adequate numbers of composite materials are available today, there is always a need to design better directionally specific properties in to the material. A stronger, lighter, more durable composite is always wanted. New types of reinforcements with effects on the nanoscale, new methods of processing, and new chemistries and structures are all promising ways to improve properties.

Why PMCs Are Critical

PMCs are desirable primarily because they provide lightweight and high-strength materials solutions. (See, for example, Figure 1-1, which compares the specific strength-specific stiffness of polymer composites and monolithic metallic materials.) Potentially more important than specific strength,

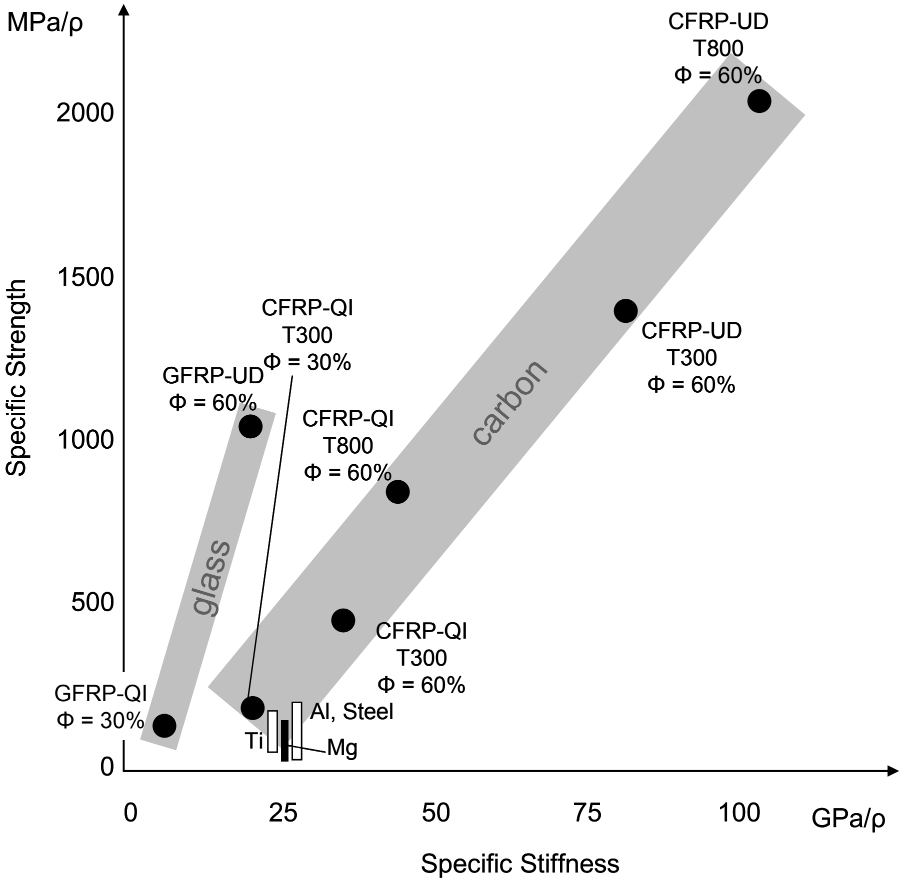

FIGURE 1-1 Specific stiffness and strength of a variety of PMCs in comparison to some metallic materials: Φ is the fiber volume fraction, ρ is density, CFRP is carbon-fiber-reinforced polymer, GFRP is glass-fiber-reinforced polymer, UD is unidirectional, and QI denotes quasi-isotropic. SOURCE: *The Research Requirements of the Transport Sectors to Facilitate an Increased Usage of Composite Materials. Part I: The Composite Material Research Requirements of the Aerospace Industry*. Report prepared by EADS Deutschland GmbH, Corporate Research Centre, June 2004.

however, is multifunctionality. A multifunctional structural material may be self-interrogating[5,6,7] or self-healing,[8,9] or it may provide stealth or protect against enemy fire. Multifunctional materials might combine sensing, moving, analyzing, communicating, and acting, in addition to providing structure. Flexibility in processing composite materials will be needed to enable these advances.

DOD programs such as the Composite Affordability Initiative (CAI) and Advanced Insertion of Materials-Composites (AIM-C) have helped to reduce the implementation cost of PMCs while increasing confidence in the use of these materials. This trend can be seen in the amount of PMCs used in fighter

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[5] Q. Zhao and H.D. Wagner. 2003. Two-dimensional strain mapping in model fiber-polymer composites using nanotube Raman sensing. *Composites Part A-Applied Science and Manufacturing* 34(11):1219-1225.

[6] K. Schulte. 2002. Sensing with carbon fibres in polymer composites. *Materials Science Research International* 8(2):43-52.

[7] P. Sittner and R. Stalmans. 2000. Developing hybrid polymer composites with embedded shape-memory alloy wires. *JOM* 52(10):15-20.

[8] S.R. White, N.R. Sottos, P.H. Geubelle, J.S. Moore, M.R. Kessler, S.R. Sriram, E.N. Brown, and S. Viswanathan. 2001. Autonomic healing of polymer composites. *Nature* 409:794-796; Correction: 2002. *Nature* 415:817.

[9] E.N. Brown, S.R. White, and N.R. Sottos. 2004. Microcapsule induced toughening in a self-healing polymer composite. *Journal of Materials Science* 39(5):1703-1710.

aircraft over the past 30 years. In the 1970s, for example, fighter aircraft such as the F-14, F-15, and F-111 had about 2 to 4 percent by weight carbon-epoxy composites. In the 1990s, this usage grew to 15 to 30 percent by weight for the A-6, AV-8, F/A-18, and F/A-22. Similar trends are shown in Figure 1-2 for commercial aircraft. Typical PMC applications in both commercial and military aircraft have been horizontal and vertical stabilizers, small fuselage sections, and some wing skins (see Figure 1-3).

Currently this usage is approaching 70 percent on the Eurofighter and other advanced aircraft, with entire airframes and support structures being constructed of PMCs. Commercial aircraft currently under development such as the Airbus A380 and the Boeing 787 are projecting extensive usage of PMCs throughout the aircraft (see Figure 1-4). Similar trends can be seen in rotor aircraft. Whereas PMCs were used for rotor blades and side conformal fuel tanks in the 1970s and 1980s, they now make up the whole airframe of the V-22. Successful application of these materials has increased the structural capability of aircraft and reduced weight, resulting in better performance. As applications and materials mature, they continue to be considered for even more extreme applications.

The combination of light weight and stiffness makes PMCs attractive candidates for structural components in both military and civilian applications. In aerospace, where thin structures and complex shapes are needed to save weight, the ability to create a unitized structure with integral stiffeners and skin significantly reduces the number of parts and fasteners. While PMCs tend to be more costly to fabricate because of a large amount of hand labor, innovations in automated tape lay-up machines, such as improved heads and expanded databases, and the application of these machines on primary structures are helping to reduce this cost. PMCs are becoming competitive with metallic structures in part due to unitized structures, which are more easily produced from PMCs.

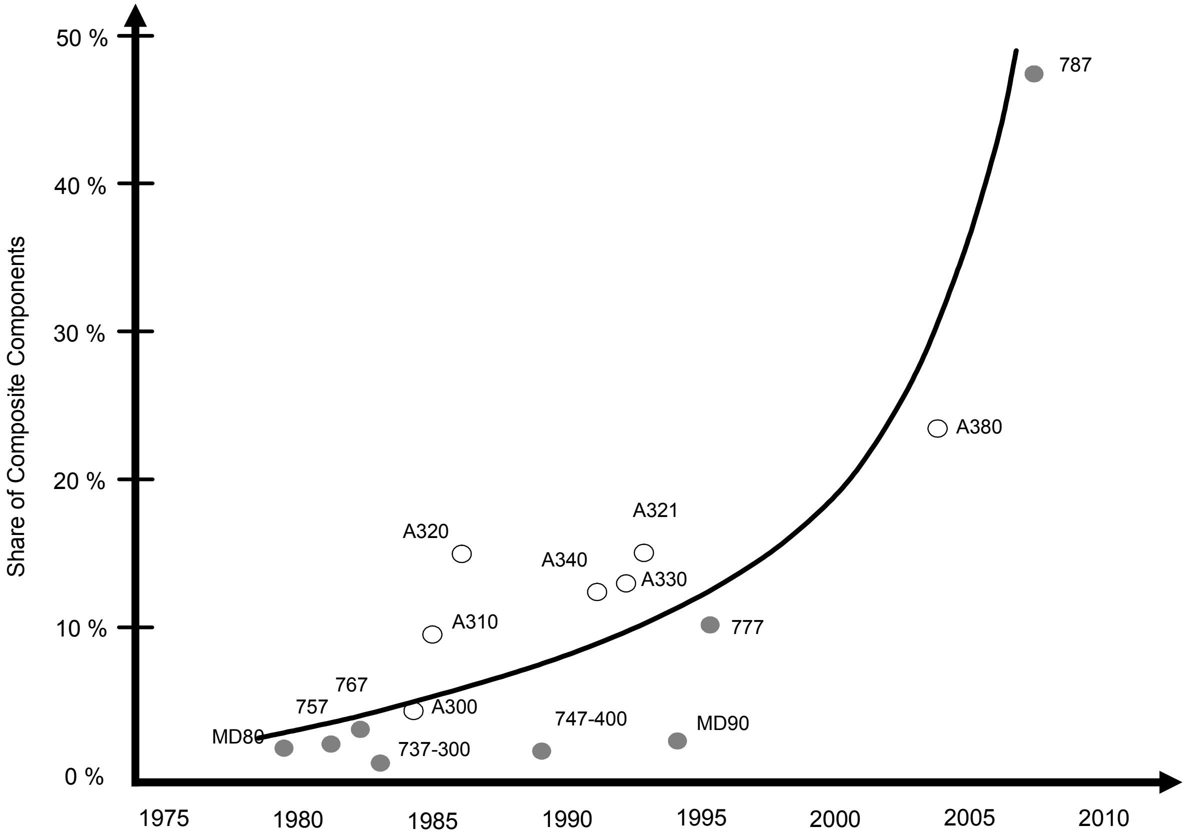

FIGURE 1-2 Percentage of composite components in commercial aircraft. SOURCE: *The Research Requirements of the Transport Sectors to Facilitate an Increased Usage of Composite Materials. Part I: The Composite Material Research Requirements of the Aerospace Industry.* Report prepared by EADS Deutschland GmbH, Corporate Research Centre, June 2004.

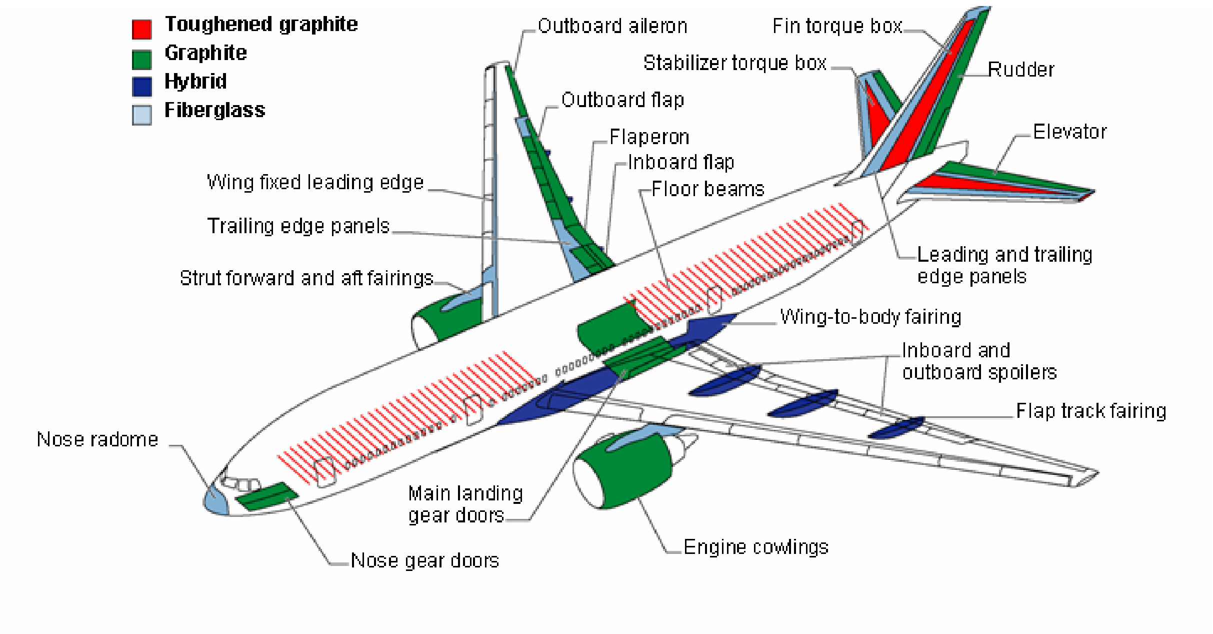

FIGURE 1-3 Production primary and secondary structure for the Boeing 777, an example of 1990s commercial application of composites.

An example of this can be seen in the redesign of the C-17 horizontal stabilizer. This critical component of the tail is approximately 7 feet wide and 35 feet long and was historically constructed of aluminum. Redesigning this component to use PMCs resulted in a 20 percent savings in weight, a 69 percent reduction in tooling, and an 81 percent reduction in the number of fasteners, for a net cost saving of 48 percent over the aluminum component. Fewer fasteners has the added benefit of reducing sources of corrosion as this is the area where corrosion most frequently occurs. In a similar vein, the original configuration of the F/A-18 fuselage used riveted aluminum, incorporating more than 30,000 rivets and fasteners. Redesign using PMCs and cast aluminum reduced the total to almost 15,000, leading to a 53 percent savings in both weight and in labor hours.[10]

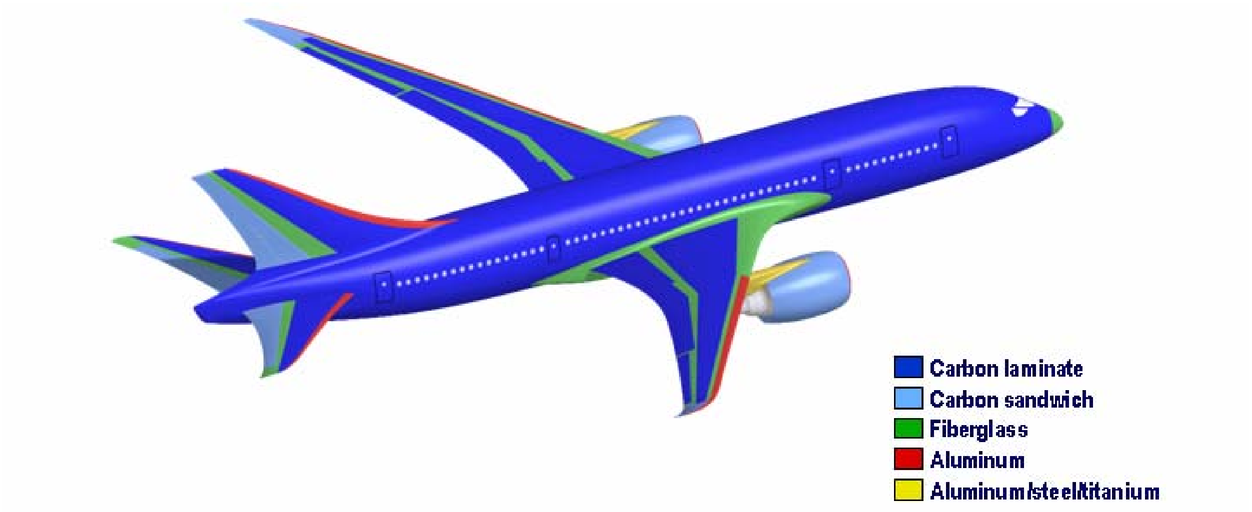

FIGURE 1-4 Projections for composite use in the Boeing 787.

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[10] G. Miller and K. Keenoy. 2001. F/A-18E/F ECP6038 forward fuselage: An affordability driven design. Presentation to the Society of Allied Weight Engineers, May 23, Arlington, Tex.

Currently most applications for PMCs are for low to moderate temperatures (−65 to 300°F). They are typically not used in high-temperature (>350°F) applications because of high resin costs and the poor knowledge base for high-temperature resins. It is believed, for example, that in some resin systems, entrapped water turns to steam and can result in debonding. However, if the temperature capability of these materials could be increased at a reasonable cost, the application window would be significantly larger (an example is shown in Figure 1-5). Advanced materials have given designers some but not yet all the solutions they need.

Examples of applications where PMCs could be used more are control flaps and structure in airplanes that receive heating from engine exhaust wash. These are currently made of titanium. These components are subjected to temperatures from 800ºF to 1000°F, possibly for several minutes and multiple times during landing or maneuvering. Because they are control flaps, they must bear aerodynamic loads similar to the wing. Research programs in progress are investigating the feasibility of making these structures out of oxide ceramics; however, a low-cost PMC with a protective coating could be an attractive alternative.

Engine nacelles of transport aircraft are typically made of aluminum with thick insulation blankets to keep the aluminum structure from overheating. With the development of more efficient, higher-thrust engines, the operating temperature of these nacelles is increasing. This results in increased insulation and structure and, therefore, increased structural weight of the entire system. An alternative would be to make them from titanium, but this leads to an increased weight penalty, and increased weight reduces both range and payload, resulting in diminished capability. The use of PMCs with temperature capabilities in the 350°F to 800°F range offers potentially lower fabrication cost and lighter-weight structures. Key design requirements include impact resistance, acoustic and vibration loads, and chemical compatibility with lubricants.

In vehicles with speeds of Mach 3 or higher, airframes and engine ducts are typically constructed of titanium or superalloys to withstand exposure to the aerodynamic heating of components and the engine heat. These components operate at between 350°F and 1000°F. The aeroshell, which includes the leading edges and control flaps, must also be capable of all-weather operation and must withstand erosion from rain, hail, and airborne particles. Engine ducts must also be resistant to erosion by the

FIGURE 1-5 The aft strut fairing heat shield on the Boeing 777. This is currently designed using a titanium alloy and might be replaceable by a higher-temperature-capable PMC.

exhaust gases. Typical properties needed in these applications are strength, thermal shock resistance, and fatigue resistance. If a PMC is developed, along with a property database for it, significant weight and cost savings could be realized by replacing a cast/welded titanium structure with PMC.

COMPLEXITIES

The structure-property relationships in composite materials are usually complex, owing largely to the presence of two or more phases having widely differing physical properties and/or structural features. Thus, the typical composite can be characterized as inhomogeneous and anisotropic. The astute reader will know of many other materials that can also be characterized as inhomogeneous and anisotropic at some length scale; for example, polycrystalline metals by virtue of their grain size and orientation.

The difference between typical structural PMCs and polycrystalline metal components such as steel I beams or superalloy turbine blades lies in the degree of anisotropy and degree of heterogeneity. In a typical composite material intended for structural applications, the heterogeneity between a polymeric matrix and a reinforcing fiber is enormous, with the ratio of Young's modulus of the two phases nearing 1,000 to 1 (with the fiber being the larger). Similarly, the ratio of coefficients of thermal expansion of the two phases is typically 100 to 1 (with the matrix being the larger). These disparities mean the composite material is a complex structure that will display large anisotropic effects at the microstructural level—that is, at length scales comparable to the fiber diameter. Further, the extreme differences in properties of the two phases make the interfacial bonding between the phases enormously important.

Similar phenomena are known to exist in metals. A single crystal metallic component can never be completely isotropic; a completely isotropic material would have two elastic constants, a simple cubic lattice has three, a more complex orthorhombic crystal has nine, and so on. However, although a single crystal is clearly anisotropic, a randomly oriented array of crystals can be isotropic—for example, the steel I beam.

Within a steel I beam, there are local anisotropic and heterogeneous phenomena, including, for example, the effects of grain boundary orientation mismatch and dislocation pileup at grain boundaries. This leads to the well-known effect of grain size on yield stress, as embodied in the Hall-Petch equation. However, even this 50-year-old established relationship is the subject of active research to determine the responsible mechanisms; recent results on yield stresses in nanoscale grain size materials show strong deviations from Hall-Petch predictions.

The anisotropy produced by grain boundary orientation mismatch is at best limited to the anisotropy within a single grain. Thus, in a polycrystalline metal composed of hexagonal, close-packed crystals, the ratio of moduli in different directions is likely to be far less than 10 to 1, and the ratio of thermal expansion coefficients is likely to be less than 2 to 1. While the anisotropy ratios for a composite can be 100 or 1,000 to 1, a polycrystalline array will not have anisotropy ratios exceeding the anisotropy ratios for a single crystal. Thus, while composite materials and polycrystalline metals share many phenomenological features, their effects on properties are vastly different.

In PMCs, property prediction is further complicated by the added levels of structure that may be present. For example, a multi-ply laminate is more complex than a single-ply one. The length scales over which structure and properties must be averaged to obtain global (or continuum) behavior is truly daunting. These lengths can range from the diameter of a fiber or smaller to the thickness of a laminate or larger. The heterogeneity at each of these levels is needed to obtain a true picture of heterogeneity within the sample. The increased complexity of a composite vs. a monolithic material may stem from such factors as the distribution of resin-rich (fiber-poor) regions within a single ply and the variation from ply to ply and near a ply-to-ply interface. Consider the number of different ways a 0/90 interface might pack compared with a 0/30 interface or stitched and three-dimensional fiber architectures.

Again, the degree of anisotropy and property heterogeneity in a PMC is enormous and vastly exceeds the corresponding degree in a polycrystalline metal. This imposes a much bigger burden on the interface between the fiber and matrix phases in a composite than on the grain boundary in a metal. However, it is important to point out that the heterogeneity and anisotropy are intentional and designed into PMCs. The nonuniformity allows the properties to be tailored to function, facilitates the advantage of light weight (stiffness in use that is needed in specific directions only), and can lead to increased fatigue resistance.

Recognizing the importance of collaboration between engineering disciplines is crucial to improving our understanding of PMCs and extending their use range. Just as in polycrystalline metals, materials science without mechanics or mechanics without materials science is likely to lead to false conclusions, invalid models, and the ultimate failure of long-term predictions of lifetime or degradation in any extreme environment.

Considering the past 50 years of research by the multitude of materials scientists, solid state physicists, and mechanical and materials engineers on the structure-property relationships and processing-properties relationships for metals, and the remaining unknown issues within the engineering metals field (fatigue crack initiation or stress-corrosion cracking are good examples), it is no surprise that interdisciplinary work remains to be done on composite materials. To amass the knowledge necessary to push the envelope for use of PMCs in extreme environments, many fundamental studies are required in an array of disciplines (remember that the solid state physics and mechanics communities supplied much of the dislocation theory for the metallurgists). This need is not only a challenge but also an opportunity.

However, the problems are more difficult in PMCs for the reasons cited. In addition, the disciplines required are even broader. They include organic polymer chemistry, polymer physical chemistry, materials science, solid-state physics, and materials and mechanical (includes mechanics and manufacturing) engineering. It is highly unlikely that any individual in a single discipline can address all of the relevant topics with any depth of understanding. Thus a key challenge is to develop a truly multidisciplinary approach to the understanding of composite performance in different environments.

It is essential that the causes of environmental interactions be identified rather than just the symptoms. For example, microcracking of the matrix may be a symptom of a hostile environment, but absorption of water followed by a particular thermal history may be the root cause of the cracking. Is the moisture absorption caused by the wrong choice of a matrix or by improper postcuring of the matrix? Is the interface being degraded by the environment, leading to a loss of interfacial bond strength and the subsequent wicking of the moisture along the fibers? These well-known examples illustrate the need to understand the chemical-physical root mechanisms before undertaking any sustained effort to model and then predict long-term performance. The challenges are enormous and will require a sustained and interactive effort by many members from many disciplines within the technical community.

2

Composite Properties and Behavior

Because composites behave differently than monolithic materials, understanding their properties and behavior in extremes of temperature, stress, and other environmental factors is a great challenge for the engineers who specify their use.

UNDERSTANDING DEGRADATION

Environmental degradation in polymer matrix composites manifests itself in many ways. A multiplicity of mechanisms can degrade performance; degradation can range from a minor loss of stiffness to a worst case of catastrophic and unexpected failure. Changes in a material during service are commonly deemed indicators of degradation. In laminated PMCs, these phenomena can include microcracking, local crazing of polymers in the vicinity of cracks, and localized fiber failures.

It is useful in this discussion to differentiate among damage mechanisms, such as oxidation, time of service, moisture absorption; failure modes, such as fiber delamination or matrix cracking; and stress factors, such as load, temperature, and chemical species available at the surface. A stress factor may or may not precipitate the tensile, shear, or compressive failures of laminates, and the impact of a stress factor depends on loading and environmental conditions. Thus, not all of these obvious damage mechanisms may represent degradation in the sense that they limit performance.

For example, microcracking in laminates is nearly unavoidable, because it is the result of processing at the high temperatures required for polymers and differences in thermal conductivities of the carbon fibers and the polymer matrices. Yet, microcracks at a low density are not necessarily performance-limiting, and their effects are dependent on the application and the evolution of damage. The means for simulating and testing the changes in properties wrought by such mechanisms has been restricted to mechanical tests, which can be relatively insensitive to some types of degradation. For example, environmental effects can manifest in ways other than mechanical performance and may not always be negative. Examples may include surface evolution due to oxidation or moisture, shifts in the glass transition temperature due to elevated temperature or moisture, or cross-linking or chain scission in the polymer due to elevated temperature. In plain terms, the microstructure may evolve in a number of ways before evidencing measurable degradation.

Matrix cracking resulting from a combination of temperature, stress, and/or humidity levels and histories is a good example because it can lead to a reduction in individual ply properties as well as in the laminate properties. However, as is well known in industry, a composite part that has been in service for considerable time invariably contains matrix cracks, but these cracks may contribute little to the measured degradation of the part. Thus, the real challenge is to define and quantify the evolution of the microstructure by measuring the number, distribution, size, origin (interface or matrix), and severity of the cracking that is critical to the performance of the composite structure.

Matrix cracking is also a major challenge for computational mechanics and modeling. Identification and quantification of the environmental factors leading to matrix (and/or interfacial) cracking and the subsequent development and implementation of chemical modifications to reduce this cracking may or may not assist the computational effort, but clearly the computational effort would provide benchmarks for the properties required of new materials. It may also help to answer the question, How much cracking is acceptable?

Thus it is important to distinguish between changes in material structures that limit performance and changes that do not. At relatively low humidity and static loads, microcracks may not be a significant design factor to prevent failure. At higher humidity and cyclic or dynamic loads, however, the effect of microcracks is greatly magnified, and microcracking emerges as a more significant failure mechanism. As the importance of individual failure mechanisms in failure changes, so does their relative importance. The reasonable subset of mechanisms to consider simultaneously also changes for extreme conditions (see Box 2-1).

While it may be interesting to ascertain a number of changes in materials from the nanoscale upward, it is more important to ascertain the mechanisms of failure. The goal is to design PMCs that perform satisfactorily at extreme conditions. However, there are knowledge gaps even for nonextreme conditions at this relatively early stage in the use of composite materials. These gaps widen for extreme conditions.

The difficulties in modeling performance and designing to take into account degraded properties are largely due to the issues noted previously—namely, extreme levels of anisotropy, heterogeneity of properties, high homologous temperature behavior of the polymer matrix, and stress transfer factors associated with fiber-matrix interfacial behavior. Additionally, the hierarchical structural levels prevalent in

BOX 2-1
Coupling of Mechanisms

The slow crack growth phenomenon that plagued the gas pipeline industry about 15 years ago exemplifies the need to understand the interactions between mechanisms. Relatively standard linear elastic fracture mechanics and nonlinear and viscoelastic adaptations that are widely used in the plastics industry were used to devise various tests for fracture toughness for polyethylene polymers to be used in the fabrication of relatively large diameter (e.g., 36 inches) natural gas distribution pipelines. In service, these pipes exhibited slow crack growth, that is, the growth of very long (many inches) cracks over periods of several years.

Based on laboratory measurements, the material appeared to have sufficient fracture toughness to preclude the growth of such cracks, even when the pipe was improperly installed in the ground, e.g., by running it over a large rock with a protrusion rather than over a bed of finely crushed gravel.

Engineers wondered why the cracks were forming and continuing to propagate for years. Were the fracture toughness tests improperly conducted? Were the theoretical foundations of fracture mechanics unable to predict or account for slow crack growth phenomena in polymers? Was there an alternative fracture toughness test that would explain the slow crack growth data? Was the polyethylene material contaminated? Was the pipe improperly fabricated—that is, did it contain excessive residual stresses due to polymer orientation or "skin" effects?

Or did the designers neglect the environmental cracking potential of trace sulfur compounds in natural gas, as was actually the case? In the presence of a small stress concentration, such as a small starter crack, and an applied stress, the trace environmental agent was sufficient to transform a relatively benign crack in an ostensibly tough material into a potentially lethal crack growing at impressively low stress levels and very slow rates! In the absence of a protocol for material degradation at a crack tip resulting from an active chemical species in the presence of an applied far-field stress state, the fracture-mechanics-based testing procedures were useless in predicting performance and gave artificially and erroneously reassuring toughness parameters for the material.

It is noteworthy that solvent stress cracking and crazing in polymers is still a subject of active investigation. Polymer matrix composites cannot realistically be expected to be more amenable than the neat polymers themselves to modeling that predicts performance and degradation. Higher performance materials require higher and more insightful levels of understanding because higher performance generally implies a higher potential for loss of that performance.

many high-performance PMCs make the simultaneous allowance for degradation at each structural level and the assignment of relative importance to each possible failure mode a daunting task. This is a challenge to multiscale modeling from a computational standpoint and is compounded when mechanistic or physical factors are considered.

Investigation of the traditional methods of monitoring structural health, both in the laboratory and in applications, may also lead to new understanding. Updated experimental methods may also be needed to understand the underlying methods of degradation.

In any new framework, well-studied failure mechanisms—such as microcracking, fracture, delamination, statistical fiber failure, creep, and fatigue—must be restudied to determine their relative importance at high temperature and high humidity, for both static and cyclic loads. In addition, data supporting an understanding of the combined effect of key failure mechanisms, or at least of an important subset of such mechanisms, are critically needed to validate these investigations.

CURRENT MODELING METHODOLOGY

Work in composite damage is voluminous and is anchored in several different academic disciplines, largely based on mechanism of interest (see Appendix D).

More than 6,000 papers concerned with composite damage have been published in scientific and engineering journals since 1955; the vast majority focus on single mechanisms, conditions, or applications (see Table 2-1). And, although literally hundreds of models of composite damage have been developed over the last six decades, only a few have been fully implemented in commercial FEA codes. To date, none apparently incorporates a materials processing history (Appendix E).

The propensity to focus on specific failure mechanisms can be attributed to three factors: (1) the scholarly imperative to focus on single mechanisms to produce broadly applicable, archival results that can be more readily validated even in a small set of conditions; (2) the paucity and inaccessibility of data on materials that have failed in real applications (such data might be able to verify one or more simultaneous failure mechanisms); and (3) the confounding effects of multiple failure mechanisms within a system, which make results even more application-dependent and specific, and also likelier to be subject to proprietary protection by the institution or company that generated them.

Indeed, truly sufficient scrutiny of failure mechanisms carries three independent burdens: (1) the cost of generating a wide range of diagnostics on materials before, during, and after processing and through the service life and of spanning optical, mechanical, and chemical assays; (2) the potential cost of legal liability for findings of failure mechanisms not uncovered or even postulated prior to construction of the failed components or during their initial testing and use; and (3) the protection of sensitive or proprietary information, either for national security or for competitive advantage.

When the damage product is obvious, as it is in matrix cracking, it is possible to define protocols and perform calculations to ascertain the degree to which various cracks can form and grow while still maintaining structural integrity. When the damage product is the degradation and weakening of material in the immediate vicinity of a crack tip and in the presence of an applied load, the protocols have yet to be established and the calculations are at best crude. The tendency for cracks to form is further affected by changes to such matrix properties as the glass transition temperature or the surface energy that may be attributed to environmental conditions. Much remains to be done before high-performance PMCs can be certified by appropriate models and computations for long-term applications under extreme environmental conditions.

An understanding of mechanisms, as well as of chemical kinetics and other phenomena, is a

TABLE 2-1 Papers Published in Selected Composite Areas, 1955-2004

Number of Papers	Search Keywords
6,940	composite* and damage
2,035	composite* and (temperature or therm*) and damage
466	composite* and micromechanic* and damage

NOTE: Asterisks indicate wild card characters used in Boolean searches.
SOURCE: Science Citation Index, at <http://www.isiknowledge.com>. Accessed February 2005.

critical missing link. These mechanisms allow making a connection between material evolution and environmental factors. Because extreme environments introduce additional mechanisms, it is key to understand which features or necessary elements of fundamental degradation (or evolution mechanisms) we need to capture in modeling, as well as how to model them.

One of the most important considerations is that PMCs are a structure rather than a monolithic material. This means that the microstructural evolution must be understood, from design, to processing, to installation, and throughout (but not limited to) the PMC component's service life.

STATE OF MODELING

The models typically used to address material degradation and failure can be broadly classified. While it is not possible here to thoroughly review these models, some of the most common types of models for the alteration, response, and failure of materials include the following:

- *Phenomenological models* may be the largest group of models. They correlate operating conditions with tabulated life data. Such data may be cycles to failure, time to failure, or stiffness change to failure. Because the models fit data to empirical observations and have no rigorous physical basis, their results cannot be extrapolated to other materials or other conditions. Phenomenological failure criteria are sometimes used to provide metrics for such correlations—for instance, energy or yield[1] functions with characteristic material parameters that may depend on time-dependent (or cycle-dependent) characterizations.[2-5] Fatigue modeling, for example, generally relies on this approach.[6] Strain-based estimation methods[7] and stiffness change methods[8,9] are also common. Time-temperature and aging time superposition methods are also used.[10,11] A few models are supported by analysis that attempts to account specifically for energy dissipation.[12-15] Models employing tensorial strength parameters[16] may be thought of

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[1] R.M. Guedes. 2004. An energy criterion to predict delayed failure of multi-directional polymer matrix composites based on a non-linear viscoelastic model. *Composites Part A—Applied Science and Manufacturing* 35(5):559-571.

[2] H.F. Brinson. 1999. Matrix dominated time dependent failure predictions in polymer matrix composites. *Composite Structures* 47(1-4):445-456.

[3] Y.T. Yeow. 1978. *The Time-Temperature Behavior of Graphite/Epoxy Laminates*. Ph.D. thesis, Virginia Polytechnical Institute.

[4] Y.T. Yeow, D.H. Morris, and H.F. Brinson. 1979. The time-temperature behavior of a unidirectional graphite/epoxy laminate. *Composite Materials: Testing and Design (5th Conference)*, STP 674, Philadelphia, Pa., pp. 263-281.

[5] M. Reiner and K. Weissenberg. 1939. A thermodynamic theory of the strength of materials. *Rheology Leaflet* 10:12-20.

[6] R. Talreja. 2000. Fatigue of polymer matrix composites. *Comprehensive Composite Materials*, C. Zweben and A. Kelly, eds. New York, N.Y.: Elsevier.

[7] J. Petermann and K. Schulte. 2002. Strain based service time estimation for angle-ply laminates. *Composites Science and Technology* 62(7-8):1043-1050.

[8] A.W. Wharmby and F. Ellyin. 2002. Damage growth in constrained angle-ply laminates under cyclic loading. *Composites Science and Technology* 62(9):1239-1247.

[9] R. Talreja. 1985. *Fatigue of Composite Materials*. Technical University of Denmark, Lyngby.

[10] Y. Miyano, M. Nakada, and N. Sekine. 2004. Accelerated testing for long-term durability of GFRP laminates for marine use. *Composites Part B—Engineering* 35(6-8):497-502.

[11] R.D. Bradshaw and L.C. Brinson. 1997. Physical aging in composites: An analysis and method for time-aging time superposition. *Polymer Engineering and Science* 37:31-44.

[12] C. Hiel. 1983. *The Non-linear Viscoelastic Response of Resin Matrix Composites.* Ph.D. thesis, University of Brussels.

[13] C. Hiel, A.H. Cardon, and H.F. Brinson. 1983. The non-linear viscoelastic response of resin matrix composites. *Composite Structures*, I.H. Marshall, ed. London and New York: Applied Science, pp. 271-281.

[14] O.S. Bruller. 1973. The energy balance of a viscoelastic material. *International Journal of Polymer Materials* 2:137-148.

[15] O.S. Bruller. 1981. Energy-related failure criteria of thermoplastics. *Polymer Engineering and Science* 21(3):145-150.

[16] S.W. Tsai and E.M. Wu. 1971. General theory of strength for anisotropic materials. *Journal of Composite Materials* 5:58-80.

as phenomenological models; though their generic tensorial forms are based on strength-of-materials considerations, the fitted variables are generally load-specific.

- *Statistical models* interpret data sets to establish probabilities of failure at various applied conditions, significance of data samples and predictions, confidence intervals, design allowables, or reliability estimates. Because this approach requires large data sets for the exact event, material, and conditions, it is not predictive. It is also very expensive and slow and can only generate relevant results after the fact. Essentially every prime contractor designs on the basis of allowables that are set from statistical analysis of data. The analysis methods are well established, typically based on Weibull statistics and incorporating a mechanistic model for damage coalescence,[17] and effective in the presence of a robust and relevant data set.
- *Mechanical models* attempt to represent durability as a mechanical process—that is, in terms of balance of forces, mass, momentum, energy; transport; and constitutive equations. Macroexamples are structural analysis methods such as fracture mechanics, strain energy release methods, and some energy dissipation schemes.[18-20] These include composite-specific models, such as those for statistical fiber breakage,[21] matrix microcracking,[22] or interfacial failure.[23] Indeed, some of these phenomena are often relatable to more complex loading conditions, including fatigue.[24] Microexamples include dislocation or slip models (and diffusion models in some cases) that represent discrete defects at the microlevel.[25,26]
- *Thermodynamic models* are representations of life in terms of thermodynamic state variables (sometimes called internal state variables and often called damage parameters) that are associated with homogenized, continuum representations of physical degradation. The process is usually called damage mechanics. These methods have the advantage of addressing material state changes as dissipative thermodynamic processes and the disadvantage of being based on homogenized representations of the physics and mechanics that do not retain specific properties of mechanisms of damage or failure. Strength-based versions of the method bridge the gap between mechanics and materials, and some versions have been modified to include micromechanics of discrete behavior of heterogeneous phases in composites.[27-30]
- *Classical strength of materials models* employ traditional, yield-based failure criteria, e.g., Tresca or von Mises limits,[31] on composite laminates, using different yield criteria for matrix- or

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[17] A.M. Sastry and S.L. Phoenix. 1994. Shielding and magnification of loads in elastic, unidirectional composites. *SAMPE Journal* 30(4):61-67.

[18] J.L. Rebiere and D. Gamby. 2004. A criterion for modelling initiation and propagation of matrix cracking and delamination in cross-ply laminates. *Composites Science and Technology* 64(13-14):2239-2250.

[19] O. Attia, A.J. Kinloch, and F.L. Matthews. 2001. Modelling the fatigue life of polymer-matrix fibre-composite components. *Composites Science and Technology* 61(15):2273-2283.

[20] C. Bathias. 1991. Fracture and fatigue of high-performance composite-materials-mechanisms and prediction. *Engineering Fracture Mechanics* 40(4-5):757-783.

[21] C. Zweben. 1994. Is there a size effect in composites? *Composites* 25(6):451-454.

[22] J.A. Nairn and S. Hu. 1994. *Damage Mechanics of Composite Materials,* R. Talreja, ed. Amsterdam: Elsevier, pp. 187-243.

[23] L.T. Drzal, M.J. Rich, M.F. Koenig, and P.F. Lloyd. 1983. Adhesion of graphite fibers to epoxy matrices. 2. The effect of fiber finish. *Journal of Adhesion* 16(2):133-152.

[24] A.L. Highsmith and K.L. Reifsnider. 1982. Stiffness reduction mechanisms in composite material. *Damage in Composite Materials*, ASTM STP 775:103-117.

[25] K.L. Reifsnider. 1994. Modeling of the interphase in polymer-matrix composite-material systems. *Composites* 25(7):461-469.

[26] S. Suresh. 1991. *Fatigue of Materials.* Cambridge, U.K.: Cambridge University Press.

[27] S.R. Patel and S.W. Case. 2000. Durability of a graphite/epoxy woven composite under combined hygrothermal conditions. *International Journal of Fatigue* 22(9):809-820.

[28] K.L. Reifsnider and S.W. Case. 2002. *Damage Tolerance and Durability of Material Systems.* New York, N.Y.: Wiley Interscience.

[29] N. Himmel. 2002. Fatigue life prediction of laminated polymer matrix composites. *International Journal of Fatigue* 24(2-4):349-360.

[30] R. Talreja. 1990. Internal variable damage mechanics of composite materials. *Yielding, Damage and Failure of Anisotropic Solids*, J. P. Boehler, ed. London: Mechanical Engineering Publications, pp. 509-533.

[31] L.J. Hart-Smith. 1998. Predictions of the original and truncated maximum-strain failure models for certain fibrous composite laminates. *Composites Science and Technology* 58(7):1151-1178.

fiber-dominated behavioral directions. These approaches are a subset of phenomenological approaches and are readily able to incorporate results of micromechanical models.

- *Chemical models* represent degradation processes as rate equations. The most common is the Arrhenius equation, which is cast in various forms to describe time-dependent failure, such as in creep rupture. The well-known principle of time-temperature superposition is one manifestation of this approach and is valid when all relaxation processes exhibit the same relative change with temperature.[32] Advantages of the approach are simplicity and explicit temperature dependence. Disadvantages include the fact that the approach is generally phenomenological and empirical and does not involve physical observables at intermediate times before failure. Chemical degradation, such as oxidation, has been explicitly incorporated into some such treatments.[33]
- *Atomistic models* describe polymers at the fully detailed level of atoms and molecules. While this is currently daunting in terms of the time needed for computation, significant progress is being made with coarse-graining approaches and combining atomistic approaches into multiscale models.[34] Bridging scale methods that link, for example, molecular dynamic simulations with finite element simulations could be one way of incorporating mechanistic-level information. The rapid advances in several areas of atomistic modeling of polymers and composites will likely play a significant role in the discovery of new materials and their application.[35]
- *Environmental models* are an important additional layer of modeling that takes a material's response to the environment into account. Such a response might be the absorption and desorption of moisture or the transport of dissolved substances (such as oxygen or other chemical species) from the surface to the interior of the composite. This class of models is itself divisible into thermodynamic, chemical, and mechanical models and even "industrial" approximations (or rules of thumb). The simplest and best developed of these are the moisture absorption models. It is important to note that a material's response to the environment cannot be modeled until the interaction with the environment is understood and incorporated adequately into the model.

In spite of the success of some of these models, several barriers remain to reducing reliance on knockdown factors (see Box 2-2). Even with the success of models such as strain-invariant failure theory (SIFT),[36] which has shown ability to predict failure under simple loadings accurately,[37] knockdown factors are still used in conjunction with this theory in predicting fatigue lifetime (absent the data needed to provide validation). Also, none of these approaches are fully mechanistic: Each is built around specific representations of degradation and failure mechanisms that are discretely described in time and space.

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[32] It is important to note that any changes in the stress transfer mechanism with temperature render this relationship invalid. Thus, semicrystalline polymers almost never exhibit such validity. Conversely, amorphous rubbery polymers often do exhibit valid time-temperature superposition. Amorphous glassy polymers often appear to exhibit such validity over relatively narrow ranges of frequency or timescale, typically three to four decades. Observations over longer timescales often show divergence from these predictions. Any extrapolations of failure lifetime data made using time-temperature superposition should be viewed with extreme caution, especially for semicrystalline or amorphous glassy polymers.

[33] K.T. Gillen and M. Celina. 2000. The wear-out approach for predicting the remaining lifetime of materials. *Polymer Degradation and Stability* 71(1):15-30.

[34] W.K. Liu, E.G. Karpov, S. Zhang, and H.S. Park. 2004. An introduction to computational nanomechanics and materials. *Computational Methods in Applied Mechanical Engineering* 193:1529-1578.

[35] S.C. Glotzer and W. Paul. 2002. Molecular and mesoscale simulation of polymers. *Annual Review of Materials Research* 32:401-436.

[36] T.E. Tay, S.H.N. Tan, V.B.C. Tan, and J.H. Gosse. 2005. Damage progression by the element-failure method (EFM) and strain invariant failure theory (SIFT). *Composites Science and Technology* 65:935-944.

[37] In a hat-stiffened panel under tension and compression, for example, SIFT recently predicted failure within 10 percent of actual, representing an improvement over the 50 percent margin provided by classical solutions of a decade ago. From R.J. Meilunas. 2004. Accelerated insertion of materials–Composites program: Methodology and toolset. Presentation at the Defense Manufacturing Conference, Las Vegas, Nev.

BOX 2-2
Knockdown Factors

Knockdown factors are commonly used to estimate properties of PMCs at use conditions. Typically, a first step is testing of as-manufactured (pristine) PMCs. Next, similar PMCs are exposed to, say, elevated temperatures, thermal cycling, and/or damage (e.g., cutting a hole) and then are retested. The ratio of conditioned (or damaged) to pristine property establishes a knockdown factor, also called the knockdown. The knockdown then would be applied across the board to the property. For example, the knockdown at room temperature could be applied across the entire use range.

Different properties are typically tested for different conditions. For example, materials would be tested in a condition that attacks the matrix in compression because this is often a critical property and is highly matrix-dependent. However, there is no set method for establishing knockdowns. The application may suggest that testing for some extreme conditions is warranted. For example, if a part will see temperatures of 475ºF for 500 hours of its life, that may warrant conditioning the samples for 500 hours at 475ºF before testing.

Knockdowns are also determined for subelement or component testing. Many projects—especially military projects—have specific damage-tolerance specifications. For example, a material might have to withstand a tool weighing 10 pounds dropped from 3 feet, which is simulated by a 1-inch diameter spherical impactor. In this case, a subcomponent or component would be damaged accordingly, then tested to the limit load or other load required by the specification. Note that a limit load is the largest load a part would see in normal use. An ultimate load is typically a defined value, normally 1.5 times the limit load.

In addition, none of these approaches are robust enough to provide specific guidance to manufacturing that will result in PMCs with improved durability, nor can they provide guidance for the knowledge-based design that is the basis for the engineering used by most original equipment manufacturers today. The approaches are also not truly multiphysical[38] in that all of the related balance equations and constitutive equations are solved as coupled field equations for the specific boundary conditions and applied conditions required for the materials.

Reducing dependence on knockdown factors in lifetime estimation will not require anything so grand as development of completely interlinking and multiscale models for a large variety of materials. Indeed, the recent exercise that compared leading failure theories in laminated PMCs[39] revealed that the head-to-head comparison of models thought of as classical show wide variation in both their predicted failures and in their correlation with experimental results, when the results are plotted as points on traditional failure envelopes with axes of principal stresses or strains. Furthermore, the closing recommendations of the group that conducted the worldwide failure exercise[40] specifically point out the serious challenges remaining in extending any of these models to extreme conditions, in applying these approaches to multiaxial loads and different environments, and in coupling models.

The physics of specific failure mechanisms or interactions with the environment remain unknown. Some current testing practices have proven inadequate: For example, a thick, flat test sample may show only limited material degradation in a given environment because the interior material (in the absence of micro- or other cracking) is not exposed to the environment. A thin, curved, microcracked component will not behave like the test sample (see Box 2-3). Conversely, this effect can be beneficial—if an oxide skin forms on the surface of exposed parts, the structural response can be much better than the response of the bulk material because most of the structure does not see the environment.

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[38] Multiphysics implies interactions among a range of physical phenomena—for example, viscous, turbulent, thermal, chemical, mechanical, electromagnetic, or plasma processes.

[39] World-wide failure exercise on failure prediction in composites. 2002. *Composites Science and Technology* 62:1479.

[40] P.D. Soden, A.S. Kaddour, and M.J. Hinton. 2004. Recommendations for designers and researchers resulting from the world-wide failure exercise. *Composites Science and Technology* 64(3-4):589-604.

BOX 2-3
Cryogenic Conformal Fuel Tanks

Cryogenic fuel tanks have traditionally been egg-shaped bottles fabricated of welded titanium. However, with the cost of placing material in orbit roughly $10,000 per pound, a strong incentive has emerged to reduce vehicle weight and increase payload space on reusable space launch vehicles. One way to increase space is to reduce the envelope allocated to the fuel tanks by having them conform to the shape of the aeroshell; they are then known as conformal fuel tanks (Figure 2-3-1). In metallic systems, it is difficult to fabricate a structure with a sharp radius and compound curvature. Polymer matrix composites allow doing this, and their use in conformal composite fuel tanks offers lower weight and lower cost fabrication.

The X-33 program entailed a one-fourth scale unmanned prototype of a reusable launch vehicle. A conformal, lightweight, full-scale, honeycomb core sandwich composite tank with carbon-fiber-reinforced epoxy face sheets and a Nomex nonperforated core was fabricated, filled with liquid hydrogen, and tested at NASA's Marshall Space Flight Center under external load. The tank, which previously had been tested unloaded at temperature, passed all load conditions without leaking but failed in one quadrant (lobe) during the liquid hydrogen dump when the tank warmed to −73°C. The core debonded from the inner face sheet with its outer face sheet intact.

Post-test analysis showed the tank's inner face sheet exhibited microcracks, which allowed hydrogen gas to leak from the tank into the core cells during and after the fill cycle. The gas became trapped in each core cell and liquified. Cryopumping caused even more gas to penetrate and liquefy. As the liquid hydrogen was dumped out of the tank, the temperature and pressure in the core cells slowly rose as the liquid hydrogen in the cells gasified. When the temperature reached −73°C, cell pressure was sufficient to overcome the adhesive bond and delaminate the inner face sheet.

The microcracking resulted from the differences in coefficient of thermal expansion between the carbon fiber and the epoxy matrix. During fabrication, the epoxy matrix is cross-linked and solidified at 350°F. When cooled, the matrix cannot contract because of the presence of the carbon fibers. Consequently, stresses are built up in the matrix that cannot be relieved; thus, the matrix either cracks, exacerbated at cryogenic temperatures, or the residual strength is lowered sufficiently so that microcracking occurs under relatively mild external stress conditions. It is likely the failure could have been prevented if a predictive model was available to forewarn of the potential presence of microcracking and reveal the critical flaw geometry.

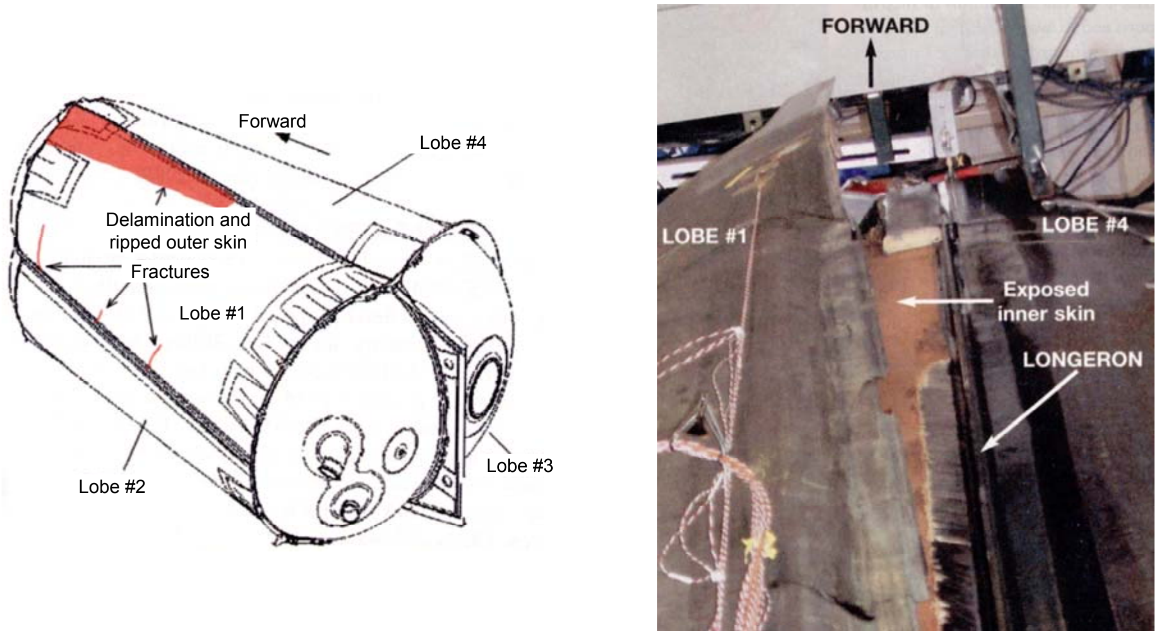

FIGURE 2-3-1 Cryogenic conformal fuel tank.

The framework for all theories currently utilized to predict failure conditions (e.g., loads, lifetimes) is phenomenological, with the attendant limitations. Thus, strain invariant failure theory is nothing more than an appropriate and proper framework in which to describe strains in three dimensions within an inhomogeneous and anisotropic material. Within this framework, it may be possible to analyze failure data obtained with a particular composite stacking sequence subjected to a particular set of stress components and then transfer that analysis in a solid-mechanics-based way to another composite stacking sequence with a different set of stresses. Thus, the SIFT method is useful for exploiting the maximum information from the failure data for any particular composite system, provided that the constituents are unchanged, the processing is unchanged, and environmental factors do not induce a new failure mechanism. SIFT is therefore not a failure theory but a failure analysis protocol.

Modularized models in validated combinations of models for specific materials systems, particularly in extreme environments, are clearly needed. There are presently two overarching barriers to developing such a suite of tools. First, there are not enough materials history and databases to independently validate such models for real materials systems. Secondly, the method of model implementation in various commercial finite element codes, analytical solutions, and proprietary codes used by industry precludes easy transition from one model or scale to another.

There are a number of specific barriers and challenges to the refinement of these theories so as to take into account the environment:

- Material properties are irretrievably linked to process history, and process history is expensive to track. The importance of process history is certainly not a new concept in materials design and use, given that we have been engineering the micro- and nanostructure of metals since the Bronze Age. However, the complexity and cost for multiphase materials are much greater, since the process histories of the components must be learned, along with the process history of the composite.
- The extrapolation of test conditions is problematic. Because conditions alter the mechanisms of failure, it is not always possible to extrapolate composite response based on a single model.
- Failure criteria are largely mechanical. Structural finite element analyses are generally employed by the end users of advanced materials to predict material response at some point in the lifetime. Mechanisms that are not linked repeatably and reliably to significant alterations in stress distributions are not readily tracked with these tools.
- So-called knockdown factors can mask the real mechanisms. Used to reduce the rated loads or other service conditions of a material based on usage, knockdown factors can be inaccurate or even misleading; more importantly, they do not result in new knowledge useful in design of improved materials.
- Models not readily implemented within a structural analysis framework will be shelved. Multivariate models that give no independent verification for each parameter are unlikely to be used widely, particularly if they are not readily implemented in a structural finite element code. Finite element analysis (FEA) is used to track not only stress distribution and evolution but also thermal and environmental history; as such, it is the gateway to analysis by end users. Simply put, if a model cannot be seamlessly incorporated into this framework, it is difficult to use.
- Models often require the sensing of alterations, which can be a tremendous challenge. Numerous environmental situations and applications exist for which the identification of damage (and its subsequent modeling) is not nearly as obvious as it is with matrix cracking, making the identification and evaluation of the relevant computational mechanics issues difficult if not impossible. In such cases, the chemical, materials, and mechanics perspectives remain inextricably linked to one another, and an interdisciplinary effort is essential for problem recognition and remediation.

Degradation mechanisms need to be understood and modeled at the mechanistic level; phenomenological models cannot extend beyond the database and cannot be used for knowledge-based (e-engineering) design and manufacturing. See Box 2-3 for a pertinent example.

Degradation, for the purposes of this report, can be defined as any process that changes the local stress/strain state or the local state of a material component. Mechanistic degradation must be based on physical measurables—that is, there must be many variables such as temperature, strain, microstructure, or other state variables that change in a measurable way as degradation alters properties such as stiffness and strength. This change in properties, in turn, determines the performance of the material element, and when that performance falls below acceptable levels, it delimits life. In certain copolymers, for example, the microstructure can change dramatically (the matrix and distributed phases can be inverted, for example) as a function of hydration and temperature, greatly altering stiffness, fracture strain and stress, creep rates, and failure times. The precise (and robust) correlation of that microstructure with the resulting full complement of properties and performance is a continuing challenge.

3

A Team Strategy

Individuals from many disciplines confront the challenge to understand the full range of factors surrounding the evolution of micro- and macrostructure of a PMC during its lifetime in extreme environments. For many years, polymer scientists used microstructural modeling and such tools as microscopy, spectroscopy, calorimetry, and sonic analysis to understand the effects of environment and stress on polymer chemistries at the microscale. At the same time, mechanists and engineers applied continuum models at the macroscale to predict the properties of polymer composite structures under test conditions and in simulations of extreme environments. More than a few intrepid souls have attempted to link these two efforts at the mesoscale. Success in this area has been less than satisfactory, but it is hoped that improved partnering among individuals with depth in areas important to this endeavor may improve the results.

A number of collaborations are needed to facilitate understanding. For example, the end users of PMCs, including the designers of components, who come primarily from industry, should interact more with researchers and developers in government and academia. A number of government programs, including DARPA's Accelerated Insertion of Materials for Composites (AIM-C) program and the Air Force MEANS program, have demonstrated the benefits of such interaction.

Other collaborations are needed at a more fundamental level. For example, the science of polymers must be brought to the mechanics community and the art of mechanics to polymer scientists. Another critical collaboration would link the validation and verification of models. Validation refers to getting the physics right, usually through comparison to test data, while verification refers to getting the math right, usually through comparison to other models. The formation of such teams could move PMC reliability forward and enable the continuing development and insertion of PMCs in critical extreme-environment applications.

Finding: Knowledge from multiple disciplines is needed to understand the evolution of a PMC's structure during its lifetime.

While the benefits of teaming are clear, there are a number of reasons why it is not done more often. The primary reason is that potential collaborators can so easily conduct individual research—that is, obtain funding and publish papers. Moreover, many have not yet recognized the need to team. However, this lack of collaboration is becoming a huge impediment to the application of many materials.

Traditionally, the use of PMCs in aircraft engine applications was a last resort. Today, PMCs are looked at as a business opportunity that provides product differentiation. These newer applications are generally more demanding and require durability in extreme environments. It is now necessary to collaborate to improve PMC reliability, because the chemical, physical, and mechanistic effects must all be considered together to describe the behavior. Polymers are as interdisciplinary as any other class of materials, and polymer composites are even more so, because they function equally as structures and materials. To the detriment of the field, the disciplines of those working in it have long been segregated.

The present paradigm (Figure 3-1) in structural durability prediction methods for PMC material systems creates a disconnect between (1) the chemists and materials researchers who develop new systems and evaluate their molecular behavior, (2) the mechanicians who develop structural durability models and evaluate materials' structural capabilities, and (3) the designers and fabricators who coordinate information, data, and models from the chemists and mechanicians as they design and fabricate components for applications in extreme environments.

- In most cases, PMC chemists and materials researchers focus their modeling efforts on material development, processing, chemical evolution, and mechanisms of damage in system constituents (fiber, matrix, interfaces, oxides, etc.) at the micro and nano levels. End-use requirements are usually only vaguely known.
- Mechanicians focus their modeling efforts on the behavior of material systems, initial material stress states from processing, damage processes/progression, and structural durability of both the constituents and the overall system on both the macro and micro levels. They have a slightly better understanding of end-use requirements.
- Using proven design methods (based on metallic components) and information from the other two groups of experts, designers and fabricators focus on component-level issues such as form, fit, and function.

Recommendation: To successfully address the complexities of predicting the performance of PMCs, organizations should assemble interdisciplinary teams with experience in chemistry, polymer physics, materials, processing, mechanics, testing, component and system design, and application of PMCs in extreme environments.

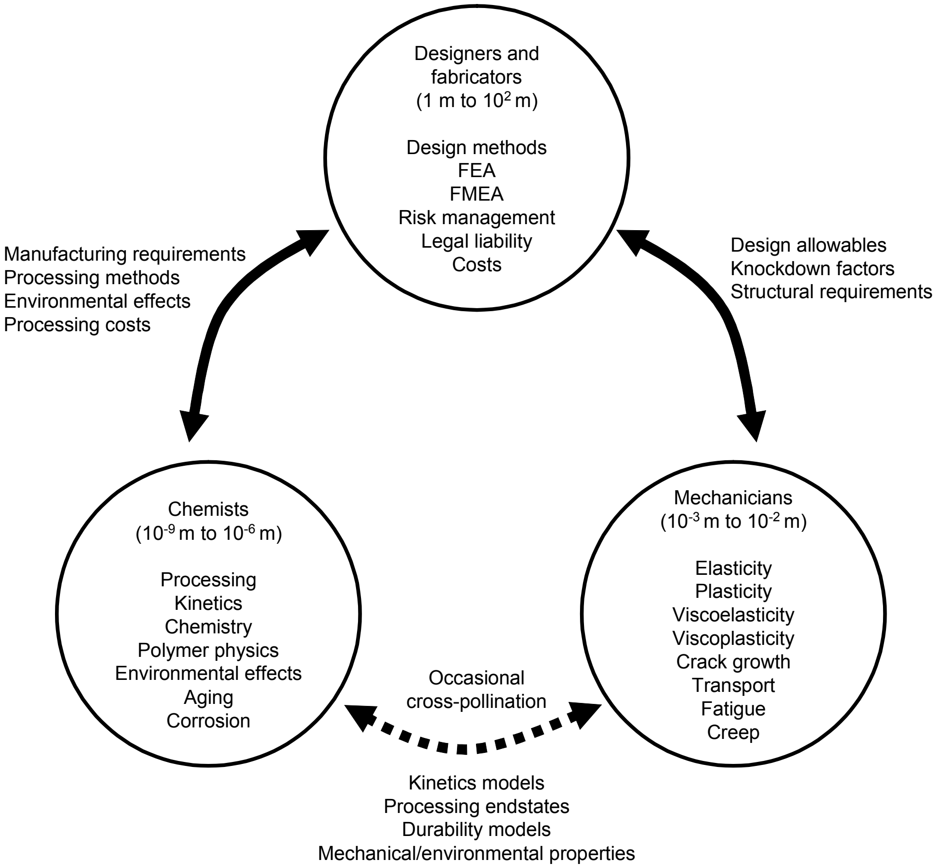

FIGURE 3-1 Teaming paradigm. The scale on which team members work is also shown.

IMPLEMENTATION STRATEGIES

One way to overcome the reluctance to form teams with members from disparate fields may be to establish more complex performance goals that need expertise in all the fields to succeed. If such goals could be established, the very proposals for meeting them would need to be drawn up by interdisciplinary teams and evaluated on the basis of common goals. A dramatic advance in structural durability prediction methods for PMC material systems will require the cross-pollination of models across different fields (Figure 3-2). This paradigm will require close communication between the collaborators, probably through workshops, meetings, the Internet, telecommunication, and other new methods of communication. At least one level of shared understanding among the disciplines is required, but two or three levels would be better.

GOALS FOR IMPROVED TEAMING

One of the most important goals of teaming is to develop a modeling approach that can replace the empirical knockdown factors currently used in PMC design. The complexity of polymers and their composites, combined with the lack of effectively integrated teams tackling common problems, leads to design decisions based on brute force knockdown factors (Figure 3-3). Because the effect of the interaction between environmental and loading conditions on the performance of the polymer matrix over very long times cannot be explicitly tested, often the only test that is run is a short aging test with one environmental parameter. During this test, changes in key properties such as strength are noted. However, while designers understand that coupled mechanisms and longer exposures modify properties further, they lack a coherent physics-based modeling strategy to make decisions. Designers ultimately resort to material parameters that have been knocked down by a factor that may be either very conservative or otherwise inaccurate.

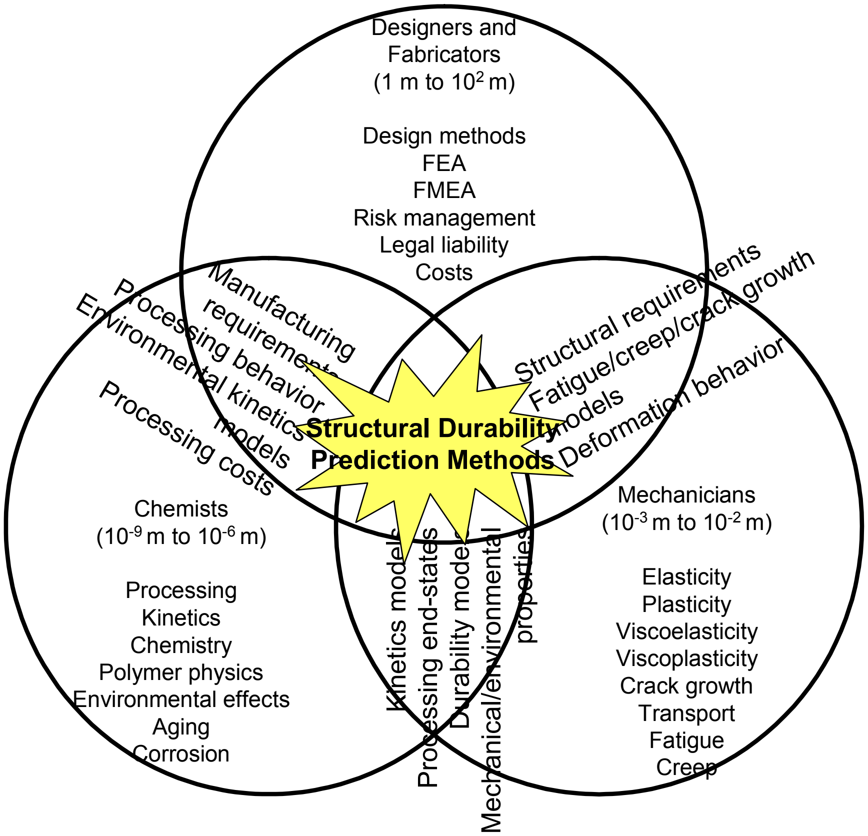

FIGURE 3-2 A new teaming paradigm.

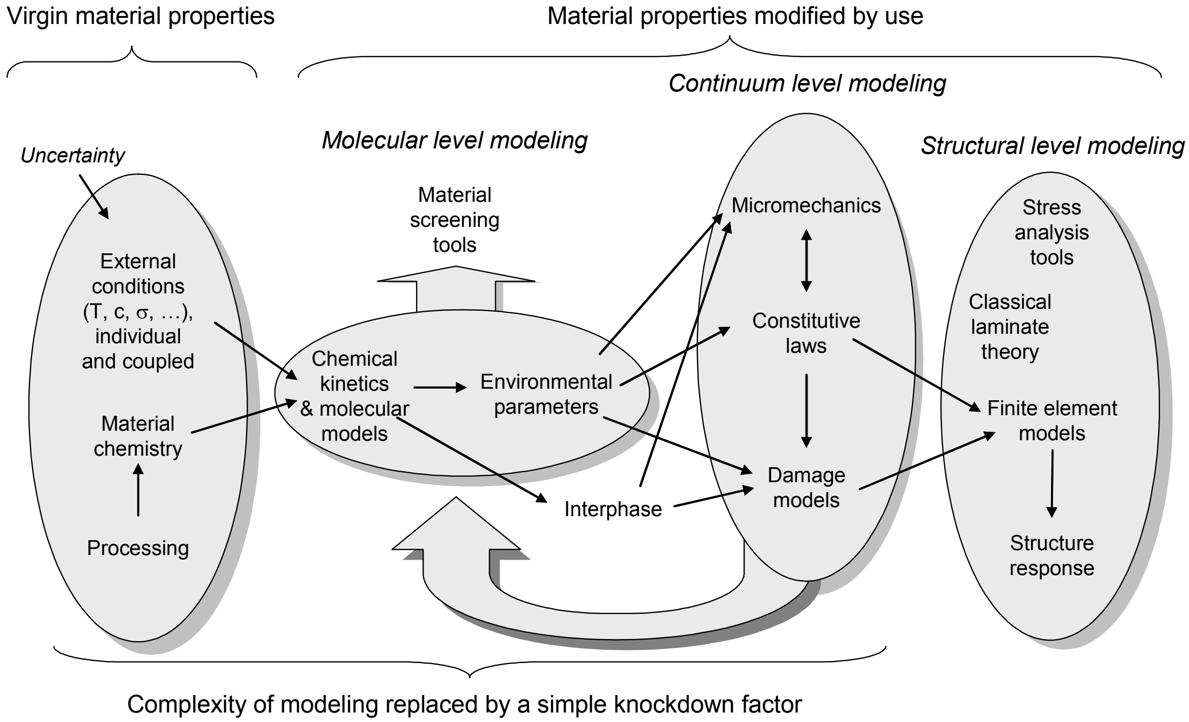

FIGURE 3-3 The desired modeling paradigm showing teaming relationships and the replacement of an uninformed knockdown factor by mechanistically and physically based models and design.

Empiricism must be replaced by accurate mechanistic modeling for many levels of damage. It is highly desired to correlate measured properties, in the form of markers, indicators, or symptoms, with meaningful conditions in the PMC. An equally important goal is to ensure that evolution is considered over the entire lifetime, from conception to death. Any such approach must include modeling the manufacturing process to understand the starting state of the material. This modeling might take into account residual stresses, initial surface and interface conditions, and other factors and would serve as the basis for understanding damage progression (i.e., evolution) and the resulting constraints on service life. Degradation mechanisms in PMCs must be understood in terms of fundamental chemical and physical mechanisms to understand material microstructure evolution.

It is critical to develop mechanistic models that range from chemical kinetics to structural dynamics. Integrating existing modeling approaches into a holistic modeling approach is a key goal. To do this, science-based multiphysics models must be implemented in structural design methods. The goal is a history-based, time-dependent reliability prediction. If experiments are designed hand-in-hand with modeling, they can be optimized to adequately inform the models.

Finally, it is vital to determine the rates of degradation in light of underlying mechanisms so as to gain a platform for accelerated testing. Accelerated testing is a central component of any durability program. Experimentalists are needed on the team to develop accelerated test methods that simulate the long-term behavior of PMCs. Eventually, additional modeling is essential for the proper interpretation and analysis of accelerated test data.

Phase I of such an implementation would use existing data to start the development of more effective models.[1] The first steps are to find holes and to identify needed parameters and then to provide this information as feedback to database developers (Phase I in Chapter 5). An additional task is to identify and develop processes (blind testing, for example) for life prediction models that can evaluate material performance. In Phase II, modelers and designers would form interdisciplinary teams to fully

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[1] For example, data on IM7/5250-4 bismaleimide resin from NASA's High Speed Research Program.

develop the needed models and strategies to replace knockdown factors with integrated, mechanistic, multiphysics models. This effort would be highly coupled with the development of the materials informatics database described in Chapter 5, which would not only contain all the critical data from chemistry through failure modes but also be accompanied by mining and analytical tools to assist extracting relationships from the data that would form a sound basis for modeling theory.

4

Roadmapping

Technology roadmaps accomplish a variety of things, but most importantly they may help to communicate among stakeholders from a wide range of communities. They can be used to direct basic science, to identify critical technology paths, or to help estimate when a technology could be available to be implemented into a system.

For example, adhesion between the matrix and the fiber clearly affects the durability of a PMC, and a number of current and potential research efforts can help to modify or improve this adhesion. The management of PMC degradation due to interfacial reactions would be greatly aided by expanding such knowledge, developing new techniques, or applying such knowledge and techniques more widely. The overall endeavor to improve the durability and life prediction of PMCs can be greatly informed by cataloging the existence and progress of such efforts.

Additional participants—also called stakeholders or team members—in the overall process include designers of the systems where the PMCs will be used. Codifying their expectations can also be very useful. In this way, roadmaps can provide a guide to where technology efforts should be focused and where technology gaps exist.

USING ROADMAPS

Roadmaps have been used extensively by a number of industries. For example, the first electronics industry roadmap, initiated by the Defense Advanced Research Projects Agency (DARPA), was published in 1994. This effort resulted in the organization of the National Electronics Manufacturing Framework Committee—a group of 200 individuals from industry, government, and academia—to study the challenges facing the nation in electronics manufacturing and to develop technology roadmaps and policy options with which to address these challenges. The National Electronics Manufacturing Initiative was incorporated the following year, and the consortium has published a roadmap every other year since 1994. Today, several roadmaps anticipate what lies ahead for the electronics industry. These additional roadmaps provide detailed information about segments of the electronics industry, such as semiconductors (International Technology Roadmap for Semiconductors) or interconnection substrates (IPC roadmap).

In the chemical industry, the first vision for future technology needs was based on then-current and anticipated market and consumer requirements. At a workshop, industry experts identify the goals, technical challenges, and priority R&D needs for a specific area, culminating in a roadmap and an extensive industry review process to build consensus among stakeholders. Progress towards achieving the goals is monitored over time. To date, 12 roadmaps have been published. However, developing roadmaps is only the beginning. To make an impact on the industry, collaborative teams need to pursue the priority R&D. The chemical industry's Vision2020 initiative encourages the development of partnerships to address the high-priority areas identified in roadmaps.[1] Collaborative R&D will ultimately lead to new commercial technology. Similar roadmaps have been developed and implemented for the steel, glass, aluminum, metal casting, forest products, and mining industries.

Roadmaps come in a variety of formats, and each is created to meet a specific need. Accordingly, separate roadmaps would need to be developed for PMCs in space applications, aerospace applications, land-based battlefront applications, and undersea applications. An example of a hierarchical roadmap for space lift vehicles is shown at the top of Figure 4-1. In this figure, the flight vehicles are grouped into near term, mid term, and far term, and under each vehicle are listed its key operational requirements. These requirements are the key capabilities needed for that vehicle implementation. While the vehicle attributes are essentially capabilities, the needs can be thought of as attributes, and how technologies satisfy those attributes is the product that the technology develops. These needs can then be broken down into distinct needs. Another way to think about it is, What does the technologist have to do to deliver the product?

At the bottom of Figure 4-1 is a notational structure product roadmap. This type of roadmap translates needs into a series of actions to develop a technology or product to meet the various space lift needs—for example, leading edges, cryogenic fuel tanks, and airframes. The technology readiness level (TRL) is noted at the end of the development cycle. The various TRLs have been defined by the Air Force and NASA; while the definitions are not exactly the same, the idea behind them is the same.[2] For example, a TRL of 6 means that the concept has been demonstrated in a relevant environment and is ready for demonstration in an operational environment.

This discussion has focused so far on high-level roadmaps, but they can be used to provide guidance on development schedules and data gaps for subtasks. For example, on the structure development chart there is a requirement to develop an integrated structure to a TRL of 6 by 2009. An integrated structure would have a thermal protection system (TPS) over it, so depending upon the efficiency of the TPS, the underlying structure could be a PMC.

Assuming a PMC could be used, the technology availability forecast shows that an airframe able to last 250 flights will be available by 2009. Assuming the PMC can operate at 350°F to 400°F, a development schedule can be drawn up that shows what is needed (for example, data feeds and funding levels) and when, to achieve a TRL of 6. Input to the chart would come from universities, researchers, industry, and fabricators. The chart would make clear when a certain technology is expected to be ready and whether it will be on time to help the vehicle.

ROADMAPPING GOALS

A roadmap for PMCs could accomplish a number of things. It could facilitate communication between database and modeling teams. A good roadmap could impact technology development and implementation by providing information for the database and justifying the allocation of funds. To accomplish this, a roadmap needs to include existing and near-term public and private programs and their intended deliverables and outcomes.

Certain organizational issues must be resolved. Like other successful roadmaps it could include an oversight committee of persons from industry, government, and academia who meet annually to develop and update the roadmap. A good roadmap should be impartial and flexible and should outline several alternative paths and timelines for achieving the stated goals.

A roadmap to guide the use of PMCs in extreme environments would need to be coordinated with PMC roadmaps for the Air Force, NASA, and their contractors. It would need to show when a material's insertion is planned, including the lead time, what testing is needed and when, and the relationships to existing and still-to-be developed models. Most importantly, a roadmap must make clear what work cannot be done in parallel.

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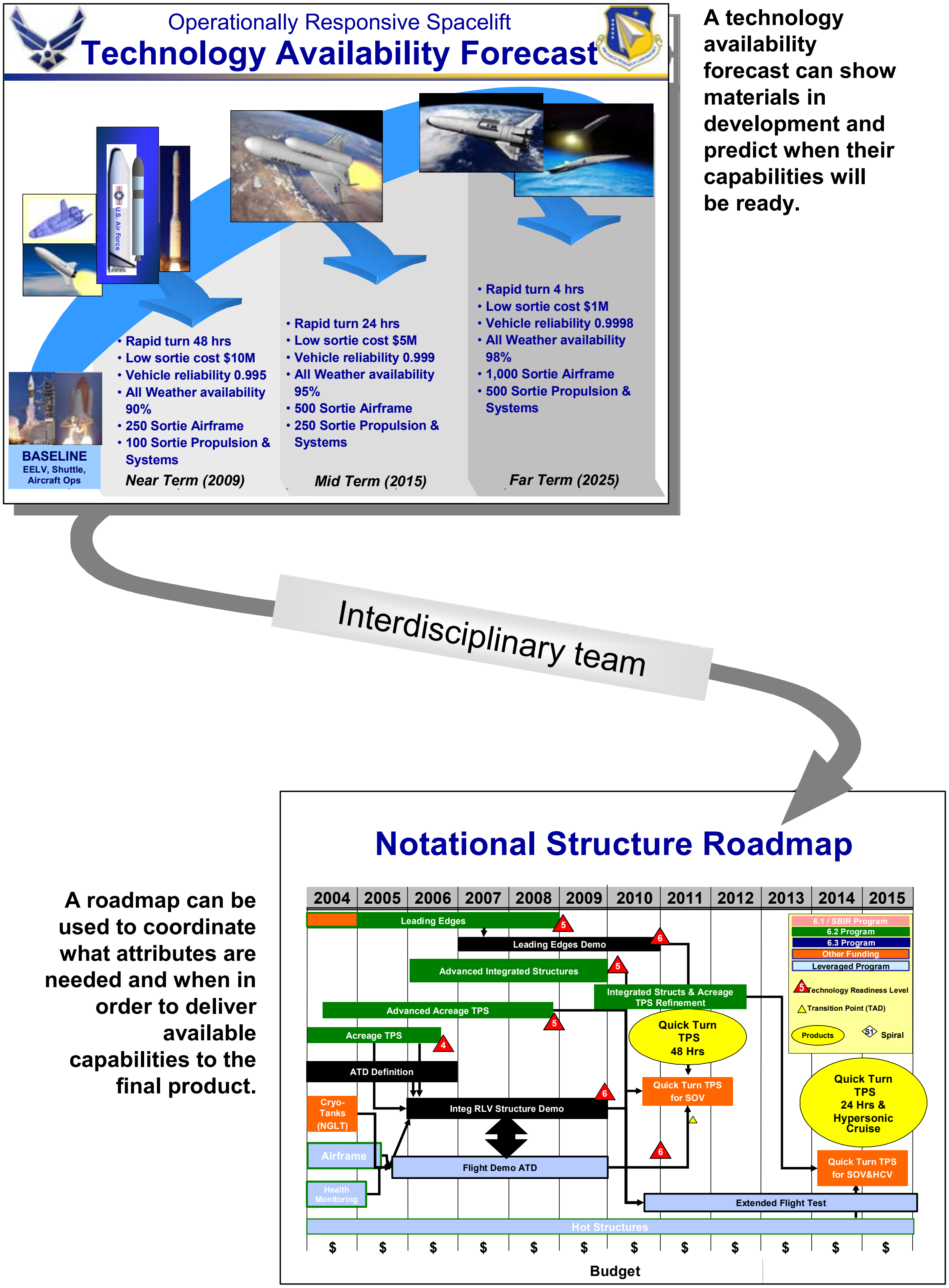
[1] A list of roadmaps developed under the Chemical Industry Vision2020 Technology Partnership are available at <http://www.chemicalvision2020.org/techroadmaps.html>. Accessed April 2005.

[2] J.C. Mankins. 1995. Technology readiness levels. Available at <http://advtech.jsc.nasa.gov/downloads/TRLs.pdf>. Accessed April 2005.



Operationally Responsive Spacelift

Technology Availability Forecast

BASELINE
EELV, Shuttle, Aircraft Ops

Near Term (2009)
- Rapid turn 48 hrs
- Low sortie cost $10M
- Vehicle reliability 0.995
- All Weather availability 90%
- 250 Sortie Airframe
- 100 Sortie Propulsion & Systems

Mid Term (2015)
- Rapid turn 24 hrs
- Low sortie cost $5M
- Vehicle reliability 0.999
- All Weather availability 95%
- 500 Sortie Airframe
- 250 Sortie Propulsion & Systems

Far Term (2025)
- Rapid turn 4 hrs
- Low sortie cost $1M
- Vehicle reliability 0.9998
- All Weather availability 98%
- 1,000 Sortie Airframe
- 500 Sortie Propulsion & Systems

Interdisciplinary team

Notational Structure Roadmap

A technology availability forecast can show materials in development and predict when their capabilities will be ready.

A roadmap can be used to coordinate what attributes are needed and when in order to deliver available capabilities to the final product.

FIGURE 4-1 Example of a technology roadmap implementation.

Recommendation: A steering committee should be created across the PMC community, initiated and supported across a number of federal organizations, to oversee the development and maintenance of a roadmap (or roadmaps) for PMCs in extreme environments.

5

The Importance of Data

Data are critical for characterization, calibration, verification, validation, and assessment of models for predicting the long-term structural durability and performance of materials in extreme environments. Without adequate data to verify and assess them, many models would have no purpose. An accurate structural durability model requires a database that consists of several master pedigrees of material systems with a uniform data set that represents a multitude of test conditions and several applications.

DATA AND MODELING

The Federal Aviation Administration (FAA) has been intent for several years on encouraging the sharing of data on composite properties and developing standards for these properties and designations. The goal, of course, is to ensure safe and efficient deployment of composite technologies for existing and future aircraft. FAA's safety and certification initiatives were started in 1999 to address issues associated with the growing use of composites for the construction of planes. A large part of this effort is to coordinate the groups that update policies, issue advisory circulars, offer training, and furnish detailed background to support standardized composite properties and engineering practices.

One of the main efforts in this area is maintaining MIL-HDBK-17, which has included standardization and shared databases in PMCs for many years—the first PMC data set was approved in 1990. Sharing of standards, guidelines, and data is intended to achieve a number of goals, including (1) the control and stabilization of raw material, which is needed for continued safe and reliable use of PMCs in aircraft products; (2) the expansion of applications for PMCs in other industries to drive materials supplier developments; and (3) the promotion of consistent engineering practices. Overall, this effort aims to share composite databases and specifications throughout industry, thereby improving the efficiency of suppliers, users, and regulators.

This ongoing effort demonstrates the need for consistency in data collection and use and the difficulties this poses. Ideally, models should be universal, accounting for all materials and every possible damage mechanism or combination of mechanisms and every possible environment and condition of application. Because this is nearly impossible, a more practical approach would be to create a central database that would allow a model developer to select a PMC material system and its associated data based on the application and the anticipated damage mechanisms. The development of such a resource would clearly require an interdisciplinary team such as that described in the recommendation on teaming (see Chapter 3).

Finding: A certain amount of data is critical for modeling and life prediction.

However, not all data that are measured or can be measured are important to modeling and life prediction. The data needed should be intelligently selected for relevance and efficiency. This means, for example, that experimentalists should not measure short-beam shear strength simply because they have always done so and there happens to be a test standard for it. A database should include properties because they support promising models or because they can be used to validate (or repudiate) promising models. Making use exclusively (or nearly exclusively) of existing ASTM or industry standards without considering their relevance is a recipe for disaster.

Data as defined today are expensive to gather, difficult to harmonize, and, many times, irrelevant to a specific model. Furthermore, data tend to become outdated and must be refreshed and improved. This calls for an overhaul of the way we collect, use, tally, and communicate data. A word has been recently coined that encompasses these concepts: *informatics*.

INFORMATICS AS A DISCIPLINE

Informatics is a relatively new field that is fast impacting the other fields it touches. A working definition of the discipline is the research, development, or application of computational tools and approaches for expanding the use of data, including those required to acquire, store, organize, archive, analyze, or visualize the data. It is important to note, however, that the field did not appear in academia fully formed but took many years to overcome academic inertia and gain the acceptance of researchers in the disciplines involved.

Biomedical Informatics

Biomedical informatics applies computer science, decision science, cognitive science, and organizational theory to the management of biological and medical information. The biological community did not universally agree on the importance of developing information resources and tools, even those that are today some of the most visible—GenBank, model organism databases, and the Human Genome Project. In retrospect, however, each of these efforts has revolutionized the accessibility and applicability of data and analysis tools to biologists, and many say these resources have created new perspectives for how biological research is done and interpreted. Extending these centralized data and analysis resource concepts to PMCs would enable researchers to make connections and draw conclusions about PMC mechanism-property relations that cannot be made with the current decentralized state of data, analysis, and algorithms in the field.

Physicians, clinical researchers, and biologists have long needed to organize and sift through large quantities of data. Since the 1970s, biomedical professionals have joined with computer and information scientists to find new ways of dealing with their data, and the field of biomedical informatics, particularly the subfield of bioinformatics, has exploded in the last 10 years. Biomedical informatics research has been able to capture significant amounts of funding, primarily from the National Institutes of Health, and there are now biomedical informatics laboratories at every institution doing major biological research. According to gradschools.com, 62 schools in the United States and another 29 outside of the United States currently have medical informatics or bioinformatics M.S. or Ph.D. programs.

The emergence of this academic discipline has opened up new areas of research, drawing in scientists who wish to make new discoveries by mining existing data. Biomedical informaticists have made basic research discoveries by creating and then applying computational tools to find subtle patterns in vast amounts of data that were previously inaccessible to biologists. In one example, computational biologists were able to analyze the genome of an intriguing and poorly understood microorganism to find a DNA sequence—unrelated to that of any other known organism—that was critical for understanding how the microorganism, an enzyme, replicated its DNA. This enzyme has been exploited in the development of the polymerase chain reaction and resulted in a Nobel prize for its achiever.

As part of their research, bioinformaticists are constantly developing new databases and computational tools and publishing them on the Internet, providing a tremendous service for biological scientists. In general, informatics researchers generate algorithms to extract valuable information from massive quantities of raw data. When the informaticists provide these tools on the Internet, the larger community of biological scientists can use them for applications specific to their research, such as comparing gene sequences of various organisms to determine their evolutionary relationships.

Of the many bioinformatics databases, Genbank may be the most widely known and has set a number of standards for such resources. Researchers have come to routinely place data in this community archive for the common good, knowing that it can be freely used by anyone.[1] In addition, all leading journals have adopted a policy that requires sequences to be deposited in the public databases and the corresponding access numbers to be cited in published articles. All publicly funded laboratories now consider it de rigueur to contribute sequence data to Genbank within 24 hours of its generation, even if there is no accompanying research paper.[2]

Genbank provided a centralized way to store and access this data, which now contains over 44 billion gene pairs. In part because of this tremendous resource, and in part because GenBank does not have an experimental division, GenBank cannot thoroughly verify the submitted data, much of which has never been experimentally validated. As a result, there are duplicate, conflicting, and erroneous entries in the database.

As with data from any other source, biological researchers must keep the nature of the submission and the curation process in mind when using data that are not their own. To some extent, such problems exist in all databases, even local, lab-based data, but the curation and semantic consistency of data are harder to assure as the size and number of sources of data increase. The resources allocated to database management, submission requirements, curation efforts, validation methods, and the nature of the included data, as well as the priority assigned to them, all affect reliability.

Biomedical Informatics as a Model

The materials science and engineering community may be able to learn much from the example set by biomedical informatics. Because most materials scientists are not biologists as well, they are not likely to see parallels between the two disciplines. For example, a materials scientist might believe that a gene sequence is always a gene sequence, just as a biologist might believe that a polymer is always a polymer, although neither is true.

In fact, gene sequences vary with many of the same factors of measurement and external conditions that PMCs do. Just as a gene sequence is identical only for clones, wet strength after exposure may be identical only for two adjacent coupons. Every person’s gene sequence differs; every 1,000 bases on average is different from one person to another. This variance in the gene sequence is sufficient to cause variations in body chemistry and performance, but it is very difficult to unravel cause and effect.

This is similar to the difficulty of determining how small changes in a polymer's structure due to processing may change the way its properties evolve during environmental exposure. The chemical structure of a particular polymer set as a reference is analogous to the setting of a map of a particular gene as a reference. Untangling how small variations in the sequence interact with other equally variable genes and with environmental variables is a huge challenge for a biologist. Similarly, understanding how a small change in polymer structure interacts with processing and environment changes to evolve properties is a huge challenge for the materials scientist.

Given these parallel challenges, some existing bioinformatics databases may serve as a model for the proposed polymer composites database. One salient example is dictyBase, at <http://dictybase.org>, which contains information on the Dictyostelium genome and functional genomics. It is a relatively new database, so at its inception the biology community understood the value of a model organism database and readily accepted the concept. The Dictyostelium research community is relatively small, with fewer than 200 laboratories actively focused on Dictyostelium as a research organism. However, in the first 18 months that dictyBase was available, 20,000 distinct computers in more than 30 countries requested pages, and many of those requests came from students in high school and undergraduate lab courses. It also provides more than 5,000 pages per week to people looking at the Dictyostelium genome and

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[1] J. McEntyre and D.J. Lipman. 2001. GenBank—a model community resource? Nature webdebates. Available at <http://www.nature.com/nature/debates/e-access/Articles/lipman.html>. Accessed February 2005.

[2] Further, the Director of the National Institutes of Health (NIH) recently issued a public access policy requiring that NIH-funded investigators whose research was supported in whole or in part with direct costs from NIH submit to the PubMed Central database an electronic version of the final manuscript upon acceptance for publication. Although the current policy allows the paper's posting to be delayed up to a year after publication, the effect of this policy on open-source access to data is expected to be profound.

associated research data. These data do not include spurious hits from search engines and the like and represent intentional usage of the site.[3] Other databases of similar size are the Saccharomyces Genome Database, at <http://www.yeastgenome.org>, and the Drosophila Genome Database, at <http://www.flybase.org>.

The popularity of these sites would seem to augur well for proposing a research project to develop a database for polymer composite materials. Today, more than 40 universities have laboratories focused on the development, characterization, environmental performance, or modeling and simulation of PMCs. More than 200 companies are listed in the *Composites Sourcebook*[4] as buying and selling PMCs or their components (in addition to the five main defense integrators). Many other universities teach courses on these topics, and the number of companies in the supply chain with interest in such data could be much greater.

It takes three curators, two programmers, and between 10 and 20 percent salary support for the project leaders to run dictyBase. Currently, this cost is $450,000 annually. Because of the relative maturity of the program codes, there were no additional costs to set up the database. The dictyBase is based on modern architecture and automation and as such is also less expensive to run than some older systems.

Operating a database, however, is more than a matter of software. The curators are responsible for reading the papers, reviewing data, coupling sequence data to function, annotating gene function and literature, and generally interrelating information and capturing the quality of the evidence within the database. The programmers are responsible for the hardware and the software, for continuously uncovering better ways to enter, retrieve, and visualize the data, and to develop user-friendly analytical tools for the research community.

While collecting the data is difficult but important, merely having it in a spreadsheet is not sufficient. More is needed than simply dollars, although funding is important. Each successful bioinformatics database started with an agency's or a research group's vision for responding to a specific scientific need. Whether the database was initiated by a proposal from a principle investigator (or group of investigators) or a call for proposals from a funding agency, it is crucial to support researchers who are committed to devoting time, energy, and dollars to develop a community resource. Success in such an endeavor requires dedication and the attention of someone who has solid experience in accumulating and working with the data and who is now willing to branch out into informatics to provide this kind of service to the community.

Other examples of public bioscience databases include these:

- Protein Data Bank (PDB), at <http://www.rcsb.org>.
- National Center for Biotechnology Information (NCBI), at <http://www.ncbi.nlm.nih.gov>.
- National Institute of Standards and Technology (NIST) databases, at <http://www.nist.gov/srd>.
- Tetrahymena Genome Database (TGD), at <http://www.ciliate.org>.

PARALLELS FOR MATERIALS DATA

In biomedical informatics, the raw data being stored might be a gene sequence and related details on specific organism function (for example, raw data on gene X along with data on blood pressure, on heart rate, and on various biochemical pathways and their responses to stress) (Figure 5-1). This is a vastly complex issue because a single function is regulated by many genes, and there is not a one-to-one correspondence of cause and effect. In addition, the history of the organism, the environment, and other stressors all feed into the organism's response.

An analogous issue in materials is the relationship between a material's structure and its properties: The raw data may include details of the material's composition and structure; related information may be data on properties, response to environmental stressors, chemical changes that occur with certain exposures, time to failure under various conditions, and many others. Again, this is a vastly complex issue. Any property, such as strength, is regulated by many details of the chemical composition

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[3] Personal communication, W.A. Kibbe, dictyBase, Northwestern University. February 2005.

[4] *Composites Sourcebook*, Ray Publishing. Available at <http://www.compositesworld.com/sb/>. Accessed February 2005.

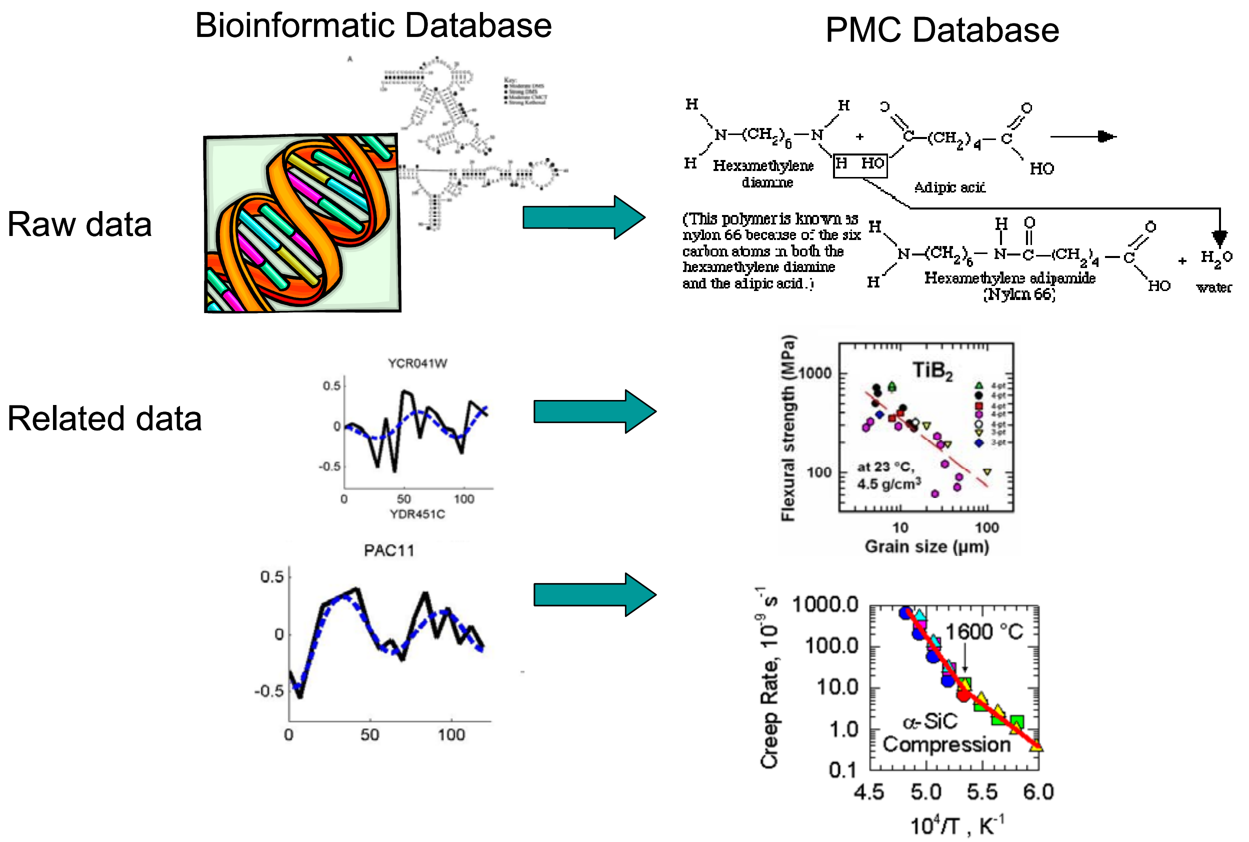

FIGURE 5-1 Parallels between bioinformatics data and materials data.

and microstructure of the specimen. Thus, the same type of algorithms that are being studied and used in bioinformatics to make connections in the vast sea of biological data can be explored and developed in the context of material informatics to learn about the mechanisms underlying a material's response.

Biomedical databases can also provide examples for the materials community in the area of protected information. As export-controlled data are guarded to maintain competitiveness, patient data must be kept confidential for personal privacy reasons. In some biomedical databases (see Box 5-1), only certain people may access patient-specific results, while summaries of multiparticipant studies can be more widely distributed.

The key point for materials data is that a comprehensive tool—data coordinated with models—is far more useful than a typical handbook.

Recommendation: Mission agencies should offer sustained support to develop and maintain comprehensive information on PMC properties in a new materials informatics initiative. A steering committee on the needs of the PMC community should be formed to ensure that this effort is effectively targeted. This committee should be responsible for developing guidelines and overseeing operations for a national PMC informatics initiative.

The members of a steering committee should be a multidisciplinary team made up of design, structural, mechanical, and fabrication engineers and organic/physical polymer chemists, as outlined in the recommendation on teaming. It should have subcommittees to direct the activities for each class of material being considered for database inclusion. For such a committee to be effective and maintain its neutral position, it must have sustained funding from several sources.

BOX 5-1
Bioinformatics in Action at PharmGKB

Bioscientists developed the first public bioscience databanks in the 1970s and have been depositing data into free, Internet-based repositories since the inception of the Internet. In general, development and maintenance of a major databank cost between $1 million and $10 million per year, and this money most often comes from the National Institutes of Health (NIH). Depending on its size and complexity, a database may be maintained by a collaborative group spanning multiple universities, a government entity such as the National Center for Biotechnology Information (NCBI), or a single research laboratory.

A relatively new and still fairly small example is the Pharmacogenetics and Pharmacogenomics Knowledge Base (PharmGKB). In April 2000, the NIH initiated a collaboration with Stanford University and granted it $9 million, spread over 5 years, to develop and maintain this database. Unveiled in February 2001, PharmGKB serves as a resource for clinicians, clinical researchers, and basic researchers to help them understand the relationship between human genetics and patients' responses to various disease treatments. When queried with the name of a drug, disease, or gene, PharmGKB offers users results of clinical drug studies along with lists of related literature references and gene sequences. The results are coded with icons to help searchers to rapidly find the type of information they need. Unlike most bioscience databases, personal privacy issues have forced PharmGKB to restrict access to some of the data. Only scientists affiliated with registered projects may access clinical trial data with individual identifiers. However, anyone may view the pooled and summary data.

Another atypical aspect of PharmGKB is that data submissions on human clinical studies come only from registered users. Many of the researchers who submit their data are required to do so as a condition of their funding from NIH/National Institute of General Medical Sciences. Most bioscience databanks allow submissions from anyone, and the scientific curators verify the data. Very often, scientific journals require that researchers submit their data to the databanks as a condition of publication. In other cases, such as the databases maintained by the National Institute of Standards and Technology, staff members search current literature and compile relevant information. The PharmGKB project director, Teri Klein, says that one of the biggest challenges has been encouraging investigators to share their information. She says that while biologists are accustomed to sharing many types of data, the concept of sharing the type of data included in the PharmGKB database is new and is not as widely accepted.

One of the frequently underestimated costs of databases is that of staffing. To maintain and improve the database, the PharmGKB project currently employs 13 people. There are 10 full-time staff for the project and 3 part-time—the principle investigator, the project director, and an administrative assistant. Three curators verify submissions and search for publications containing relevant unsubmitted data; five software developers and two IT specialists deal with the data. The heavy presence of computational staff reflects the complexities of data representation and manipulation and the importance of providing a consistent architecture and analysis environment to the community.

6

A Path Forward

A number of key issues have been found to affect the durability and lifetimes of polymer composites in extreme environments.

The most important finding is the need for data at extreme conditions, given that models without data to verify and validate them will not be used. It is also true that although modelers want their models to be accurate, they often do not have the expertise, time, or funding to run experiments for such correlation.

Accessible data would accelerate the development of accurate models, particularly coupled models. Experiments have been done to examine coupled aging effects (for example, temperature and stress, or moisture and ultraviolet radiation), but lacking data, modelers are not motivated to test and improve models that couple such effects. Yet this is the most challenging area for modeling and needs more effort.

The second finding is that while data are scarce in the open literature, large amounts exist but are not available to modelers. A lot of money was spent to create data under a number of programs, including the NASA High Speed Research (HSR) program, but these data have not been made available. Much of the HSR data currently exists in an spreadsheet file on a few personal computers.[1] In addition, large amounts of data funded through government contracts are under the proprietary control of technology development companies. Currently, there is no easy way for modelers to know what data exist or to access the data for modeling verification.[2] This is true for researchers inside these government programs as well as researchers in industries other than aerospace or those engaged in purely academic pursuits.

It is clear that tasks such as materials informatics, roadmapping, or integrated team design will not be carried out without a change in overarching processes. For example, a roadmap will not be created unless someone is officially responsible for it and his or her job performance depends on its successful implementation. A database will not be created or maintained unless a curator is assigned to house, validate, distribute, update, and run the database. The links between chemical kinetics and mechanics and structural design will not be modeled unless a program is funded to carry out this research.

It has also become clear over time that commercial companies do not invest in these types of activities on their own. Similarly, academicians lack sufficient knowledge of the application requirements to be successful on their own, nor are government program managers able to accomplish these goals in isolation. Because the success of any federal initiative will depend on the appropriate review of collaborative work, expertise from all sides—academic and industrial experts across a number of disciplines—will be needed to assess all elements of the work.

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[1] One might wish to compare the cost of generating the data in the HSR program with the cost of creating a database and maintaining the data there.

[2] "Accessing" data for model verification or validation might not entail actually seeing the data or using it in ways that would violate either defense or proprietary protocols.

Finally, the advantages of materials development in the context of verified models are becoming clear. An effective approach would link models of chemical kinetics to property evolution and incorporate environmental exposure. This would allow using the predictive ability of models to design new materials with modified chemistries that would provide the resistance required for a particular application. Models of damage at a structural level based on component property information can allow designers to come up with composite structures (fibers plus resin plus morphology) appropriate for a given application.

Accurate and reliable modeling, coupled with accelerated testing, is key to expanding the use of PMCs in extreme environments. Currently, haphazard testing on a shortened timescale is used to derive simple knockdown factors that are used to sanction PMC materials and allow their application in structural components. This testing does not illuminate the underlying mechanisms of property evolution. The use of weight loss measured after exposure to high temperature to rank materials without understanding what caused the weight loss or how it is related to failure demonstrates how accelerated testing can be used with no couple to modeling. To establish such a connection and to link chemical kinetics to mechanical properties, modeling must mature. Only then can a coupled modeling approach be used to design experiments specifically to accelerate a mechanism that is critical for the lifetime of the given component.

A PMC steering committee such as that recommended in Chapter 5, which would oversee the composition of teams, the development of roadmaps, and the establishment of database parameters, could have the following duties:

- Define initial baseline application(s) and their extreme environments;
- Establish real temperature limits for material systems;
- Select master pedigree composite materials (resin and fiber);
- Identify anticipated damage mechanisms;
- Establish security criteria that would respect export controls and proprietary databases;
- Establish a standardized list of critical material properties;
- Coordinate the critical properties list with the national testing standards of ASTM subcommittee D-30;
- Identify sources of reliable data, assuring its pedigree and suitability;
- Coordinate government and commercial activities to increase database acceptance and use;
- Provide feedback loops to end users to assure database accuracy and relevance;
- Organize and coordinate roadmapping and database workshops with national societies at their venues;
- Estimate the costs of database development and maintenance;
- Develop strategies for funding database upkeep through user fees, dues to a newly created oversight organization, or coordination with an existing national PMC working organization; and
- Ensure that experts in the appropriate disciplines participate in all of these activities.

PMC PHASE I ACTIVITIES

It is recommended that a steering committee gather low-hanging fruit by immediately developing a format and contracting for the assembly of a database utilizing existing PMC databases available from industry and government. Serious consideration should be given to including PMC resins in current practice in extreme environments, including, for example, PMR-15, 5250-4, and 977-3. The selection process needs to be closely coordinated with the roadmapping and teaming recommendations in this report.

This first database effort should be targeted at utilizing data from existing PMC databases from industry and government, with emphasis on creating an architecture that will be robust and allow the insertion of new material systems and new properties. Initial efforts should also begin to examine the creation of tools for mining and analyzing the data. Connection to the modeling community must also be included at the outset, with modelers involved in the process, and initial efforts to use the data in model development should be targeted.

PMC PHASE II ACTIVITIES

Phase II activities will begin with roadmap development, concentrating on the context of data as part of materials informatics. Each master pedigree PMC system identified through this process should represent a PMC class (for example, brittle/ductile, brittle/brittle, epoxy or resin) that has all the salient characteristics (for example, thermal, environmental, mechanical) representing that class of PMC. Likewise, each master pedigree PMC system should be mature enough to have sufficient manufacturing consistency that there is no significant batch-to-batch variability. A steering committee should work to define the PMC classes and master pedigrees and should be involved in the creation of the requests for proposals to fund the work for each material. Working with PMC material classes will provide end users with qualitative, albeit not quantitative, material behavior. This can provide a cost savings for the whole database generation activity. Each PMC class will require only one specific PMC material system. The end user can investigate the salient characteristics of a specific material class to formulate the general form of a model. The model can be further calibrated using a series of specialized tests that are model dependent.

PMC PHASE III ACTIVITIES

A mechanism to fund curators and informaticists to collect, verify, evaluate, maintain, update, warehouse, and distribute such database concepts will also be needed. It is imperative that a curator's sense of ownership in this activity be considered in funding decisions and that such efforts be intimately connected to PMC roadmapping groups linked to existing community-wide efforts in professional societies and others.[3] Curators would also be tasked to coordinate with the national testing standards developed through ASTM D-30 and related groups.

Considerations for such a roadmapping and data activity include the following:

- Determination of which properties are critical versus which are simply nice to have.
- Evaluation of PMCs in current practice.
- Availability of data restricted by export controls (such as ITAR) or by proprietary limits.
- Development of a method to demonstrate how processing changes the properties of a sample material.
- Establishment of master pedigrees for a few key materials, such as epoxy resin.
- Establishment of real limits on materials systems imposed by temperature and other factors.

A number of organizational issues will also need serious consideration. The need for sustained funding is primary, and examples should be studied from bioinformatics and other fields to learn how consortium funding can be organized. Feedback must also be solicited from groups working to develop an understanding of underlying mechanisms to ensure that the data will meet their needs and also to determine what is needed to test models against existing data. Cost is an important consideration, but is difficult to gauge. This issue will best be considered when the benefits of this effort are more fully understood.

In summary, the use of PMCs in increasingly extreme environments will depend on a considered, consolidated, and sustained effort by government, industry, and academia to achieve the goal of durability—and trust in that durability. (Figure 6-1 shows one looming reason for this trust.) Such an effort will require sufficient federal funding focused on changing the paradigms for teaming, roadmapping, and informatics.

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[3] The potential curators for some of these functions include academic research collaboratives. Some private enterprises may also be useful, such as the current curator for *MIL-HDBK-17: Composite Handbook,* Materials Sciences, Inc. Other potentially relevant organizations include ASM International, the National Institute for Aviation Research, and the Aerospace Materials Technology Consortium.

FIGURE 6-1 The Boeing 787 as designed will utilize composite materials and new manufacturing techniques, including building full barrel fuselage sections with integrated stringers, as shown here. This application of composite materials could result in fewer parts and improved aerodynamic performance and fuel efficiency.

Appendixes

Appendix A

Committee Members

L. Catherine Brinson (*Chair*) is currently the Jerome B. Cohen Professor of Engineering at Northwestern University, with primary appointment in the Mechanical Engineering Department and a secondary appointment in the Materials Science and Engineering Department. After receiving her Ph.D. in 1990 from the California Institute of Technology, Dr. Brinson performed postdoctoral studies in Germany at the DLR (German Air and Space Agency), and since 1992 she has been on the faculty at Northwestern University. She focuses on the modeling and characterization of advanced material systems, including high-performance composites and intelligent materials. Current research investigations involve studies of aging in polymeric-based systems, nanomechanics of nanoreinforced polymers, characterization of microporous materials for bone implants, and experiments and modeling of shape memory alloys, where investigations span molecular interactions, micromechanics, and macroscale behavior. Dr. Brinson has received several awards, including the ASME Special Achievement Award for Young Investigators, an Alexander von Humboldt Research Award, an NSF Career Award, and the ASEE New Mechanics Educator Award; she held the June and Donald Brewer Junior Chair at Northwestern University from 1992 to 1994 and was a member of the Defense Science Study Group (1998-1999). She has made numerous technical presentations on her research, co-organized symposia at conferences, and authored over 50 journal articles. She is a member of several professional societies and served 5 years on the Society of Engineering Science's board of directors, including 1 year as president of the society. She has also been an associate editor of the *Journal of Intelligent Material Systems and Structures* and the *Journal of Engineering Materials and Technology.*

Kenneth L. Reifsnider (*Vice Chair*) is the Pratt & Whitney Chair of Design and Reliability in the Mechanical Engineering Department at the University of Connecticut and is the director of the Connecticut Global Fuel Cell Center at that University. He is a member of the National Academy of Engineering. He joined the School of Engineering and the Connecticut Global Fuel Cell Center in 2002 from Virginia Polytechnic Institute and State University, where he was the Alexander Giacco Chair Professor of Engineering Science and Mechanics. Dr. Reifsnider serves on the editorial boards of five journals and is the current editor in chief of the *International Journal of Fatigue*. In addition, he is the co-founding editor of the *Journal of Composites Technology and Research* and the *International Journal of Fuel Cell Science and Engineering*, published by ASME. He recently completed his signature text, entitled *Damage Tolerance and Durability of Composite Material Systems*. While at Virginia Tech, Dr. Reifsnider cofounded the Virginia Tech Center for Composite Materials and Structures and served as director of the Virginia Institute for Material Systems. He also served as deputy director of the NSF Center for High Performance Polymeric Adhesives and Composites. From 1974 to 1992, he was chairman of the Materials Engineering Science Ph.D. program at Virginia Tech. Dr. Reifsnider also served as associate provost for interdisciplinary programs at Virginia Tech from 1995 to 2000. He holds the Distinguished Research Award from the American Society for Composites, the J. Shelton Horsley Research Award from the Virginia Academy of Science, the Award of Merit from the American Society for Testing and Materials, and the Alumni Award for Research Excellence from Virginia Tech. He has served on the board of directors of ASTM and the Institute for Standards Research, serving as chairman of the board of trustees of the latter in 1989. Dr. Reifsnider earned his Ph.D. (1968) in mechanics and in metallurgy and solid mechanics from the Johns Hopkins University.

Paul A. Bartolotta is a senior technical staff member at the NASA Glenn Research Center. He has worked for the past 20 years in the area of advanced high-temperature material systems for NASA. Dr. Bartolotta has created new material systems, identified and corrected potential design flaws in propulsion and power systems, investigated new advanced material systems, developed specialized test methods, and created world-renowned test facilities. Dr. Bartolotta is also involved with the development, characterization, evaluation, and verification of life prediction models used by government and industry. He was a pioneer in conducting strain-controlled, high-temperature fatigue tests on composite materials and identified the phenomenological damage progression within a composite from both the environmental and mechanical viewpoints. Dr. Bartolotta is a recipient of NASA's Exceptional Service medal award, four NASA Space Act Awards for technical achievement, one R&D 100 award, and the NorTech Innovation Award. He has authored or coauthored over 100 articles and technical presentations.

Matthew B. Buczek is a principal engineer for composites in the Materials and Process Engineering Department of GE Aircraft Engines. Dr. Buczek has held several different positions of growing responsibility, from engineer to department staff engineer, and is currently leading the DARPA Engine System Prognosis program. He has led or participated in numerous efforts to develop and demonstrate new materials and processes for engine application, including the F414 composite inlet device, the GE90 composite fan blade, 700ºF polyimide composite materials, and the F118 polyimide composite exhaust ducts. Dr. Buczek holds over 20 patents on materials and processes. He is a graduate of GE's Six Sigma Black Belt program in its Commercial Engine Division, where he supported GE's airline customers. Prior to joining GE, Dr. Buczek was a materials engineer for the Atlantic Research Corporation, where he led efforts to analyze and evaluate high-temperature composites for solid propulsion rocket motors. He holds a Ph.D. in materials engineering from the University of Dayton, an M.S. in engineering mechanics from Virginia Tech, and a B.S. in mechanical engineering from Michigan Tech. He is a registered professional engineer in the State of Ohio.

John W. Davis is a senior manager at the Boeing Company. For the past 40 years Mr. Davis has been actively involved in the development in high-temperature materials and structures for hypersonic vehicles and advanced energy systems. The group is currently investigating new materials such as aluminum-lithium-based alloys, oxide- and silicon-based ceramic composites, and chlorofluorocarbons. In addition, the group is evaluating new thermal barrier materials that could function as insulators or fire barriers for flight vehicles. His group is designing and fabricating high-heat-flux components for Sandia National Laboratories for use in fusion experiments. It is also supporting the ARIES magnetic and inertial confinement studies and the Princeton FIRE design. Prior to joining McDonnell Douglas (later, Boeing) in 1969, Mr. Davis worked at Fansteel, Inc., on the development of refractory metals (molybdenum, niobium, tantalum, and tungsten alloys) and dispersion-strengthened nickel-based alloys for use in reentry vehicles and hot structure. Later, he worked on the metallic thermal protection system (TPS) of the space shuttle Orbiter and on a predictive model for cyclic creep under NASA Langley sponsorship. Mr. Davis has a B.S. degree in metallurgical engineering from the University of Illinois.

Norman J. Johnston, retired from the NASA Langley Research Center, is an expert in composites technology for aeronautics and space applications. Dr. Johnston received his Ph.D. in organic chemistry from the University of Virginia in 1963. He was a polymer development chemist for GE and an assistant professor of chemistry at Virginia Tech prior to joining the NASA Langley Research Center senior research staff in 1967. He served as a section head and, from 1989 until his retirement in 2001, he was manager, Composites Technology, Advanced Materials and Processing Branch, Structures and Materials Competency. At NASA, Dr. Johnston championed the development of high-temperature polymers such as pyrrones and polyimides and toughened composite materials. He worked on multi-million-dollar programs to develop high-performance fiber-reinforced polymer matrix composites and associated automated fabrication technologies for both subsonic and supersonic commercial aircraft, including NASA’s Advanced Composites Technology program and its High Speed Research program. He also consulted for various government agencies and industries and served on several NMAB committees. More recently, he served on the X-33 composite liquid hydrogen tank failure investigation team and helped develop a recovery plan for the X-33 composite cryotank. He also helped conduct an assessment of the state of the art in high-performance composites technology in the United States. He coauthored over 90 technical papers and patents and gave over 150 technical presentations on his research activities, including coauthoring two Best Papers at SAMPE International Meetings. He received numerous NASA awards for his technical achievements, including the prestigious NASA Exceptional Service Medal.

Ann Marie Sastry is associate professor of mechanical engineering, biomedical engineering, and materials science and engineering at the University of Michigan. She holds M.S. and Ph.D. degrees from Cornell University and a B.S. from the University of Delaware, all in mechanical engineering. After receiving her doctorate, she was a senior member of the technical staff at Sandia National Laboratories. She joined the faculty at the University of Michigan in 1995. Her contributions to research in disordered biological systems span modeling and experiments on biometal homeostasis in cells, collagen alterations in the diabetic nerve, deformations and failure in marine invertebrate eggs, and formation of apoptotic pores in neural mitochondria. In engineered materials, her group has investigated statistical damage progression in composites, the processing of polymeric materials, and mechanical failures in Li-ion and nickel-based batteries. Dr. Sastry, a fellow of the ASME, has received several awards for her work, including the University of Delaware Presidential Citation for Outstanding Achievement, the UM College of Engineering 1938E award, the University of Michigan Henry Russel Award, and the NSF Presidential Early Career Award for Scientists and Engineers (PECASE). She has delivered over 40 invited university seminars and has also given invited lectures at Gordon, NSF, and NIH workshops. She also organized numerous ASME symposia and served as chair of the composites committees of both the Applied Mechanics division and the Materials division of the ASME. She has been serving as associate editor of the ASME *Journal of Engineering Materials and Technology* since 2000.

Sanford S. Sternstein received his Ph.D. in chemical engineering in 1961 from Rensselaer Polytechnic Institute and joined the Rensselaer faculty in chemical engineering shortly thereafter. In 1976 he was appointed the William Weightman Walker Professor of Polymer Engineering in the Materials Science and Engineering Department. He also served from 1987 to 2003 as director of the Center for Composite Materials and Structures, which coordinated composite activities on the campus, including the Composite Sailplane Program, which began in 1976. Professor Sternstein's research interests focus on the physics and physical and mechanical properties of polymers and composites, and particularly on viscoelastic behavior, dynamic mechanical spectroscopy, polymer-filler interactions, inhomogeneous swelling theory, thermal conductivity, and instrumentation for rheological measurements. Dr. Sternstein has also investigated the dynamic behavior of ceramic single fibers and their creep rates at temperatures to 1600ºC in custom equipment developed in his laboratory. In this investigation, techniques used for many years to characterize polymers are being applied to ceramic fibers. Currently he is investigating the mechanisms of reinforcement and damping in nanofilled elastomers and melts as related to filler surface characteristics and volume fraction, and the intrinsically nonlinear viscoelastic behavior of polymers at large shear strains.

Appendix B

Frequently Used Abbreviations

CAI	Composite Affordability Initiative
CFRP	carbon-fiber-reinforced polymers
CMC	ceramic matrix composite
DOD	Department of Defense
EMI	electromagnetic interference
FAA	Federal Aviation Administration
FEA	finite element analysis
FRP	fiber-reinforced polymers
GFRP	glass-fiber-reinforced polymers
HSR	high-speed research
ITAR	International Trade and Arms Regulations
MIL-HDBK	the former military handbook
NASA	National Aeronautics and Space Administration
PMC	polymer matrix composite
RF	radio frequency

Appendix C

Why Polymers Are More Susceptible Than Other Materials to Environmental Damage

S.S. Sternstein

Polymer matrix composites are highly susceptible to damage when used in various environmental extremes. This susceptibility results from a number of physical factors common to polymers in general and to the interface (or interphase, as appropriate) between the matrix and the reinforcing fibers.

Cohesive energy density, or intermolecular binding energy density, is a primary factor for polymer matrixes. This energy is very low in polymers compared to metals or ceramics. In polymers, the intermolecular forces binding polymer molecules together are classified as weak, meaning that these forces arise from bonds that are typically less than 5 kilocalories per mole. These include London dispersion forces,[1] hydrogen bonds, and an assortment of dipolar and induced-dipolar intermolecular van der Waals forces that govern the interactions between two noncovalently bound atoms or molecules. These weak bonds are classified as secondary bonds when compared, for example, to the strong primary (20 to 80 kcal/mole) intermolecular bonds within metals or ceramics or to the intramolecular carbon-carbon backbone bonds holding the polymer molecule together. Note that these are also weak when compared to chemical crosslinking in a thermoset polymer matrix.

This structure, with very stiff (strong) bonding along the chain and very soft (weak) bonding among chains, leads to anisotropy that is observed in the polymeric matrix. The combination of weak and strong bonding leads to the polymer's complex deformation and flow behavior. Very long polymeric chains cannot simply translate past each other, as is the case for metallic atoms, but rather must allow each other to interdiffuse in a cooperative manner. This behavior is described by the term “reptation,” as it is symbolic of the way that snakes (reptiles) move across a surface. The ability to reptate is a very strong function of the ability of the chain to change its conformation, and this in turn is a strong function of temperature, because temperature governs the weak intermolecular forces.

For polymers, then, the weak intermolecular forces control chain conformation and therefore determine physical properties. This is especially important when interactions with the environment are considered, including moisture and other chemical species. In polymers, entropy changes associated with chain conformation are thermodynamically comparable with internal energy changes. This situation is seen in metals or ceramics only at very high temperatures—for example, at the melting point or at the glass transition temperature.

The weak intermolecular bonding in polymers leads to a correspondingly higher homologous temperature, which is the ratio of actual absolute temperature divided by the absolute glass transition temperature. In other words, a polymer at room temperature displays physical characteristics that are relatively speaking much closer to glass transition behavior than an inorganic glass at room temperature. In the case of inorganic silicate glasses, the strong intermolecular forces lead to glass transition temperatures that are typically many hundreds of degrees higher than typical glass transition

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[1] The London dispersion force is an attractive force between atoms or molecules caused by the numerous transient dipoles resulting from electronic superposition.

temperatures in the weakly bonded polymers. Indeed, attempts to synthesize polymers with higher glass transition temperatures (e.g., above 250ºC) usually involve (1) very stiff backbone polymers with greatly reduced conformational mobility or (2) very highly crosslinked polymers, which effectively replace weak intermolecular bonds with strong (covalent) intermolecular bonds. In either case, polymers with higher glass transition temperatures tend to behave more like inorganic glasses than polymeric glasses, primarily because of the polymer molecule's reduced ability to conform, leading to a reduced or eliminated ability to reptate.

Semicrystalline polymers follow the same pattern—that is, these polymers at room temperature are at much higher homologous temperatures than are metals at room temperature. Metals, of course, have much higher melting points owing to their higher intermolecular binding energies relative to polymers. Therefore, whether they are semicrystalline, amorphous, or crosslinked, polymers display behavior that is consistently representative of high homologous temperatures when compared to metals or ceramics.

For metals, high-temperature behavior (e.g., high-temperature creep) typically refers to behavior at temperatures higher than 0.5 of the melting point. It should be no surprise then that polymers at room temperature are already at high homologous temperature insofar as their behavior is concerned. For polymers, interactions that do not occur at low temperatures are to be expected at room temperature. Conversely, in the case of metals vacancies are known to exist at all temperatures but have little interactive effect at room temperature. Only at high temperatures is the vacancy concentration sufficient to allow edge dislocations to climb (move perpendicular to the slip plane). This climb is the result of the diffusion of atoms at the edge of the dislocation into adjacent vacancy sites. The result is higher dislocation mobility and greatly increased creep rates. At lower temperatures, the required diffusion process is too slow to provide significant climb, and this eliminates the enhanced creep rate. At room temperature, climb is essentially nonexistent and the interactions between vacancy concentration and dislocation mobility vanish. Thus a metal at room temperature exhibits "low" homologous temperature behavior.

A somewhat analogous situation exists in polymers when the glass transition temperature is approached, in that the greatly increased conformational diffusion rate leads to increased reptation rates. It should therefore be no surprise that the diffusion rate of small foreign molecules (e.g., from the environment) through the polymer is greatly increased as the glass transition temperature is approached or exceeded. In effect, the increased mobility of the polymeric chains provides the equivalent of "vacancies," which facilitate the diffusion of the small foreign molecules. This is analogous to high-temperature behavior in a metal except that the polymer may actually be at room temperature! This further illustrates the concept that the sensitivity of polymer matrix composites to their environment is largely a result of the weak intermolecular forces and the resulting high homologous temperatures.[2]

To summarize, the weak intermolecular forces that are responsible for the unique physical properties of polymers (in the present context, most notably their low densities and viscoelastic behavior, including rate dependence, toughness, and ductility) are also responsible for their high sensitivity to their environment. This is illustrated by the fact that high homologous temperatures lead, in general, to conformational entropy related motions that are strongly dependent on temperature and external perturbations such as stress or the presence of foreign diffusing species. The interactive processes that can occur at high homologous temperatures complicate the mechanism-based, predictive modeling of extreme environmental effects on polymer-based composite performance. In effect, the noninteractive "low" homologous temperature regime is rarely encountered in polymer-based composites, and this clearly complicates the environmentally induced physical processes and their modeling. In turn, this makes the proper modeling of the interface even more important, since the complex behavior of the

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[2] This conclusion is perhaps best illustrated by life itself. Consider the contraction of your muscle when you flex your arm. Muscle contraction and extension is known to be the result of a helix coil transition (or change in conformational state) of the muscle macromolecules, and this transition is the result of a tiny electrical impulse and the associated change in local electrolytic environment around the muscle. In other words, muscle motion is all about conformational entropy changes that are enabled by the presence of weak intermolecular bonds. It is noted for completeness that the strongest intermolecular forces in muscle tissue are due to hydrogen bonds, noted earlier to be one of the weak bonds. The hydrogen bond is very sensitive to its environment in that it is highly susceptible to changes in pH or local ionic field. Joule concluded quite correctly from his 19th century experiments on frog muscle contractions that the process was entropic in nature. Unfortunately, the kinetic theory of rubber elasticity (conformational entropy elasticity) was not postulated until around 50 years later; thus, Joule was unable to define in molecular terms the mechanism by which the muscle contraction took place.

matrix by itself may tend to obscure the role (or degradation) of the interface itself. Consequently, deconvolution of observed environmental phenomena into component matrix and interface phenomena may be severely complicated.

Finally, the dominant role played by conformational entropy in the structure and properties of high polymers leads to a huge multiplicity of morphological states having small differences in internal energy but huge differences in conformational entropy, as exemplified by heat-activated shrink wrap used in the electronics industry. This deformation recovery mechanism is entropy driven, with the polymeric chains going spontaneously upon heating from a low entropy state (prestretched and unshrunk) to a higher entropy state (shrunk). In the context of polymeric matrices for composites, the enormous range of morphological states leads to extreme sensitivity of the polymer matrix composite to its processing history and to a concomitant variability in its response to extreme environments. Thus, the “initial,” or baseline, properties of the composite may contain the “entropic memory” of the deformation history to which the matrix polymer was subjected during fabrication of the composite. Once again, this is comparable to the effects of processing history (cold forming, forging, hot drawing) of steel on subsequent properties. However, polymers display even more memory of prior history and a far greater range of morphologies, owing to the importance of conformational entropy.

An excellent example is given by polypropylene, which, depending on tacticity (atactic, syndiotactic, isotactic) and the distribution of tacticity, can exhibit morphologies ranging from completely amorphous to nearly completely crystalline, all at room temperature and without any change in chemical composition! Similar ranges of morphology can be obtained by the incorporation of small amounts of copolymer such as polyethylene. Any effort to develop a database or predictive model for polymer-based composites that does not consider the starting morphology of the polymeric matrix (including effects of prior deformation or processing history) is unlikely to be successful. Once again, recognition of the multidisciplinary character of this activity is scientifically compelling and essential for success.

As is the case with most engineering situations, advantages must be balanced with liabilities. The enormous advantages of polymer-based composites carry with them the added complexities and sensitivities to environmental extremes. Notwithstanding the difficulties, the potential payoff and advantages of environmentally stable, polymer-based composites makes long-term investigations of the type proposed herein not only appropriate but also essential to future engineering missions.

Appendix D

Organizations Interested in Damage in Composite Materials

COMPOSITE MATERIALS

The Adhesion Society
Advanced Composite Materials (ACM) (http://www.vsppub.com/journals/jn-AdvComMat.html)
Aluminum Metal Matrix Composites Consortium (ALMMCC) (http://www.almmc.com)
The American Ceramic Society (ACerS) (http://www.ceramics.org)
The American Composites Manufacturers Association (ACMA) (http://www.cfa-hq.org)
American Concrete Institute (ACI)
  (http://composite.about.com/gi/dynamic/offsite.htm?site=http%3A%2F%2Fwww.aci-int.org%2F)
American Helicopter Society International (AHS)–The Vertical Flight Society (http://www.vtol.org)
American Institute of Aeronautics and Astronautics (AIAA) (http://www.aaia.org)
American Kenaf Society (AKS) (http://kenafsociety.org)
American Society for Composites (ASC) (http://roger.ecn.purdue.edu/~asc/)
The American Society for Nondestructive Testing (ASNT) (http://www.asnt.org)
American Society for Testing and Materials (ASTM) (http://www.astm.org)
American Society of Civil Engineers (ASCE) (http://www.asce.org)
American Society of Mechanical Engineers (ASME) (http://www.asme.org)
American Technion Society (ATS) (http://www.ats.org)
ASM International (ASM) (http://www.asminternational.org)
National Association of Manufacturers (NAM) (http://www.nam.org)
North American Thermal Analysis Society (NATAS) (http://www.natasinfo.org)
Society for Experimental Mechanics (SEM) (http://www.sem.org/TDIV-Composites.asp)
Society for the Advancement of Material and Process Engineering (SAMPE) (http://www.sampe.com)
Society of Automotive Engineers (SAE) (http://www.sae.org/servlets/index)
Society of Manufacturing Engineers (SME) (http://www.sme.org)
Society of Plastics Engineers (SPE) (http://www.4spe.org)

DAMAGE IN COMPOSITE MATERIALS

Advanced Composite Materials (ACM) (http://www.vsppub.com/journals/jn-AdvComMat.html)
The American Ceramic Society (ACerS) (http://www.ceramics.org)
American Society for Composites (ASC) (http://roger.ecn.purdue.edu/~asc/)
The American Society for Nondestructive Testing (ASNT) (http://www.asnt.org)
American Society for Testing and Materials (ASTM) (http://www.astm.org)
American Society of Civil Engineers (ASCE) (http://www.asce.org)
American Society of Mechanical Engineers (ASME) (http://www.asme.org)

POLYMERIC MATERIALS

American Chemical Society (ACS) (http://www.chemistry.org/portal/a/c/s/1/home.html)
American Fiber Manufacturers Association and the Fiber Economics Bureau (http://www.fibersource.com/)
American Mold Builders Association (AMBA) (http://www.amba.org)
American National Standards Institute (ANSI) (http://www.ansi.org/)
American Plastics Council (APC) (http://www.plastics.org/s_plastics/index.asp)
American Society for Mass Spectrometry (ASMS) (http://www.asms.org)
American Society for Plasticulture (ASP) (http://www.plasticulture.org/)
American Society for Quality (ASQ) (http://www.asq.org)
American Society for Testing and Materials (ASTM) (http://www.astm.org)
American Society of Mechanical Engineers (ASME) (http://www.asme.org)
ASM International (ASM) (http://www.asminternational.org)
Association of Rotational Molders (ARM) (http://www.rotomolding.org/)
Automotive Industry Action Group (AIAG) (http://www.aiag.org)
Automotive Recyclers Association (http://www.autorecyc.org/)
Film and Bag Federation (FBF) (http://www.plasticbag.com/)
Flexible Packaging Association (http://www.flexpack.org/)
Future Scientists and Engineers of America (FSEA) (http://www.fsea.org/)
Industrial Designers Society of America (IDSA) (http://idsa.org)
International Association of Plastics Distributors (IAPD) (http://www.iapd.org/)
I.T. Quarnstrom Foundation (http://www.itqfoundation.org/)
National Association of Manufacturers (NAM) (http://www.nam.org)
Polymer Processing Society (PPS) (http://www.poly-eng.uakron.edu/pps/)
Society of Plastics Engineers (SPE) (http://www.4spe.org)
The Society of Rheology (SOR) (http://www.rheology.org/sor/)
The Society of Vacuum Coaters (SVC) (http://www.svc.org)

World Wide Web Resources for Composite Materials, by Serge Abrate, is a very useful summary. Available at <http://www.egr.msu.edu/classes/me426/liu/WEBSITES/webresource.pdf>. Accessed February 2005.

Appendix E

Survey of Some Computational Models for Failure, Damage, and Degradation in Composite Materials

Code	General Survey	Detailed Information	Note
ABAQUS	General-purpose finite-element package with wide variety of element types, suitable for analysis of laminate shells and nonlinear behavior of polymeric materials.	General-purpose, extensive finite-element package with wide variety of element types suitable for analysis of laminate shells and nonlinear behavior of plastics. Currently, ABAQUS utilizes the virtual crack closure technique (VCCT), which has been used by Boeing and plays an important role in the design of aero structures involving composites. Development of this implementation of the VCCT was sponsored by the Composite Affordability Initiative, of which Boeing is a member. Boeing has filed a patent application for this implementation of the VCCT, and ABAQUS, Inc., will market the technology.	Commercial code
Algor	General-purpose, low-cost finite-element package with composite elements. Extensive information available online, including case studies and tutorials.	General-purpose, low-cost, finite-element package with composite elements. Tons of info online, including case studies and tutorials. Use their search engine.	Commercial code
Analysis of Progressive Failure in Laminated Composites		This work was done by David W. Sleight of Langley Research Center. For further information, access the technical support package free online at <http://www.nasatech.com> under materials category L-17660. A computational methodology for predicting the initiation and propagation of failures in laminated matrix/fiber composite material structures has been developed. The	Laboratory

Code	General Survey	Detailed Information	Note
		methodology follows the progressive-failure approach, in which it is recognized that a laminated composite structure can develop local failures or exhibit such local damage as matrix cracks, fiber breakage, fiber/matrix debonds, and delaminations under normal operating conditions and that such damage can contribute to the eventual failure of the structure. The ability to predict the initiation and growth of such damage is essential for predicting the performances of composite structures and developing reliable, safe designs that exploit the advantages offered by composite materials.	
ANSYS	A general finite-element package comparable in capabilities to NASTRAN. Most online info is in pdf format.	A method for incorporating a damage model for composite structures into the ANSYS general-purpose, finite-element program was developed using MRLife, a damage model developed at Virginia Polytechnic Institute and State University. The damage model was incorporated into a subroutine linked to ANSYS, creating a life prediction system in which entire composite structures can be evaluated for damage using realistic geometry and loading.	Commercial code
bmi3	Buckling analysis of composite shells, including postcritical path, using ABAQUS. Free executable for DEC/Alpha and SGI UNIX. Site includes full text paper, which documents the program.		
COSMOS/M	Mid-range, general-purpose package from SRAC. Information available onsite. Primarily for PCs but available on some workstations.	Mid-range, general-purpose package from SRAC. It has included several different modules, such as advanced nonlinear analysis, stress and displacement analysis, buckling and frequency analysis, heat transfer analysis, dynamic response analysis, fatigue analysis, and design optimization. This package has been used for analysis of failure in composite materials.	Commercial code

(continued)

Continued

Code	General Survey	Detailed Information	Note
DYNA3D	Using user-defined material (UDM), the package can be used for composite/plastic analysis.	A finite-element code developed at Lawrence Livermore National Laboratory. The composite damage model used was for progressive damage of polymer matrix composites as developed at the Stanford University composites and structures group. The DYNA3D code used is an explicit three-dimensional finite-element code for the nonlinear dynamic analysis of materials and structures. The composite damage model used is based on the work of Fu-Kuo Chang and the thesis project of Iqbal Shahid (1993). The implementation of the model into DYNA3D was performed by Steven Kirkpatrick as an independent research project with the assistance of Prof. Chang and Dr. Shahid.	Laboratory
Dynamic Composite Simulator module of LS-DYNA		This enhancement to LS-DYNA enables the most effective and accurate dynamic progressive failure modeling of composite structures currently available. The integration of this module, known as MAT 161, into LS-DYNA allows users to account for progressive damage of various fiber, matrix, and interplay delamination failure modes. Implementing this code will result in the ability to optimize the design of composite structures, with significantly improved survivability under various blast and ballistic threats.	Commercial code
FEMAP	General pre- and postprocessor for finite-element analysis. Not a solver itself but interfaces with 20 different programs. Has a good interface for defining laminates. SDRC also offers structural and thermal solver modules based on the I-DEAS engine.		
GENOA	Structural analysis, part manufacturability, virtual testing, micromechanics. Supports braids, weaves, laminates, stitched laminates.	GENOA was selected to receive the Software of the Year award from NASA in 1999 for its unique predictive capabilities of aging and failure of structural materials. Dedicated to the high-speed analysis of next-generation materials, the GENOA software	Commercial code

Code	General Survey	Detailed Information	Note
		package employs cutting-edge technology from the fields of composites, structures, and parallel computing sciences to deliver unequaled performance and analytical capability directly into the hands of today's engineers. This package can calculate the equivalent material properties of metallic, polymer, and ceramic composites. Evaluates the structural and material response, including life cycle, degradation of material properties due to initiation, location of failure, and growth of damage under in-service operations and environments (static, dynamic, thermal, creep, impact, and low/high/random frequency cyclic fatigue). Identifies the percent contribution of various possible composite failure modes. Predicts the inspection interval, incipient damage locations, and margins of safety.	
I-DEAS	Full-featured CAD system from SDRC, including built-in FEA (or use as a pre- and postprocessor for other systems). Powerful laminates module with a sometimes awkward interface.		
INERTIA	Modular finite-element package from Meridian Marketing. Parametric modeler; structural, dynamic, and thermal analyses; and more.		
LAMPAT	Finite element pre- and postprocessor for analyzing thick composite laminates. Integrates with PATRAN. Originally developed by the U.S. Army Research Laboratory.		
LUSAS A	Collection of finite-element programs, including bridge, structural, civil, composite, and analyst (for general FEA). Detailed product descriptions and case studies.		

(continued)

Continued

Code	General Survey	Detailed Information	Note
MAC/GMC (Micromechanics Analysis Code with Generalized Method of Cells)		This code was authored by NASA Glenn Research Center. MAC/GMC is a comprehensive, user-friendly, efficient computer program that predicts the elastic and inelastic thermomechanical responses of continuous and discontinuous composite materials with arbitrary internal microstructures and reinforcement shapes. It enables the efficient analysis of composite structures subjected to complex thermomechanical load histories. MAC/GMC won second place in the 1997 NASA Software of the Year competition and has been applied in industrial, government, and academic settings to such diverse composite-material structures as turbine parts, tires, and even brain tissue.	Laboratory
MECANO	Software for nonlinear analysis, including structures, mechanisms, and cables.		
MRLife		MRLife calculates the residual or remaining strength during the application of cyclic loading and compares this value to the failure function. As cyclic loading is applied, the remaining strength will decrease as a result of damage to the composite material. The failure function is based on the applied loading and the known strength of the composite. When the remaining strength decreases enough so that it reaches the value of the failure function, failure of the composite occurs. MRLife predicts the residual life at any time in addition to predicting failure.	Commercial code
MSC. NASTRAN		MSC.NASTRAN can be efficiently and effectively used to model laminated composites. MSC.NASTRAN allows the user to specify the material properties, orientation, and thickness for each lamina in the composite layup. The program then calculates the properties of the equivalent plate. This automatic representation of laminated composites is available in all MSC.NASTRAN solution sequences; however, stresses, strains, and failure indices can be recovered at the lamina	Commercial code

Code	General Survey	Detailed Information	Note
		level for only statics, normal modes, and nonlinear statics. In addition, MSC.NASTRAN can be used for multidisciplinary structural optimization of laminated composite materials.	
MSC.PATRAN	MSC's pre- and postprocessor, compatible with several codes. Specialized modules include a materials database and a laminate modeler.	MSC.PATRAN laminate modeler is an MSC.PATRAN 2003 application module to aid engineers in the design, analysis, and manufacture of laminated composite structures.	Commercial code
NASTRAN	PC NASTRAN compatible with FEMAP. ME/NASTRAN included for full-feature support.		
PDALC (Progressive Damage Analysis of Laminated Composite)		PDALC is a computational model implemented in the NASA COMET finite-element code. The relationship employed in this analysis describes the matrix crack damage and fiber fracture via kinematics-based, volume-averaged variables. Damage accumulation during monotonic and cyclic loads is predicted by damage evolution laws for tensile load conditions. The implementation of this damage model required the development of two testbed processors. The damage accumulation, stress redistribution, and changes to the global response that occur during the load history can be calculated for laminates subjected to monotonic and cyclic loads.	Laboratory
Pro/ MECHANICA	The simulation portion of Pro/ENGINEER. Full analysis can be run within Pro/E, or it can be used with an external solver. It has the capability to solve laminated shells.		
RESTRAN (Residual Strength Analysis of Impact Damaged Composite Laminates)		This code is developed at the Army Research Laboratory at Aberdeen Proving Ground in Maryland. A general predictive methodology for determining residual strength in impact-damaged composite laminates has been developed and incorporated into a computer code designated RESTRAN (REsidual STRength ANalysis). RESTRAN is a finite-element-based design tool that can analyze composite structures with arbitrary three-dimensional geometry, loading and	Laboratory

(continued)

Continued

Code	General Survey	Detailed Information	Note
		support conditions, material properties, and initial material and delamination damage. Material failure modes are predicted using a robust suite of failure criteria and damage laws. Structural failure as a result of sequential sublaminate buckling of delaminated layers is also accounted for. A progressive failure analysis is performed until ultimate structural failure is predicted, thereby yielding an estimate of the residual strength. This report contains a user's manual for the RESTRAN program with complete descriptions of input statements and program output. Several examples are shown to illustrate the use of the RESTRAN computer code.	
SOLVIA	General-purpose finite-element program with integrated pre- and postprocessor. Laminate and concrete elements.		
STAGS	An open-source finite-element program for general-purpose analysis of shell structures.	STAGS 2.0 is a finite-element program for general-purpose analysis of shell structures. STAGS can be applied to linear systems, but its forte is the analysis of complex, nonlinear systems that depend on post-buckling strength and require analysis well into the postbuckled regime. It is routinely used for pre- and post-test verification of complex systems, especially those sensitive to initial geometric imperfections. Analysis capabilities include stress, stability, vibration, and transient analyses, with both material and geometric nonlinearities permissible. Shells may be thin or thick, with or without stiffeners, which may be modeled either as beams or as shells. The availability of numerous wall fabrication and stiffener-cross-section options, combined with a variety of material models, permits tremendous flexibility in modeling a wide spectrum of construction types. Isotropic and orthotropic materials are permitted. Easily defined standard wall types include laminate composite, permitting up to 100 layers of arbitrary orientation, and corrugation-stiffened composite. STAGS has been under	

Code	General Survey	Detailed Information	Note
		continuous development since the 1960s by Lockheed's Research and Development Division.	
STRANAL-PMC (Strain Rate Dependent Analysis of Polymer Matrix Composites)		This program was written by Robert K. Goldberg of Glenn Research Center and is available free online at <http://www.nasatech.com/tsp> under the Software category. This computer program is for analyzing strain-rate-dependent, nonlinear deformation and failure responses of composite materials in which the matrices are ductile polymers. Modified versions of the Ramaswamy-Stouffer constitutive equations of viscoplasticity, originally developed for metals, are used to represent deformation of a polymeric matrix. The equations are applied in a micromechanical approach, in which each unit cell is divided into several slices. Appropriate uniform stress and uniform strain assumptions, along with the constitutive equations for the fiber and matrix, are used to compute the response of the slice. Laminate theory is then applied to obtain the effective response of a ply and is applied again to obtain the effective response of a multilayered composite laminate. To predict the ultimate strength of each composite ply, the Hashin failure criteria are implemented within the micromechanics. The constitutive equations are integrated in time by a Runge-Kutta technique. The inputs to STRANAL-PMC are the geometry of the composite laminate, the properties of the fiber and matrix materials, and the applied stress or strain versus time. The outputs of STRANAL-PMC are the stress and strain at the slice, ply, and laminate levels at each time step.	Laboratory
SYSPLY	Finite-element program for design and optimization of composite structures. Extensive capabilities include micromechanics, 3D stresses, winding options, and more.		

Appendix F

Roadmapping Process

The following is included as a guide to future roadmapping activities, as recommended in Chapter 4.

BEFORE THE WORKSHOP

- Define the scope of the roadmap.
    - —Define the charter, mission, system boundary, scope, and team participants.
    - —Identify priority focus areas.
- Recruit leaders and experts.
    - —Identify all stakeholder groups.

AT THE WORKSHOP

- Hold inclusive sessions.
    - —Provide overviews of focus areas.
    - —Hold panel discussions.
        - ▪ Describe facts, issues, challenges, and opportunities.
        - ▪ Differentiate between facts and assumptions.
    - —Conduct open brainstorming session.
        - ▪ Welcome all input.
        - ▪ Forecast any and all candidate technologies, projects, goals, barriers, ideas.
        - ▪ Identify overarching groups of ideas and transfer them to breakout sessions.
- Hold breakout sessions.
    - —Refine and add to list of potential roadmap elements.
        - ▪ Identify long-term goals, midterm targets, and near-term achievables.
        - ▪ Identify gaps and showstoppers in the existing technology.
    - —Time-phase near-term (0-2 years), mid-term (2-7 years), and long-term (>7 years) activities.
        - ▪ Include sample elements:
            - –When a product characteristic will be achieved,
            - –When a technology goal will be reached,
            - –When a basic research project will begin and end,
            - –When an applied research project will begin and end,
            - –When a processing/manufacturing technology will be needed,
            - –When a technology demonstration is warranted,

      - –When clinical trials will being and end, and
      - –Others.
  - —Network roadmap elements.
    - Identify critical paths, higher-level goals, and decision points.
    - Identify fundamental research with the greatest potential for multiple impacts.
    - Point out critical capabilities as focal points for R&D priority.
    - Highlight specific opportunities for partners and projects, programs, and partnerships.
    - Find highest risks and highest payoffs.
    - Identify relevant barriers as they affect these goals and paths forward.

WITH ROADMAP IN HAND

- Critique and validate.
  - —Refine product and technology definitions.
  - —Gather data to back up any uncertainties or assumptions made in roadmapping process.
  - —Develop consensus on needs and actions.
- Develop implementation plan.
  - —Focus resources on roadmap elements with the most promise.
  - —Leverage resources to accomplish the roadmap goals.
    - Coordinate with other organizations.
    - Identify common elements and synchronize timelines.
- Communicate goals and planning.
  - —Utilize professional societies, parallel organizations.
  - —Review and update as needed.

Appendix G

Attendees at the July 2004 Workshop

COMMITTEE MEMBERS

L. Catherine Brinson, *Chair*
Northwestern University

Kenneth L. Reifsnider, *Vice Chair*
University of Connecticut

Paul A. Bartolotta
NASA Glenn Research Center

Matthew B. Buczek
GE Aircraft Engines

John W. Davis
The Boeing Company

Norman J. Johnston (retired)
NASA Langley Research Center

Ann Marie Sastry
University of Michigan

Sanford S. Sternstein
Rensselaer Polytechnic Institute

LIAISON TO THE NATIONAL MATERIALS ADVISORY BOARD

Linda Schadler
Rensselaer Polytechnic Institute

OTHER PARTICIPANTS

Fred Arnold
Air Force Research Laboratory

Scott Case
Virginia Tech

Steven Donaldson
Air Force Research Laboratory

Dana Granville
Army Research Laboratory

Richard Hall
Air Force Research Laboratory

David Koshiba
The Boeing Company

Bruce LaMattina
Army Research Laboratory

Charles Lee
Air Force Office of Scientific Research

Hugh McManus
Metis Design

Mary Ann Meador
NASA Glenn Research Center

Ozden Ochoa
Air Force Research Laboratory

Robert Rapson
Air Force Research Laboratory

Warren Ronk
GE Aircraft Engines

Erol Sancaktar
University of Akron

Greg Schoeppner
Air Force Research Laboratory

Chad Snyder
National Institute of Standards and Technology

Katie Thorp
Air Force Research Laboratory

Tia Benson Tolle
Air Force Research Laboratory

NRC STAFF

Toni Marechaux
Laura Toth