NASA SUMMARY OF RESEARCH REPORT

Project Title:

COMPUTATIONAL MATERIALS RESEARCH

Grant No.:

NCC-1-270

Total Award:

$20,964.00

PI Name: David R. Veazie

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Technical Monitor: Dr. Thomas S. Gates

Duration of Grant: 1 Years

Start Date: 15 December 97

End Date: 14 December 98

Technical Objectives:

High temperature thermoplastic polyimide polymers are incorporated in engineering structures in the form of matrix materials in advanced fiber composites and adhesives in bonded joints. Developing analytical tools to predict long term performance and screen for final materials selection for polymers is the impetus for intensive studies at NASA and major industry based airframe developers. These fiber-reinforced polymeric composites (FRPCs) combine high strength with lightweight. In addition, they offer corrosion and fatigue resistance, a reduction in parts count, and new possibilities for control through aeroelastic tailoring and "smart" structures containing fully-integrated sensors and actuators. However, large-scale acceptance and use of polymer composites has historically been extremely slow. Reasons for this include a lack of familiarity of designers with the materials; the need for new tooling and new inspection and repair infrastructures; and high raw materials and fabrication costs.

In response to the four aforementioned technical challenges, Clark Atlanta University proposed a project to address some of these reasons. This project involved predicting the static and long-term behavior of FRPCs by a finite element micromechanics model to indirectly account for molecular weight and cross-linked density of the polymeric matrix. The result is an integrated predictive computer model that bridges the constitutive (fiber/matrix) and effective (overall) descriptions of unidirectional FRPCs and thereby significantly reduce development costs. The model utilizes both experimental data and predictions of other models. A closed form analytical solution is the ultimate goal as well as to develop the pathway to bring physical and microstructural information into the realm of the design engineer.

Technical Approach:

1. *Data correlation from momentary resin tests:* Creep compliance testing was performed on neat LaRC-SI resin to provide material constants for the predictive model. This short-term (momentary) data will be fit to a three parameter model. The dissipative part of the material behavior is defined by giving the Prony series expansion representation of the normalized shear and bulk relaxation moduli,

$$g_R(t) = \frac{G_R(t)}{G_o} = 1 - \sum_{i=1}^{N} \bar{g}_i^P \left(1 - e^{-t/\tau_i}\right) \tag{1}$$

$$k_R(t) = \frac{K_R(t)}{K_o} = 1 - \sum_{i=1}^{N} \bar{k}_i^P \left(1 - e^{-t/\tau_i}\right) \tag{2}$$

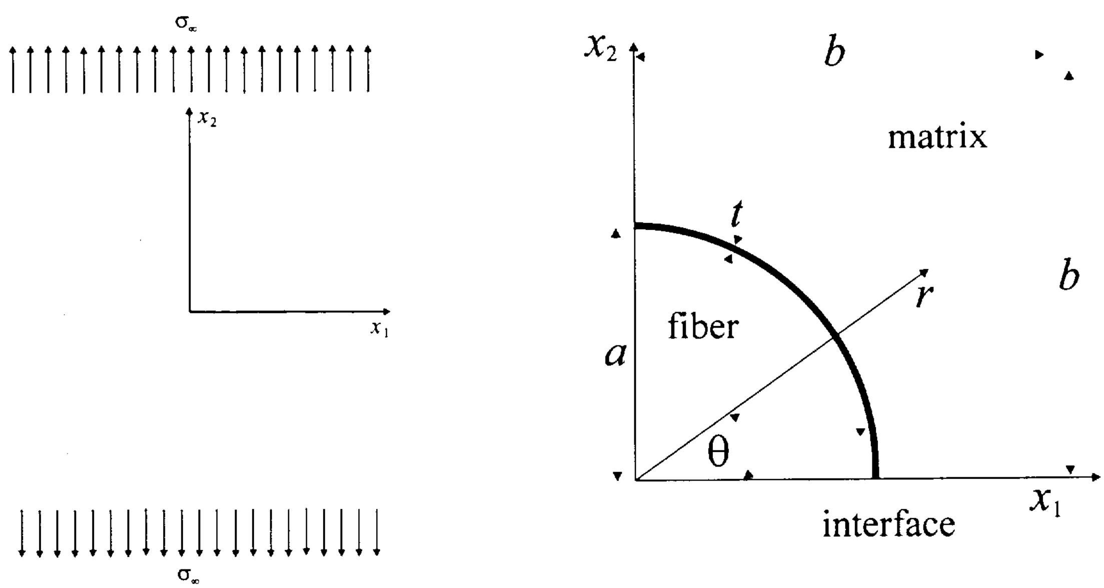
to be used by the finite element formulation. G_o and K_o are the instantaneous shear and bulk moduli (from the Young's Modulus E and Poisson's Ratio ν), and $\bar{g}_i^P$, $\bar{k}_i^P$, and τ_i are the Prony series parameters. These parameters are determined from the experimental creep test data in the form of compliance-time pairs. The influences of molecular weight and cross-linked density on the physical aging and short-term momentary properties are represented in the prony series constants. The creep compliance data are converted to relaxation modulus data through the convolution integrals

$$\int_0^t g_R(\tau) J_s(t-\tau)\,d\tau = t \tag{3}$$

$$\int_0^t k_R(\tau) J_k(t-\tau)\,d\tau = t \tag{4}$$

where the relaxation data are then used in a nonlinear least squares fit to determine the Prony series parameters.

2. *Finite element simulations:* In this study, a unidirectional composite is modeled and a square array packing of circular cross-section fibers is assumed. A schematic of the cross-section of the unidirectional fiber reinforced composite is shown Fig. 1a, and for a normal load applied in the x_2-direction, the composite is subjected to plane strain deformation. Furthermore, due to symmetry and the periodicity of fiber spacing, the state of stress and deformation in the composite can be completely defined by the stresses and strains in a quarter region of a unit cell as shown in Fig. 1b.



(a) (b)

Figure 1. (a) Transverse cross-section of the composite and (b) the quarter unit cell.

It can be easily verified that the proper boundary conditions on the quarter unit cell shown in Fig. 1b are given by

$$u_2(x_1,0)=0\,,\quad \tau_{12}(x_1,0)=0\,,\quad \text{for } 0\le x_1\le b \tag{5.1a,b}$$

$$u_2(x_1,b)=d_2\,,\quad \tau_{12}(x_1,b)=0\,,\quad \text{for } 0\le x_1\le b \tag{5.2a,b}$$

$$u_1(0,x_2)=0\,,\quad \tau_{12}(0,x_2)=0\,,\quad \text{for } 0\le x_2\le b \tag{5.3a,b}$$

$$u_1(b,x_2)=d_1\,,\quad \tau_{12}(b,x_2)=0\,,\quad \text{for } 0\le x_2\le b \tag{5.4a,b}$$

where $d1$ and $d2$ are constants that need to be determined from the solution procedure. Of course, the stresses and displacements in the quarter unit cell must satisfy the equilibrium, compatibility and the constitutive equations. The fibers are modeled as isotropic, linear elastic solids, and a perfect fiber/matrix interface is assumed.

3. *Static predictions:* The finite element micromechanics model was used to analyze the static behavior (stiffness) of the LARC-SI based composite as a function of the variations in the SI

based properties. The modeling effort included the effects of the process-induced residual stresses. Process-induced residual stress in composites is essentially thermal in nature, and is caused by a significant mismatch in the coefficients of thermal expansion between the fiber and the matrix with large temperature differential during the cooling process. By the use of the finite element method, a numerical analysis for the basic cell provides results for the micromechanical fields of stress and the macromechanical properties of the unidirectional fiber reinforced composite under process-induced residual stresses.

4. *Long-term predictions:* Through the use of the finite element method, the momentary creep compliances of the composite were found. A model which uses a time dependent form influenced by the ongoing physical aging process, along with an effective time that is used to replace time provided the long term compliance predictions.

Research Accomplishments:

The finite element micromechanics model was used to predict the static behavior (stiffness) of the LARC-SI based composite IM7/LaRC-SI as a function of the variations in the LaRC-SI based properties. In Figure 1 for example, the Young's Modulus in the transverse direction is predicted for the IM7/LaRC-SI composite using input from the neat SI resin. As shown in Figure 2, the long term viscoelastic compliance is predicted for IM7/LaRC-SI composite using momentary data from neat LaRC-SI. All these results are in functions of temperature and molecular weight (or cross-linked density in terms of % offset). Results were obtained for five different molecular weights of the IM7/LaRC-SI composite and for up to five different testing temperatures.

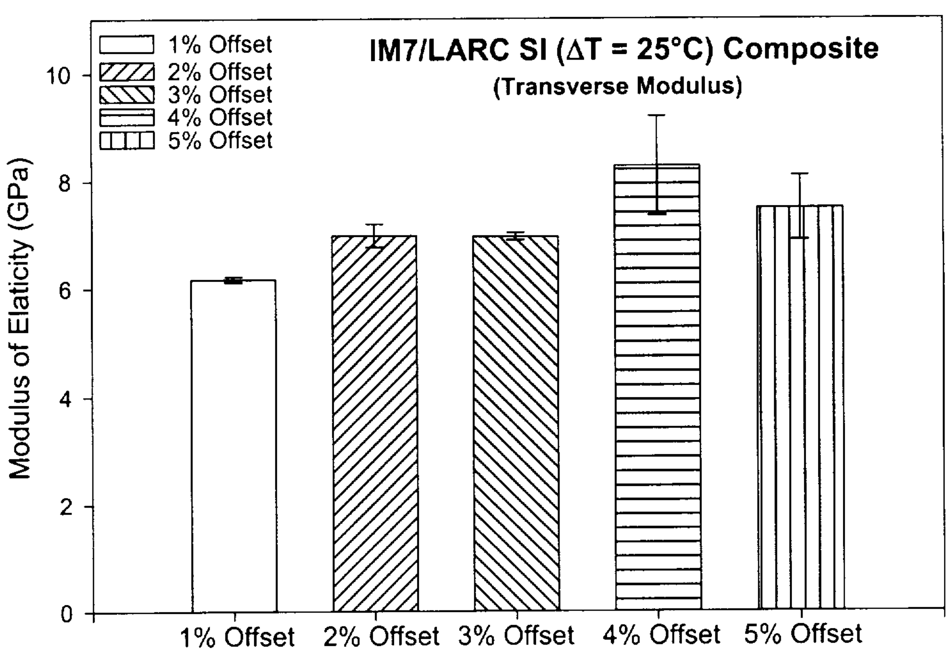


Figure 1. Transverse modulus predictions for the IM7/LaRC-SI Composite at $\Delta T = 25^{o}C$.

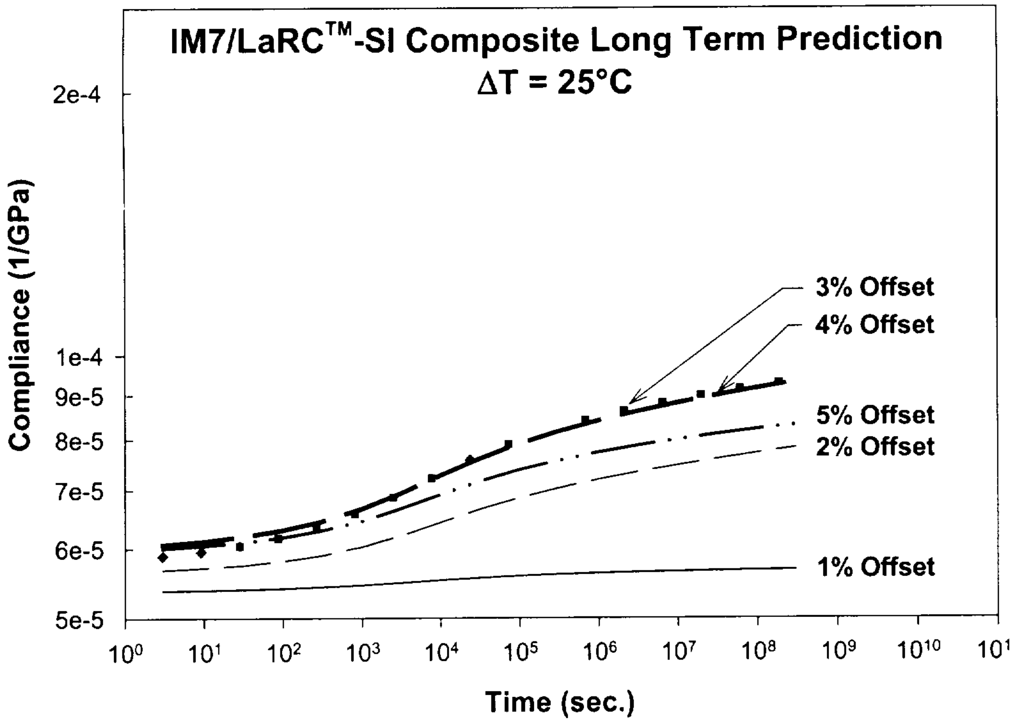


Figure 2. Long term viscoelastic predictions for the IM7/LaRC-SI Composite at $\Delta T = 25^{o}C$.

Impact, Uniqueness, Benefits to Society, and Relevance to the Aeronautics Enterprise:

This funding enabled Dr. Veazie and an undergraduate student to conduct experimental and analytical research to explore the viscoelastic constitutive relationship between elevated temperature exposure and the change in mechanical properties that will lead to improved high-performance, high temperature structural polymer matrix composite materials. The funding allowed Dr. Veazie's mainstream research to focus on the development of accelerated test methods and life prediction methodology for the long term durability of polymer matrix composites for potential use on commercial aircraft, high-speed aircraft, and military vehicles.

Methods unique to this research include the development and use of a finite element micromechanics model to predict the long term viscoelastic behavior of PMC's using the time dependent properties of the matrix material as input. The long term viscoelastic behavior of a unidirectional composite was modeled using the momentary creep compliance experimental results from the neat matrix material.

Interactions/collaborations with NASA Center Investigators:

Collaborations: Dr. Thomas S. Gates
NASA Langley Research Center

Dr. Gates has been influential in the experimental methods and modeling efforts of Dr. Veazie for several years. Collaborations on projects including Durability Modeling Development for the

HIGH SPEED RESEARCH PROGRAM and Micromechanics Modeling and Computational Materials for the AIRCRAFT MORPHING PROGRAM are ongoing.

Collaborations: Mr. Shannon C. Arnold
NASA Langley Research Center

Mr. Arnold has collaborated with Dr. Veazie on the processing of polymer matrix composites including resin transfer molding of composites. Mr. Arnold has also provided some of the composite materials used in this research.

Collaborations: Dr. Joycelyn Simpson
NASA Langley Research Center

Dr. Simpson has been instrumental in providing direction for graduate researchers under Dr. Veazie's supervision in the processing of advanced polyimides. These graduate students have visited NASA-LaRC to work with Dr. Simpson in her laboratory.

Interactions/collaborations with U.S. Industry Investigators:

Collaborations: Mr. Ronald Zabora
The Boeing Commercial Airplane Group

Collaborations with Mr. Zabora include issues concerning the materials, experimental methods and procedures for durability modeling development for Boeing projects including the HIGH SPEED CIVIL TRANSPORT. Topics including fracture mechanics and viscoelastic properties of laminated composites, bonded joints, and hybrid composite laminates have been studied.

Collaborations: Dr. Jim Criss
Lockheed/Martin

Dr. Criss has collaborated with Dr. Veazie on the resin transfer molding of advanced polyimide resins and composites.

Interactions/collaborations with other NASA PIs:

Interactions: Dr. C. T. Sun
Purdue University

Interactions with Dr. Sun has been ongoing for the past few years. Dr. Sun recently organized a special ASTM Symposium on Time-Dependent and Nonlinear Effects in Polymers and Composites of which the Dr. Veazie was a presenter. Dr. Sun's project DYNAMIC AND NONLINEAR RESPONSE AND FAILURE IN THICK-SECTION COMPOSITES AND LAMINATES has been influential in the development and progression of Dr. Veazie's project.

Transitions (Accomplishments being used by others, especially Government Laboratories and U.S. Industries)

NASA Langley Research Center
Dr. Thomas S. Gates

Experimental methods and modeling efforts from this research has been useful on projects including Durability Modeling Development for the HIGH SPEED RESEARCH PROGRAM.

The Boeing Commercial Airplane Group
Mr. Ronald Zabora
Mr. Ronan Cunningham

Composite material characterization, experimental methods and procedures from this research has been influential for composite structures and durability modeling development for the Boeing project HIGH SPEED CIVIL TRANSPORT.

Lockheed/Martin Aerospace Systems
Dr. Jim Criss

Processing methods to improve the durability of advance polymer matrix composite materials have been collaborated with Dr. Criss. Durability testing was performed in the hopes of demonstrating that resin transfer molded composites will be useful as structures for the F22 Fighter Aircraft.

Awards, Honors:

1. Best Student Paper - Third Place - (Christie Gooch) GEM Summer Institute's 1998 GEM Conference, Ft. Lauderdale, FL, July 15 - 18, 1998. (The Effects of Processible Additives on the Long Term Behavior of Advanced Polyimide Resins)

2. Dr. David R. Veazie: Publications Editor (Mechanical and Industrial Engineering), National Technical Association (NTA), appointed 1997.

Refereed Publications (*Students*):

- Veazie, D. R., Badir, A. M., and *Grover, R. O.* (1998), Titanium Ply Effects on the Behavior of a Hybrid Thermoplastic Composite Laminate, *Journal of Thermoplastic Composite Materials,* **11**, No. 5, September 1998, pp. 443-454.

- Veazie, D. R., and Gates, T. S. (1998) Tensile and Compression Creep of a Thermoplastic Polymer and the Effects of Physical Aging on the Composite Time-Dependent Behavior, ***ASTM – STP 1357****, Time Dependent and Nonlinear Effects in Polymers and Composites.*

Publications (Students)/Presentations (*by Students*):

- *Gooch, C.* and Veazie, D. R. (1998), "The Effects of Processible Additives on the Long Term Behavior of Advanced Polyimide Resins", *Proceedings of the GEM Summer Institute's 1998 GEM Conference*, July 15 - 18, 1998, Ft. Lauderdale, FL.

- Veazie, D. R., Garrett, L. W., Harruna, I., and Gooch, C. (1998), Effects of Additives on the Rheological Properties of Polyimides for Composites, *Proceedings of the International Community for Composites Engineering Fifth Annual Conference*, July 5 - 11, 1998, Las Vegas, NV. p. 917.

- Veazie, D. R., and Gates, T. S. (1998), Effects of Aging-Time Reference on the Long Term Behavior of the IM7/K3B Composite, *Proceedings of the AIAA/ASME/ASCE/AHS/ACS 39th Structures, Structural Dynamics and Materials Conference*, April 20 – 23, 1998, Long Beach, CA.

- *Garrett, L.,* Harruna, I. and Veazie, D. R. (1998), Synthesis and Characterization of Bisamic Acid and Bisimide Additives to Reduce the Melt Viscosity of Polyimides, *Proceedings of the NASA URC-TC '98 Conference*, February 22 - 26, 1998, Huntsville, AL.

Participants in research grant: (PI, Grad Students, Undergraduate Students; specify minority/female participants)

Principal Investigator:	David R. Veazie (Minority – African American)
Undergraduate Student:	Charmin Roundtree (Female, Minority – African American)
Undergraduate Student:	Genine Bryant (Female, Minority – African American)

Other Grants/Contracts during Funding Period: (agency, title, period, budget)

P.I. Veazie

Fracture Toughness Testing of Aged Bonded Joints Under Fatigue for Titanium Graphite Hybrid Laminates

Grant No. 0375538	Boeing	7/15/98-5/14/99	$15,000

P.I. Veazie

Impact Damage and Residual Strength of Structural Composites

Grant No. N00014-97-1-0832	ONR	07/01/97-7/01/99	$230,000

P.I. Veazie

Computational Materials - Macro-Level Composite Modeling

Grant No. NAG-1-1919	NASA	05/01/97-12/01/97	$13,591