

Final Report to the

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION  
GLENN RESEARCH CENTER AT LEWIS FIELD

for

**Life Modeling and Design Analysis for Ceramic Matrix Composite Materials**

OAI-01-140

Federal ID Number 34-1621676

**Modeling and Testing**

The primary research efforts focused on characterizing and modeling static failure, environmental durability, and creep-rupture behavior of two classes of ceramic matrix composites (CMC), silicon carbide fibers in a silicon carbide matrix (SiC/SiC) and carbon fibers in a silicon carbide matrix (C/SiC).

An engineering life prediction model (Probabilistic Residual Strength model) has been developed specifically for CMCs. The model uses residual strength as the damage metric for evaluating remaining life and is posed probabilistically in order to account for the stochastic nature of the material's response. In support of the modeling effort, extensive testing of C/SiC in partial pressures of oxygen has been performed. This includes creep testing, tensile testing, half life and residual tensile strength testing. C/SiC is proposed for airframe and propulsion applications in advanced reusable launch vehicles. Figures 1 and 2 illustrate the models predictive capabilities as well as the manner in which experimental tests are being selected in such a manner as to ensure sufficient data is available to aid in model validation.

Experimental observations (see Figure 3) have shown the degradation of strength of C/SiC in an oxidizing environment to be a function of time at 1200 °C and to be dependent upon both time and applied stress at an intermediate temperature of 800 °C.

Additional recent tests have investigated the effects of various "enhancements" touted by the material manufacturer. Results include creep rupture data for C/Enhanced SiC with an external CBS (carbon-boron-silicon) coating,

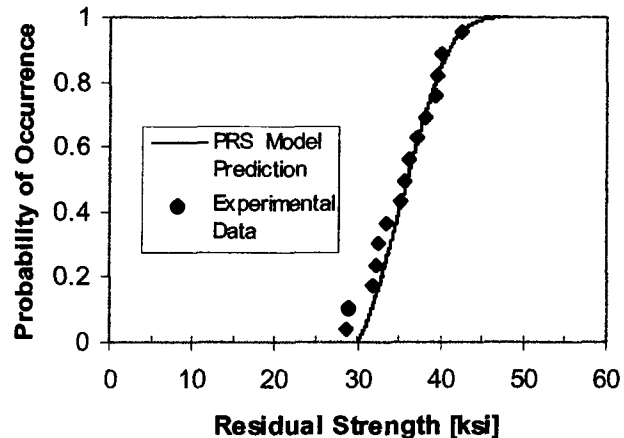


Fig. 1: Residual strength of C/SiC after 15 hrs, 30 ksi, 1200 °C, 1000 ppm O<sub>2</sub> exposure.

which were obtained at 800 and 1200 °C. The “enhancement” in this material is boron carbide, which is put in the composite matrix in order to protect the carbon fibers from oxidation. The external CBS coating was applied as an attempt to provide additional environmental durability for the C/SiC material. Tests were conducted using a stress of 30 ksi, and in an environment of 1000 ppm O<sub>2</sub>/Ar. The CBS coated C/Enhanced SiC had a life at 1200 °C of 350 hours, which is 7X longer than the life of the uncoated C/Enhanced SiC. However, at 800 °C, the average life of the CBS coated C/Enhanced SiC was 13.7 hours, which is 12% of the average life of the same material without the CBS coating (113.2 hours). The standard C/SiC, which has neither matrix enhancement nor an external coating, had an average life at 800 °C which was 5X longer than the CBS-coated C/Enhanced SiC material.

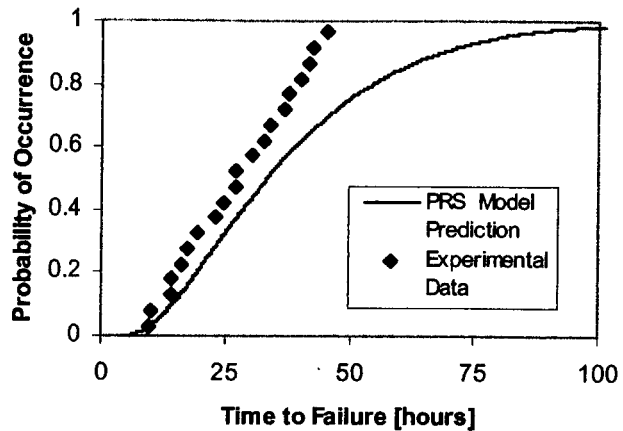


Fig. 2: Time to failure of C/SiC after 15 hrs, 30 ksi, 1200 °C, 1000 ppm O<sub>2</sub> exposure.

Also, a multitude of tests, both creep and tensile, have been performed on SiC/SiC in air. This testing supports development of SiC/SiC for turbine engine combustor liners. SiC/SiC combustor liners have been fabricated and engine-tested for land-based turbine engines and similar activities are in progress for aircraft turbine engines. Exploratory Creep rupture tests in air were also carried out for SiC/SiC to evaluate composite life with both the baseline boron nitride (BN) and silicon-doped BN interphases. The silicon dopant was introduced to act as an oxygen getter to improve oxidation resistance. Two levels of Si doping were evaluated.

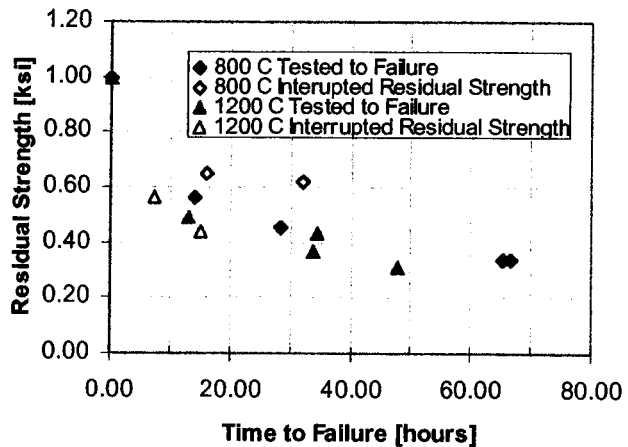
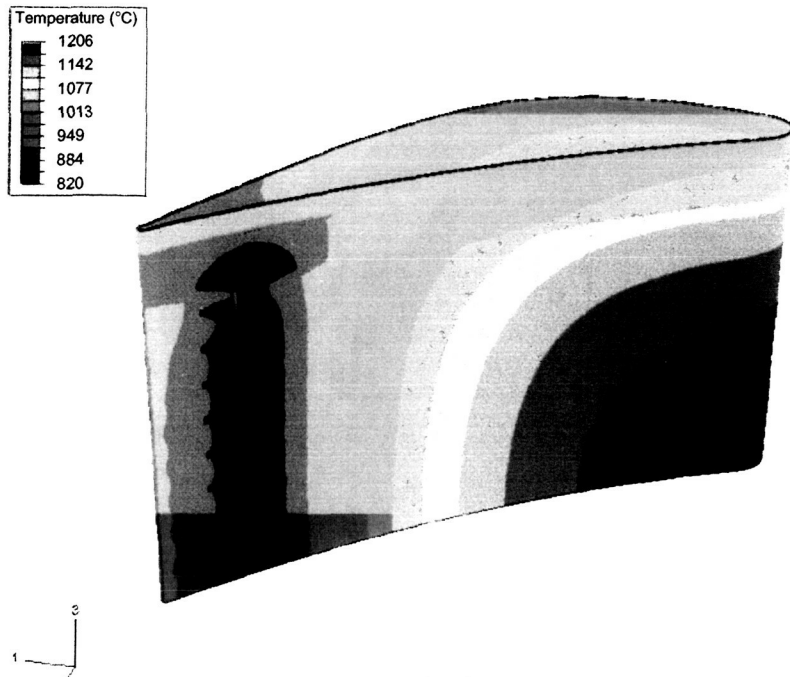


Fig. 3: Results of C/SiC strength measurements made in 1000 ppm O<sub>2</sub> environment. Interrupted tests initially held at 30 ksi for time shown.

## Analysis

Finite element analysis of CMC structures has also been carried out under this cooperative agreement.

As part of a CMC vane development effort in NASA Glenn's UEET Program, CMC vanes are currently being tested in the High Pressure Burner Rig Facility located at Glenn. The vane test conditions have been modeled and thermal and structural analyses have been performed. Figure 4 illustrates thermal results for a CMC vane with trailing edge cooling. Trailing edge cooling holes are a recent addition to the prototype vanes as well as the analysis.



**Figure 4** Finite element analysis results for temperature profile on CMC vane tested in NASA Glenn's High Pressure Burner Rig.

Under the NGLT effort for the X-37 vehicle, hybrid panels comprised of a CMC face sheet bonded to a high temperature foam core were investigated for leading edge applications. Analyses were performed to evaluate residual stresses present due to processing issues related to CTE mismatch between candidate materials.

## Summary

All information (experimental data, theoretical models, analytical results) has been delivered to the NASA technical monitor through one of the publications or presentations listed below, or through daily informal interaction.

## Publications

1. Thomas, D.J., "Probabilistic Residual Strength Model for Stress Rupture of SiC/SiC Composites" to be published in ASME Journal of Engineering for Gas Turbines and Power.
2. Stephen F. Duffy, Lesley A. Janosik, Andrew A. Wereszczak, Akihiko Suzuki, Jacques Lamon, and David J. Thomas, "Chapter 25: Life Prediction of Structural

Components” in **PROGRESS IN CERAMIC GAS TURBINE DEVELOPMENT Ceramic Gas Turbine Component Development and Characterization, Volume II** edited by Mark van Roode, Mattison K. Ferber, and David W. Richerson, published by ASME Press, 2003.

3. Michael Verrilli, Anthony Calomino, and David Thomas, “Stress/Life Behavior of a C/SiC Composite in a Low Partial Pressure of Oxygen Environment Part I: Static Strength and Stress Rupture Database”, *Ceramic Engineering and Science Proceedings*, vol. 23, issue 3, pages 435-442, 2002.
4. Anthony Calomino, Michael Verrilli, and David Thomas “Stress/Life Behavior of a C/SiC Composite in a Low Partial Pressure of Oxygen Environment Part II: Stress Rupture Life and Residual Strength Relationship”, *Ceramic Engineering and Science Proceedings*, vol. 23, issue 3, pages 443-451, 2002.
5. David Thomas, Michael Verrilli, and Anthony Calomino, “Stress/Life Behavior of a C/SiC Composite in a Low Partial Pressure of Oxygen Environment Part III: Life Prediction Using Probabilistic Residual Strength Rupture Model”, *Ceramic Engineering and Science Proceedings*, vol. 23, issue 3, pages 453-460, 2002.
6. Thomas, D.J., "Design and Analysis of UHTC Leading Edge Attachment," NASA/CR 2002-211505 (2002).

### **Presentations**

1. Thomas, D.J. and Srivastava, R., “Analysis of CMC Vanes Subjected to Gas Turbine Environment Testing,” presented at the 27<sup>th</sup> Annual Conference on Composites, Materials and Structures (*U.S. Only/ITAR-Restricted Sessions*), January 27-31 2003, Cocoa Beach/Cape Canaveral, Florida.
2. Stanley Levine, Anthony Calomino, Michael Verrilli, David J. Thomas, Michael Halbig, Elizabeth Opilia, and John R. Ellis, “Ceramic Matrix Composites (CMC) Life Prediction Development - 2003”, NASA TM-2003-212493, August, 2003. Also to appear in *The Proceedings of the 27th Annual Conference on Composites, Materials, & Structures*, held in Cocoa Beach, Fl, January 27-31, 2003.
3. Thomas, D.J., Verrilli, M.J. and Calomino, A.C., “Stress Rupture Life Prediction of C/SC Composites Using Probabilistic Residual Strength Model,” presented at 26<sup>th</sup> International Conference on Advanced Ceramics and Composites, Cocoa Beach, Florida, USA, January, 2002.
4. Calomino, A.C., Verrilli, M.J. and Thomas, D.J., “Stress-Rupture Life and Residual Strength Relationship for a Carbon Fiber-Reinforced Silicon Carbide (C/SiC) Ceramic Matrix Composite,” presented at 26<sup>th</sup> International Conference on Advanced Ceramics and Composites, Cocoa Beach, Florida, USA, January, 2002.

5. Verrilli, M.J., Calomino, A.C. and Thomas, D.J., "Strength and Stress-Rupture Database for a Carbon Fiber-Reinforced Silicon Carbide (C/SiC) Ceramic Matrix Composite in a Low Partial Pressure of Oxygen," presented at 26<sup>th</sup> International Conference on Advanced Ceramics and Composites, Cocoa Beach, Florida, USA, January, 2002.
6. Levine, S.R., Verrilli, M.J., Thomas, D.J., Halbig, M.C., Calomino, A.M., Ellis, J.R. and Opila, E.J., "Ceramic Matrix Composites (CMC) Life Prediction Development," presented at 26<sup>th</sup> Annual Conference on Ceramics Metal and Carbon Composites, Materials and Structures, Cocoa Beach, Florida, USA, January, 2002.
7. Thomas, D.J., "Probabilistic Residual Strength Model for Stress Rupture of SiC/SiC Composites" given at ASME Turbo Expo Conference, New Orleans, LA (June 2001).
8. Thomas, D.J., "Probabilistic Residual Strength Model- Approach, Capabilities and Results" presented at IHPTET Symposium Workshop Session on CMC Component Life Prediction, Dayton, OH (September 2000).