Design analysis and thermo-mechanical fatigue of a polyimide composite for combustion chamber support

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Polyimide composites are being evaluated for use in lightweight support structures designed to preserve the ideal flow geometry within thin shell combustion chambers of future space launch propulsion systems. Principles of lightweight design and innovative manufacturing techniques have yielded a sandwich structure with an outer face sheet of carbon fiber polyimide matrix composite. While the continuous carbon fiber enables laminated skin of high specific stiffness; the polyimide matrix materials ensure that the rigidity and durability is maintained at operation temperatures of 316 °C. Significant weight savings over all metal support structures are expected.

The prototypical structure is the result of ongoing collaboration, between Boeing and NASA-GRC seeking to introduce polyimide composites to the harsh environmental and loads familiar to space launch propulsion systems. Design trade analyses were carried out using relevant closed form solutions, approximations for sandwich beams/panels and finite element analysis. Analyses confirm the significant thermal stresses exist when combining materials whose coefficients of thermal expansion (CTEs) differ by a factor of about 10 for materials such as a polymer composite and metallic structures. The ramifications on design and manufacturing alternatives are reviewed and discussed.

Due to stringent durability and safety requirements, serious consideration is being given to the synergistic effects of temperature and mechanical loads. The candidate structure operates at 316 °C, about 80% of the glass transition temperature $T_g$. Earlier thermomechanical fatigue (TMF) investigations of chopped fiber polyimide composites made this near to $T_g$, showed that cyclic temperature and stress promoted excessive creep damage and strain accumulation. Here it is important to verify that such response is limited in continuous fiber laminates.

A comparison of the isothermal and thermomechanical fatigue of stitched and unstitched cross-ply laminates of M40J carbon fiber reinforced polyimide is being made. Test waveforms for thermal and mechanical load cycles were chosen to be representative of the combustion chamber operation cycle. Deformation and stiffness degradation due to fatigue loading is monitored during each fatigue test. Residual strength testing and microscopic observations are being made to quantify the extent of the damage. Preliminary results are reported including the accelerating influence of TMF and the relative durability of stitched laminates. Guidelines for design of durable support structures are discussed.
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Sponsored by NASA-GRC Aeropropulsion and Power

Improved Thrust/Weight Ratio

- Carbon Fiber/Polyimide Composite
- Titanium Honeycomb
- Estimated ~25% weight reduction
Current Situation

- Rectangular Cross Section
- Thin Metallic Walls
- Inefficient Support
- Stringent Safety Conditions

Agenda Topics

- Design Requirements
- Analytical Methods and Results
- Thermal Mechanical Fatigue: Testing and Results
Benefits

- Improved Thrust/Weight Ratio
- Efficient Design Approach
- Exceeds Tensile Durability Requirements

Design Requirements

- Design wall support of Rect. Pressurized Tube
- 600 °F Degree with 200 °F/sec
- 125 Psi Internal Pressure
- Metallic Wall Deflection < 0.050 in
- Ease of Manufacturing

Improve Engine Thrust/Weight Ratio
Analytical Methods and Results

- Principles of Optimal Lightweight Construction
- Beam Solutions Bound Plate Models
- 2D FE Analysis – Rapid Turn around
- 3D FE Analysis – Enhance Confidence
- Feedback to Materials Durability Requirement

Efficient Design Approach

Rectangular vs Cylindrical Pressure Containment

Efficient Design Approach
**Sandwich Construction:**

*Thin Skin/Flexible Core*

- Optimal Sandwiches: Simple Design Equations
- Faces carry bending as membrane stress
- Core carries transverse force as shear stress

**Flexural Stiffness**

\[ D = \frac{E_f t_f d^2}{2} \]

**Shear Stiffness**

\[ S = \frac{G_c d^2}{t_c} \]

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**Upper Bound Solution for Stress:**

*Simply Supported Beam*

Max Bending Moment and Stress

\[ M_{\text{max}} = \frac{qL^2}{8} \]

Max Shear Force and Stress

\[ T_{\text{max}} = R_L = R_R = \frac{qL}{2} \]

Max Deflection

\[ W_{\text{max}} = \frac{5qL^4}{384D} + \frac{qL^2}{8S} \]

\[ \sigma_{\text{max}} = \frac{qL^2}{8(t_f d)} \]

\[ \tau_{\text{max}} = \frac{qL}{2d} \]
**Beam Sizing Results: t/d = 0.07**

- **Face Sheet Stresses** = 24% UTS
- **Cores Shear Stresses** = 4.7 q
- **Deflection** = 48% Design Allowable

<table>
<thead>
<tr>
<th>Face Sheet Stiffness</th>
<th>% Allowable Deflection</th>
<th>Core Shear Stiffness</th>
<th>% Allowable Deflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
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<td>100%</td>
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<td>50%</td>
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**Efficient Design Approach**

**Candidate Designs**

- Single Face Sheet Design
- Wrapped PMC Faceplate
- HT Adhesive Bonding
- Ti Honeycomb Core

**Efficient Design Approach**

Glenn Research Center at Lewis Field
Single Face Sheet Results

Allowable Deflection: 40%
Face sheet Max Principle Stress: 24%UTS

Efficient Design Approach

Wrapped Face Sheet Results

Allowable Deflection: 38%
Face sheet Max Principle Stress: 23%UTS

Efficient Design Approach
3D FE Results: Single Face Sheet

Allowable Deflection: 26.2%
Face sheet Max Principle Stress: 20% UTS

Efficient Design Approach

Thermal Mechanical Fatigue:
Testing and Results

- Castelli et al: TMF accelerates creep processes
- Synthesis of Temperature and Load Cycle from Operations Cycle
- TMF Rig Set-Up
- At 2 x design load the PMC survives 10 x longer than design life

PMC Exceeds Tensile Durability Requirements
Synthesis of thermo-mechanical fatigue cycle

Boeing Operation Cycle

<table>
<thead>
<tr>
<th>Temperature (°F)</th>
<th>Time (s)</th>
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<tbody>
<tr>
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<td>7200</td>
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<tr>
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<tr>
<td>300</td>
<td>7800</td>
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<tr>
<td>150</td>
<td>8000</td>
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TMF Cycle: Simulated Operations Cycle

<table>
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<th>Stress (ksi)</th>
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<tbody>
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<td>40</td>
</tr>
<tr>
<td>600</td>
<td>30</td>
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<tr>
<td>500</td>
<td>20</td>
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<tr>
<td>400</td>
<td>10</td>
</tr>
<tr>
<td>300</td>
<td>0</td>
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PMC Exceeds Tensile Durability Requirements

Test Rig Set-Up

- Dogbone Specimen
- Extensometer
- Quartz Lamps
- Thermocouple Calibration Block

Edge View

Side View
TMF Compressed Air Cooling Cage and Specimen

Specimen Thermal Response

- Control
- Top
- Middle
- Bottom

Glenn Research Center at Lewis Field
**Strain Response:**

**Isothermal Fatigue and TMF**

**Isothermal Fatigue:**

Strain Response 40 ksi

- Max Strain vs. Time (s)
- Cycle 1 vs. Cycle 500

- 3.5% Secant Modulus Reduction

**Thermal Mechanical Fatigue:**

Strain Response 40 ksi

- Max Strain vs. Time (s)
- Cycle 1 vs. Cycle 500

- 3.6% Secant Modulus Increase

**PMC Exceeds Tensile Durability Requirements**

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**Fatigue Strength:**

**Isothermal and TMF**

**Fatigue Strength**

- % of Tensile Strength vs. Cycles
- Isothermal vs. TMF

**PMC Exceeds Tensile Durability Requirements**
## Conclusion

### Agenda Topics

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### Benefits

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Near term actions: Build & hotfire test at GASL

Long term actions: Apply this knowledge to a broader variety of engine components