

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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Improved Thrust/Weight Ratio

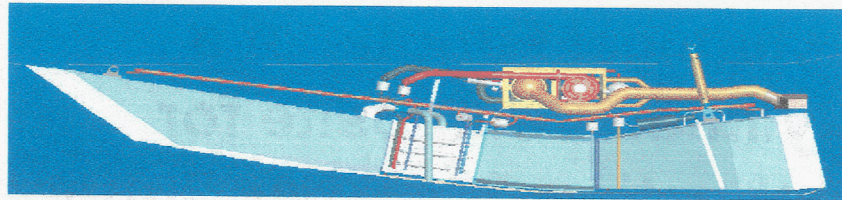
- Carbon Fiber/Polyimide Composite
- Titanium Honeycomb
- Estimated ~25% weight reduction



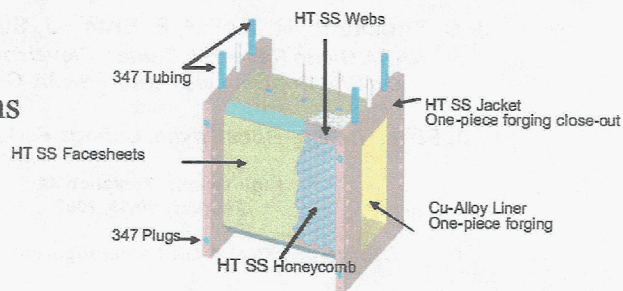
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Current Situation



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



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Agenda Topics

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



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Benefits

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



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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



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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

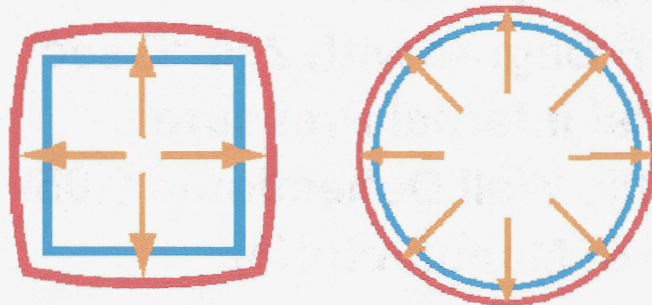
Efficient Design Approach



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Rectangular vs Cylindrical Pressure Containment



Efficient Design Approach

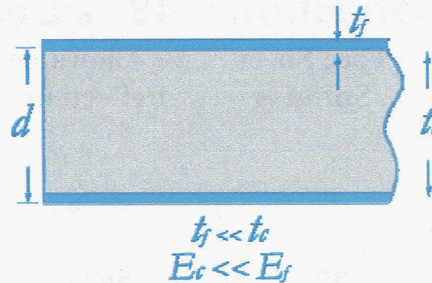


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Sandwich Construction: Thin Skin/Flexible Core

- 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

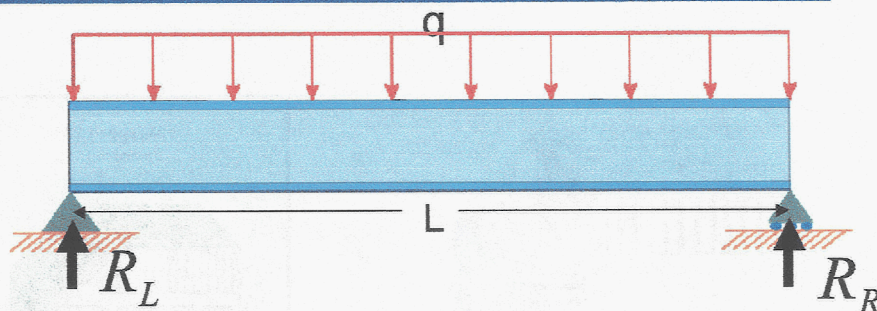
$$S = \frac{G_c d^2}{t_c}$$



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Upper Bound Solution for Stress: Simply Supported Beam



Max Bending Moment
and Stress

$$M_{\max} = \frac{qL^2}{8}$$

Max Shear Force
and Stress

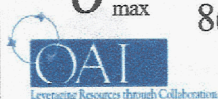
$$T_{\max} = R_L = R_R = \frac{qL}{2}$$

Max Deflection

$$w_{\max} = \frac{5qL^4}{384D} + \frac{qL^2}{8S}$$

$$\sigma_{\max} = \frac{qL^2}{8(t_f d)}$$

$$\tau_{\max} = \frac{qL}{2d}$$



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Beam Sizing Results: $t/d = 0.07$

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

Face Sheet Stiffness	% Allowable Deflection	Core Shear Stiffness	% Allowable Deflection
100%	48%	100%	48%
80%	56%	66%	57%
66%	64%	50%	65%

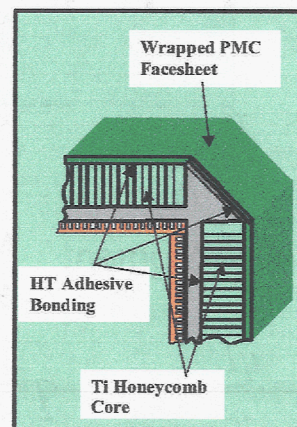
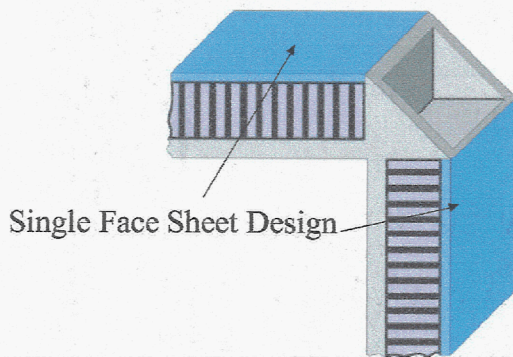
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Candidate Designs



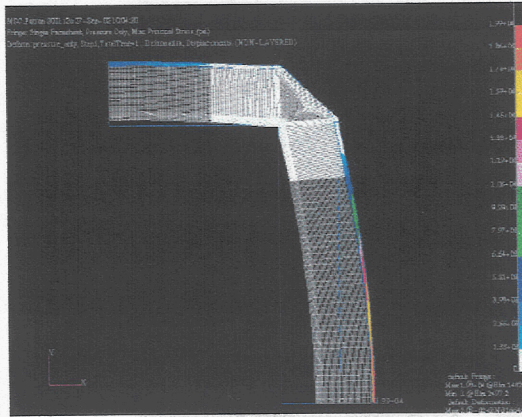
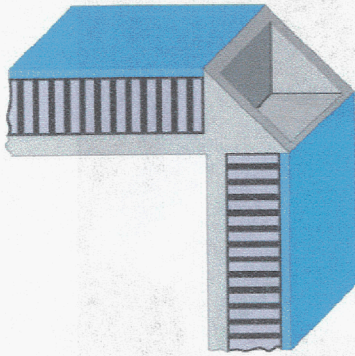
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Single Face Sheet Results



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

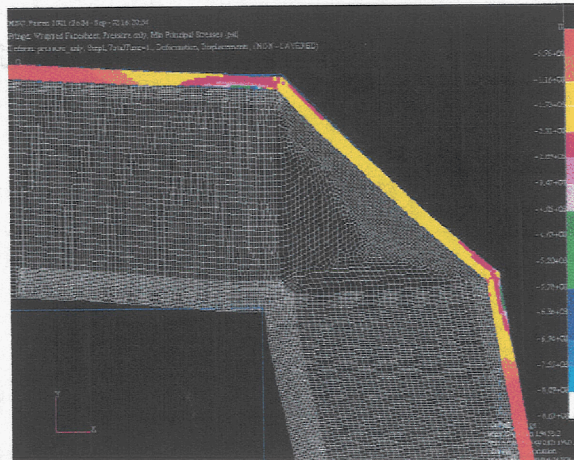
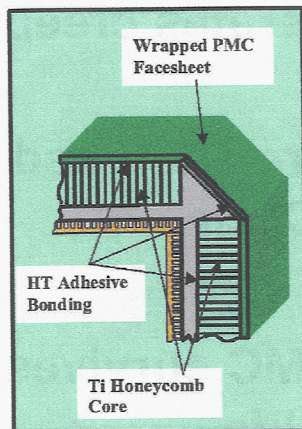
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Wrapped Face Sheet Results



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

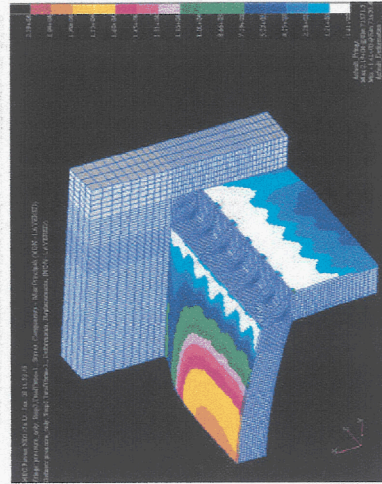
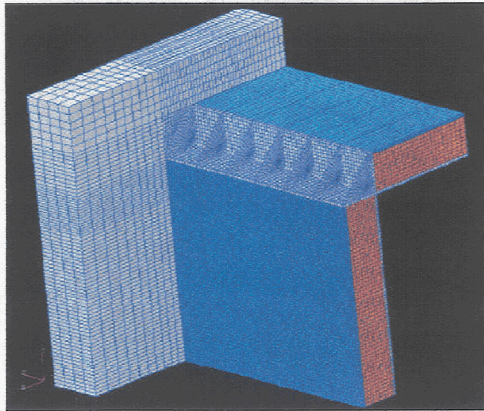
Efficient Design Approach



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3D FE Results: Single Face Sheet



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



Efficient Design Approach

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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

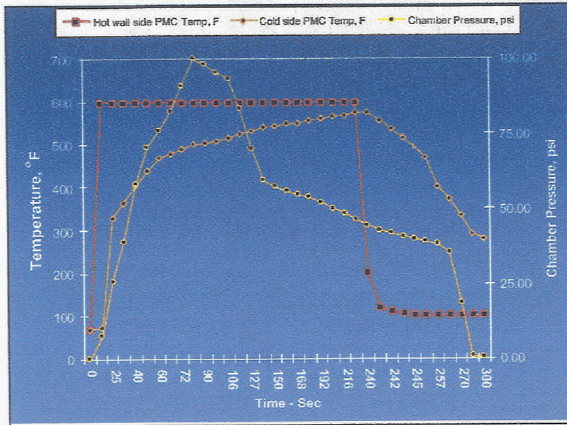


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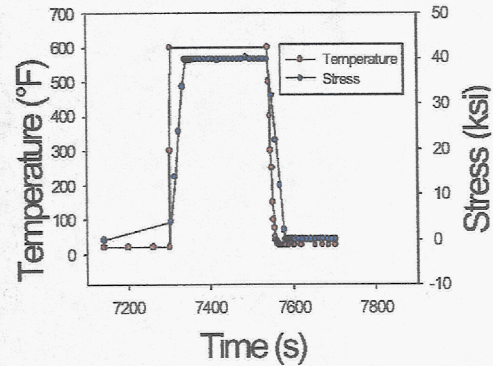


Synthesis of thermo-mechanical fatigue cycle

Boeing Operation Cycle



TMF Cycle: Simulated Operations Cycle



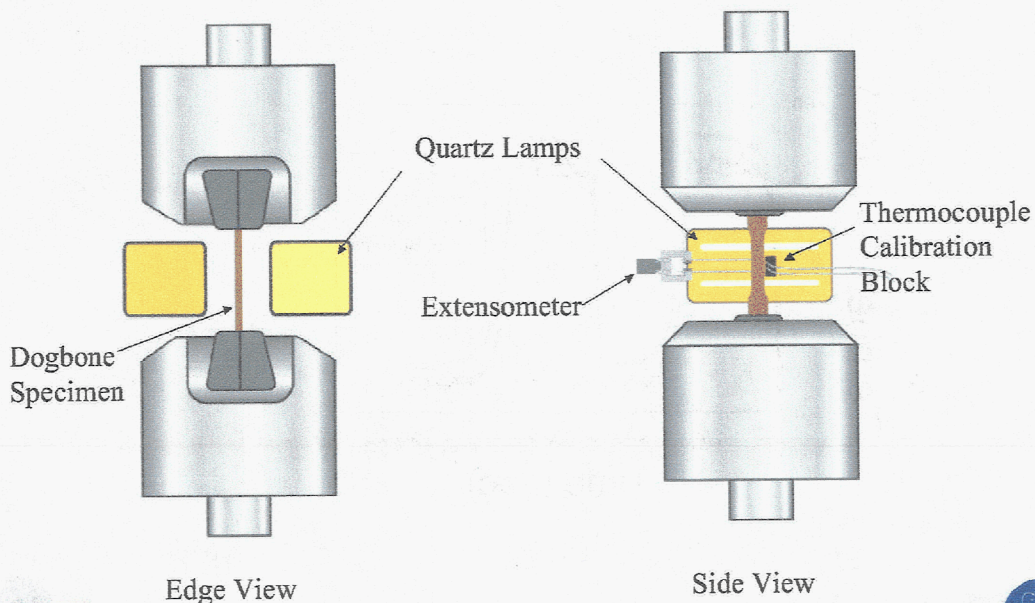
PMC Exceeds Tensile Durability Requirements



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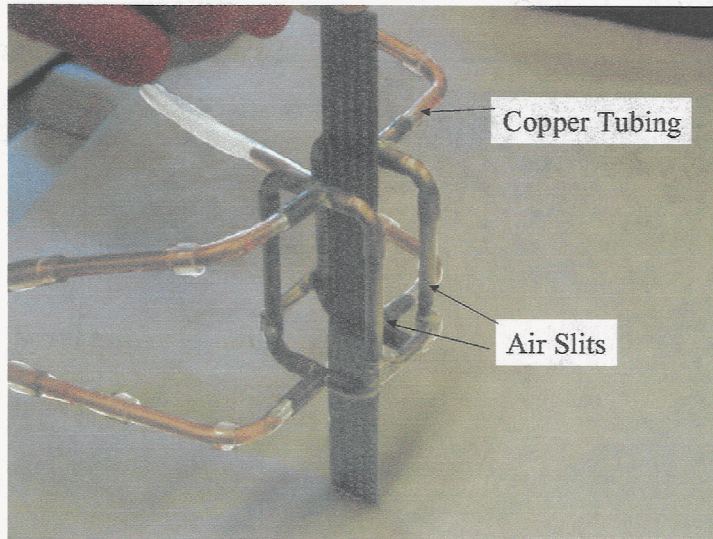
Test Rig Set-Up



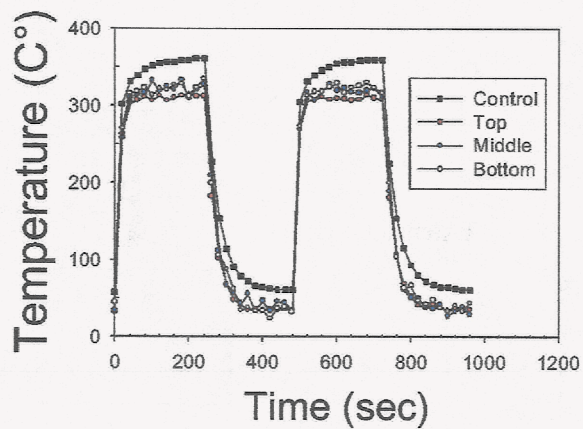
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TMF Compressed Air Cooling Cage and Specimen



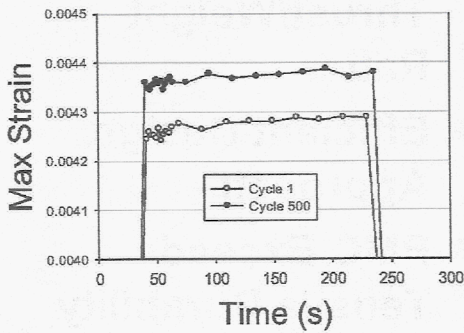
Specimen Thermal Response



Strain Response: Isothermal Fatigue and TMF

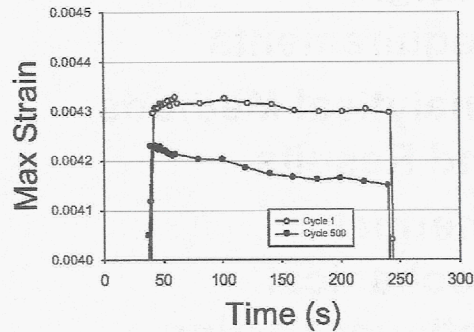
M40J/HFPE II-52: Boeing Stitched Cross-Ply

Isothermal Fatigue:
Strain Response 40 ksi



3.5% Secant Modulus Reduction

Thermal Mechanical Fatigue:
Strain Response 40 ksi



3.6% Secant Modulus Increase

PMC Exceeds Tensile Durability Requirements



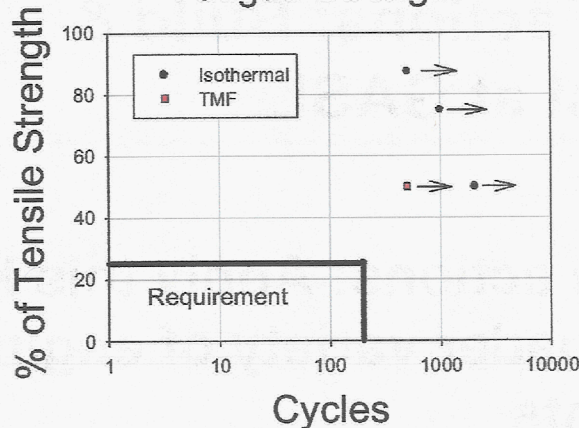
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Fatigue Strength: Isothermal and TMF

M40J/HFPE II-52: Boeing Stitched Cross-Ply

Fatigue Strength



PMC Exceeds Tensile Durability Requirements



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Conclusion

Agenda Topics

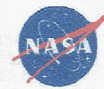
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Benefits

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Near term actions: Build & hotfire test at GASL

Long term actions: Apply this know how to broader variety of engine components



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