Thermal-Mechanical Testing of Hypersonic Vehicle Structures

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U.S. Laboratories for Hot Structures Testing

- Large-scale thermal, structural and dynamic testing
  - Thermal-structural and dynamic analyses
  - High-temperature instrumentation
  - Non-destructive evaluation

Flight Loads Laboratory
NASA DFRC, Edwards, CA

Structures Test Facility, Bldg. 65
AFRL/VA Wright-Patterson AFB, Dayton OH

Structures & Materials Research Laboratory
NASA LaRC, Hampton, VA
**General Description**
- Laboratory for structural and thermal testing of aerospace structures
- Large high-bay test area (164’ x 120’)

**Structural Loading Capabilities**
- Structural loading equipment: load frames, load cells, and hydraulic actuators
- Aircraft ground vibration and structural mode interaction testing
- 84 channels of hydraulic load control

**Thermal Loading Capabilities**
- Vacuum furnaces, low and high temperature chambers, liquid and gaseous nitrogen supply systems
- Quartz lamp and graphite element heating
- 20 MW of available power
- 4000 gal of liquid nitrogen storage for cryogenic testing
- Potential for 512 channels of thermal control

**Data Acquisition Capabilities**
- Potential for 1280 channels of data acquisition
Hot Structures Test Programs (1990’s)

- 1500°F w/ Load: NASP TMC Panels DFRC, 1990-1994
- 2000°F w/ Load: NASP C/C Wing Box AFRL, 1992
- 1200°F w/ Load: NASP TMC Panel Joint Test LaRC, 1993
- 1200°F w/ Load: NASP TMC Splice Joint Panel AFRL, 1993
- 900°F w/ Load: NASP TMC Side Shear Panel DFRC, 1995
- 2250°F w/ Load: AFRL C/C Wing Box AFRL, 1999
Hot Structures Test Programs (2000’s)

- NGLT C/C Control Surface
  - DFRC, March 2003
  - 2000°F w/ Load

- NGLT C/SiC Bodyflap
  - DFRC, Nov 2003
  - 2100°F w/ Load

- X-37 C/SiC Flaperon Subcomponent
  - DFRC, May 2004
  - 2400°F w/ Load

- X-37 C/C Flaperon Qual Unit
  - DFRC, Aug 2005
  - 2500°F

- X-37 C/C Ruddervator Subcomponent
  - AFRL, Sep 2004
  - 2300°F

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**Hot Structures Test Programs**

- **NASP / NGLT Carbon-Carbon Elevon (2003)**
  - Concept validation test of a flight-weight C/C hot structure component
  - Fabricated in 1989 for the NASP Tech Mat program
  - Simultaneous heating and loading to 2000°F and 100% DLL in nitrogen atmosphere
  - 128 quartz-lamp heaters (32 control zones)
    - Approximately 1.5 MW of electrical power
  - Instrumentation
    - 50 thermocouples and 54 strain gages (first hot structure application of fiber optic strain sensors)

Test at 2000°F & 100% DLL
Hot Structures Test Programs

♦ X-37 Carbon-Carbon Flaperon (2005)
  • Thermal & mechanical qualification test of a flight design C/C hot structure control surface
  • Tested in nitrogen purged atmosphere
  • 35 quartz lamp heaters (18 control zones)
  • Instrumentation
    – 82 thermocouples channels (124 on test setup)
    – 14 fiber-optic strain sensors
    – 12 deflection measurements
  • Key test challenges
    – Bonding high-temp instrumentation to C/C
    – Achieving desired boundary conditions
Typical Sequence for Hot Structures Testing

Design / Development
- Aero / Aerothermal Database
- Hot Structure Design
- Hot Structure Modeling & Analysis
- Hot Structure Fabrication
- Hot Structure Test Condition Analysis
- Pre-Test Predictions

Testing
- Test Requirements (loads, boundary conditions, instrumentation, NDE, etc.)
- Test Plan (procedures, lab systems instrumentation, safety, etc.)
- Test Setup Design
- Test Setup Fabrication (PDRs, CDRs)
- Hot Structure Baseline NDE
- Test Setup Instrumentation
- Hot Structure Instrumentation

- Test Setup Assembly
- Test Readiness Review
- Test Execution
- Hot Structure Post-Test NDE
- Test Report
- Hot Structure Design & Model Validation (data correlation)
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15. Test Report
16. Hot Structure Design & Model Validation (data correlation)
17. Pre-Test Predictions
18. Hot Structure Test Condition Analysis
Test Requirements Definition

- Test article description (material, size, type, etc.)
- Type of test (proof, acceptance, qualification, validation, research)
- Type of loading (thermal, mechanical, dynamic, combined)
- Boundary condition definition
- Type of heating system (quartz lamp, graphite)
- Type of test atmosphere (purged, air, level of O₂)
- Test matrix definition (test sequence)
- Instrumentation (type, number, location)
- Handling requirements
- Inspection requirements
- Documentation requirements
Test Setup Development

♦ Goal: Design test setup to simulate desired boundary conditions
  • Heating system to meet desired temperature distribution
  • Mechanical loading system to meet desired pressure distribution

♦ Perform a test condition analysis to include real boundary conditions
  • Provides more representative pre-test predictions
  • Provides best correlation between test data and analysis
**Test Setup Development**

Quartz Lamp Heater

- Aluminum reflector
- Six 2000 W quartz lamps
- Water & gas cooled

\[ T_{\text{max}} \approx 2700^\circ F \]

Current Quartz Lamp Heater Setup

Graphite Heater

\[ T_{\text{max}} \approx 3200^\circ F \]

Graphite Heater Evaluation Test (3100°F)
High-Temperature Instrumentation

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**Issues**
- Hot structures are utilizing advanced materials that operate at temperatures that exceed current ability to measure structural performance
- Robust strain sensors that operate accurately and reliably beyond 1800°F do not exist

**Implications**
- Hinders ability to validate analysis and modeling techniques
- Hinders ability to optimize structural designs
High-Temperature Instrumentation

- **Goal:** Provide valid strain and temperature data to analysts
  - Supports FEM and thermal-structural analysis validation

- **Key Issue:** Develop attachment techniques for strain & temperature sensors on hot structure materials (superalloys, C/C, C/SiC, etc.)
  - Validate attachment techniques through characterization testing

Typical Systems for Sensor Validation Testing
High-Temperature Instrumentation

Evolution of Hot-Structure Strain Measurements

1960-1970

Flame-Sprayed Resistive
Weldable Resistive
Weldable Capacitive

Large thermal outputs and measurement uncertainties

1980-1990

Improved temperature-compensation using flame-sprayed resistive gages

Improved measurement accuracy applying Silica and Sapphire EFPI Technology

>2000

Fiber-Optic Strain Sensor

X-33
NASP
X-37
CEV

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High-Temperature Instrumentation

Fiber Optic Strain Sensor Installation

- Gold-coated silica fiber (125 micron)
- Nextel overbraid
- Ceramic cement
- Plasma/Rokide basecoat
- Max use ≈ 1850°F

Thermocouple Installation

- Ceramic cement
- Plasma/Rokide thermal sprayed basecoat
- C/SiC
- Max use ≈ 2500°F
High-Temperature Instrumentation

- Dryden advanced fiber-optic measurement system for heat shield health monitoring
  - Simultaneous strain and temperature measurements
  - Flight system currently available
    - 480 sensors per optical fiber
    - 2-fiber mode at 35 sps
    - 4-fiber mode at 20 sps
  - Flight testing on Predator B in Sep '07

Proposed Ground Validation Test of Heat Shield Health Monitoring System
Hot Structures NDE

- NDE is an essential part of any hot structures test program
  - Must be able to detect, locate, identify and track defects / damage to fully characterize the hot structure component under test
- IR Pulsed Thermography NDE for high-temperature composite structures (C/C, C/SiC)
  - Locates and maps material delaminations and porosity
  - Locates precise depth of defect
  - Technique improvements are required to better characterize damage in C/C & C/SiC materials
  - Currently looking to develop standards with engineered defects
Current Hot Structures Testing

♦ Objective: Test a C/SiC Ruddervator Subcomponent under relevant thermal, mechanical & dynamic loading

♦ Supports NASA ARMD Hypersonics Material & Structures Program


♦ Test Phases
  • Phase 1: Acoustic-Vibration Testing (LaRC) – completed
  • Phase 2: Thermal-Mechanical Testing (DFRC) – in design / fab
  • Phase 3: Mechanical Testing (DFRC) – in design / fab
  • Phase 4: Thermal-Acoustic Testing (LaRC) – in design
Concluding Remarks

♦ Hot structures are currently finding applications on real vehicles

♦ Current structural sensing technologies do not meet the peak temperature requirements for hot structure applications
  - Innovative sensors are needed
  - Advanced sensor attachment techniques are required
  - Sensor characterization and validation is required

♦ Improved NDE techniques and engineered standards are required to better detect and identify damage in C/C & C/SiC materials

♦ U.S. laboratories must maintain core competencies to effectively meet imminent demands for hot structures testing