Thermal-Mechanical Testing of Hypersonic Vehicle Structures

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U.S. Laboratories for Hot Structures Testing

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

- Flight Loads Laboratory
  NASA DFRC, Edwards, CA

- Structures & Materials Research Laboratory
  NASA LaRC, Hampton, VA

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

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

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

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

- **2300°F**
  - X-37 C/C Flaperon Subcomponent
  - DFRC, Aug 2004

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

- **2500°F**
  - X-37 C/C Flaperon Qual Unit
  - DFRC, Aug 2005
Hot Structures Test Programs

  • 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)
Hot Structures Test Programs

  - 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

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)
Typical Sequence for Hot Structures Testing

1. **Aero / Aerothermal Database**
   - Hot Structure Design
   - Hot Structure Modeling & Analysis
   - Hot Structure Fabrication

2. **Test Requirements** (loads, boundary conditions, instrumentation, NDE, etc.)
   - Test Plan (procedures, lab systems instrumentation, safety, etc.)
   - Test Setup Design

3. **Test Setup Assembly**
   - Test Readiness Review
   - Test Execution
   - Hot Structure Post-Test NDE
   - Test Report

4. **Test Setup Fabrication** (PDRs, CDRs)
   - Hot Structure Baseline NDE
   - Hot Structure Test Condition Analysis
   - Pre-Test Predictions

5. **Test Setup Instrumentation**
   - Hot Structure Instrumentation

6. **Hot Structure Design & Model Validation** (data correlation)

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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

Heating System

Temperature Distribution

Mechanical Loading System

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
$T_{max} \approx 2700^\circ F$
- Aluminum reflector
- Six 2000 W quartz lamps
- Water & gas cooled

Current Quartz Lamp Heater Setup

Graphite Heater
$T_{max} \approx 3200^\circ F$

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

**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

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**Strain Sensor Type**
- Foil Strain Gage
- Weldable Strain Gage
- Wire Wound Strain Gage
- Silica Fiber Optic Strain Gage
- Sapphire FO Strain Gage (in development)

**Difficulty of Installation**
- Low
- Medium
- High

**Difficulty of Use**
- Low
- Medium
- High
**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**

- Dilatometer (3000°F, inert/air)
- High-temp FO sensors on C/C in sampleholder
- Strain Sensor Validation System
  - Loading mandrel
  - LVDT
  - Load bar
  - Clamp
- 3000°F, inert/air
- Thermal Cycling Furnace
  - 3000°F, inert/air

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**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
  - NASP
  - X-33
  - X-37
  - CEV

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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

- Instrumented heat shield (w/out ablator)
- Heating system
- Pressure loading
- Optical fiber
- Fiber bonded to simulated heat shield
- Heat gun
- Thermal Loading

Fiber-Optic Health Monitoring System

Pressure Loading
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