Thermal-Mechanical Testing of Hypersonic Vehicle Structures

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Outline

♦ U.S. Laboratories for Hot Structures Testing
♦ NASA Dryden Flight Loads Laboratory
♦ Hot Structures Test Programs
♦ Typical Sequence for Hot Structures Testing
♦ Current Hot Structures Testing
♦ Concluding Remarks
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

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

Structures & Materials Research Laboratory
NASA LaRC, Hampton, VA
Dryden Flight Research Center

**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

**E2C Hawkeye Loads Calibration Test**

**C/C Elevon Thermal/Structural Test**
NASA Dryden Flight Loads Laboratory

Proof Loading

Loads Calibration

Ground Vibration Testing

Moment of Inertia

Strain Gage Installation

Aerodynamic Heating Simulation

Thermostructural Testing

High-Temp Instrumentation
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

- **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)
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
- Hot Structure Test & Model Validation (data correlation)

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

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Typical Sequence for Hot Structures Testing

1. **Aero / Aerothermal Database**
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6. **Test Requirements** (loads, boundary conditions, instrumentation, NDE, etc.)
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8. **Test Setup Design**
9. **Test Setup Assembly**
10. **Test Readiness Review**
11. **Test Execution**
12. **Hot Structure Post-Test NDE**
13. **Test Report**
14. **Hot Structure Design & Model Validation** (data correlation)

- **Test Setup Assembly**
- **Test Readiness Review**
- **Test Execution**
- **Hot Structure Test Condition Analysis**
- **Test Setup Fabrication (PDRs, CDRs)**
- **Hot Structure Baseline NDE**
- **Test Setup Instrumentation**
- **Hot Structure Instrumentation**
- **Hot Structure Post-Test NDE**
- **Test Report**
- **Hot Structure Design & Model Validation** (data correlation)
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

Current Quartz Lamp Heater Setup
- Aluminum reflector
- Six 2000 W quartz lamps
- Water & gas cooled

Graphite Heater Setup
- Graphite Heater Evaluation Test (3100°F)
- Tmax ≈ 3200°F

Quartz Lamp Heater
- Tmax ≈ 2700°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
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


Flame-Sprayed Resistive

Weldable Resistive

Weldable Capacitive

Large thermal outputs and measurement uncertainties

Improvement in temperature-compensation using flame-sprayed resistive gages

Improved measurement accuracy applying Silica and Sapphire EFPI Technology

NASA  X-33  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

- C/C
- Rokide flame spray
- Plasma spray (2 mils)
- Plasma/Rokide thermal sprayed basecoat
- Ceramic cement
- Max use ≈ 2500°F
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

Pressure Loading
Fiber bonded to simulated heat shield

Heat gun

Thermal 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