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)

- **NGLT C/C Control Surface**
  - DFRC, March 2003
  - 2000°F with load

- **NGLT C/SiC Bodyflap**
  - DFRC, Nov 2003
  - 2100°F with load

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

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

- **X-37 C/C Ruddervator Subcomponent**
  - DFRC, Sep 2004
  - 2500°F

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

- Test Setup Assembly
- Test Readiness Review
- Test Execution
- Hot Structure Post-Test NDE
- Test Report
- Hot Structure Design & Model Validation

Test Requirements:
- (loads, boundary conditions, instrumentation, NDE, etc.)

Test Plan:
- (procedures, systems, instrumentation, safety, etc.)

Test Setup Design:
- Test Setup Fabrication (PDRs, CDRs)
- Test Setup Instrumentation

Aero / Aerothermal Database

Hot Structure Design

Hot Structure Modeling & Analysis

Hot Structure Fabrication

Hot Structure Test Condition Analysis

Pre-Test Predictions
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
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**
  - Tmax ≈ 2700°F
  - Aluminum reflector
  - Six 2000 W quartz lamps
  - Water & gas cooled

- **Graphite Heater**
  - Tmax ≈ 3200°F

- **Current Quartz Lamp Heater Setup**

- **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
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
- X-37
- CEV

Dryden Flight Research Center
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

Quartz tube

- Rokide flame spray
- Plasma spray (2 mils)
- Plasma/Rokide thermal sprayed basecoat

Thermocouple Installation

- 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
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

Phase 1

Phase 2

Phase 3

Phase 4

C/SiC Ruddervator Subcomponent
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