NASA SUBSONIC ROTARY WING PROJECT - STRUCTURES AND MATERIALS DISCIPLINE

Michael C. Halbig
Army Research Laboratory, NASA Glenn Research Center
Cleveland, OH, USA

Susan M. Johnson
NASA Glenn Research Center
Cleveland, OH

Abstract
The Structures & Materials Discipline within the NASA Subsonic Rotary Wing Project is focused on developing rotorcraft technologies. The technologies being developed are within the task areas of:

- 5.1.1 Life Prediction Methods for Engine Structures & Components
- 5.1.2 Erosion Resistant Coatings for Improved Turbine Blade Life
- 5.2.1 Crashworthiness
- 5.2.2 Methods for Prediction of Fatigue Damage & Self Healing
- 5.3.1 Propulsion High Temperature Materials
- 5.3.2 Lightweight Structures and Noise Integration

The presentation will discuss rotorcraft specific technical challenges and needs as well as details of the work being conducted in the six task areas.

NASA Subsonic Rotary Wing Project - Structures & Materials Discipline

Michael C. Halbig - Associate Principal Investigator (API)

Contact info: (216) 433-2651, Michael.C.Halbig@nasa.gov

Susan M. Johnson – Associate Project Manager (APM)

Contact info: (216) 433-2163, Susan.M.Johnson@nasa.gov

Fundamental Aeronautics Program Annual Meeting
Atlanta, GA, October 7-9, 2008.

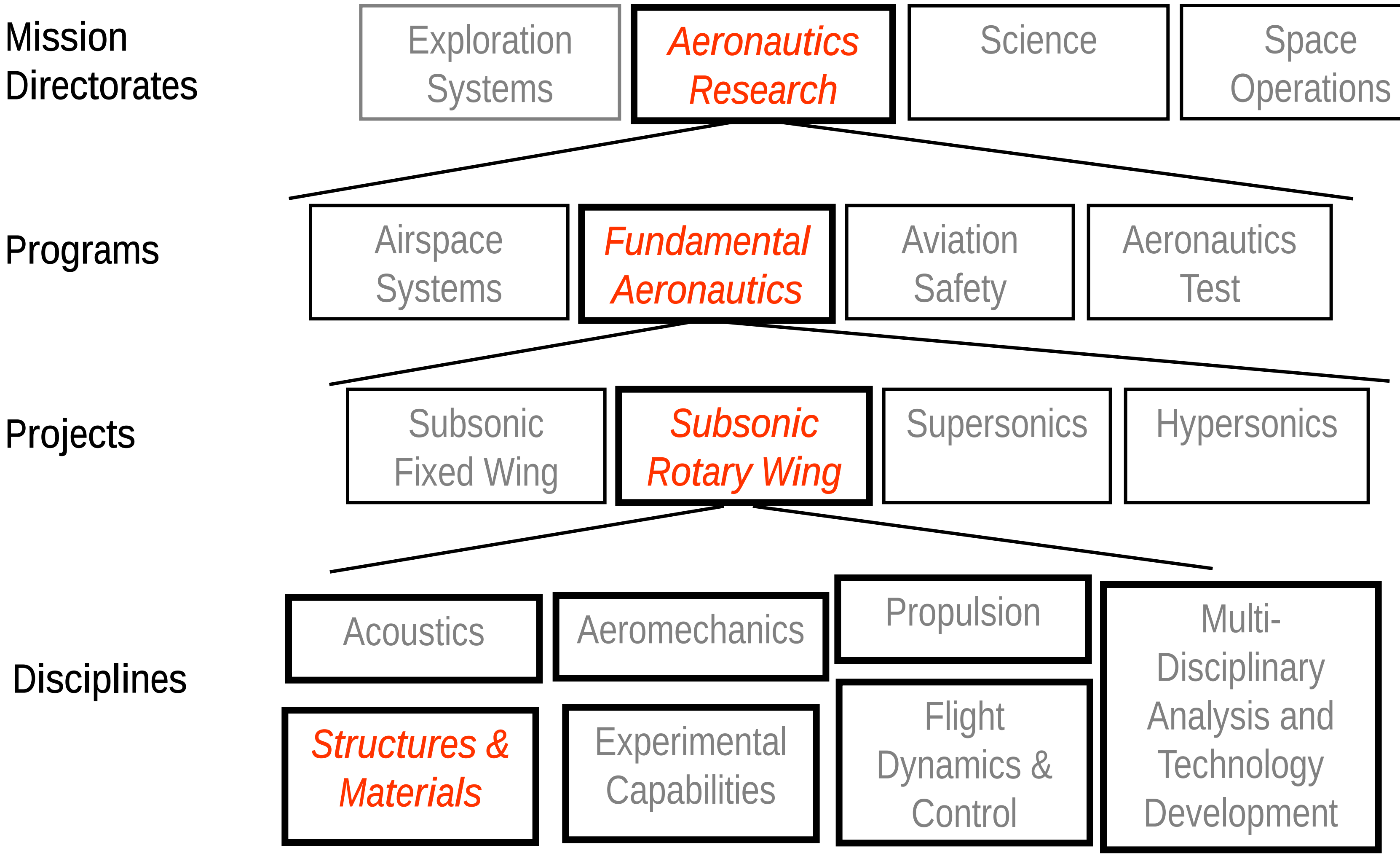
Outline

- Project Structure and Technology Focus
- Tasks Areas

    5.1.1 Life Prediction Methods for Engine Structures & Components (GRC)
    5.1.2 Erosion Resistant Coatings for Improved Turbine Blade Life (GRC)
    5.2.1 Crashworthiness (LaRC)
    5.2.2 Methods for Prediction of Fatigue Damage & Self Healing (LaRC)
    5.3.1 Propulsion High Temperature Materials (GRC)
    5.3.2 Lightweight Structures and Noise Integration (LaRC/GRC)

- Collaboration Mechanisms and Current NRAs

The Structures & Materials Discipline within SRW



The SRW Project Management Structure

Fundamental Aeronautics Program Director
Dr. Juan Alonso

SRW Principal Investigator
Susan Gorton

Project Scientist
Isaac López

Project Manager
Barbara Esker

Special Projects
DoD Liaison: Mike Watts
NRTC Liaison: Dan Dugan

Special Projects
JPDO Liaison:
Odilyn Santa Maria

NRA Manager:
Karen Crandall

Associate Principal Investigators

- **Experimental Methods** – Luther Jenkins
- **Propulsion** – Dr. Chris DellaCorte
- **Aeromechanics** – Tom Norman
- **Flight Dynamics & Control** – Bill Decker
- **Acoustics** – Dr. David D. Boyd
- **Structures & Materials** – **Michael C. Halbig**
- **Multi-Disciplinary Analysis & Technology** – Dr. Gloria Yamauchi

Associate Project Managers

- Odilyn Santa Maria
- **Susan Johnson**
- Bob Kufeld
- Dan Dugan

Business Team

- Deb Findley, Lead Analyst
- Julie Fowler
- Sandra Young

Unique Structures and Materials Issues For Rotorcraft

- Propulsion system
  - Turboshaft engines vs emphasis on turbofans for fixed wing
  - Higher temperature materials for improved efficiency, higher horsepower, reduced weight, and reduced emissions
  - Engine mission cycle
    - Short duration flight with hover and lift requirements (low cycle fatigue)
    - Low altitude flight with take-off from unimproved sites (erosion)
- Airframe
  - Unique durability and damage tolerance requirements
    - Local skin buckling is allowed in normal operation to minimize weight
  - Crashworthiness
    - Seats and other energy absorbing structures contribute significantly to human occupant survivability
    - Must limit cabin volume reduction caused by heavy engine/transmission located on top of fuselage structure
- Propulsion/airframe integration
  - Interior cabin noise caused by structure-born vibration from the gearbox
- Main rotor structures
  - High axial loads combined with bending
  - Particulate and rain erosion
  - Challenges with fabrication and integration of controls and data acquisition systems

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- Collaboration Mechanisms and Current NRAs

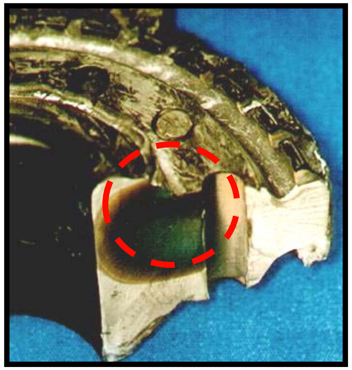
5.1.1 Life Prediction Methods for Engine Structures & Components (GRC)

POC: Jack Telesman, GRC

- Objective
  - Identify, evaluate and model key variables controlling fatigue life of rotary wing superalloy turbine disks:
    - Non-metallic inclusions
    - Machining damage
- Approach
  - Experimental
    - Study machining parameters of broaching speed, tool life (sharpness), and post-processing surface treatments
    - Determine the effect of extrusion and forging strains on the size and shape of inclusions
    - Perform LCF testing on realistic forging shapes
  - Computational
    - Development of the Probabilistic Life Prediction Model to Account for presence of inclusions in Nickel Powder Metallurgy (P/M) Turbine Components
    - Integrate NASA GRC developed probabilistic life prediction method into the DARWIN probabilistic damage tolerance based life prediction code
- Current collaborations
  - Honeywell - contract for machining study
  - Southwest Research Institute - implementation of probabilistic life prediction methodology into the Darwin code

5.1.1 Life Prediction Methods for Engine Structures & Components (GRC)

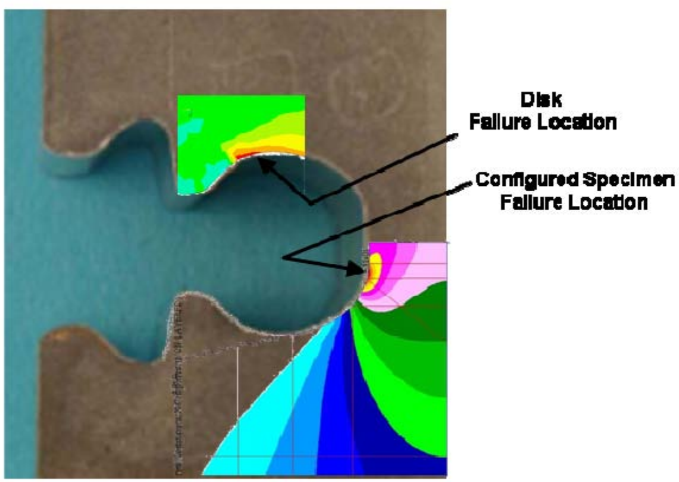
POC: Jack Telesman, GRC



The probability of failure depends on materials, processing, damage, design, and engine operating conditions

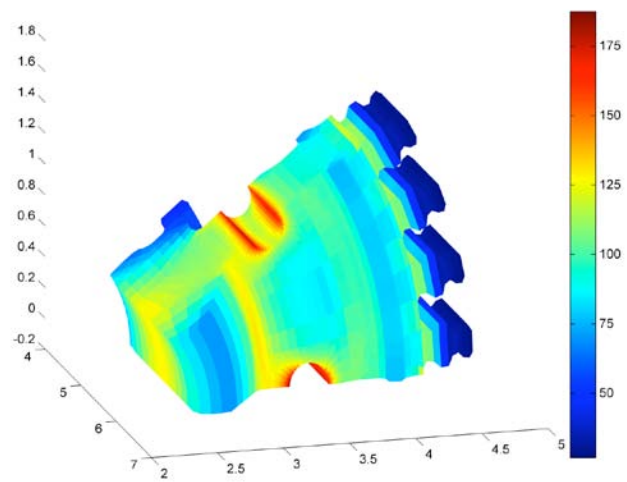
- Ceramic inclusions are the primary flaw in powder metallurgy superalloys
- Processing affects the local alloy microstructure and flaw distribution
- Surface defects occur as a result of machining, finishing, and damage

Machining Studies and Stress Analysis



Broach slot indicating regions of interest for microstructural evaluation and residual stress determination.

Disk Stress Modeling



Stress distribution in a sector model of a stage two gas generator turbine disk.

5.1.2 Erosion Resistant Coatings for Improved Turbine Blade Life (GRC)

POC: Bob Miller and Dongming Zhu, GRC

- Objectives
  - Develop erosion models for realistic engine conditions in the turbine
  - Develop thermal barrier coatings with improved erosion resistance

- Approach
  - Experimental
    - Add oxides to zirconia-yttria ceramic coatings to improve toughness
    - Perform erosion tests at U of Cincinnati and at NASA
  - Computational
    - Develop a mechanics-based erosion model that accounts for sintering of the coating

- Current collaborations
  - University of Cincinnati (NRA, PIs: Tabakoff and Hamed) - “Experimental and Numerical Simulation of TBC Erosion in Gas Turbines”
  - Aviation Applied Technology Directorate - blades and lead for possible future engine test
  - Howmet: PVD doped zirconia TBCs
  - Army SBIR Phase II with Directed Vapor Technologies International, Inc. - collaboration and integration
  - Engine companies - contacts and possible supply of new scrap blades

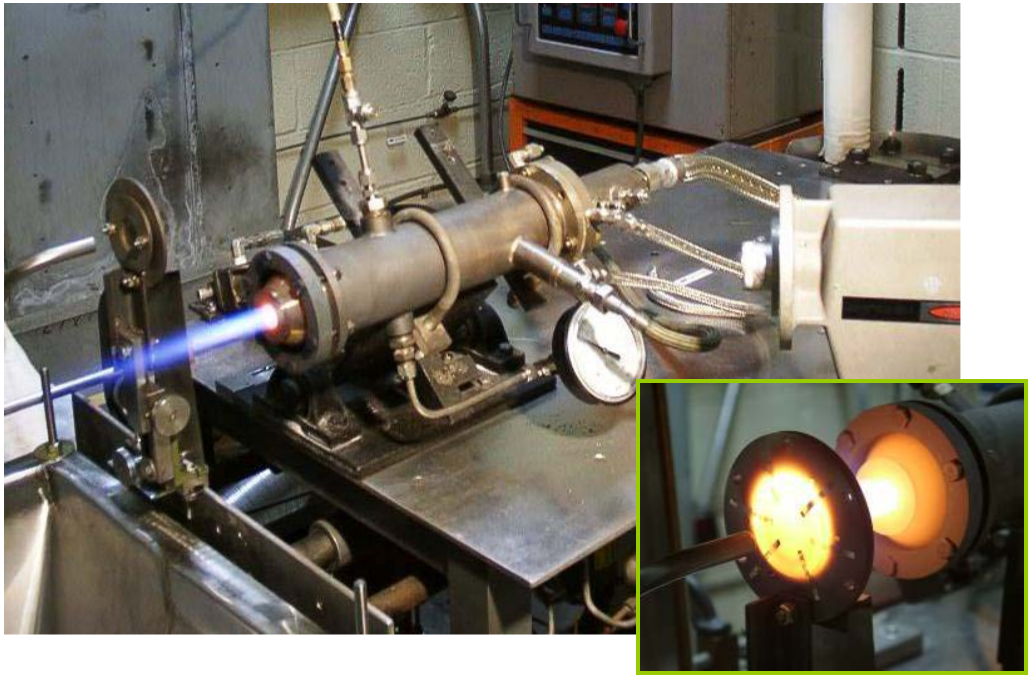
5.1.2 Erosion Resistant Coatings for Improved Turbine Blade Life (GRC)

POC: Bob Miller and Dongming Zhu, GRC

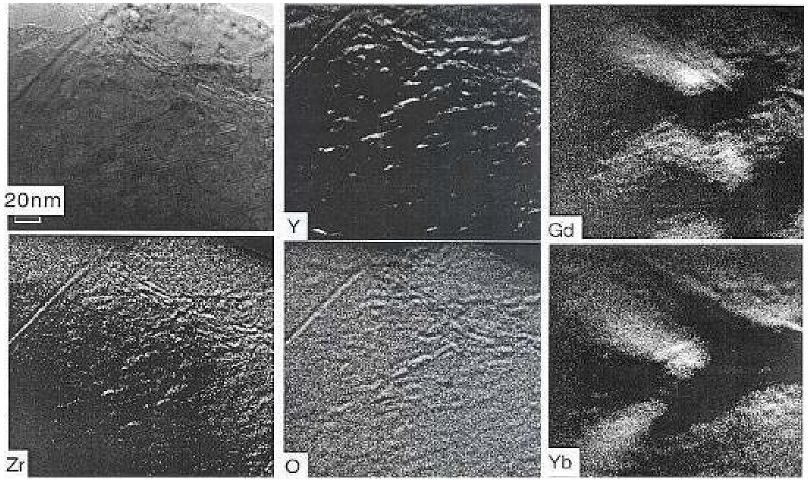
Erosion resistance of turbine blade thermal barrier coatings

- Ingested particulates and carbon particles cause erosion
- The best (lowest thermal conductivity) coatings have poor erosion resistance
- Erosion models currently do not account for thermally-induced material changes
- The burner erosion rig can be run in the coatings screening mode or the model validation mode

Mach 0.3 - 1.0 burner erosion rig at NASA GRC



Candidate Thermal Barrier Coatings for Turbine Blade Applications are Doped Zirconia-Yttrias



SRW Discipline: Structures & Materials

5.2.1 Crashworthiness (LaRC)

POC: Karen Jackson, LaRC

- Objectives
  - Demonstrate advanced structural concepts for crash energy management
  - Improve predictive capabilities for structural impact and multi-terrain impact

- Approach
  - Demonstrate energy absorbing concepts by component crash testing
  - Validate advanced simulation methods through component and full scale testing
    - Tests to evaluate HeloWerks skid gear are completed
    - Crash tests of two MD 530 helicopters are planned – one with external airbags and the second with a deployable energy absorber

- Current collaborations
  - U.S. Army Aviation Applied Technology Directorate (AATD) – Survivable, Affordable, Repairable Airframe Program (SARAP) test
  - Bell Helicopter, Sikorsky, Boeing - Information exchange on future crash testing
  - Stanford (NRA, PI: Fu-Kuo Chang) – "Crash Energy Absorption of Composite Rotorcraft Structures"

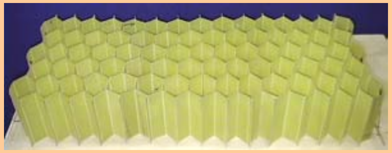
5.2.1 Crashworthiness (LaRC)

POC: Karen Jackson, LaRC

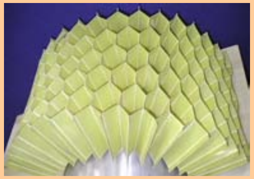
Vertical Drop Test of the Sikorsky Test Validation Article (TVA) – Survivable, Affordable, Repairable Airframe Program (SARAP)

Composite fuselage section shown in the load test machine at AATD.

Deployable Energy Absorber (DEA) concept developed at NASA LaRC

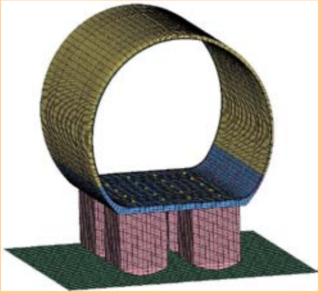


Linear deployment



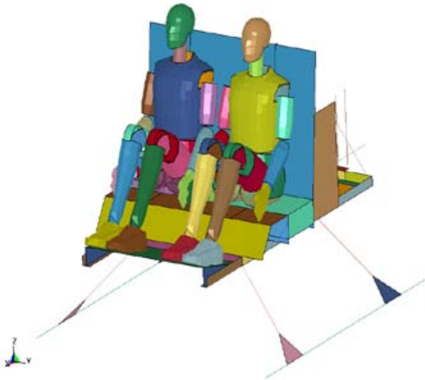
Radial deployment

Fuselage retrofit



LS-DYNA model

WASP Skid Gear



LS-DYNA shell skid gear analysis model and test article.

Test article.

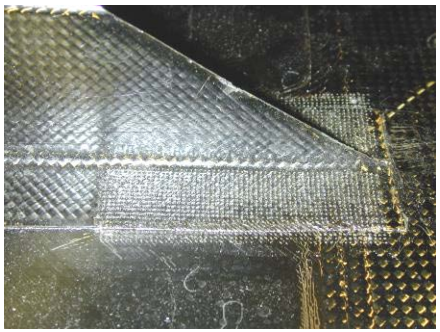
5.2.2 Methods for Prediction of Fatigue Damage & Self Healing (LaRC)

POC: Kevin O'Brien, LaRC (ARL/VTD)

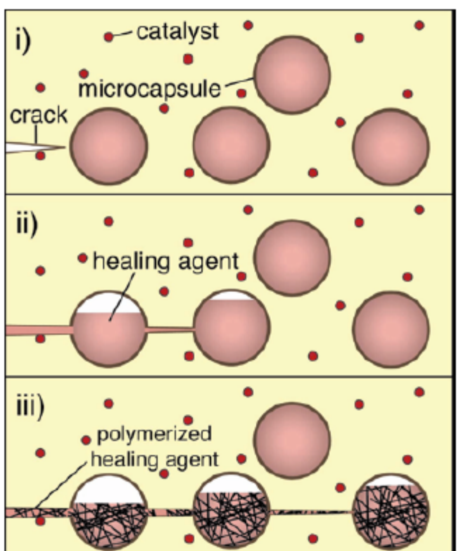
- Objective
  - Improve the durability and damage tolerance of composite rotorcraft structure
- Approach
  - Perform fatigue tests on stiffened thin skin specimens to determine if z-pinning combined with a self healing matrix can reduce delamination and improve fatigue life
  - Measure residual compressive strength of impacted sandwich structures
    - Identify failure modes
    - Develop new analytical techniques to predict residual strength
  - Use flex beam specimens (high axial loading with bending) to evaluate the effect of embedded sensors on fatigue life in rotor structures
- Current collaborations
  - Center of Rotorcraft Innovation (CRI) - SAA through NASA Aircraft Aging and Durability Project, "Development of a Delamination Fatigue Methodology for Composite Structures"
  - Bell Helicopters – Supplier of flex beams with embedded sensors

Approaches for improved durability and damage tolerance

Self healing matrix combined with through thickness reinforcement to improve fatigue life

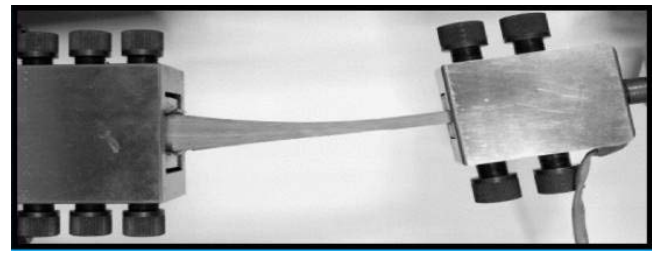


Z-pin reinforced composite flange



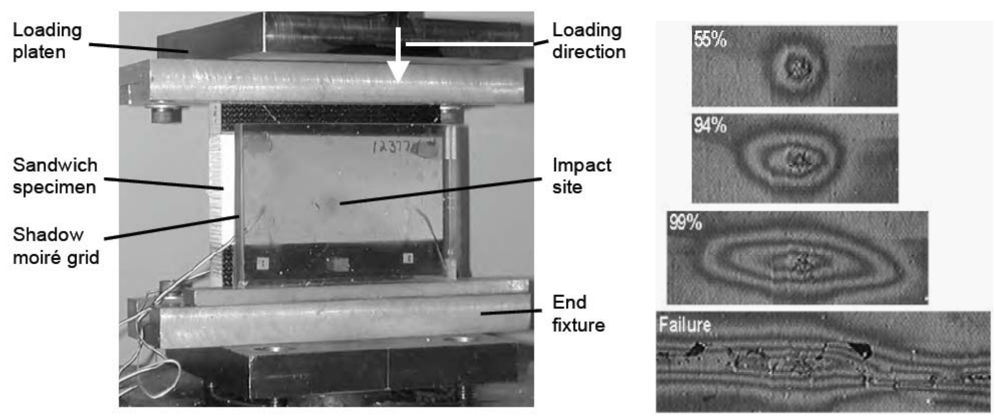
Micro-encapsulation technique for self-healing

Effect of embedded sensors on fatigue life of rotor structures



Flex beam specimen test

Failure modes and analysis methods for alternative sandwich structures and core materials



SRW Discipline: Structures & Materials

5.3.1 Propulsion High Temperature Materials (GRC)

POC: Mike Halbig, GRC

- Objectives
  - Determine advantages of substituting metallic material with monolithic ceramics (i.e. Si_3N_4) and fiber reinforced ceramic matrix composites (CMCs) (i.e. SiC/SiC) for:
    - turbine engine components
    - transmission components.

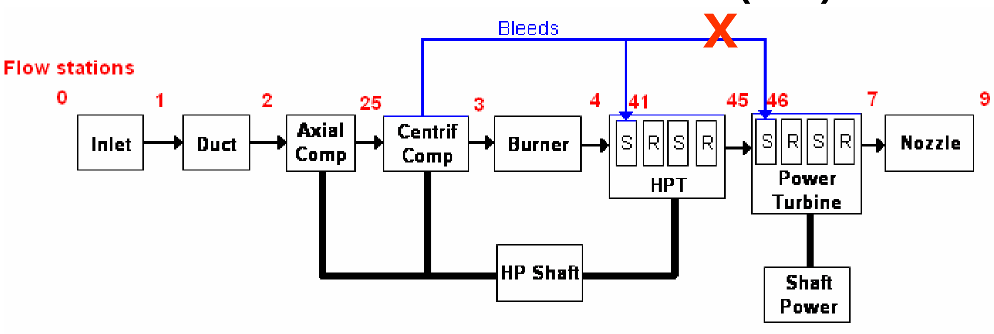
- Approach
  - Perform engine system analysis and trade-off studies to determine the feasibility and benefits of using advanced monolithic and CMC in a T-700 engine.
  - Design and predict stress in turbine components of advanced materials.
  - Develop joining technology for fabricating complex shaped ceramic components and for integration with dissimilar materials (i.e. metal alloy).
  - Fabricate/procure and test components.

- Current collaborations
  - Coatings for silicon nitride
    - Ceramatech (coating development)
    - Cleveland State University (coating development and modeling)

5.3.1 Propulsion High Temperature Materials (GRC)

POC: Mike Halbig, GRC

Trade Study for Using Uncooled Ceramics in the Power or Low Pressure Turbine (LPT)



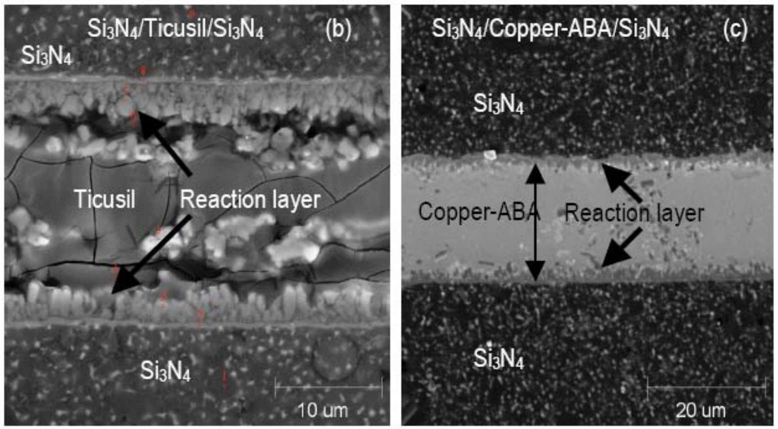
The stages of a T700 turbo-shaft engine. Note: HP-High pressure; HPT-High pressure turbine, S-Stator (Vane), R-Rotor (Blade)

Parameters	With LPT bleed (Baseline)	No LPT bleed (Match T4)
T3, ºR (ºC)	1319 (460)	1432 (522)
T4, ºR (ºC)	3063 (1429)	3063 (1429)
T41, ºR (ºC)	2855 (1313)	2885 (1330)
T45, ºR (ºC)	2128 (909)	2141 (916)
T46, ºR (ºC)	2060(871)	2141 (916)
Mass flow (lb/s)	10.48	11.35
BSFC (lb/hr/hp)	0.4507	0.3994
HP shaft speed (rpm)	44000	47145
Ratio of (HP shaft speed /Base line shaft speed)	1	1.07
Power turbine shaft power (hp)	1800	2371

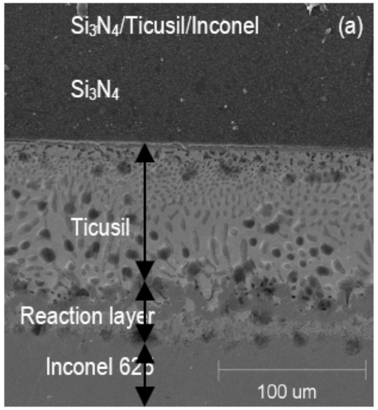
For case of no LPT bleed and T4 matching, uncooled LPT components offer:

- **31% increase in turbine shaft power**
- **11% decrease in BSFC**

Joining and Integration of Ceramics



Polished cross-sections of Si_3N_4 joined to Si_3N_4 using Ticusil braze (left), and Si_3N_4 using Copper-ABA braze (right), and Inconel 625 using Ticusil braze (below).



5.3.2 Lightweight Structures and Noise integration (LaRC/GRC)

POC: Rob Bryant, LaRC; Chris Johnston, GRC

- Objectives
  - Develop lightweight materials and structures for cabin treatment
  - Develop methods for improved passive and active control of noise and vibration

- Approach
  - Develop low density open cell absorber/core materials (polyimide foam, aerogels, hybrids)
  - Provide composite materials to the Acoustics Discipline for vibration testing and modeling
  - Review past work in passive and active control of noise and vibration and assess the potential for improvement with current materials and structures technology

- Current collaborations
  - Polyumac Inc. (licensed NASA LaRC polyimide foam technology)
  - Patz Materials and Technologies (SBIR) - “Optimized Cellular Core for Rotorcraft”
  - Bell - Informal discussions on composite panel design for vibration testing and modeling
  - Ohio State University’s Smart Vehicle Concept Center – assessment of the state of the art in active and passive noise control

SRW Discipline: Structures & Materials

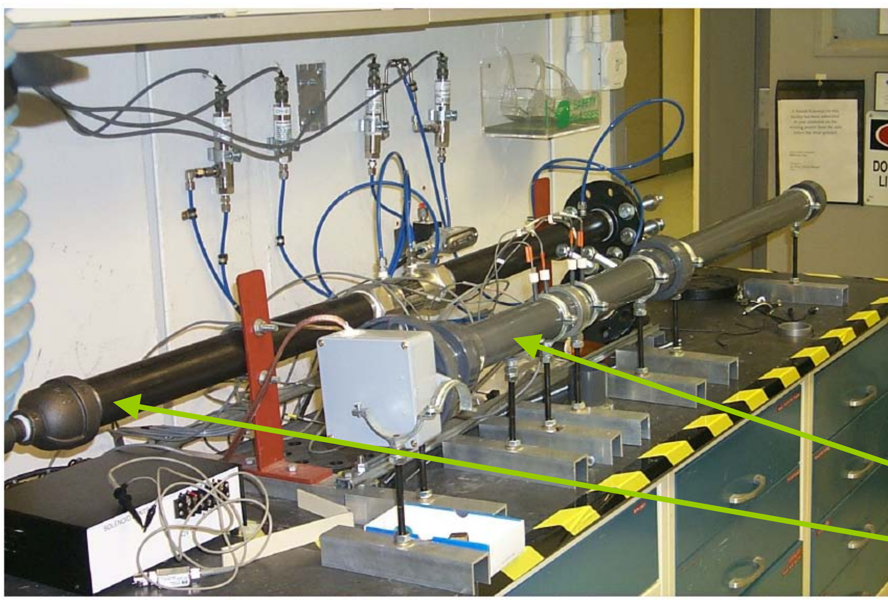
5.3.2 Lightweight Structures and Noise integration (LaRC/GRC)

POC: Rob Bryant, LaRC; Chris Johnston, GRC

Goal is to reduce cabin noise without increasing weight

- Current work is focused on development of lightweight bulk absorbing materials and controlling the open cell structure to optimize sound absorption at specific frequencies
- Acoustic materials testing is used assess material performance and to provide inputs for the acoustic models

Lightweight hybrid foam concept



GRC acoustic property screening lab consisting of:
- a modular acoustic impedance tube
- a flow resistance rig

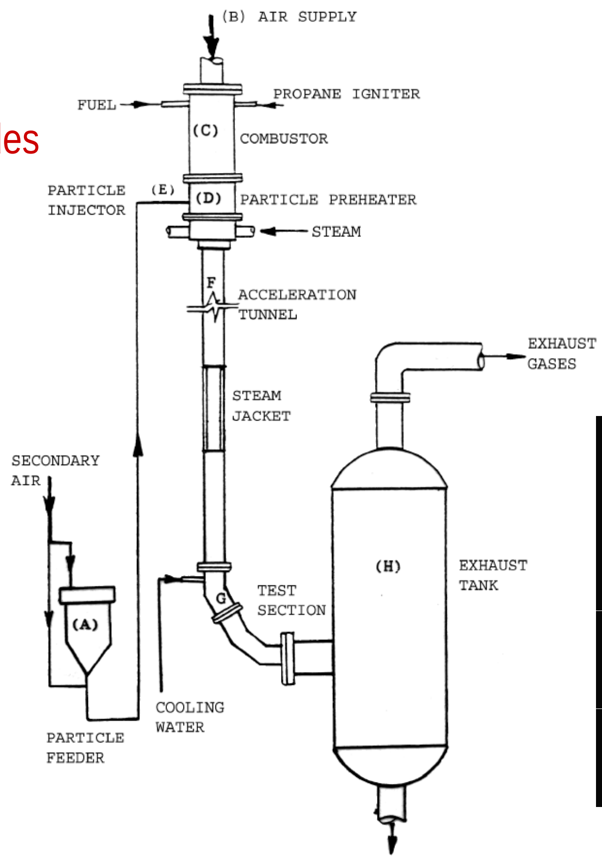
At LaRC, detailed acoustic testing is done to obtain acoustic parameters for model development

NRA (Round 1) – Experimental and Numerical Simulation of TBC Erosion in Gas Turbines, University of Cincinnati, Prof. Tabakoff and Prof. Hamed

Goals:

- Measure erosion rate in properly simulated aero-thermal environment
- Assess advances in TBC erosion resistance
- Predict TBC erosion pattern on Turbine blades

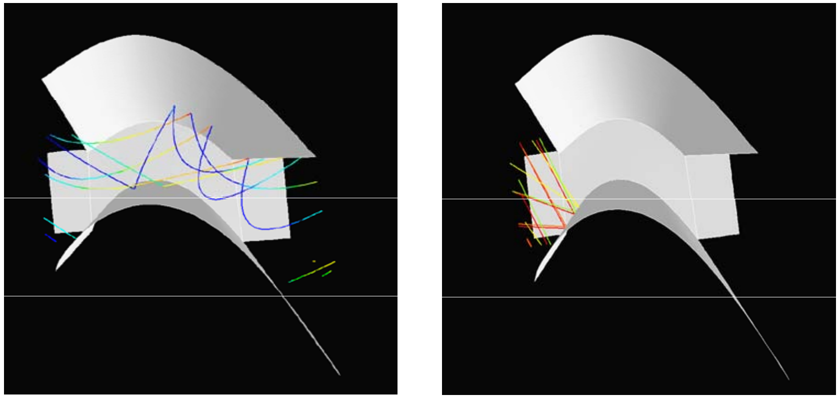
High Temperature Erosion Tunnel



10 mils TBC Cumulative Erosion Test Results
(T = 1800 F, V = 1000 ft/s , β = 90º & Total Q_p = 15 g)

Sample ID	$W_{initial}$ (g)	W_{final} (g)	ΔW (mg)	Q_p (g)	ε (mg/g)
1a	6.9369	6.8134	123.5	5	24.70
1b	6.8134	6.6962	117.2	+5	23.44
1c	6.6962	6.5786	117.6	+5	23.52

Effect of Particle Size on Trajectories Through Rotor



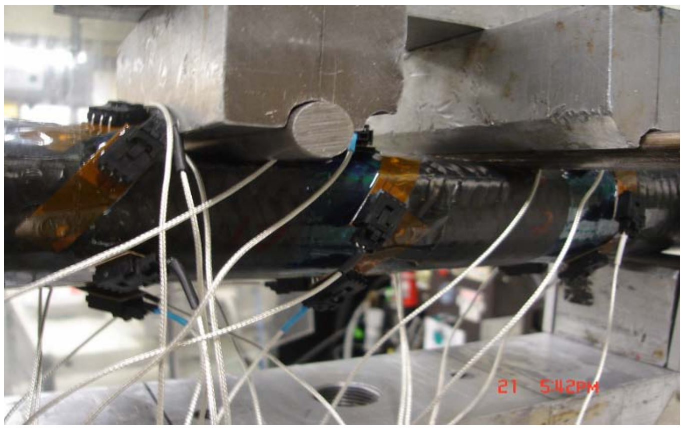
30μ particles 1500μ particles

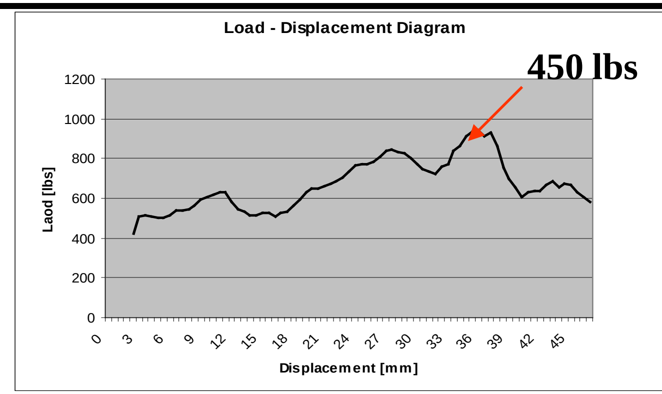
NRA (Round 1) - Crash Energy Absorption of Composite Rotorcraft Structures, Stanford University. Prof. Fu-Kuo Chang

Tasks:
- Analysis to develop relevant damage modes and material response.
- Implementation of a dynamic material model into a commercial FEM code.
- Study of relevant parameter and improvements for energy absorption.

Test, Data, and Modeling at 650 LBS Load

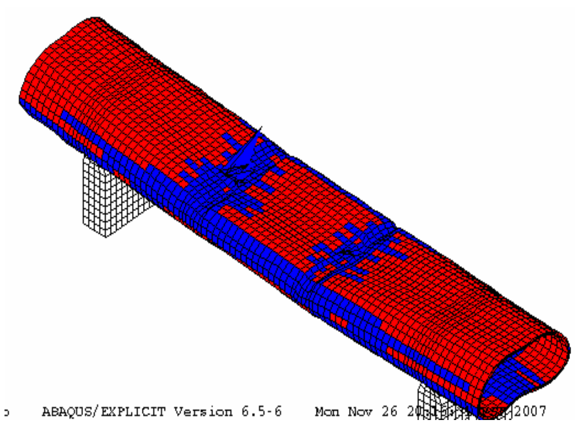
Four-point bend test with built-in acousto-ultrasound sensors to monitor damage growth

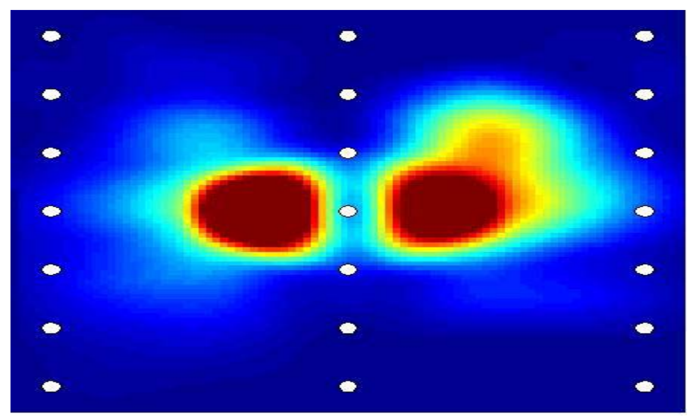




Load and displacement diagram at 450 lbs (650 lbs diagram not available)

FEM model of four-point test





Acoustic sensor data for unfolded tube

Summary

- The Structures & Materials Discipline is focused on technology areas that are most relevant to rotary wing applications.
- Resources are directed toward tasks where we can have the most significant impact on the structures and materials within the propulsion system and the airframe.
- Development of the technologies is leveraged with NRAs, SBIRs, SAAs, academic programs, and collaborations.
- The discipline is interested in continued collaboration and industry perspective on critical technology areas.