Joint Centers of Excellence for Advanced Materials

Evaluation of Aged Structural Bonds on Rotor Blades

Waruna Seneviratne, John Tomblin, and Caleb Saathoff

JAMS Technical Review
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Seattle, WA

Wichita State University

Evaluation of Aged Structural Bonds on Rotor Blades

Research Team

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Industry

LEONARDO

SIKORSKY

A LOCKHEED MARTIN COMPANY

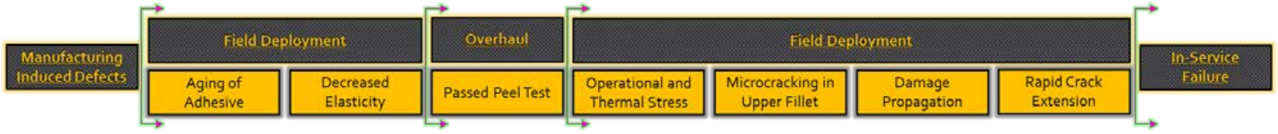
BELL

COLUMBIA HELICOPTERS

Project Overview

Background and Motivation:

- **Long-term durability under operational environments must be understood and the aging mechanism must be investigated to support maintenance practices and to establish criteria for structural retirement**
- **Detailed nondestructive inspections (NDI), teardown inspections, and laboratory testing of bonded repairs on aircraft components that have been retired from service provide vital information related to the aging mechanism and any undetected material degradation**
- **Concerns related to process sensitivity of the bondline as an improperly accomplished in-service repair could become a safety threat**
  - Potential for weak bond to degrade in an unpredictable manner when subjected to operational environments and ground-air-ground (GAG) thermo-mechanical loads
- **Concern that unique dynamic loads for rotor blades yield complex history-dependent behavior for products with shifting missions**



Objective:

- **Evaluate bondline integrity and durability of adhesively bonded composite rotor blades for understanding the aging mechanisms with respect to various operational conditions.**

Project Goals:

- **Compare "state of adhesive" or "state of resin" on old blades to the initial state of these polymeric materials on new blades**
  - Teardown and evaluate bondline performance parameters
- **Compare existing repairs on old blades and new repairs on old blades to new repairs on new blades**
  - Use existing repairs or perform repairs → mechanical performance evaluation
- **Compare accelerated aging protocols to real life**
  - Structural testing based on lower building block findings
- **Demonstrate improved accelerated testing in rotor blade bench tests**

Task List:

Task I: Structural Test Rig Development

1) Steering Committee Formation
2) FAA Tech Center Fixture Design
3) NIAR ATLAS Fixture Design and Manufacturing

Task II: Rotor Blade Acquisition

4) Blade History Documentation
5) Receiving Inspections

Task III: Full-scale Structural Testing

6) Mechanical Performance Analysis of Rotorcraft Blades

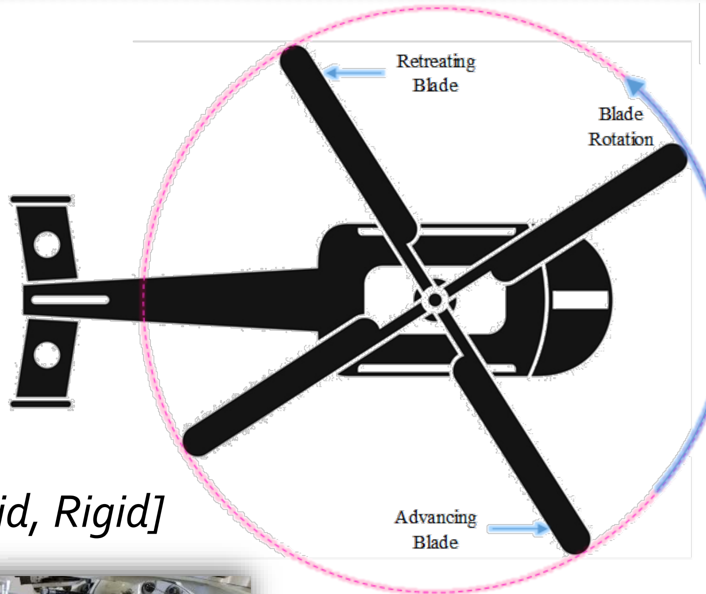
Task IV: Rotor Blade Teardown and Lower-Level Testing

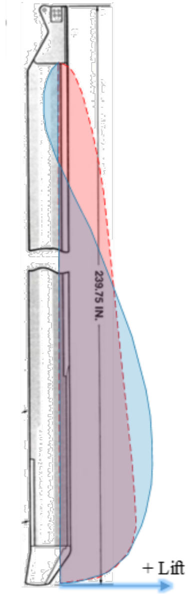
7) Failure Documentation and Analysis
8) Detailed Experimental Investigations

Structural Test Rig Development

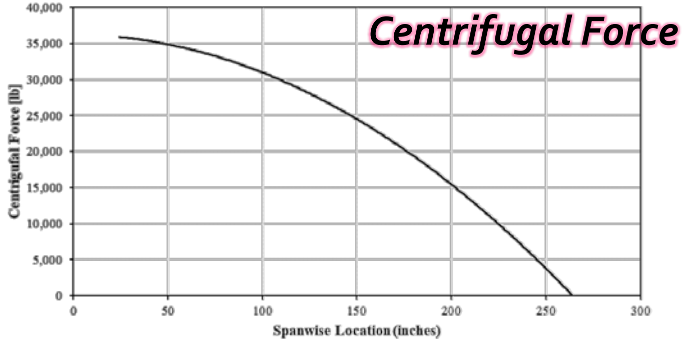
Objective: *Establish the capability, and enhance subject matter knowledge, for rotorcraft main rotor blade structural testing efforts at FAA Technical Center and NIAR ATLAS.*

- **Loading Requirement Definition**
  - Centrifugal Force: ***120.0****-kip*
  - Lift Force: ***44.4****-kip*
  - Drag Force: ***14.2****-kip*
  - Damper Force (Not on all rotor types): ***9.8****-kip*
    - Considerations Required: *[Fully Articulated, Semirigid, Rigid]*





- **Fixture Definition**
  - FAA Technical Center: *Standalone*
  - NIAR ATLAS: *Incorporation into Existing Multipurpose Test Rig*



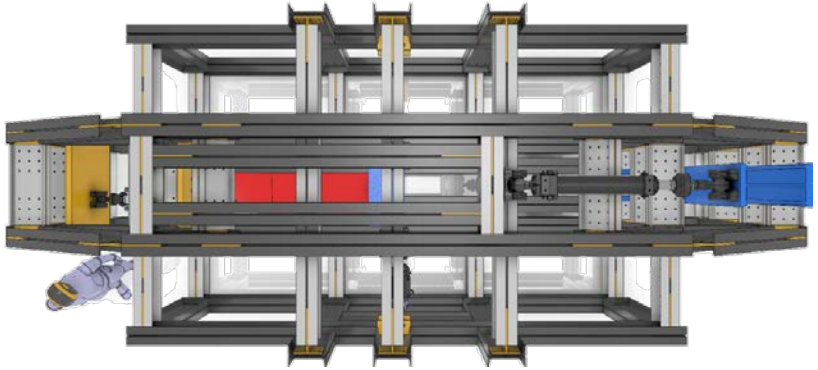
Structural Test Rig Development

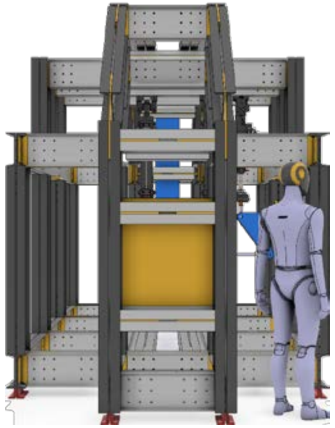
Objective: *Establish the capability, and enhance subject matter knowledge, for rotorcraft main rotor blade structural testing efforts at FAA Technical Center and NIAR ATLAS.*

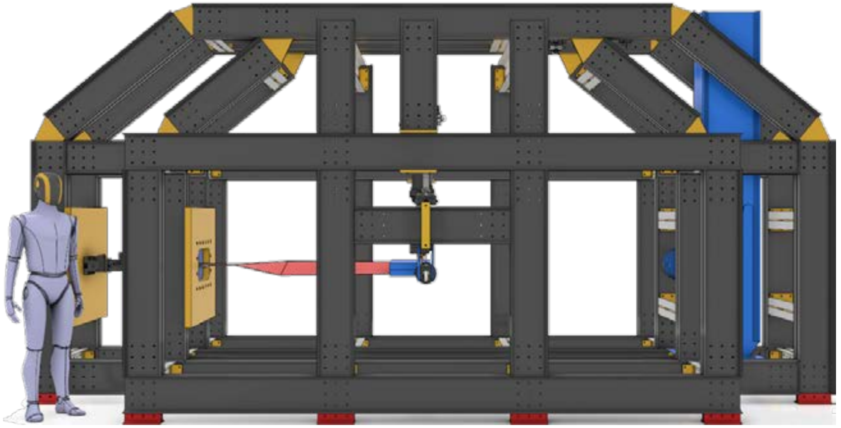
- **Fixture Overview**
- **Centrifugal Force Application**
  - Class 2 Lever: *Pressurized Air Spring*

Force Table (Use for Airstroke™ actuator design)

Assembly Height (in.)	Volume @ 100 PSIG (in³)	Pounds Force @20 PSIG	@40 PSIG	@60 PSIG	@80 PSIG	@100 PSIG
10.0	3,064	4,480	9,320	14,130	19,110	24,190
9.0	2,796	4,990	10,200	15,520	20,940	26,410
8.0	2,512	5,440	10,990	16,680	22,480	28,270
7.0	2,206	5,780	11,650	17,620	23,740	29,830
6.0	1,889	5,950	12,090	18,330	24,640	31,000
5.0	1,559	6,310	12,720	19,340	26,040	32,740
4.0	1,211	6,650	13,320	20,150	27,140	34,100







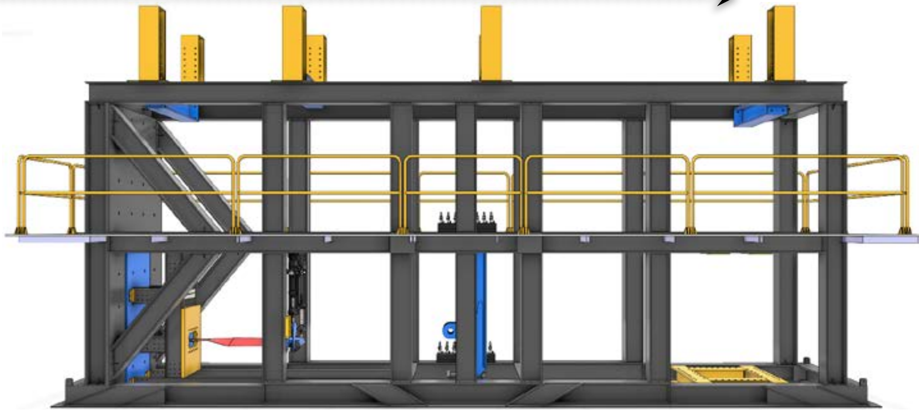
1 Planning → 2 Fix.FAA → 3 Fix.NIAR → 4 History → 5 NDI → 6 Mech.Test → 7 Failure(s) → 8 LL.Test

Structural Test Rig Development

Objective: *Establish the capability, and enhance subject matter knowledge, for rotorcraft main rotor blade structural testing efforts at FAA Technical Center and NIAR ATLAS.*

- **Force Application**
  - Lift: ***28.4**-kip*
    - 2 x Servohydraulic Actuators
  - Drag: ***14.2**-kip*
    - 1 x Servohydraulic Actuators
  - Centrifugal: ***100**-kip via Airbag*
- **Cyclic Rate Capacity**
  - 6.0-inch Displacement: ***0.44**-Hz*
  - 1.1-inch Displacement: ***1.0**-Hz*

Dual 8-Channel Distribution Manifolds HSM



Actuator ID	Load Capacity [kip]		Radii [in]		Expected Stroke [in]		Volume [in^3]		Required Time [s]	Servovalve Size [gps]		Servovalve Size [gpm]		Frequency [Hz]
	Tension	Compression	Bore	Rod	Cap Side	Rod Side	Cap Side	Rod Side		Cap Side	Rod Side	Cap Side	Rod Side	
Centrifugal Force	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Lift Force	22.2	36.4	2.00	1.25	6.0	6.0	75.40	45.95	0.50	0.65	0.40	78.34	47.74	1.00
Drag Force	7.3	14.2	1.25	0.88	3.0	3.0	14.73	7.51	0.50	0.13	0.07	15.30	7.80	1.00
MR Damper Force	3.7	9.8	0.94	0.69	0.3	0.3	0.69	0.32	0.50	0.01	0.00	0.72	0.33	1.00

Actuator ID	Load Capacity [kip]		Radii [in]		Expected Stroke [in]		Volume [in^3]		Required Time [s]	Servovalve Size [gps]		Servovalve Size [gpm]		Frequency [Hz]
	Tension	Compression	Bore	Rod	Cap Side	Rod Side	Cap Side	Rod Side		Cap Side	Rod Side	Cap Side	Rod Side	
Centrifugal Force	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Lift Force	22.2	36.4	2.00	1.25	1.1	1.1	14.44	8.80	0.50	0.13	0.08	15.00	9.14	1.00
Drag Force	7.3	14.2	1.25	0.88	0.6	0.6	2.82	1.44	0.50	0.02	0.01	2.93	1.49	1.00
MR Damper Force	3.7	9.8	0.94	0.69	0.3	0.3	0.69	0.32	0.50	0.01	0.00	0.72	0.33	1.00

Actuator ID	Load Capacity [kip]		Radii [in]		Expected Stroke [in]		Volume [in^3]		Required Time [s]	Servovalve Size [gps]		Servovalve Size [gpm]		Frequency [Hz]
	Tension	Compression	Bore	Rod	Cap Side	Rod Side	Cap Side	Rod Side		Cap Side	Rod Side	Cap Side	Rod Side	
Centrifugal Force	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Lift Force	22.2	36.4	2.00	1.25	6.0	6.0	75.40	45.95	1.14	0.29	0.17	15.00	9.14	0.44
Drag Force	7.3	14.2	1.25	0.88	3.0	3.0	14.73	7.51	1.14	0.06	0.03	2.93	1.49	0.44
MR Damper Force	3.7	9.8	0.94	0.69	0.3	0.3	0.69	0.32	1.14	0.00	0.00	0.14	0.06	0.44

Structural Test Rig Development

Objective: *Establish the capability, and enhance subject matter knowledge, for rotorcraft main rotor blade structural testing efforts at FAA Technical Center and NIAR ATLAS.*

1 Planning → 2 Fix.FAA → 3 Fix.NIAR → 4 History → 5 NDI → 6 Mech.Test → 7 Failure(s) → 8 LL.Test

Rotor Blade Acquisition

Objective: *Acquire rotorcraft main rotor blades exhibiting same construction materials and methods while exhibiting varying environmental/operational applications.*

A. Sikorsky S-76A

FOCUS

Blade Details
- **Quantity**
  - Two main rotor blades
- **Historical Information**
  - Hours: 3,274

Status
- **Inspections**
  - Shearography: Complete
  - Thermography: Complete
  - Ultrasonics: Complete

Path Forward
- **Teardown**
  - Root-end extraction
  - Preparation for F.S. testing
- **Testing**
  - Strain surveys
  - Fixture validation

B. Leonardo AW109

Blade Details
- **Quantity**
  - One main rotor blade
- **Historical Information**
  - Hours: 4,352

Status
- **Inspections**
  - Shearography: On-Hold
  - Thermography: On-Hold
  - Ultrasonics: On-Hold

Path Forward
- **Holding**
  - Focusing efforts on other blade sets that exhibit same material systems with various service histories

C. Eurocopter HH-65

Blade Details
- **Quantity**
  - One main rotor blade
- **Historical Information**
  - Hours: 10,457.7

Status
- **Inspections**
  - Shearography: Complete
  - Thermography: Complete
  - Ultrasonics: Complete

Path Forward
- **Holding**
  - Focusing efforts on other blade sets that exhibit same material systems with various service histories

D. Sikorsky S-92

FOCUS

Blade Details
- **Quantity**
  - Two main rotor blades
- **Historical Information**
  - Hours: In-Work

Status
- **Inspections**
  - Shearography: Complete
  - Thermography: Complete
  - Ultrasonics: In-Work

Path Forward
- **Teardown**
  - Extraction plan development
  - Preparation for F.S. testing
- **Testing**
  - High level and low level

1 Planning → 2 Fix.FAA → 3 Fix.NIAR → 4 History → 5 NDI → 6 Mech.Test → 7 Failure(s) → 8 LL.Test

Testing Approach

Objectives

Assessment of structural bonded repairs performed during service and/or determine effects of newly bonded repairs on degraded components; additional future efforts can allow for assessments for life extension via fatigue testing beyond original certification testing

Assessment of structural bonds related to skin-to-core performance and establishment of any correlations between NDT and Mechanical testing that may exist

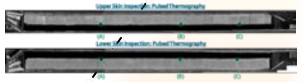
Assessment of substrates, adhesive, core, and failure modes for evaluation of influence on performance

Non-destructive Testing

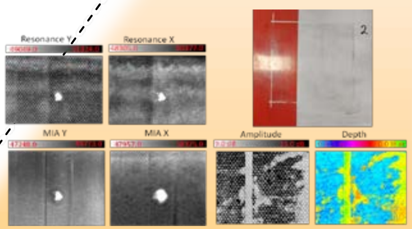
Level of Testing

Start

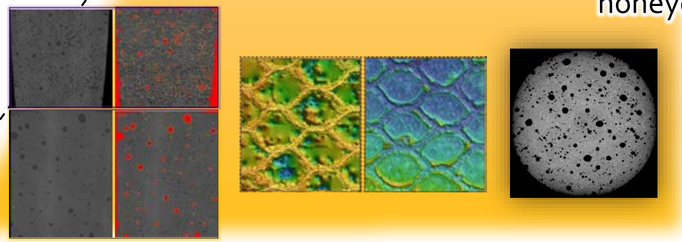
Component
Main Rotor Blade

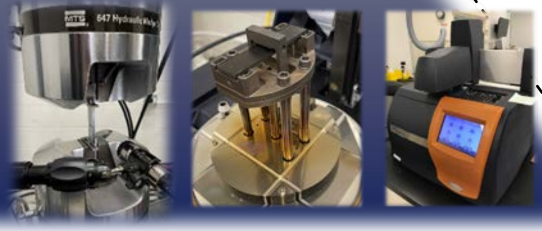


Details
Skin-to-core Bonds



Constituents & Coupons
Upper skin, Lower skin, Upper structural adhesive, Lower structural adhesive, honeycomb core





Finish

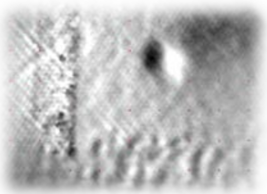
Component
Failure
Details
Failure
Constituents & Coupons

Mechanical Testing

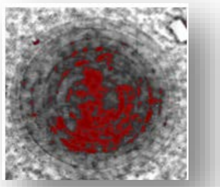
Component Level NDI

Objective: *Establish whether fleet blades received have traditional damage we would typically see with NDI & do they have other aging effects that we don't normally measure?*

- **Laser Technology Inc. (LTI)**
  - Laser Shearography: LTI-2100HP-300
    - 300-mW @ 532-nm Green Laser
    - 2-kW Thermal Stress System
    - In-house Vacuum System and Local Chamber



- **Thermal Wave Imaging (TWI)**
  - Pulsed Thermography: X8500 SC Camera
    - Resolution: 1280x1024
    - Frequency: 180-Hz



- **NDTS MAUS**
  - Pulse Echo UT: Single-element 5.0-MHz
  - Resonance Testing: 270-kHz and 320-kHz
  - Mechanical Impedance Analysis: 19-kHz

S-76A Inspection

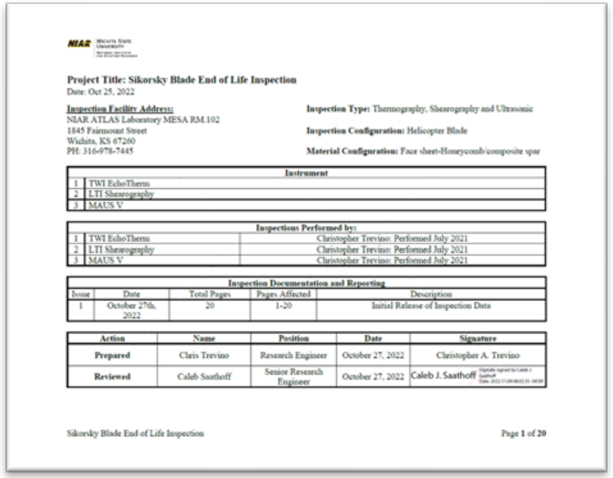
1 → 2 → 3 → 4 → **5** → 6 → 7 → 8

Planning | Fix.FAA | Fix.NIAR | History | NDI | Mech.Test | Failure(s) | LL.Test

Component Level NDI

Objective: *Establish whether fleet blades received have traditional damage we would typically see with NDI & do they have other aging effects that we don't normally measure?*

- **Inspection Reporting**



Project Title: Sikorsky Blade End of Life Inspection
Date: Oct 25, 2022

Inspection Facility Address:
NIAR ATLAS Laboratory MESA RM.102
1845 Fairmount Street
Wichita, KS 67260
PH: 316-978-7445

Inspection Type: Thermography, Shearography and Ultrasonic

Inspection Configuration: Helicopter Blade

Material Configuration: Face sheet-Honeycomb/composite spar

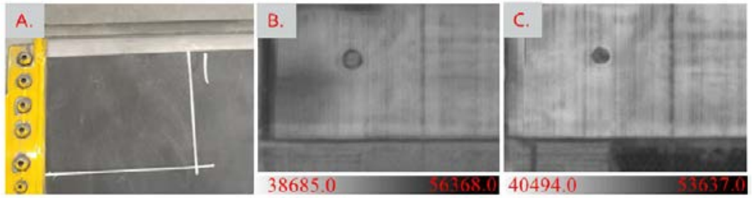
Instrument	
1	TWI EchoTherm
2	LTI Shearography
3	MAUS V

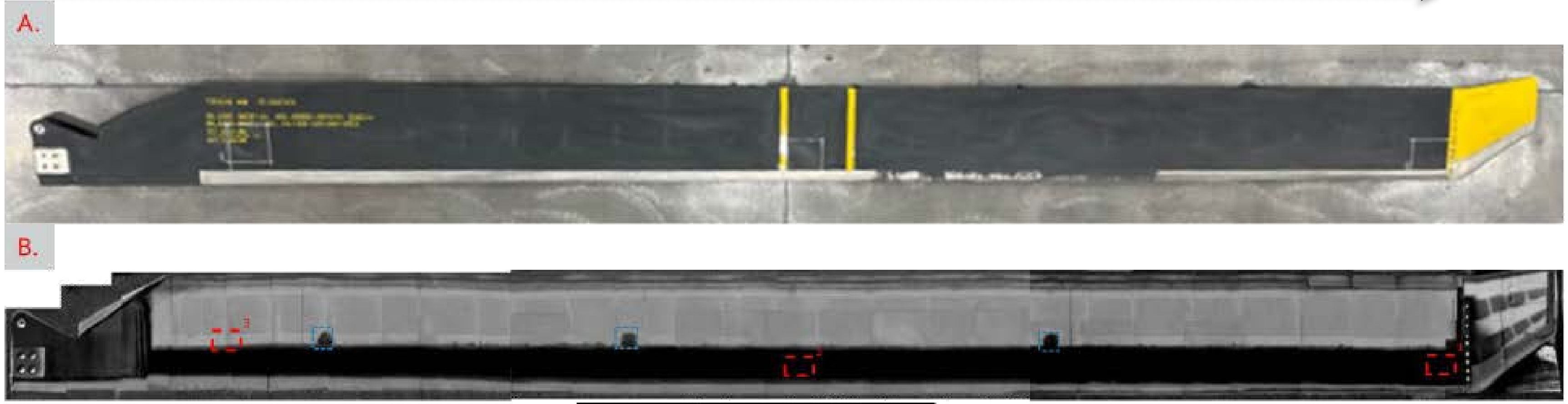
Inspections Performed by:		
1	TWI EchoTherm	Christopher Trevino: Performed July 2021
2	LTI Shearography	Christopher Trevino: Performed July 2021
3	MAUS V	Christopher Trevino: Performed July 2021

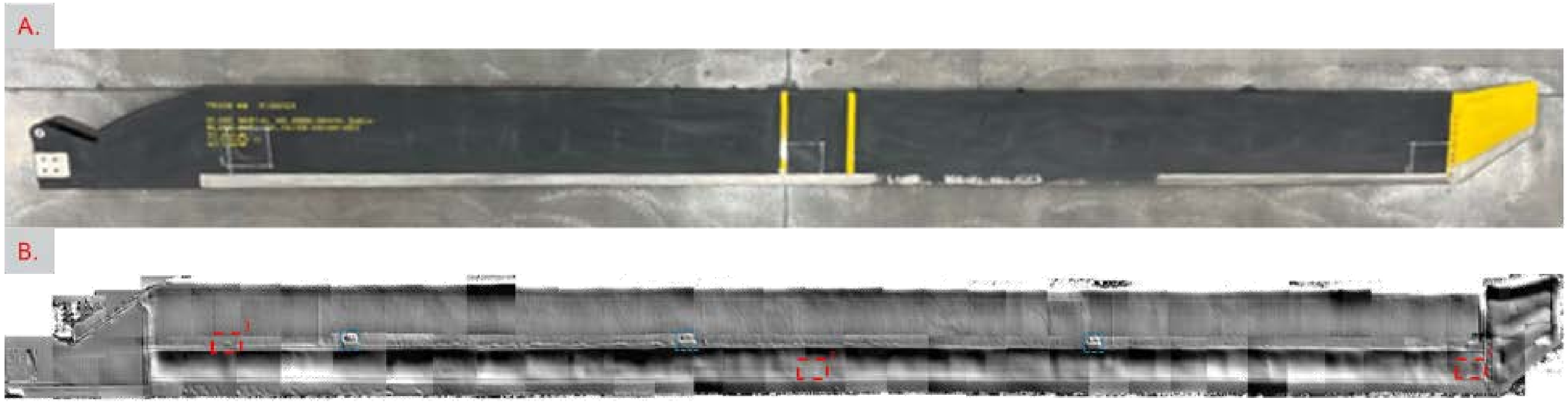
Inspection Documentation and Reporting				
Issue	Date	Total Pages	Pages Affected	Description
1	October 27th, 2022	20	1-20	Initial Release of Inspection Data

Action	Name	Position	Date	Signature
Prepared	Chris Trevino	Research Engineer	October 27, 2022	Christopher A. Trevino
Reviewed	Caleb Saathoff	Senior Research Engineer	October 27, 2022	Caleb J. Saathoff

Sikorsky Blade End of Life Inspection — Page 1 of 20







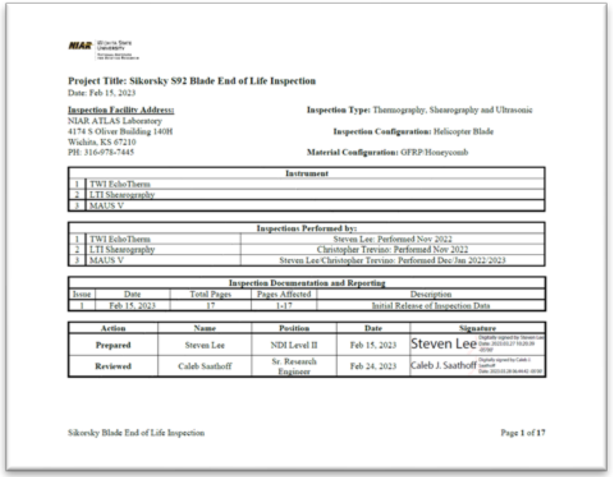
1 → 2 → 3 → 4 → 5 → 6 → 7 → 8

Planning | Fix.FAA | Fix.NIAR | History | NDI | Mech.Test | Failure(s) | LL.Test

Component Level NDI

Objective: *Establish whether fleet blades received have traditional damage we would typically see with NDI & do they have other aging effects that we don't normally measure?*

- **Inspection Reporting**



Project Title: Sikorsky S92 Blade End of Life Inspection
Date: Feb 15, 2023

Inspection Facility Address:
NIAR ATLAS Laboratory
4174 S Oliver Building 140H
Wichita, KS 67210
PH: 316-978-7445

Inspection Type: Thermography, Shearography and Ultrasonic
Inspection Configuration: Helicopter Blade
Material Configuration: GFRP/Honeycomb

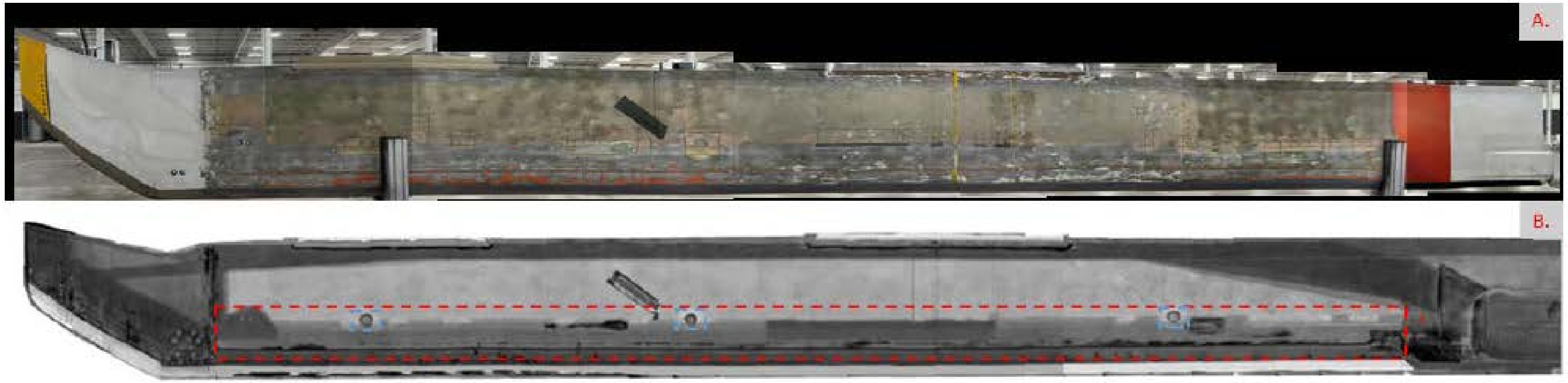
Instrument	
1	TWI EchoTherm
2	LTI Shearography
3	MAUS V

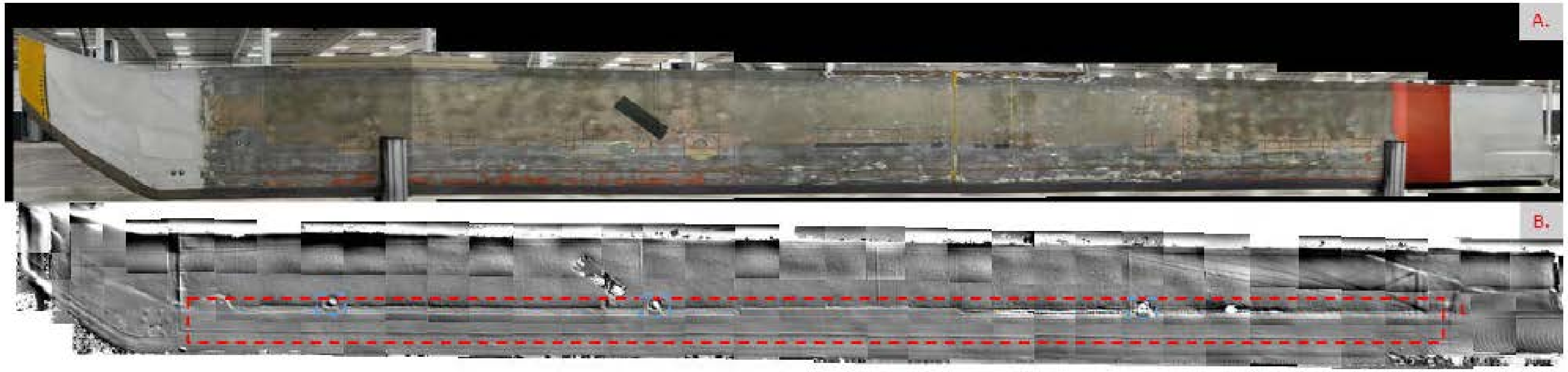
Inspections Performed by:		
1	TWI EchoTherm	Steven Lee: Performed Nov 2022
2	LTI Shearography	Christopher Trevino: Performed Nov 2022
3	MAUS V	Steven Lee/Christopher Trevino: Performed Dec/Jan 2022/2023

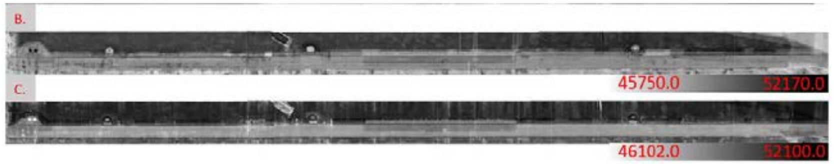
Inspection Documentation and Reporting				
Issue	Date	Total Pages	Pages Affected	Description
1	Feb 15, 2023	17	1-17	Initial Release of Inspection Data

Action	Name	Position	Date	Signature
Prepared	Steven Lee	NDI Level II	Feb 15, 2023	Steven Lee
Reviewed	Caleb Saathoff	Sr. Research Engineer	Feb 24, 2023	Caleb J. Saathoff

Sikorsky Blade End of Life Inspection — Page 1 of 17







1 → 2 → 3 → 4 → 5 → 6 → 7 → 8

Planning | Fix.FAA | Fix.NIAR | History | NDI | Mech.Test | Failure(s) | LL.Test

Component Level NDI

Objective: *Establish whether fleet blades received have traditional damage we would typically see with NDI & do they have other aging effects that we don't normally measure?*

- **Approach for S-92 Blades**
  - Two identical blades exhibiting vastly different levels of skin-to-core bond strength as determined by OEM in-situ peel testing.
    - Evaluation of operational conditions (environment, flight profiles, etc.).
    - Performance of NDI for receiving condition evaluation and region of interest (ROI) determination (defects/damages).
    - Evaluation of skin-to-core bond characteristics.

Initial NDI Findings: *Utilizing standard inspection techniques, no change from nominal was discernable in severely aged blades.*

Summary of Status

Task I: Structural Test Rig Development

1) Steering Committee Formation ✓ *- Complete*

2) FAA Tech Center Fixture Design ✓ *- Complete*

3) NIAR ATLAS Fixture Design and Manufacturing ⇢ *In-progress*

Task II: Rotor Blade Acquisition

4) Blade History Documentation ✓ *- Complete*

5) Receiving Inspections ✓ *- Complete*

Task III: Full-scale Structural Testing

6) Mechanical Performance Analysis of Rotorcraft Blades ⇢ *In-progress*

Task IV: Rotor Blade Teardown and Lower-Level Testing

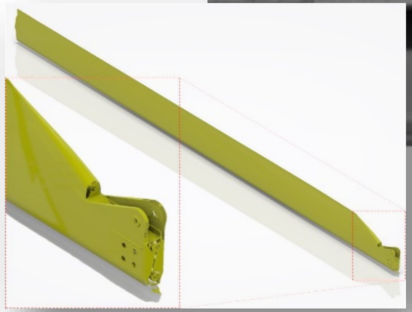
7) Failure Documentation and Analysis ⇢ *In-progress*

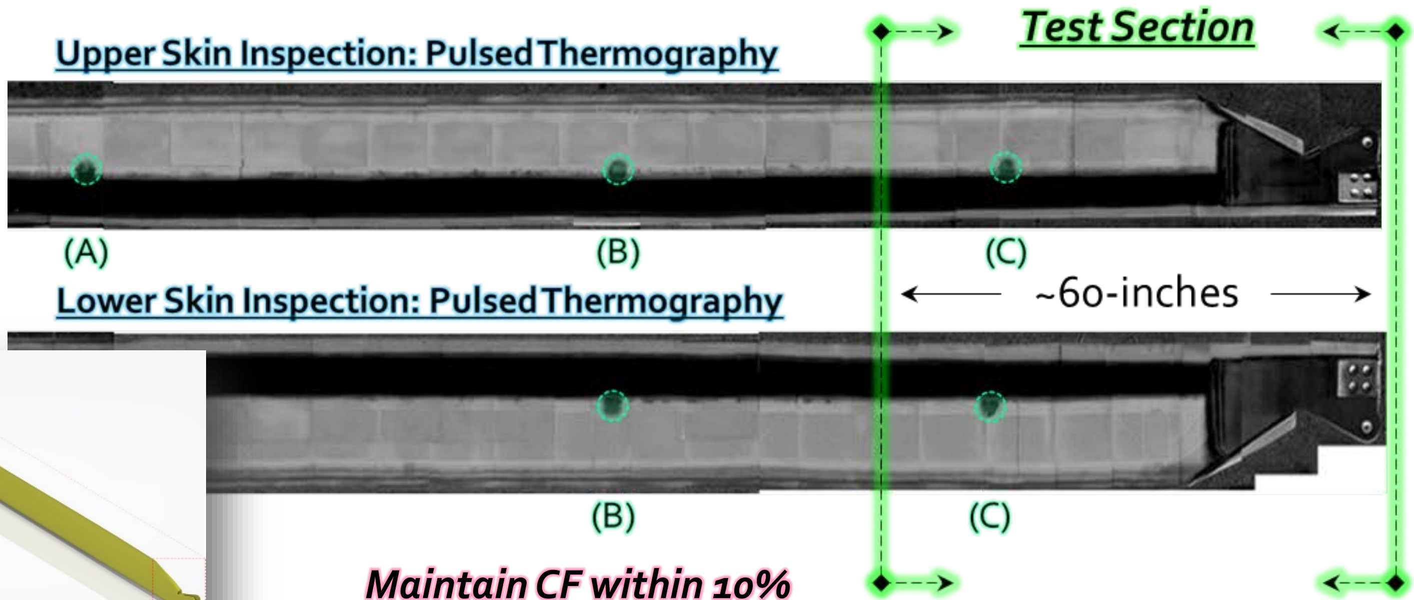
8) Detailed Experimental Investigations ⇢ *In-progress*

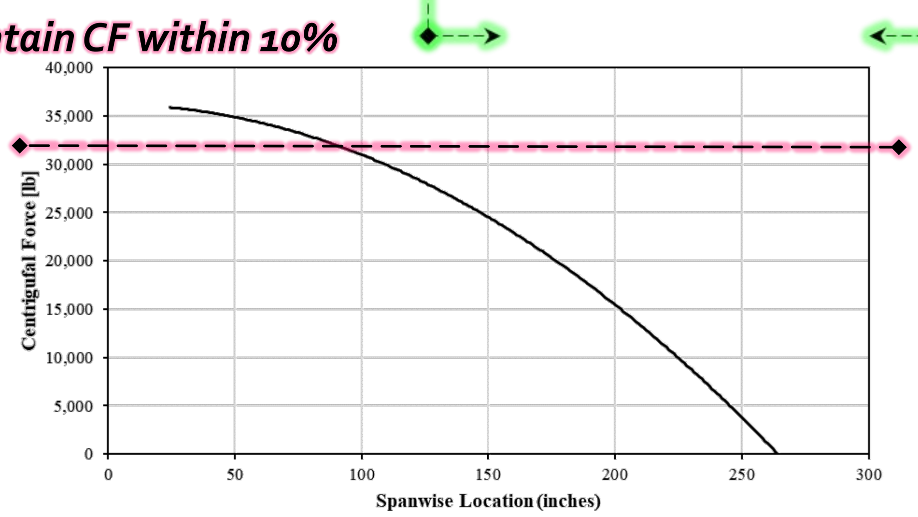
Moving Forward: Full-Scale Structural Testing – Stage 1

Objective: *Risk Mitigation and Confidence.*

- **General Approach:**
  - Assumptions for Force Estimations
    - Blade Weight: ***88.0-lbs***
    - Blade Speed: ***300-RPM***
    - Blade Length: ***19.98-ft***
    - Main Rotor Dia: ***44.0-ft***
    - Takeoff Weight: ***10,500****-lb*
    - Disk Area: ***1520.5****-sqft*
  - Reverse engineer blade loft for both INBD and OTBD attach
- **Full-scale testing :** *Quasistatic strain surveys*



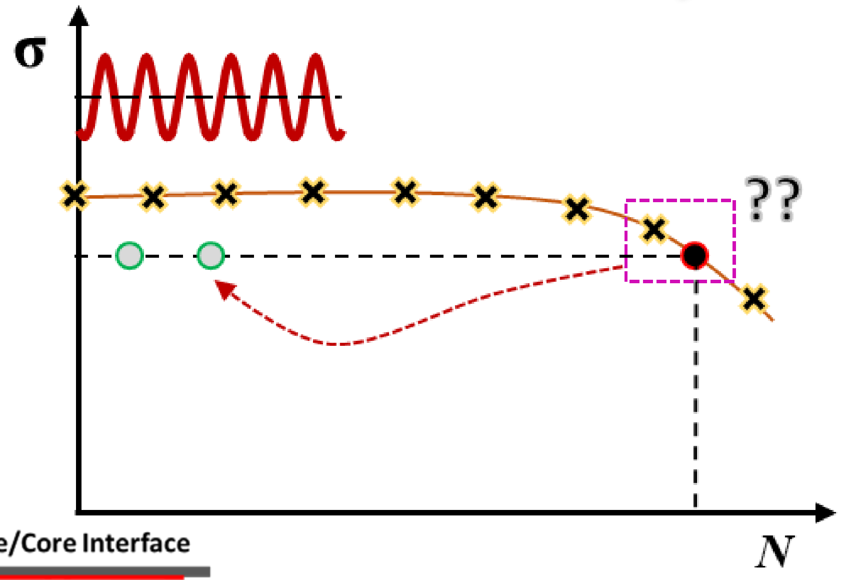


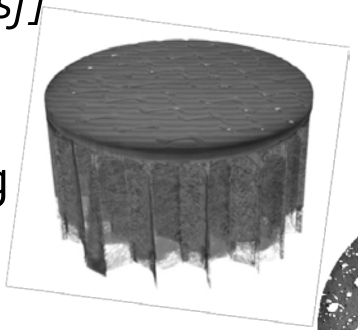


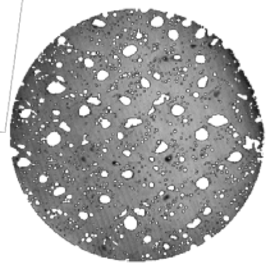
Moving Forward: Coupon Level Testing for Artificial Aging

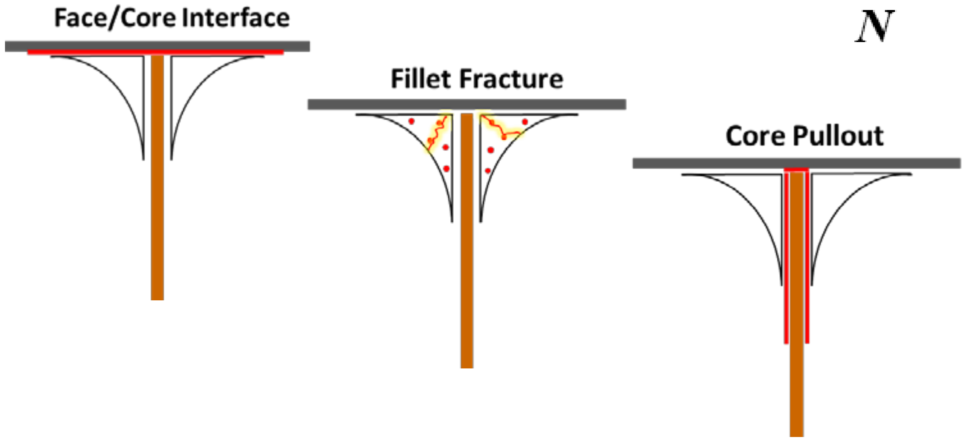
Objective: *Establish testing methodology for laboratory aging of structural details in which a strength knockdown is observed due to environmental exposure.*

- **Approach**
  - Two Configurations: *Pristine vs. Porosity*
    - Based upon dried vs. wet* core utilization when bonding
  - Use of material systems, to an extent, from rotor blade
    - Facesheet: T650/5320-1 PW
    - Adhesive: *Metlbond 1113 [0.06-psf]*
    - Core: *HRH10-3/16-2.0*
  - Baseline and Intermediate Testing
    - Peel and Flatwise Tensile
    - Hi-fidelity NDI via X-ray CT









1 Planning → 2 Fix.FAA → 3 Fix.NIAR → 4 History → 5 NDI → 6 Mech.Test → 7 Failure(s) → 8 LL.Test

Questions?

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