Structural Integrity Assessment for Aviation Parts with Inherent or Induced Material or Manufacturing Anomalies

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Qualification/Certification of Additively Manufactured Parts
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Summary

• The DARWIN software was originally developed to address structural integrity issues in high-energy gas turbine engine rotating components using zone-based probabilistic fracture analysis.

• DARWIN capabilities have grown through 21 years of industry collaboration and funding from the FAA, AFRL, NASA, and NAVAIR.

• DARWIN is now a mature tool with broad applicability to metallic aviation parts where inherent or rogue material or manufacturing anomalies (surface or volume distributed) can compromise structural integrity and safety.

• DARWIN’s current capabilities are well-suited to address the structural integrity challenges associated with AM parts.
Sioux City disk failure was the catalyst for unprecedented levels of industry/FAA cooperation regarding rotor safety … FAA Titanium Initiative

AIA Rotor Integrity Sub-Committee (RISC) established to develop new lifing strategies

ACCIDENT
UAL 232, July 19, 1989 - Sioux City, Iowa

- In-Flight separation of Stage 1 Fan Disk
- Failed from cracks out of material anomaly
  - Hard Alpha produced during melting
- FAA Review Team Report (1991) recommended:
  - Changes in Ti melt practices, quality controls
  - Improved manufacturing and in-service inspections
  - Lifing Practices based on damage tolerance
Background– Pensacola Accident

Manufacturing Surface Damage

ACCIDENT

DL 1288, July 6, 1996 - Pensacola, Florida

- MD-88 engine failure on take-off roll
- Stage 1 Fan Disk separated; impacted cabin
- Failure from abusively machined bolthole
- NTSB Report recommended ...
  - Changes in inspection methods, shop practices
  - Fracture mechanics based damage tolerance

- Pensacola failure motivated expansion of industry/FAA cooperation
  - RISC Activities Focused on Surface Damage Tolerance Methodology Development
  - Spawned FAA Enhanced In-Service Inspection and Rotor Manufacturing Initiatives
  - Developed “Lessons Learned” Database Capturing Industry Best Practices

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As RISC and the FAA developed the enhanced life management process, they saw that further research and development (R&D) was needed to address shortfalls in technology and data, including support for new damage tolerance framework.

SwRI (guided by RISC) proposed to the FAA and was awarded a series of R&D grants to address these shortfalls:
- Enhanced predictive tool capability (DARWIN)
- Supplementary material/anomaly behavior characterization and modeling

- “Turbine Rotor Material Design” (TRMD) program
- OEMs are integral members of project team
- Goal to provide direct support for implementation and improvement of FAA advisory material such as AC 33.14-1 & 33.70-2
Generalizing the DARWIN Background

• Specific threats to structural integrity of aviation parts caused by inherent or induced material or manufacturing anomalies
• An enhanced life management process based on probabilistic fracture analysis (damage tolerance)
• A life management process that is integrated into the overall process for component design and manufacture
• Application to a variety of structural materials, including different chemistries (titanium, nickel) and different manufacturing methods (cast & wrought, powder)
• Direct support to advisory and regulatory documents
• Active collaboration between government, industry, and researchers
Probabilistic Fracture Mechanics Methodology

- Cycles to Fracture
- Stressed Volume/Area
- Statistical Integration

Thermal & Stress Analysis

Anomaly Distribution

Initial Crack

Probability of Detection

POD

Crack Size

Inspection

Probability

Flights

Time

Cyclic Usage

Loads

Growth Rate

Material Properties

Stress Intensity Factor

Crack Growth

Probability

Cycles

Probability of Fracture

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DARWIN Analysis Modes

Inherent Anomalies

Zone-Based Risk (Volume)

Surface Damage

Feature-Based or Zone-Based Risk (Area)
Anomaly Distribution

Exceedance Curve

- # of anomalies per volume/area of material as function of anomaly size
- Key analysis input variable

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2D & 3D Anomalies in DARWIN

- Anomaly distributions associated with titanium hard alpha are described in AC 33.14-1
  - 2D, spherical
- Additional parameters may be required to define inherent anomalies in other materials
  - 3D, ellipsoid
  - Six DOF (all potentially random variables)
    - Length
    - Width aspect ratio
    - Depth aspect ratio
    - Three rotation angles
- Multiple (competing) anomaly types can be addressed
- Any number of anomalies can be accommodated (rare or frequent)

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Probability of Detection Curve

- Define probability of NDE crack detection as function of crack size
- Can specify different PODs for different zones, schedules
Basic DARWIN Random Variables

- Initial Anomaly Area
- Anomaly Detection (POD)
- Inspection Time
- Stress scatter
  - FE modeling error & usage variability
- Life Scatter
  - Material variability & life model error
  - Separate formation and growth values
- Other RVs have been added to address other issues
DARWIN Interface with Finite Element Models

- Input finite element files
  - Geometry model
  - Stress results (multiple load steps)
- File translators currently available for ANSYS & ABAQUS
  - Execute directly from GUI
  - Includes element filtering
- 2D and 3D models
- View FE models in DARWIN GUI
Integrated Fracture Mechanics Modeling

- Automatic FM modeling with direct import of stress & dimensions from FE model
- State-of-the-art weight function stress intensity factor solutions
  - *SIF solutions are common with NASGRO software*

Finite Element Model

Retrieve stresses along line
Zone-Based Risk Assessment

- The probabilistic fracture analysis method implemented in DARWIN is based on “zones”
- A “zone” is a practical subset of the component volume with common properties
  - Stress and temperature
  - Anomaly distributions
  - Material properties
  - NDI methods and POD
- Zoning provides a practical framework for
  - Managing different properties across the volume of the part
  - Calculating and managing risk across the volume of the part
DARWIN Offers Manual (Expert-Based) or Automatic Zoning Modes to Determine Fracture Risk
DARWIN 3D FE Model Interface
for Modeling Complex Geometries

1. Load 3D FE model

2. Select crack location & show principal stress plane

3. Slice 3D model to reveal 2D crack growth plane

4. Build 2D fracture model

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• Continuous DARWIN funding ($30M from FAA) since 1995 has facilitated significant capability growth.

• DARWIN can now be applied to most monolithic 3D metallic components with inherent or induced anomalies.
Additional DARWIN funding from other government agencies and licensees has supported additional capabilities:

- Integration with manufacturing process simulation (AFRL)
- Integration with 3D fracture mechanics (AFRL)
- Integration with NDI simulation (AFRL)
- New anomaly formation due to corrosion (NASA)
- Time-dependent crack growth (NAVAIR)
Integration with Manufacturing Process Simulation

Link DEFORM output with DARWIN input

- Finite element geometry (nodes and elements)
- Finite element stress, temperature, and strain results
- Residual stresses at the end of processing / spin test
- Location specific microstructure / property data
- Tracked location and orientation of material anomalies
Influence of Location-Specific Microstructure on Life & Risk

- ANSYS
- ABAQUS
- DEFORM
- DARWIN
- DEFORM

Stress Results Files

Grain Size Results File

grain size contours

crack growth rate multiplier

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Influence of Location-Specific Residual Stress on Life (and Risk)

Without Residual Stress

With Residual Stress

DEFORM-DARWIN integration can also consider uncertainties in manufacturing analysis
Integration of NDE and Fracture Risk Models

CAD

NDE Process Simulation

Probability of Detection Curve

Risk of Fracture With Inspection

Stress and Fracture Mechanics Analysis
Structural Integrity Challenges for Additive Manufacturing

- A variety of potential material anomalies that can occur anywhere in the volume of an AM part
- Anomalies can lead to crack formation and fracture, depending on the local stresses in the part
- AM parts often have geometric complexity that can lead to significant variability in inspectability
- Material properties are uncertain and can vary from location to location in the part
DARWIN Relevance to Additive Manufacturing

• DARWIN already contains many capabilities that are directly relevant to AM applications
  - Calculate fracture risk due to distributions of material anomalies
  - Consider potential anomalies anywhere in the part volume
  - Data framework facilitates location-specific properties in a 3D model
  - Directly consider effect of location-specific POD on fracture risk
  - Easily integrated with manufacturing process or NDE software
  - FE model integration addresses location-specific stress, temperature
  - Probabilistic methods characterize effects of multiple uncertainties without introducing unquantified over-conservatism
  - Zoning simplifies analysis and data management process
  - Automation reduces analysis time and training requirements

• AM applications can take full advantage of a prior $37M investment in DARWIN method/software development
Side Note: A New Framework for Qualification

The traditional building block approach for qualification was not designed for technologies like AM where the part and material are made simultaneously.

As part of the DARPA Open Manufacturing project, SwRI has developed a new framework for qualification that relies on computational tools and rigorous uncertainty quantification.
Additional Capabilities Needed

• Some further incremental development of DARWIN may be useful for AM applications
  - Treatment of material property anisotropy
  - Interfaces with AM process simulation models/software
  - Microstructure-property relationships for AM materials
  - Logic for creating zones with slightly dissimilar properties
  - Interfaces with additional NDE simulation software
  - Other needs identified by the AM community
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