

# Using SMART|DT to Ensure the Continued Structural Safety of Textron Aviation's Fleet

Beth Gamble, Chris Hurst and Perry Saville March 24, 2016



#### Cessna 172 Skyhawk

#### Beech Bonanza



Beechcraft 1900D

Textron Aviation is the company formed from Cessna and Beechcraft in March 2014 – together 250,000+ airplanes have been delivered Cessna 208 Caravan



Cessna O-2 Skymaster



Beechcraft T-6A Texan II

Cessna Citation X

Textron Airland Scorpion

#### Agenda



- Background
- Cessna 402C
- SMART|DT Methodology
- Using SMART|DT
- Service History
- SMART|DT Analysis Wing
- SMART|DT Analysis Engine Beam
- Recommendations

#### Background



- FAA Roadmap for General Aviation (GA) Aging Airplanes Programs
  - A guide to proactively manage the overall airworthiness of aging GA airplanes
  - Prompted by series of primary component failures
  - Development of data-driven risk assessment and risk management methods
- University of Texas San Antonio (UTSA)
  - Developed a comprehensive probabilistic methodology and computer software to conduct risk assessments of GA airplanes
  - Software is called SMART <u>SMall Aircraft Risk Technology</u>
    - SMART consists of two modules:
      - » SMART|LD Linear Damage (fatigue)
      - » SMART|DT Damage Tolerance (crack growth)
  - Software gives Federal Aviation Administration (FAA) engineers the tools to conduct a risk assessment of general aviation (GA) structural issues in support of policy decisions
- Cessna awarded a contract from UTSA to evaluate SMART using real world examples



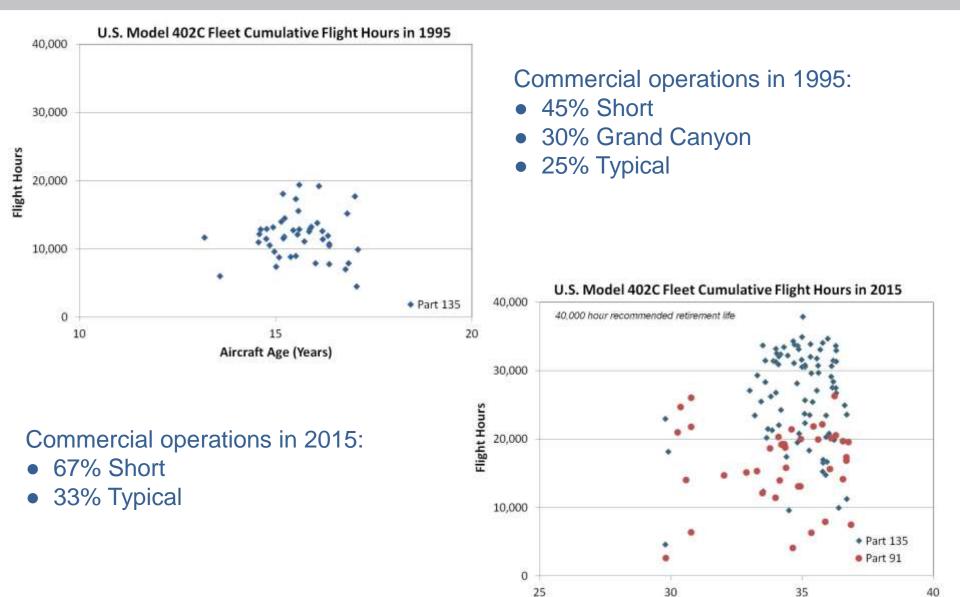
- Cessna Model 402C selected to evaluate SMART
  - Twin engine piston
  - Non-pressurized
  - Seats up to 9 passengers
  - Used in Part 135 Commuter
  - 381 402C's manufactured from 1979 to 1985





- Cessna was awarded an FAA contract to apply damage tolerance methods to the Model 402C in 1995
  - New development tests, service experience and applications of current technology in the areas of loads, stress, fatigue and fracture mechanics were utilized to identify and establish structural inspections and modifications
  - Resulting inspection program for the Model 402C is based on 3 different usages
    - » Typical Usage 6 flight profiles, 68 minute average
    - » Grand Canyon Usage 2 flight profiles, 60 minutes each
    - » Short Flight Usage 1 flight profile, 25 minutes

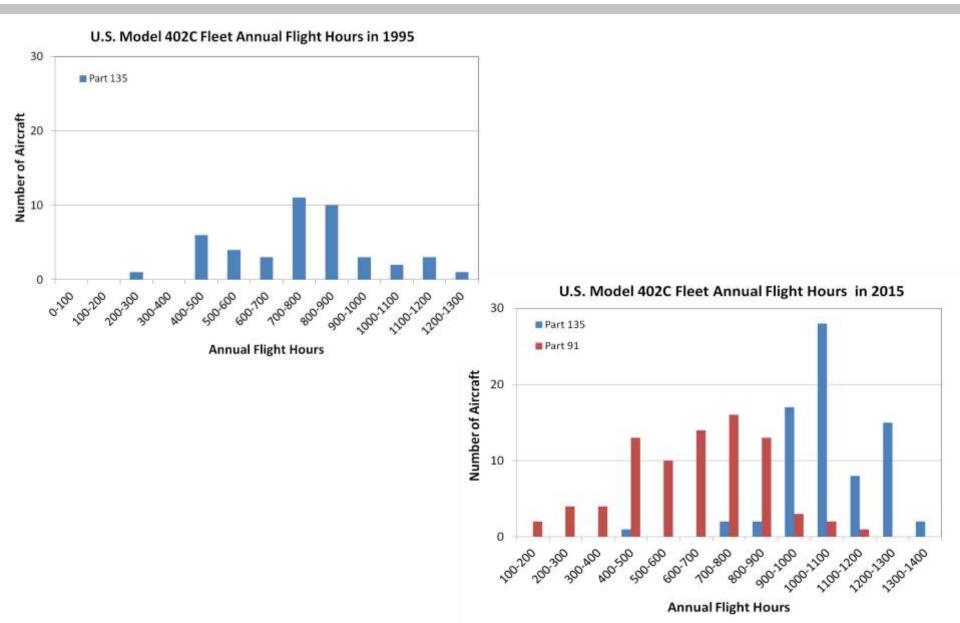




35 Aircraft Age (Years)



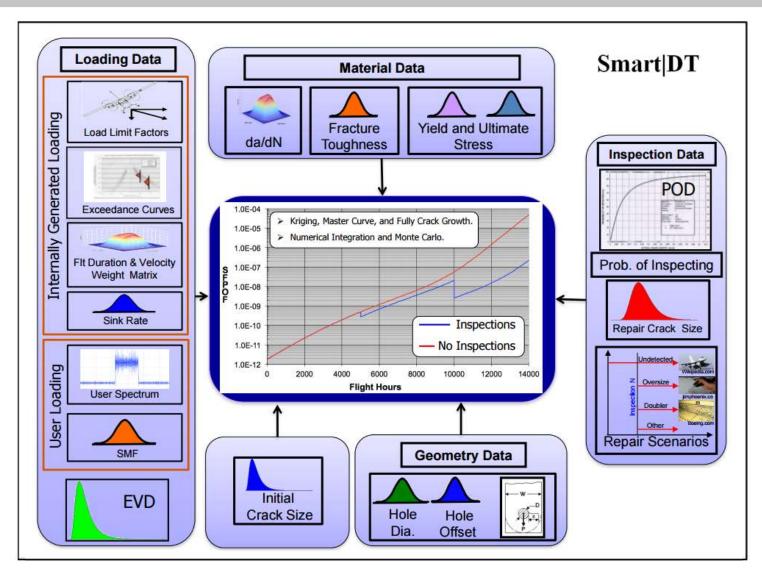
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#### SMART|DT Methodology Summary<sup>1</sup>



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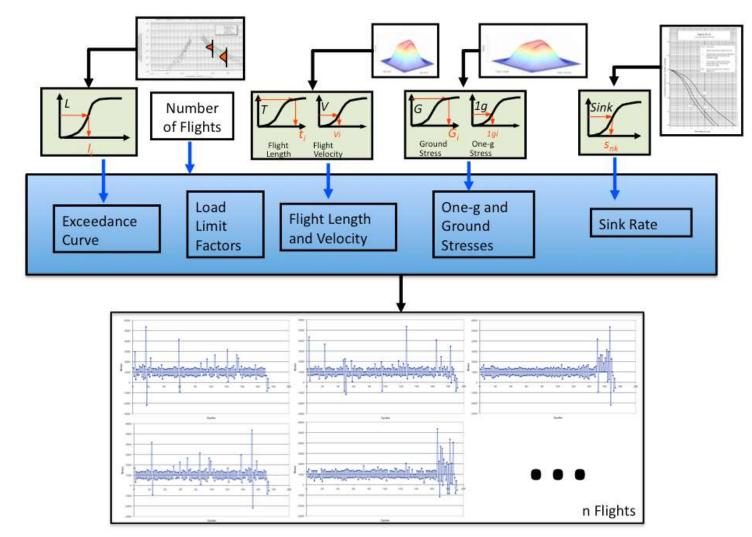


<sup>1</sup> Millwater H. & Ocampo, J., 'Multiple Repair Scenarios in Aircraft Fleets Using the Weighted Branch Integration Method', presented at 2015 Aircraft Airworthiness and Sustainment Conference.

# **SMART Spectrum Generation Methodology Summary**<sup>1</sup>



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<sup>1</sup> Ref. Ocampo, J., Castaldo, A. and Millwater H., 'Probabilistic Damage Tolerance Analysis for Small Airplanes', presented at 2012 Aircraft Airworthiness & Sustainment Conference.



**NASGRO** Parameters

- Crack Growth Methods
  - Master Curve
    - NASGRO
    - User Generated
    - AFGROW
    - FASTRAN
  - Surrogate Model
  - External Code
- Random Variables
  - Initial Crack Size
  - Crack Aspect Ratio\*
  - Fracture Toughness
  - Paris Constant Log (c)\*
  - Paris Constant m\*
  - Hole Diameter\*
  - Yield Stress\*
  - Ultimate Stress\*
  - Hole Offset\*

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Ultimate Strees		0.5	0.0		PDFACE		

## **Random Variables**

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\* Random variables unique to SMART



**AFGROW** Parameters

- Crack Growth Methods
  - Master Curve
    - NASGRO
    - User Generated
    - AFGROW
    - FASTRAN
  - Surrogate Model
  - External Code
- Random Variables
  - Initial Crack Size
  - Crack Aspect Ratio\*
  - Fracture Toughness
  - Paris Constant Log (c)\*
  - Paris Constant m\*
  - Hole Diameter\*
  - Yield Stress\*
  - Ultimate Stress\*
  - Hole Offset\*

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Geometric Model

\* Random variables unique to SMART



- Crack Growth Methods
  - Master Curve
    - NASGRO
    - User Generated
    - AFGROW
    - FASTRAN
  - Surrogate Model
  - External Code
- Random Variables
  - Initial Crack Size
  - Crack Aspect Ratio\*
  - Fracture Toughness
  - Paris Constant Log (c)\*
  - Paris Constant m\*
  - Hole Diameter\*
  - Yield Stress\*
  - Ultimate Stress\*
  - Hole Offset\*

# Kriging Parameters

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Random Variables Prob	Mean	Standard Devis	tion		Nasgro Stress C	
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F Hole Diameter	0.15625	0.005		PDF/CDF		
Vield Stress	67.0	2.0		FDF/CDF		
🔽 Ultimate Stress	122.0	5.0		PDF/CDF		
	0.5	0.1		PD/7/20/		

## **Random Variables**

\* Random variables unique to SMART



- Spectrum Generation
  - Two Methods
    - User Defined in AFGROW Format
    - AC23-13A Derived

Spectrum -

- Extreme Value Distribution
  - EVD Direct
  - Limit/Ultimate Load
  - Fitting from Loading Parameters

Documentation	ding  inspecting   Method/Output   Launch Panel	
	te Value Distribution Location: 145 Scale: 0.8 Shape: 0.0	Spectrum Editing Spectrum Length in Flights 1000 C Rainflow Stress Randomization Deadband Stresses Colly C Stresses and Flights
ading Parameters    (		I Ree/Fall
ad Usages	Usage Spectre Aircraft Usage: TWIN_ENGINE_UNPRESS_GENERAL Fraction of Total Usage: 10 Design Moneuver LF High: 36 Design Gust LF High: 4.35 Design Moneuver LF Low: -1.44 Design Gust LF Low: -0.5 Ground Stress (psi): -1000.0	USAGE Plot Exceedances  Plot Exceedances  Cone G Stress (pa):  Average Velocity (Vno/Vmo(Knots))  Number of Flight Times  Number of Velocities:  Losd Metrices  Matrix
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F\/D



**Inspection Schedule** 

- Inspection Definition
  - Single Repair
  - Multiple Repairs\*
- Inspection Type
- Probability of Inspection
- Probability of Detection
  - Lognormal
  - Deterministic
  - Tabular (user input)
- Repair Crack Size
  - Same as initial
  - Deterministic
  - Lognormal
  - Weibull
  - Tabular (user input)

Inspection	Туре
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#### SMART - Small Aircraft Risk Technology \_ 🗆 X Fle Documentation Overview Fracture Load og Inspection Method/Output Launch Panel Single Repair C Multiple Repairs 6 Inspection Data Inspection Schedule Time Inspection Type Inspection Type Inspection 1 5000 Inspection 1 ٠ . 6000 Inspection 1 7000 Inspection T + • 8000 Inspection 1 • 9000 Inspection 1 • 10000 Inspection 1 • 11000 Inspection 1 . 12000 Inspection 1 . 13000 Inspection 1 . 14000 Inspection 1 Probability of Inspection 0.8 Probability of Detection Meen Std Dev CDF 0.03 . 0.15 Lognormal Repair Crack Size Mapri Std Dev PDF/CD Same As Initial 💌 07/10/2015-V4.0.7

# **Inspection Criteria**

\* Capability unique to SMART



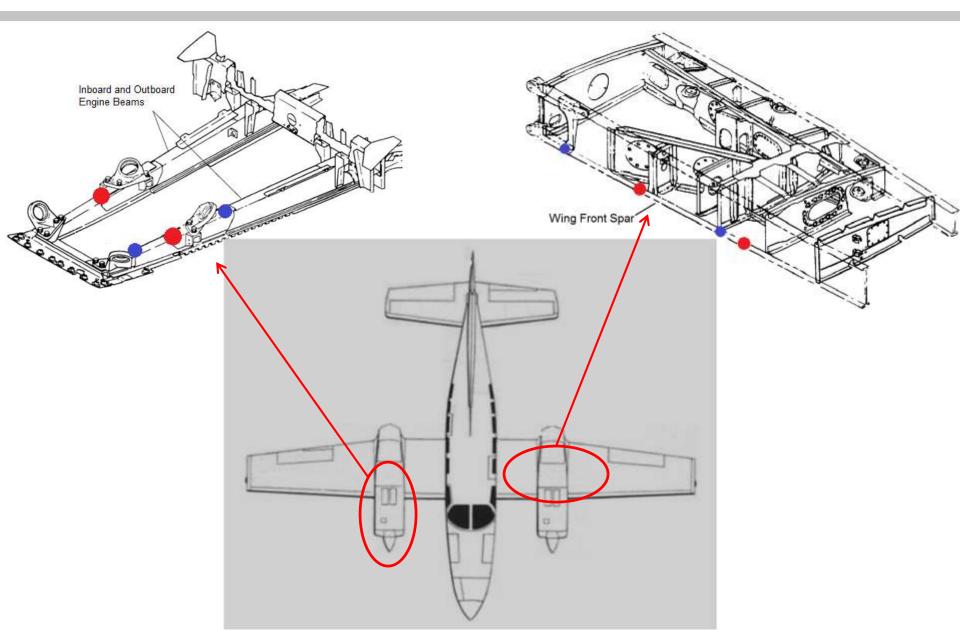
- Two Analysis Methods
  - Monte Carlo
  - Numerical Integration

<ul> <li>Numerical Integration</li> </ul>	🚮 SMART - Small Aircraft Risk Technology	×
3	Ele Documentation	
	Overview Fracture Loading Inspection Method/Output Launch Panel	
	Method	
Monte Carlo —	Monte Carlo	
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Numerical Integration	Max Evaluations 10000000 Evaluation Fraguency 500	
	Seed: [6388552 Max Flights Calculation: [40000	
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# **Service History**

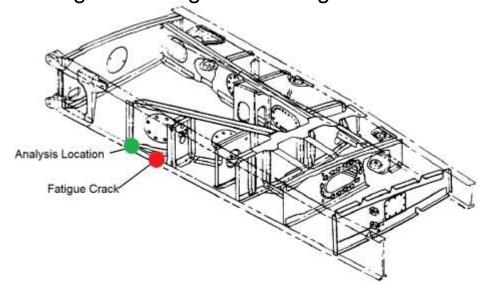


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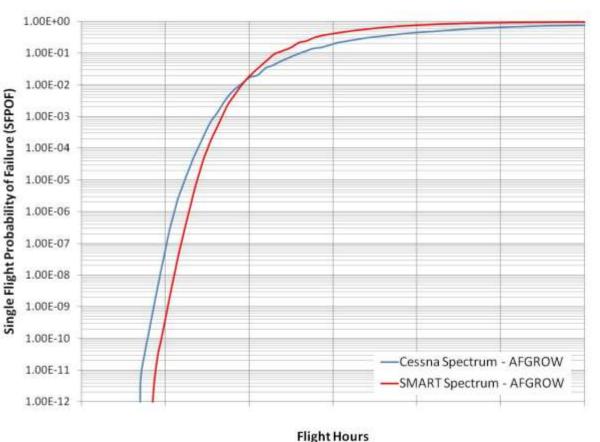
- In 1999, a Cessna 402C wing main spar cracked near WS 86
- Right wing separated in flight as a result
- Airplane had ten owners, one owner operated in Grand Canyon
- At the time of wing failure aircraft was used to carry cargo (typical usage)
- Maintenance records indicated numerous repairs to the right wing, including:
  - Skin cracks
  - Working rivets
  - Wing aux spar straps
- Crack initiated in an area of mechanical damage and rough machining marks
- Airplane had 20,000+ hours





- Analysis Assumptions W.S. 86
  - AFGROW
  - Grand Canyon Usage
  - Two Spectra
    - Cessna
    - SMART (AC23-13A)
  - Probabilistic Variables
    - Initial Crack Size
  - EVD
    - Limit Load
  - No Inspections

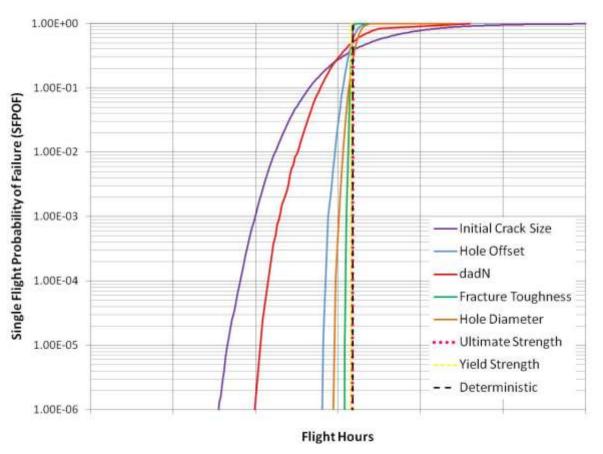
#### Comparison of Cessna Spectra to SMART Internal Spectra





#### • Analysis Assumptions – W.S. 86

- NASGRO
- Typical Usage
- SMART Spectrum
- Probabilistic Variables
  - Initial Crack Size
  - Hole Offset
  - dadN
  - Fracture Toughness
  - Hole Diameter
  - Ultimate Strength
  - Yield Strength
- EVD
  - Limit Load
- No Inspections



Comparison of Probabilistic Variables



Typical .10 inch Detectable

Typical .15 inch Detectable

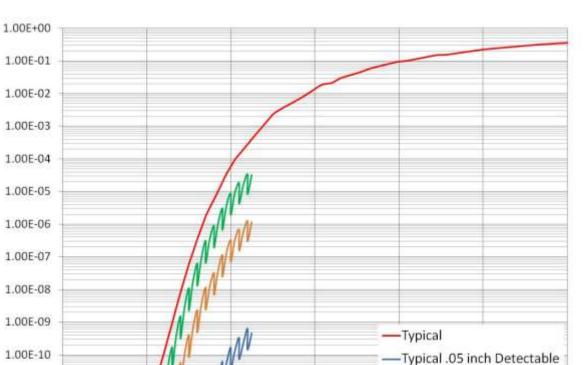
- Analysis Assumptions W.S. 86
  - AFGROW
  - Typical Usage
  - Cessna Spectrum
  - Probabilistic Variables
    - Initial Crack Size

Single Flight Probability of Failure (SFPOF)

1.00E-11

1.00E-12

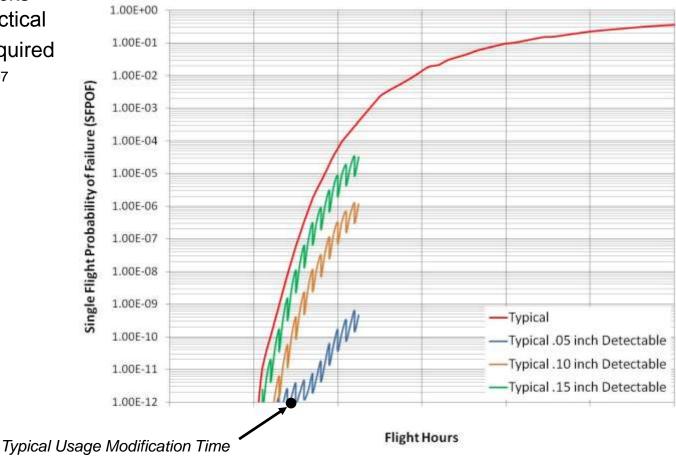
- EVD
  - Limit Load
- 80% POD
- 1000 hour Inspections
  - .05" Detectable
  - .10" Detectable
  - .15" Detectable



Comparison of Detectable Flaw Sizes – Typical Usage



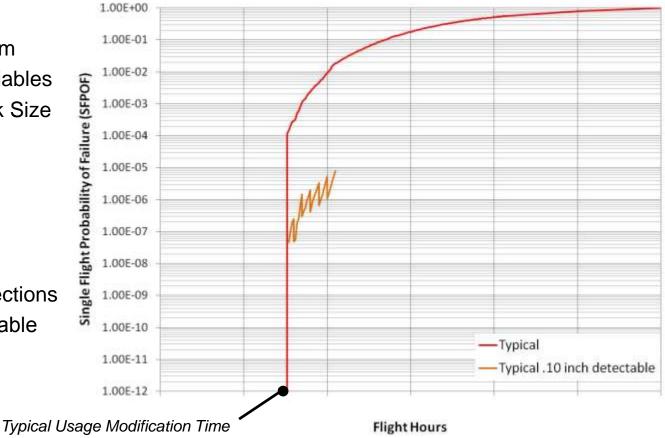
- Analysis Results W.S. 86
  - Detection of cracks
     < .15" is not practical</li>
  - Modification Required
  - SFPOF < 1.0E<sup>-07</sup>



#### Comparison of Detectable Flaw Sizes – Typical Usage



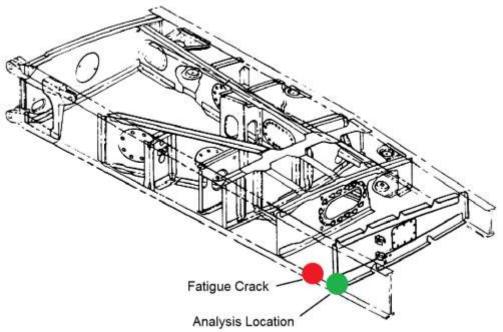
- Analysis Assumptions W.S. 86
  - NASGRO
  - Typical Usage
  - SMART Spectrum
  - Probabilistic Variables
    - Initial Crack Size
    - Hole Offset
    - dadN
  - EVD
    - Limit Load
  - 80% POD
  - 1000 Hour Inspections
    - .10" Detectable



Single Flight Probability of Failure for Typical Usage



- In 2005, main spar and skin cracked near WS 107 on two Model 402Cs
- One aircraft had cracks located on both the right and left sides
- Both aircraft had 20,000+ flight hours when cracks were discovered
- Both airplanes operated in passenger service when cracks were discovered
  - Current usage representative of short spectrum
- Airplanes previously flew in Grand Canyon
- Higher time aircraft, but not fleet leaders

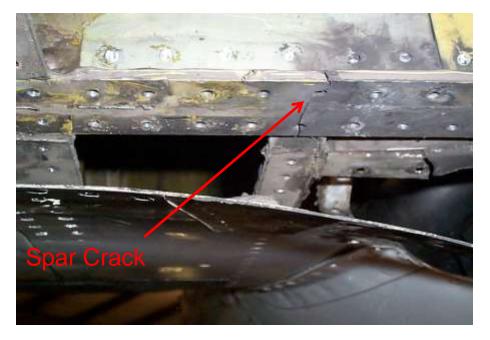




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View looking forward at front spar

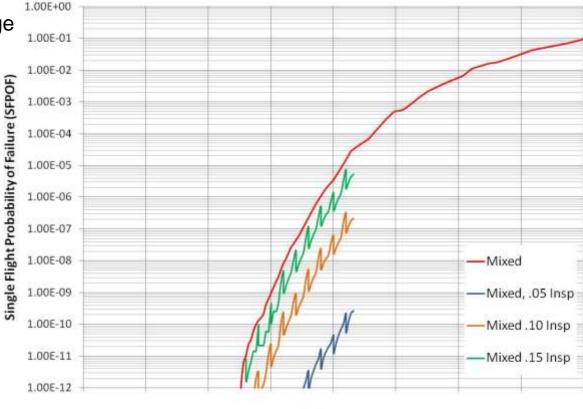


View looking forward at front spar



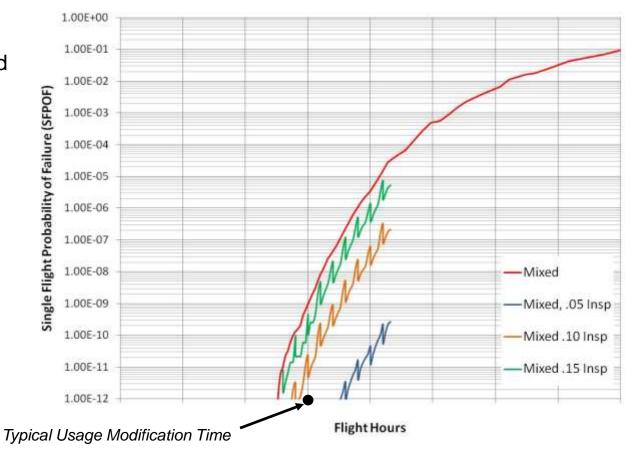
- Analysis Assumptions W.S. 107
  - AFGROW
  - Short & GC (Mixed) Usage
  - Cessna Spectrum
  - Probabilistic Variables
    - Initial Crack Size
  - EVD
    - Limit Load
  - 80% POD
  - 1000 Hour Inspections
    - .05" Detectable
    - .10" Detectable
    - .15" Detectable

Comparison of Detectable Flaw Sizes – Mixed Usage





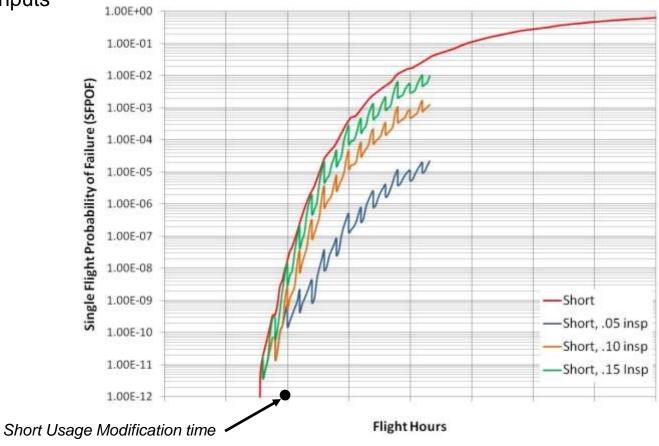
- Analysis Results W.S. 107
  - Detection of cracks
     < .15" is not practical</li>
  - Modification Required
  - SFPOF < 1.0E<sup>-07</sup>



#### Comparison of Detectable Flaw Sizes – Mixed Usage



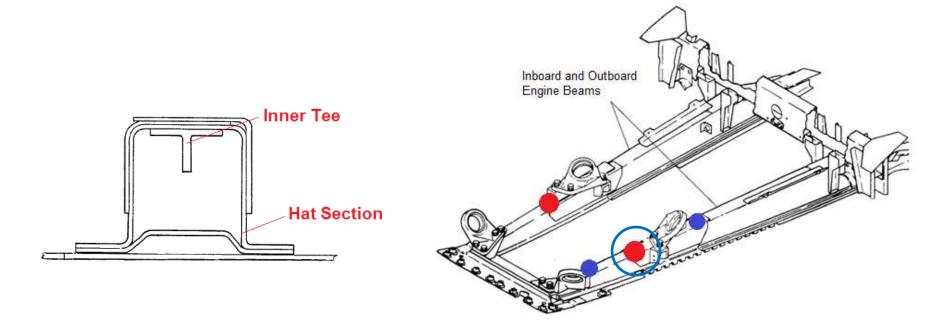
- Analysis Assumptions W.S. 107
  - Same Analysis Inputs
  - Short Usage



Comparison of Detectable Flaw Sizes – Short Usage



- In 2015, engine beam support structure "hat section" cracked on 8 airplanes
  - Four cracks on inboard beam and four cracks on outboard beam
  - Six of the eight cracks were just forward of aft engine mount
- Airplanes had 29,000 34,000 flight hours when cracks were discovered
- Each airplane was operating in passenger service at the time (short usage)
- Airplanes flown approximately 40% in Grand Canyon and 60% in Short Usages





• Engine Beam Cracks Under Forward and Aft Engine Mounts

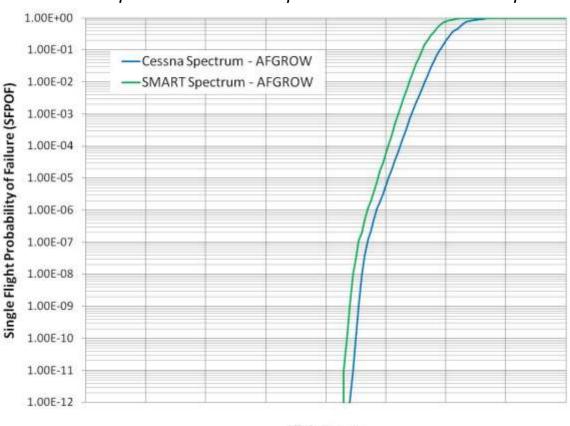


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RH Outboard Beam Fwd of Aft Engine Mount RH Inboard Beam Aft of Fwd Engine Mount



- Analysis Assumptions
  - AFGROW
  - Grand Canyon Usage
  - Two Spectra
    - Cessna
    - SMART (AC23A-13)
  - Probabilistic Variables
    - Initial Crack Size
  - EVD
    - Limit Load
  - No Inspections

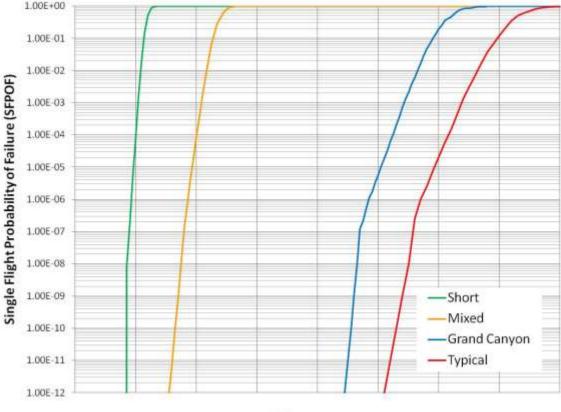


Comparison of Cessna Spectra to SMART Internal Spectra



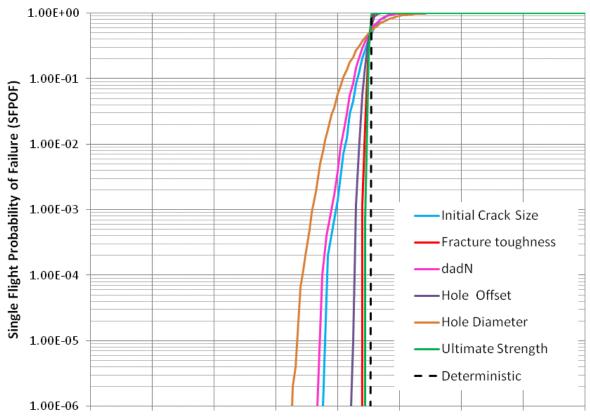
- Analysis Assumptions
  - AFGROW
  - Four Usages
    - Grand Canyon
    - Short
    - GC & Short (Mixed)
    - Typical
  - Cessna Spectrum
  - Probabilistic Variables
    - Initial Crack Size
  - EVD
    - Limit Load
  - No Inspections

#### Comparison of Four Flight Usages





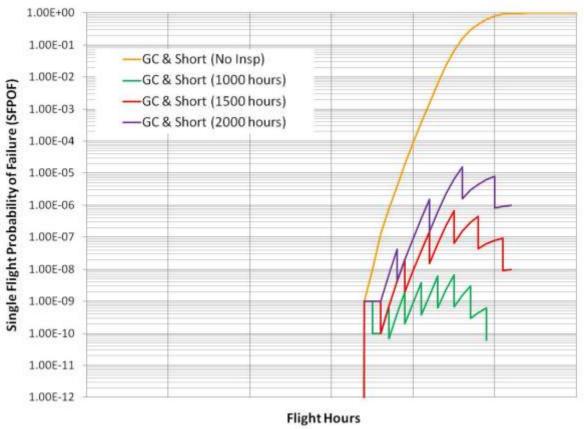
- Analysis Assumptions
  - NASGRO
  - Grand Canyon Usage
  - SMART Spectrum
  - Probabilistic Variables
    - Initial Crack Size
    - dadN
    - Fracture Toughness
    - Hole Offset
    - Hole Diameter
    - Ultimate Strength
  - EVD
    - Limit Load
  - No Inspections



#### Comparison of Probabilistic Variables



- Analysis Assumptions
  - AFGROW
  - GC & Short (Mixed) Usage
  - Cessna Spectrum
  - Probabilistic Variables
    - Initial Crack Size
  - EVD
    - Limit Load
  - With Inspections
    - 1000 hours
    - 1500 hours
    - 2000 hours



#### Comparison of Inspection Intervals



- Analysis Assumptions
  - NASGRO
  - Grand Canyon Usage
  - SMART Spectrum
  - Probabilistic Variables
    - Initial Crack Size
    - dadN
    - Hole Offset
  - EVD
    - Fitting
  - 1000 Hour Inspections

#### Single Flight Probability of Failure for Grand Canyon Usage





- SMART|DT is a powerful tool that allows user to tune analysis based on available information
- Enhancements yet to come
  - Build in 2 or 3 frequently used K solutions
  - Incorporate libraries of random variables
  - Reduce the computational time
    - Implement advanced sampling methods



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