SMART (SMALL AIRCRAFT RISK TECHNOLOGY) SPECTRUM DEVELOPMENT METHODOLOGY

Chris Hurst, Beth Gamble, Perry Saville and Andy Ghosh
April 1, 2015

SMall Aircraft Risk Technology (SMART)

- Fatigue management program software for general aviation.
- Created by the University of Texas-San Antonio under FAA contract.
- Provide tools for data driven risk assessment and fleet management.
- Develop damage tolerance based inspections, or replacement/modification time limits for structural elements.
- The SMART software consists of two modules:
  - Linear Damage (fatigue crack initiation)
  - Damage Tolerance (crack growth)
- Goals for this presentation
  - Demonstrate SMART spectrum provides rational spectra
  - Demonstrate SMART capabilities to tune spectra
  - Compare different exceedance curve sources

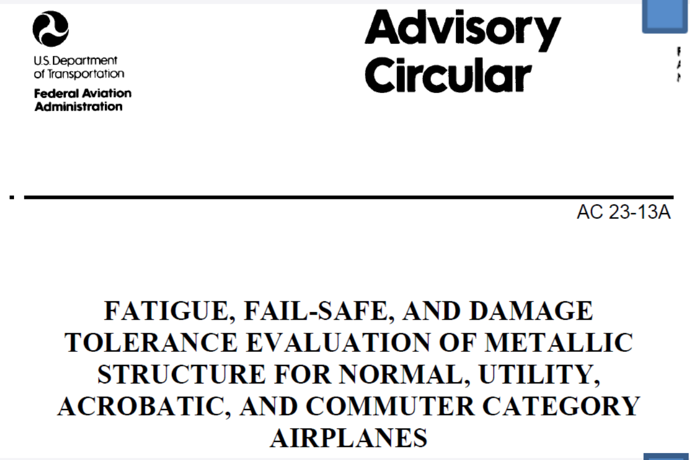
SMART Spectrum

- Cessna awarded a contract from the FAA/University of Texas-San Antonio to review SMART fatigue management program software.
- Objective is to validate the software using real-world applications.

SMART$_{LD}$

SMall Aircraft Risk Technology – Linear Damage Analysis

Spectrum generation process

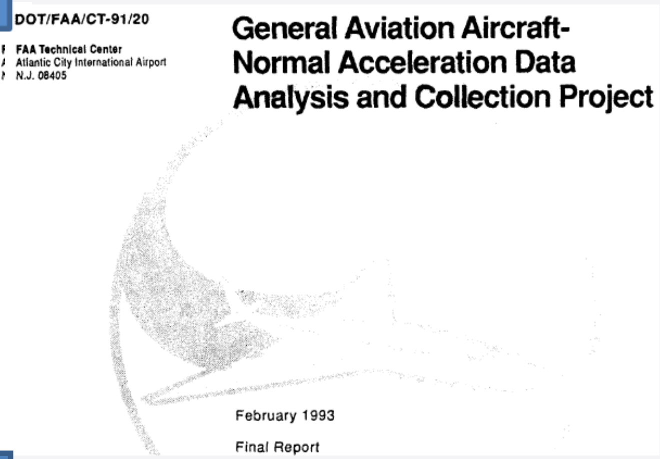


U.S. Department of Transportation
Federal Aviation Administration

Advisory Circular

AC 23-13A

FATIGUE, FAIL-SAFE, AND DAMAGE TOLERANCE EVALUATION OF METALLIC STRUCTURE FOR NORMAL, UTILITY, ACROBATIC, AND COMMUTER CATEGORY AIRPLANES



DOT/FAA/CT-91/20

FAA Technical Center
Atlantic City International Airport
N.J. 08405

General Aviation Aircraft-Normal Acceleration Data Analysis and Collection Project

February 1993

Final Report

SMART$_{DT}$

SMall Aircraft Risk Technology - Damage Tolerance Analysis

History

- Cessna was awarded an FAA contract in 1995 to apply damage tolerance methods to small commuter airplanes.
    - Damage tolerance methods were applied to develop a Supplemental Inspection Document (SID).
        - 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 (SID) for the Model 402C is based on 3 different usages.
        - Typical Usage – 6 flight profiles with 68 min. flight avg.
        - Grand Canyon Usage – 2 flight profiles, both one hour flights
        - Short Flight Usage – 25 minute flight

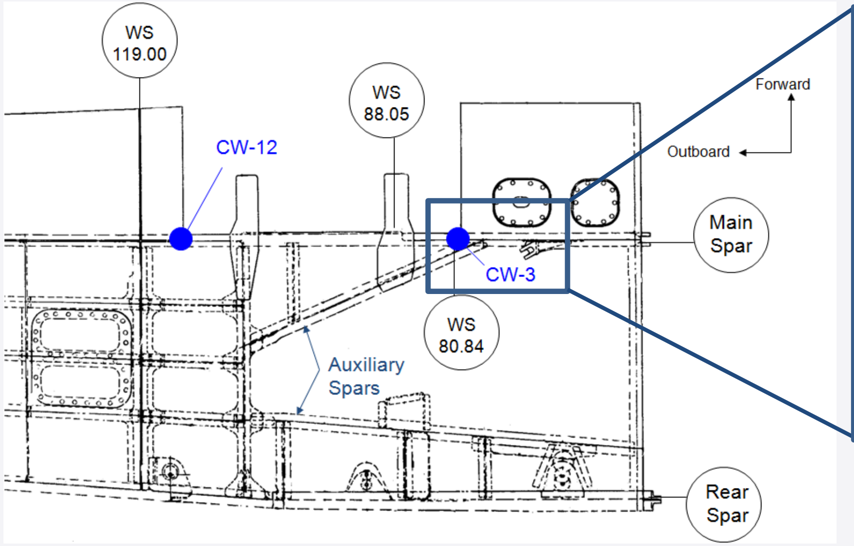
Cessna Model 402C “Businessliner”/”Utililiner”

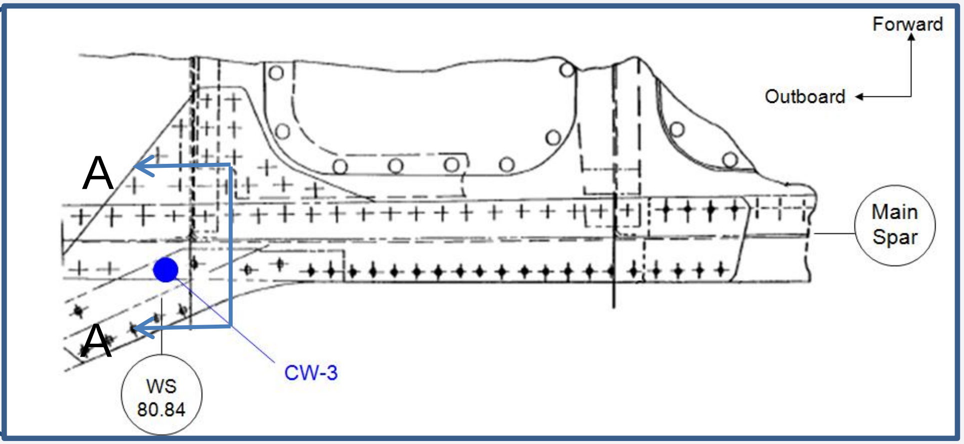
- Twin engine (piston), non-pressurized, (up to) 9 passengers
- 381 402C’s manufactured from 1979 to 1985
- Service ceiling = 26,900 ft.
- Max speed = 230 knots
- Range = 1,243 NM

Wing Location CW-3

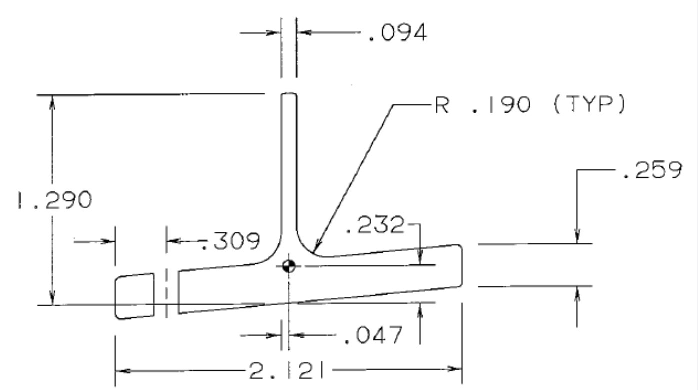
Beechcraft | Cessna | Hawker
TEXTRON AVIATION

- One instance of cracks in the field. Resulted in an in-flight wing failure.
- Crack located at WS 86.00
- Failed after 20,000 hours
- Airplane was used to carry cargo at the time of wing failure





Section A-A

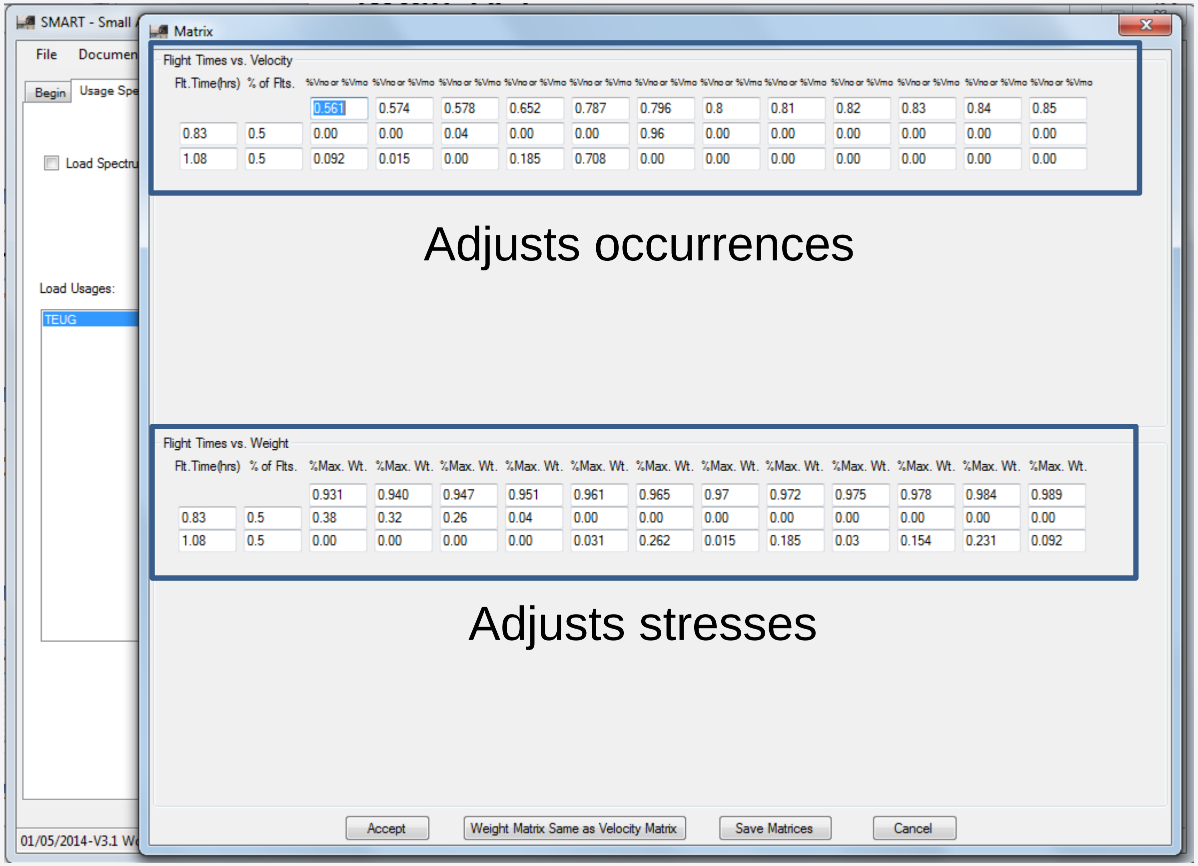


SMART Spectrum

- SMART allows user to either:
  - Create a spectrum within SMART
  - Import their own spectrum
- Internal spectrum tool is exceedance curve based
  - Gust = DOT/FAA/CT-91/20 exceedance curves
  - Maneuver = DOT/FAA/CT-91/20 exceedance curves
  - Landing impact & rebound
    - Landing max stress = 2/3(1g_stress)
    - Landing min stress = (Ground_stress) * g
      - Where g = 0.1877*(Sink Rate Velocity)+1.3422
        - » Gear drop test data from AFS-120-73-2
    - Rebound max stress = 0.6 * Landing max stress
    - Rebound min stress = 0.6 * Landing min stress
  - Taxi = AC23-13A exceedance curve
- Probabilistic analysis tool uses mean exceedance curves
  - Gust and maneuver exceedances not offset at standard deviations as done for AC23-13A curves

SMART Velocity and Weight Matrices

- Adjust SMART spectrum severity using weight/velocity matrices
- SMART spectrum matrices can be used two ways
  - Simulate flight profiles
  - Simulate different operations



Flight Times vs. Velocity

Flt.Time(hrs)	% of Flts.	%Vno or %Vmo	%Vno or %Vmo	%Vno or %Vmo	%Vno or %Vmo	%Vno or %Vmo	%Vno or %Vmo	%Vno or %Vmo	%Vno or %Vmo	%Vno or %Vmo	%Vno or %Vmo	%Vno or %Vmo	%Vno or %Vmo
		0.561	0.574	0.578	0.652	0.787	0.796	0.8	0.81	0.82	0.83	0.84	0.85
0.83	0.5	0.00	0.00	0.04	0.00	0.00	0.96	0.00	0.00	0.00	0.00	0.00	0.00
1.08	0.5	0.092	0.015	0.00	0.185	0.708	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Adjusts occurrences

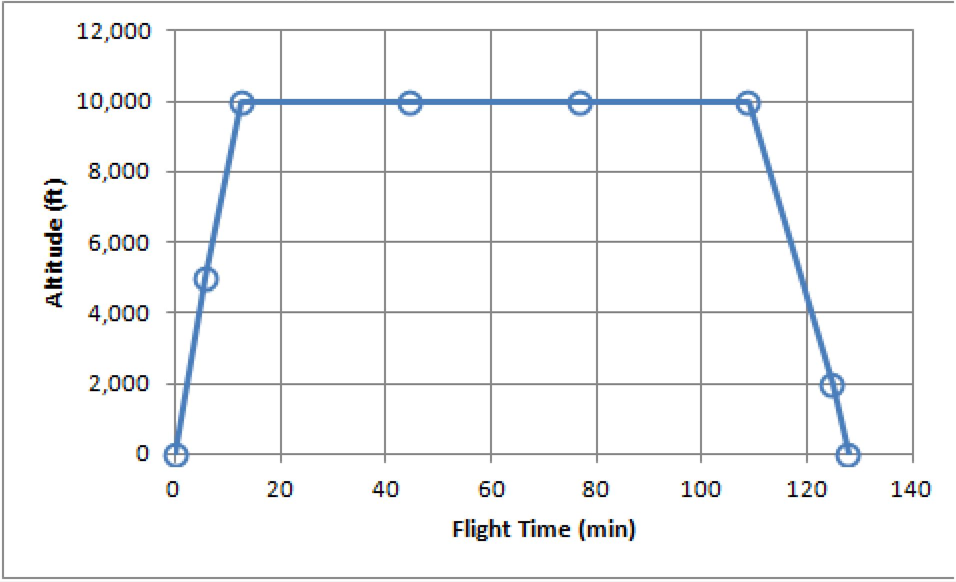
Flight Times vs. Weight

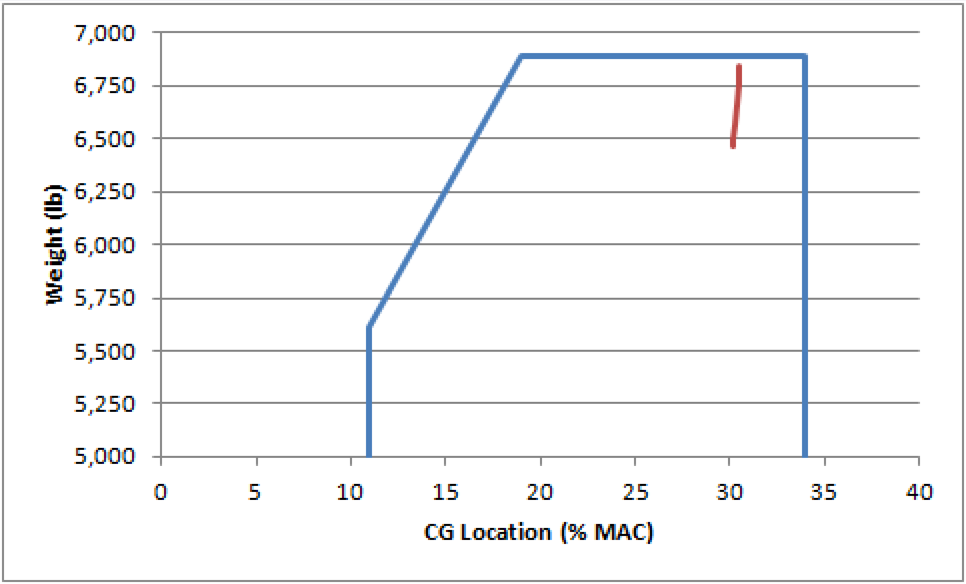
Flt.Time(hrs)	% of Flts.	%Max. Wt.	%Max. Wt.	%Max. Wt.	%Max. Wt.	%Max. Wt.	%Max. Wt.	%Max. Wt.	%Max. Wt.	%Max. Wt.	%Max. Wt.	%Max. Wt.	%Max. Wt.
		0.931	0.940	0.947	0.951	0.961	0.965	0.97	0.972	0.975	0.978	0.984	0.989
0.83	0.5	0.38	0.32	0.26	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.08	0.5	0.00	0.00	0.00	0.00	0.031	0.262	0.015	0.185	0.03	0.154	0.231	0.092

Adjusts stresses

Cessna Spectrum

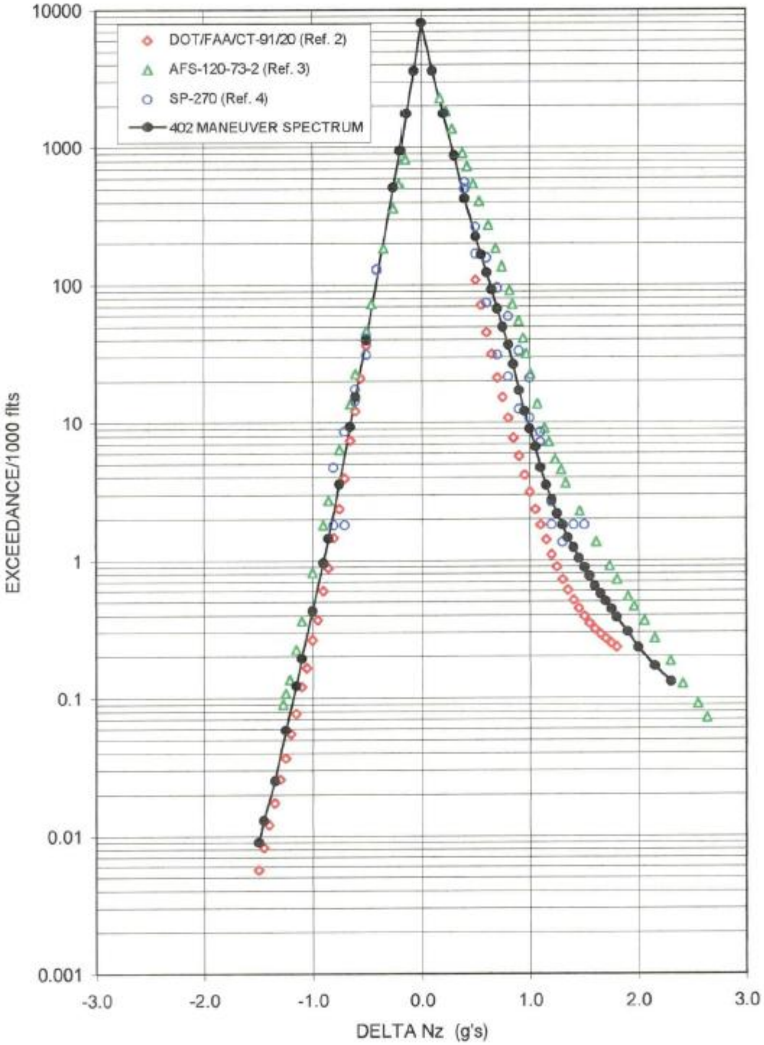
- Flight strain based spectrum (exceedance curve based)
  - Maneuver = consolidated fit using data from AFS-120-73-2, NASA SP-270 & DOT/FAA/CT-91/20
  - Gust = ESDU 69023
  - Taxi = AFS-120-73-2
  - Landing impact – time history from flight test landings
  - Adjust spectrum stresses and occurrence for each flight segment
    - Based on typical operations from owner surveys
  - Cycle counted



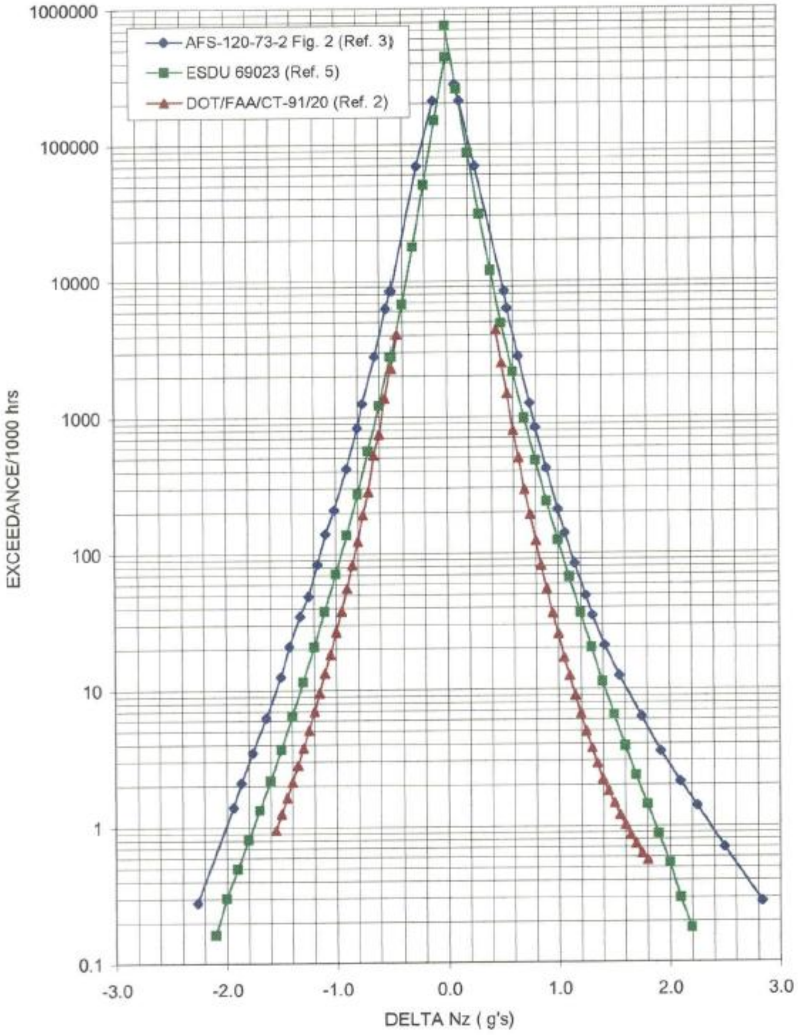


Cessna Spectrum Maneuver & Gust Exceedances

Maneuver Exceedances



Gust Exceedances



Spectrum Review

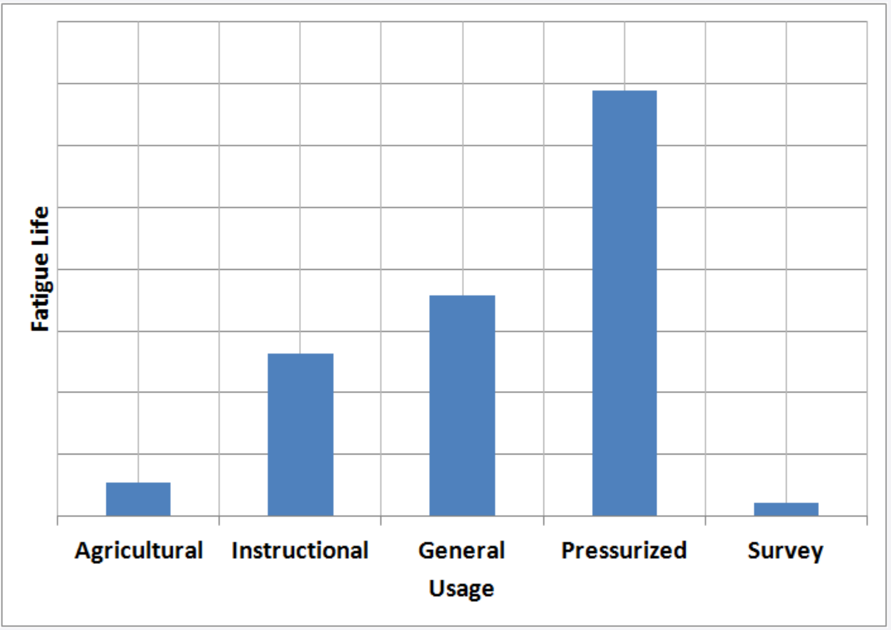
- SMART spectrum methods
  - Uses DOT/FAA/CT-91/20 mean data for exceedance curves for gust & maneuver
    - Curves in the AC23-13A are offset at standard deviations to ensure conservatism
  - Unique method for landing impact derived from AFS-120-73-2 data
- Comparing the SMART spectrum methods to other industry methods:
  - Cessna Flight Strain
  - SMART
    - Single reference speed and weight
    - Using speed and weight matrices to match Model 402C profiles
  - AFS-120-73-2
  - AC23-13A
- AFS-120 and AC23-13A (initially) based on single 1g reference stress
  - No separate 1g stress for landing impact

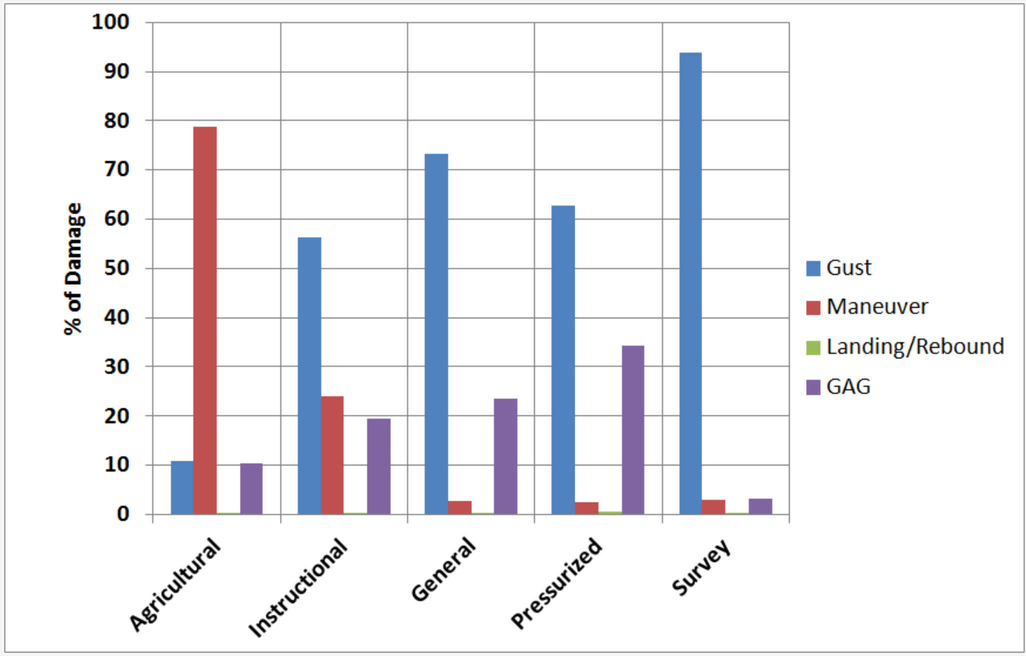
Analysis Assumptions

- Mission Exceedance Curves (SMART)
  - Grand Canyon
    - Maneuver = single/twin engine special usage, agricultural
      - Using agricultural exceedances to generate a maneuver critical mission
    - Gust = single/twin engine special usage, agricultural
  - Typical
    - Maneuver = twin engine unpressurized usage, general
    - Gust = twin engine unpressurized usage, general
  - Short
    - Maneuver = twin engine unpressurized usage, general
    - Gust = twin engine unpressurized usage, general
- Fatigue analysis uses AC23-13A S-N data
  - $K_{t\_net} = 4$
  - No Stress Severity Factors applied to fatigue analyses

Usages

- Comparing AC23-13A twin engine missions
- Fatigue or DT lives vary dramatically by mission or usage
- Contribution of damage is also different
  - Ag mission is maneuver critical
  - Other missions are gust critical
  - Landing/rebound damage is negligible





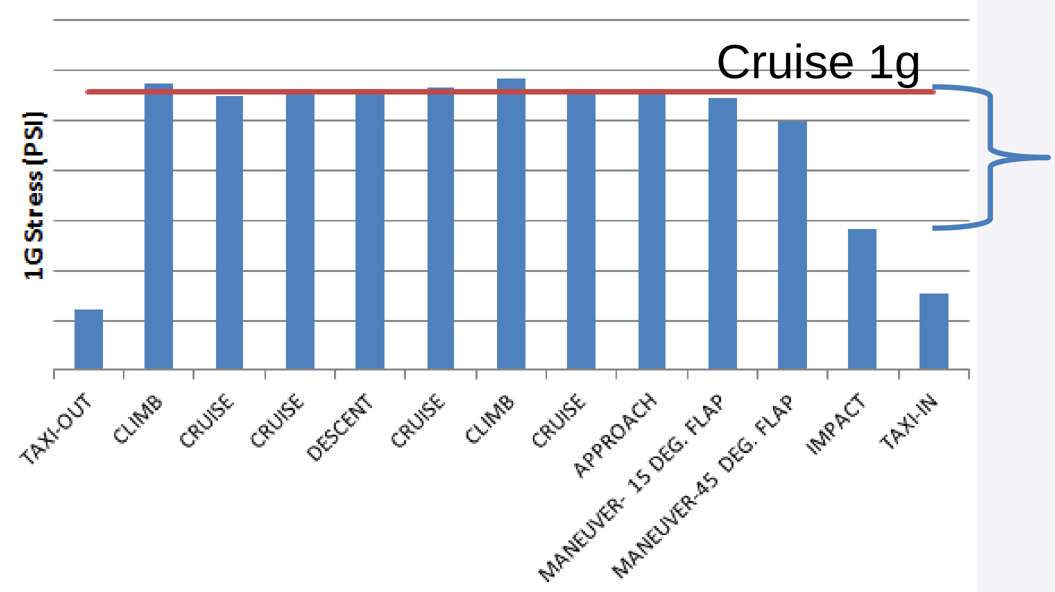
Initial Results

Spectrum	Flight Strain	SMART	AFS-120-73-2	AC23-13A
Grand Canyon	1X FH	1.12X FH	0.39X FH	0.22X FH

- Large variation in results are not surprising
- Simplifying assumptions result in conservatism
  - AFS-120, & AC23-13A analyses all using single reference stress
    - Does not account for segment by segment variation
    - Overstates landing impact damage
      - Assumed 1g stress at impact is not known
- Different exceedance curves
  - AFS-120-73-2
  - ESDU 69023
    - Adjusts for altitude
  - AC23-13A
    - Offset curves at standard deviation to ensure conservatism
    - Adds agricultural mission
  - SMART (probabilistic based)
    - DOT/FAA/CT-91/20 (same as AC23-13A but w/o standard deviation offsets)

Landing Impact

- Using single reference (cruise 1g) stress overestimates landing impact damage
  - What is typically known for aging Part 23 aircraft?
    - ~ cruise 1g stress
  - What is not known?
    - 1g stress by flight segment (including impact)
  - Using 1g cruise stress for impact 1g stress is conservative
- SMART method better matches flight test data



Over-predicts Impact stress

Correcting 1g Stress

- Change impact 1g stress
  - Single reference stress (Cruise 1g)
  - SMART landing impact method
  - Impact 1g stress derived from flight tests
  - With flight test derived impact spectrum
- Solution converges on SMART and Cessna results
- Impact no longer contributes significant damage

Don’t know 1g impact stress? SMART method is a simple, rational approach to scale.

Spectrum Method	Cessna	SMART	AFS-120-73-2	AC23-13A
Single Reference Stress (Cruise 1g)	-	-	0.39X FH	0.22X FH
SMART Method	-	1.12X FH	1.40X FH	0.35X FH
Impact 1g Stress from Flight Test	-	-	1.44X FH	0.35X FH
Flight Test Impact Spectrum	1X FH	-	1.43X FH	0.35X FH

Increasing precision

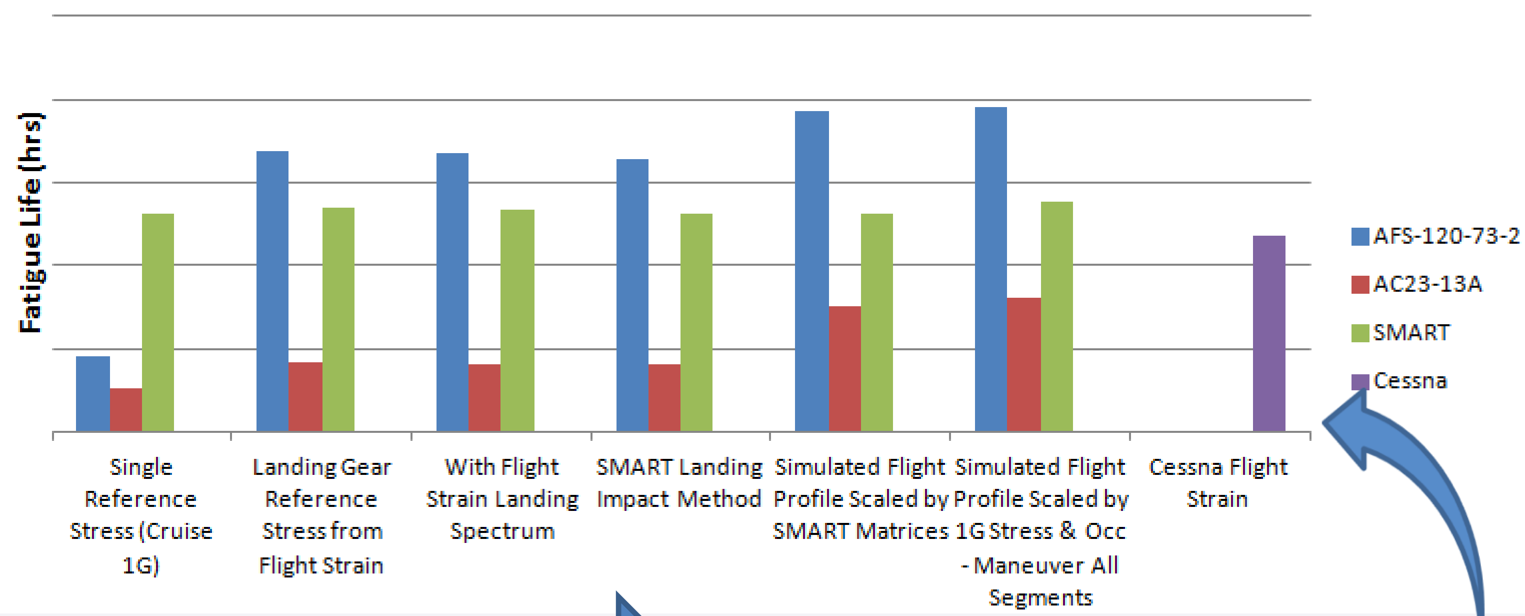
Simulating Flight Profiles

- Compare different spectrum assembly methods
    - Single reference stress (Cruise 1g)
    - Simulate flight profiles in SMART (2 different methods)
        - With speed and weight matrices (similar to SMART)
        - By adjusting 1g stress and occurrences (similar to Cessna)
- Using matrices improves precision and takes out conservatism (at least for this case)

Spectrum Method	Cessna	SMART	AFS-120-73-2	AC23-13A
Single Reference Stress (Cruise 1g)	-	1.12X FH	1.44X FH	0.35X FH
Simulate profile w/ speed/weight matrix	-	1.12X FH	1.65X FH	0.65X FH
Simulate profile w/ 1g stress/speed matrix	-	1.18X FH	1.67X FH	0.68X FH
Cessna Flight Test	1X FH	-	-	-

Increasing precision

Fatigue Summary



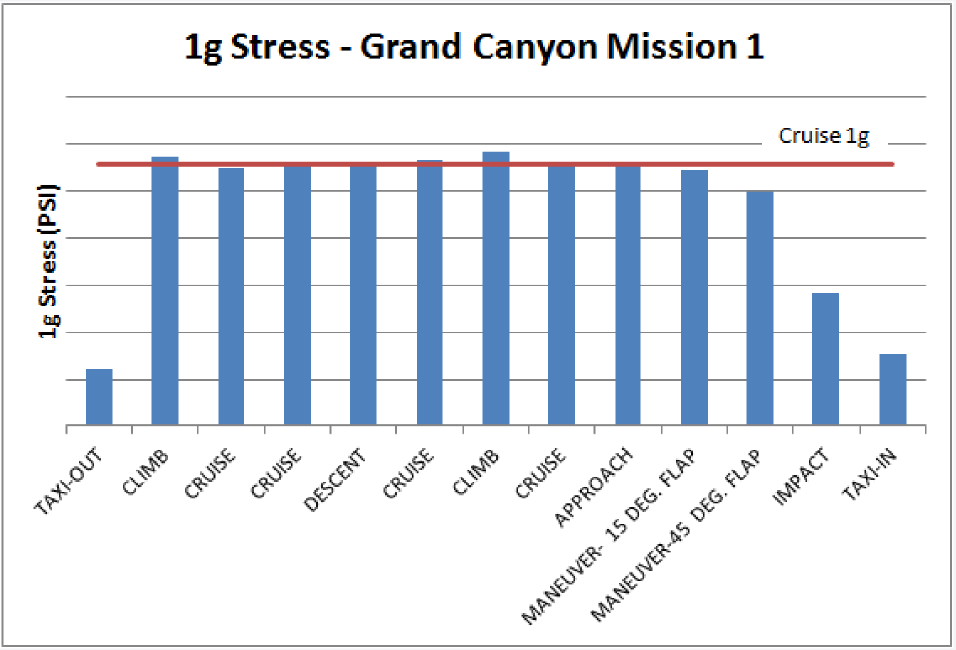
Increasing precision

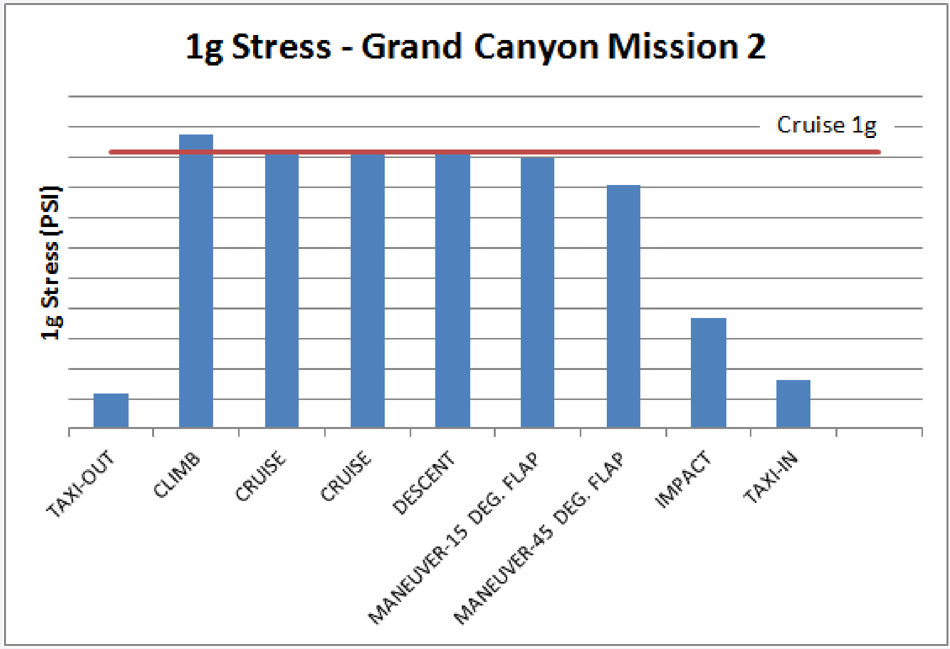
Cessna spectrum uses different exceedance curves than SMART

Choosing Reference Stress

- Why are SMART answers so close for the different spectrum methods?
  - Selected good reference stress (average cruise 1g stress)
  - Using max stress results in more conservative life

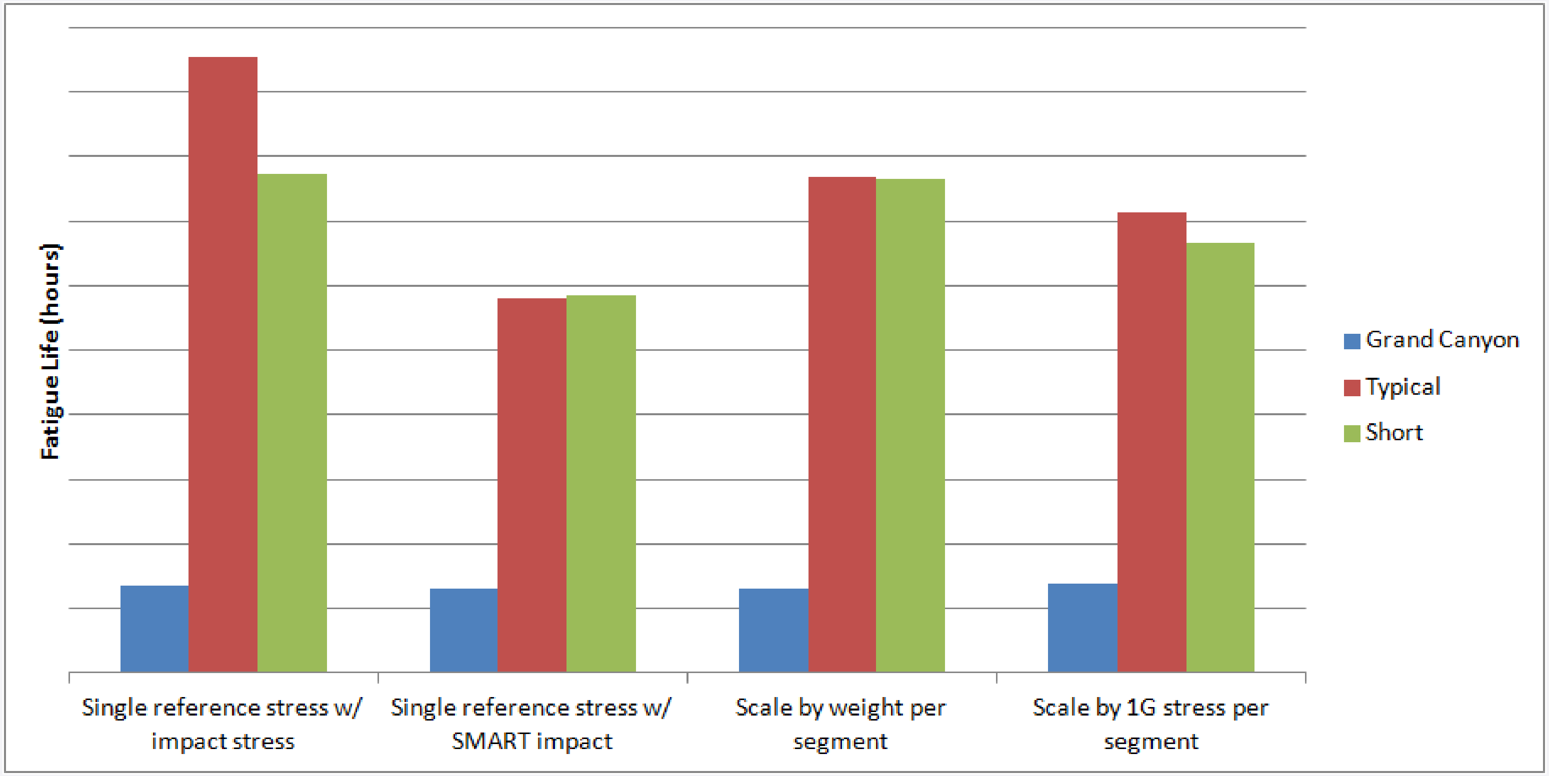
	Average Cruise 1g	Max 1g Stress
Cycles to Failure	**1X FH**	0.82X FH





Typical and Short Missions

- Effects of applying speed and weight/1g matrices are mission dependent
  - Grand Canyon mission life increased by applying weight or 1g matrices
  - Scaling by weight is unconservative for typical and short missions compared to scaling by 1g stresses



Cycle Counting vs. G-A-G Cycle

- Methods for accounting for transitioning cycles
  - Ground-Air-Ground cycle
    - Add additional cycle that pairs the highest maximum stress with lowest minimum stress expected to occur during the flight.
    - Does not take into account known flight sequences
      - Example: Taxi → Climb → Cruise →Descent → Approach → Impact → Taxi
  - Cycle counting
    - Pair up major cycles based on known flight sequence
- SMART uses G-A-G cycle
  - Simple, one size fits all
  - Flight sequences for missions may not be known
- Cessna cycle counts
  - Uses NLR range pair method
  - Known flight sequences for missions

Cycle Counting vs GAG Cycle

- Compare cycle counting and G-A-G methods
  - 2 different G-A-G methods
    - Tradition full flight
    - SMART
  - Cycle counted on different size spectrum & sequences
    - Larger block sizes converge on SMART method

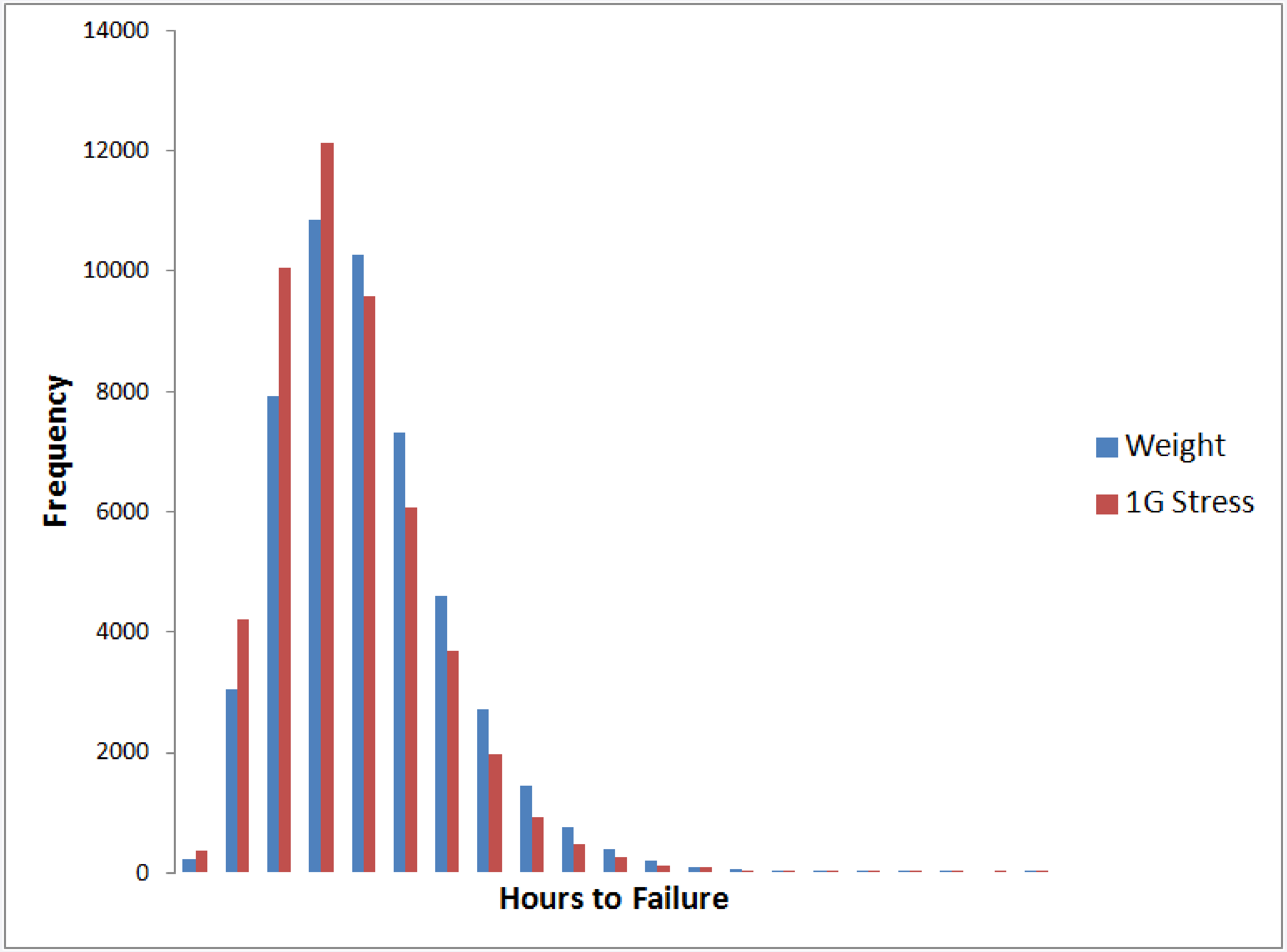
	Low-High	High-Low	Random
G-A-G (full flight)	N/A	N/A	0.90X FH
G-A-G (SMART method)	N/A	N/A	1X FH
Cycle count (1 FH)	1.38X FH	1.41X FH	1.40X FH
Cycle count (10 FH)	1.05X FH	1.09X FH	1.07X FH
Cycle count (100 FH)	1.01X FH	1.01X FH	1.01X FH
Cycle count (1000 FH)	1.00X FH	1.01X FH	1.00X FH

Spectrum assembly effect on probabilistic analysis

- **Performed SMART LD and DT analysis for CW-3 Grand Canyon mission**
  - **Use AC23-13A spectrum two different ways**
    - **Scale spectrum stresses using profile weights**
    - **Scale spectrum stresses using profile 1g stress**
      - **Substitute 1g stress for weight in weight matrix**

SMART|LD Probabilistic Fatigue – Grand Canyon

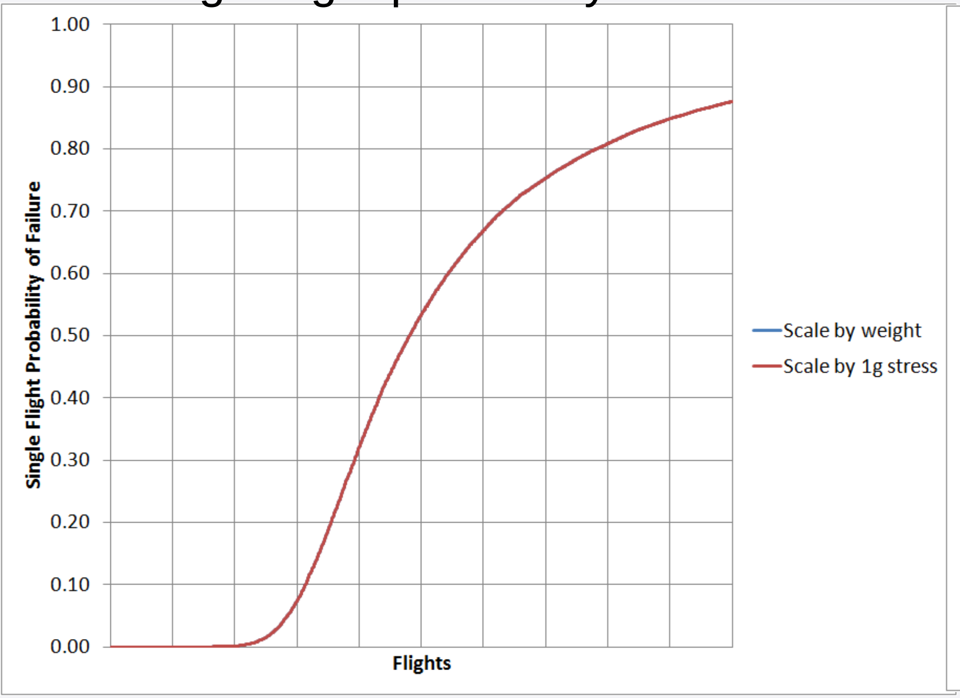
- Scaling by weight is slightly less conservative than the 1g stress distribution for this mission



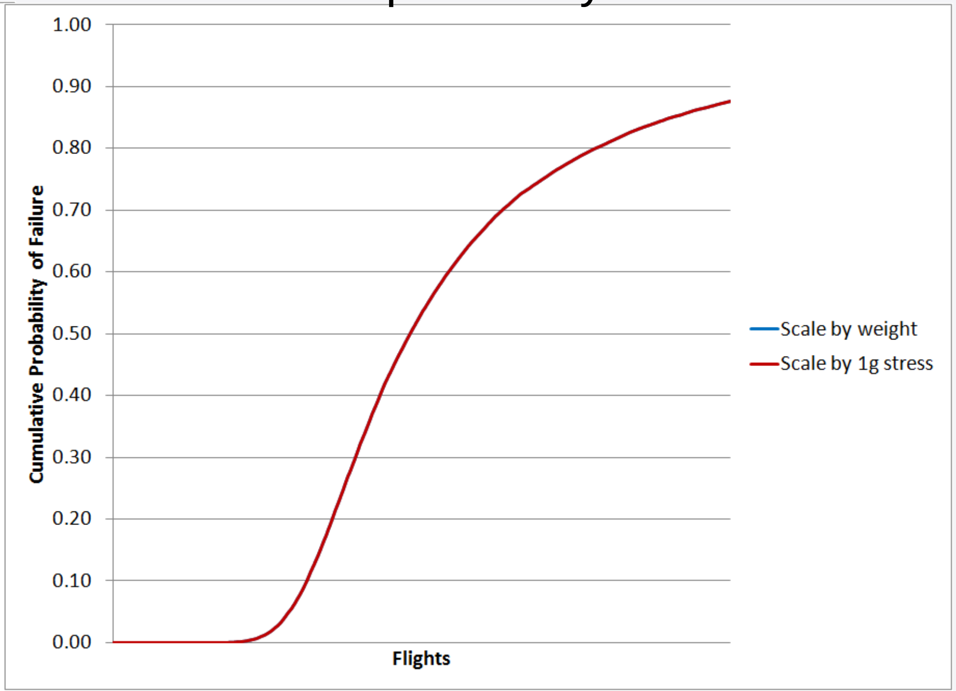
SMART|LD Probabilistic DT – Grand Canyon

- SMART DT analysis without inspections
  - EIFS = 0.005” w/ 0.003” standard deviation
  - K_C = 35 ksi√in w/ 1 ksi√in standard deviation
- Single flight and cumulative probability of failure nearly identical between scaling by weight or 1g stress

Single flight probability of failure



Cumulative probability of failure



Summary

- Exceedance curves are scaled by the gust and maneuver load factors.
  - Different airplanes can have different criticality based on different design load factors.
  - One airplane may be maneuver critical and another gust critical.
- SMART has powerful tools to adjust spectrum remove conservatism
  - Provides rational method to generate Impact spectrum
  - Scaling by weight & speed matrices can be used to refine spectrum
  - Can also “trick” SMART to scale on 1g stress using weight matrix
    - Recommend adding advanced options or guidance materials for experienced users.
- Different G-A-G methods provide similar results.
  - Cycle counting also returns similar results when blocks represent a large 3 of flights (100 or 1,000 FH)

The End

Questions?