Probabilistic Continued Operational Safety Risk Assessment for General Aviation Airplanes

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Introduction

Beechcraft Cessna Hawker
TEXTRON AVIATION

- Cessna Aircraft has used damage tolerance to evaluate general aviation aircraft for over 25 years
  - Currently most OEM’s use deterministic methods
  - Analyses use average values per FAA guidance
- Increasing discussion for applying probabilistic methods to DT
  - USAF has Probability of Fracture (PROF) software
  - UTSA and FAA developing probabilistic tool for GA aircraft
- Opportunities and challenges exist for probabilistic analyses of GA aircraft
  - A significant population of the GA fleet consists of airplanes certified before damage tolerant, fail-safe and/or fatigue regulations existed
  - Where will the data come from?

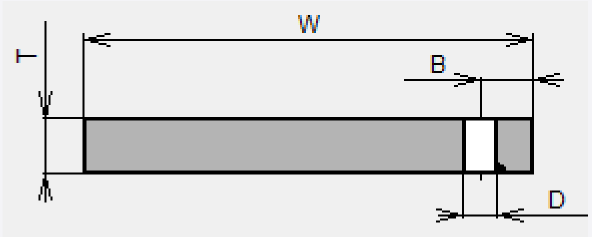


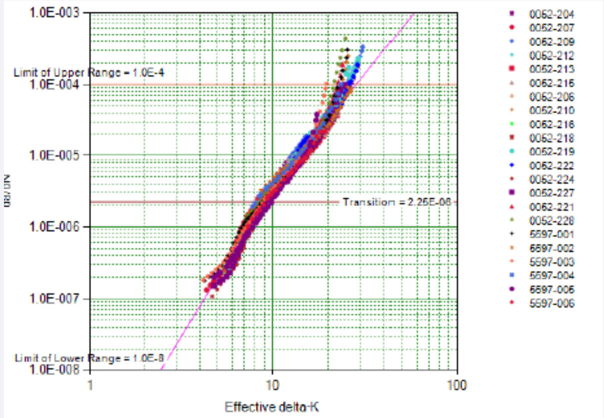

About Textron Aviation

- Textron Aviation is the General Aviation company formed in March 2014 from Cessna Aircraft Company and Beechcraft Corporation
  - Cessna
  - Beechcraft
  - Hawker
- Textron Aviation products account for more than half the GA fleet flying today
- Over 250,000 aircraft delivered
- Fleet is a mix of modern damage tolerant certified aircraft and non-damage tolerant aging aircraft

What variables affect typical DT analyses

- Flaw characteristics
  - Size
  - Crack aspect ratio (a/c)
- Geometry
  - Part thickness/width
  - Fastener/hole diameter
  - Edge distance/hole offset
- Material data
  - da/dN
  - Fracture toughness
  - Yield/ultimate strength
  - Environment
- Loading/operations
  - Flight lengths, speeds, altitudes
  - Weight and balance
  - Gust, maneuver & ground loads exceedances
  - Limit loads





Available probabilistic data

Random Variable	Data available for modern A/C?	Data available for older A/C?	Can data be generated?
Initial flaw size	No	No	Yes
Crack aspect ratio	No	No	Maybe
Width & thickness	No	No	Yes
Hole diameter	Yes	No	Yes
Edge distance	Yes	No	Yes
da/dN	Yes	Yes	Yes
Fracture toughness	Yes	Yes	Yes
Yield/ultimate strength	Yes	Yes	Yes
Environment	No	No	Maybe

Available probabilistic data

Random Variable	Data available for modern A/C?	Data available for older A/C?	Can data be generated?
Flight lengths, speeds, altitudes	Yes	Some	Yes
Weight & balance	No	No	Maybe
Accumulated flight hours	Yes	Limited	Yes
Loads exceedances	Yes	Yes	Yes
Limit loads	Yes	Yes	Yes

Initial flaw size

- No EIFS distributions for GA aircraft
- Publicly available data for USAF F-4, A-7 & others
- Is USAF data applicable to GA?
  - Probably not
- USAF aircraft
  - Low rate, high quality production
  - Likelihood of a large flaw is very low
  - Operating at high stresses
- GA is more custom built
  - Most older aircraft predate fatigue & damage tolerance regulations
  - Assembled by hand
  - Manufactured at high rates
  - Typically operating at lower stress levels

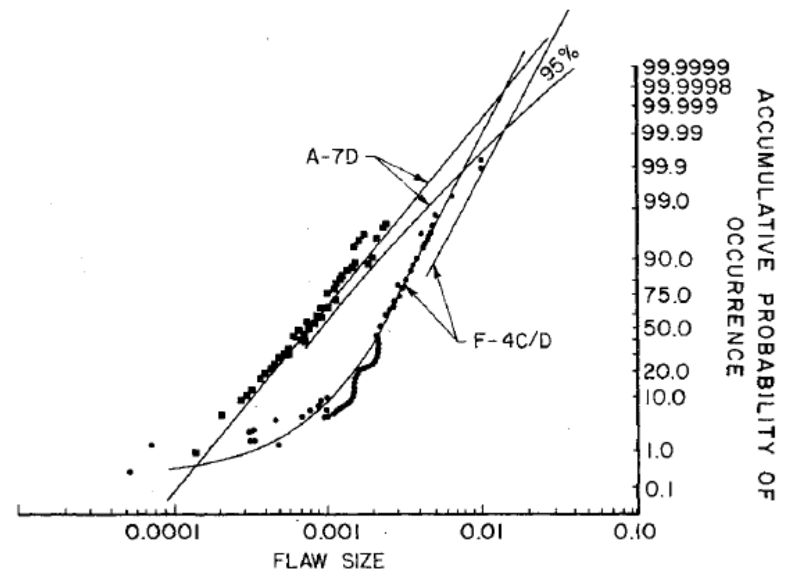


Fig. 11 Cumulative probability of occurrence of A-7D and F-4C/D equivalent initial quality.

Current state:

(red)	Data quality
(yellow)	Publicly available data
(red)	OEM likely to have data

How to get initial flaw size data for GA aircraft

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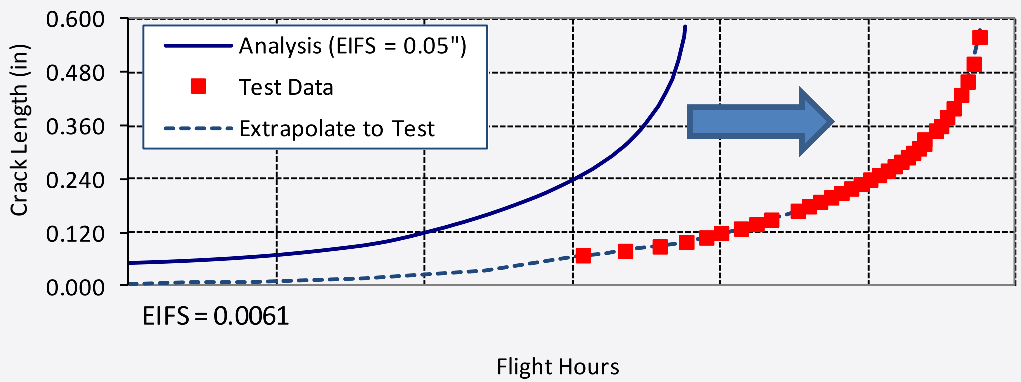
- Textron Aviation full-scale cyclic tests all new aircraft
  - Crack growth data available for most recent full-scale cyclic tests
  - Can generate EIFS for some cracks
    - Known test spectrum
    - Known stress state
  - Derived EIFS would only be valid for modern jets
- What can be done for aging aircraft?
  - Perform teardowns
  - New cyclic tests of components

Model	Cyclic Inspection Number of Cracks	Tear Down Inspection Number of Cracks	Total Number of Cracks
A	88	89	177
B	7	0	7
C	26	70	96
D	34	76	110
	155	235	390

Model	Probable EIFS	Borderline EIFS	Total EIFS
A	41	32	73
B	0	0	0
C	2	16	18
D	23	24	47
	66	72	138



How to get initial flaw size data for GA aircraft

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- Options for defining EIFS from test data
  - Sample and verify test data fits into an existing EIFS distribution
    - i.e. use F-4/A-7 distributions
  - Define new EIFS distributions
    - Round-robin evaluation of OEM data
      - Need samples from multiple OEMs
    - Coupon testing
      - Verify full-scale test results match coupon test results

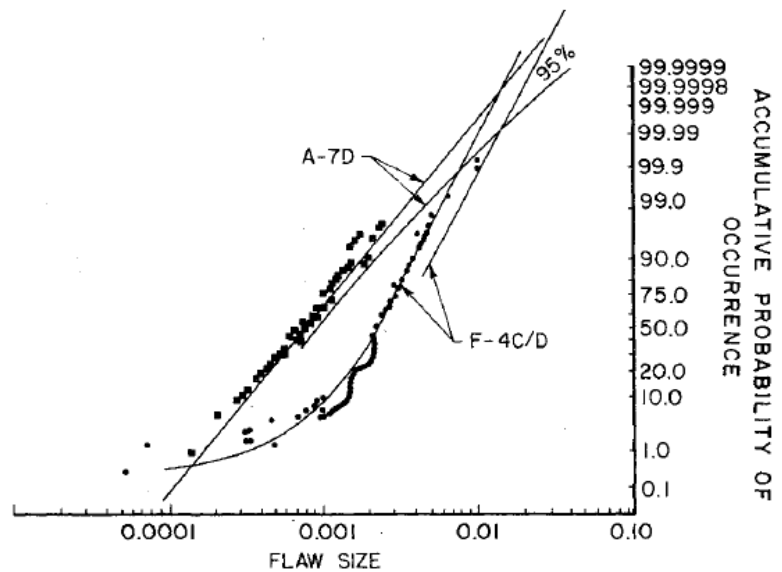
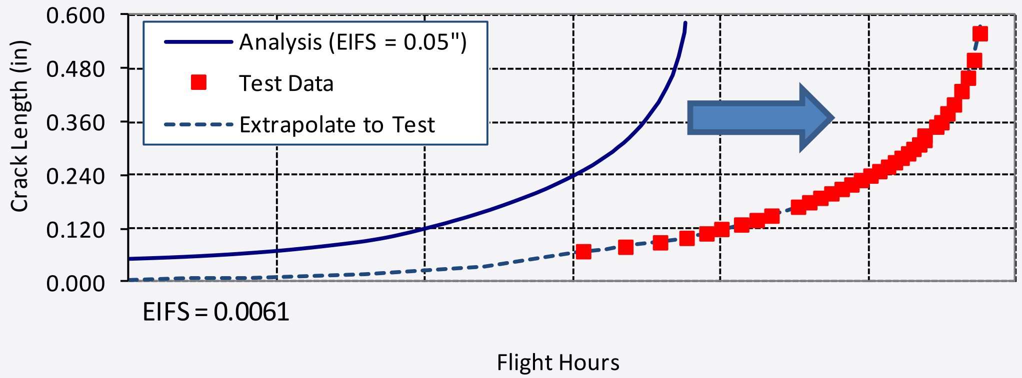
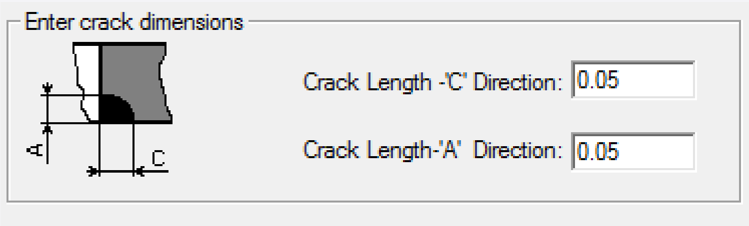


Fig. 11 Cumulative probability of occurrence of A-7D and F-4C/D equivalent initial quality.



Crack aspect ratio

- Standard assumption is starting aspect ratio (a/c) = 1.
- Don't know crack shape until it has been observed in the field or during testing.
  - May not have sufficient data to develop know standard deviation

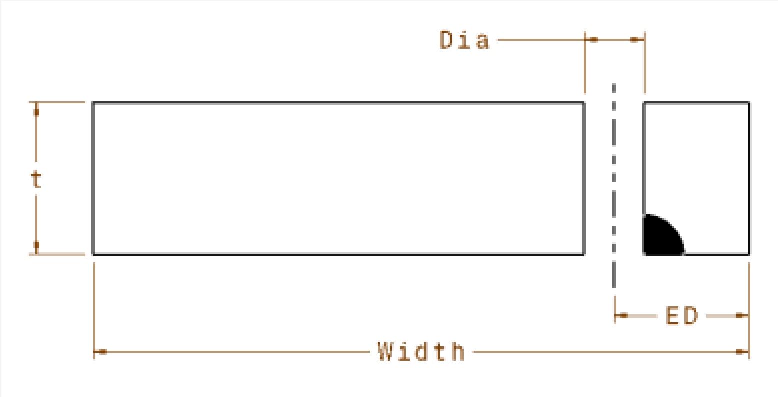


Current state:

	Data quality
	Publicly available data
	OEM likely to have data

Part geometry – thickness and width

- DT analyses typically use nominal dimensions
  - Part width
  - Part thickness
- Part drawings or process specs typically define sheet metal and machined tolerances
- OEM likely knows spec means and minimums, but doesn't know standard deviation
- Impact of thickness variation may be significant for sheet metal parts
  - Thinning during stretch forming, etc.
- Expect hole diameter and fastener edge margin to have larger influence



Current state:

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	OEM likely to have data

Hole diameter

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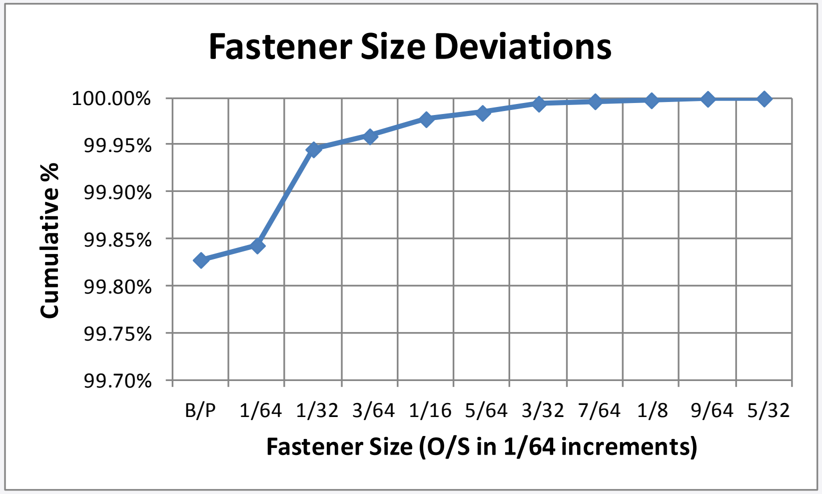
- Some OEM's have mean and variance data for production quality
  - No publicly available data
  - Likely represents modern production methods & tooling only
    - Not applicable for older aircraft
- OEM's not likely to have metrics for field service
- Vast majority of fasteners installed at nominal size
- Hole size deviations are typically in 1/64" or 1/32" increments
- Could derive aging aircraft data from teardown inspections



Current state:

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	Publicly available data
	OEM likely to have data

Edge distance or edge margin

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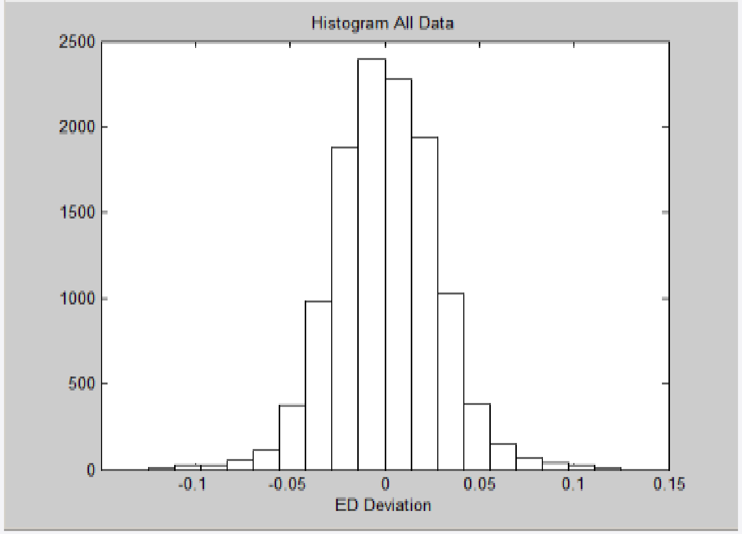
- Some OEM's have mean and variance data for production quality
  - No publicly available data
  - Likely represents modern production methods & tooling only
    - Not applicable for older aircraft
- Minimum edge margin requirements typically defined in OEM specs
- Could derive aging aircraft data from teardown inspections

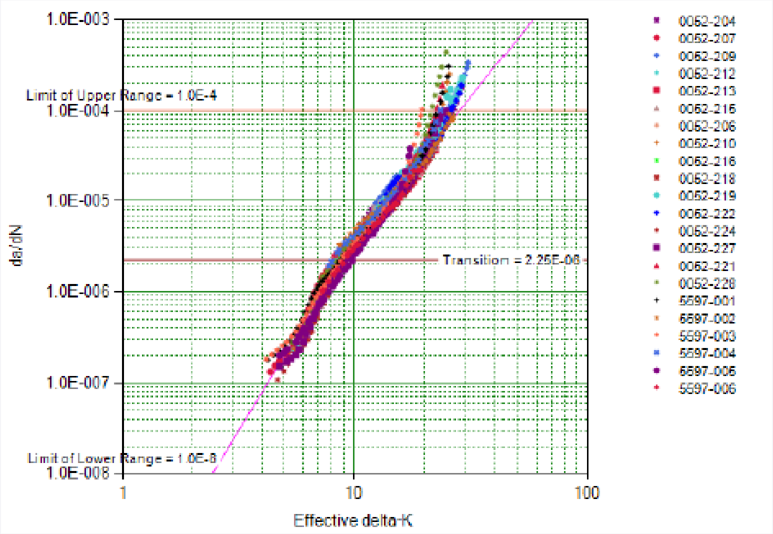


Current state:

(green)	Data quality
(red)	Publicly available data
(yellow)	OEM likely to have data

da/dN crack growth rates

- Multiple equations used to fit da/dN data in the industry
  - Paris, Walker, or NASGRO equations are most typically used in GA
- Most OEM's use industry data
  - NASGRO or Damage Tolerant Design Handbook
  - Do not have access to raw data to define variance
- Some OEM's have own test data
  - Could define variance
- Need methods/tools for defining variance in da/dN



Current state:

	Data quality
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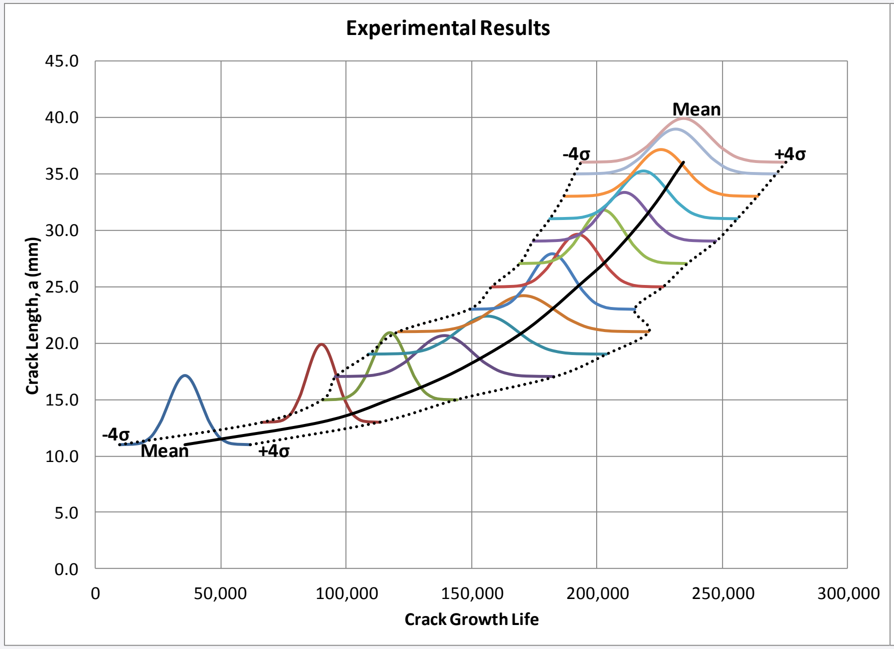
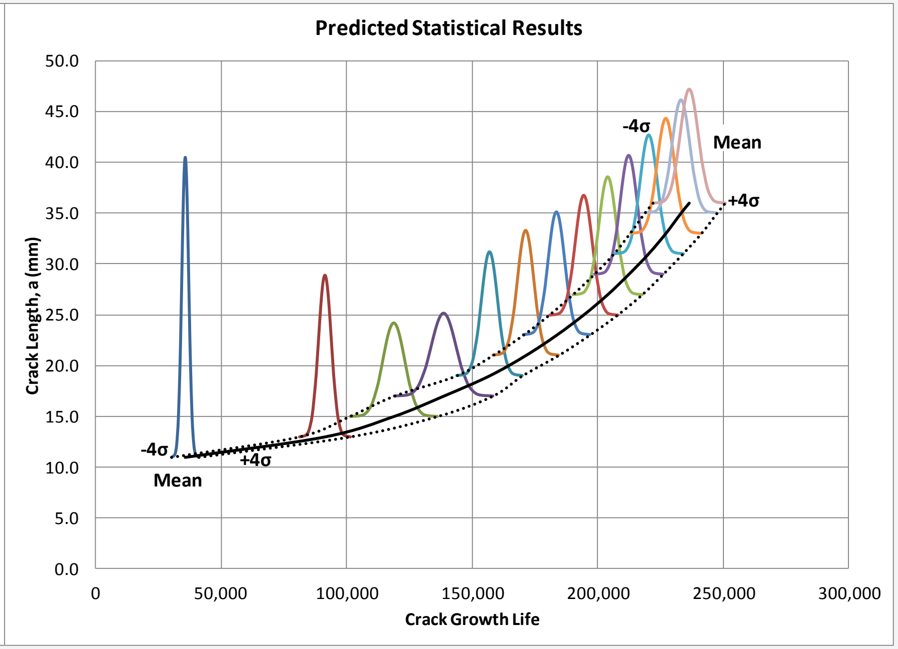
a vs N variation

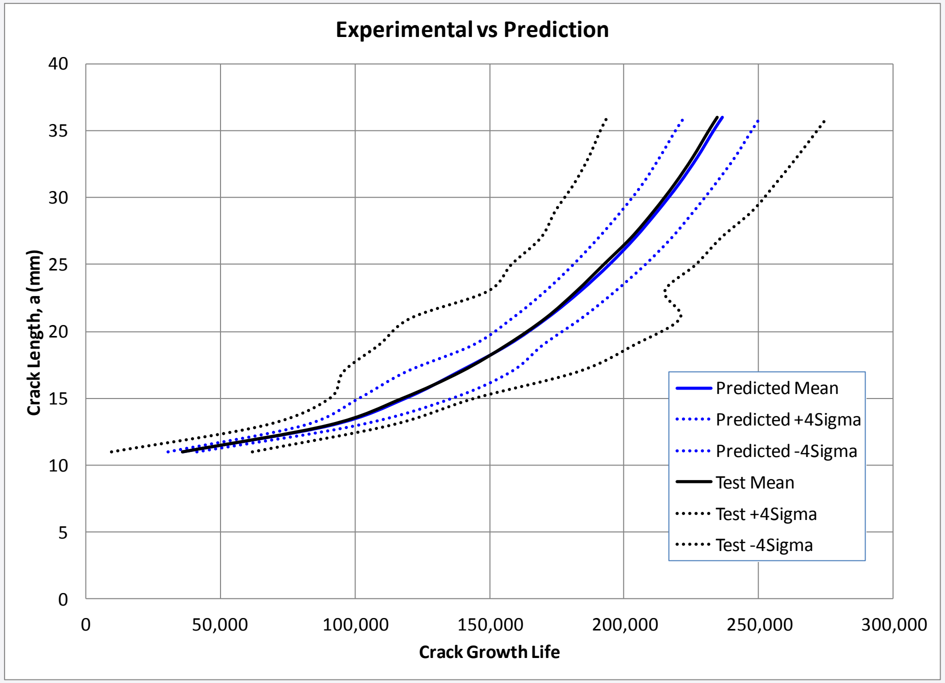
- Virkler, et al (AFFDL-TR-78-43) attempted to define statistical material variation
- Statistical description of data did not match experimental results
  - Mean matches well, but 4σ is vastly different
- Similar results observed in Textron Aviation data





a vs N variation

- Why so much variation?
  - Material behavior is different at different stress ratios (R)
  - Aluminum alloys are not homogenous
  - AMS specs have broad range of alloying agents in the chemical composition of an alloy
  - Raw material can vary from manufacturer to manufacturer
  - AMS specs also allow for additional processes (i.e. stress relieving)
- What the industry needs?
  - Access to test data
  - Better model for defining da/dN variance



Fracture toughness

- Plane strain fracture toughness (K_{IC}) for many Aluminum alloys available in MMPDS & Damage Tolerant Design Handbook
- Plane stress fracture toughness (K_C) data is available in Damage Tolerant Design Handbook
- OEM's may also have own test data, but typically only test small sample size

Table 3.1.2.1.4. Values of Room Temperature Plane-Strain Fracture Toughness of Aluminum Alloys[a]

Alloy/ Temper[b]	Product Form	Orien-tation[c]	Product Thickness, inches	Number of Sources	Sample Size	Date of Data Generation	Approved		Specimen Thickness, inches	K_{IC}, ksi $\sqrt{in.}$				
							Date	Item		Max.	Avg.	Min.	COV	Spec. Min.
2014-T651	Plate	L-T	≥0.5	1	24	1980-1983	10/85	85-03	0.5-1.0	25	22	19	8.4	
2014-T651	Plate	T-L	≥0.5	2	34	1980-1983	10/85	85-03	0.5-1.0	23	21	18	6.5	
2014-T652	Hand Forging	L-T	≥0.5	2	15	1973-1975	5/82	78-09	0.8-2.0	48	31	24	21.8	
2014-T652	Hand Forging	T-L	≥0.8	2	15	1973-1975	5/82	78-09	0.8-2.0	30	21	18	14.4	

Current state:

●	Data quality
●	Publicly available data
●	OEM likely to have data

Yield and ultimate strengths

- A & B basis data available in MMPDS
  - 99/90% probability with 95% confidence
- MMPDS does <u>not</u> provide standard deviation for strength data.
  - Some OEM's may have own test data
- Typical GA structure fails by critical fracture toughness and not net section yield
- Expect most engineers to analyze F_{ty} and F_{tu} as deterministic variable with a minimum value
  - Conservatism in A/B basis allowables has been shown to have minimal impact of DT results

MMPDS-06
1 April 2011

Table 3.2.4.0(b_1). Design Mechanical and Physical Properties of 2024 Aluminum Alloy Sheet and Plate

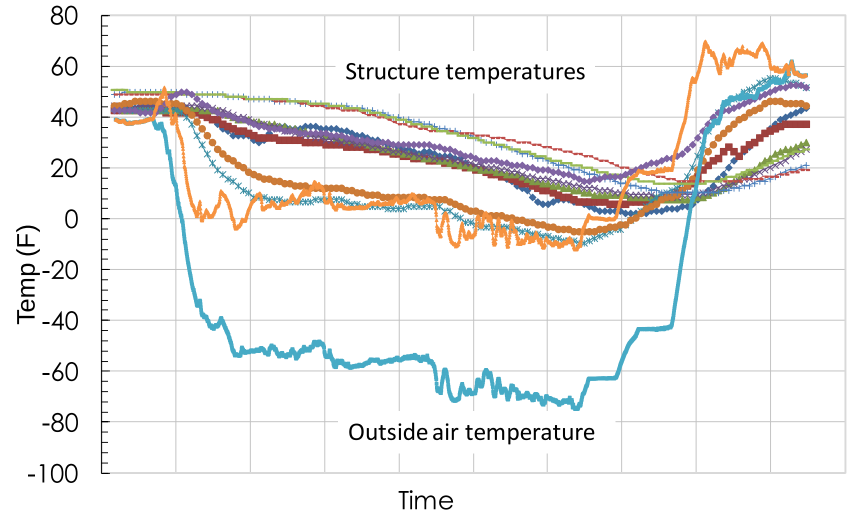
Specification	AMS 4037 and AMS-QQ-A-250/4[a]					AMS-QQ-A-250/4[a]		
Form	Sheet					Sheet		Plate
Temper	T3					T361		
Thickness, in.	0.008-0.009	0.010-0.128		0.129 - 0.249		0.020-0.062	0.063-0.249	0.250-0.500
Basis	S	A	B	A	B	S	S	S
Mechanical Properties:								
F_{tu}, ksi:								
L	64	64	65	64	66	68	69	67
LT	63	63	64	63	65	67	68	66
ST	...	...	...	...	...	...	...	...
F_{ty}, ksi:								
L	47	47	48	47	48	56	56	54
LT	42	42	43	42	43	50	51	49
ST	...	...	...	...	...	...	...	...
F_{cy}, ksi:								
L	39	39	40	39	40	47	48	46
LT	45	45	46	45	46	53	54	52
ST	...	...	...	...	...	...	...	...
F_{su}[b], ksi	39	39	40	40	41	42	42	41
F_{bru}[b,c], ksi:								
(e/D = 1.5)	104	104	106	106	107	111	112	109
(e/D = 2.0)	129	129	131	131	133	137	139	135
F_{bry}[b,c], ksi:								
(e/D = 1.5)	73	73	75	73	75	82	84	81
(e/D = 2.0)	88	88	90	88	90	97	99	96
e, percent:								
LT	10	[d]	...	[d]	...	8	9	9[e]

Current state:

●	Data quality
●	Publicly available data
●	OEM likely to have data

Environmental variables

- Corrosion is often a larger contributor to field damage than cracks
- How does industry address environmental conditions?
  - da/dN is often tested in a high humidity environment
    - da/dN tests typically take 1 to 5 days to run
    - Little time for crack face to be affected by corrosion
- Most da/dN and fracture toughness data is at room temp
  - Temperature of structure in flight > outside air temperature
- Stress corrosion cracking data available in MMPDS
- Do not always know where individual GA aircraft are being operated

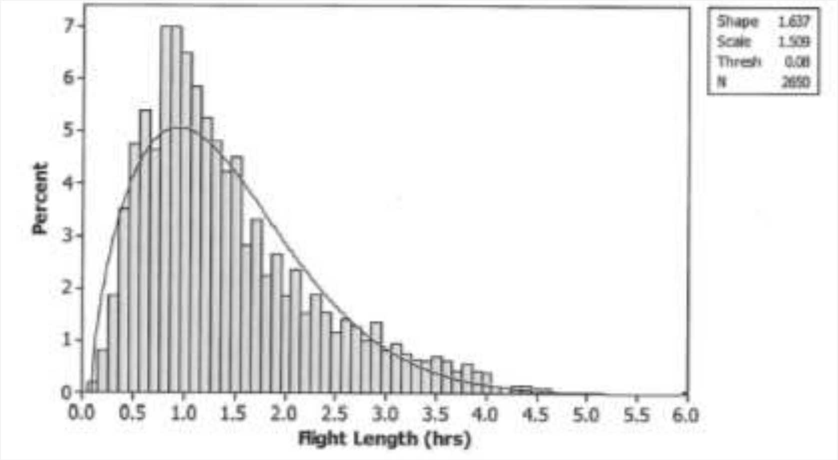


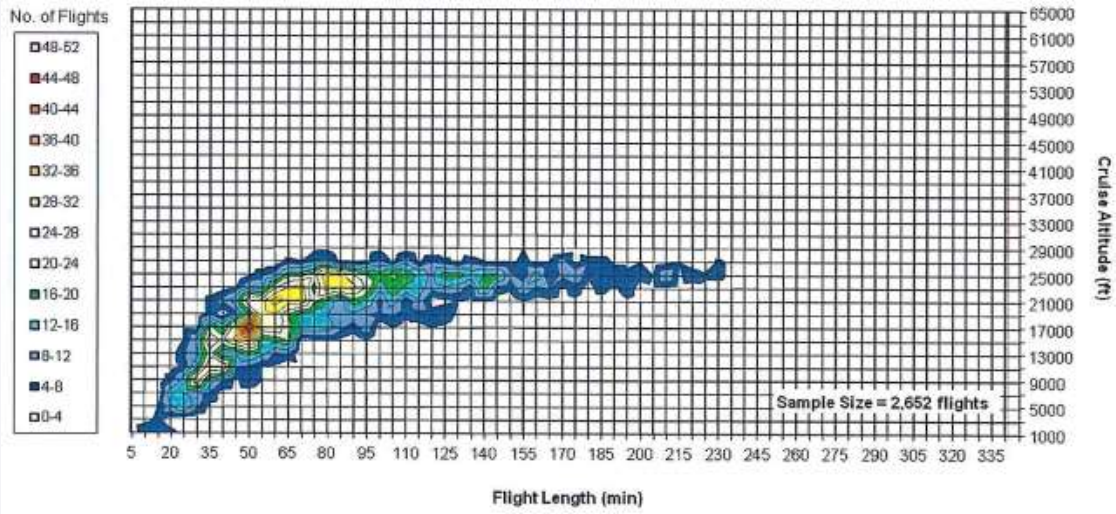
Current state:

	Data quality
	Publicly available data
	OEM likely to have data

General Aviation flight operations – flight lengths, speeds & altitudes

- Unlike airlines or the military, GA manufacturers do not know how customers operate their aircraft
- Operating data can be obtained from commercial ATC flight tracking service
  - Flight lengths
  - Cruise altitude and speeds
- Represents aggregate data for the fleet
  - Do not know individual a/c operations
  - Some operators block data
  - Does not track VFR operations



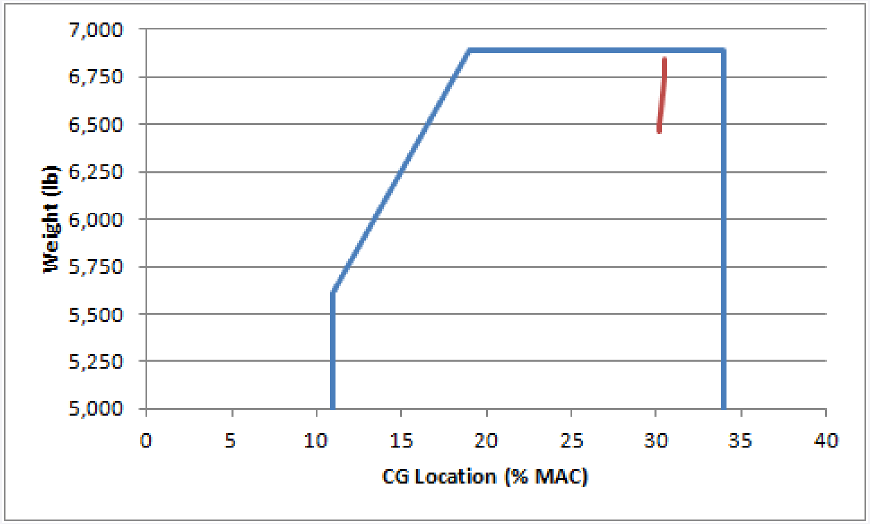


Current state:

	Data quality
	Publicly available data
	OEM likely to have data

General Aviation flight operations – weight & balance

- Weight and balance data is not publicly available
  - Cannot track through 3rd party source
- Many operators do not share typical weight and balance configurations
  - Exception is special mission aircraft
- OEM’s typically assume a range of weight & balance configurations for generating flight profiles
- Operator surveys required to obtain weight & cg data
  - Expect low response rate without FAA involvement
- GA airplanes are often modified by 3rd parties. OEM doesn’t have knowledge of modifications.

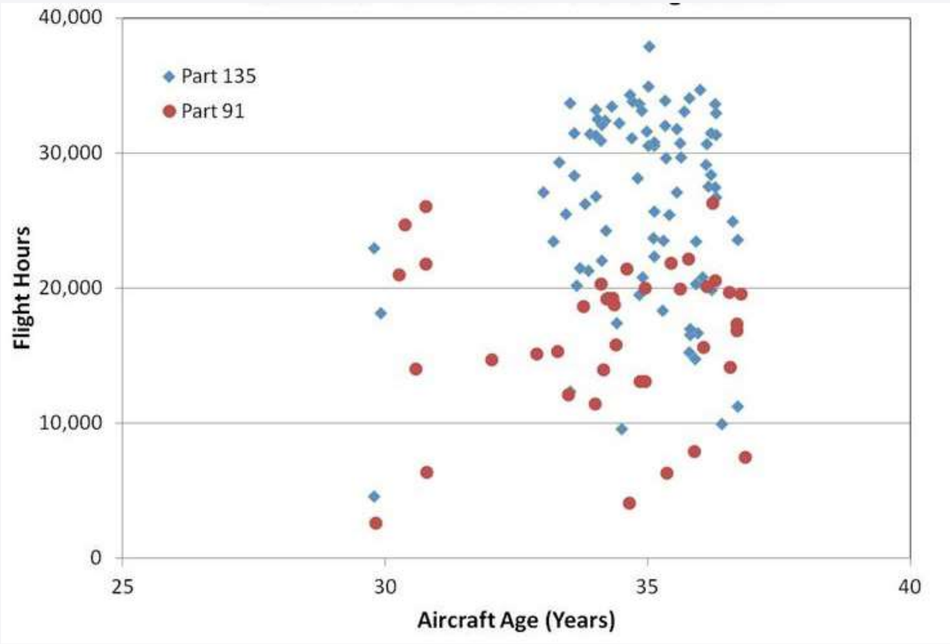


Current state:

Yellow	Data quality
Red	Publicly available data
Yellow	OEM likely to have data

Accumulated flight hours

- To assess risk to the fleet need to know how many are still airworthy
- Only know flight hours for aircraft serviced by OEM
  - Most aircraft serviced by other maintenance facilities once they are out of warranty
  - More likely to have data for newer aircraft
- How to get better data?
  - Operator surveys
  - Fleet reporting to FAA

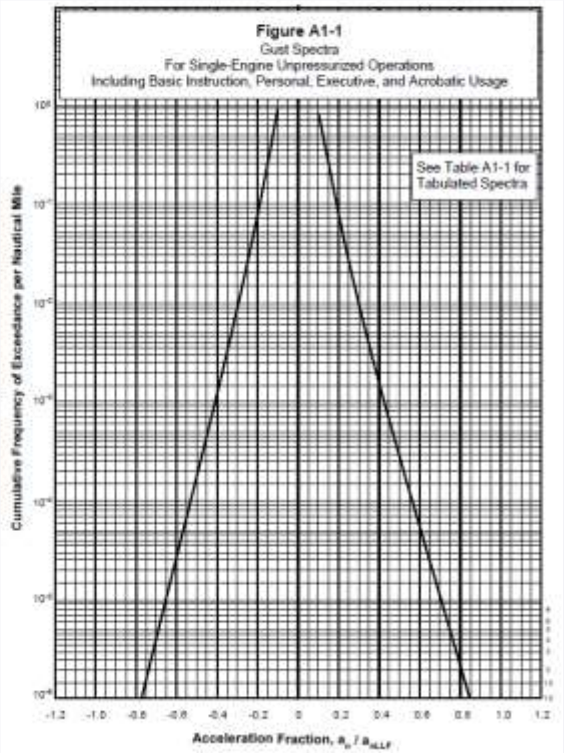


Current state:

🟡	Data quality
🔴	Publicly available data
🟡	OEM likely to have data

Load exceedances and limit loads

- Develop spectrum using:
  - Exceedance curves
    - AFS-120-73-2
    - FAA Advisory Circular AC23-13A
  - PSD analysis per 14 CFR Part 25.341
- Deterministic data available for limit loads
  - Design limit loads and limit load factors available
- Can calculate limit loads at different probability levels from exceedance curves



Current state:

●	Data quality
●	Publicly available data
●	OEM likely to have data

Challenges for probabilistic damage tolerance analyses

- EIFS data is not available for general aviation or transport aircraft
  - Is the USAF EIFS data applicable?
- da/dN data is not readily available and do not have reliable method for defining variance
- Environmental data is not available
- Many OEM's may not have hole size and edge margin variance data
  - Textron Aviation has data for modern production a/c
- Understand operations for fleet, but individual aircraft usage is not known
- Weight and balance operations data not available
  - Likely known for transport aircraft
- Will likely treat some variables as deterministic
  - a/c
  - Yield and ultimate strengths
- Modifications and repairs are an additional challenge

DT random variable summary

Random Variable	Data quality	Publicly available data	OEM likely to have data	Analyze deterministic	Risk of not knowing
Initial crack size	🔴	🟡	🔴		High
a/c	🟡	🟡	🟡	✓	Low
Part geometry	🟡	🔴	🟡		Low
Hole diameter	🟢	🔴	🟡		Moderate
Edge distance	🟢	🔴	🟡		High
da/dN	🟢	🔴	🟡		Moderate
Fracture toughness	🟢	🟢	🟢		Low
Yield/ultimate strength	🟢	🟢	🟢	✓	Low
Environment	🟡	🟡	🟡		Low
Ops-missions	🟢	🟡	🟡		High
Ops-wt & bal	🟡	🔴	🟡		Moderate
Flight hours	🟡	🔴	🟡		Moderate
Loadings	🟢	🟢	🟢		High

Questions