Air Force Life Cycle Management Center



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Assessing Limited Pedigree da/dN Crack Propagation Data

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Overview



Motivation

Data Evaluation Example

7050

- Fixed Ranges of da/dN (Scatter of 2)
- Fixed Ranges of ∆K (+/- 5%)

• R = 0.1, 0.4, 0.8

2024

• Fixed Ranges of ∆K (+/- 5%)
• R = 0.1
■ Observations

Concluding Remarks



Is the earth flat or spherical? Turns out that even though evidence has suggested otherwise since about Aristotle's time, it is a recurring debate!²





Motivation



Access to da/dN v \(\Delta K\) data in the public domain is limited to

MMPDS, Damage Tolerance Design Handbook, Software/models, AFMAT, etc.

Data pedigree is often minimal

- $\Delta K_{\text{Applied}}$ or $\Delta K_{\text{Effective}}$, etc.
- Constant Amplitude (CA), K-Decreasing, K-Increasing, etc.
- Product Form, thickness range, test environment, etc.

Modification and sustainment engineers and DERs struggle to acquire data

- Limited expertise in
 - Testing and data evaluation
 - Scatter, test invalidities (angle, symmetry, etc.)
- Limited funding



Specific Example



7050-T7451 L-T

- What we know about this data set
 - 7050 is a controlled damage tolerant alloy: Composition and processing are controlled to meet specific requirements, e.g. strength, toughness, and corrosion resistance to include stress corrosion
 - Stress Ratio
 - Range of ΔK
 - Grain orientation
- What we do not know
 - Specimen configuration
 - Product form thickness
 - Testing environment and frequency
 - Test Type (CA, K-Decreasing, etc.)
 - Test data supplier
 - Producer/lot variation



Generic Test Data Example



7050-T7451 L-T Crack Growth Rates (C-17 Only)





Data Comparison (Establishing 'Confidence')



7050-T7451 L-T Crack Growth Rates (C-17 compared to Other Sources)





Option 1: Analyze ΔK in Ranges of da/dN



Choose ranges of da/dN (Max/Min = 2) to analyze from total population of data

- No justification on scatter factor of 2 (folklore)
- Develop Maximum Likelihood Estimation (MLE)⁴ distribution parameters for ΔK within each given range of da/dN
 - 1388 data pairs across 13 da/dN ranges
 - Approximately 107 ΔK points/da/dN

Resulting shape parameters as a function of ΔK

Fixed da/dN	Weibull parameters			
Midpoint	for De	elta K		
da/dN	Delta K	Shape		
1.920E-08	2.56	31.615		
6.940E-08	3.32	12.620		
1.130E-07	3.68	12.200		
1.650E-07	4.17	12.143		
2.240E-07	4.70	10.457		
2.770E-07	5.11	12.020		
1.176E-06	8.12	8.285		
3.050E-06	10.95	8.458		
9.490E-06	15.81	11.675		
4.460E-05	21.59	10.608		
1.650E-04	26.35	12.993		
6.110E-04	31.69	16.812		
1.750E-03	34.18	13.136		





Characterizing C-17 Data (2-P Weibull R = 0.1 Δ K)



1.00E+00 1.00E-01 △ NASGRO 0.10 1.00E-02 × C-17 0.10 1.00E-03 MMPDS 0.10 1.00E-04 daydk (inch/cycle) 1.00E-05 1.00E-07 - Harter-T DTDH 0.0 × C-17 Delta K 1.00E-08 Weibull Scales 1.00E-09 1.00E-10 1.00E-11 1.00E-12 1.00E-13 1 10 100

7050-T7451 L-T Crack Growth Rates (Weibull da/dN MLE Analysis)

ΔK (KSI√inch)



Constant Probability Curves $(\Delta K R = 0.1)$



7050-T7451 L-T Crack Growth Rates





Constant Probability (Low da/dN R = 0.1)







Constant Probability (High da/dN R = 0.1)



7050-T7451 L-T Crack Growth Rates





63% Look-up Curve (R = 0.1)



7050-T7451 L-T Crack Growth Rates (Weibull ∆K MLE Analysis)





Option 2: Analyze da/dN in Ranges of ∆K (R = 0.1)



Choose ranges of △K (+/-5%) to analyze from total population of data

- 1616 data pairs
- 5% based on loads accuracy
- Develop Maximum Likelihood Estimation (MLE) distribution parameters for da/dN within each chosen range of △K
 - 799 data pairs across 13 ∆K ranges
 - Approximately 61 da/dN points/∆K range
- Resulting shape parameters as a function of da/dN

Weibull Para	ameters for	Target for da/dN				
da/dN at F	Fixed ∆K	Distributions				
Shape	Scale	ΔK	Range			
1.41	1.985E-08	2.50	2.375-2.625			
2.77	6.936E-08	3.00	2.850-3.150			
3.59	1.136E-07	3.50	3.325-3.675			
5.79	1.650E-07	4.00	3.800-4.200			
7.77	2.240E-07	4.50	4.275-4.725			
7.54	2.810E-07	5.00	4.750-5.250			
4.42	1.176E-06	7.50	7.125-7.875			
3.74	3.049E-06	10.00	9.500-10.500			
3.22	9.724E-06	15.00	14.250-15.750			
1.85	4.698E-05	20.00	19.000-21.000			
2.05	1.701E-04	25.00	23.750-26.250			
1.07	6.814E-04	30.00	28.500-31.500			
0.88	2.047E-03	35.00	33.250-36.750			





Characterizing C-17 Data (2-P Weibull R = 0.1 da/dN)



1.00E+00 1.00E-01 △ NASGRO 0.10 1.00E-02 × C-17 0.10 1.00E-03 MMPDS 0.10 1.00E-04 AFGROW 0.10 gaydM (inch(cycle) 1.00E-05 1.00E-06 1.00E-07 - Harter-T DTDH 0.0 C-17 da/dN Weibull 1.00E-08 Scales 1.00E-09 1.00E-10 1.00E-11 1.00E-12 1.00E-13 1 10 100

7050-T7451 L-T Crack Growth Rates (Weibull da/dN MLE Analysis)

∆K (KSI√inch)



Constant Probability Curves (R = 0.1 da/dN)



7050-T7451 L-T Crack Growth Rates





Constant Probability (Low $\Delta K R = 0.1$)







Constant Probability (High $\Delta K R = 0.1$)



7050-T7451 L-T Crack Growth Rates





Scatter in da/dN (R = 0.1)



Is a factor of 2 sufficient?

- At 1.65x10⁻⁷ in/cycle it captures 90% of the data
- At 1.18x10⁻⁶ in/cycle it captures 82% of the data
- In order to capture more than 80% of the data at the lowest and highest growth rates, scatter factors of 17 and 95, respectively, result

М	iddle Growth F						
		Probability		Bottom			
	1.65E-07	0.63		1.99E-08			
Scatter = 2	1.10E-07	0.09		3.76E-09	Scatter =	17	
	2.20E-07	0.99	90%	6.46E-08			90%
		Probability		Тор			
	1.18E-06	0.63		2.05E-03			
Scatter = 2	7.84E-07	0.15		1.43E-04	Scatter =	95	
	1.57E-06	0.97	82%	1.35E-02			82%

Only about 1 decade of data fits within a scatter factor of 2



Characterizing C-17 Data (2-P Weibull R = 0.4 da/dN)





653 da/dN points analyzed across 12 Δ K ranges 20



Constant Probability (R = 0.4 da/dN)

7050-T7451 L-T Crack Growth Rates



1.00E-02 1.00E-03 1.00E-04 da/dN (inch per cycle) ×C-17 0.40 1.00E-05 ■P = 0.050 ▲ P = 0.100 $\times P = 0.400$ $\bullet P = 0.632$ 1.00E-06 -P = 0.800◆ P = 0.900 P = 0.950 1.00E-07 1.00E-08 1.00E-09 10.000 1.000 100.000 ∆K (ksi√inch)



Scatter in da/dN (R = 0.4)



Is a factor of two sufficient?

- At 1.04x10⁻⁷ in/cycle it captures 89% of the data
- At 5.97x10⁻⁶ in/cycle it captures 89% of the data
- In order to capture more than 80% of the data at the lowest and highest growth rates, scatter factors of 3 and 21, respectively, result

N	liddle Growth F						
		Probability		Bottom			
	1.04E-07	0.63		5.13E-08			
Scatter = 2	6.95E-08	0.10		2.50E-08	Scatter =	3	
	1.39E-07	0.99	89%	8.56E-08			89%
		Probability		Тор			
	5.97E-06	0.63		1.68E-03			
Scatter = 2	3.98E-06	0.11		2.80E-04	Scatter =	21	
	7.95E-06	0.99	89%	6.00E-03			89%

About 1.5 decades near the lower da/dN range falls within the scatter factor of 2



Characterizing C-17 Data (2-P Weibull R = 0.8 da/dN)





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Scatter in da/dN (R = 0.8)



Is a factor of two sufficient?

- At 3.03x10⁻⁸ in/cycle it captures 91% of the data
- At 4.61x10⁻⁷ in/cycle it captures 95% of the data
- In order to capture more than 80% of the data at the lowest and highest growth rates, scatter factors of 2 and 1315, respectively, result

Μ	iddle Growth F	Rates Scatte	r				
		Probability		Bottom			
	3.03E-08	0.63		3.03E-08			
Scatter = 2	2.02E-08	0.08		2.02E-08	Scatter =	2	
	4.04E-08	1.00	91%	4.04E-08			91%
		Probability		Тор			
	4.61E-07	0.63		8.23E-05			
Scatter = 2	3.07E-07	0.05		1.23E-06	Scatter =	1315	
	6.15E-07	1.00	95%	1.62E-03			95%

Only the lowest decade da/dN falls within the scatter factor of 2



Observations



Scatter across the range of da/dN is not consistent

- A scatter factor of two for this data set has limited applicability
- Only about 1-1.5 decades of data on the lower end of the da/dN range fit across all three stress ratios
- Characterizing behavior based on fixed ranges of da/dN, therefore, is complicated by the inconsistent scatter observed
- Weibull shape parameter behavior between stress ratios for distributions of da/dN for fixed ∆K differs significantly
 - R = 0.4 and 0.8 data tends to converge on very narrow distributions
 - $\Delta K_{\text{Applied}}$ and $\Delta K_{\text{Effective}}$ affect

Shape Parameter Summary (7050)

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Additional Observations (da/dN R = 0.1)



Upper bound da/dN distribution is potentially indicative of testing specimen and methods

- Net section yield
- Instability

Lower bound (R = 0.1) da/dN distribution might indicate transition from "short crack" behavior

- Physically
- Microstructurally



In-situ short crack growth test system circa 1990



Figure 3.12 Fatigue microcracks that nucleated due to various mechanisms. (a) Elevated temperature (700°C) grain boundary crack in Waspaloy. (b) Surface inclusion? slip band crack in Waspaloy. (c) Elevated temperature (500°C) surface pore/slip band in Waspaloy. (d) Cracking within a and # phases in lamellar structure in titanium alloy IMIR34 (courtesy of R. R. Stephens). 5



Transitioning from Short Crack Behavior?



 Iso-probabilities highlight potential transition from short crack, i.e. microstructural barriers, corrosion, etc. to long (through thickness) crack behavior
 Limited High R, short crack, data and observations



Further Considerations



- "Long Crack Threshold" for R = 0.1 is defined by the NASGRO equation as approximately ∆K = 3.1 ksi√in at 10⁻⁹ in/cycle (Slide 15) would be expected to occur less than about 1/100,000 times (for distributions of da/dN)
- Consistent loads accuracy, +/- 5%*, is recommended (?) as the basis for defining fixed ∆K range to determine distributions on da/dN
 - *Established practice within aerospace fatigue analysis
 - For a fixed crack size, geometry, applied force, and stress ratio, we calculate ΔK and da/dN results
 - Should the tolerance be tighter? +/-2%, +/-1% (test instrumentation calibration ASTM E4 Force Calibration)?



Alternative Example



2024-T351 L-T

- What we know about this data set
 - Stress Ratio
 - Range of ΔK
 - Grain orientation
 - Data developed between 1975 and 2015
- What we do not know
 - Specimen configuration
 - Product form thickness
 - Testing environment and frequency
 - Test Type (CA, K-Decreasing, etc.)
 - Test data supplier
 - Producer/lot variation



Generic Test Data Example







da/dN within Discrete Ranges of $\Delta K (R = 0.1)$



Choose ranges of △K (+/-5%) to analyze from total population of data

- 1625 data pairs
- 5% based on loads accuracy
- Develop Maximum Likelihood Estimation (MLE) distribution parameters for da/dN within each chosen range of △K
 - 749 data pairs across 14 ∆K ranges
 - Approximately 54 da/dN points/∆K range
- Resulting shape parameters as a function of da/dN

Weibull Para	ameters for	Target for da/dN		
da/dN at	Fixed ∆K	Distributions		
Shape	Scale	ΔK	Range	
1.12	1.461E-08	2.50	2.375-2.625	
1.17	3.521E-08	3.00	2.850-3.150	
2.68	7.675E-08	3.50	3.325-3.675	
10.14	1.290E-07	4.00	3.800-4.200	
11.14	1.601E-07	4.50	4.275-4.725	
11.54	1.868E-07	5.00	4.750-5.250	
3.71	3.32E-07	6.25	5.938-6.563	
1.97	1.815E-06	7.50	7.125-7.875	
3.77	7.051E-06	10.00	9.500-10.500	
4.79	2.277E-05	15.00	14.250-15.750	
3.21	5.550E-05	20.00	19.000-21.000	
2.23	1.472E-04	25.00	23.750-26.250	
3.79	2.058E-04	30.00	28.500-31.500	
2.38	3.600E-04	35.00	33.250-36.750	





Constant Probability Curves (R = 0.1 da/dN)







Constant Probability (Low $\Delta K R = 0.1$)







Constant Probability (High $\Delta K R = 0.1$)





Max da/dN and ∆K from data



Concluding Remarks



- Obtaining crack growth data and establishing a working 'confidence' in that data can be a tedious process
- Implementing consistency in how this data is further characterized for use in damage tolerance assessments is open to debate
- These examples highlighted the following
 - da/dN scatter can vary widely across the range of ΔK
 - Statistical representations can provide insight into the applicability of established concepts and why challenges in predictions can occur
 - The behavior of the R = 0.1 data, specifically, at low ΔK values shares similarity to Short Crack behavior
 - •Coincidence?



References and Related Bibliography



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