Probabilistic Aspects of Fatigue

Case Studies

Professor Darrell F. Socie
Department of Mechanical and Industrial Engineering

Probabilistic Aspects of Fatigue

- Introduction
- Basic Probability and Statistics
- Statistical Techniques
- Analysis Methods
- Characterizing Variability
- **Case Studies**
- FatigueCalculator.com
- GlyphWorks

Case Studies

- DARWIN
  - Southwest Research
- Bicycle
- Loading Histories

A Software Framework for Probabilistic Fatigue Life Assessment

ASTM Symposium on
Probabilistic Aspects of Life Prediction
Miami Beach, Florida
November 6-7, 2002

R. C. McClung, M. P. Enright, H. R. Millwater*,
G. R. Leverant, and S. J. Hudak, Jr.
Southwest Research

Slides 6 – 27 used with permission of of Craig McClung

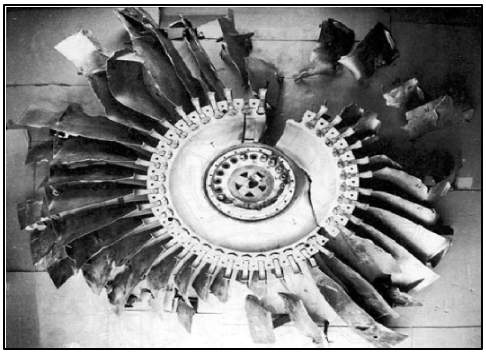
Motivation

UAL Flight 232

July 19,1989

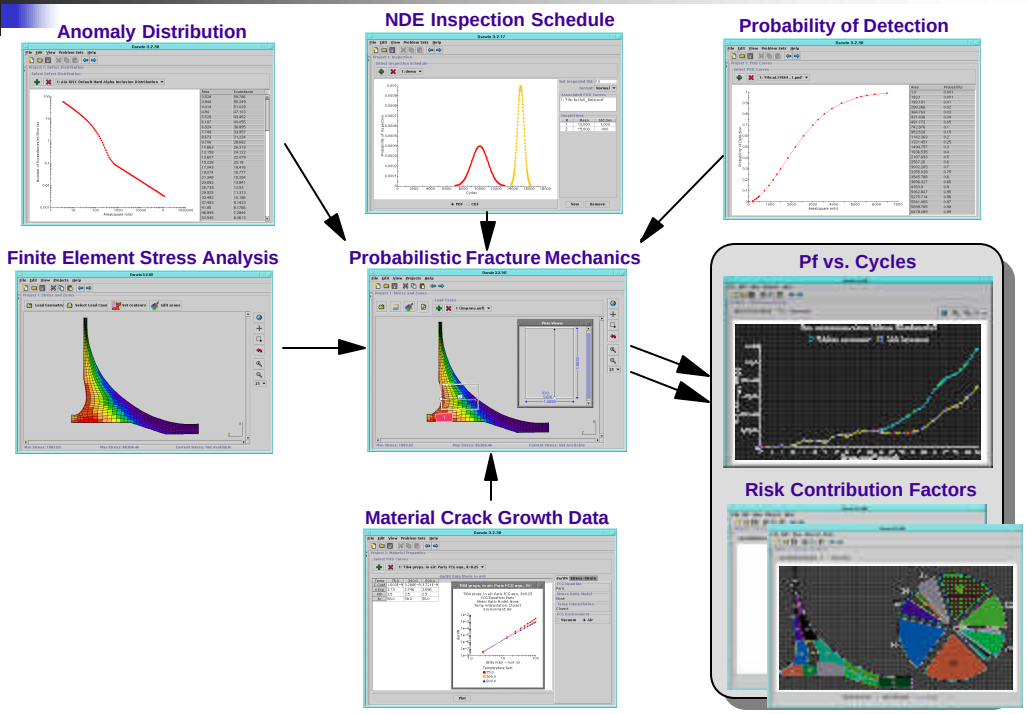
Turbine Disk Failure

Anomalies in titanium engine disks



- Hard Alpha
  - Very rare
  - Can cause failure
  - Not addressed by safe life methods
- Enhanced life management process
  - Requested by FAA
  - Developed by engine industry
  - Probabilistic damage tolerance methods
  - Supplement to safe life approach
- SwRI and engine industry developed DARWIN with FAA funding

Probabilistic Damage Tolerance



Zone-Based Risk Assessment

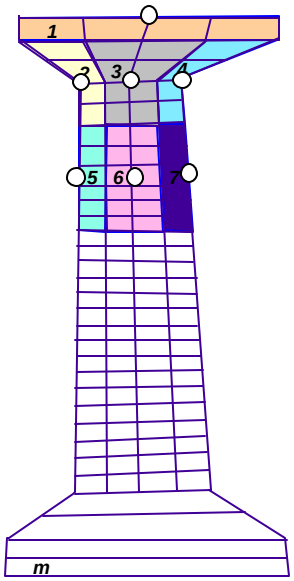
Define zones based on similar stress, inspection, anomaly distribution, lifetime

Total probability of fracture for zone:

- (probability of having a defect) x (POF given a defect)
- Defect probability determined by anomaly distribution, zone volume
- POF assuming a defect computed with Monte Carlo sampling or advanced methods

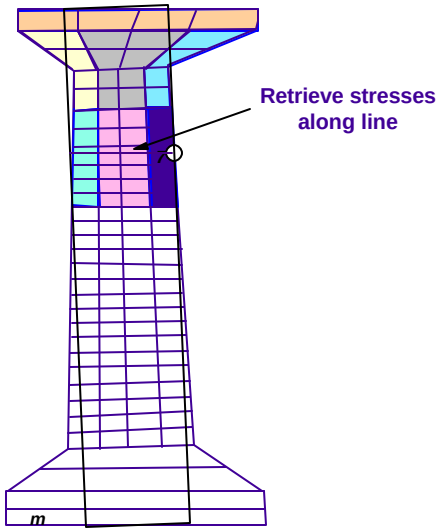
POF for disk obtained by summing zone probabilities

As individual zones become smaller (number of zones increases), risk converges down to "exact" answer

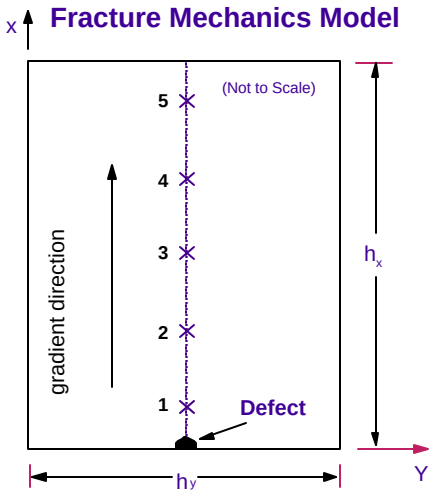


Fracture Mechanics Model of Zone

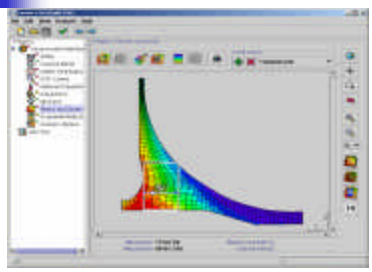
Finite Element Model



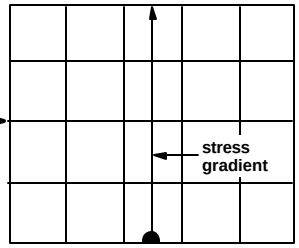
Fracture Mechanics Model



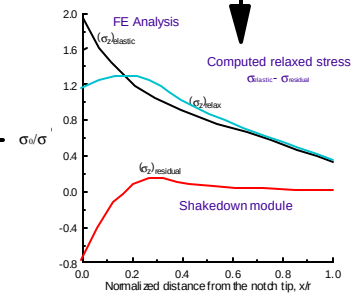
Stress Processing



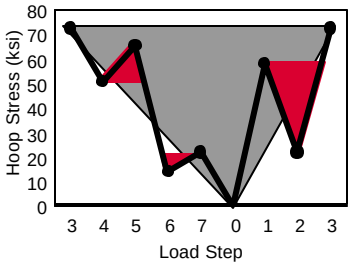
FE Stresses and plate definition



Stress gradient extraction



Residual stress analysis

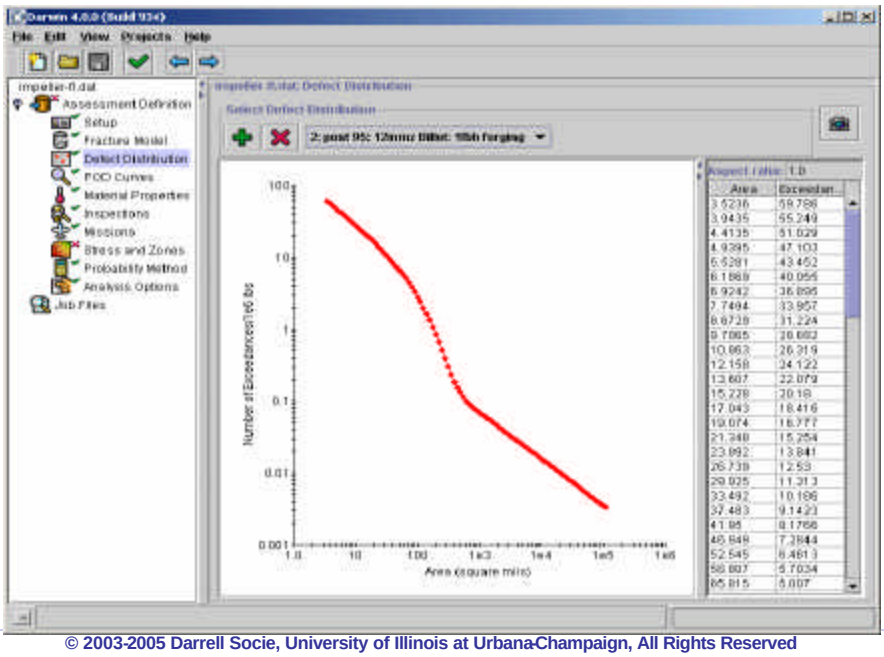


Rainflow stress pairing

Anomaly Distribution

of anomalies per volume of material as function of defect size

Library of default anomaly distributions for HA (developed by RI SC)

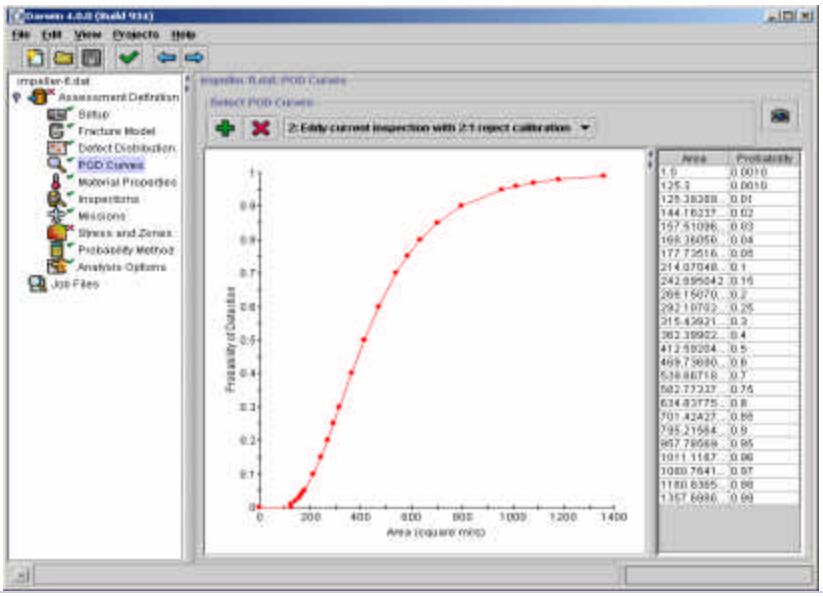


Probability of Detection Curves

Define probability of NDE flaw detection as function of flaw size

Can specify different PODs for different zones, schedules

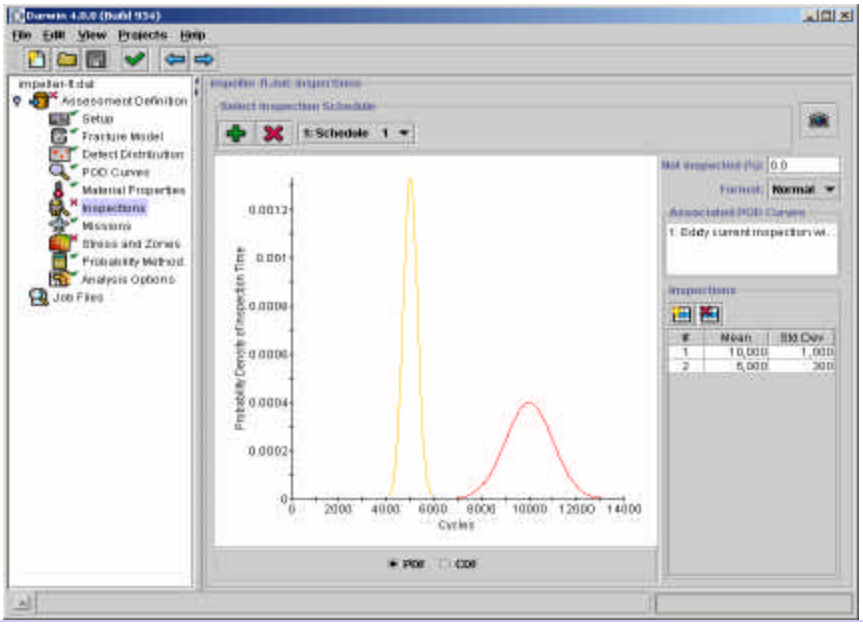
Built-in POD library or user-defined POD



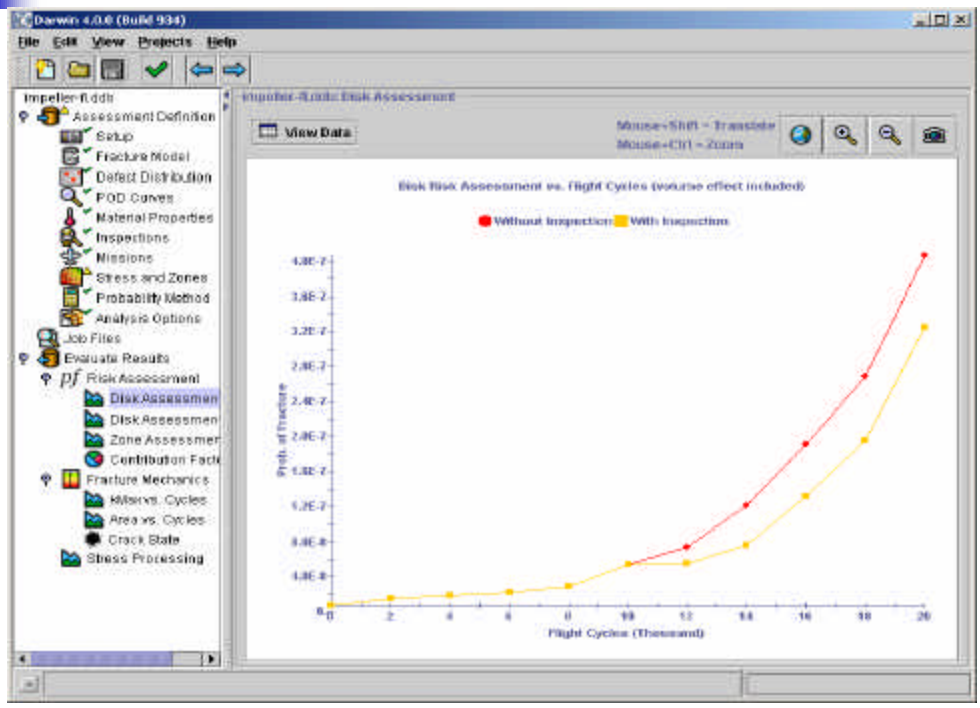
Random Inspection Time

"Opportunity Inspections" during on-condition maintenance

Inspection time modeled with Normal distribution or CDF table

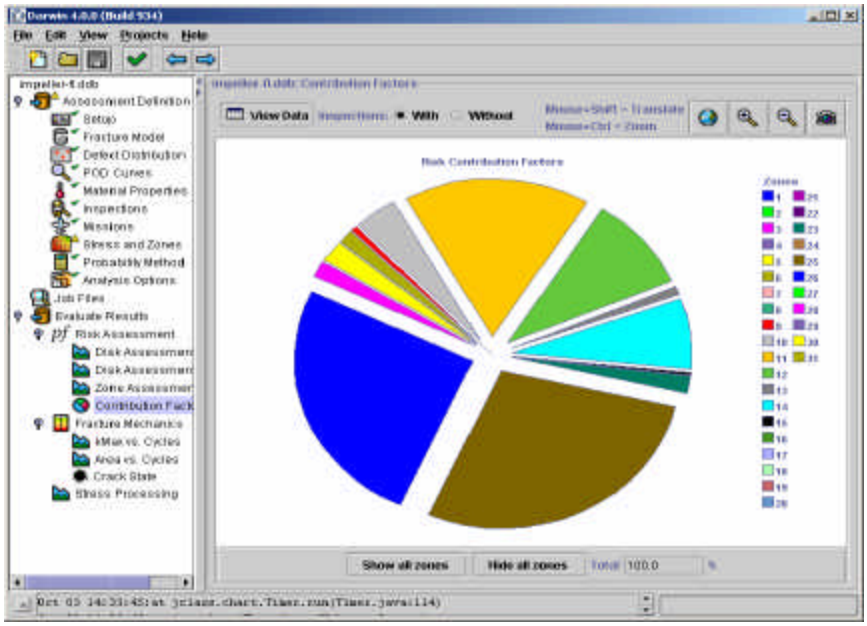


Output: Risk vs. Flight Cycles



Output: Risk Contribution Factors

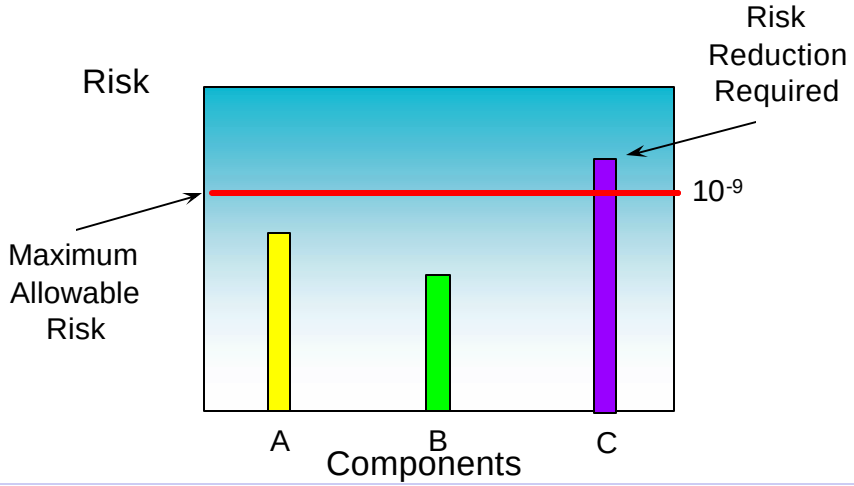
Identify regions of component with highest risk



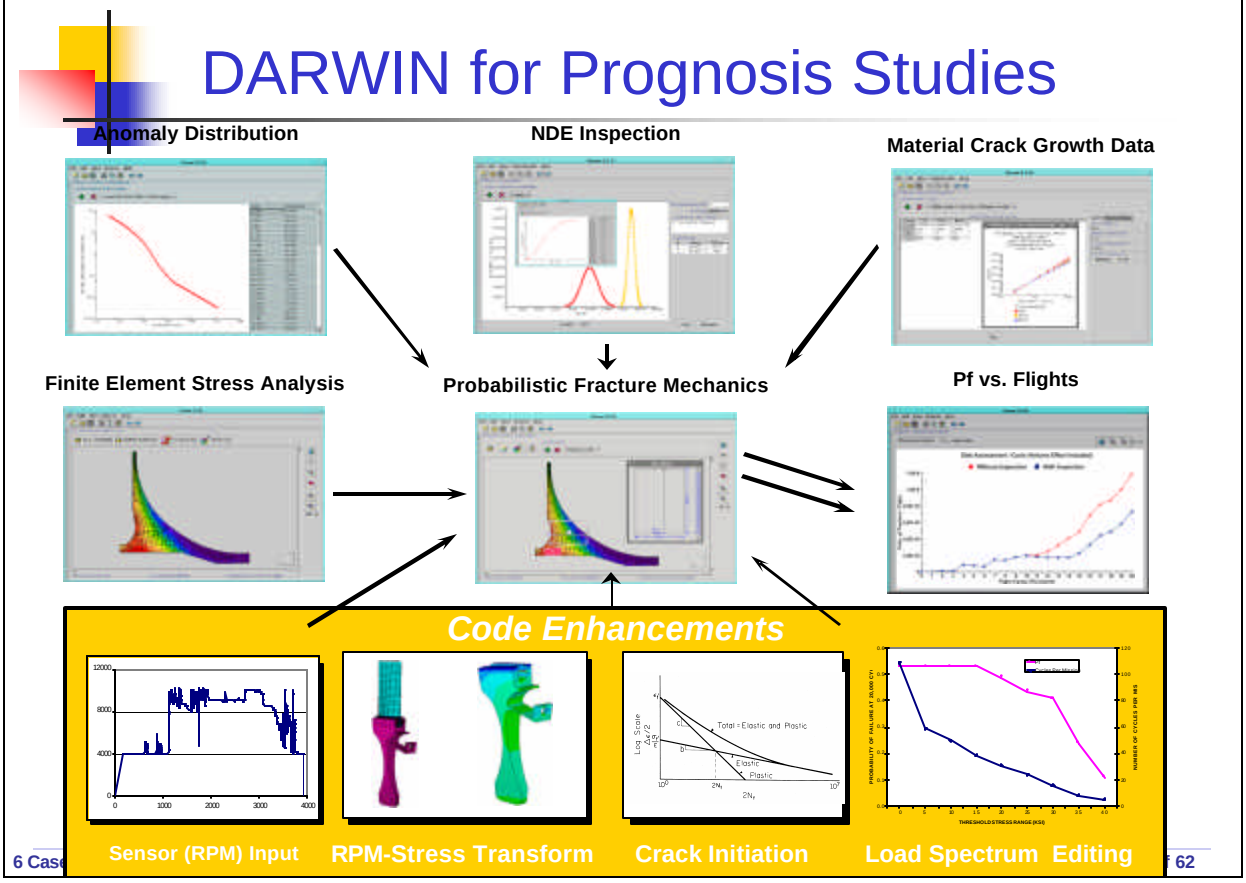
Implementation in Industry

FAA Advisory Circular 33.14 requests risk assessment be performed for all new titanium rotor designs

Designs must pass design target risk for rotors



DARWIN for Prognosis Studies

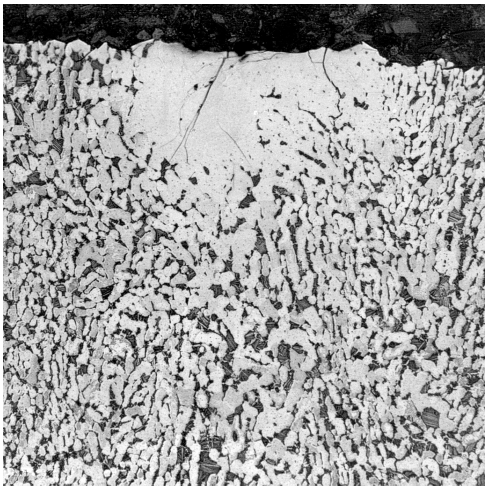


Three Sources of Variability

- Anomaly size (initial crack size)
- FCG properties (life scatter)
- Mission histories (stress scatter)

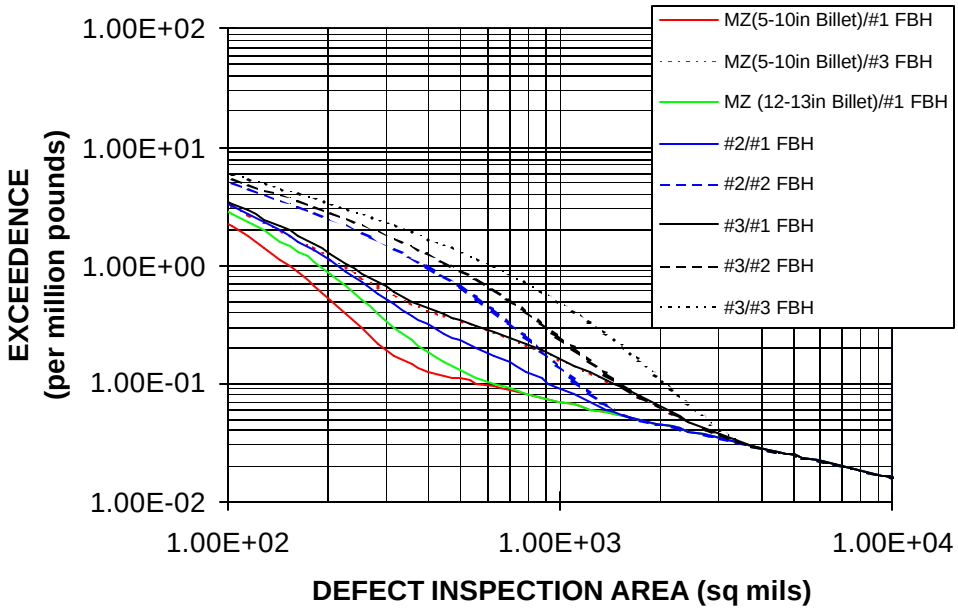
Hard Alpha Defects in Titanium

- Initial DARWIN focus on Hard Alpha
  - Small brittle zone in microstructure
  - Alpha phase stabilized by N accidentally introduced during melting
  - Cracks initiate quickly
- Extensive industry effort to develop HA distribution



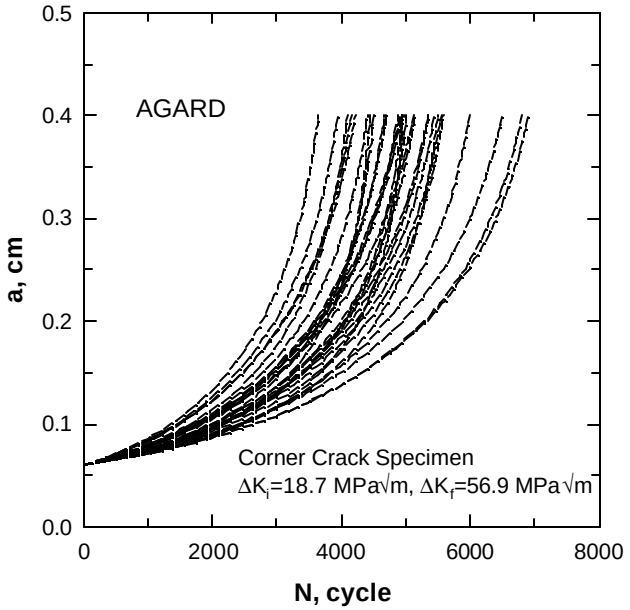
Resulting Anomaly Distributions

Post 1995 Triple Melt/Cold Hearth + Vacuum Arc Remelt



FCG Simulations for AGARD Data

- Use individual fits to generate set of *a* vs. *N* curves for identical conditions
- Characterize resulting scatter in total propagation life
- Lognormal distribution appropriate in most cases



Engine Usage Variability

Stress/Speed:

$\Delta\sigma \propto (RPM)^2$

Total Cyclic Life (LCF):

$N_f = N_i + N_p$

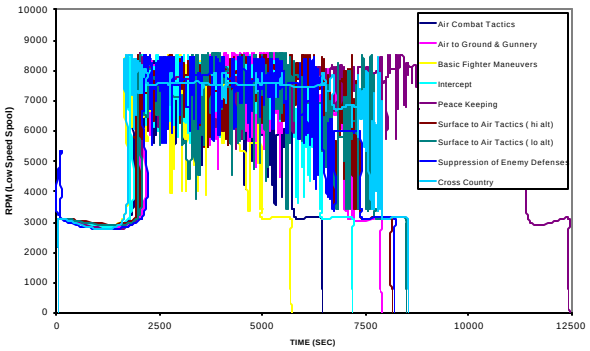
$N_i \propto \Delta\sigma^{3\text{-}5}$

$N_p \propto \Delta\sigma^{3\text{-}4}$

Life/Speed:

$N_f \propto (RPM)^6$

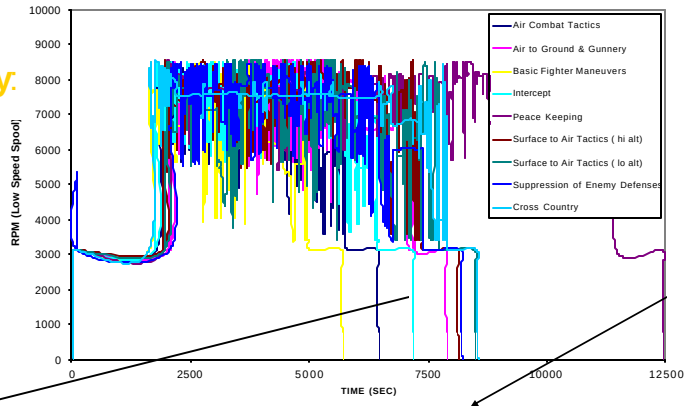
Component life is very sensitive to actual usage



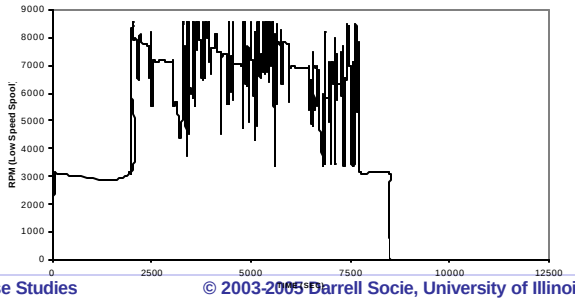
Usage Variability

Components of Usage Variability:

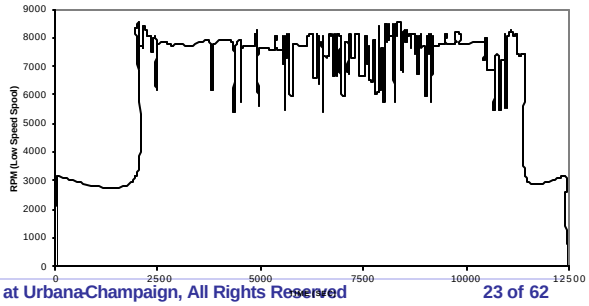
- Mission type
- Mission-to-mission variability
- Mission mixing variability



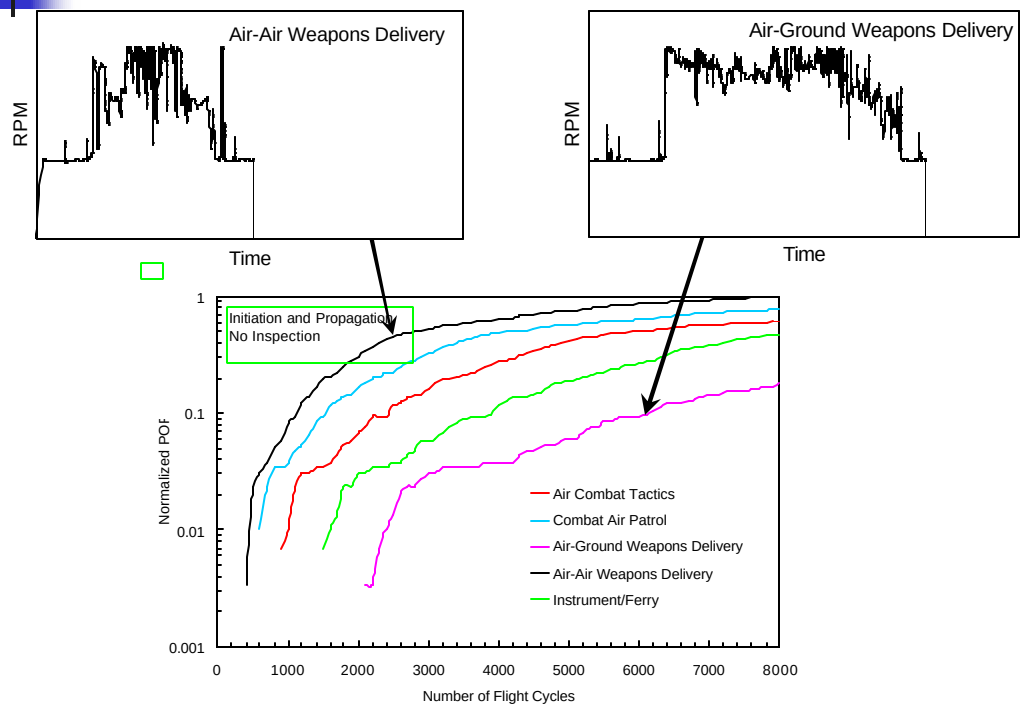
Surface to Air Tactics (lo alt)



Peace Keeping



Variability in Mission Type



Web Site: www.darwin.swri.org

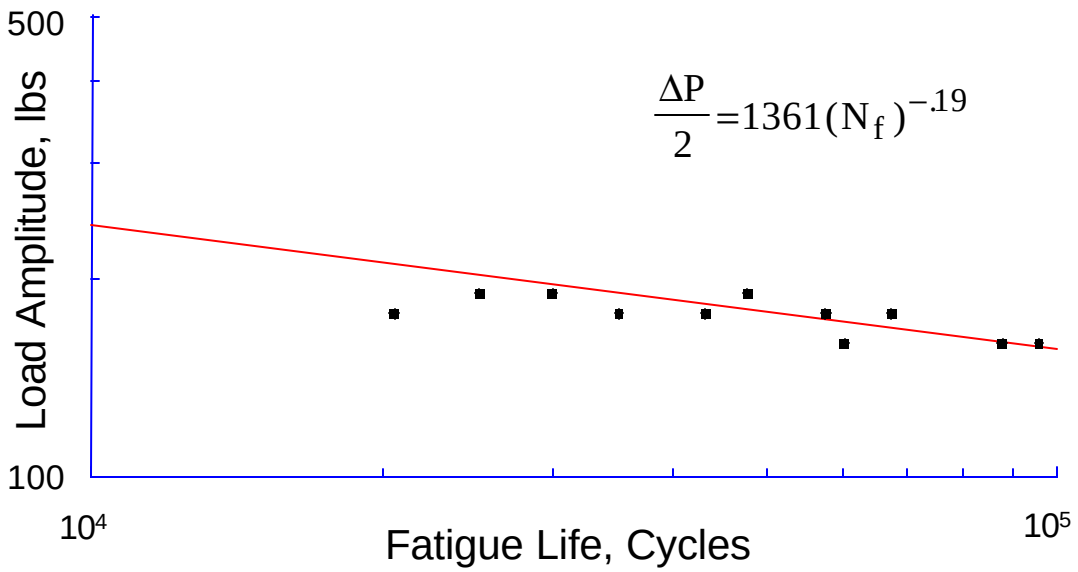
Bicycle

Assess risk in a new design

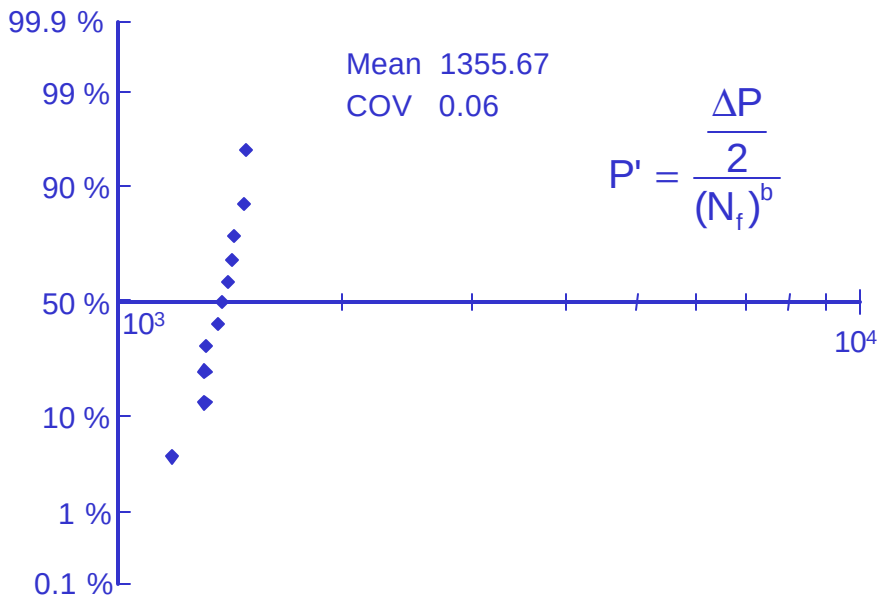
Variability / Uncertainty

- Fatigue strength of fork
- Load history variability
- Load history uncertainty
- Analysis uncertainty

Load-Life Data

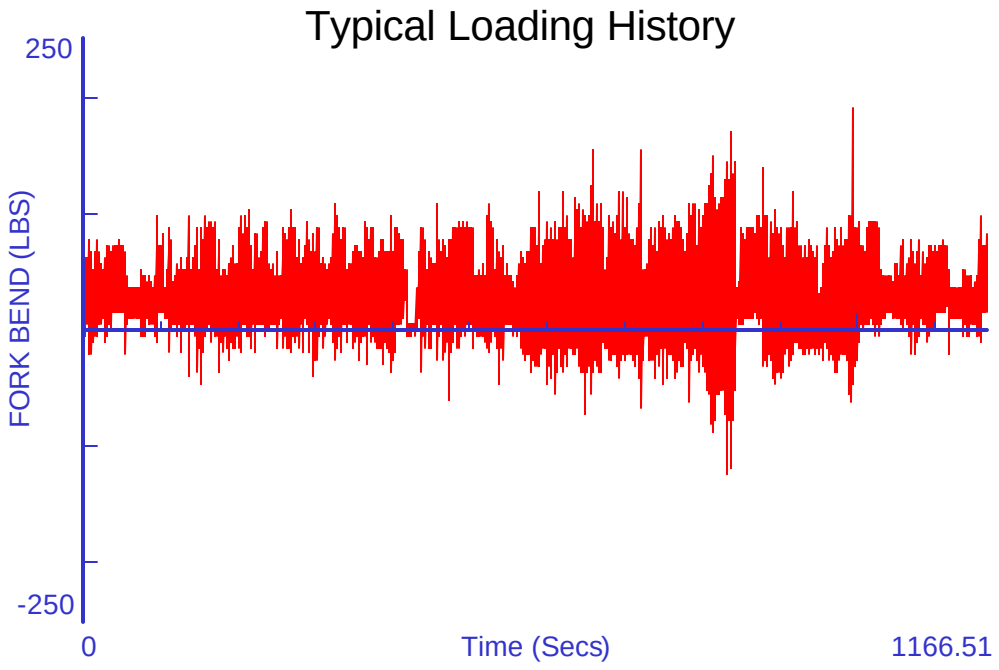


Variability

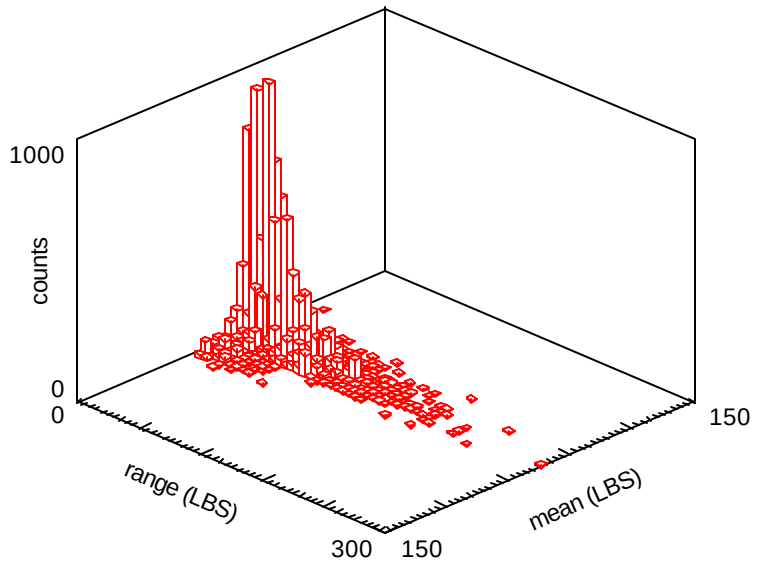


$$P' = \frac{\frac{\Delta P}{2}}{(N_f)^b}$$

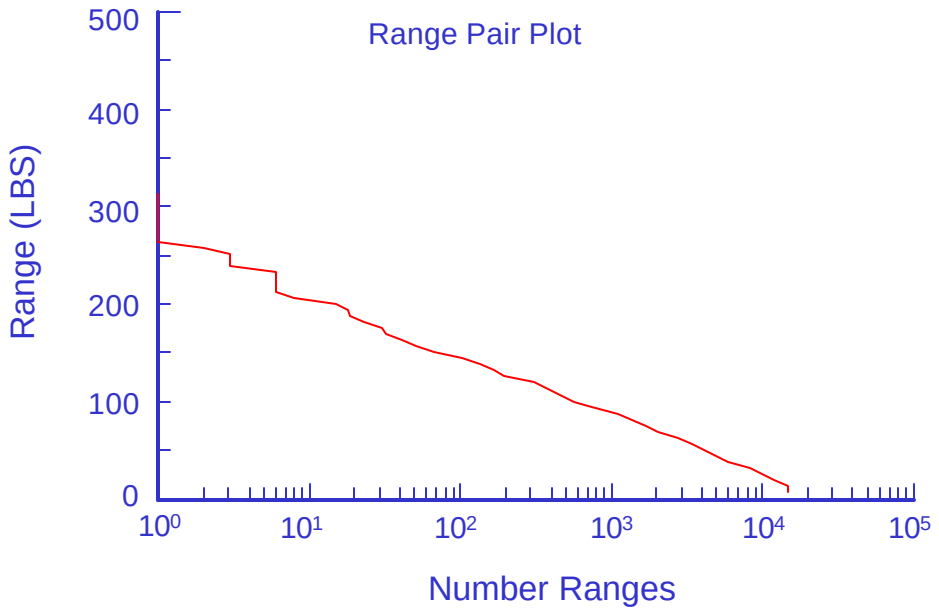
Loading History



Rainflow



Exceedance Diagram



Random Variables

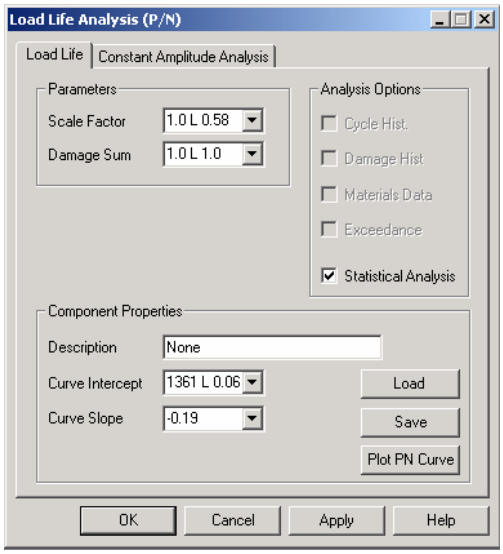
- Strength LN(1356 , 0.06)
- Loading History LN(1 , 0.3)
  - Estimated from other data
- Loading History Uncertainty in Mean
  - Could be “off” by a factor of 2 LN(1.0 , 0.25)
- Analysis
  - Estimated from other data LN(1.0 , 1.0)

Combined Variability for Loads

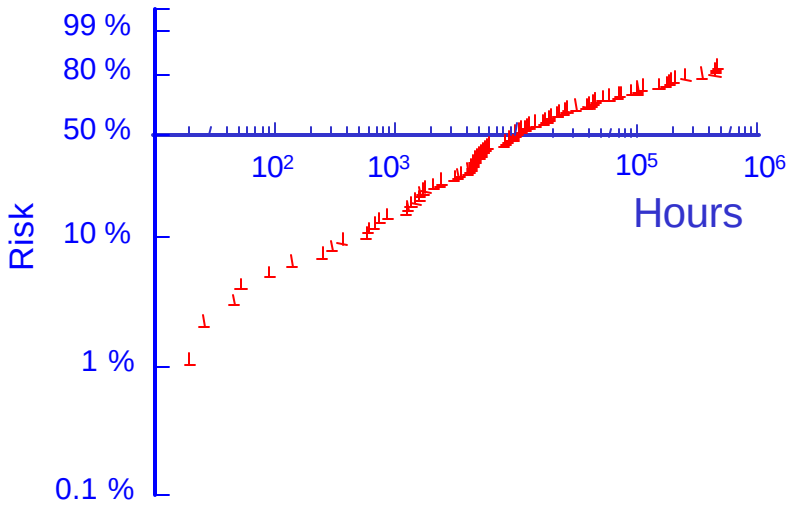
$$\text{COV} \quad C = \sqrt{\prod_{i=1}^{n}\left(1+C_{X_i}{}^{2}\right)^{a_i{}^{2}} - 1}$$

$$\text{COV} = \sqrt{\left(1+0.3^2\right)^2\left(1+0.25^2\right)^2 - 1} = 0.58$$

Analysis



Results

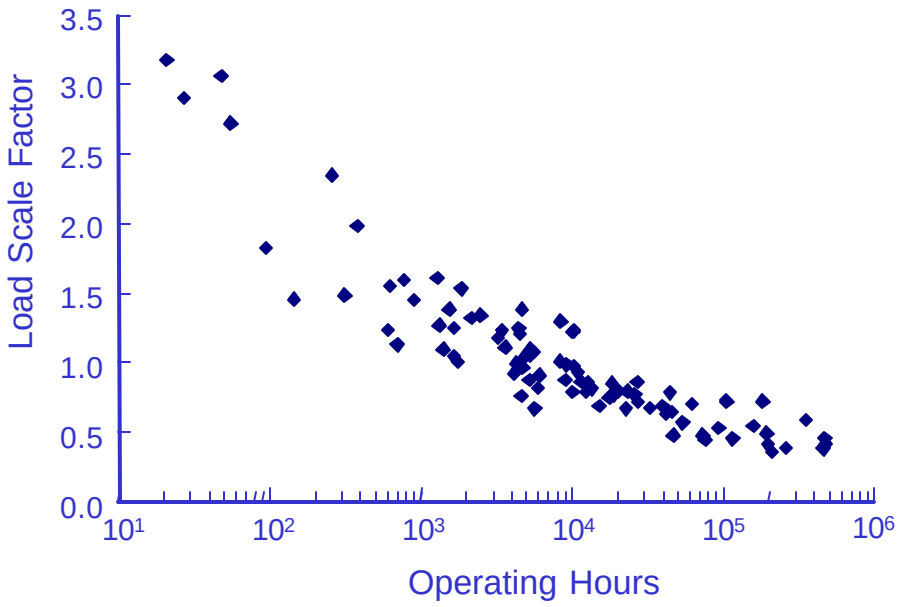


Results

Monte Carlo Simulation Results Table

	mean	COV	r^2	$S_{\mu i}$	α_i
Blocks	7.778e+04	6.132			
intercept	1.360e+03	0.061	0.015	5.4	0.10
slope	-1.900e-01	0.000	0.000	-13.9	
damage	9.856e-01	0.980	0.016	0.99	0.31
scale	9.981e-01	0.588	0.928	-5.4	0.94

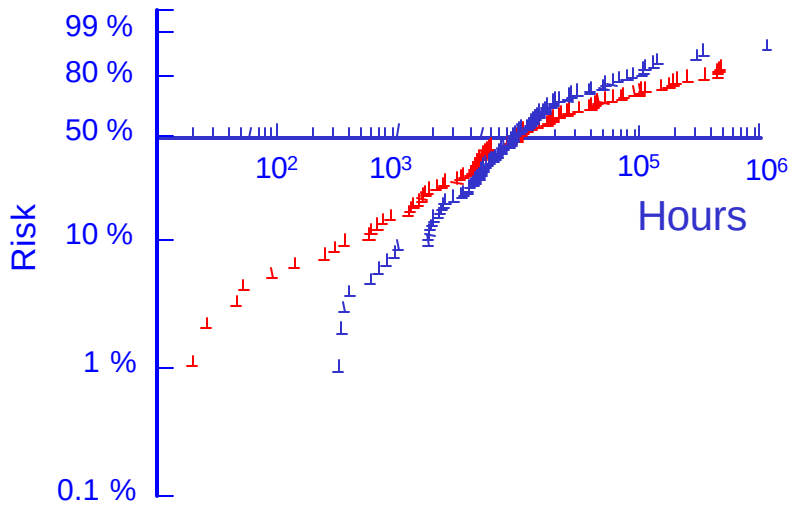
Correlation Coefficient



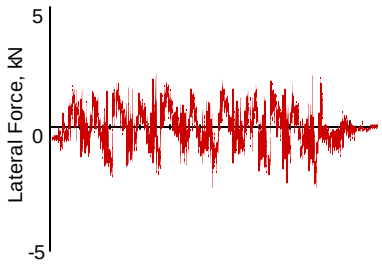
Course of Action

- Make it stronger
- Run tests to reduce analysis uncertainty
- Field tests to reduce loading uncertainty

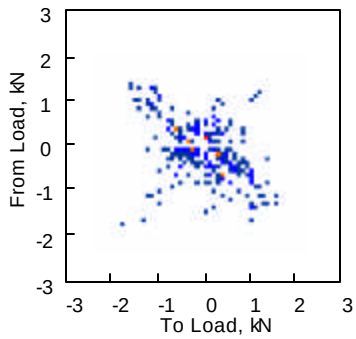
Eliminate Mean Uncertainty



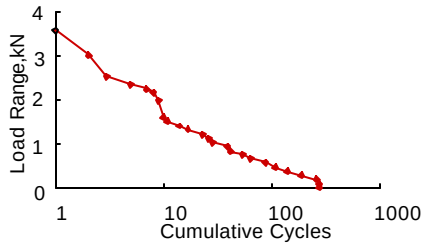
Service Loading Spectra



Time history



Rainflow Histogram



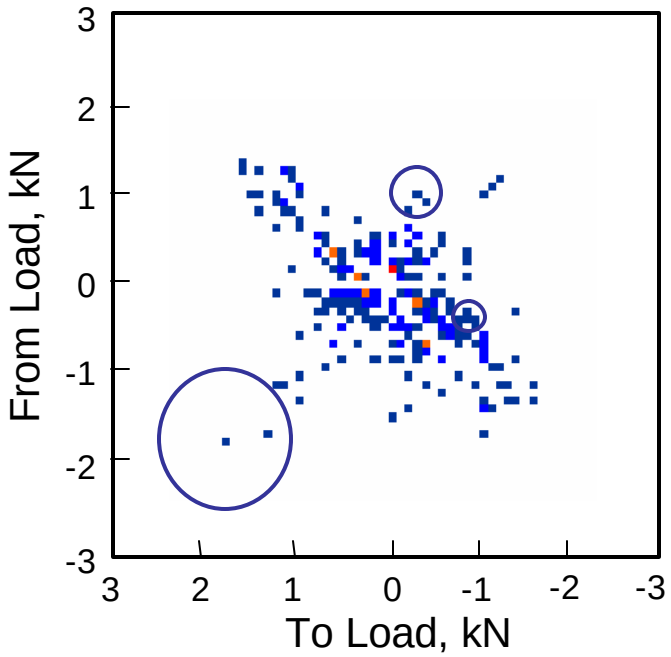
Exceedance Diagram

Problem Statement

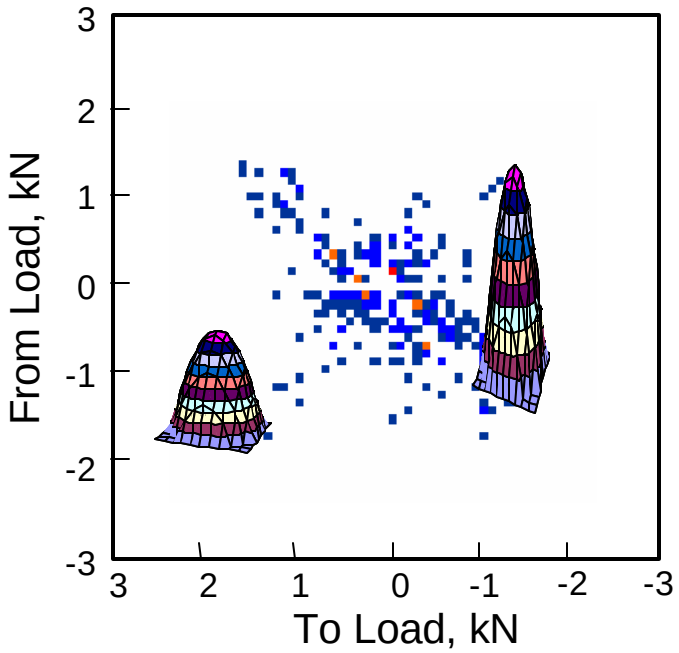
Given a rainflow histogram for a single user, extrapolate to longer times

Given rainflow histograms for multiple users, extrapolate to more users

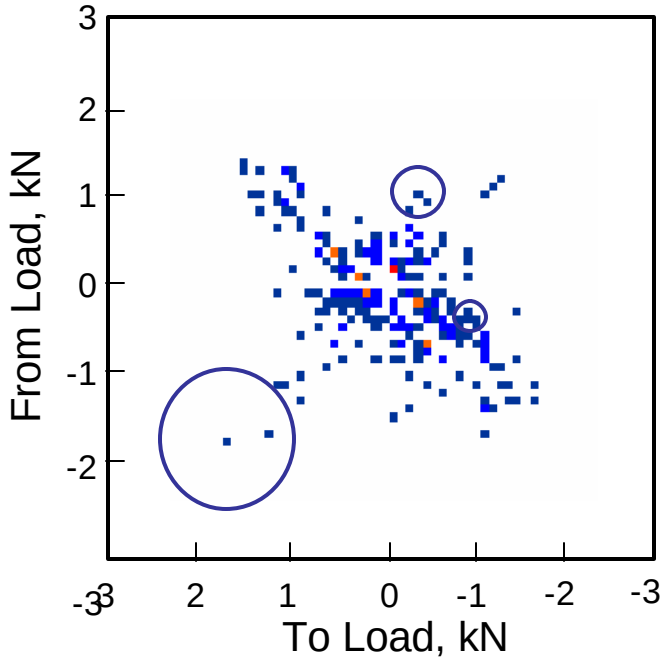
Probability Density



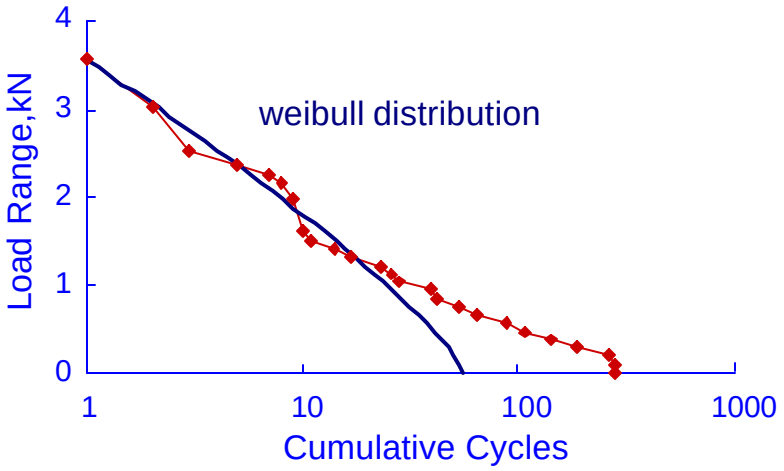
Kernel Smoothing



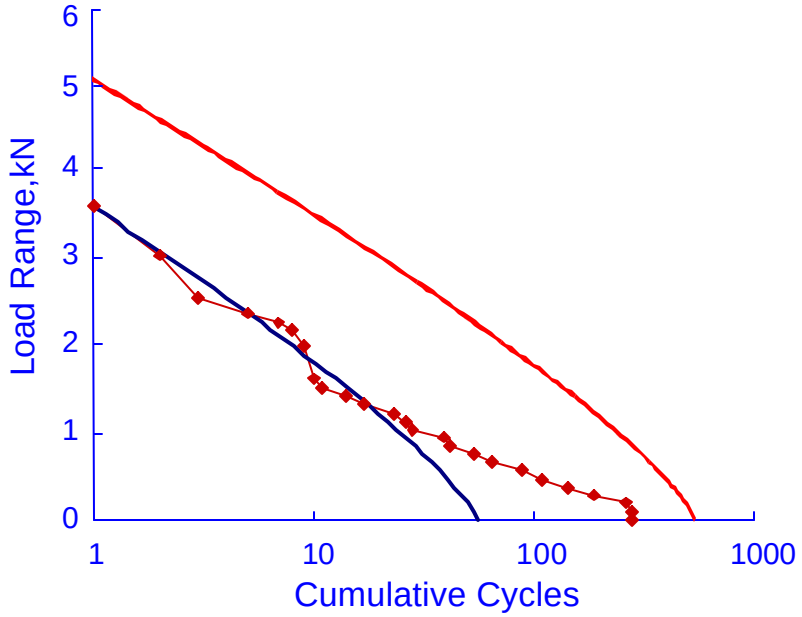
Sparse Data



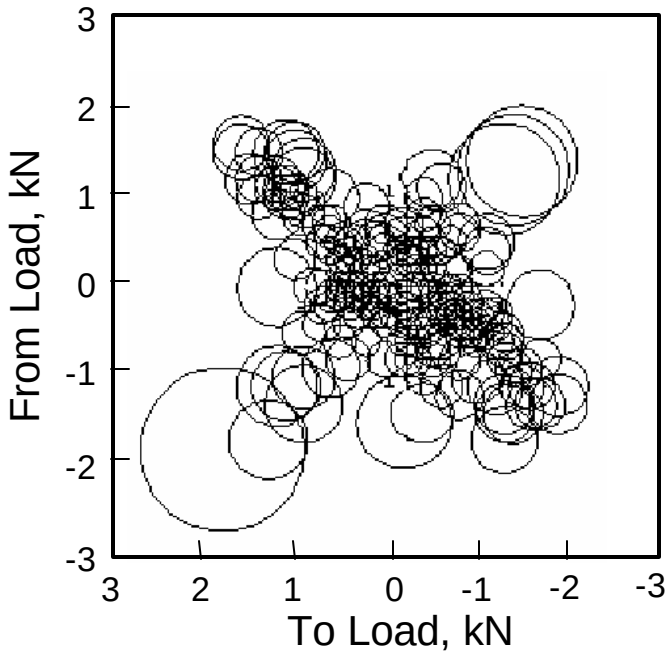
Exceedance Plot of 1 Lap



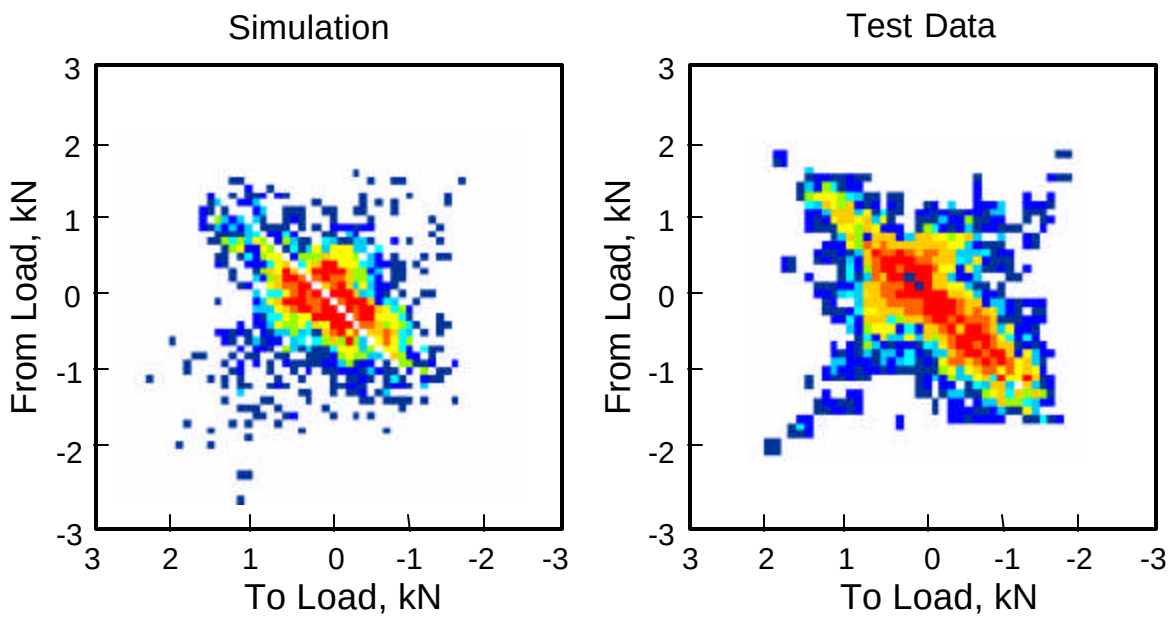
10X Extrapolation



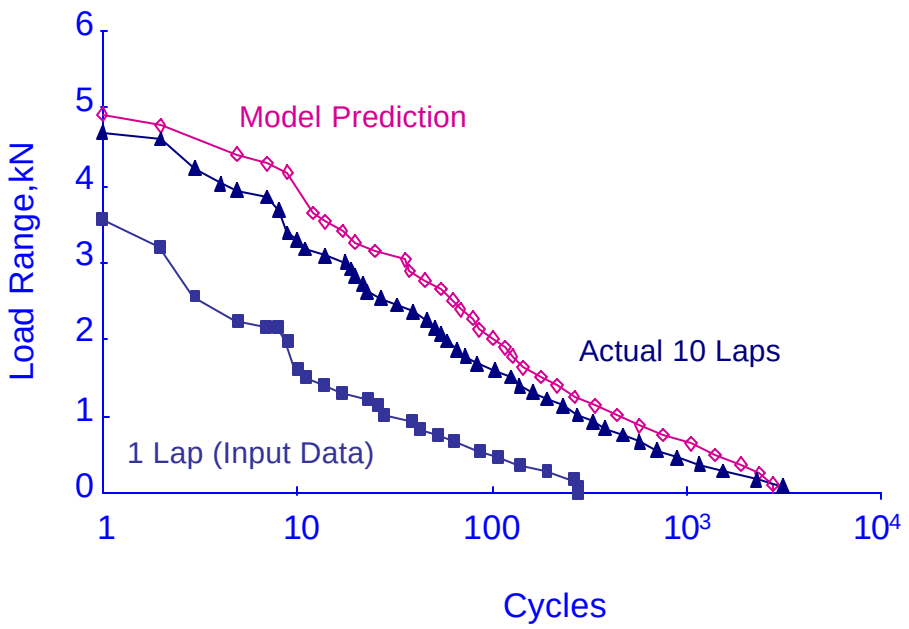
Probability Density



Results



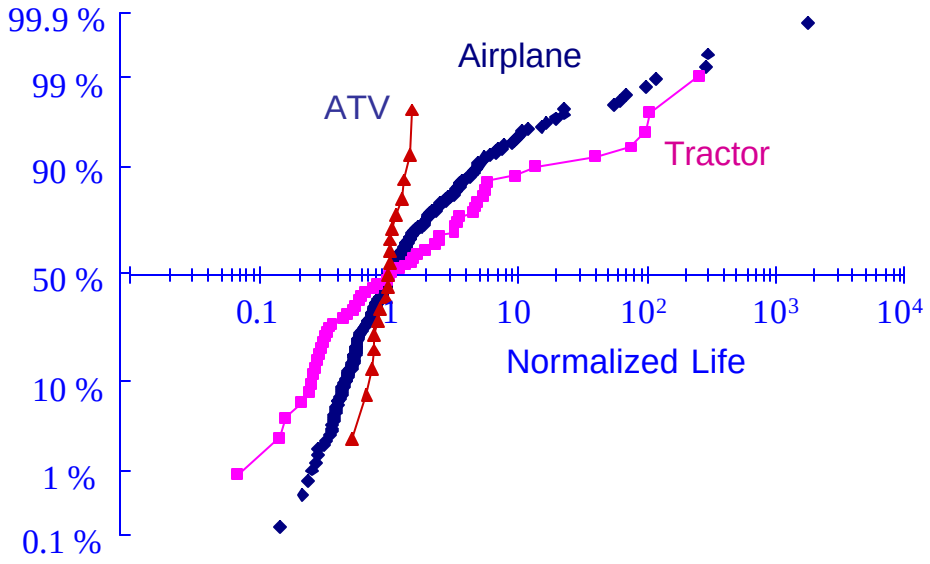
Exceedance Diagram



Problem Statement

- Given a rainflow histogram for a single user, extrapolate to longer times
- Given rainflow histograms for multiple users, extropolate to more users

Extrapolated Data Sets



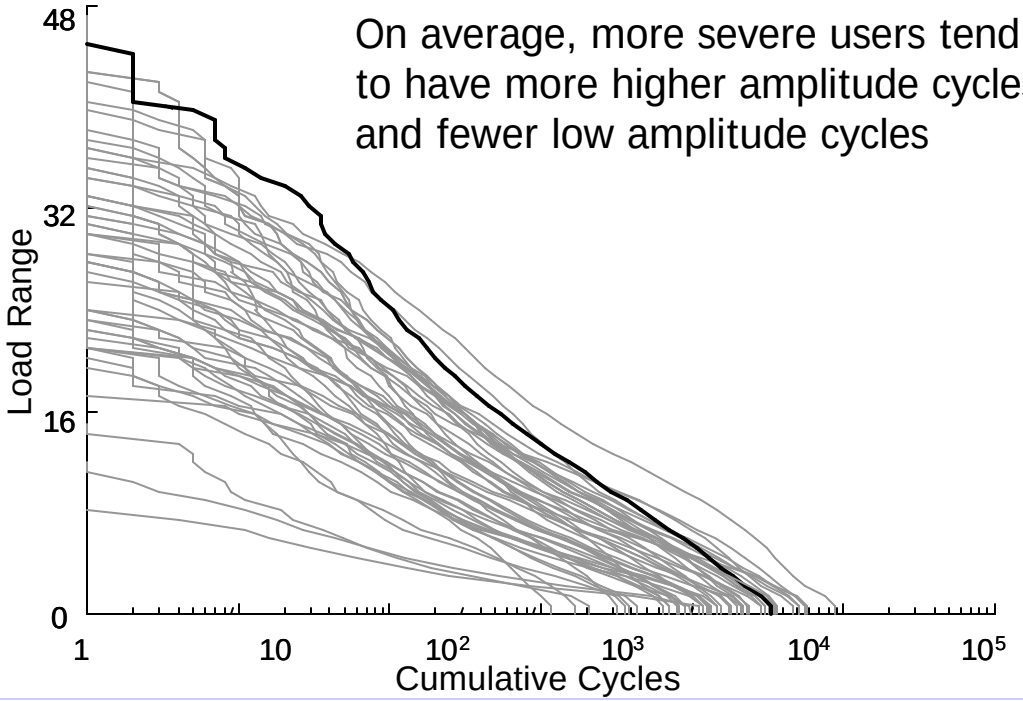
Issues

In the first problem the number of cycles is known but the variability is unknown and must be estimated

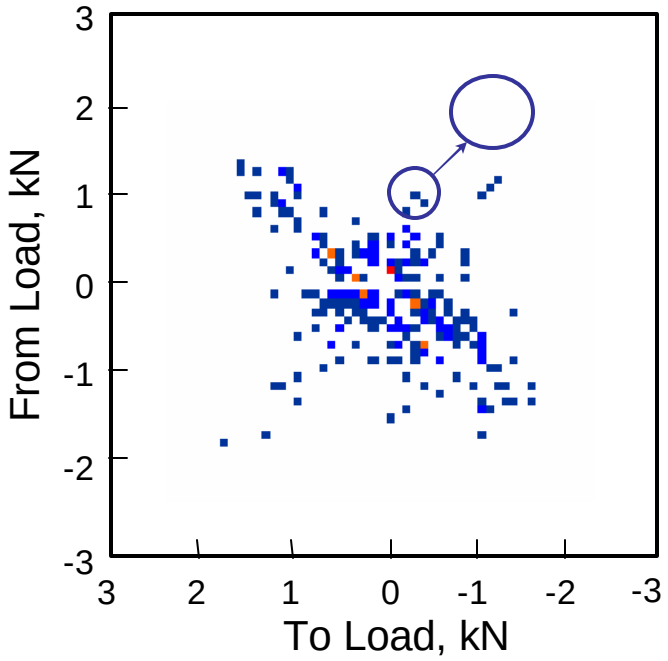
In the second problem the variability is known but the number and location of cycles is unknown and must be estimated

Assumption

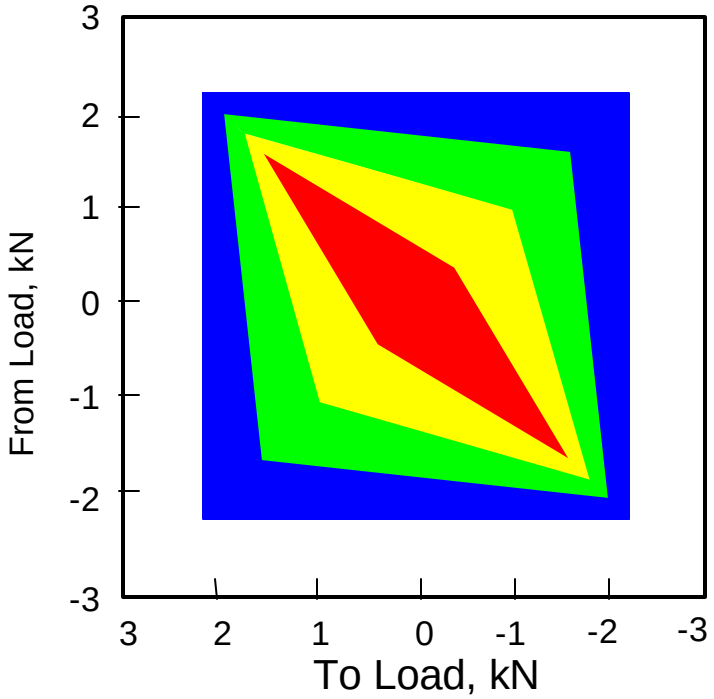
On average, more severe users tend to have more higher amplitude cycles and fewer low amplitude cycles



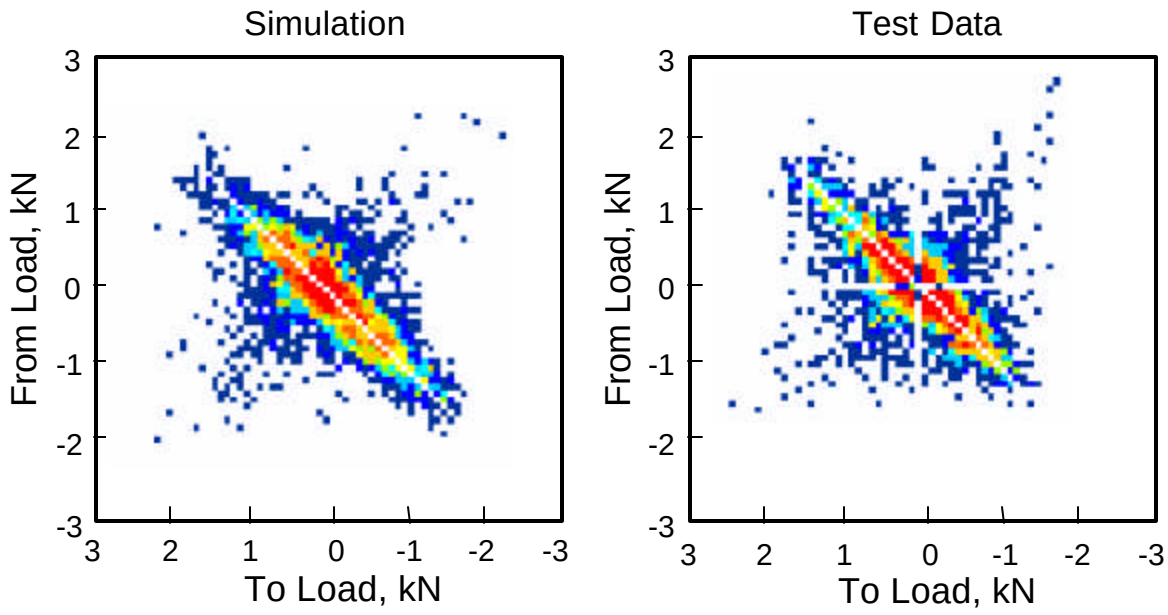
Translation



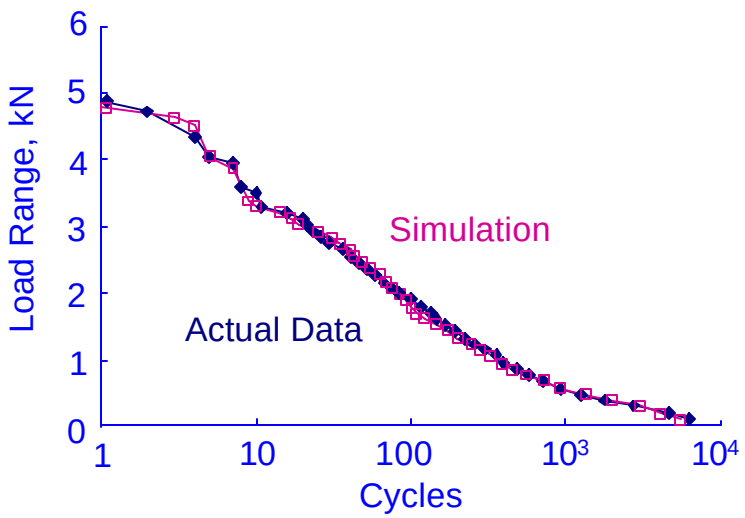
Damage Regions



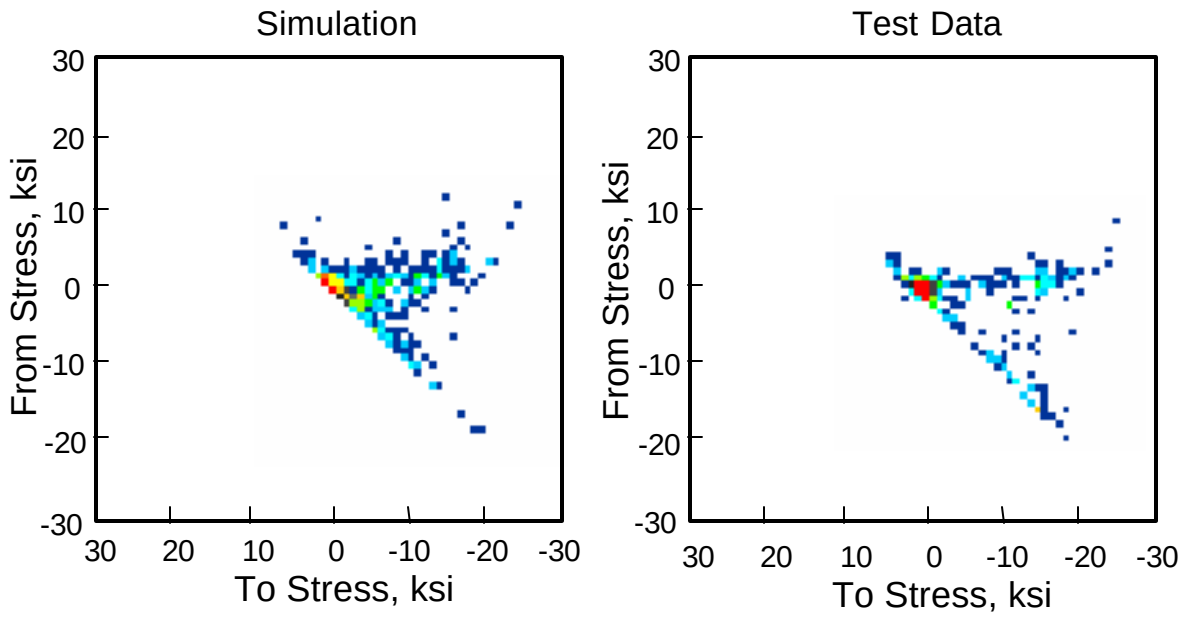
ATV Data - Most Damaging in 19



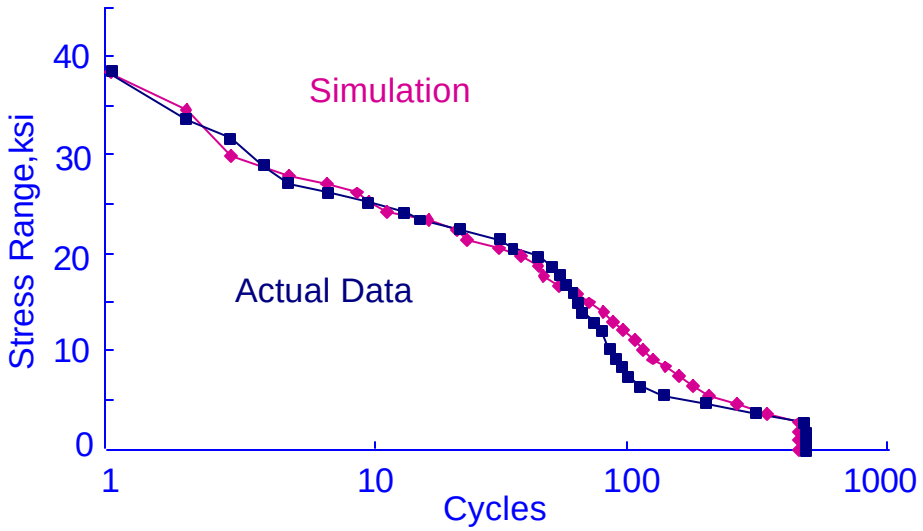
ATV Exceedance



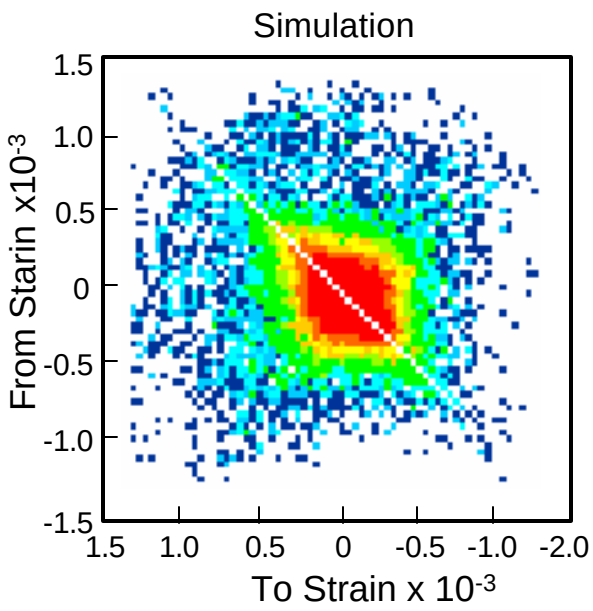
Airplane Data - Most Damaging in 334

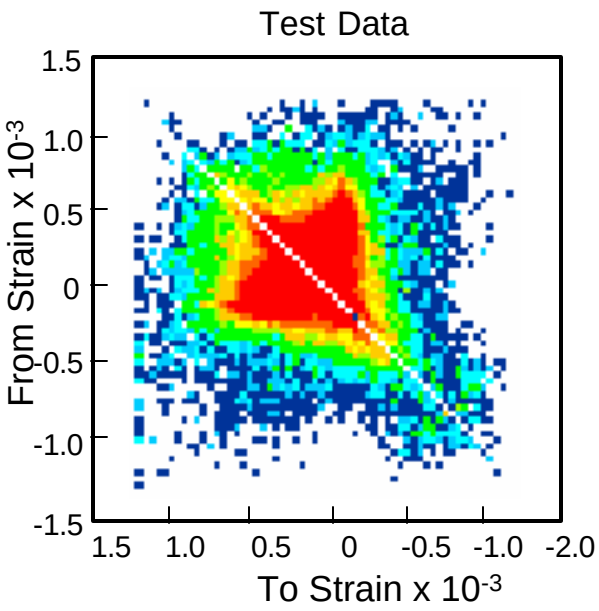


Airplane Exceedance

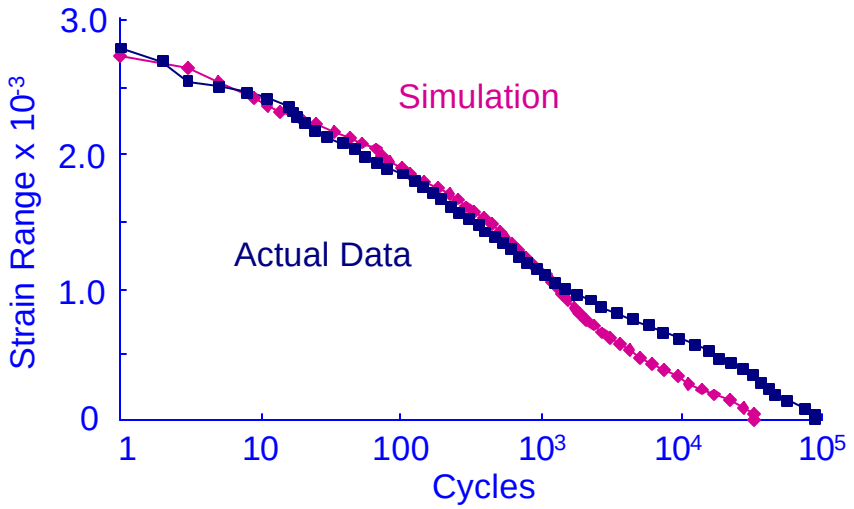


Tractor Data - Most Damaging in 54





Tractor Exceedance



Probabilistic Aspects of Fatigue