Reliability of Aircraft Structure Joints Under Corrosion-Fatigue Damage

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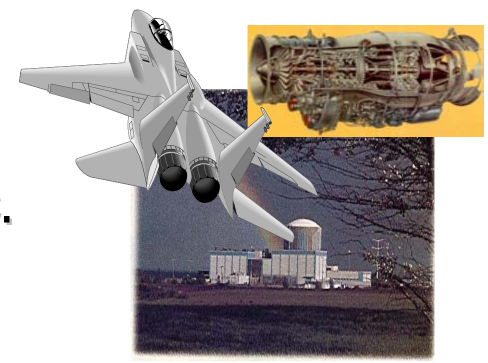


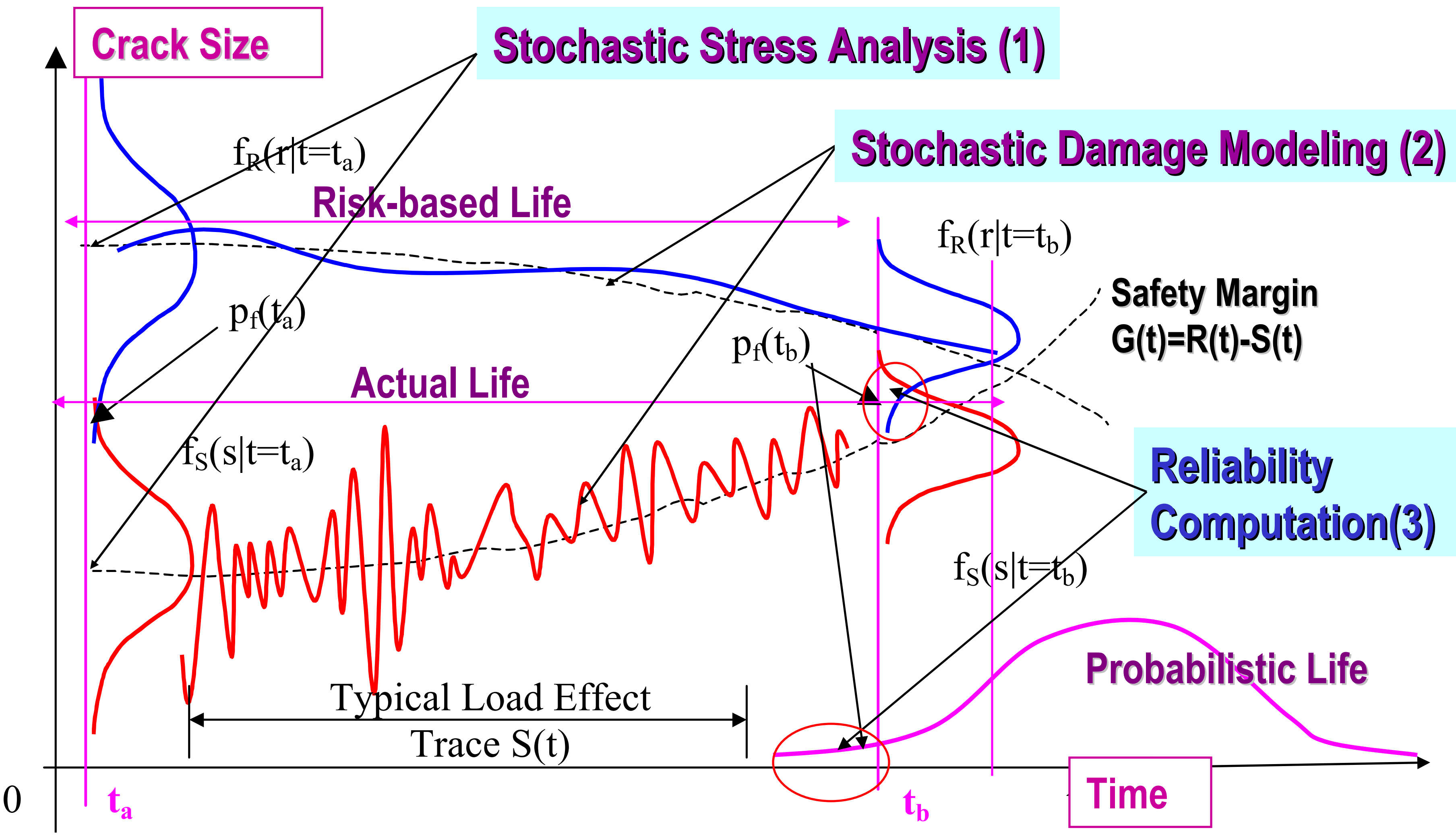
REDUCED VERSION

46th AIAA/ASME/ASCE/AHS/ASC/ Structural Dynamics and Materials Conference, NDA Forum, April 11-15, 2005

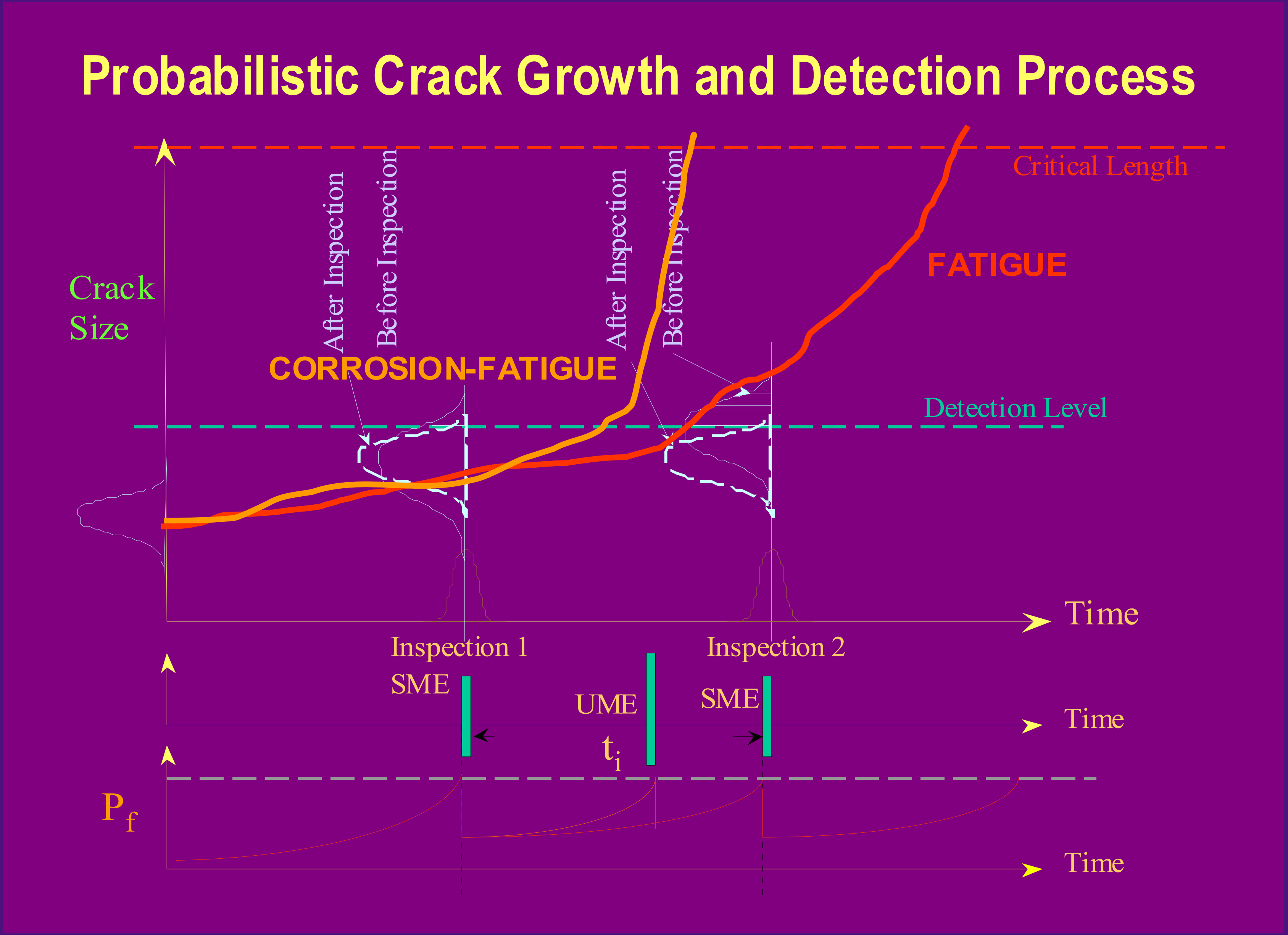
Presentation Content:

1. Reliability Analysis for Aging Structures
2. Corrosion-Fatigue Damage Modeling
3. Stochastic Multi-Scale FE Analysis
4. Aircraft Lapjoint Example
5. Concluding Remarks

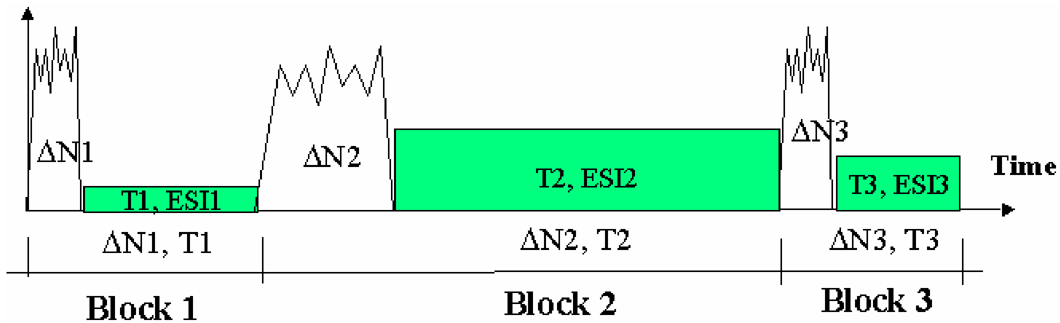
1. Reliability Analysis for Aging Components

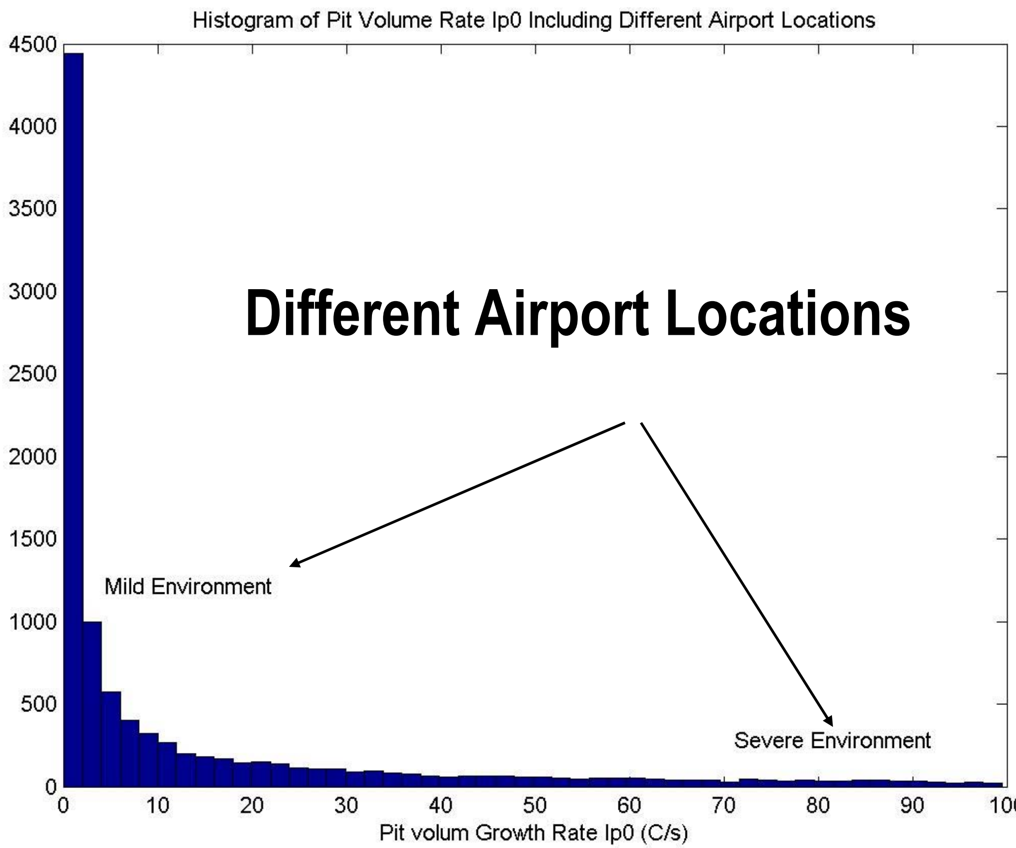


Risk-Based Maintenance Analysis Concept



Stochastic Aircraft Operating Environment

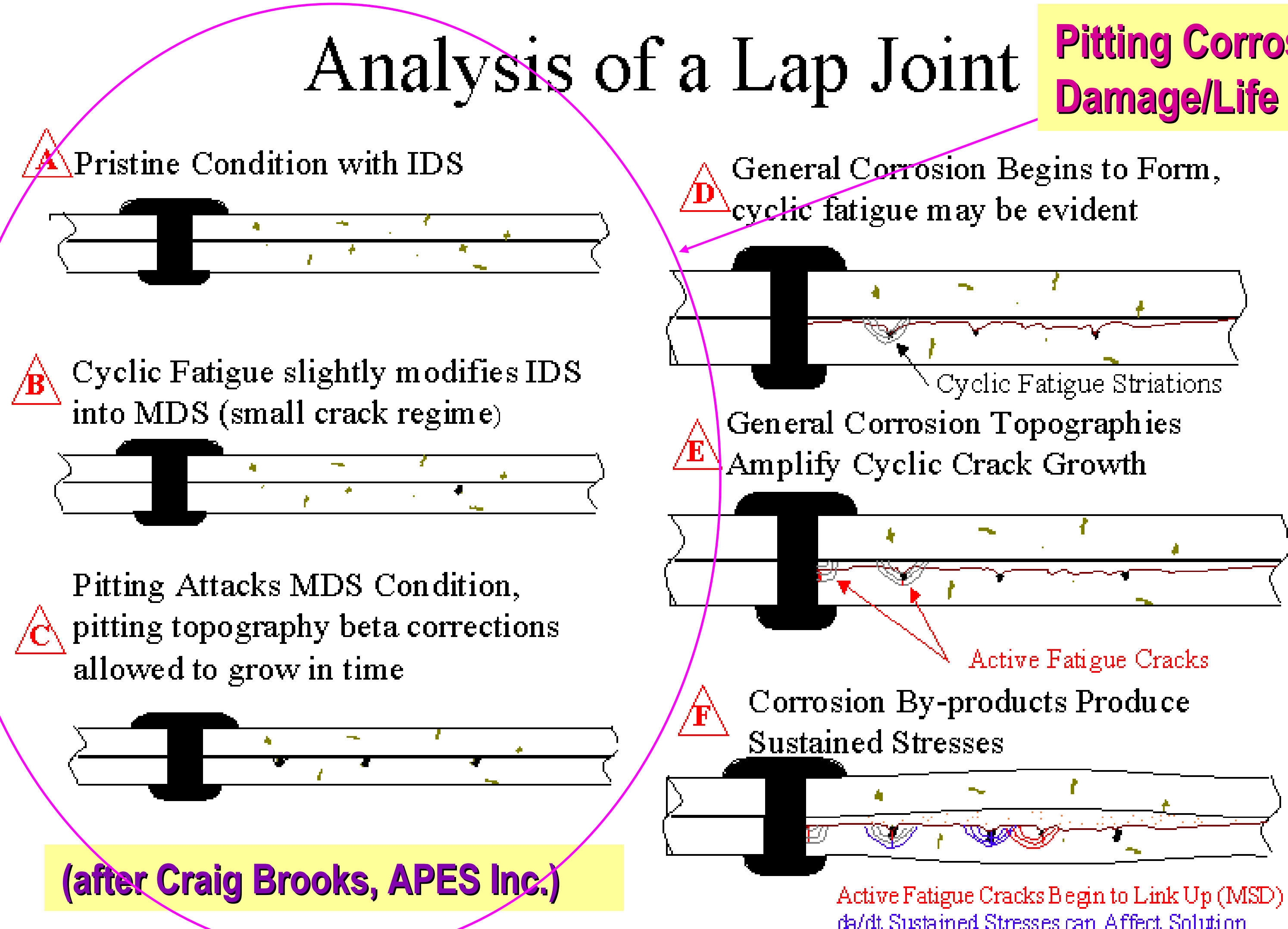




2. Corrosion-Fatigue Damage Modeling

Six Aging Stages (A-F)

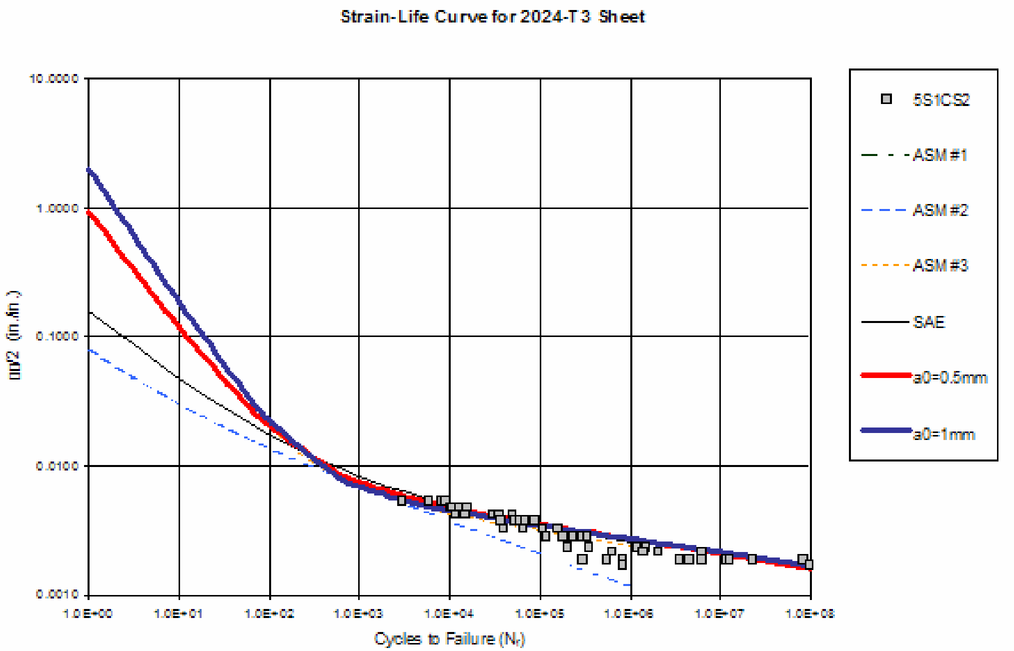
Pitting Corrosion-Fatigue Damage/Life Models



(after Craig Brooks, APES Inc.)

Model 1: Simultaneous CF Model (SCF)

Crack Initiation



Strain-Life Curve:

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f'}{E}(2N_f)^b + \varepsilon_f'(2N_f)^c$$

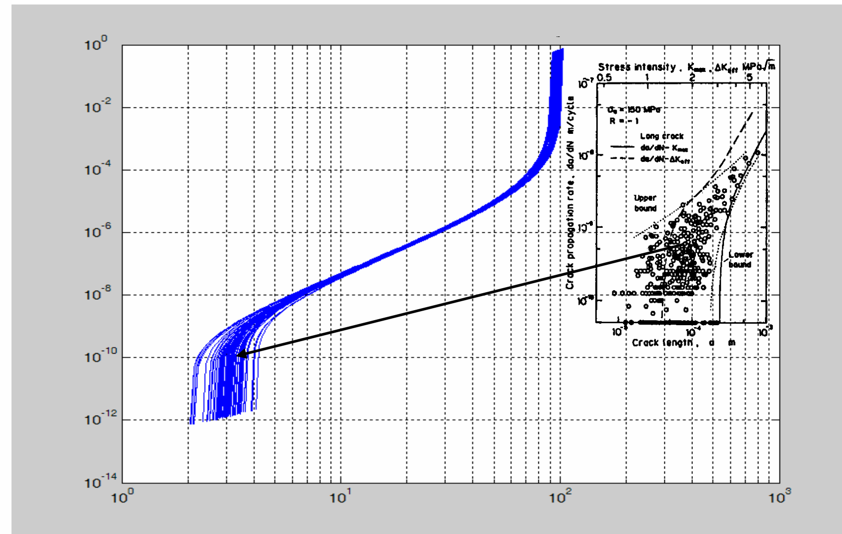
Ramberg-Osgood Curve:

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2K'}\right)^{1/n'}$$

Uncertain Parameters

$$a(t) = IDS + [\sum_{n,t} a(n)^{\alpha} + p(t)^{\beta}]^{\gamma}$$

Crack Propagation



Forman FCG Model (NASA JPL, 1996)

$$\frac{da}{dN} = \frac{C(1-R)^m \Delta K^n (\Delta K - \Delta K_{th})^p}{[(1-R)K_C - \Delta K]^q}$$

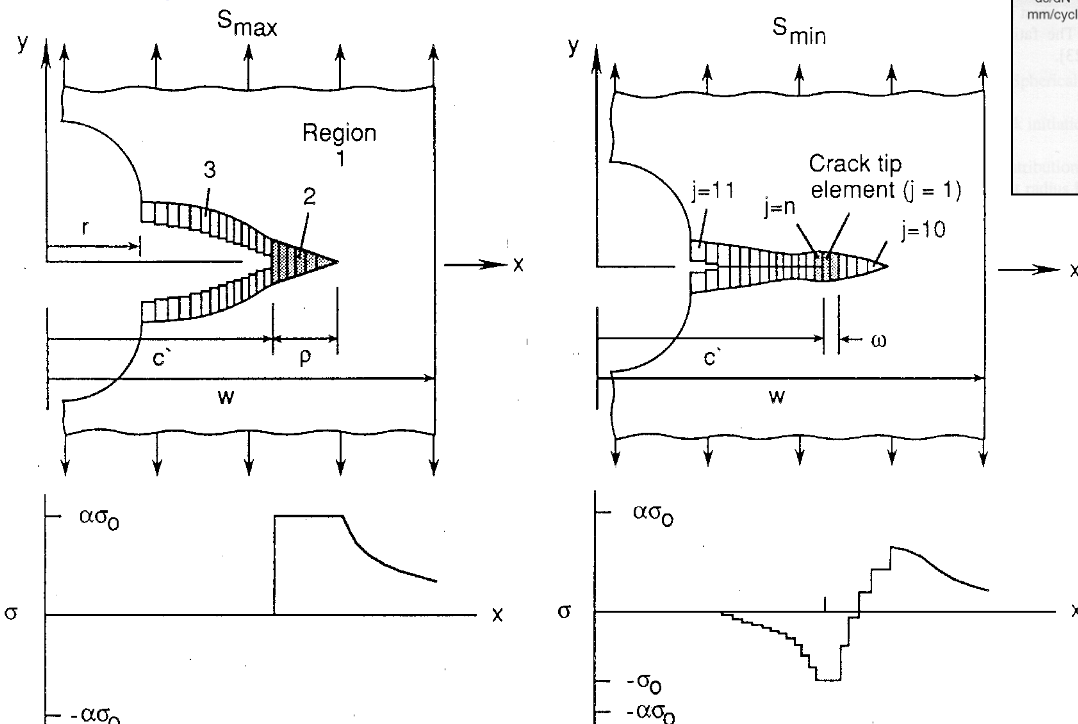
$$\Delta K_{CF} = \psi(t)\Delta K_F$$

$$\psi(t) = \sqrt{1 + \frac{p(t)}{a(n)}}$$

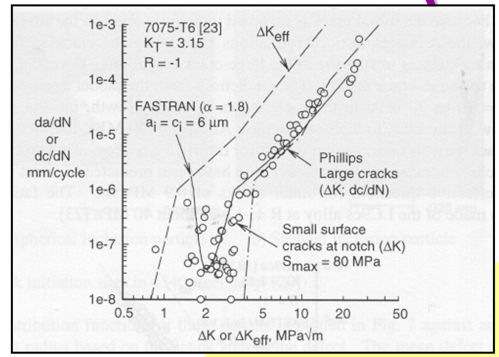
Uncertain Parameters

Model 1: FASTRAN-CF Model for CF (CCCF)

Fatigue Model



(a) Maximum stress. (b) Minimum stress.



$$\frac{dc}{dN} = C_1 \Delta K_{eff}^{C_2} \frac{1 - \left(\frac{\Delta K_0}{\Delta K_{eff}}\right)^2}{1 - \left(\frac{K_{max}}{C_5}\right)^2}$$

where

$$\Delta K_0 = C_3 \left(1 - C_4 \frac{S_0}{S_{max}}\right)$$

$$K_{max} = S_{max} \sqrt{\pi c}\ F$$

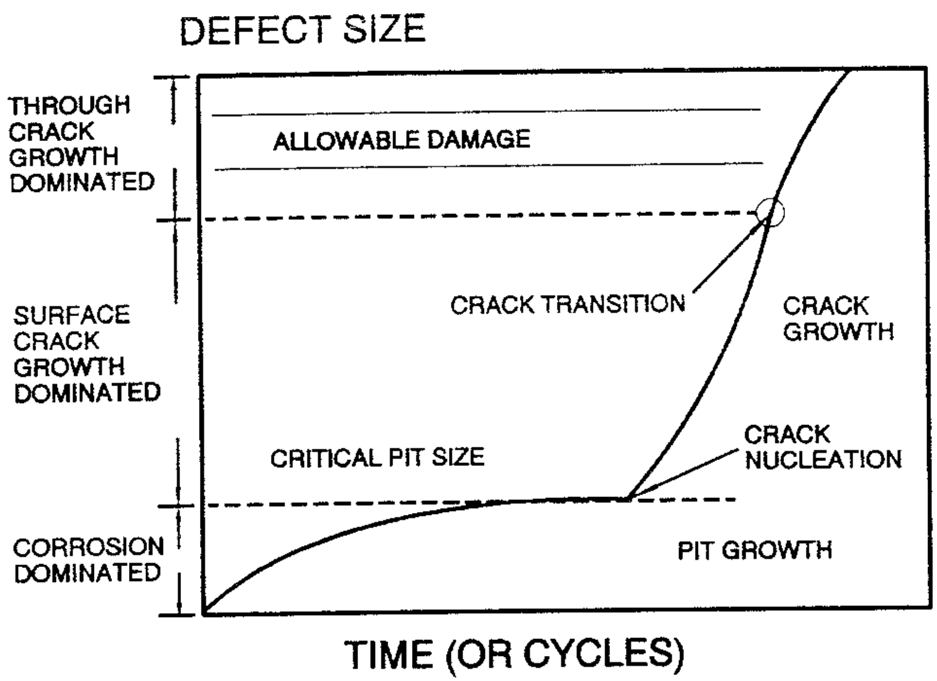
$$\Delta K_{eff} = (S_{max} - S_0)\sqrt{\pi c}\ F$$

Pitting Corrosion-Fatigue Model (FASTRAN-CF)

$$\Delta K'_{eff} = \psi(t)\Delta K_{eff}$$

$$\psi(t) = \sqrt{1 + \frac{a_{pit}(t)}{c_{crack}(t)}} \longleftarrow \textbf{FASTRAN-CF}$$

Model 2: Wei Corrosion-Fatigue Model (WCF)



Pit Growth

$$a = \left\{ \left[\frac{3MI_{p0}}{2\pi nF\rho} \exp\left(-\frac{\Delta H}{RT} \right) \right] t + a_0^3 \right\}^{1/3}$$

Corrosion-Fatigue Life Model

$$t_f = t_{ci} + t_{tc} + t_{cg}$$

$$t_{ci} = \frac{2\pi nF\rho}{3MI_{P0}} (a_{ci}^3 - a_0^3) \exp\left(\frac{\Delta H}{RT} \right)$$

$$t_{tc} = \frac{2\left(\sqrt{\pi}\right)^{n_C} \left[\left(\sqrt{a_{ci}}\right)^{2-n_C} - \left(\sqrt{a_{tc}}\right)^{2-n_C} \right]}{\nu (n_C - 2) C_C (2.2 K_t \Delta\sigma)^{n_C}}$$

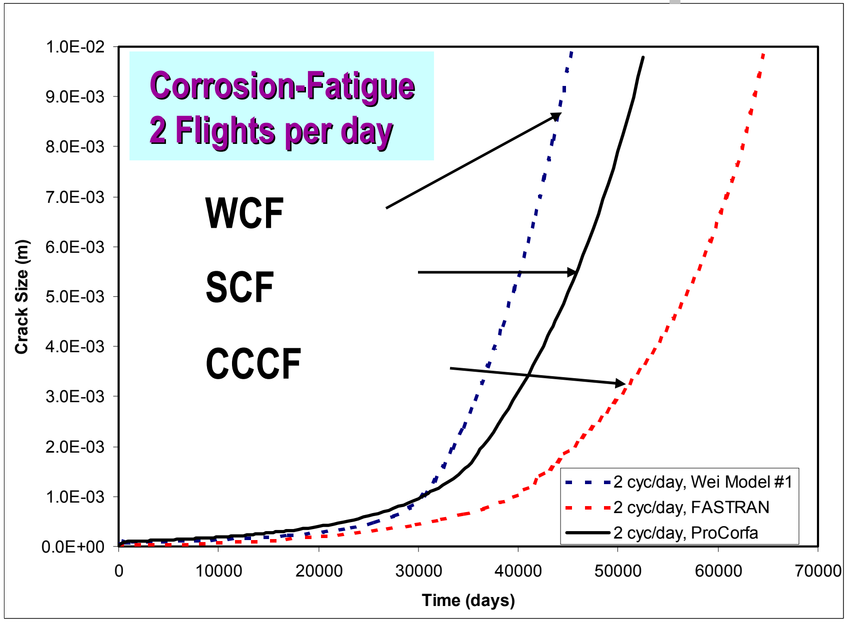
$$t_{cg} = \int_{a_{tc}}^{a_f} \frac{1}{\upsilon C_c \left(\Delta\sigma\sqrt{\pi}\right)^{n_C}} \left(\frac{0.324 r_0 + a}{1.086 r_0 \sqrt{a} + 0.681\left(\sqrt{a}\right)^3} \right)^{n_C} da$$

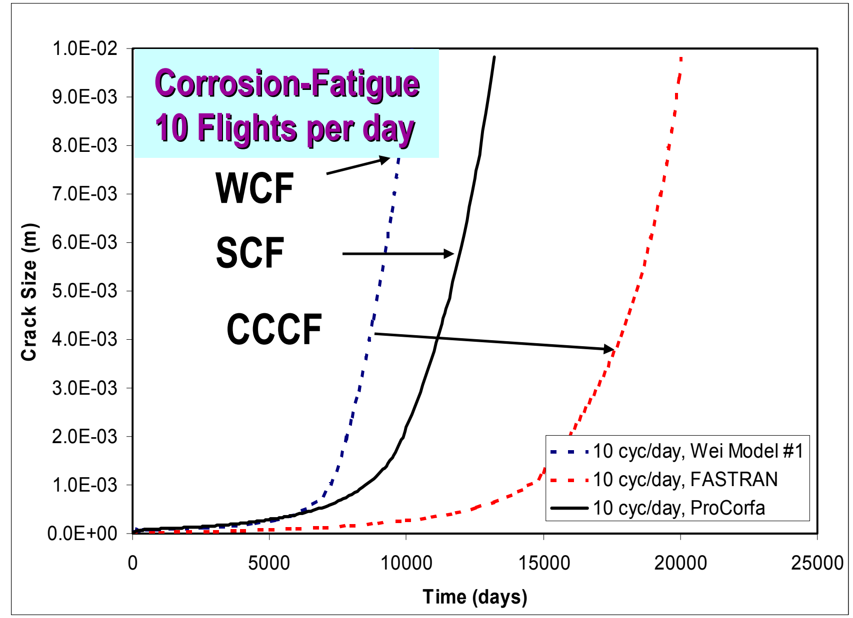
Fatigue Model

Paris's Law

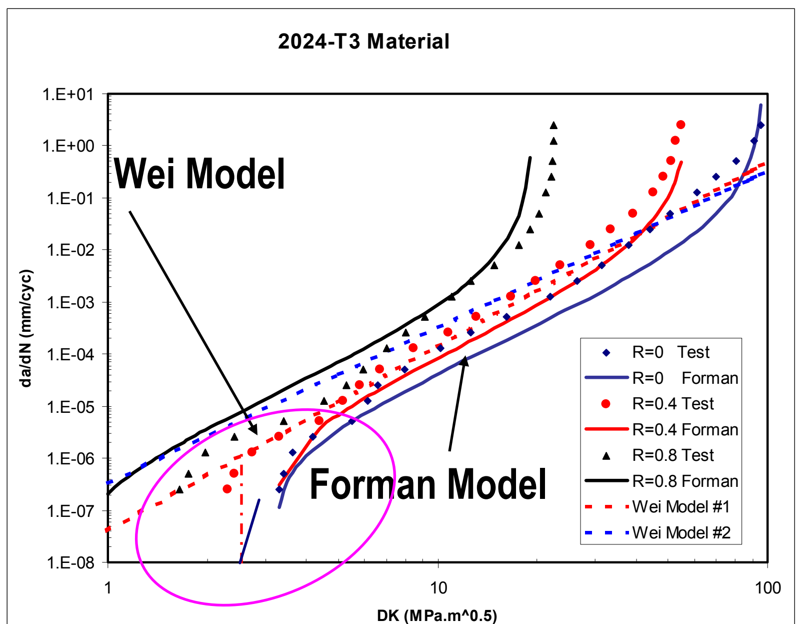
$$\left(\frac{da}{dN} \right)_C = C_C (\Delta K)^{n_C}$$

Comparative Results

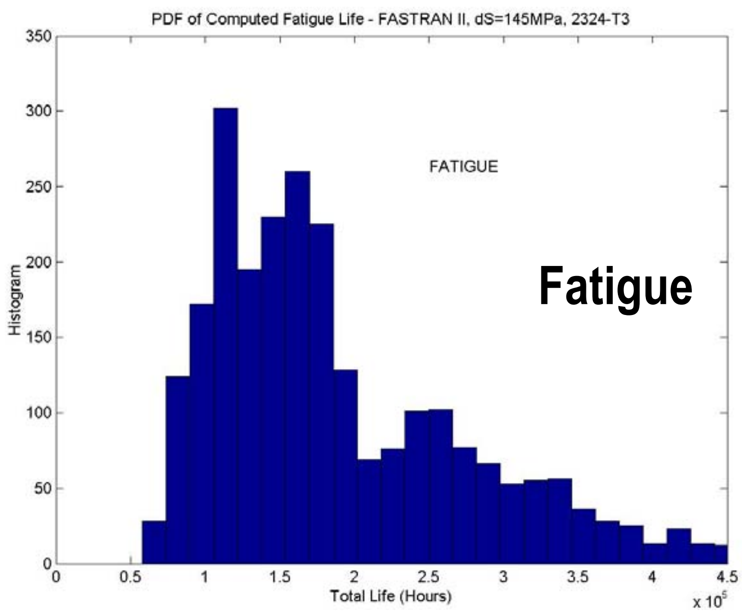


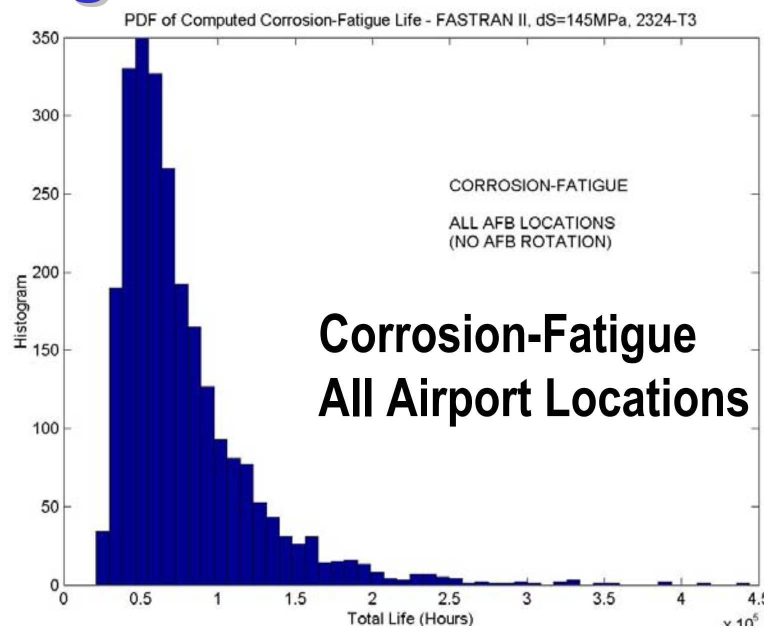


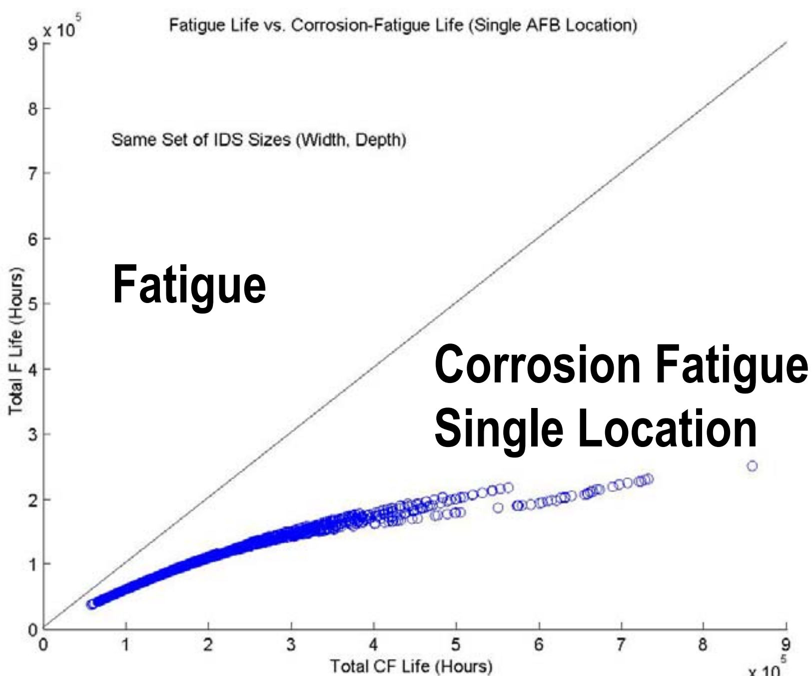
Comparative Results for SCF Model (ProCORFA) vs. CCCF Model (FASTRAN-CF) and WCF Model (Wei)

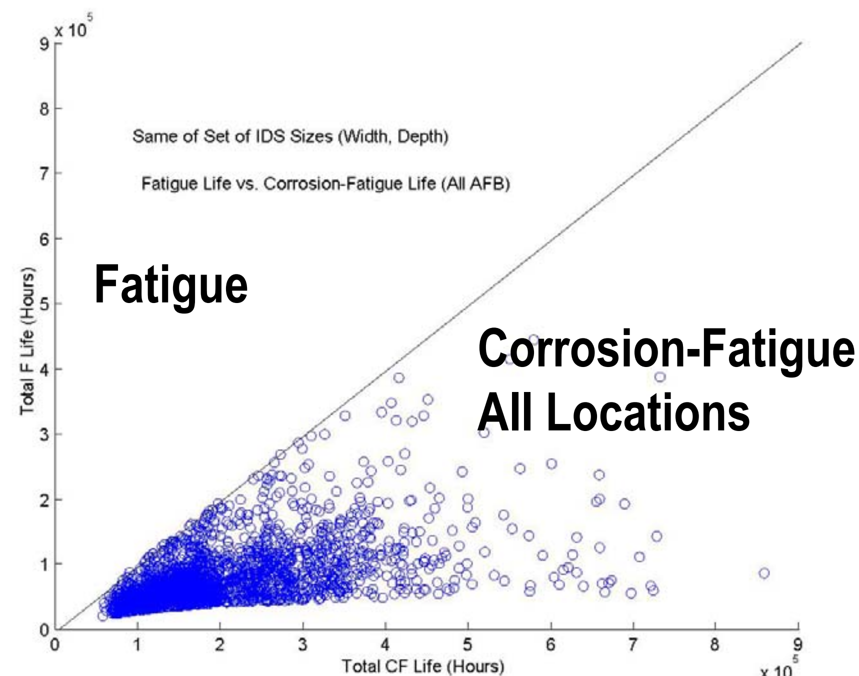


Stochastic Corrosion-Fatigue Life Simulation

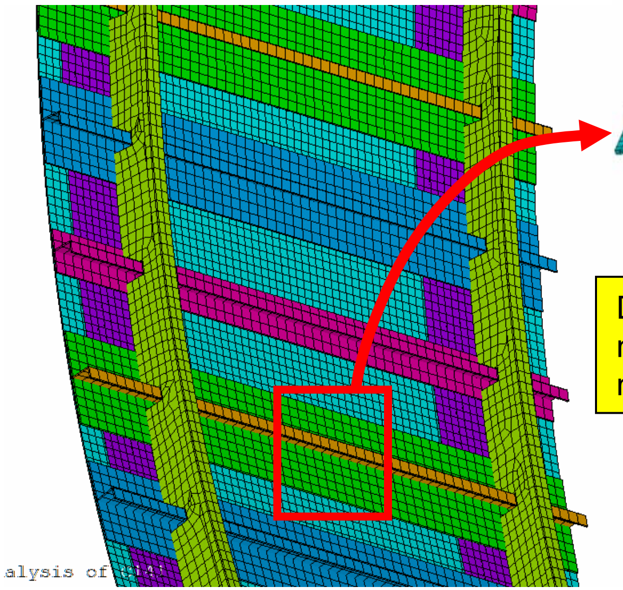


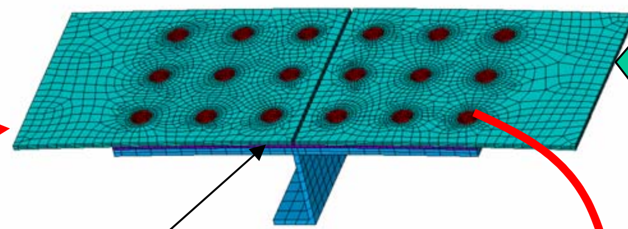






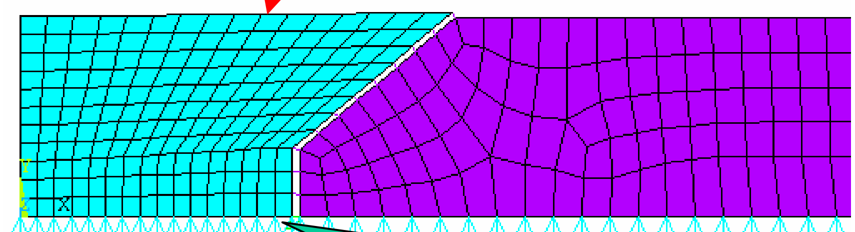
3. Stochastic Multi-Scale FE Analysis





Displacement constraints of boundary nodes are interpolated from global model using sub-modeling technique

Local Model:
- Solid elements
- Includes contacts
- Obtain BCs from global model
- Consider stochastic parameters
- Detailed local stresses



Global Model:
- Shell and beam elements
- "Weld" stringers and frames with skin panel
- Linear analysis
- Find critical locations

Very Local Model:
- Axisymmetric elements
- Material and full contact nonlinearity
- Residual stress and interference analysis

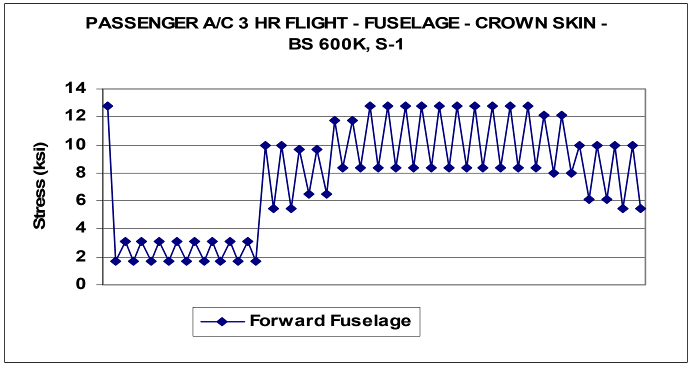
Stochastic Modeling for Aircraft Lap Joint

Define Stochastic Variables

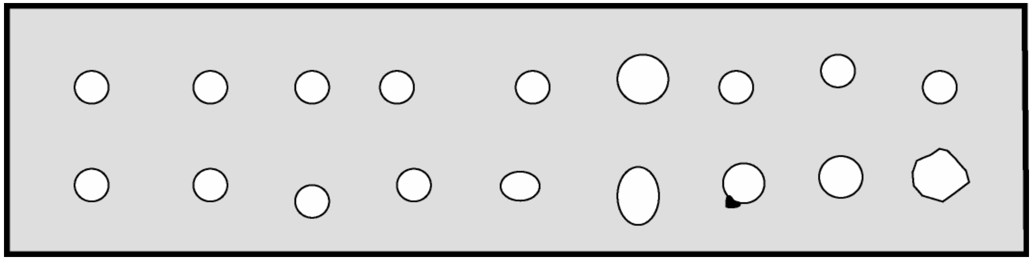
- Loading/Cabin Pressure Cycles
- Manufacturing Tolerances
- Material (Elastic modulus, etc.)
- Corrosion Material Loss

Governing Stochastic Variables

- Rivet interference
- Skin panel thickness
- Rivet hole location
- Rivet hole diameters
- Corrosion Loss



Loading spectrum



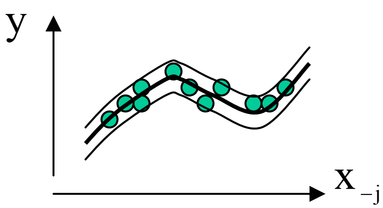
Manufacturing tolerances

Remarks: *We consider up to 55 random variables within a single stochastic FEA. However, only a limited number of variables, say 5-6, are of significance at different critical locations*

Stochastic Response Surface Approximations

Second-Order (SO) Approximation of Stochastic Fields

Explicit Formulation: Using function approximation via nonlinear regression



$$\boxed{y|\mathbf{x} = r(\mathbf{x}) + \varepsilon(\mathbf{x})}$$

--- Least-square fitting (y is explicit)

Limited

$$E[y|\mathbf{x}] = r(\mathbf{x})$$

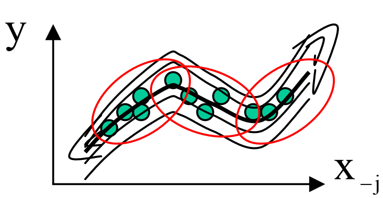
Defined by stochastic vector or field

Convergence: Minimizing Mean-Square Error (in Mean-Square sense)

Causal relationship. We used spatial Krigging.

High-Order (HO) Approximation of Stochastic Fields

Implicit Formulation: Using joint PDF estimation of $z = [y, \mathbf{x}]^T$



$$\boxed{f(y|\mathbf{x}) = \frac{f(y,\mathbf{x})}{f(\mathbf{x})} =}$$

--- Stochastic Neural Networks (y is implicit)

Decomposes overall complex JPDF in localized simple JPDFs.
Solution is obtained by stochastic interpolation

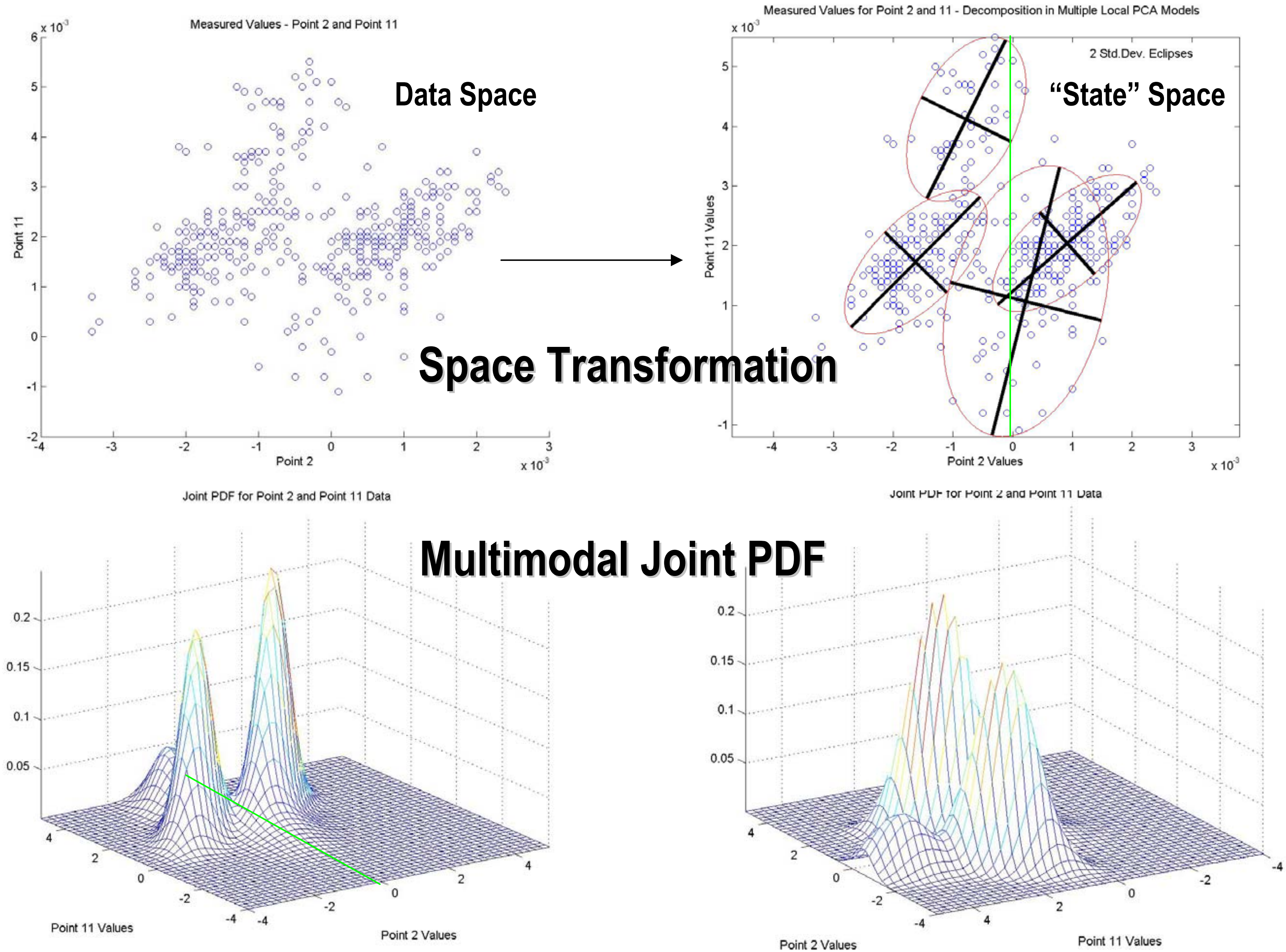
$$E[y|\mathbf{x}] = \int_{-\infty}^{\infty} y f(y|\mathbf{x}) dy$$

Refined

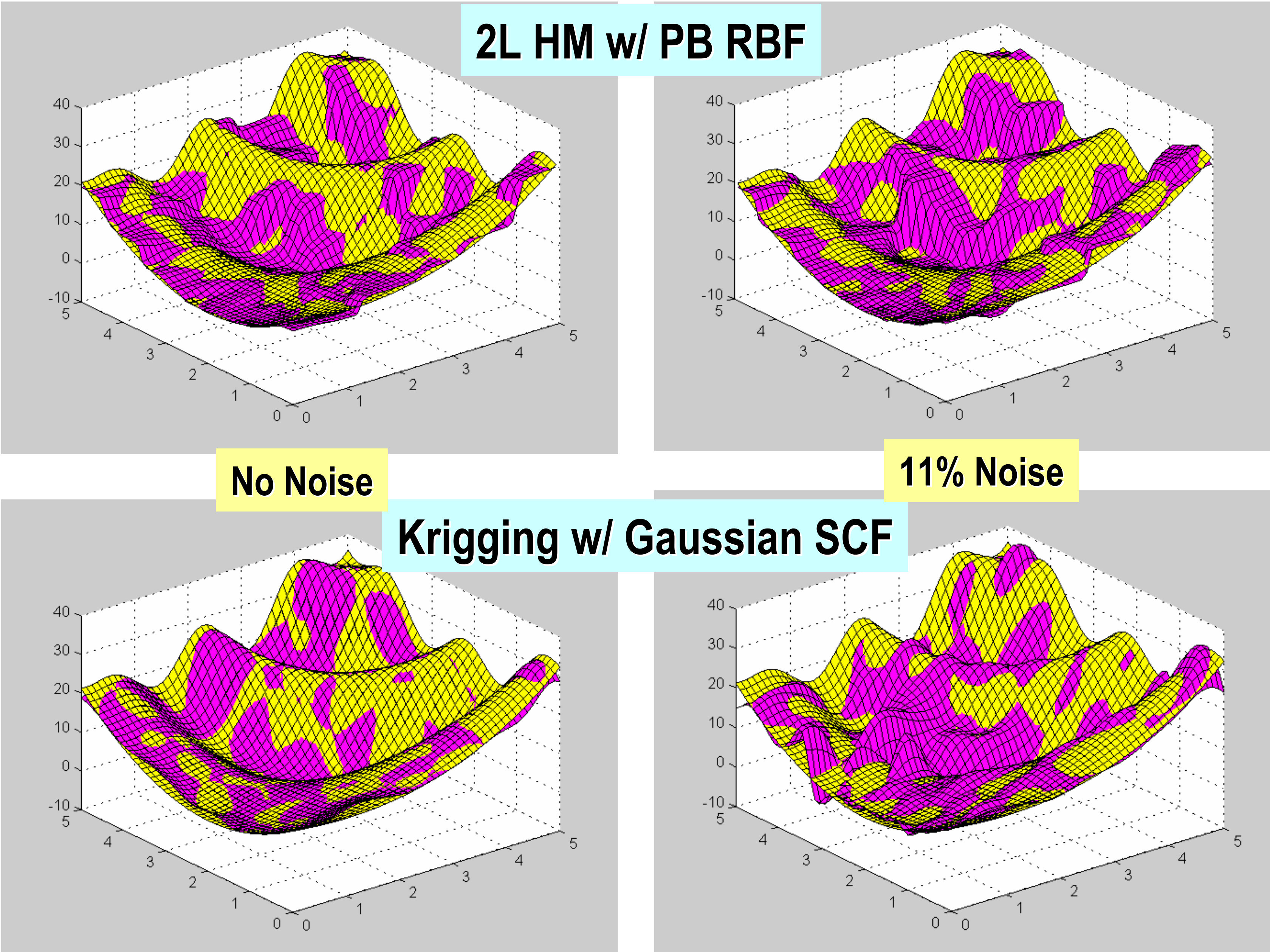
Convergence: Using Maximumum Likelihood Function (in Probability sense)

Non-causal relationship. We use 2-and 3-Level Hierarchical Models

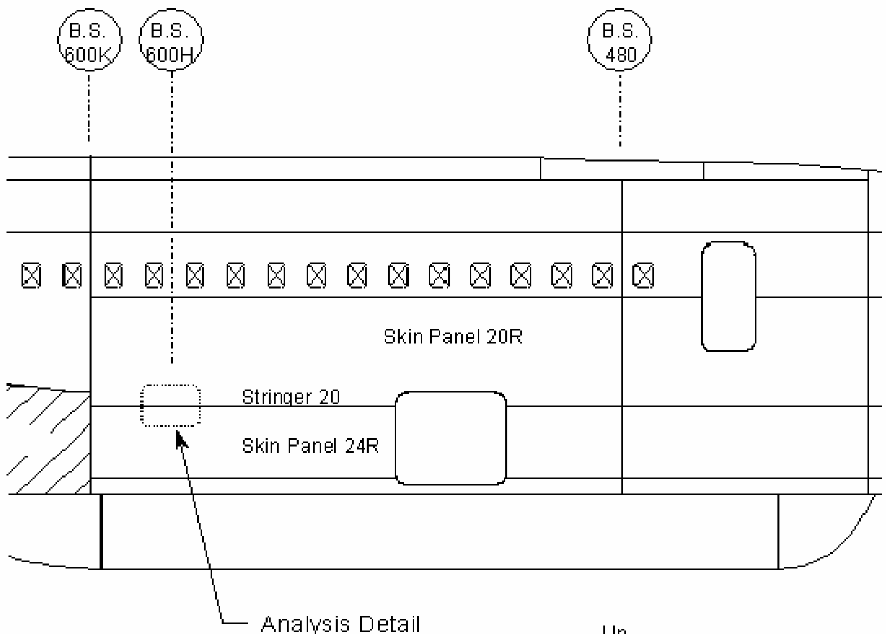
HO SF Models Applicable to Highly Non-Gaussian RS

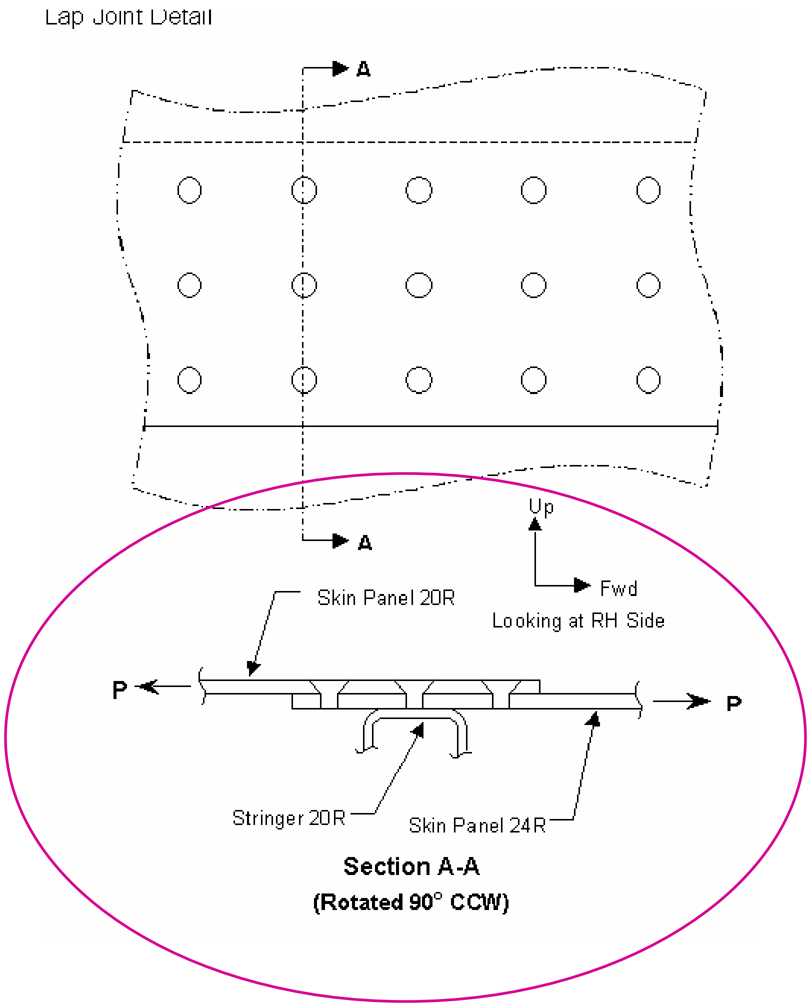


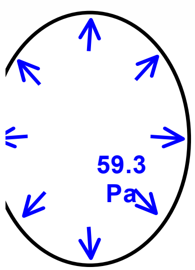
Two-Level Hierarchical Model Versus Krigging with 11% Noise



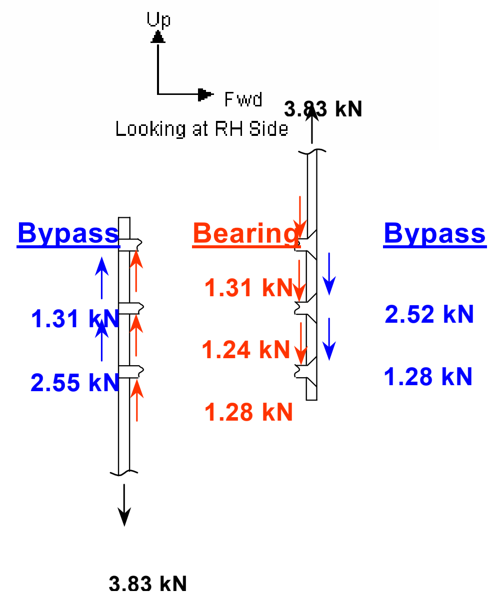
4. Aircraft Lapjoint Example







Pressurization
Inside Aircraft

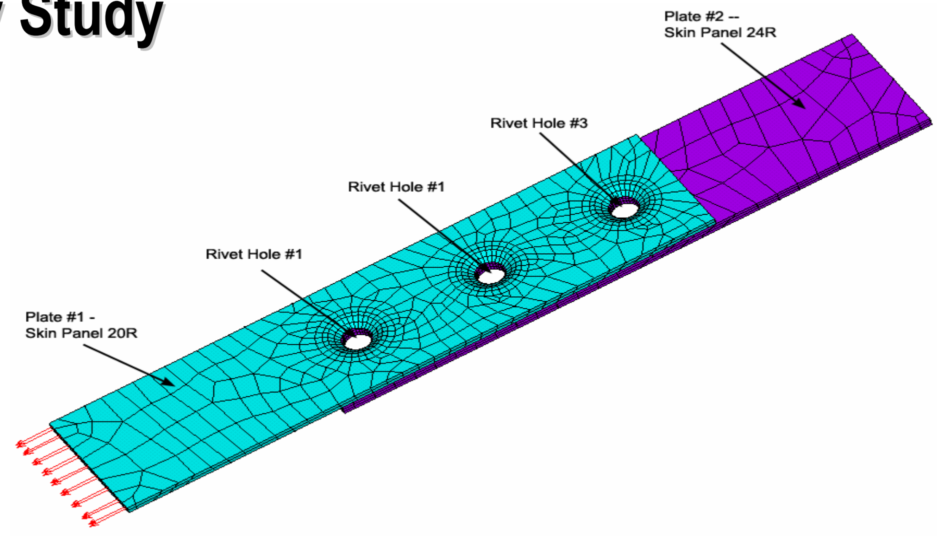


Load Transfer in the Lapjoint

Sensitivity Studies for Identifying Critical Stress Locations and Input Variables

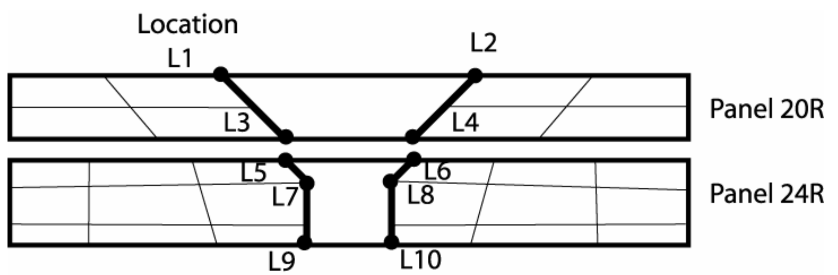
Random Variables used in Sensitivity Study

Elasticity modulus
Thickness change of the splices
Location shift of rivets
Diameters of rivet holes
Interferences at the rivet holes



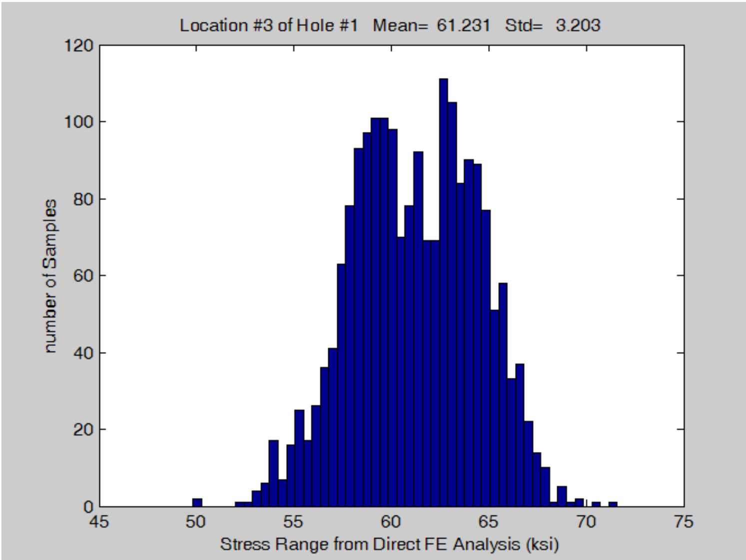
Governing Random Variables

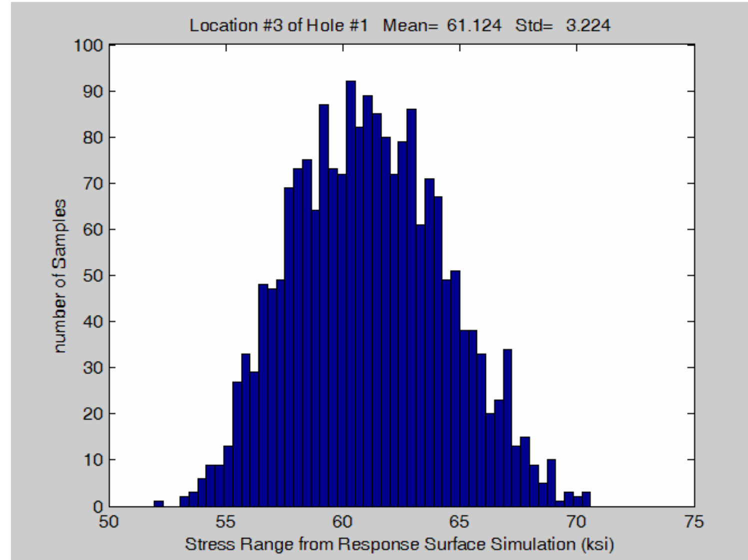
Thickness change of splices
Hole location shifts
Interference between the rivet and holes



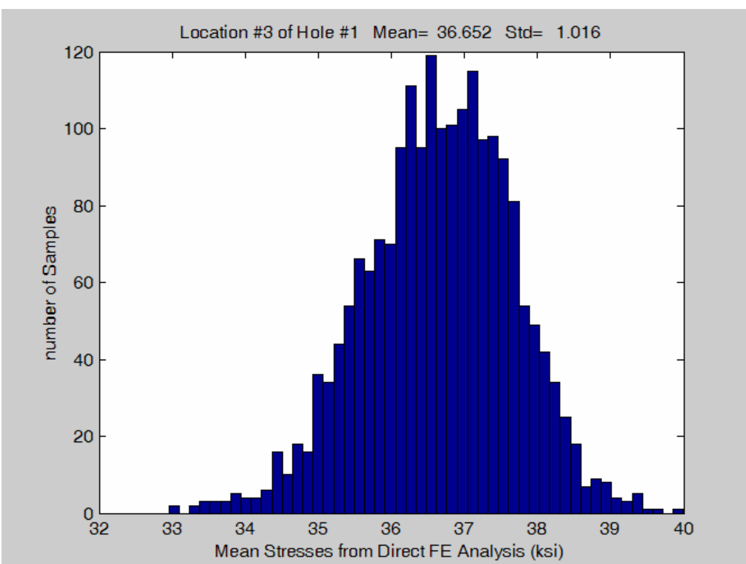
Comparison of FEA and Response Surface Results - Location 7 of Hole 3

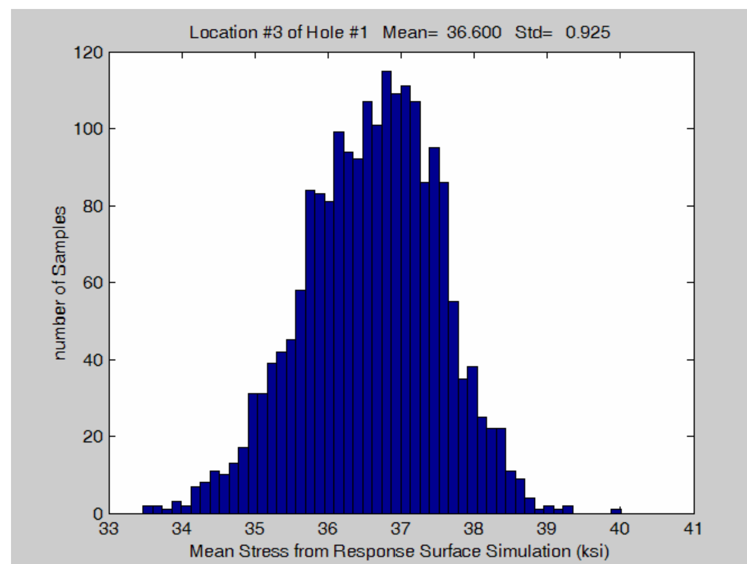
Stress Range





Mean Stress





Direct Stochastic FE Analysis

Response Surfaces

Stochastic Response Surface Sections in 2D

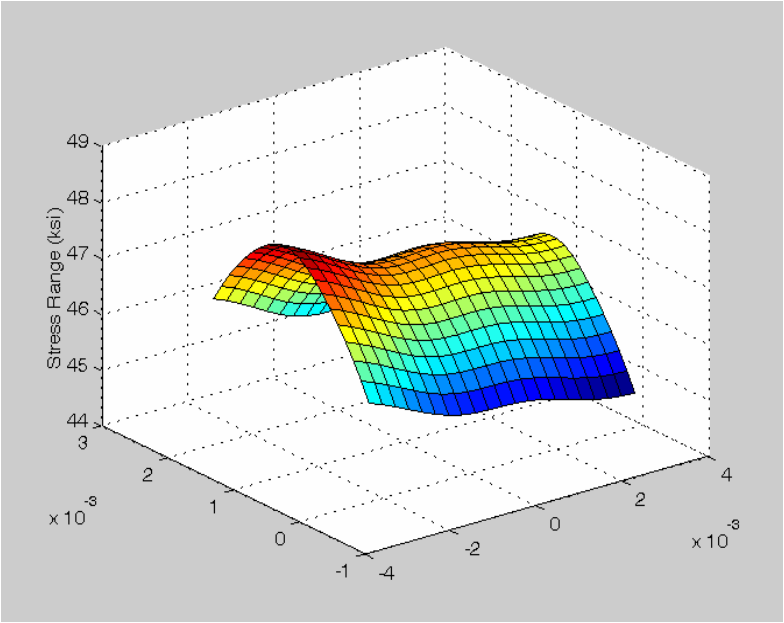
Response of L7 at Hole 3

Input Variables: Interference of Hole 1

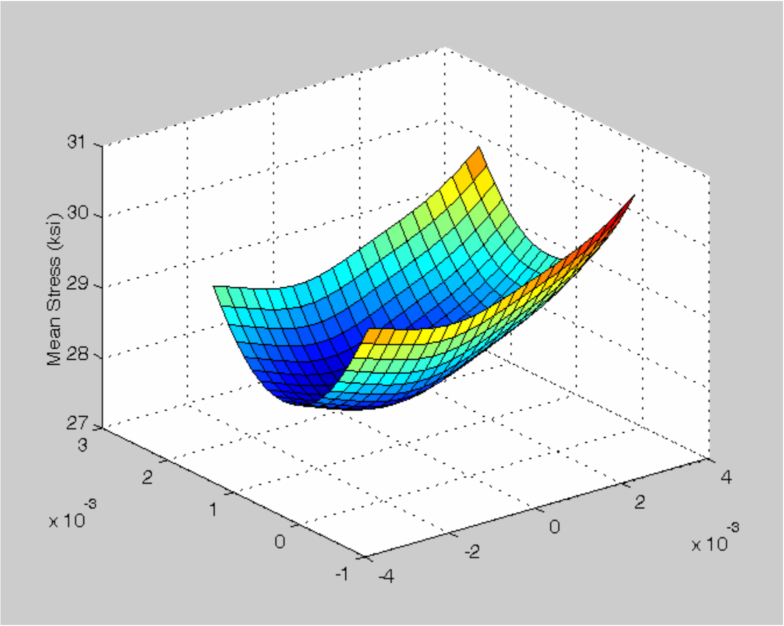
Thickness change of Plate #1

Fixed values for other variables

Remark: *Both variables show significant influences to the response surface*

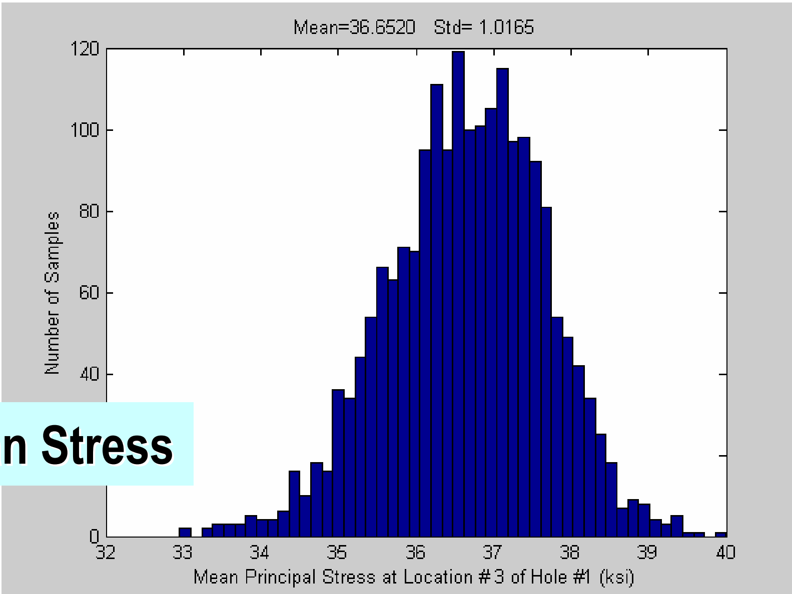


Stress Range at L7 of Hole 3

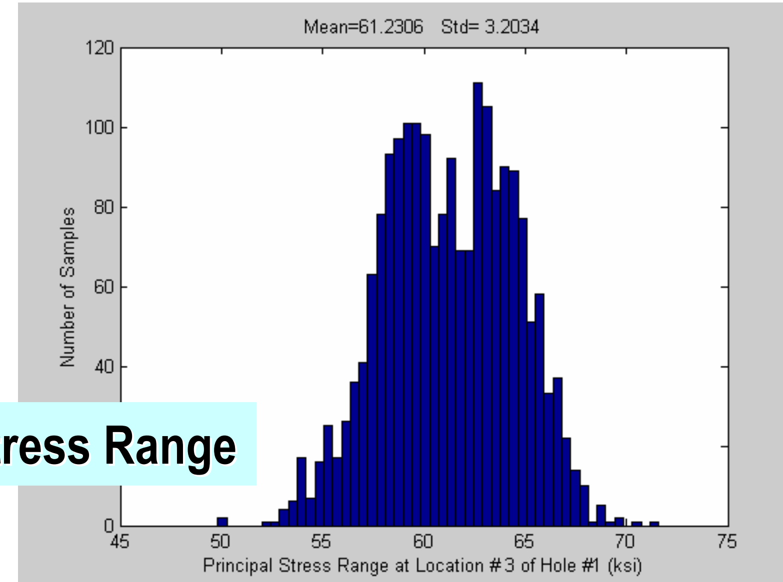


Mean Stress at L7 of Hole 3

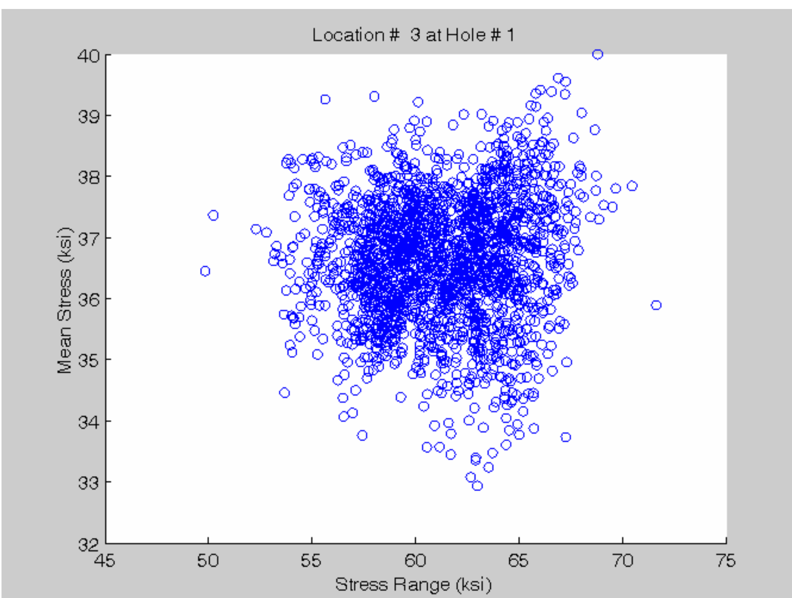
Bivariate Stress Distribution at L3 of Hole 1

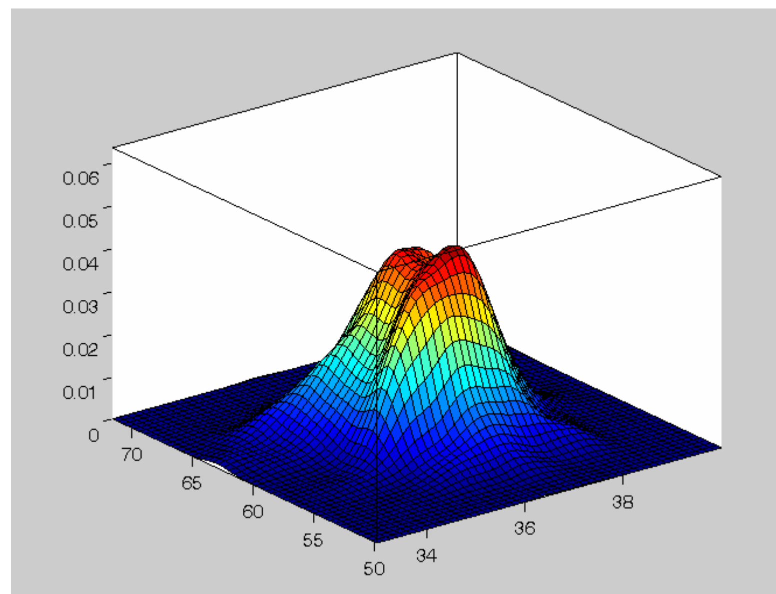


Mean Stress

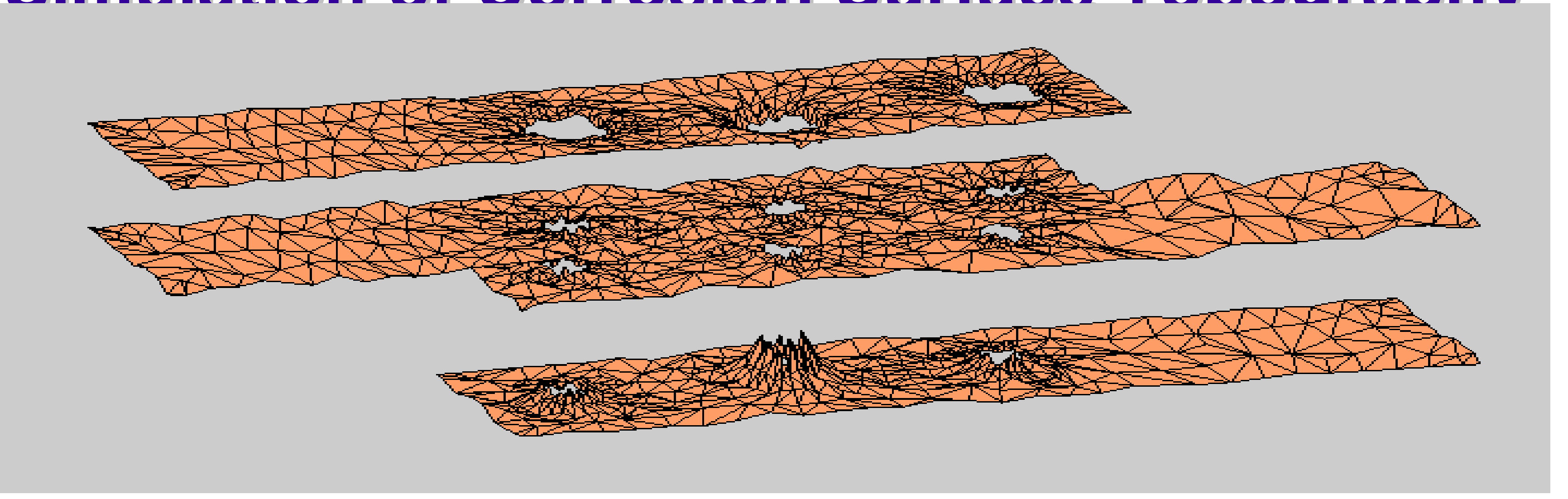


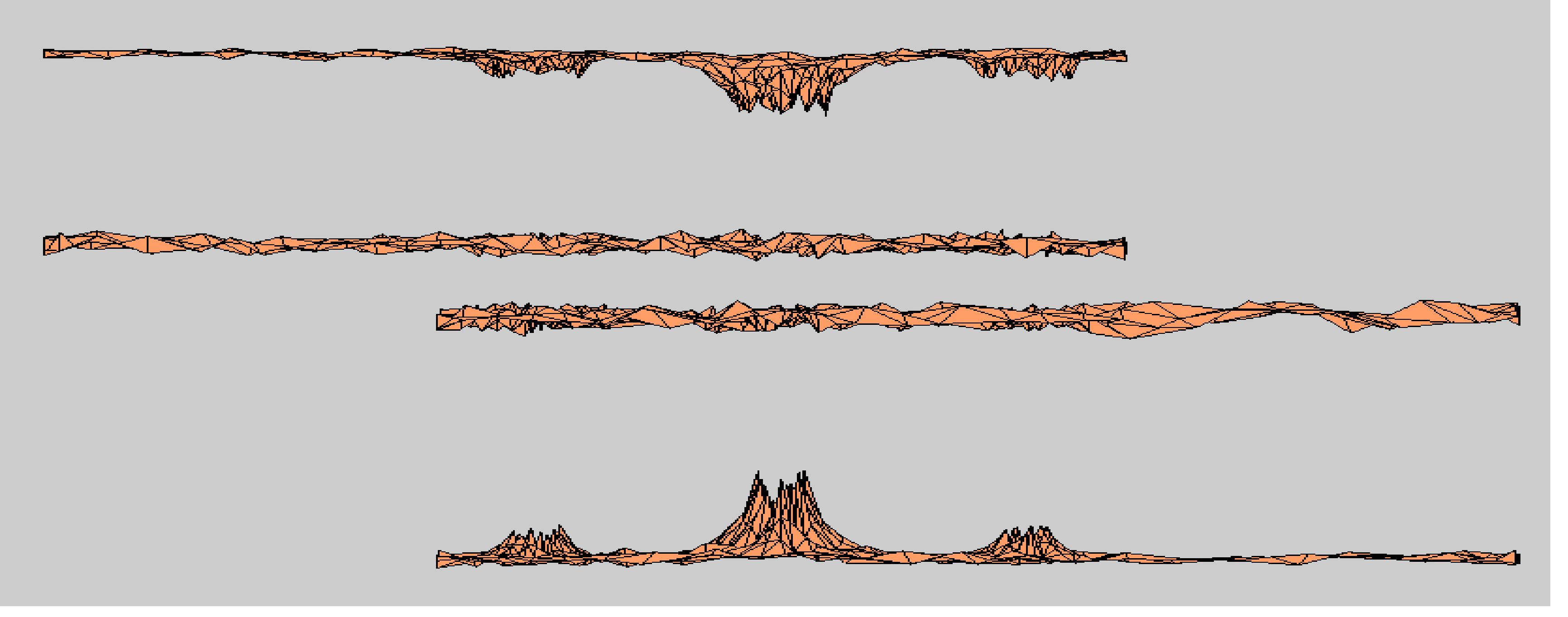
Stress Range



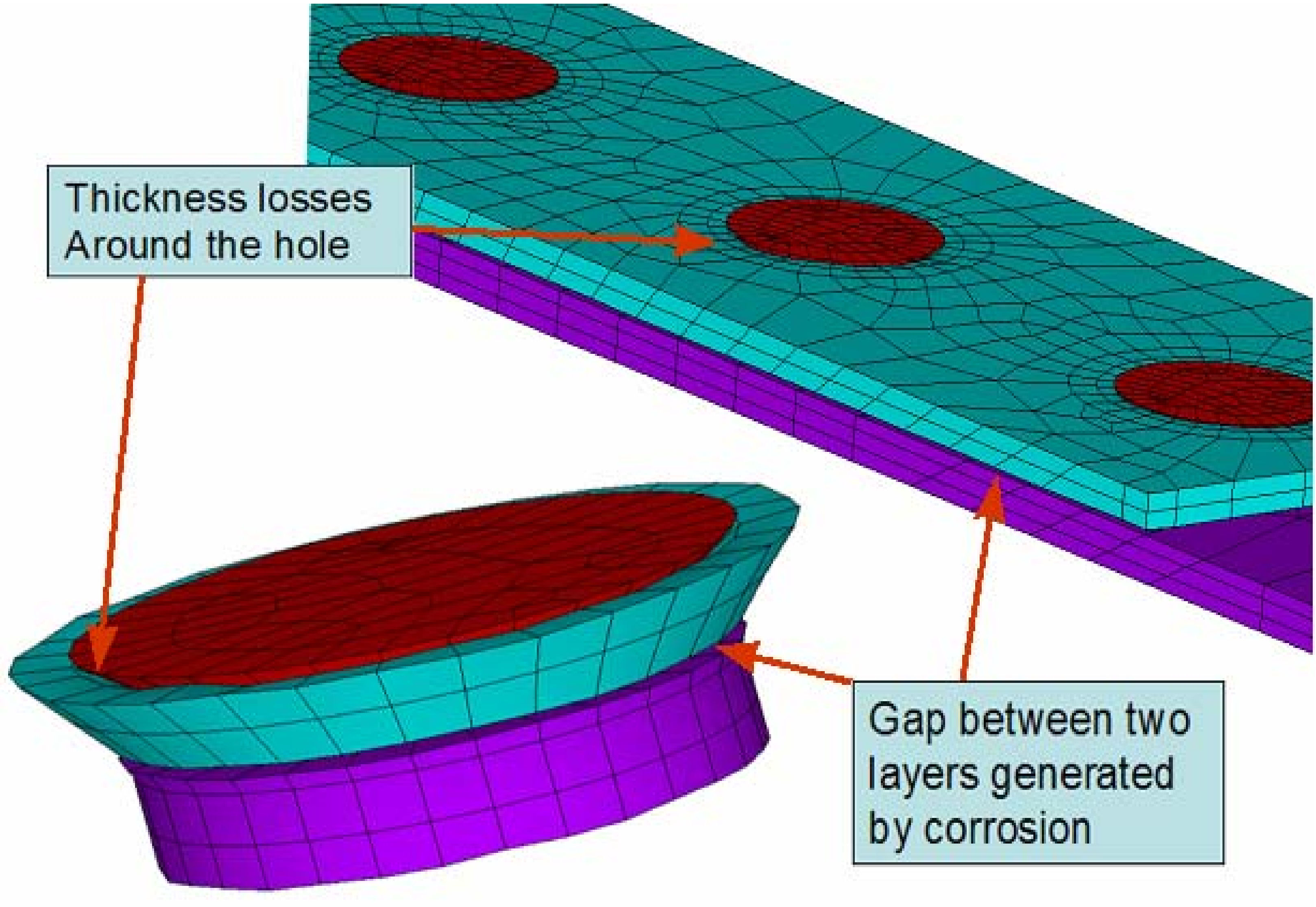


Simulation of Corrosion Surface Topography



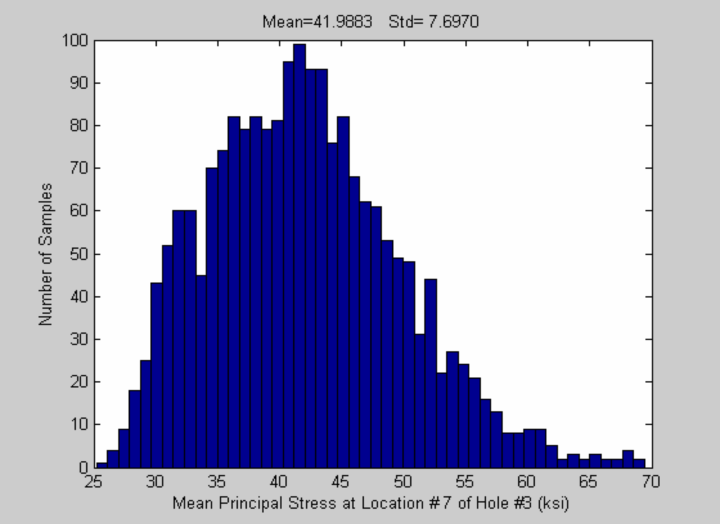


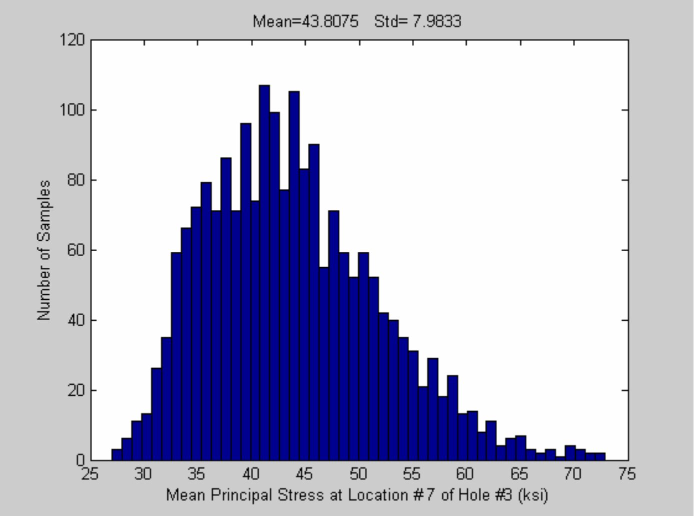
Simulation of FE Model with Material Loss Due to Corrosion (Details of Local Lap Joint Model)



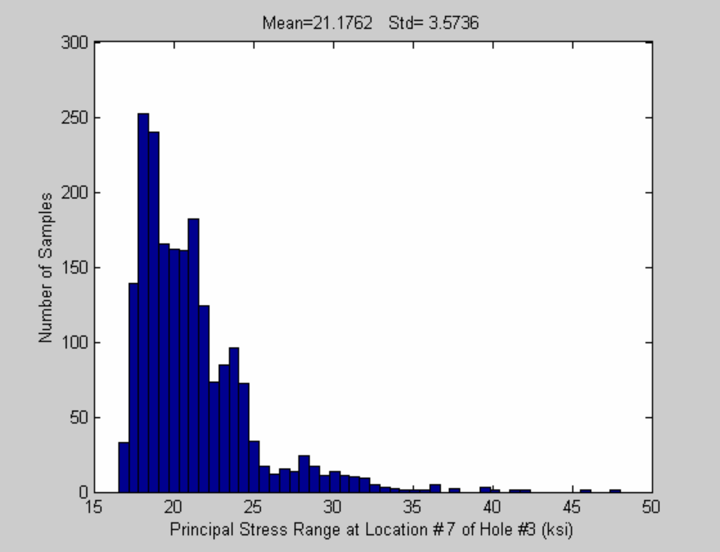
Histogram Comparisons for With and Without Material Loss Due to Corrosion (at L7 of Hole #3)

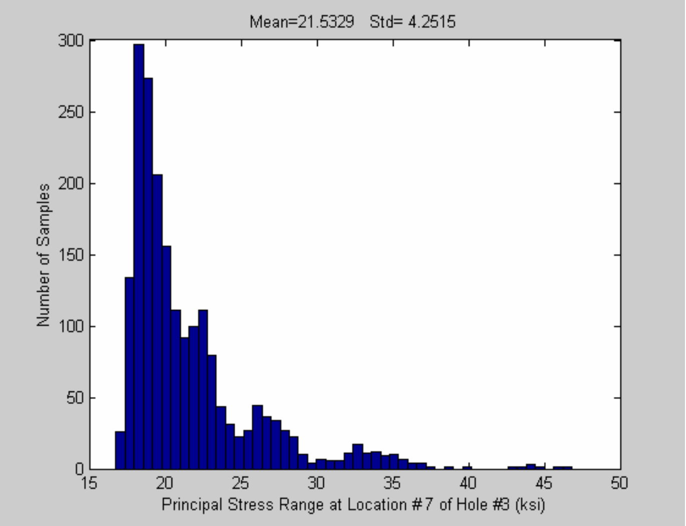
Mean Stresses





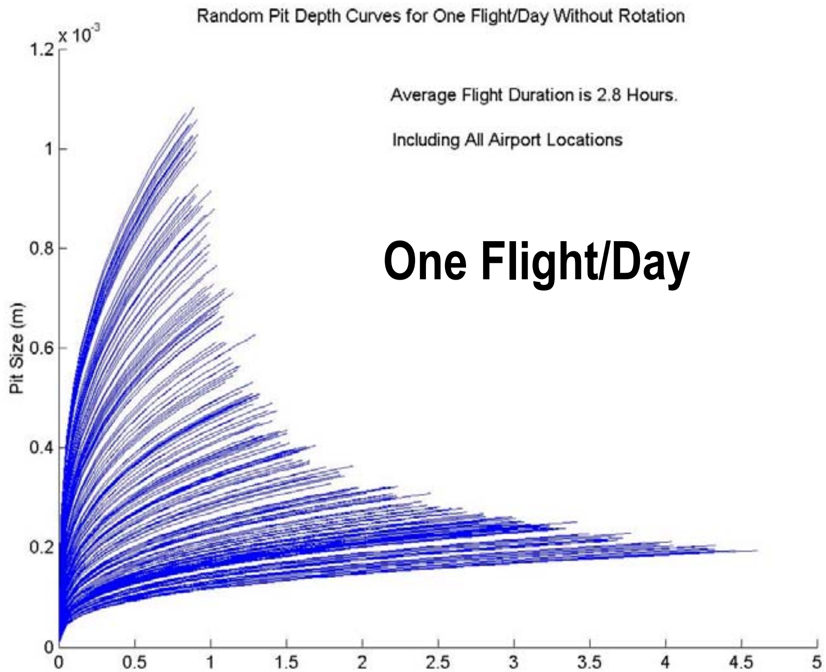
Stress ranges

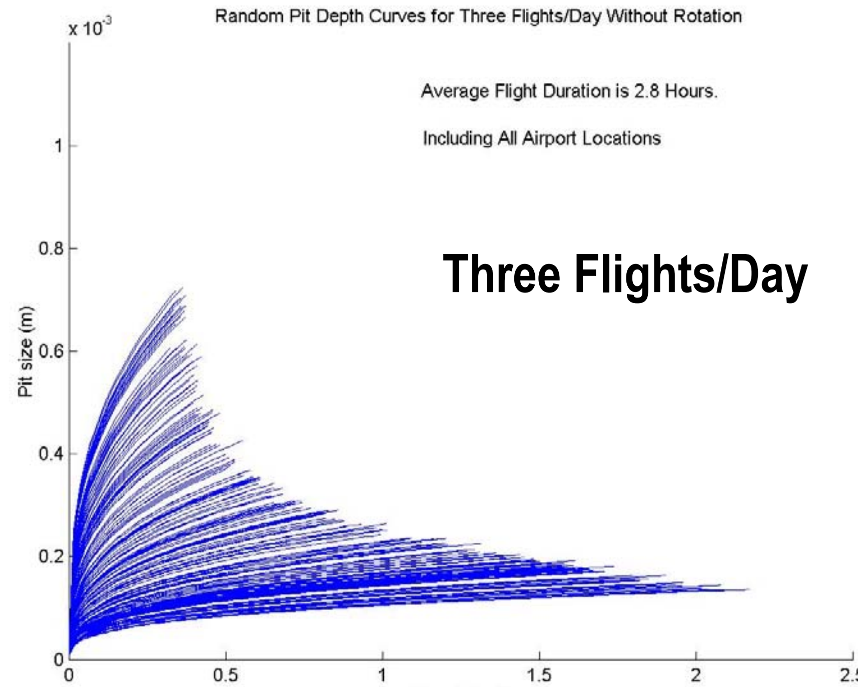


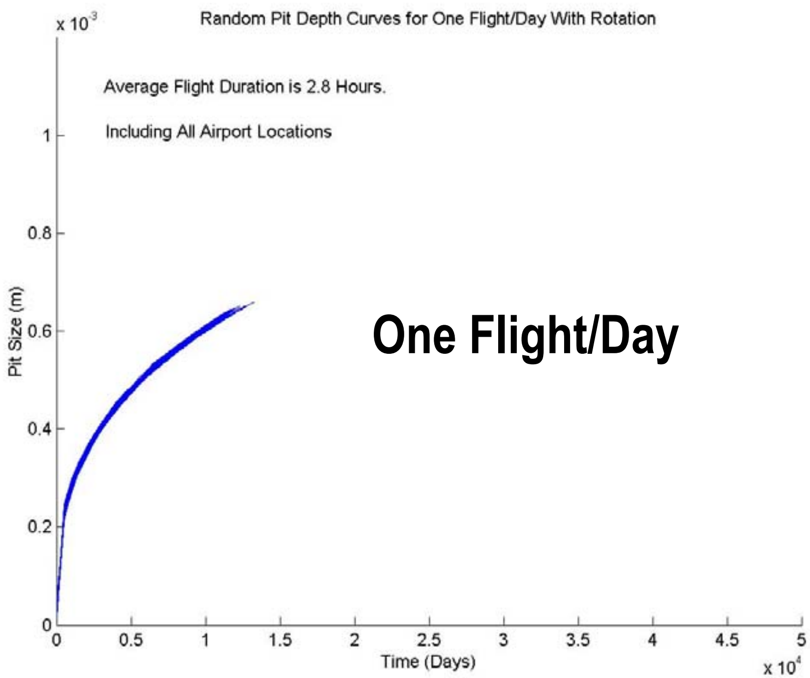


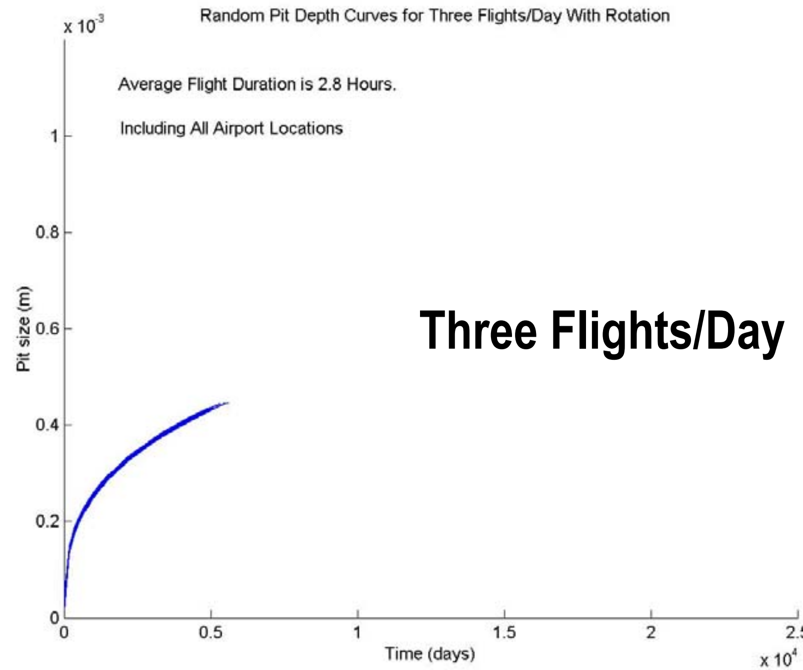
No Corrosion

With Corrosion


Random Pit Depth Curves for One Flight/Day Without Rotation
Average Flight Duration is 2.8 Hours.
Including All Airport Locations
One Flight/Day
Pit Size (m)
x 10^-3
0
0.2
0.4
0.6
0.8
1
1.2
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

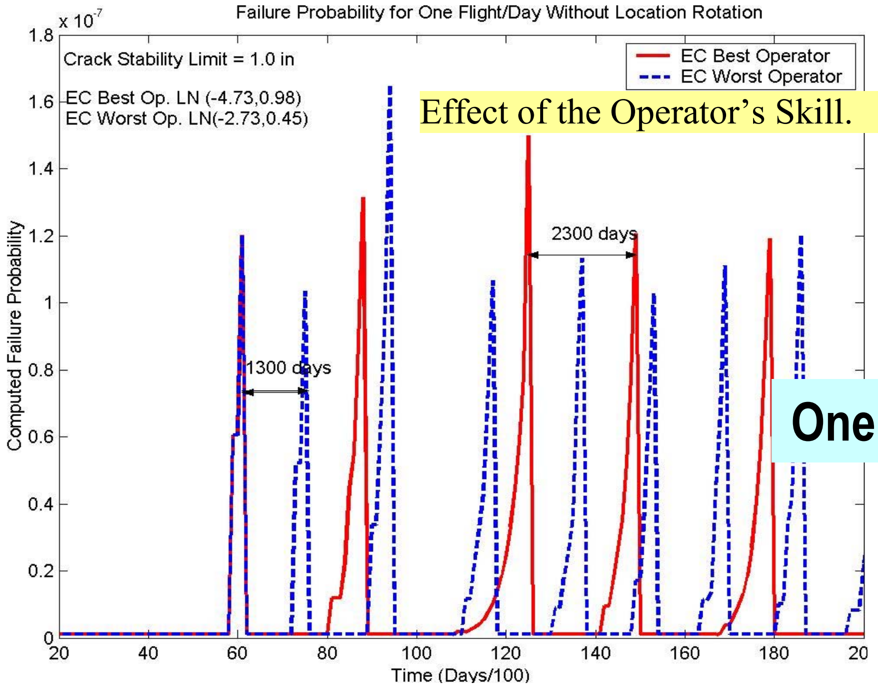

Random Pit Depth Curves for Three Flights/Day Without Rotation
Average Flight Duration is 2.8 Hours.
Including All Airport Locations
Three Flights/Day
Pit size (m)
x 10^-3
0
0.2
0.4
0.6
0.8
1
0
0.5
1
1.5
2
2.5

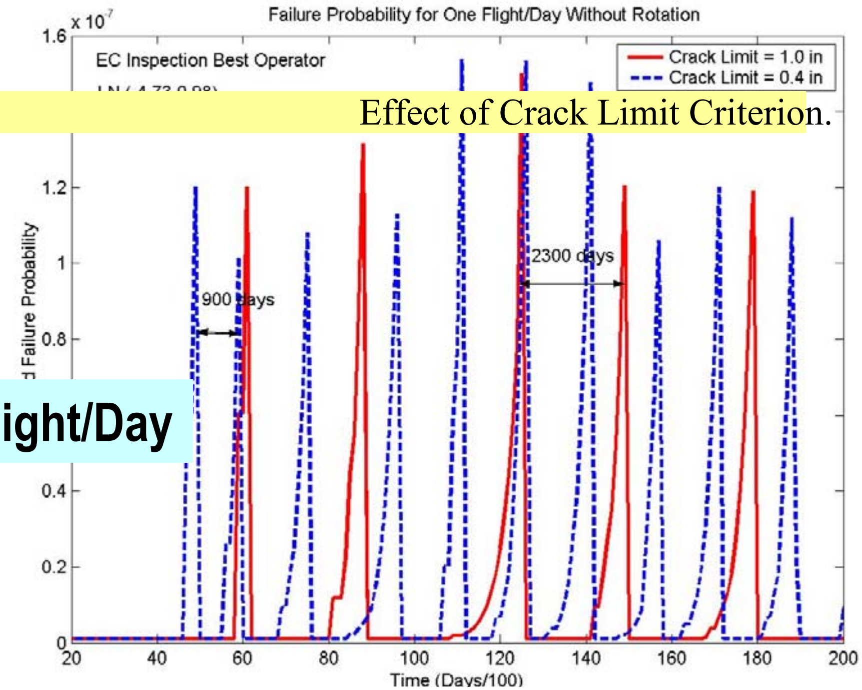

Random Pit Depth Curves for One Flight/Day With Rotation
Average Flight Duration is 2.8 Hours.
Including All Airport Locations
One Flight/Day
Pit Size (m)
x 10^-3
0
0.2
0.4
0.6
0.8
1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (Days)
x 10^4


Random Pit Depth Curves for Three Flights/Day With Rotation
Average Flight Duration is 2.8 Hours.
Including All Airport Locations
Three Flights/Day
Pit size (m)
x 10^-3
0
0.2
0.4
0.6
0.8
1
0
0.5
1
1.5
2
2.5
Time (days)
x 10^4

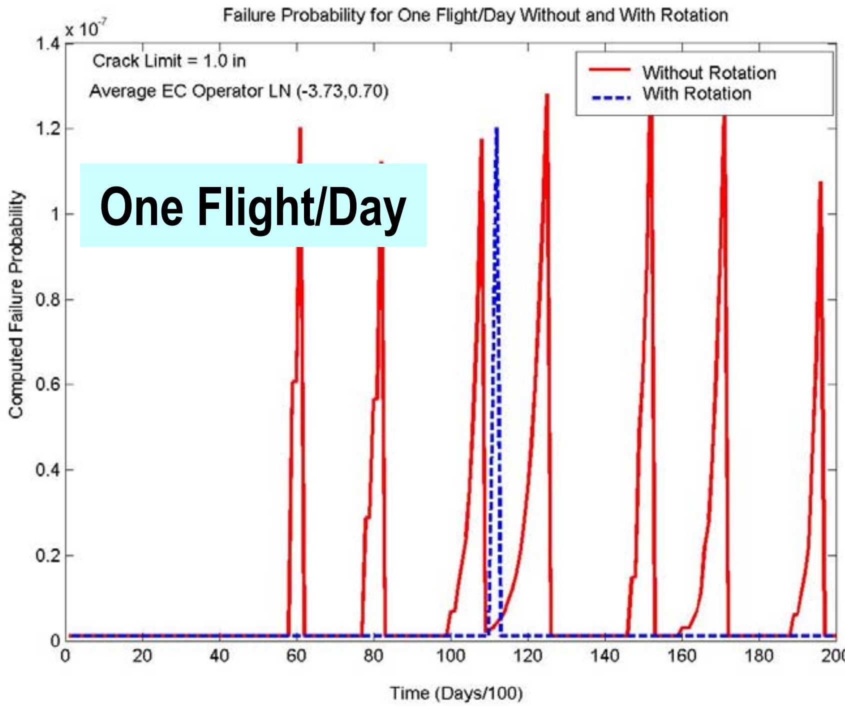
Effect of the Operator's Skill.

Effect of Crack Limit Criterion.

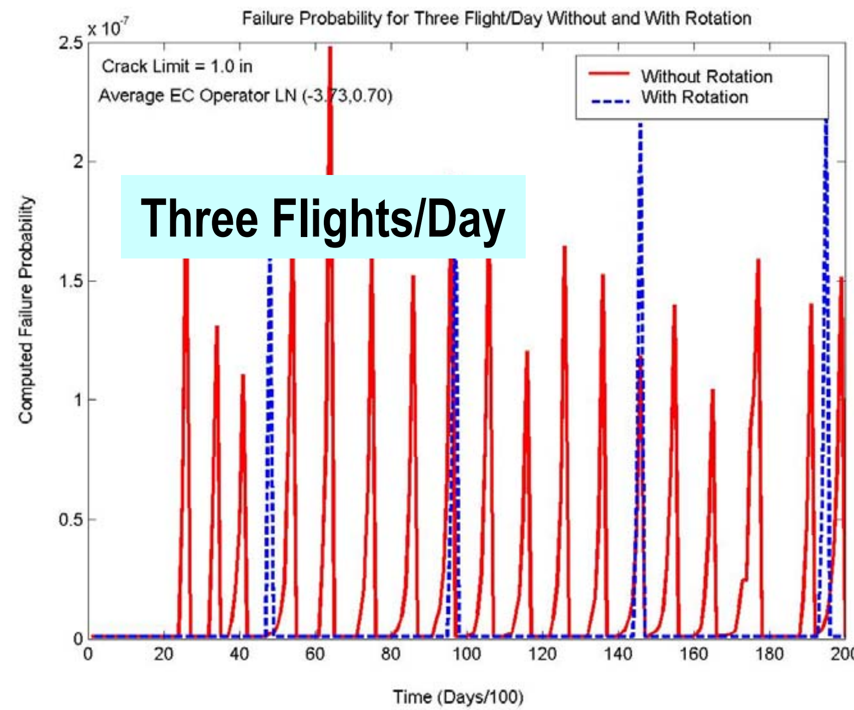




One Flight/Day



One Flight/Day



Three Flights/Day

5. Concluding Remarks

1. Computational reliability analysis for aging aircraft structures using physics-based stochastic corrosion-fatigue damage models provides a quantitative tool for reducing maintenance while maintaining the safety.

   Availability of statistical data and their collection and use based on an in-depth understanding of the physics and stochastic modeling of the problem represent critical aspects of probabilistic technology implementation (need of sharing the available data between the people with data and the people with physics and stochastic modeling expertise that are often in different business organizations… cross communication is key!).

2. Airport rotation is an important factor for lowering aircraft risks per fleet.
3. IDS sizes near surface, corrosion pit depths, airport environment severity, number of flights/day, FE modeling including manufacturing tolerances, and inspection quality appears to be the main critical factors for aircraft risk prediction.
4. Stochastic FEA accuracy has a significant impact on aircraft risk prediction. Neglecting structural uncertainties is highly unconservative.