B-1 Experience in Determining An Optimal Maintenance Schedule Using Risk Assessment Strategy

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2006 USAF ASIP Conference

November 28, 2006

Agenda

- Why risk assessment strategy?
- Key ingredients for the B-1 risk assessment strategy and tool
  - Risk analysis process
  - Input random variable distributions
  - Probabilistic analysis method
- Proposed analysis procedure to determine the optimal maintenance schedule
  - Demonstration examples: wing location 2, wing carry through 12 and wing carry through 61
- Summary

Why Risk Assessment Strategy?

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- Mil-Std-1530C task 5.5.6.3 (risk analysis updates) specifies three major reasons to update the risk analyses are to:
  - Evaluate detected and anticipated aircraft structural damage. The results shall be used in conjunction with IAT data described in 5.5.1 to establish the individual aircraft maintenance times.
  - Evaluate economic and/or availability impacts associated with maintenance options such as inspection and repair/replacement as needed versus modification.
  - Determine the structural integrity risk associated with operating the aircraft beyond the design service life.

The Goal Is to Determine An Optimal Maintenance Schedule Using Risk Assessment Strategy Given A 1.E-7 Requirement

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Key Ingredients for the B-1 Risk Assessment Strategy and Tool

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- Apply recognized risk analysis process – The PROF code
- Define a uncertainties modeling and updating process for selecting input distributions
  - Aircraft usage characterization: Loads and Environmental Spectra Survey (L/ESS) or Individual Aircraft Tracking (IAT) data
  - Crack growth and residual strength based on demonstrated usage and location of interest, material parameters, and stress intensity solution ($\alpha = K/\sigma$)
  - Inspection data: Crack size and usage hours at detection
- Select an advanced and robust probabilistic analysis method because:
  - Extremely small probability of single flight probability of failure
  - Percentage of detection and repair
  - Irregular-shaped distributions with large coefficient of variation
  - Table input of the crack growth curve and geometry data.

PROF Code Analysis Process Will Be Used by The Proposed Risk Assessment Strategy

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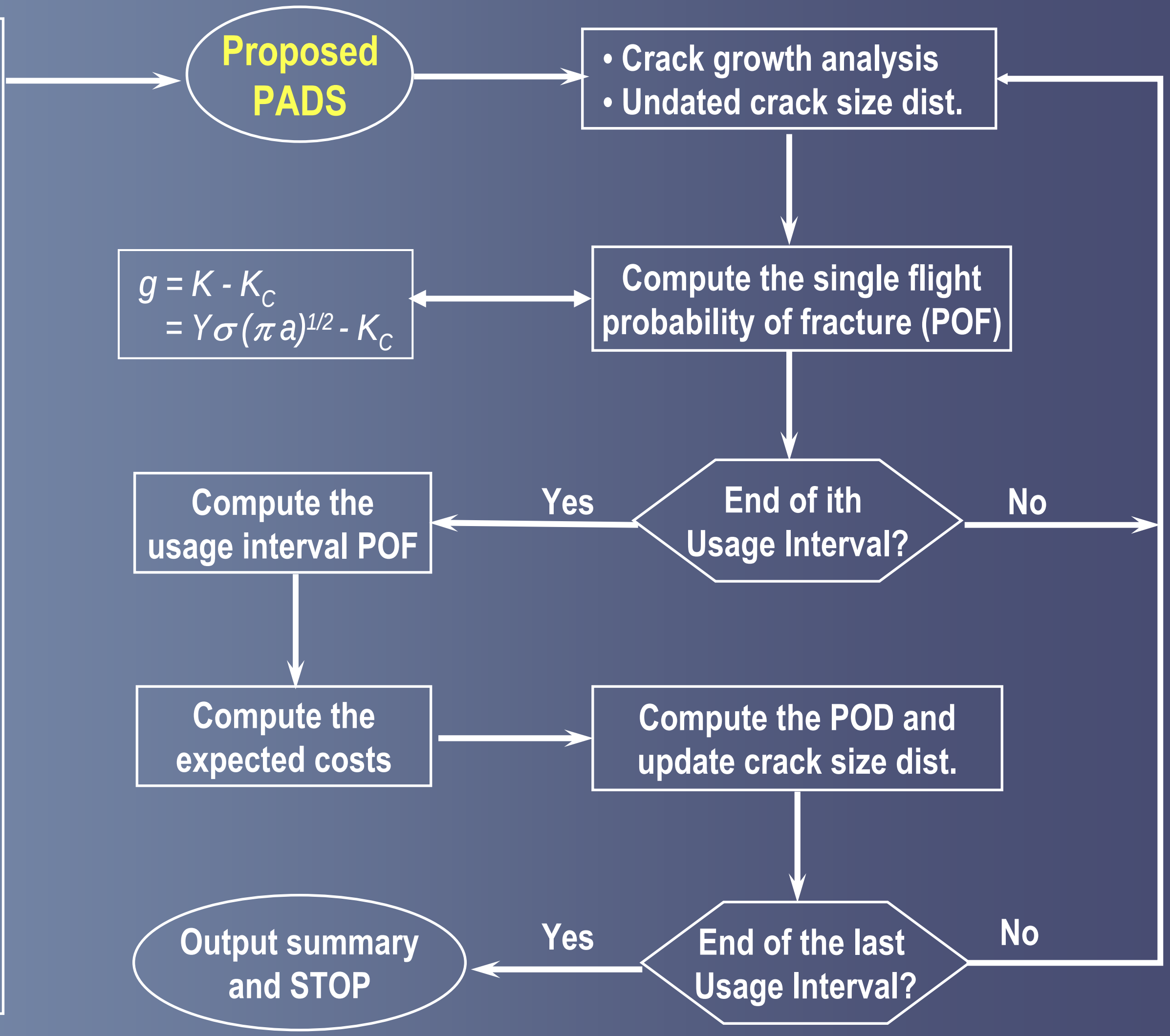
Input data requirements:

- K/sigma vs a file
- Fracture toughness distribution
- Initial crack size distribution
- a vs T file
- Max stress Gumbel Dist. (loads exceedance curve)
- POD parameters
- Repair crack size distribution
- Inspection number and time
- Number of locations per airframe
- Number of airframes in the fleet



Proposed PADS

- Crack growth analysis
- Undated crack size dist.

$$g = K - K_C = Y\sigma(\pi a)^{1/2} - K_C$$

Compute the single flight probability of fracture (POF)

End of ith Usage Interval?

Yes

No

Compute the usage interval POF

Compute the expected costs

Compute the POD and update crack size dist.

End of the last Usage Interval?

Yes

No

Output summary and STOP

Develop A Process to Define/Select the Most Appropriate Distributions

- Define a process to define all random variables with proper distributions for risk assessment will be an important next step.
  - For example, how to select the distribution for the initial crack size distribution after durability tests (Mil-Std-1530C task 5.3.4)
  - A standardized process will be developed in the future
- For computation accuracy sake, a rigorous distribution modeling technique is proposed to handle irregular crack size distributions which include: the initial crack size, crack size after growing to a specific time period, and crack size after inspection and repair actions
  - A data table file will be used to cover the crack size distribution range from -6 sigma to +6 sigma
  - The goal is to avoid extrapolation
  - Automatic checking process to examine the distribution

Proposed Robust Importance Sampling Method Is Able to Solve Several Technical Difficulties

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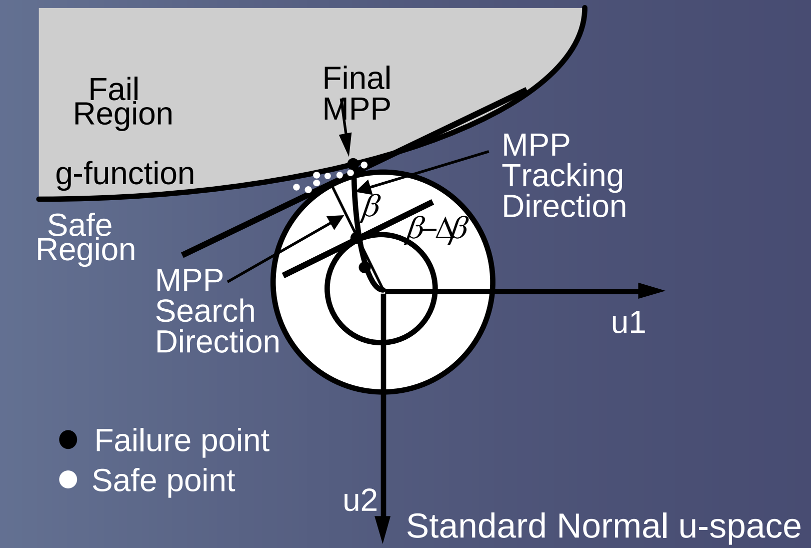
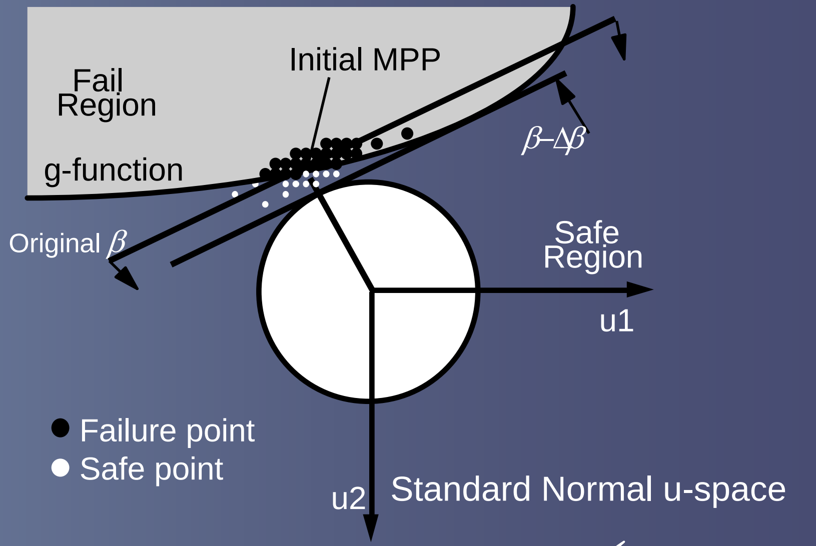
- Random variable with irregular-shape distribution type and large coefficient of variation
  - Crack size distribution after multiple inspections and repairs
- Failure function or limit state function is a function of multiple random variables and can be extremely nonlinear
  - Discrete random variable, for example, geometry factor (k/sigma vs. a) file
  - Large coefficient of variation
- Extremely small probability of failure
  - Single flight probability of failure requirement of 1.E-7





Proposed Analysis Procedure to Determine the Optimal Maintenance Schedule

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- Study the demonstration problem
  - Collect all the necessary data for random variables selection
  - Risk requirement = 1.E-7
- Problem solving
  - Inspection time data from the deterministic safety factor analysis will be used as initial design point to calculate its corresponding risk and compare with the 1.E-7 risk requirement
    - Both the PROF code and PADS code will be used to compute the results. When there is a difference, more analyses will be done to understand the causes.
    - Link deterministic safety factor with risk. Risk results can be used to validate/demonstrate the success of deterministic approach and to calibrate the safety factor (2) when needed
  - Identify an optimal maintenance schedule with 1.E-7 risk constraint

Demonstration Example One
Wing Location Two Problem Definition

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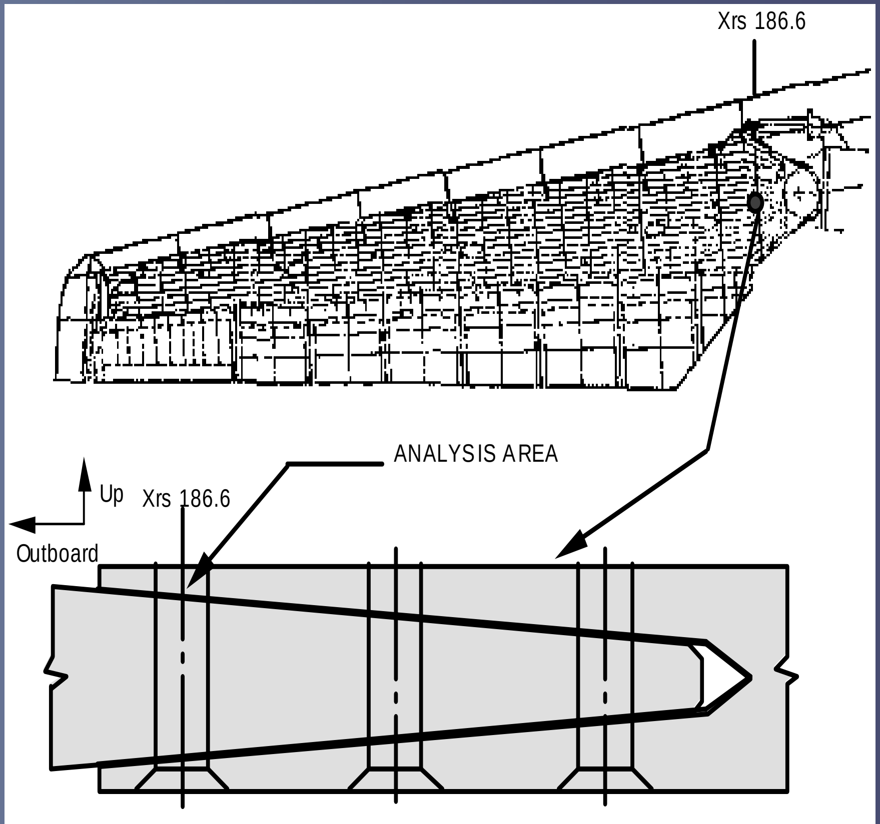
- The wing splice is the singular load path for the primary wing bending load. It is a fish mouth joint comprised of two titanium plates with an aluminum plate in between. The joint is held together with three rows of high interference fit TaperLok fasteners.
- Damage tolerance analysis currently shows this joint is in need of inspections. Because of the inspection requirement and the criticality of the load path, it was determined that the wing splice was a candidate for using probabilistic analysis techniques.
- Deterministic approach select two inspection intervals, 5000 and 5000.



CROSS SECTION OF LWR WING OUTER PANEL
VIEW LOOKING AFT

Wing Location Two
Input Data Uncertainties Modeling

- Initial crack size distribution
  - Deterministic approach assumed 0.05”
  - Probabilistic approach will use a mixed distribution of lognormal (0.0008, 0.63) and Uniform (0.0, 0.05)
  - From comparison, it shows that probabilistic approach has modeled deterministic approach’s 0.05” into its distribution
- Repair crack size distribution
  - Since we will use Eddy Current inspection technique for finding the crack, it is reasonably to assume 0.05” as the repaired initial crack size
  - Given the same 0.05”, the uniform distribution with lower and upper bounds of 0.0 and 0.05 should be a reasonable distribution to model the repair crack size distribution.

Wing Location Two
Input Data Uncertainties Modeling

- Fracture toughness distribution
  - To determine the mean value of this distribution usually can be done by using deterministic approach's A-based or B-based value. From both values, with an assumption of coefficient of variation, we can calculate the mean and standard deviation of this distribution
  - For this example, we will use 33 as mean and COV of 0.0125.
- Crack growth Curve – the same deterministic analysis results will be used
- Geometry file data file – the same deterministic analysis results will be used

Wing Location Two
Input Data Uncertainties Modeling

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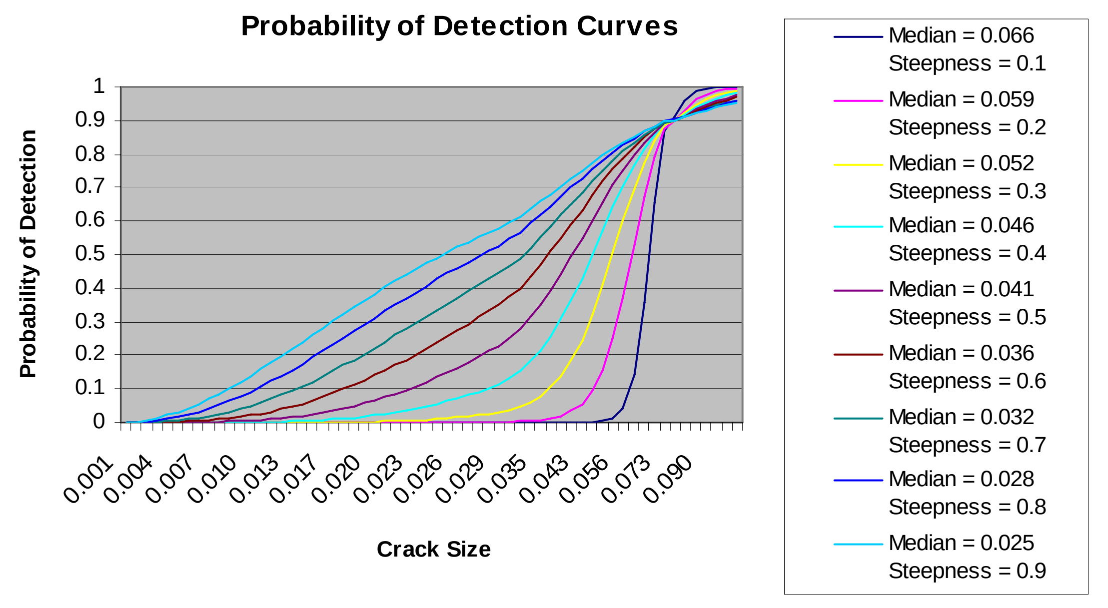
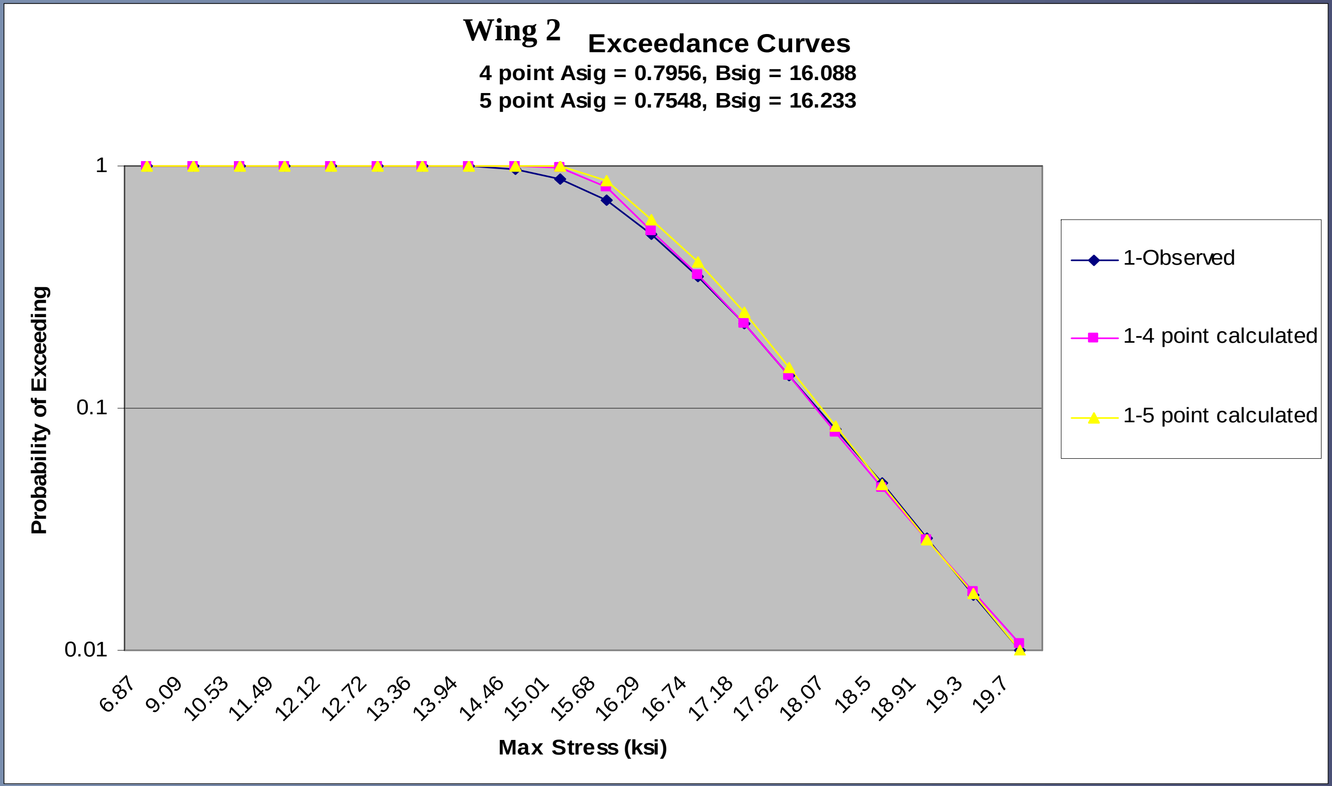
- Probabilities of detection (POD) curves were produced based on 90% detection (95% confidence level) of 0.075 inches using the eddy current inspection method.
- The curves shown below are produced using combinations of mean (mu) and steepness (sigma) evaluated over the crack distribution provided by the B-1 program. The final set of mean and steepness used is 0.06 and 0.184, respectively. The minimum detectable value is 0.



Wing Location Two
Input Data Uncertainties Modeling

- Load exceedance curve – extreme value distribution is used to model load exceedance data. Since the largest data area will produce largest failure, the fitted distribution will consider the largest few points (4 or 5).



Wing Location Two
Results Summary and Discussions

- Results comparison based on deterministic results

PADS Code Results Summary

	5000 Before	5000 After	10000 Before	10000 After
POD%		0.09		0.46
Prof. of Failure (Critical crack size)	0	0	0	0
Prof. of Failure (fracture toughness)	1.12E-8	<1.E-16	2.0E-8	<1.E-16
Prof. of Failure	1.12E-8	<1.E-16	2.0E-8	<1.E-16

PROF Code Results Summary

	5000 Before	5000 After	10000 Before	10000 After
POD%		0.116		0.86
Prof. of Failure	5.44E-9	5.3E-12	1.74E-8	1.1E-10

- As shown, both codes produced < 1.E-7 data. In other words, we can consider larger inspection intervals.

Wing Location Two
Results Summary and Discussions

- Results comparison – Consider 7454 and 7454 intervals

PADS Code Results Summary

	7454 Before	7454 After	14908 Before	14908 After
POD%		0.17		1.96
Prof. of Failure (Critical crack size)	0	0	0	0
Prof. of Failure (fracture toughness)	3.08E-6	2.49E-11	1.43E-5	3.29E-11
Prof. of Failure	3.08E-6	2.49E-11	1.43E-5	3.29E-11

PROF Code Results Summary

	7454 Before	7454 After	14908 Before	14908 After
POD%		0.387		3.16
Prof. of Failure	1.09E-8	3.81E-11	1.8E-7	1.42E-10

- As shown, only the PROF code produced < 1.E-7 data and the PADS code did not. To check the accuracy, further investigation was performed.

Wing Location Two
Results Summary and Discussions

- Results comparison – 10000, 10000, and 10000 hours case

PADS Code Results Summary

	10000 Before	10000 After	20000 Before	20000 After	30000 Before	30000 After
POD%		12.92		24.08		32.82
Prof. of Failure (crack size exceeds the critical crack size)	0.0		3.98E-9		2.61E-7	
Prof. of Failure (fracture toughness)	7.48E-5	4.7E-10	1.12E-2	2.44E-8	1.78E-2	4.07E-8

PROF Code Results Summary

	10000 Before	10000 After	20000 Before	20000 After	30000 Before	30000 After
POD%		14.78		27.76		41.74
Prof. of Failure	1.51E-8	4.01E-11	2.51E-6	8.12E-11	4.97E-6	7.35E-10

- As shown, the PROF code results remains small but the PADS code produced much larger risk. Since large risk identified, we can verify by using the Monte Carlo simulation approach.

Wing Location Two
Results Summary and Discussions

- Monte Carlo simulation was used to verify the results

Verification Results Using Monte Carlo Method

Prof. of Failure	10000 Before	20000 Before	30000 Before
PADS Code	7.48E-5	1.12E-2	1.78E-2
PROF Code	1.51E-8	2.51E-6	4.97E-6
Monte Carlo	9.E-5 (90/1000000)	1.005E-2 (1005/100000)	1.891E-2 (1891/100000)

- As shown, the PADS code produces results very close to the Monte Carlo simulation results; however, the PROF code’s results are not.
- Further investigation of the discrepancies between the codes is required
  - Use the distribution data produced by the PROF code to perform a Monte Carlo simulation instead of using the distributions created by the PADS code. Data will be shown in the next page.
  - Actually, both PADS and PROF codes produced pretty similar crack size distributions.

Wing Location Two
Results Summary and Discussions

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- Obtain the crack size distribution from the PROF code results

Crack Size	10000 Before	20000 Before	30000 Before
0.000101	8.30E-05	2.65E-05	1.18E-05
0.001001	1.25E-04	1.20E-04	8.35E-05
0.009993	2.01E-04	2.14E-04	2.21E-04
0.024979	2.53E-04	2.74E-04	2.93E-04
0.049955	3.09E-04	3.36E-04	3.62E-04
0.099999	3.89E-04	4.24E-04	4.59E-04
0.149858	4.55E-04	4.96E-04	5.39E-04
0.199809	5.14E-04	5.61E-04	6.11E-04
0.299711	6.28E-04	6.88E-04	7.53E-04
0.499516	8.73E-04	9.71E-04	1.06E-03
0.69932	1.25E-03	1.70E-03	**5.46E-03**
0.799227	1.69E-03	3.405E-3	**0.52204**
0.84918	2.05E-03	4.74E-02	0.61096
0.899135	2.66E-03	**5.48E-01**	0.660768
0.949095	4.48E-03	**0.664**	0.69471
0.97408	8.88E-03	0.6955	0.708266
0.989079	3.55E-02	0.7107	0.71609
0.998113	**2.44E-01**	0.7198	0.72059
0.999066	**0.391337**	0.7206	0.720957
0.9992	0.443258	0.7207	0.721038
0.9994	0.589	0.7208	0.721189
0.9996	0.652595	0.721	0.721401
0.9998	0.692069	0.7214	0.7216
0.9999	0.707459	0.7216	0.72164

- The Monte Carlo method was used to verify the results – Same Conclusion

Prof. of Failure	10000 Before	20000 Before	30000 Before
PROF Code	1.51E-8	2.51E-6	4.97E-6
Monte Carlo	8.1E-5 (81/1000000)	1.111E-2 (1111/100000)	2.161E-2 (2161/100000)
PADS Code	*7.48E-5*	*1.12E-2*	*1.78E-2*

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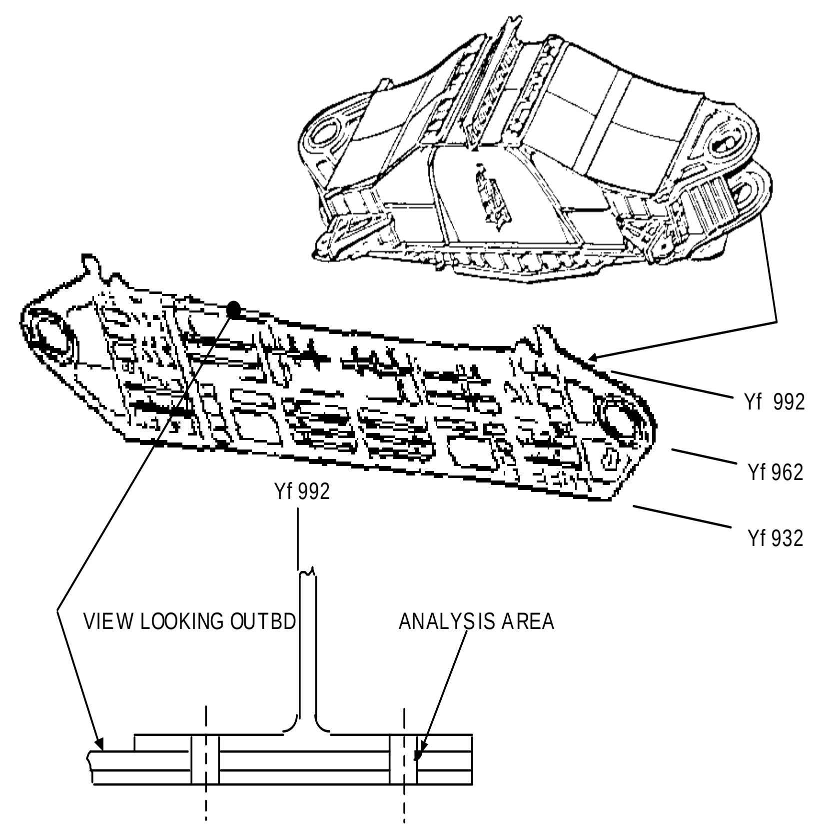
Demonstration Example Two
Wing Carry Through 12 Problem Definition

- The lower wing carry through cover is the primary load path cross ship wing loads. The lower cover is comprised of two integrally stiffened titanium plates. The plates are held together with high interference fit TaperLok fasteners.
- Damage tolerance analysis currently shows inspections will be required prior to the end of the B-1 service life. Because of the inspection requirement and the criticality of the load path, it was determined that the wing carry through lower cover was a candidate for using probabilistic analysis techniques.
- Deterministic approach select two inspection intervals, 9000 and 9000.



Wing Carry Through Location Twelve Input Data Uncertainties Modeling

- Initial crack size distribution
  - Same as W02
- Repair crack size distribution
  - Same as W02
- Fracture toughness distribution
  - For this example, we will use 105 as mean and COV of 0.0125.
- Crack growth Curve – the same deterministic analysis results will be used
- Geometry file data file – the same deterministic analysis results will be used
- Probability of detection curve – use the same as the W02 case

Wing Carry Through Location Twelve Input Data Uncertainties Modeling

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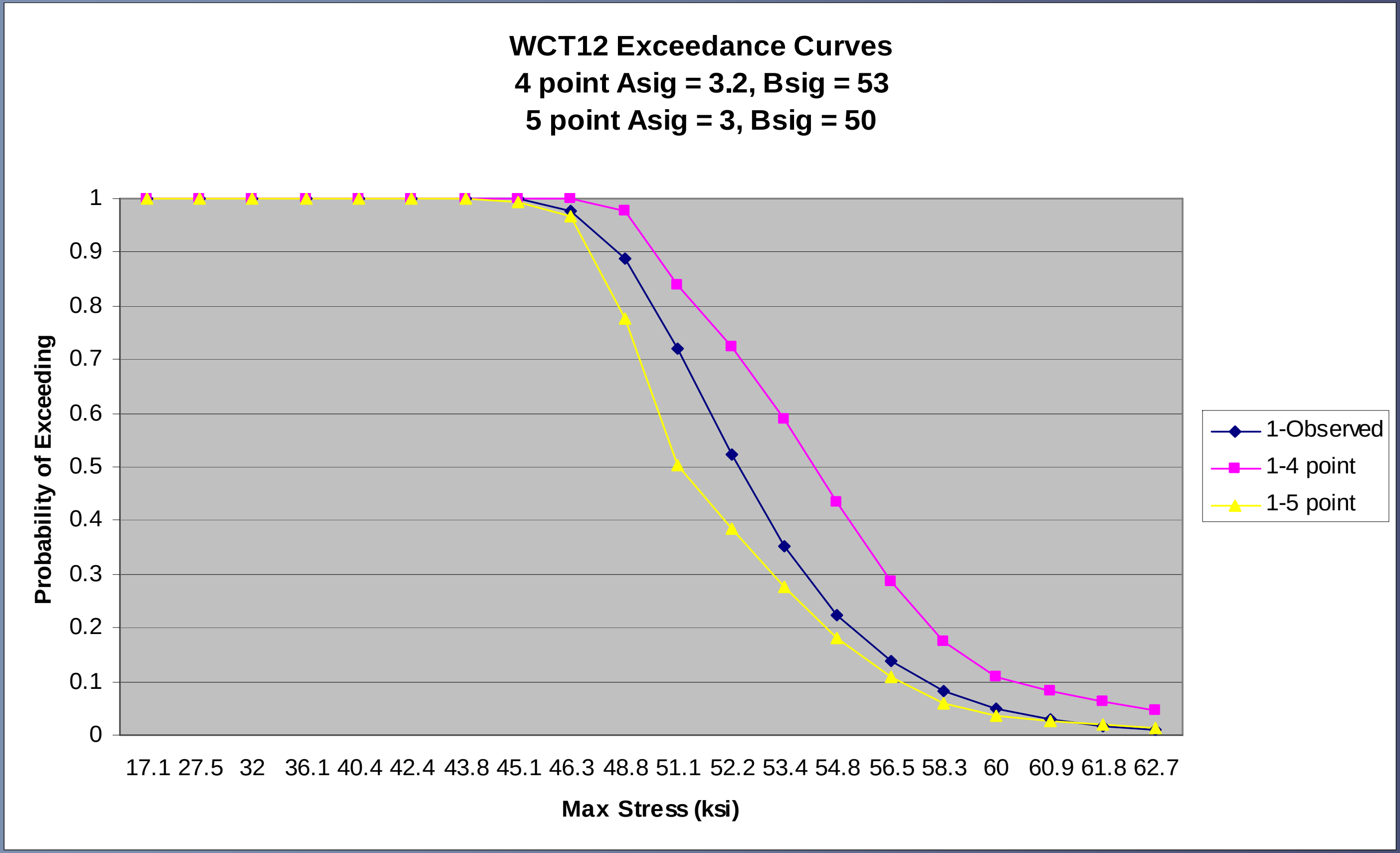
- Load exceedance curve – extreme value distribution is used to model load exceedance data. Since the largest data area will produce largest failure, the fitted distribution will consider the largest few points (4 or 5).



Wing Carry Through Location Twelve Results Summary and Discussions

- Results comparison based on deterministic results

PADS Code Results Summary (0.06, 0.184)

	9000 Before	9000 After	18000 Before	18000 After
POD%		0.0676		0.062
Prof. of Failure (Critical crack size)	<1.E-16	<1.E-16	2.35E-6	<1.E-16
Prof. of Failure (fracture toughness)	< 1.E-16	< 1.E-16	< 1.E-16	< 1.E-16
Prof. of Failure	< 1.E-16	< 1.E-16	2.35E-6	< 1.E-16

PROF Code Results Summary

	9000 Before	9000 After	18000 Before	18000 After
POD%		0.067		0.076
Prof. of Failure	1.31E-6	2.73E-45	5.11E-6	5.88E-68

- As shown, both codes produced > 1.E-7 data. In other words, we must consider smaller inspection intervals.

Wing Carry Through Location Twelve Results Summary and Discussions

- Results comparison – Consider 11000 and 7000 intervals ⇒ 18000 hours

PADS Code Results Summary (0.06, 0.184)

	11000 Before	11000 After	18000 Before	18000 After
POD%		0.073		0.054
Prof. of Failure (Critical crack size)	< 1.E-16	< 1.E-16	6.75E-8	< 1.E-16
Prof. of Failure (fracture toughness)	< 1.E-16	< 1.E-16	< 1.E-16	< 1.E-16
Prof. of Failure	< 1.E-16	< 1.E-16	6.75E-8	< 1.E-16

PROF Code Results Summary

	11000 Before	11000 After	18000 Before	18000 After
POD%		0.073		0.065
Prof. of Failure	3.3E-5	2.73E-45	1.29E-7	1.5E-42

- As shown, only the PADS code produced < 1.E-7 data and the PROF code did not. To check the accuracy, further investigation was performed.

Wing Carry Through Location Twelve Results Summary and Discussions

- Fracture Failure Mode:

  Limit state function can be defined as follows,

$$g = K_C / \left[\sqrt{\pi a}\, \beta(a) \right] - \sigma_{\max}$$

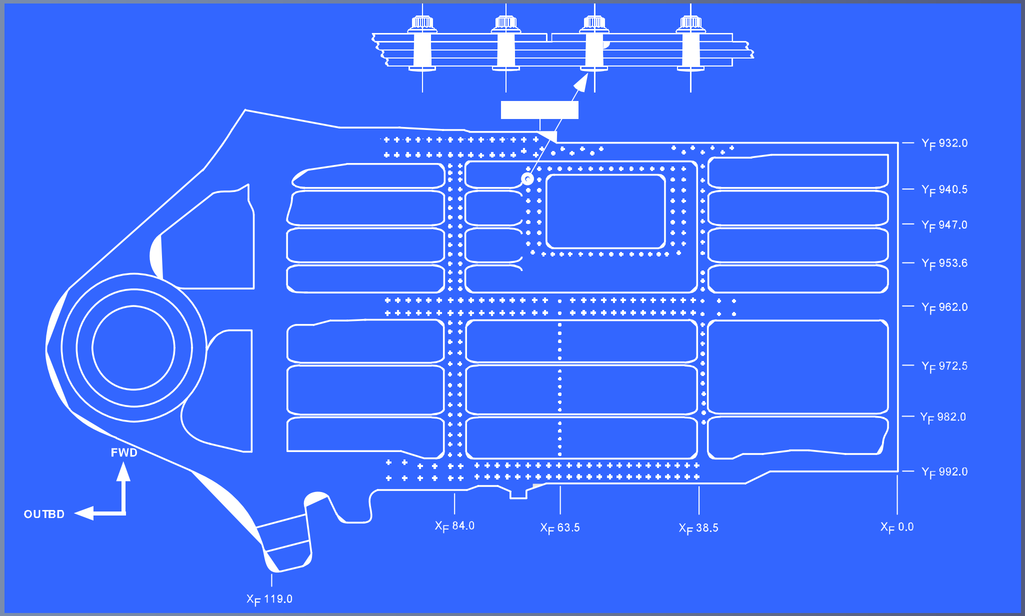
- Kc – Normal (205.6, 7.8)
- Sigma – EVD (55.14, 0.75)
- Critical crack depth = 0.924
- Geometry factor at 0.924 = 1.36
- Assume the worst case of crack depth and geometry factor we have

$$g = K_C / \left[\sqrt{\pi(0.924)} \times 1.36 \right] - \sigma_{\max} = K_C / 2.32 - \sigma_{\max}$$

- Based on this limit state function, the approximate mean = 33.48 and approximate std dev. = 3.45. Thus, the estimate beta > 10, i.e., the probability of failure should be very small.
- In other words, the PROF code's estimate is suspicious because g should be larger than 0, i.e., very small probability of failure should be found. The PROF code estimated 3.3E-5 appears too large for this analysis

Demonstration Example Three
Wing Carry Through 61 Problem Definition

- Another critical location on the B-1 wing carry through lower cover is the fastener of the main landing gear cutout adjacent to the Yf 932 bulkhead. This location contains high interference fit Taper-Lok fasteners and has a high load transfer due to the cutout. It is, therefore, considered critical though the damage tolerance analysis currently does not shows inspections will be required prior to the end of the B-1 service life. Due to the criticality the main landing gear cutout was a candidate for using probabilistic analysis techniques.
- Deterministic approach select two inspection intervals, 10000 and 10000.



Wing Carry Through Location 61 Input Data Uncertainties Modeling

- Initial crack size distribution
  - Same as WCT 12
- Repair crack size distribution
  - Same as WCT 12
- Fracture toughness distribution
  - Same as WCT 12.
- Crack growth Curve – the same deterministic analysis results will be used
- Geometry file data file – the same deterministic analysis results will be used
- Probability of detection – Same as WCT 12
- Load data – Same as WCT 12

Wing Carry Through Location 61 Results Summary and Discussions

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- Results comparison based on deterministic results

PADS Code Results Summary (0.06, 0.184)

	10000 Before	10000 After	20000 Before	20000 After
POD%		0.073		0.075
Prof. of Failure (Critical crack size)	<1.E-16	<1.E-16	< 1.E-16	<1.E-16
Prof. of Failure (fracture toughness)	< 1.E-16	< 1.E-16	< 1.E-16	< 1.E-16
Prof. of Failure	< 1.E-16	< 1.E-16	< 1.E-16	< 1.E-16

PROF Code Results Summary

	10000 Before	10000 After	20000 Before	20000 After
POD%		0.072		0.126
Prof. of Failure	< 1.E-16	< 1.E-16	< 1.E-16	< 1.E-16

- As shown, both codes produced < 1.E-7 data. In other words, we must consider larger inspection intervals.

Wing Carry Through Location 61
Results Summary and Discussions

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- Results comparison – Consider different inspection intervals to satisfy risk of 1.E-7 requirement

PADS Code Results Summary (0.06, 0.184) – 26700 and 23300

	26700 Before	26700 After	50000 Before	50000 After
POD%		0.134		0.73
Prof. of Failure (Critical crack size)	7.47E-8	< 1.E-16	5.37E-8	< 1.E-16
Prof. of Failure (fracture toughness)	< 1.E-16	< 1.E-16	7.E-9	< 1.E-16
Prof. of Failure	7.47E-8	< 1.E-16	6.07E-8	< 1.E-16

PROF Code Results Summary – 25000 and 27500

	25000 Before	25000 After	52500 Before	52500 After
POD%		0.187		1.86
Prof. of Failure	3.33E-8	< 1.E-16	8.21E-8	< 1.E-16

- As shown, both codes produced similar results – combined hours of 50,000 hours (PADS) and 52,500 hours (PROF).

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Wing Carry Through Location 61 Results Summary and Discussions

Consistency in results

- By examining the inspection interval times and Probability of Detection percentage, the PADS code produced much more consistent results than the PROF code as shown in the following Table.

Interval No.	PADS Time	PADS Risk	PADS POD %	PROF Time	PROF Risk	PROF POD %
1	26700	7.468E-8	0.134	25000	3.33E-8	0.187
2	23300	6.075E-8	0.73	27500	8.21E-8	1.86
3	22000	4.54E-8	2.01	23300	6.88E-8	4.41
4	22000	7.95E-8	3.49	19600	4.42E-8	5.25
5	21900	8.84E-8	4.76	10500	4.1E-8	8.6
6	21800	8.13E-8	6.12	19500	6.04E-8	9.62
7	21700	7.81E-8	7.5	11000	4.62E-8	8.71
8	21600	7.74E-8	8.79	19500	9.43E-8	9.687
9	21500	7.19E-8	9.95	11000	4.70E-8	9.414
10	21400	6.65E-8	13.0	19000	3.65E-8	14.4
Sum	223900			185900		

Wing Carry Through Location 61 Results Summary and Discussions

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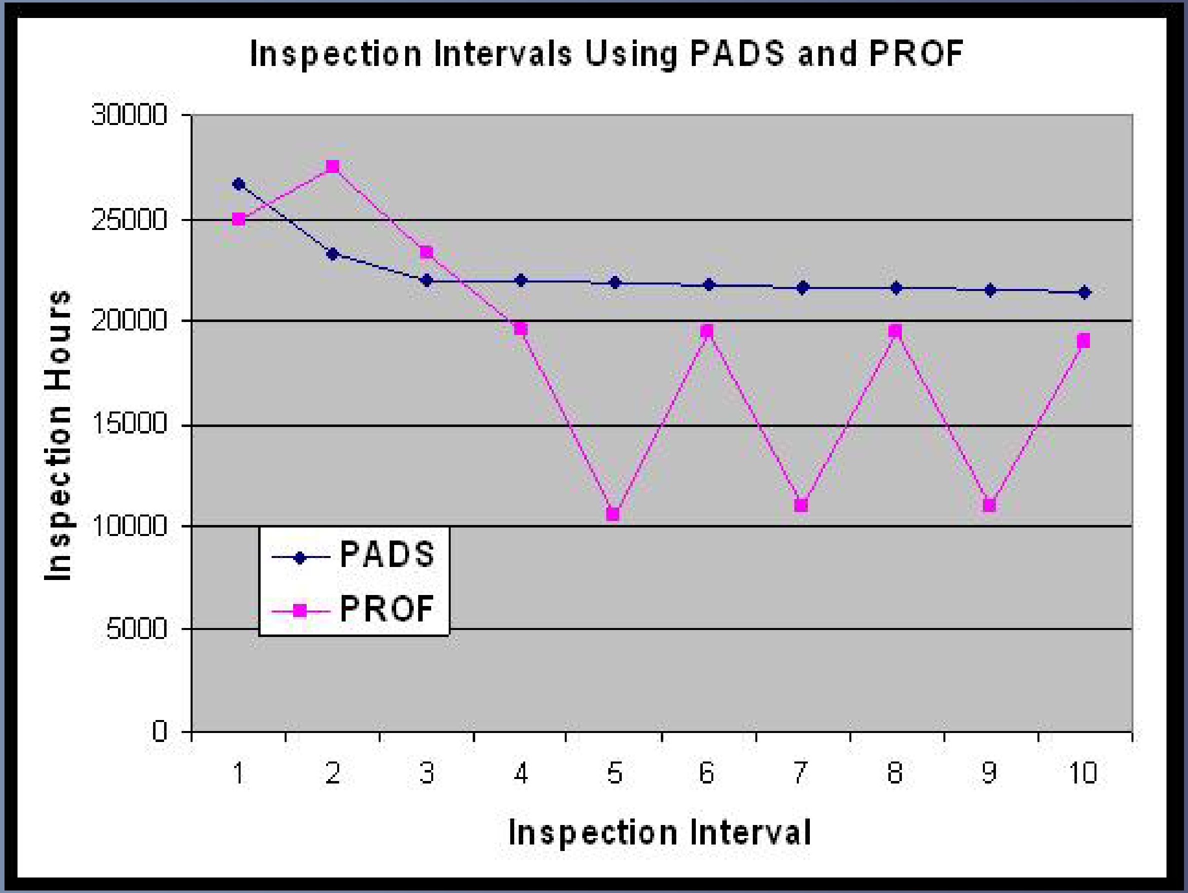
Consistency in results

- Inspection interval times for both PADS and PROF codes



Summary

- Based on the proposed analysis procedure, all three demonstration examples showed the risk of 1.E-7 is a reasonable choice for risk requirement.
- Demonstrate the success of the deterministic safety factor approach because the corresponding risks for the selected inspection intervals were close to the 1.E-7 risk requirement
- Optimal maintenance schedule can be easily found by modifying the inspection intervals when calculated risk > or < 1.E-7
- Need further investigation and experience for using both PADS and PROF codes. At this stage, we proposed that both PROF and PADS codes be used to compute and verify the risk

PADS Code Results Summary

	1st Insp. Before	1st Insp. Before	2nd Insp. Before	2nd Insp. Before
W-2 (5000, 5000)	1.12E-8	<1.E-16	2.0E-8	<1.E-16
WCT-12 (9000, 9000)	< 1.E-16	< 1.E-16	2.35E-6	< 1.E-16
WCT-12 (11000, 7000)	< 1.E-16	< 1.E-16	6.75E-8	< 1.E-16
WCT-61 (10000, 10000)	< 1.E-16	< 1.E-16	< 1.E-16	< 1.E-16
WCT-61 (26700, 23300)	7.47E-8	< 1.E-16	6.07E-8	< 1.E-16

PROF Code Results Summary

	1st Insp. Before	1st Insp. Before	2nd Insp. Before	2nd Insp. Before
W-2 (5000, 5000)	5.44E-9	5.3E-12	1.74E-8	1.1E-10
WCT-12 (9000, 9000)	1.31E-6	< 1.E-16	5.11E-6	< 1.E-16
WCT-12 (11000, 7000)	3.3E-5	< 1.E-16	1.29E-7	< 1.E-16
WCT-61 (10000, 10000)	< 1.E-16	< 1.E-16	< 1.E-16	< 1.E-16