Australian Government
Department of Defence
Science and Technology

Developments on Risk-Based Fatigue Failure Prediction for Application to Military Aircraft

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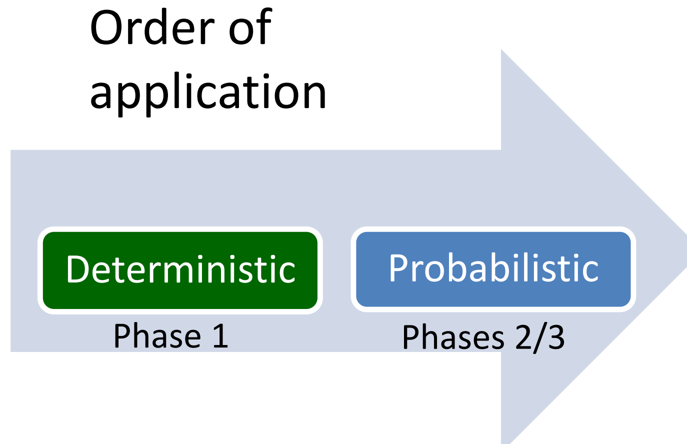
Outline of presentation

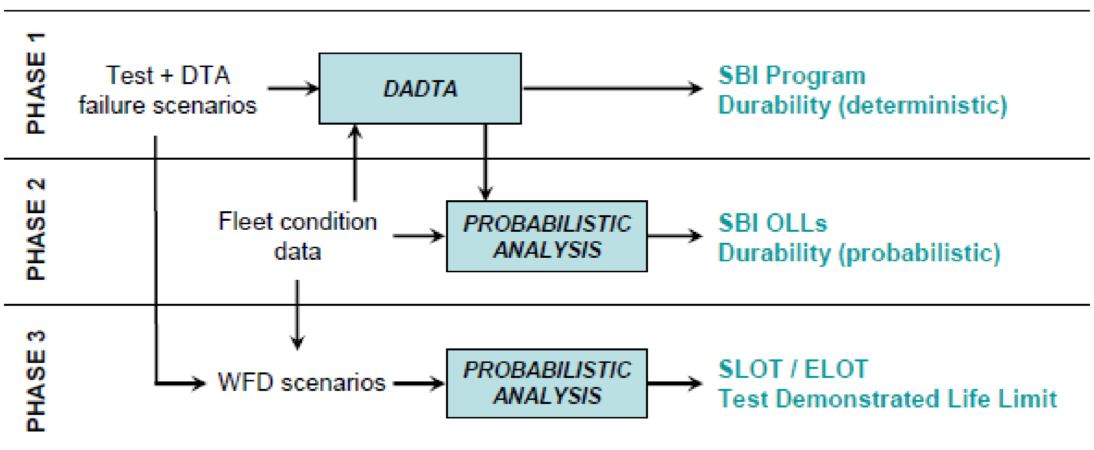
- Fatigue failure analysis – what it can deliver to Defence
- When does fatigue failure occurs?
- Why probabilistic approach in fatigue failure assesssment?
- Operational safety of military aircraft based on fatigue failure assessment
- Comparison of deterministic and probabilistic requirements of inspection intervals for military aircraft
- Conclusion

Fatigue failure analysis – what it can deliver to Defence as operator of large fleets of aircraft

- Enhance safety
- Maximise availability
- Minimise cost of ownership

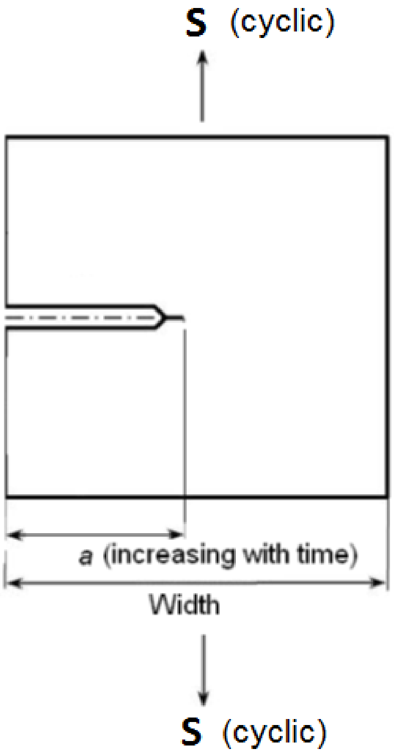
DSTO involvement in C-130J Full Scale Fatigue Test





credits to : D. Hartley, R. Ogden and L. Meadows

When does fracture failure occur?

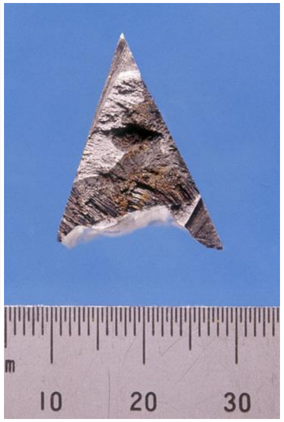


$$S \cdot \beta(a)\sqrt{\pi a} > K_C$$

or

$$S > S_{RS}$$

K_c : fracture toughness
S : applied stress
a: crack size
b(*a*) : geometry correction factor
S_{RS}=residual strength [min(Fy,$\frac{K_C}{\beta(a)\sqrt{\pi a}}$)]
Fy = yield strength



Why probabilistic fracture failure prediction?

Stresses

Fatigue cracks

$$K_C \leq S \cdot \beta(a)\sqrt{\pi a}$$

Failure can occur

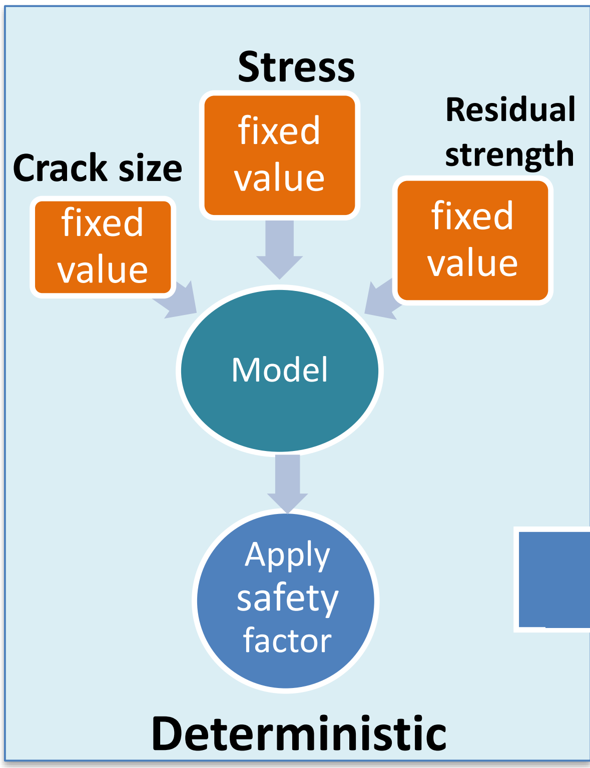
- ✓ **at a wide range of crack sizes and stresses**

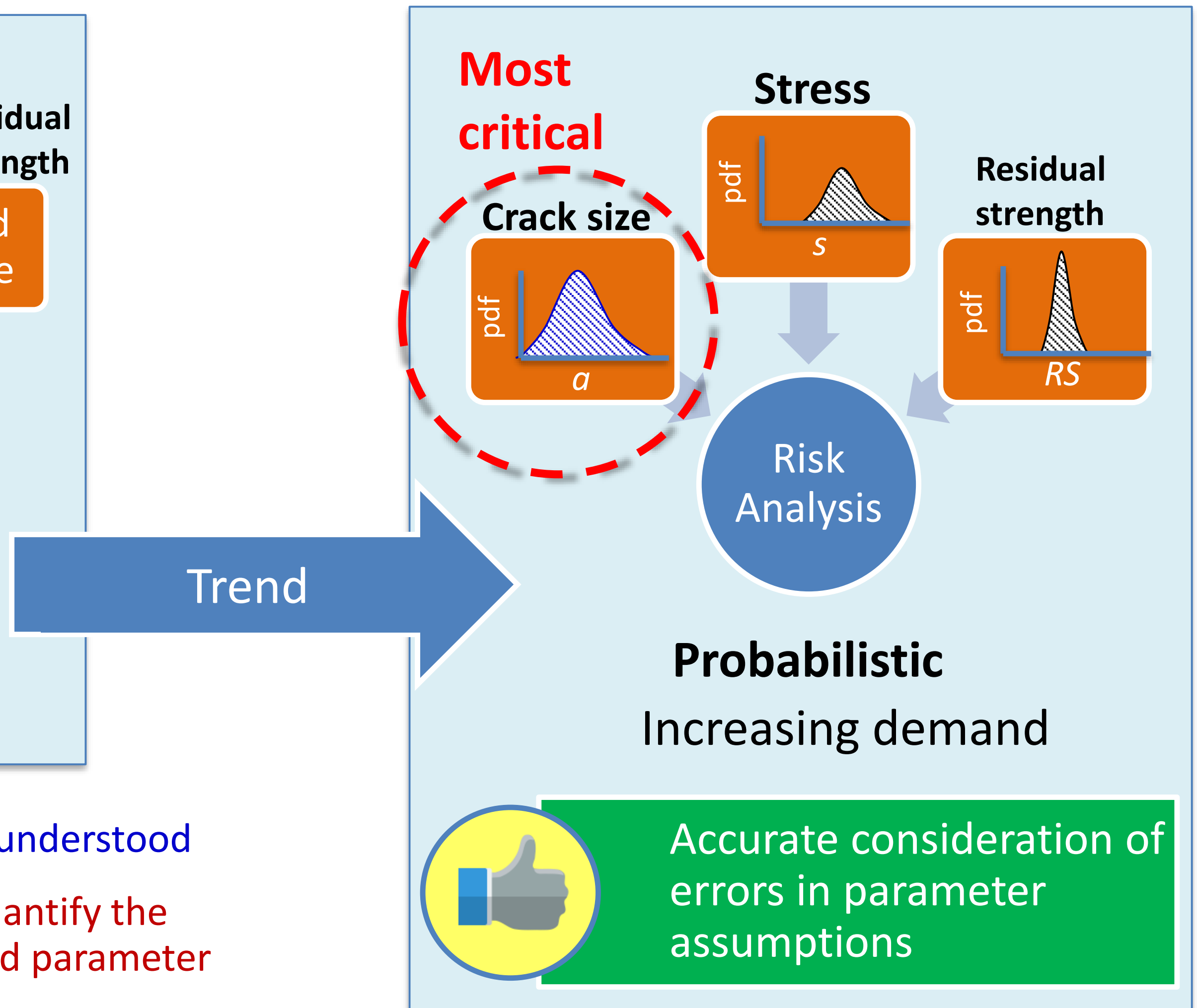
Infinite combinations of stress and crack to cause failure

Deterministic vs Probabilistic approach

"Those who will begin with certainties, shall end in doubts;
but those who will be content to begin with doubts, shall end in certainty"

- Francis Bacon

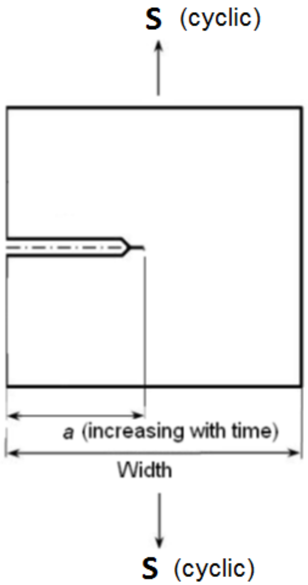


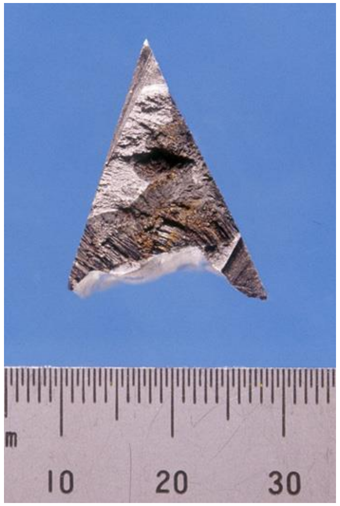


Well established, better understood

Safety factor does not quantify the errors from each assumed parameter

Probability of Failure





- Risk - probability of failure or unstable fracture
- Failure occurs when applied stress exceeds the residual strength

Probability of Failure (PoF) calculation:

$$PoF = \int_0^{\infty} \boldsymbol{f}(\boldsymbol{a}) \left(1 - \int_0^{S_{RS}(a)} \boldsymbol{h}(\boldsymbol{s})\, ds \right) da$$

Where :

s = stress

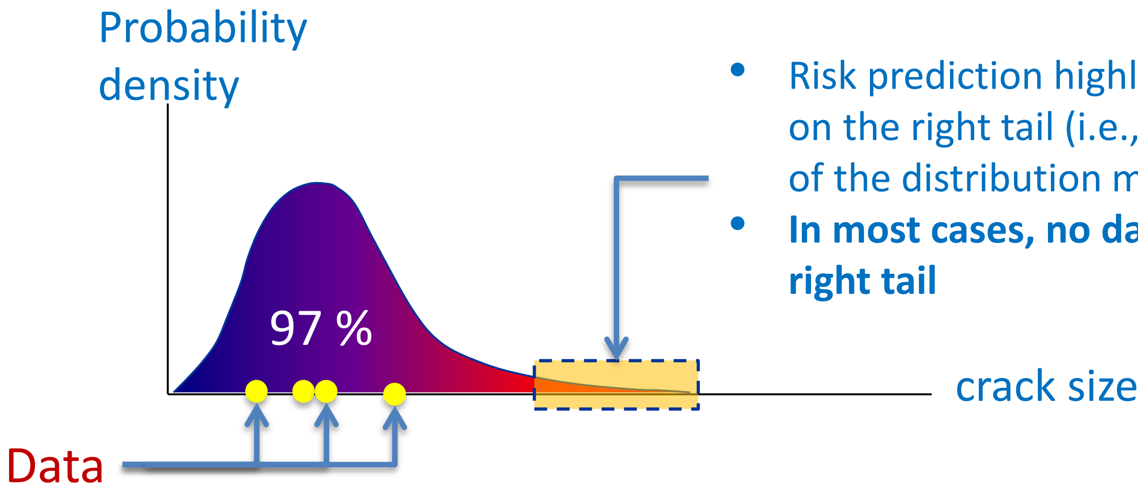
a = crack size

s_{RS}= residual strength

$\boldsymbol{f}(\boldsymbol{a})$= crack size probability density function

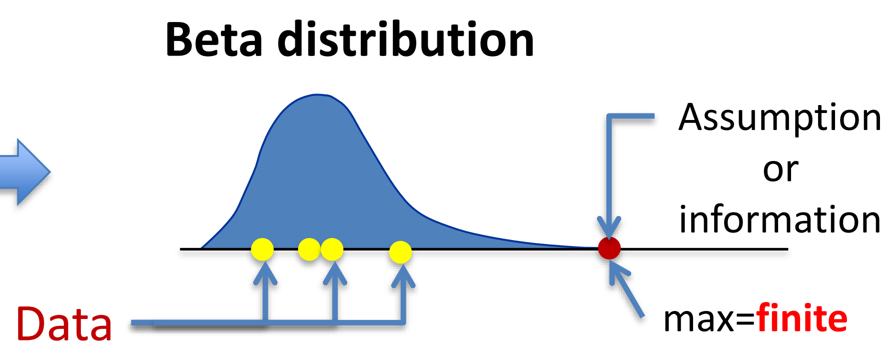
$\boldsymbol{h}(\boldsymbol{s})$= maximum stress probability density function (per given time interval)

Crack size probability distribution, $f(a)$ modelling



- Risk prediction highly dependent on the right tail (i.e., *small portion*) of the distribution model
- **In most cases, no data inside the right tail**

crack size probability distribution $f(a)$



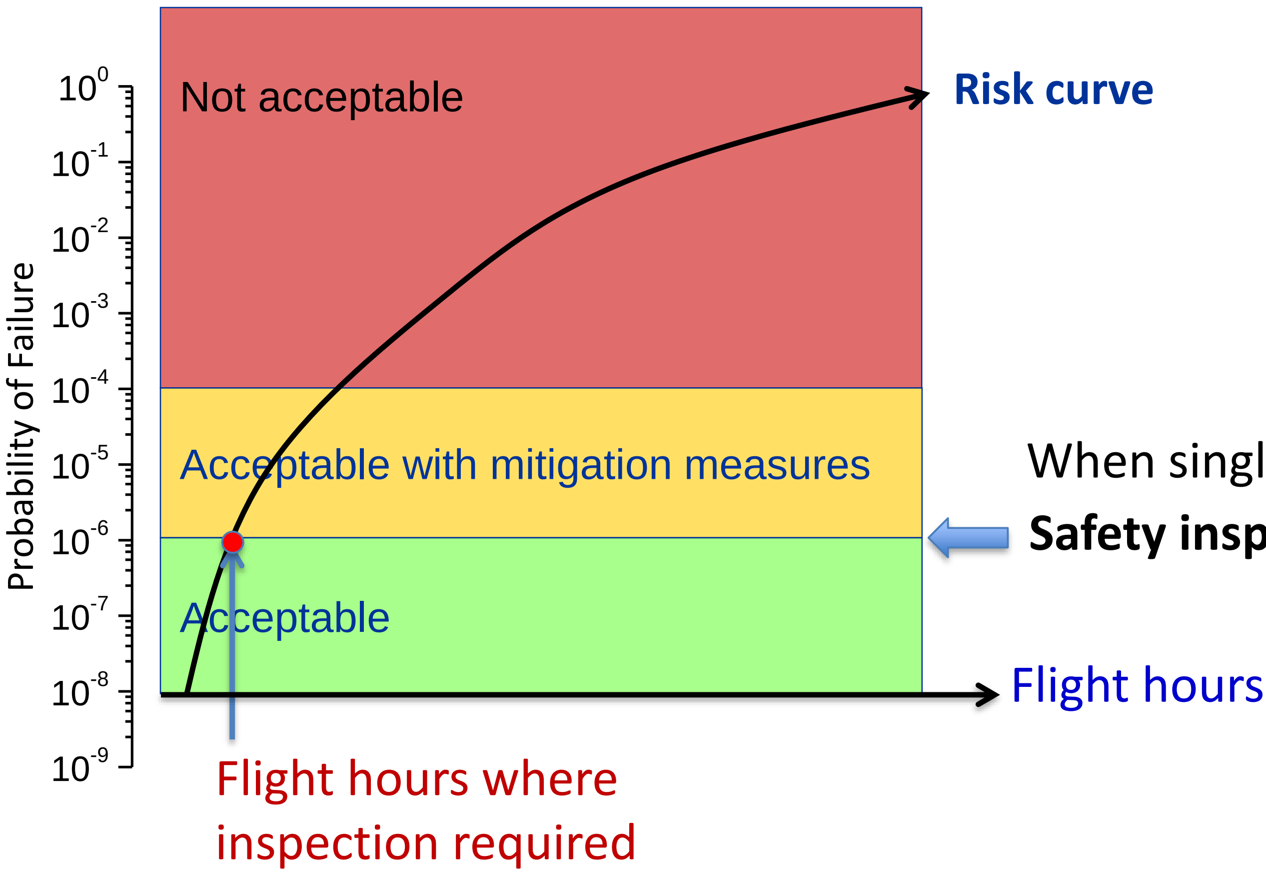
Bounded model

(Realistic model)

Operational safety based on fatigue failure assessment

Operational safety based on fatigue failure assessment

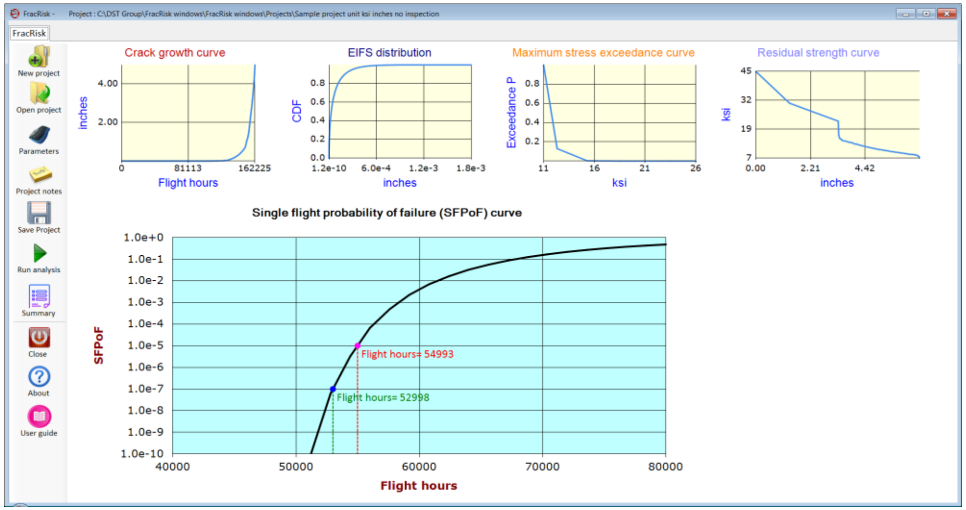
Inspection requirement by MIL-STD1530



When single flight PoF = 10^{-7}

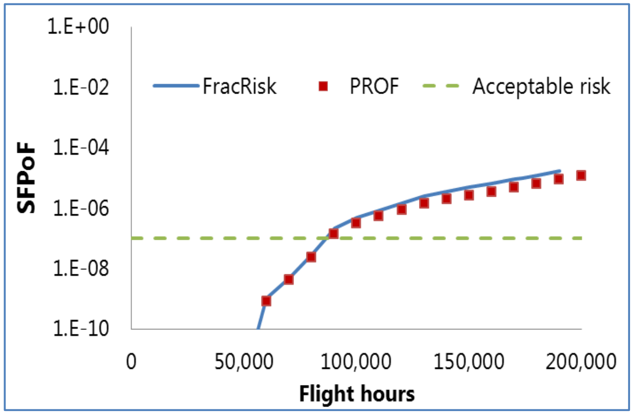
Safety inspection required

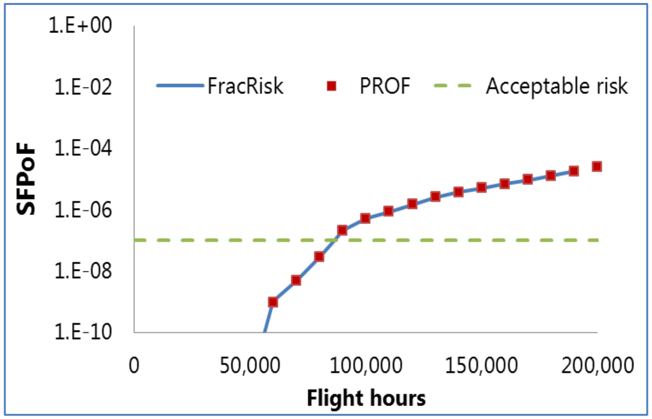
DST developed risk-based fatigue failure assessment tool



PROF / USAF

FracRisk / RAAF





Independent analysis tool evaluation by QinetiQ Australia

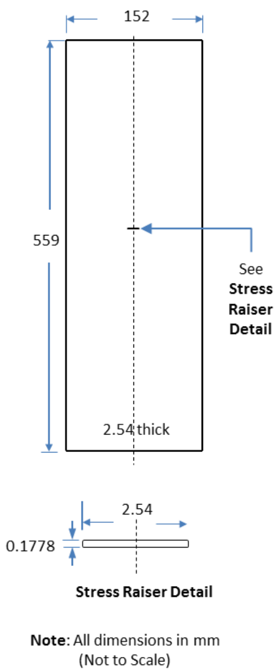
Assessment of Deterministic and Probabilistic Approaches to Inspection Intervals Specified by MIL-STD-1530D

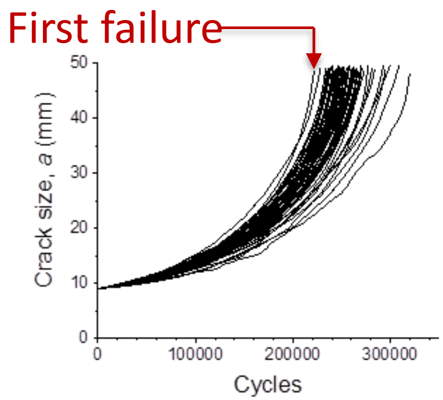
Aircraft structural integrity standards:

- **Def-Stan 970 (UK)**
- **Mil-Std1530 (US)**

Experimental Results Used in the Assessment

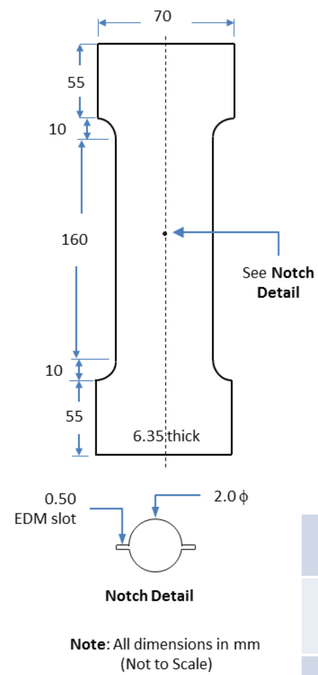
Virkler Data

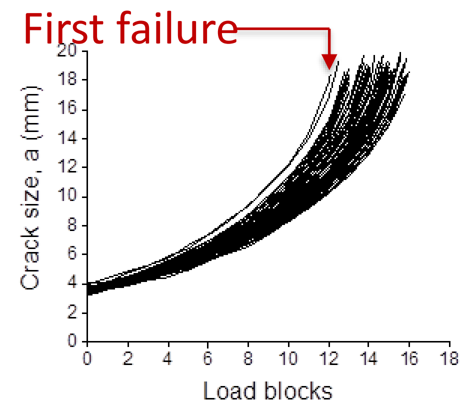




Material	Al 2024-T3
Load	Constant amplitude
Specimen tested	68

DST Data





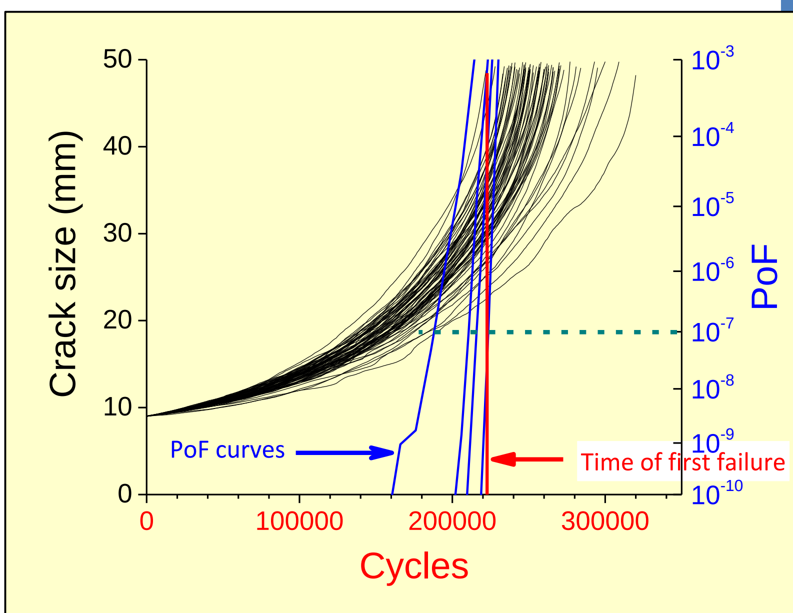
Material	Al 7075-T7351
Load	Variable amplitude
Specimen tested	85

Comparison of deterministic and probabilistic requirements of inspection intervals as specified by MIL-STD-1530D

Safety Inspection : Deterministic vs Probabilistic

Assessment using Virkler Data

Minimum specimen fatigue life (Cycles)	Predicted inspection time (cycles)			
	Deterministic Kc = 25 $\mathrm{MPa}\sqrt{m}$	Probabilistic Fixed Kc = 25 $\mathrm{MPa}\sqrt{m}$	Probabilistic Mean Kc = 25 $\mathrm{MPa}\sqrt{m}$	
			Kc standard deviation	
222798	129700	231117	1.5	188101
			1.0	210649
			0.8	215851
			0.5	223529

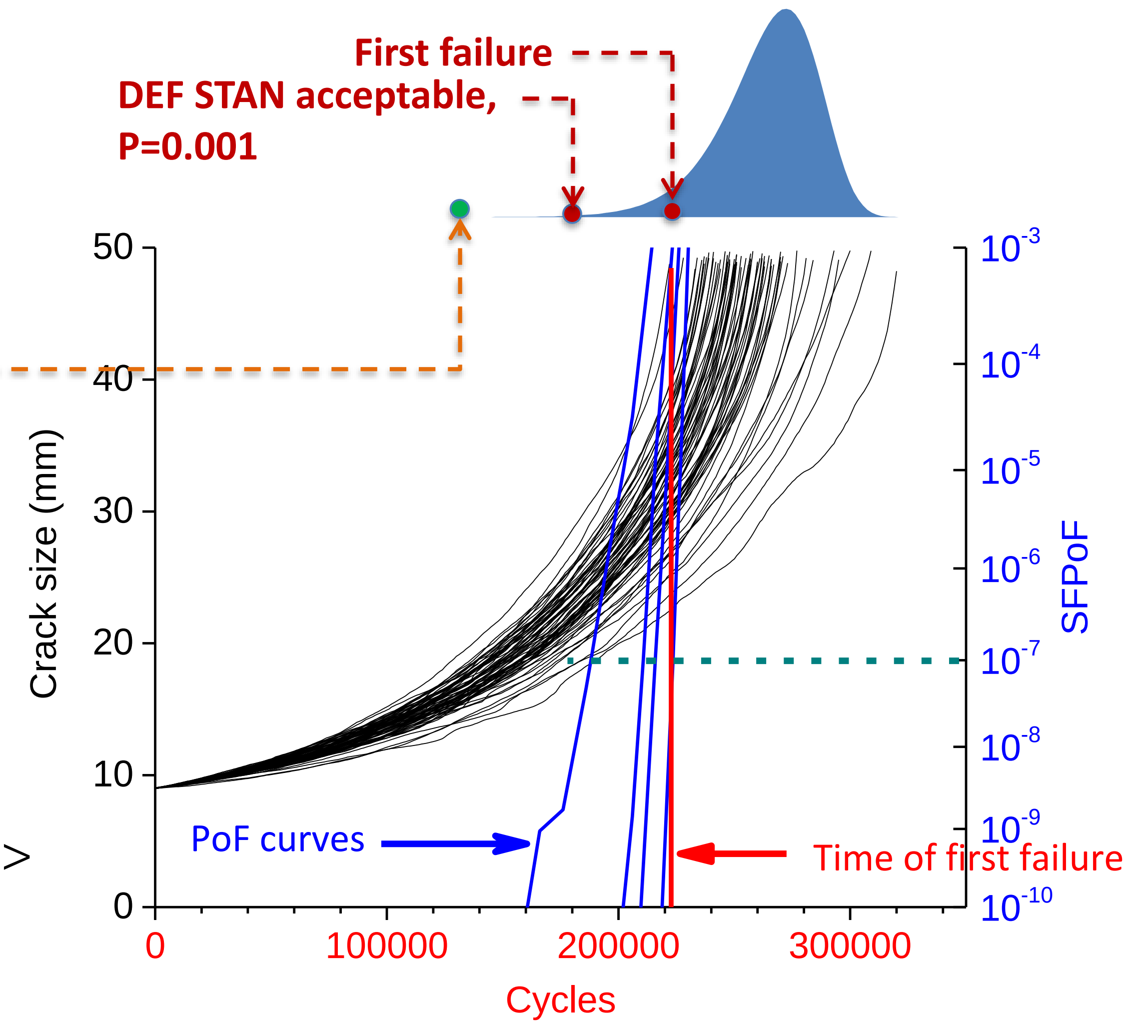


Objective of the test:

- Experimentally evaluate if the first failure of all test specimen happens before PoF=1x10^{-7} ?
- Investigate the effect of material property variability

Safety Inspection : Deterministic vs Probabilistic

Assessment using Virkler Data

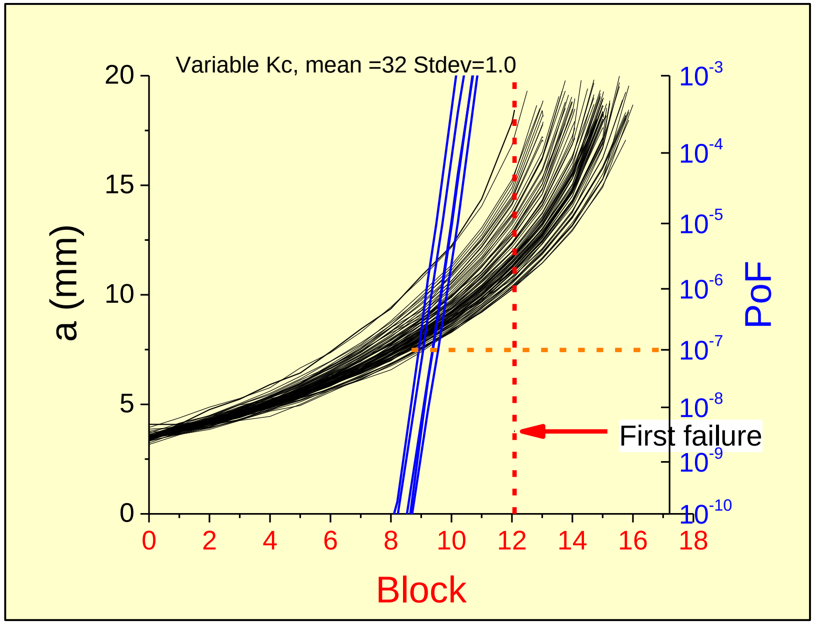


- Probabilistic method close to DEF STAN acceptable when Kc standard deviation is set to $\mathbf{1.5}\ \mathrm{MPa}\sqrt{m}$
- Increasing Kc standard deviation to > $\mathbf{1.5}\ \mathrm{MPa}\sqrt{m}$ will give relatively conservative prediction

Safety Inspection : Deterministic vs Probabilistic

Assessment with DST experimental data

Minimum specimen fatigue life (Load blocks)	Trial	Predicted inspection time	
		Deterministic (Load blocks) Kc=32 MPa$\sqrt{m}$	Probabilistic (Load block) P=10^{-7} Kc=32 MPa$\sqrt{m}$
12.1	1	7.7	9.9
	2	7.6	10.4
	3	7.3	9.7
	4	7.8	10.2
	5	7.5	10.2

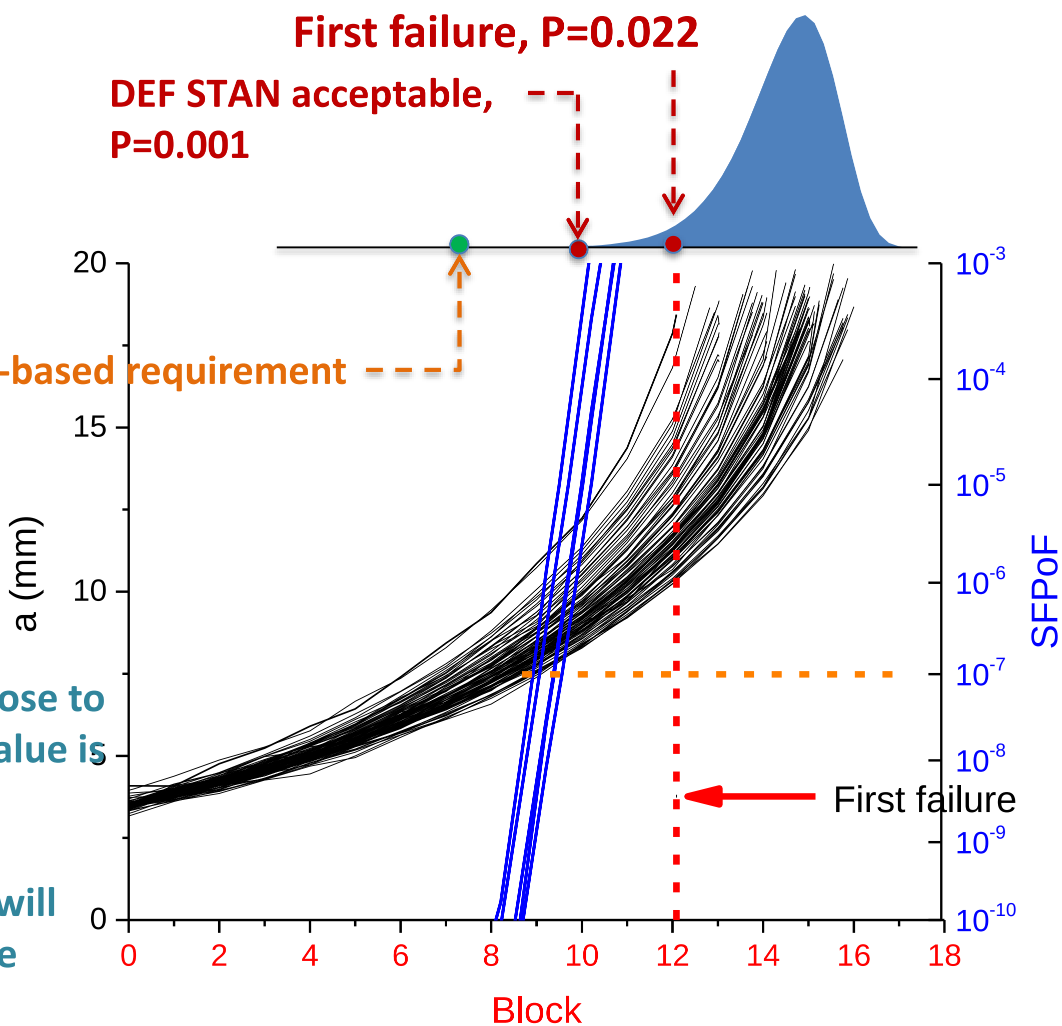


Objective of the test:

- Experimentally evaluate if the first failure of all test specimen happens before PoF=1×10^{-7} ?
- Investigate the effect of material property variability

Safety Inspection : Deterministic vs Probabilistic

Assessment using DST experiment



- Probabilistic based prediction close to DEF STAN acceptable when Kc value is fixed
- Applying Kc standard deviation will result in a relatively conservative prediction

Comparison of allowable risks from standards

	MIL-1530D			Def-Stan 970
	First inspection (deterministic)	Single Flight Probaility of failure (Fixed K_C) $P=10^{-7}, 10^{-5}$	Single Flight Probaility of failure (Variable K_C) $P=10^{-7}, 10^{-5}$	(Probability of failure of an aircraft during its entire life)
Inspection times (Blocks)	7.7	11.5, 11.8	9.9, 10.5	10.3
Total Probability of Failure	1/15401	1/155, 1/99	1/1790, 1/706	1/1000

- Probabilistic approach inspection times from two standards are close
- Deterministic approach requires inspection at much earlier time

Conclusions

- Probabilistic based inspection interval is consistently close to the DEF STAN acceptable risk level
- Using probabilistic method, a slight increase in the variability of the fracture toughness value will result in a conservative estimate

Future Works

- Use of actual aircraft teardown crack data in the analysis
- Application of probabilistic structural integrity assessment to RAAF aircraft fleets (from 2019)

Questions?