Australian Government
Department of Defence
Science and Technology

Preliminary Investigation of Deterministic and Probabilistic Risk Assessment of Fatigue Failures Using Experimental Results

Dr. Ribelito F. Torregosa and **Dr. Weiping Hu**
Aerospace Division
Defence Science and Technology Group, Australia

Presented by Ribelito F. Torregosa

9th European Workshop on Structural Health Monitoring, Manchester, UK, 10-13 July 2018

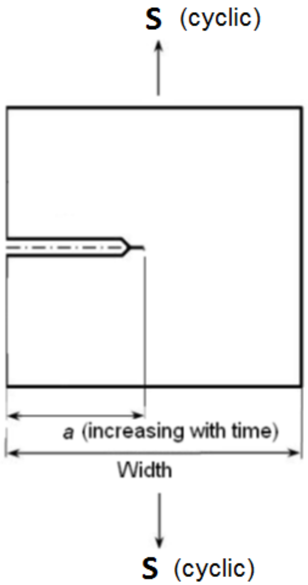
Outline of presentation

- Background on probabilistic approach to failure assessment
- Advantages of probabilistic approach
- New approach to equivalent initial flaw size modelling
- Comparison of Deterministic and Probabilistic prediction of inspection intervals for military aircraft
- Conclusion

Fatigue failure risk analysis – what it brings to Defence

- Enhance safety
- Maximise availability
- Minimise cost of ownership

When does fracture failure occur?



Fracture failure occurs when :

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

or

$$S > SRS$$

Kc : stress intensity factor

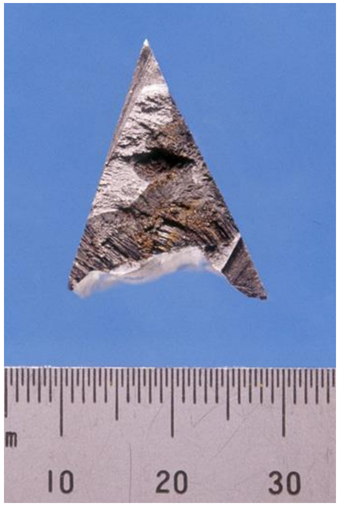
S : applied stress

a: crack size

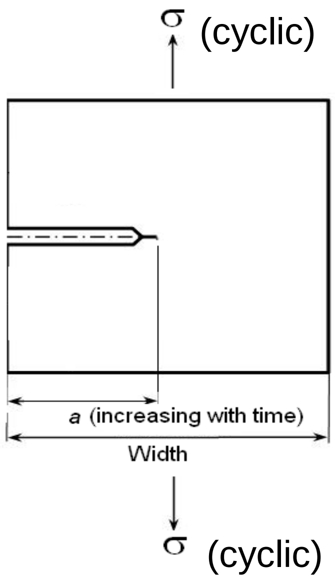
β(*a*) : geometry correction factor

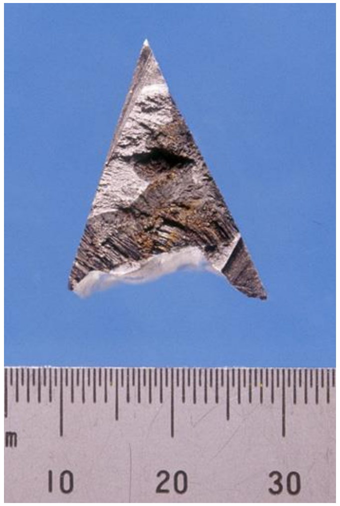
S_{RS}=residual strength [min(Fy,$\frac{K_C}{\beta(a)\sqrt{\pi a}}$)]

Fy = yield strength



Probability of Failure





- Risk - probability of failure or unstable fracture
- Failure occurs when; $\sigma \geq \text{Residual strength}$

Probability of Failure (PoF) calculation:

$$PoF = \int_{0}^{\infty} \boldsymbol{f(a)} \left(1 - \int_{0}^{S_{RS}(a)} f(s)\, ds \right) da$$

Where :

s = stress

a = crack size

s_{RS}= residual strength

$f(a)$= crack size probability density function

f(s)= maximum stress probability density function (per given time interval)

Trend Towards Probabilistic Approach in Structural Integrity Management

"In the future, structural integrity decisions will be based on Hazard Risk Analysis (HRA) and Hazard Risk Index, like it or not!"

- **Rick Ryan, NAVAIR AASIS 2015**

Aircraft Structural Integrity Management – MIL STD 1530D

a) The initial inspection shall occur at or before one-half the life from the assumed maximum probable initial damage size to the critical damage size.

b) The repeat inspection intervals shall occur at or before one-half the life from the minimum detectable damage size (based on the probability of detection established by the NDIT described in 5.1.6) to the critical damage size.

c) **Risk analysis shall be used** to determine if a reduction in the inspection intervals are required to control the safety risk to an acceptable level or **to reduce economic or availability consequences** associated with damage repair.

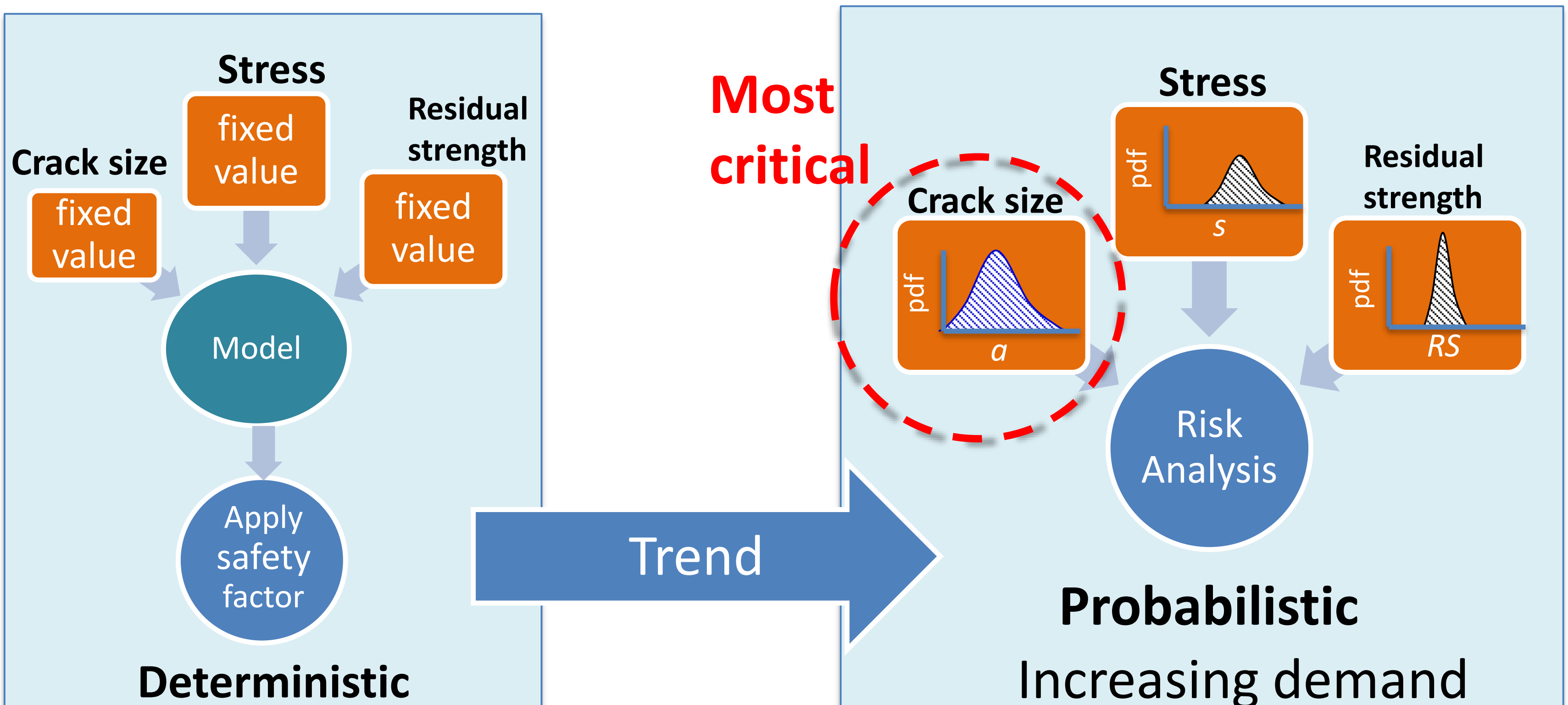
Deterministic (Initial inspection)

↓

Probabilistic (Repeating inspections)

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**

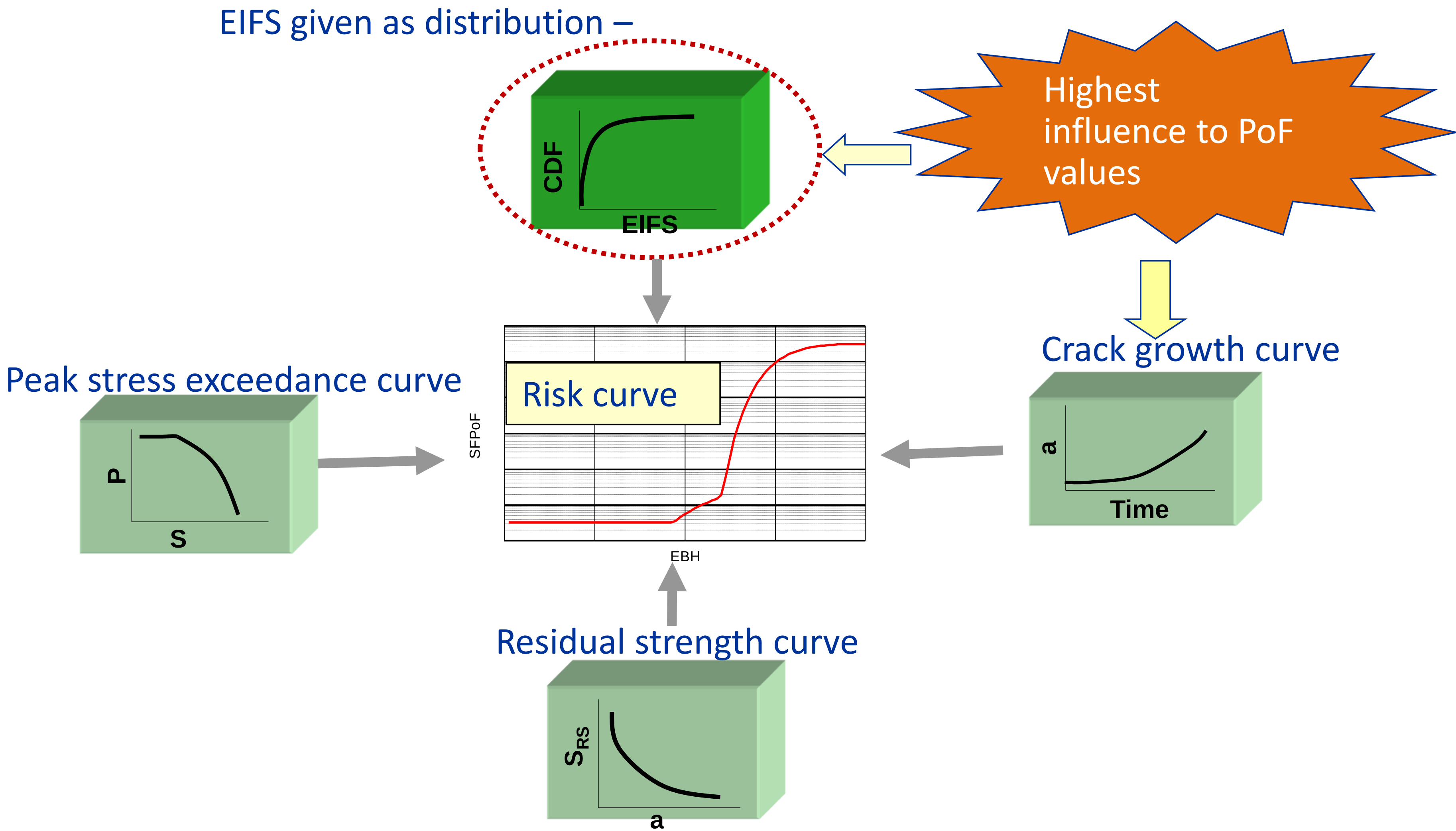


Well established, better understood

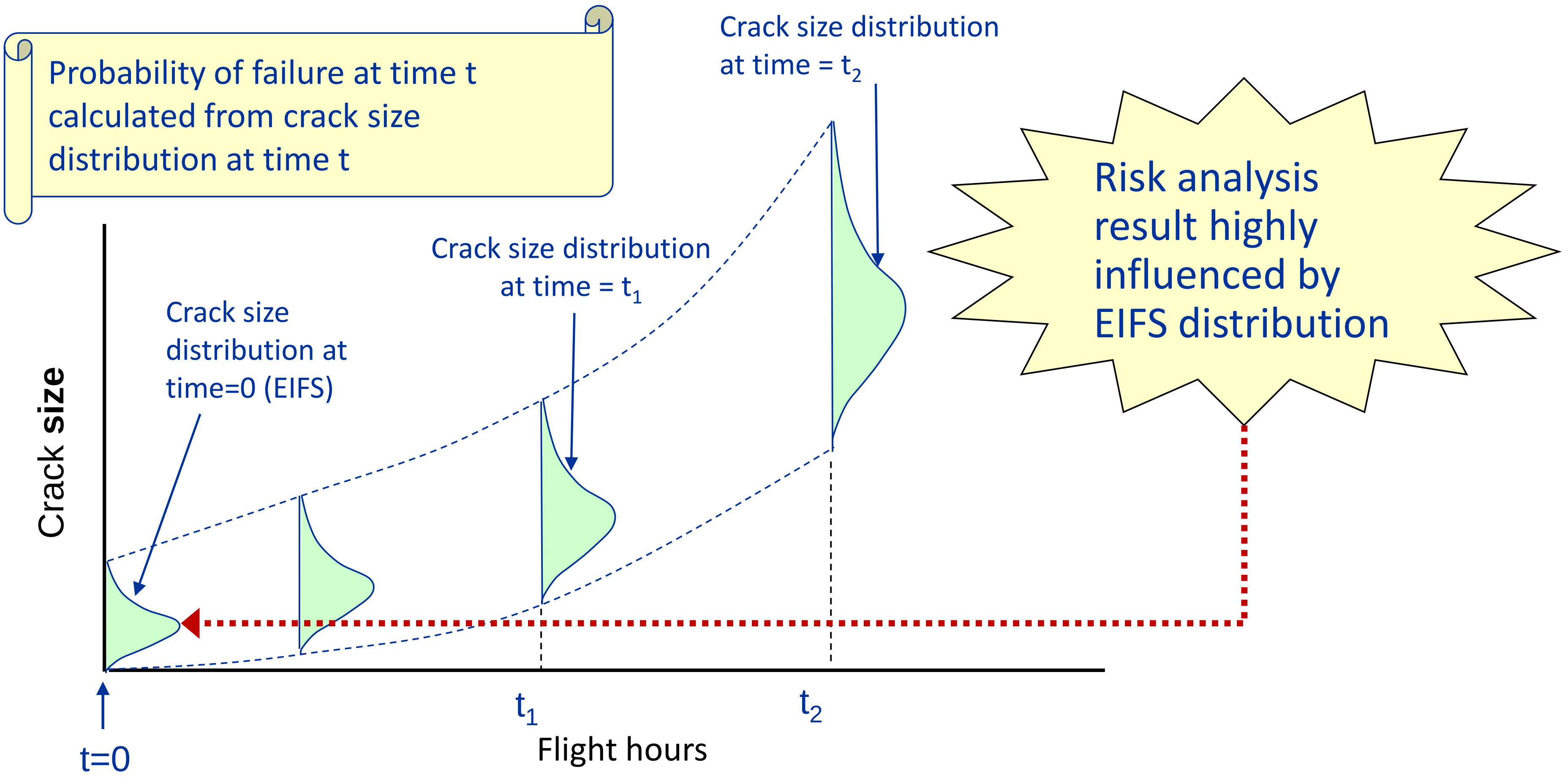
Safety factor does not quantity the errors from each assumed parameter

Accurate consideration of errors in parameter assumptions

Probabilistic Risk Analysis of Fracture – (Parameters)

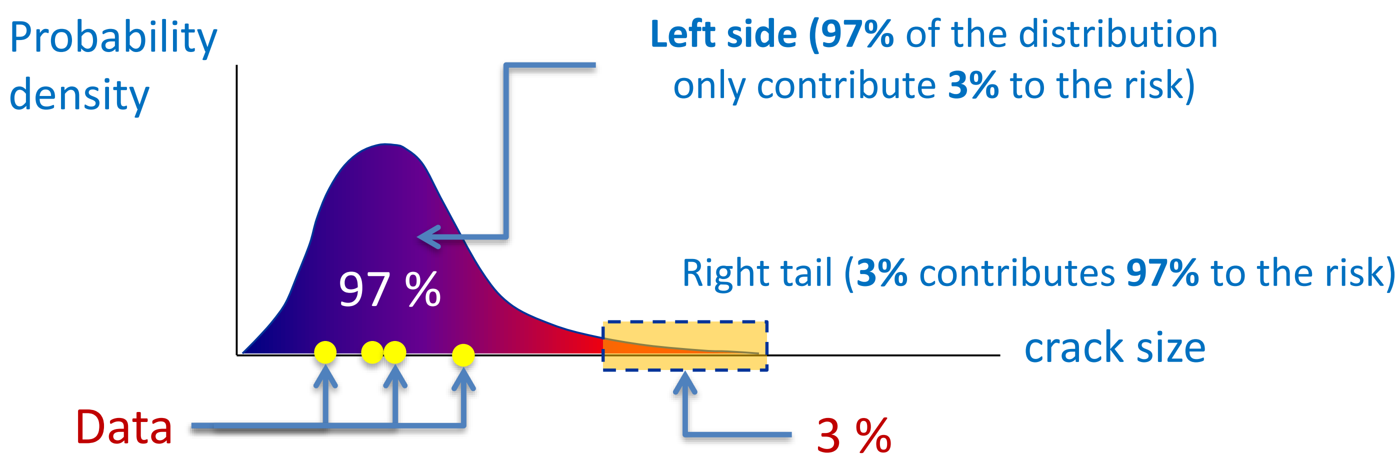


Influence of EIFS distribution to the Probability of Failure

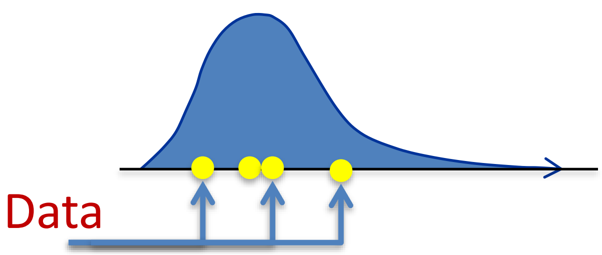


New modelling of the Equivalent Initial Flaw Size (EIFS) Distribution

Innovation on Initial Flaw Size Distribution Modelling

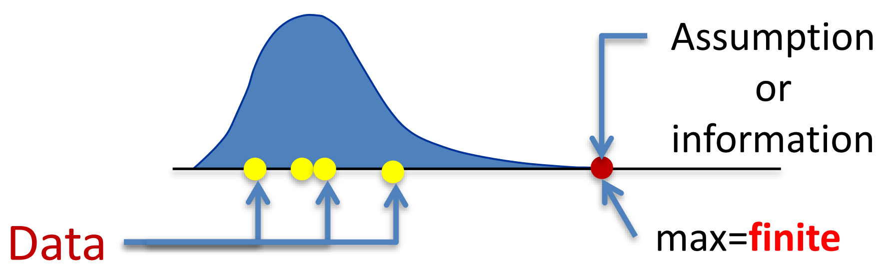


Lognormal distribution



Unbounded model

Beta distribution

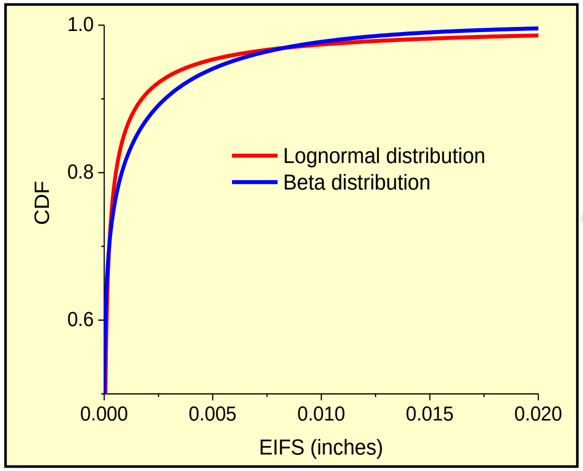


Bounded model

(Realistic model)

Innovation on Initial Flaw Size Distribution Modelling

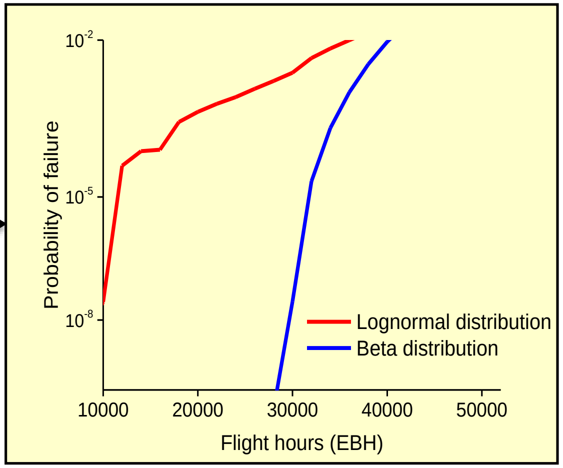
EIFS distribution, $f(a)$



POF for "next flight"

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

POF curves



- Lognormal distribution risk prediction way higher

Impact to Defence

!

- Preliminary results show use of bounded distribution (i.e., Beta distribution) will reduce inspection cost

When to conduct Safety Inspection ?

➢ According to MIL-STD1530

Deterministic method

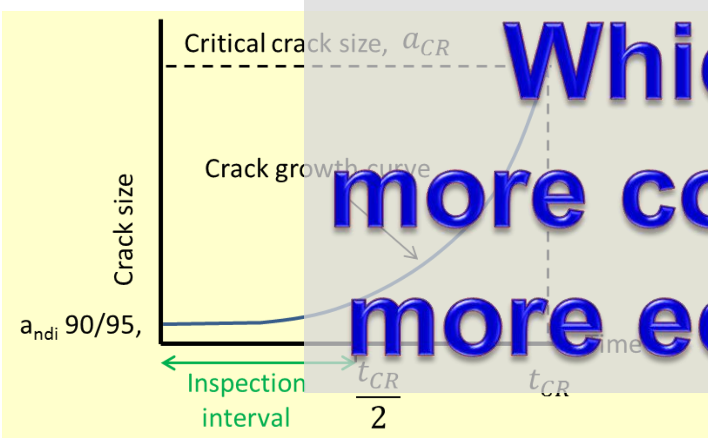
5.4.3.1.1 NDI intervals

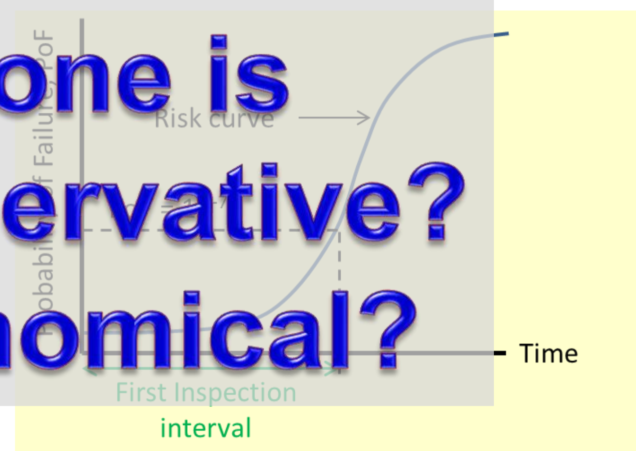
The initial inspection shall occur at or before one-half the life from the assumed maximum probable initial damage size to the critical damage size.

Probabilistic method

5.5.6 Structural Risk Analysis Update

A probability of catastrophic failure at or below 10-7 per flight for the aircraft structure is considered adequate to ensure safety for long-term military operations.





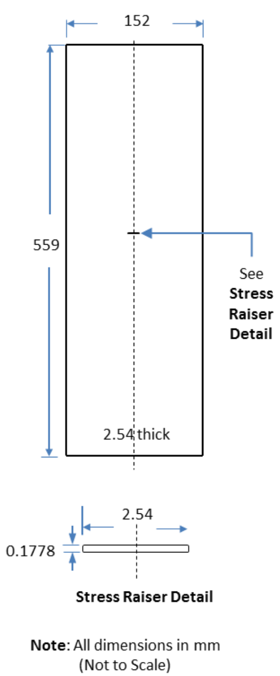
Which one is more conservative? more economical?

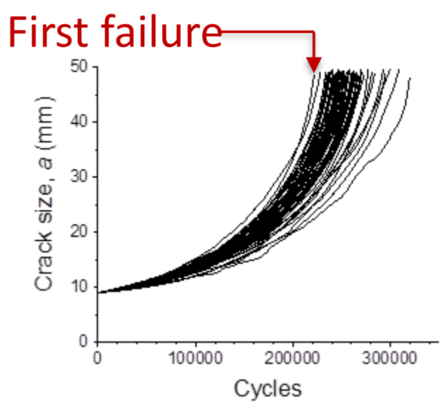
Assessment of Deterministic and Probabilistic Approaches to Inspection Intervals Specified by MIL-STD1530

Using two experimental data

Experimental Results Used in the Validation

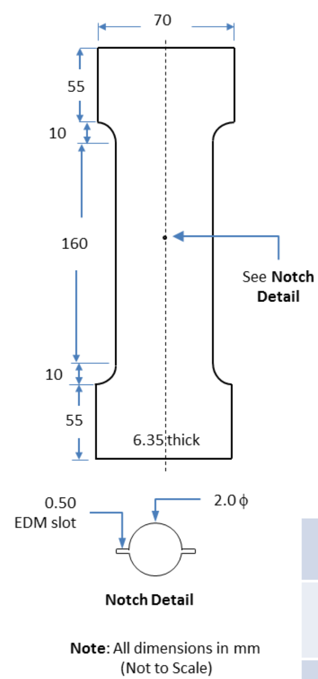
Virkler Data

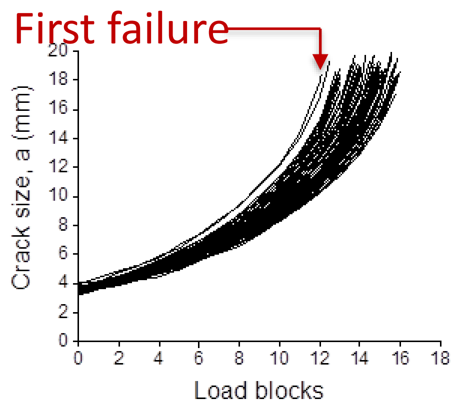




Material	Al 2024-T3
Load	Constant amplitude
Specimen tested	68

DST Data



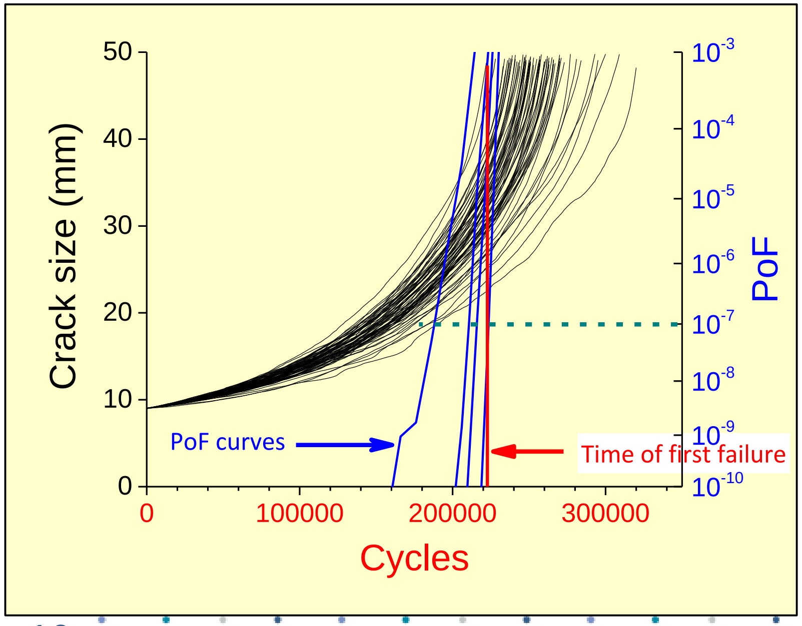


Material	Al 7075-T7351
Load	Variable amplitude
Specimen tested	85

Safety Inspection Prediction : Deterministic vs Probabilistic

Assessment using Virkler Data

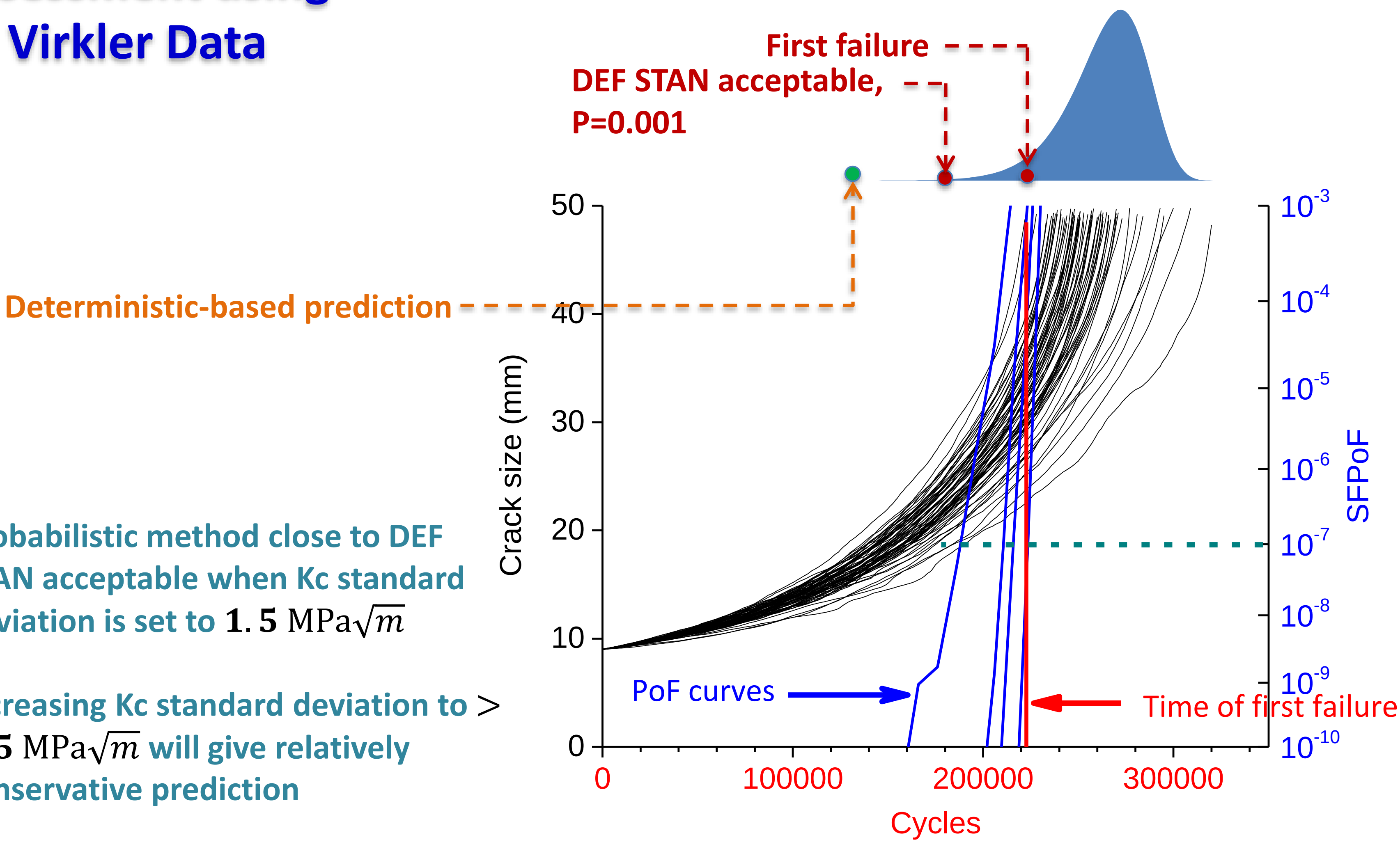
Minimum specimen fatigue life (Cycles)	Predicted inspection time (cycles)			
	Deterministic Kc = 25 MPa$\sqrt{m}$	Probabilistic Fixed Kc = 25 MPa$\sqrt{m}$	Probabilistic Mean Kc = 25 MPa$\sqrt{m}$	
			Kc standard deviation	
222798	129700	231117	1.5	188101
			1.0	210649
			0.8	215851
			0.5	223529



"next flight" = "next load cycle"

Safety Inspection Prediction : Deterministic vs Probabilistic

Assessment using Virkler Data

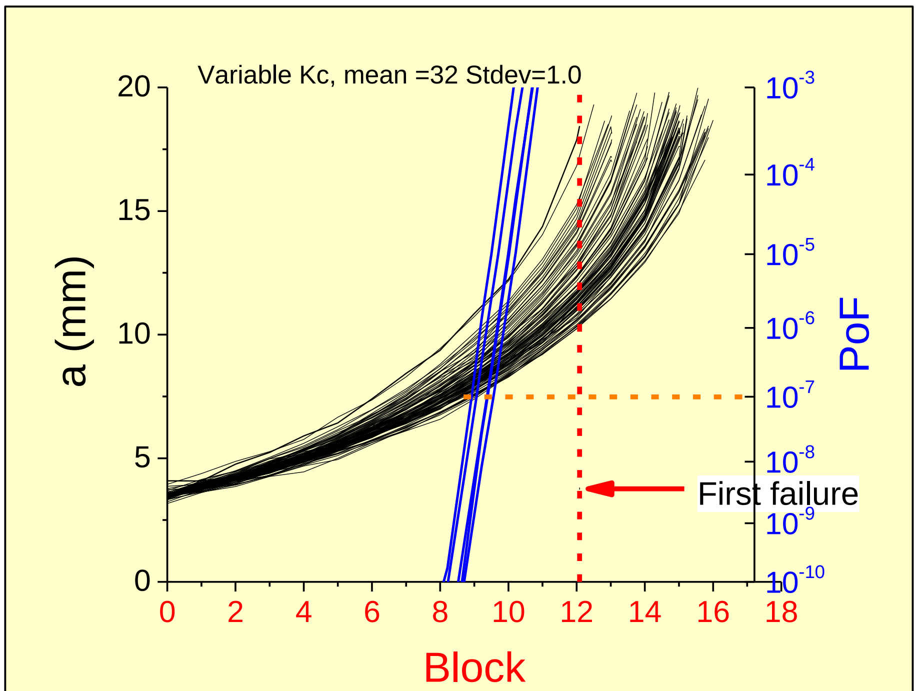


- Probabilistic method close to DEF STAN acceptable when Kc standard deviation is set to $\mathbf{1.5}\ \mathrm{MPa}\sqrt{m}$
- Increasing Kc standard deviation to > $\mathbf{1.5}\ \mathrm{MPa}\sqrt{m}$ will give relatively conservative prediction

Safety Inspection Prediction : Deterministic vs Probabilistic

Comparison with DST experimental data

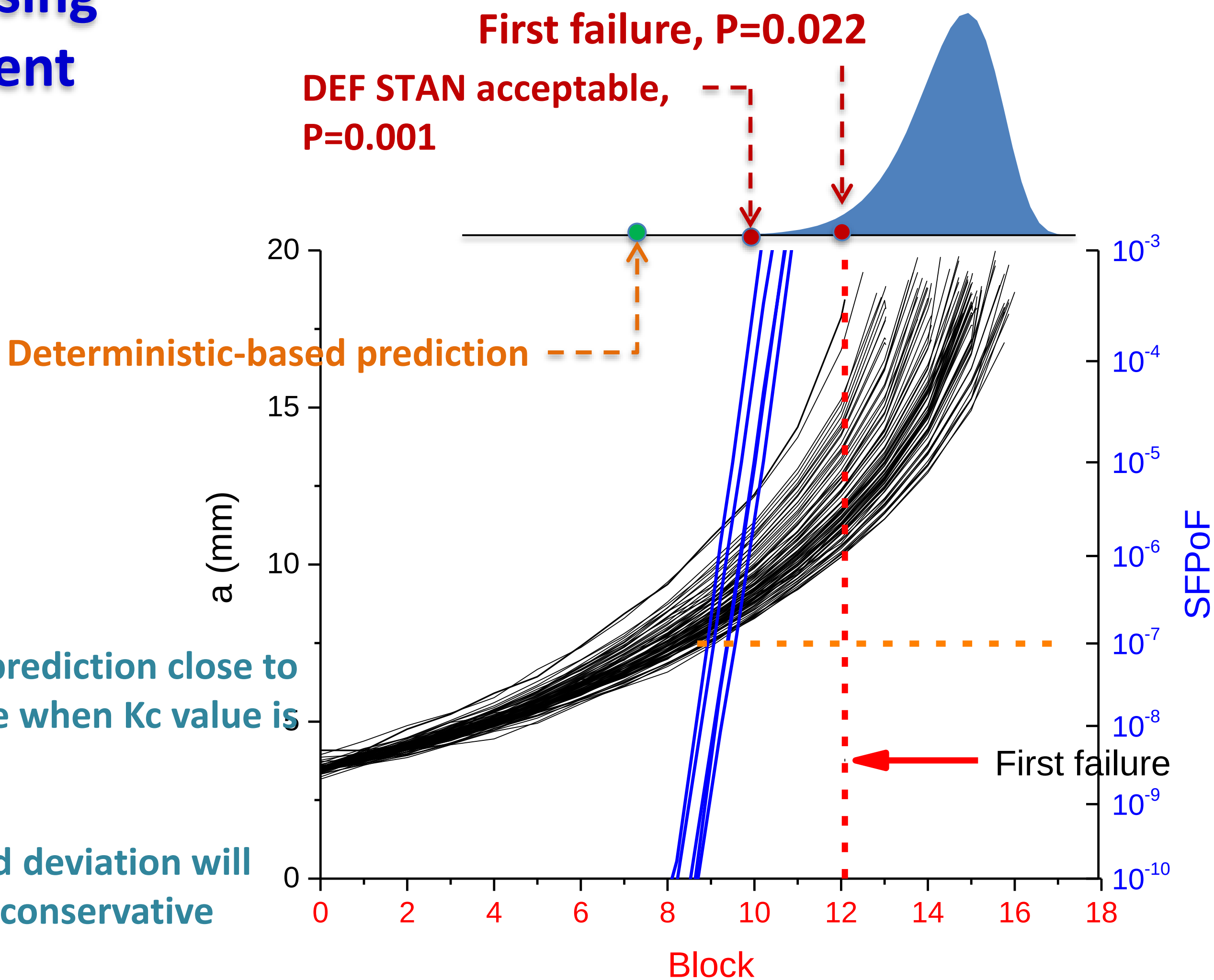
Minimum specimen fatigue life (Load blocks)	Trial	Predicted inspection time	
		Deterministic (Load blocks) Kc=32 MPa$\sqrt{m}$	Probabilistic (Load block) P=10^{-7} Kc=32 MPa$\sqrt{m}$
12.1	1	7.7	9.9
	2	7.6	10.4
	3	7.3	9.7
	4	7.8	10.2
	5	7.5	10.2



"next flight" = "next load block"

Safety Inspection Prediction : 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

Conclusions

- Probabilistic based prediction consistently close to DEF STAN acceptable risk
- Slight increase in the assumption of the variability of the fracture toughness value will result to conservative prediction from probabilistic method

Future Works

- Use of actual aircraft teardown crack data in the analysis
- Consider aircraft single flight hours as the metrics in the failure lifeing

Questions?