icaf 2013 presentation

The importance of flight spectrum cycle sequences to fatigue calculations.

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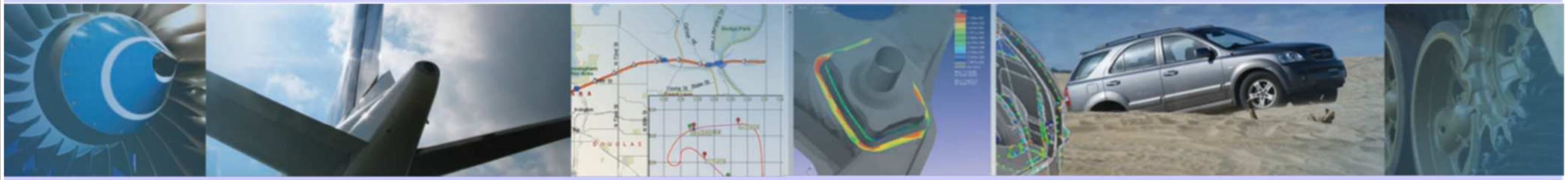
Agenda

- A fatigue question from 2007 and its multiple answers
- Load reconstruction methods
- Common factors
- Modification of the simple spectrum
- Transition cycles and cyclic residual stress
- MIL-A-8866 Cargo Transport Spectrum
- Conclusions



The Original Fatigue Question

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- estimate the fatigue damage (stress-life) arising from the 3 cycles of the 1000 hour operating spectrum below
- assume the component is manufactured from the aluminium alloy 2024 in the T3 condition using material data from MMPDS
- assume a geometric stress concentration, Kt = 4.

Label	Max Stress MPa (ksi)	Min Stress MPa (ksi)	Cycles per 1000 flight hours
A	207 (30)	69 (10)	5,000
B	138 (20)	-138 (-20)	1,000
C	69 (10)	-69 (-10)	20,000

Multiple Choice Answers

Load Reconstruction Method	Damage
Simple damage summation	0.394
Block concatenation	0.395
Sequential cycle concatenation	1.617
Random cycle concatenation	1.392

- four load reconstruction methods were used
  (to show the software options)
- …but, I did not know what answer was expected
- …and, I did not want to give the wrong fatigue damage
- …so, I gave all the answers that I could
- …but, I then had to explain why all 4 answers were different!

Load Reconstruction Methods – Simple Damage Summation

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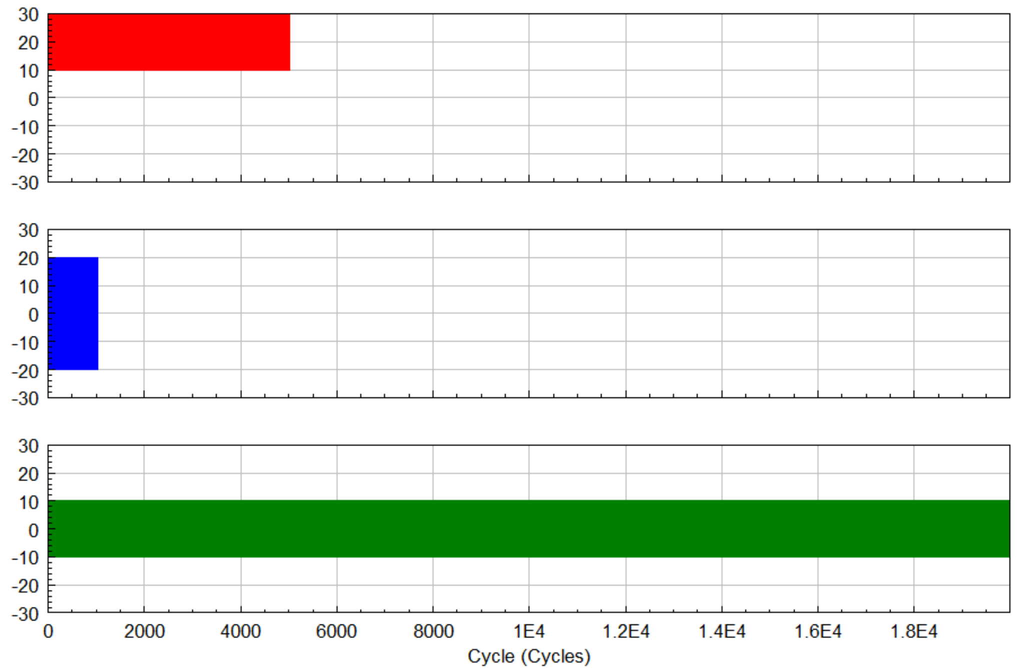
Expanded cycles shown for the simple damage summation method.

Fatigue analysis of each block of cycles is independent of the other blocks.



Max Stress MPa (ksi)	Min Stress MPa (ksi)	Damage per Cycle	Cycles per 1000 flight hours	Damage
207 (30)	69 (10)	3.333e-5	5,000	0.1666
138 (20)	-138 (-20)	1.610e-4	1,000	0.1610
69 (10)	-69 (-10)	3.334e-6	20,000	0.0667
		Total	26,000	0.394

Load Reconstruction Methods – Block Concatenation

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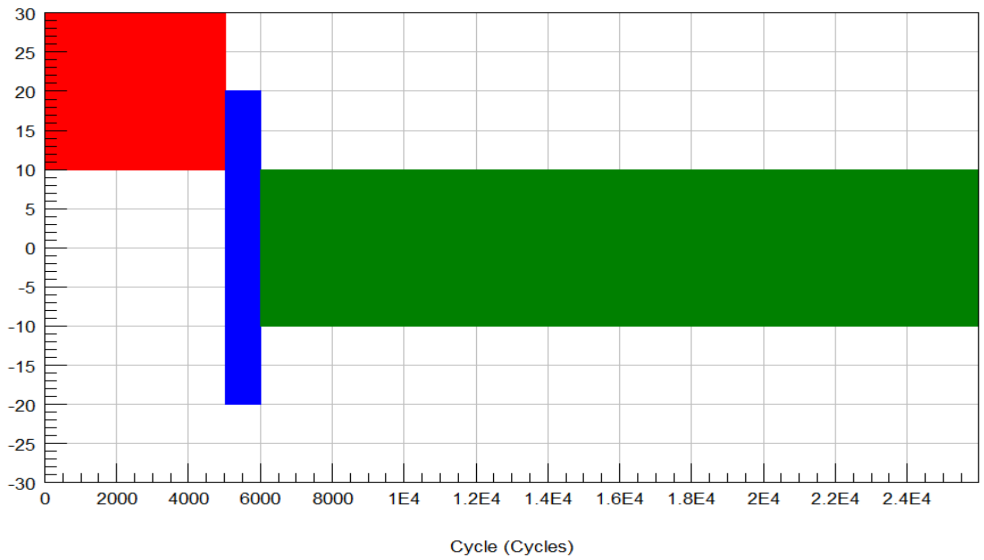
Expanded cycles shown for the block concatenation method.

This requires Rainflow cycle counting to identify the fatigue cycles.



Max Stress MPa (ksi)	Min Stress MPa (ksi)	Damage per Cycle	Cycles per 1000 flight hours	Damage
207 (30)	69 (10)	3.333e-5	4,999	0.1666
138 (20)	-138 (-20)	1.610e-4	999	0.1608
69 (10)	-69 (-10)	3.334e-6	20,000	0.0667
207 (30)	*-138 (-20)*	*5.157e-4*	*1*	*0.000516*
138 (20)	*69 (10)*	*7.018e-7*	*1*	*0.000001*
		Total	26,000	0.395

Load Reconstruction Methods – Sequential Concatenation

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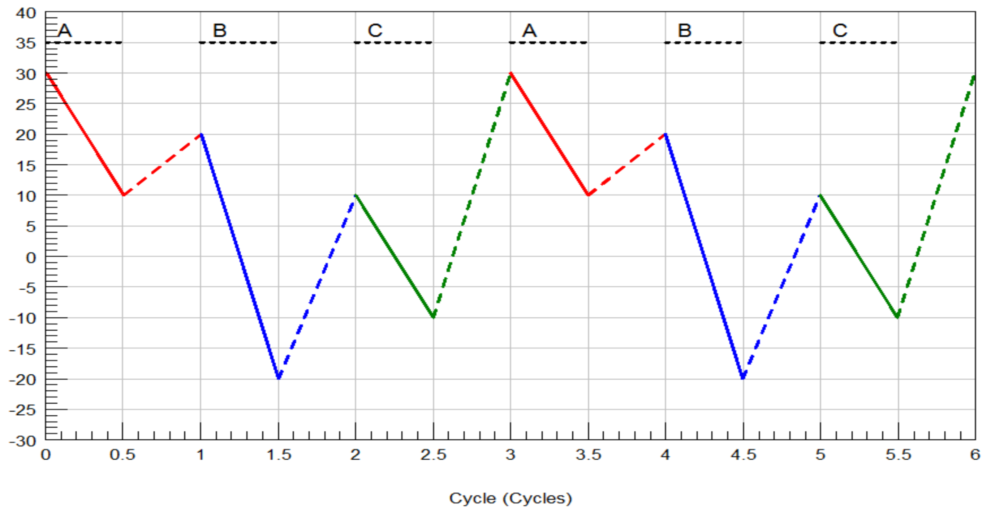
Expanded cycles shown for the first few cycles of the sequential concatenation method.

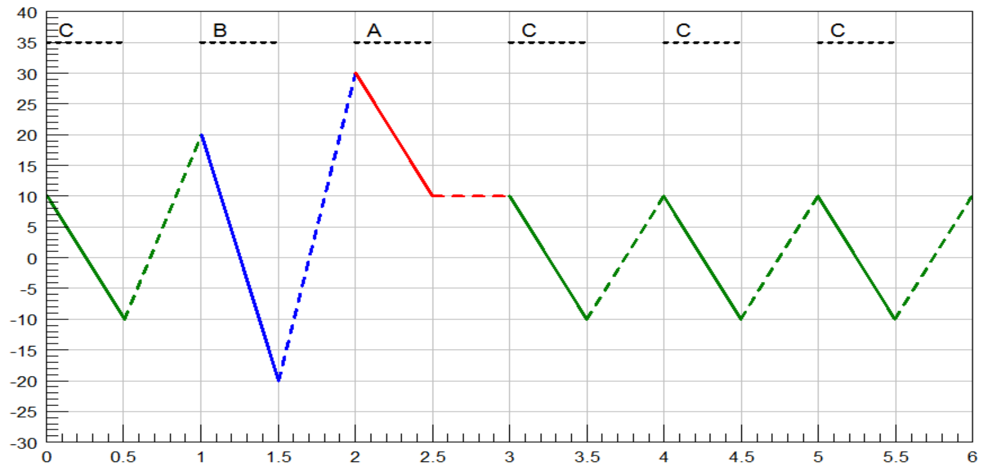
1 of cycle A, followed by 1 of B, followed by 1 of C until all the cycles are used.



Max Stress MPa (ksi)	Min Stress MPa (ksi)	Damage per Cycle	Cycles per 1000 flight hours	Damage
207 (30)	69 (10)	---	0	---
138 (20)	-138 (-20)	---	0	---
69 (10)	-69 (-10)	3.333e-6	16,000	0.0533
207 (30)	*-138 (-20)*	*5.157e-4*	*1,000*	*0.5157*
207 (30)	-69 (-10)	*2.618e-4*	*4,000*	*1.0470*
138 (20)	*69 (10)*	*7.018e-7*	*1,000*	*0.0007*
		Total	22,000	1.6167

Expanded cycles shown for the first few cycles of the random concatenation method.

The cycles are randomly distributed.



Max Stress MPa (ksi)	Min Stress MPa (ksi)	Damage per Cycle	Cycles per 1000 flight hours	Damage
207 (30)	69 (10)	3.333e-5	2992	0.09973
138 (20)	-138 (-20)	1.609e-4	568	0.09140
69 (10)	-69 (-10)	3.333e-6	18,080	0.06027
207 (30)	*-138 (-20)*	*5.157e-4*	*432*	*0.22280*
207 (30)	-69 (-10)	*2.617e-4*	*1,576*	*0.41250*
138 (20)	*69 (10)*	*7.018e-7*	*90*	*0.00006*
138 (20)	-69 (-10)	*5.775e-5*	*342*	*0.01975*
		Total	24,080	0.9065

Load Reconstruction Methods - Summary

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1000 hour operating spectrum

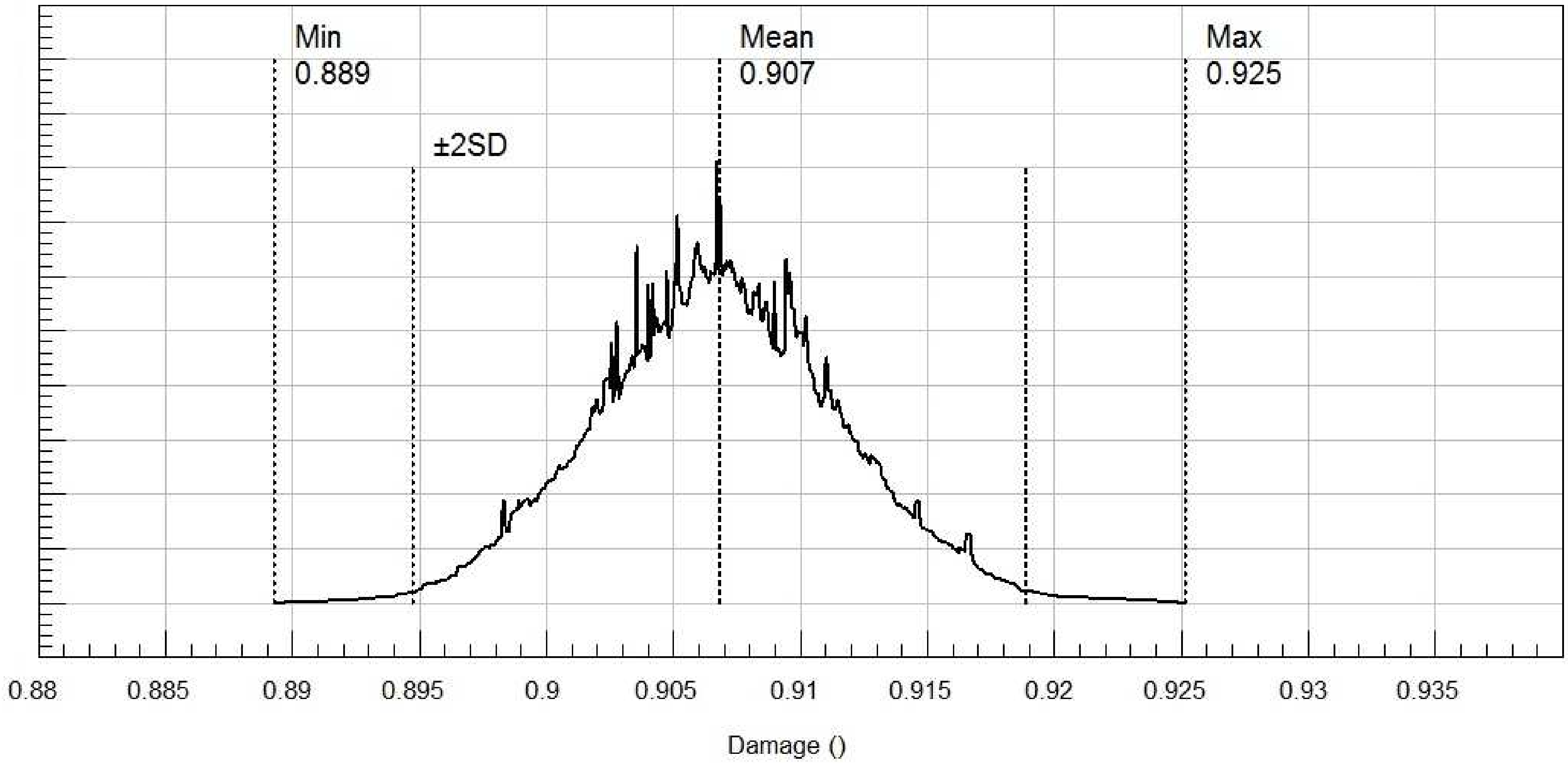
Label	Max Stress MPa (ksi)	Min Stress MPa (ksi)	Cycles per 1000 flight hours
A	207 (30)	69 (10)	5,000
B	138 (20)	-138 (-20)	1,000
C	69 (10)	-69 (-10)	20,000

Method	Cycle Sequence	Damage
Simple damage summation	A*5000 B*1000 C*20000	0.394
Block concatenation	A*5000 + B*1000 + C*20000	0.395
Sequential cycle concatenation	A+B+C+A+B+C+A+B+C+… (repeat until all cycles used)	1.617
Random cycle concatenation	C+A+A+B+C+B+C+A+C+C+… (repeat randomly until all used)	0.9065

Load Reconstruction Methods – Random Cycle Concatenation

- 1000 repeats of this random cycle concatenation gave a distribution of damage from 0.889 to 0.925.

- this is a narrow distribution, and quite different to the damage 1.392 originally answered – what is causing this difference?



Common Factors

- For operating spectra with high cycle counts, common factors are often extracted in order to reduce computational analysis time and reduce signal complexity.

- For this example; A*5000 + B*1000 + C*20000 , there are many common factors, for example;
  - ➔ (A*500 + B*100 + C*2000) * 10
  - ➔ (A*50 + B*10 + C*200) * 100
  - ➔ (A*5 + B*1 + C*20) * 1000

- Depending on the load reconstruction method, using these common factors will change the calculated fatigue damage

Common Factors – Stress Life Damage Table

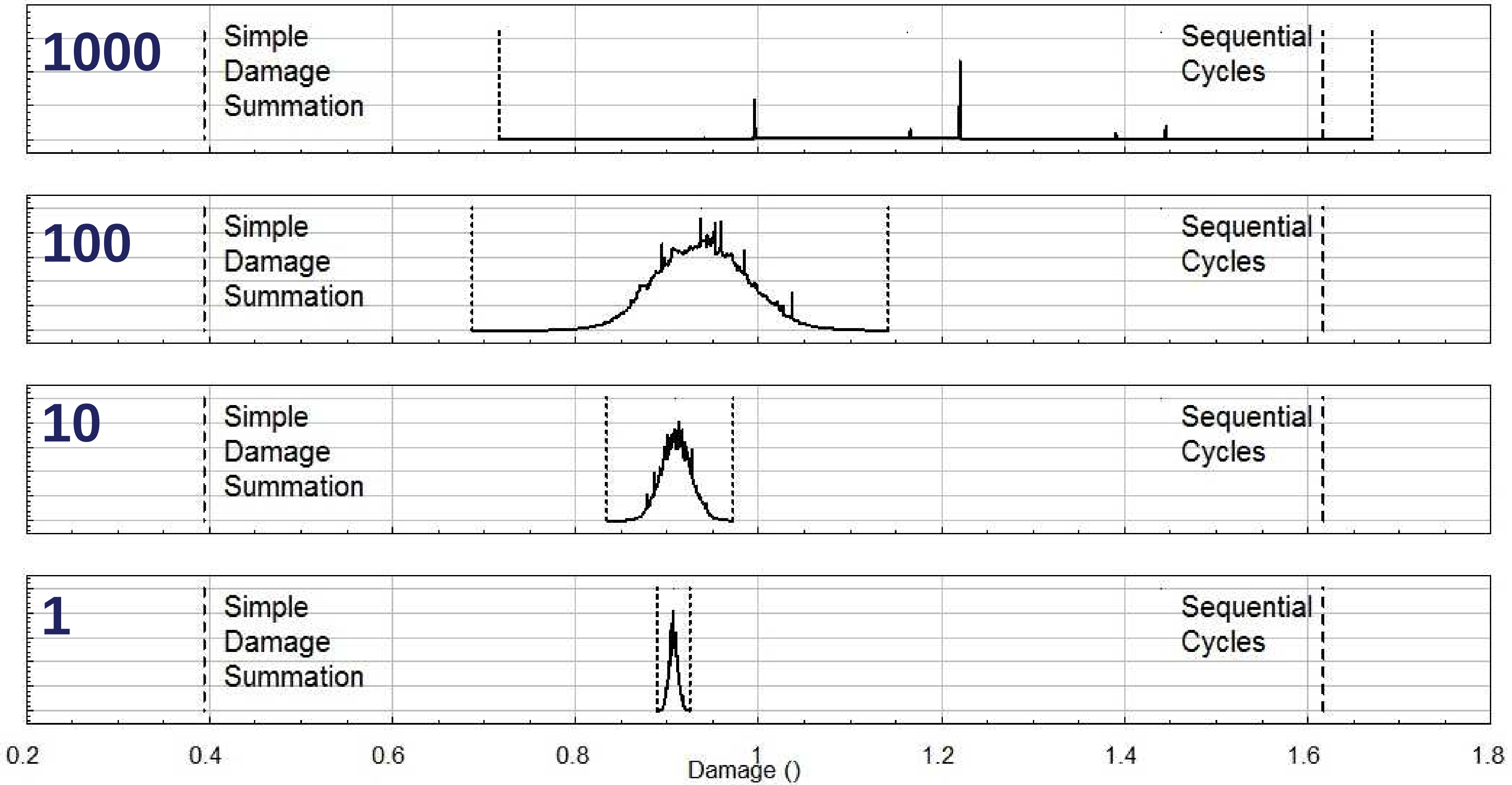
Method	Cycles in Sequence	Scale Factor	Stress-Life (SN) Damage	Total Damage
Simple Damage Summation	26 260 2600 26000	1000 100 10 1	0.000394 0.003943 0.039426 0.394257	**0.394**
Block Concatenation	26 260 2600 26000	1000 100 10 1	0.000716 0.004265 0.039748 0.394579	**0.716** **0.426** **0.397** **0.395**
Sequential Cycle Concatenation	26 260 2600 26000	1000 100 10 1	0.001617 0.016166 0.161660 1.616599	**1.617**
Random Cycle Concatenation	26 260 2600 26000	1000 100 10 1	not applicable	**0.716 to 1.67** **0.687 to 1.142** **0.834 to 0.972** **0.889 to 0.925**

Common Factors – Comparison with Damage Answer

Load Reconstruction Method (Damage Answer)	Effect of Common Factors (Damage Range)
Simple damage summation (0.394)	No effect on damage (0.394)
Block concatenation (0.395)	Changes the damage (from 0.395 to 0.716)
Sequential cycle concatenation (1.617)	Negligible effect on damage (1.617)
Random cycle concatenation (1.392)	Changes the damage and the damage variability (from “0.716 to 1.67”, to “0.889 to 0.925”)

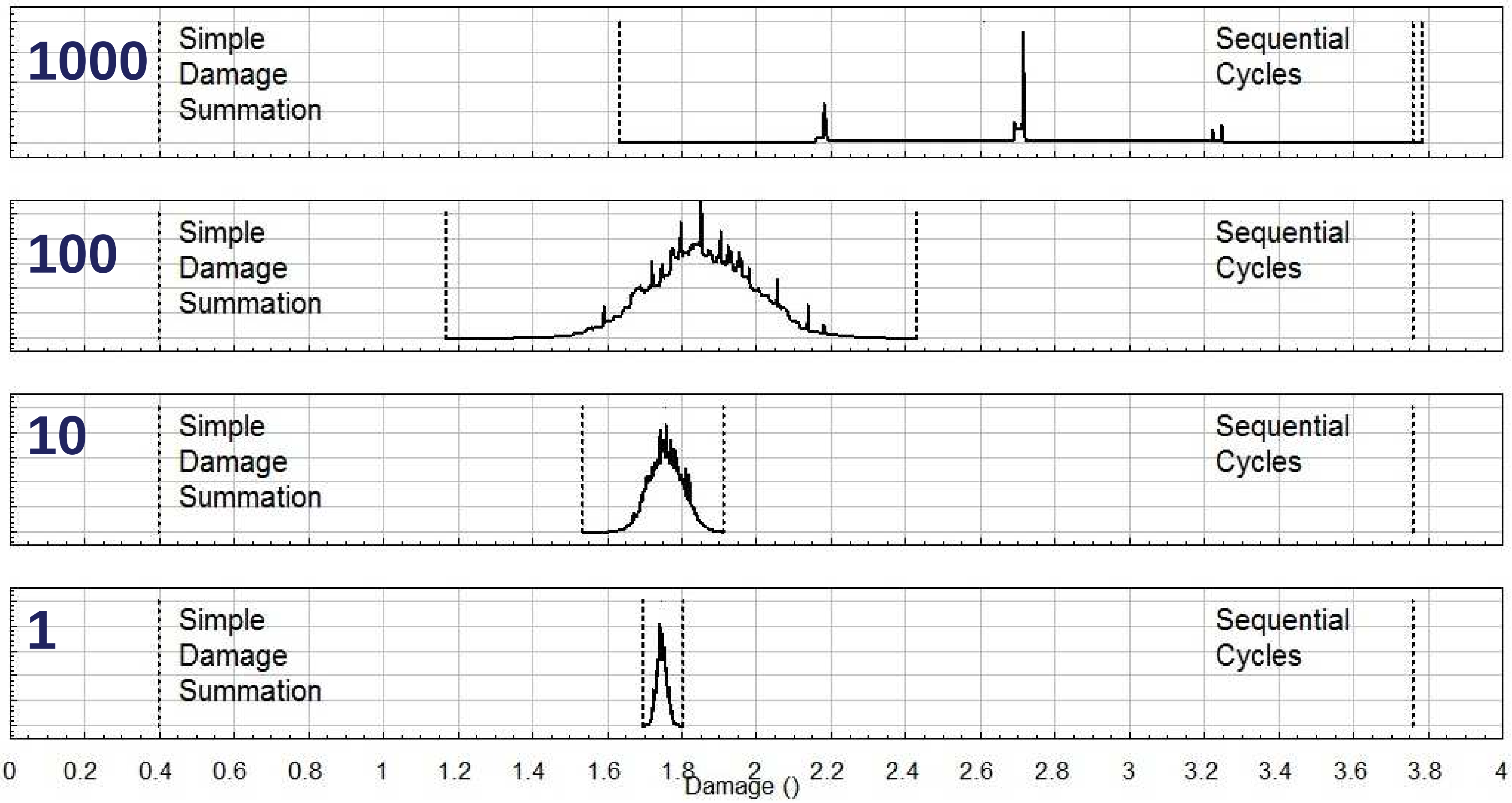
Common Factors – Stress Life Damage Distribution Plots

- Distribution of stress-life (SN) fatigue damage results for 1000 random sequences with common factors; 1000, 100, 10 and 1



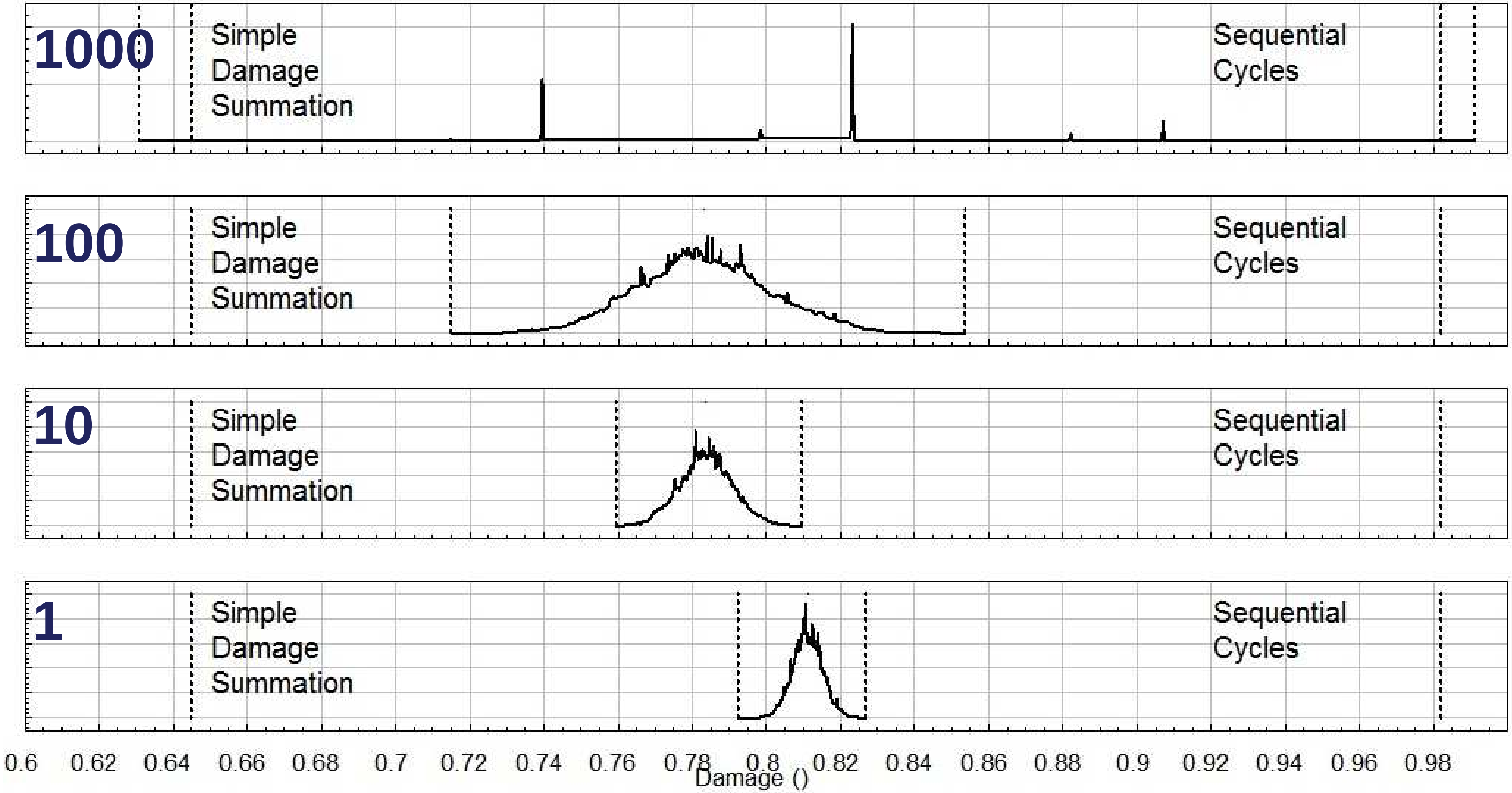
Common Factors – Strain Life Damage Distribution Plots

- Analyses repeated for strain-life (EN) with nominal material data to represent known 2024-T3 strain-life materials data, a Smith-Watson-Topper mean stress correction, and fatigue concentration factor 2.8



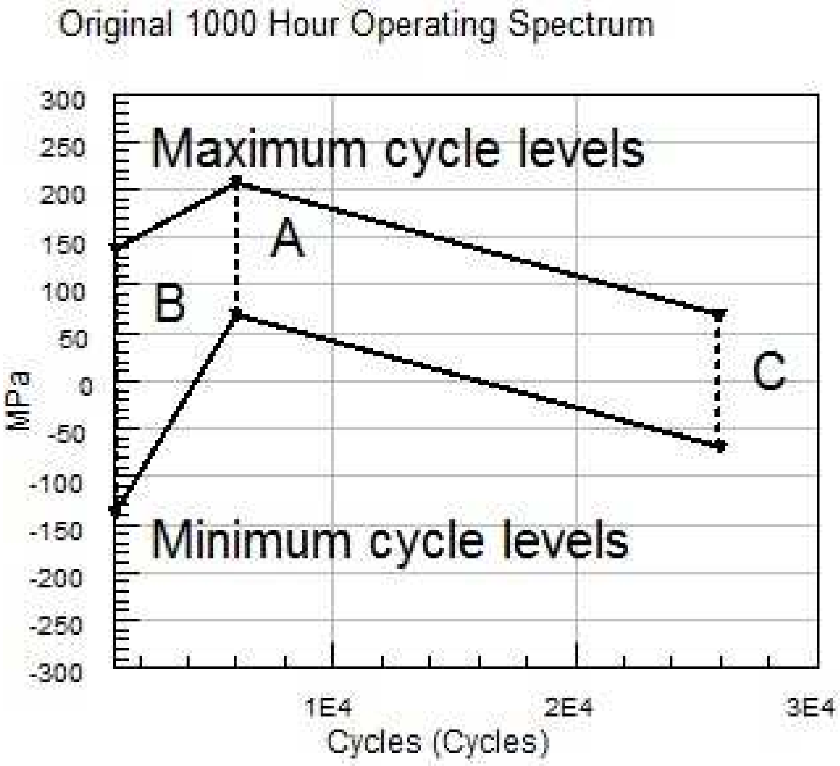
Common Factors – Crack Growth Damage Distribution Plots

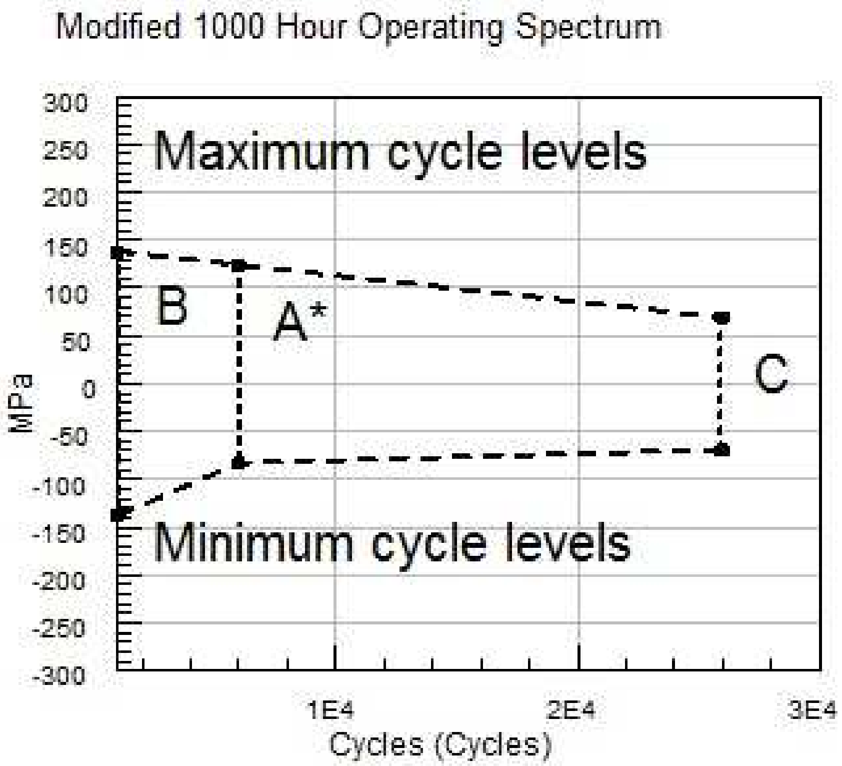
- Analyses repeated for a Walker crack growth model of a single edge crack in tension growing from 0.0254mm (.001in) to 25.4mm (1in)
- For consistency, results are shown as damage (= cycles / 26,000)



Modified 1000 hour operating spectrum

Label	Max Stress MPa (ksi)	Min Stress MPa (ksi)	Cycles per 1000 flight hours
A*	124 (18)	-83 (-12)	5,000
B	138 (20)	-138 (-20)	1,000
C	69 (10)	-69 (-10)	20,000





Modification of the Simple 1000 Hour Spectrum - Results

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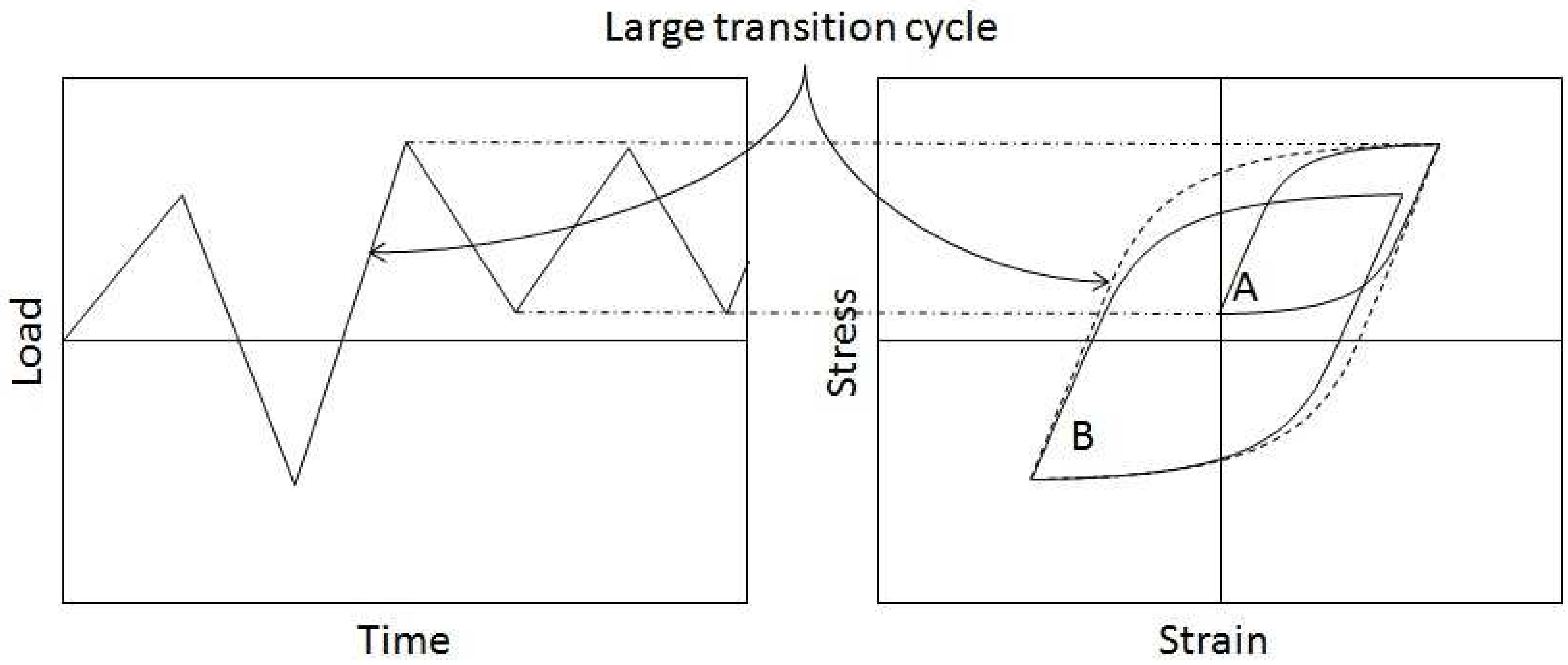
Method	Damage	Comments
Stress-Life (SN)	0.459	All sequence methods for all common factors, and all randomisations give exactly the same result.
Strain-Life (EN)	from 0.507 to 0.515	The sequence methods give exactly the same result for all of the common factors, but the result is slightly different for each sequence method. Randomising the cycles gives a distribution of results within a very narrow range.
Crack Growth	from 0.155 to 0.163	The sequence methods give slightly different results for each of the common factor and for each sequence method. Randomising the cycles only gives a distribution of results within a very narrow range when no common factor is applied. (ie. common factor = 1)

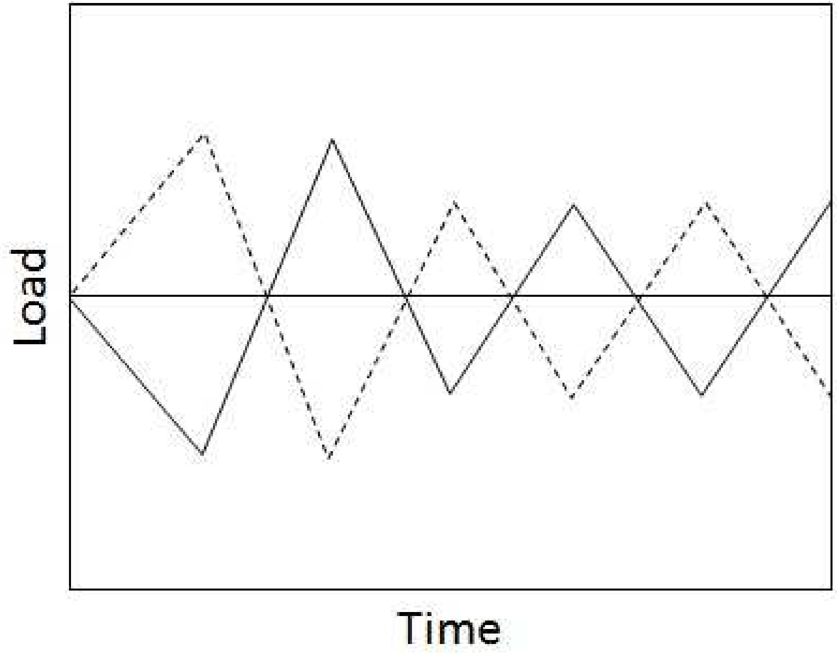
Transition Cycles

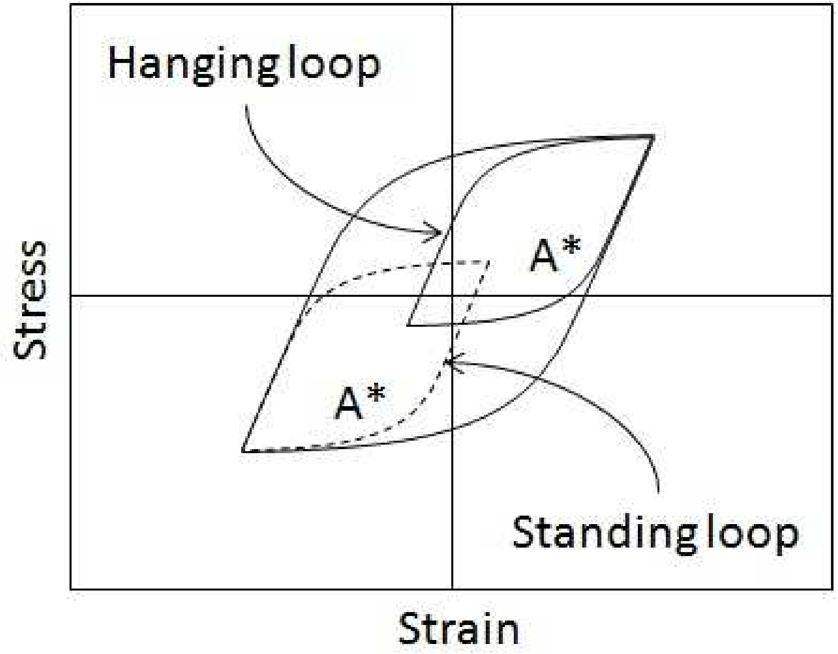
- The variability reduces significantly as the modification eliminates the large transition cycle.
- All the smaller cycles are now completely enclosed by the largest cycle.



Cyclic Residual Stresses

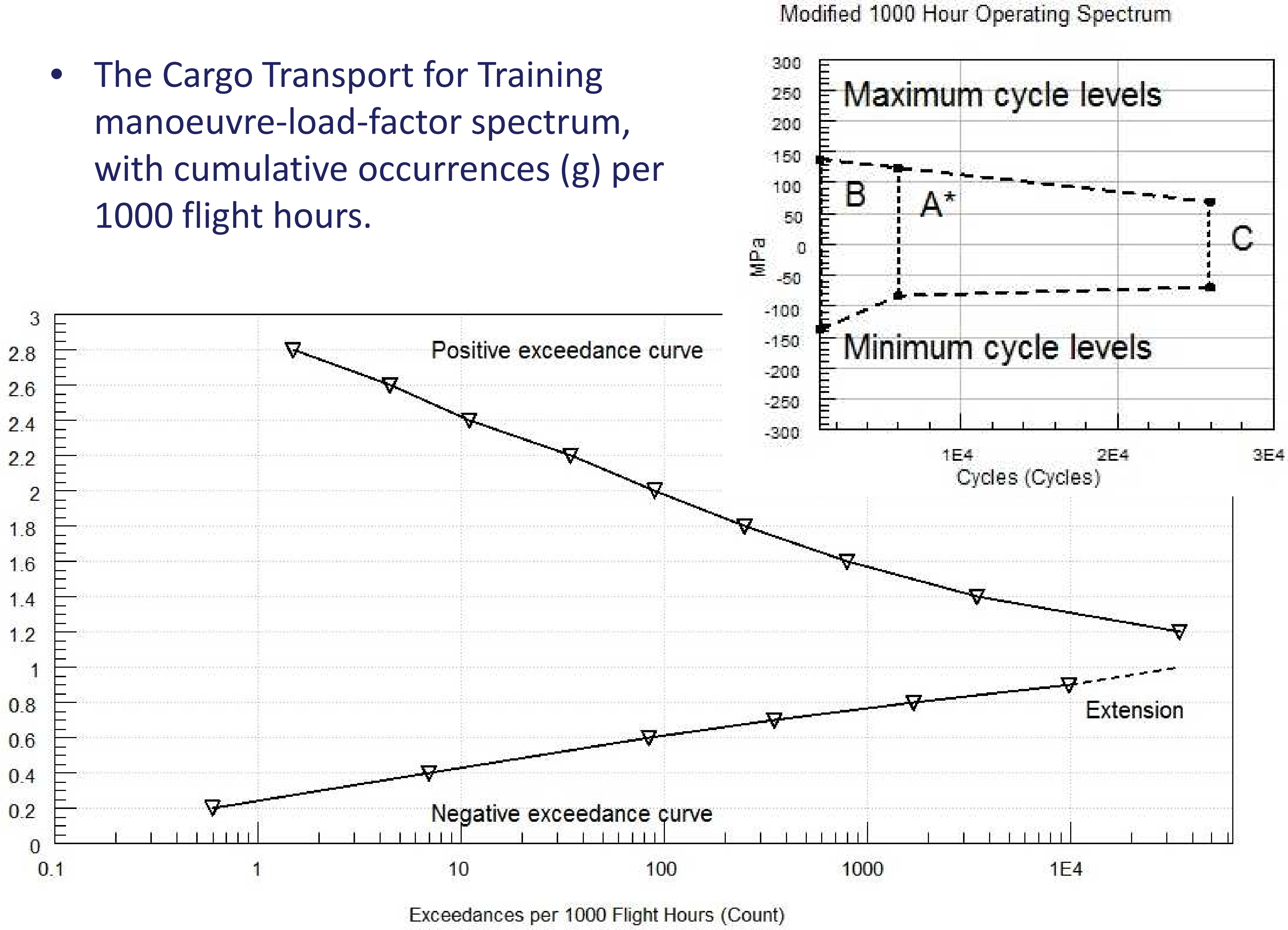
- The remaining variation in damage estimate is due to cyclic residual stresses.
- The residual stresses contribute a second-order effect on fatigue damage with residual tensile stresses yielding the most damage.
- However, simple block loading tests can contrive to create wholly hanging or wholly standing loops which over the entire duration of the test will impact significantly on the damage content





MIL-A-8866 Cargo Transport Spectrum

- The Cargo Transport for Training manoeuvre-load-factor spectrum, with cumulative occurrences (g) per 1000 flight hours.



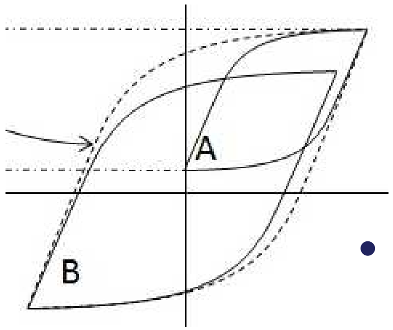
MIL-A-8866 Cargo Transport Spectrum - Results

- There are no common factors

Method	Damage	Comments
Stress-Life (SN)	0.0017	All sequence methods and all randomisations give exactly the same result.
Strain-Life (EN)	Separate: 0.001 Others: 0.0005	The separate sequence method gives a result distinct from the other sequence methods (Concatenate, Sequential and Random). Randomising the cycles gives a distribution of results within a very narrow range.
Crack Growth	Random: 0.04 Others: 0.0414	All sequence methods give exactly the same result. Randomising the cycles gives a distribution of results within a very narrow range.

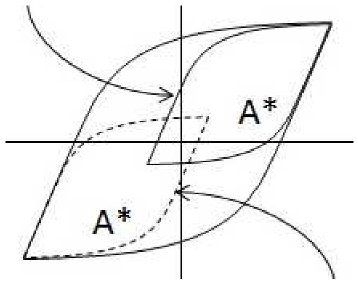
Conclusions

- There can be large variations in calculated fatigue damage due to transition cycles – a primary effect - introduced by the load reconstruction method.



- Where a load spectrum contains smaller amplitude cycles which exceed the bounds of larger cycles, then transition cycles will occur.
- When all the smaller cycles are completely enclosed by larger cycles then there are no transition cycles and the situation is avoided.

- There are smaller variations in calculated fatigue damage due to cyclic residual stresses – a secondary effect.



- Smaller cycles can be forced into a state of tensile residual stress (hanging) or compressive residual stress (standing).
- Block load sequences can contrive to force one state and this can lead to non-conservative fatigue damage calculations.

Conclusions – Is Load Reconstruction Required?

- The effect of transition cycles is always an issue where load history reconstruction is used to derive test rig drive signals. For computer-based fatigue analysis we often have a choice, Tom Deiters' AFGROW Blog (15-Jan-2013) "Spectra – to count or not to count" concludes;

  - If a spectrum has been developed **including** the correct transition cycles, and the cycle occurrences have been sequenced then load reconstruction is not required.
    (This is the simple damage summation method with no common factors giving stable results with no variation.)

  - If a spectrum has been developed **without including** the correct transition cycles, and the cycle occurrences have not been sequenced then load reconstruction is required in order to determine the transition cycles.
    (The spectrum must be reconstructed into a time history for cycle counting, and could give wide variation in results as a consequence of the load reconstruction method used.)

Conclusions – Next Steps?

- No transition cycles were introduced when using the Cargo Transport for Training manoeuvre-load-factor spectrum.
- What would a similar assessment of load reconstruction methods show when using more complex mixed mission spectrums?
- What would be the variability of the random cycle concatenation method?
- Does the sequential cycle concatenation method continue to be the worst case – most damaging – result?
- Is this abstract or relevant?

Conclusions – Abstract or Relevant?

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- An example of a real spectrum containing >1 million points, using block concatenation.
- This is the resulting stress at 1 node in a finite element model containing 1000's of nodes
- The big cycle forces a compressive residual stress, causing smaller following cycles to be less damaging.

Method	Normalised Damage
Simple damage summation	100%
Block concatenation	40%
Sequential cycle concatenation	43%

Conclusions – Abstract or Relevant?

- In email correspondence with Tom Deiters, and his discussions with Jim Harter, he made some additional comments;
  (which I hope I do not mis-represent)

  - Great to know that some one really reads the stuff. :-)

  - For many years Mssrs. Harter, Honeycutt, Brooks, and myself, have assumed that everybody just kinda knew about the importance of transition cycles, counting (when necessary) and especially sequencing. That everyone just kinda knew about plasticity effects. But we have become aware that it is just the opposite, hence the reason for my little notes in the blog.

  - But your findings are correct, in fact, we have found in the past that transition cycles or cycle counting (as appropriate) may account for 70 to 90 percent of the life, especially for wing assessments. The affect of transition cycles on load interaction is simply outstanding.

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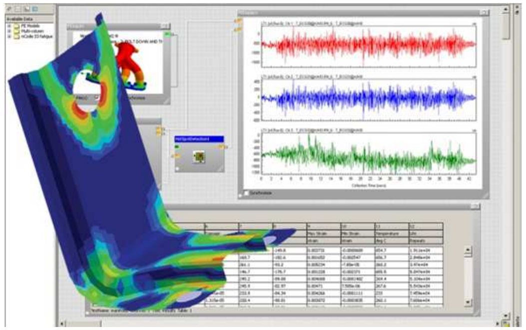

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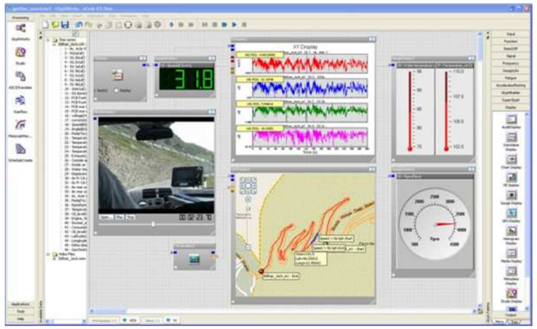

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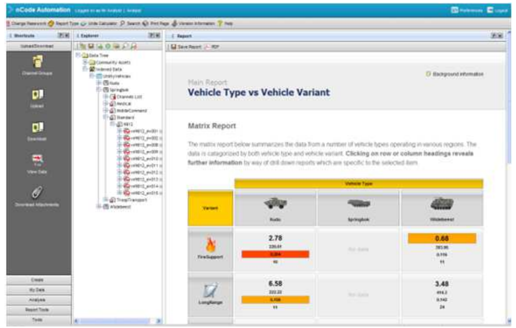

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