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Rotorcraft Maneuver-to-Maneuver Damage With Structural Usage Monitoring System Data

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16. Abstract

This study had two tasks. The first was to compare load pair methods. No functional difference was found between using the max-min, min-max, or sequenced load pairs in the determination of maneuver-to-maneuver (MTM) damage. Virtual flights were constructed based on the sequence of regimes as flown according to aircraft structural usage monitoring systems (SUMS). Comparing MTM damage determined by virtual flights against the sequenced load pairs showed they are accurate, though it is not adequate to simply rainflow count and determine damage from the series of load pairs. The damage induced by the half cycles of the load pairs must be subtracted out.

The second task of this study was the evaluation of different methods of MTM calculation. In all cases, the methods were compared to virtual flights using a biasing of mean + 2* standard deviation across aircraft.

Based on the results of this study, original equipment manufacturer (OEM) method B, equivalent cycles, equivalent loads, and regression approaches are not recommended. Virtual Flights or max-min approaches could be used directly for tracking damage of parts on a serial-number basis or for applying an MTM damage rate directly to a spectrum-based safe-life calculation. OEM method A was found to be fairly effective for spectrum-based safe-life calculations. In addition, binning of cycles by load is an accurate method for providing a statistical SUMS-based loads model.

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LIST OF ACRONYMS

AED	Aviation Engineering Directorate
CONUS	Continental United States
csv	Comma Separated Variable
EL	Endurance limit
FLS	Flight load survey
GAG	Ground-Air-Ground
M+2	Mean + 2* standard deviation
MTM	Maneuver-to-maneuver
N	Min-max load pair method
No-RSS	No-Rotor Startup and Shutdown
OEM	Original equipment manufacturer
RRA	Regime recognition algorithm
RSS	Rotor Startup and Shutdown
S	Sequenced load pair method
SN	Load versus cycle to failure
SUMS	Structural usage monitoring system(s)
TO	Takeoff
X	Max-min load pair method

EXECUTIVE SUMMARY

Virtual flights were constructed based on the sequence of regimes flown according to aircraft structural usage monitoring systems (SUMS). Time-history data for each regime were then gathered from flight load survey (FLS) testing. The recorded time-history data for each regime were then constructed based on the sequence from the flight. That overall time history could then be cycle counted and used to determine damage.

The first part of this study compared load pair methods: max-min, min-max, and sequenced. These methods assess maneuver-to-maneuver (MTM) damage by taking the maximum and minimum loads for a series of regimes, rainflow counting the cycles, and determining the damage. Max-min has the highest load first, min-max has the lowest load first, and sequenced has them in the actual order determined by FLS testing. It was determined through the comparison of several flights that there is no functional difference between using the max-min, min-max, or sequenced load pairs in the determination of MTM damage.

Comparison of the load pair methods against the virtual flights showed that the sequenced load pairs are accurate, though it is not adequate to simply rainflow count and determine damage from the series of load pairs. The damage induced by the half cycles of the individual maneuver load pairs must be subtracted out.

The second part of this study was the evaluation of different methods of MTM calculation. In all cases, the methods were compared to virtual flight simulations of 3362 collected flight hours using a biasing of mean + 2* standard deviation (M+2) across aircraft.

The max-min load pairing method was studied over all the available recorded flight times. This evaluation repeated the virtual flight damage calculations but with each regime represented by only two load points, with the maximum load first. With the half cycles of within-regime damage removed, the max-min approach was found to agree well with the virtual flight damage calculations, verifying that use of sequenced load pairs is a valid approach to determining MTM damage.

The original equipment manufacturer (OEM) method B assumes a certain number of Ground-Air-Ground (GAG) cycles per hour and matches them with the maximum loads recorded in the FLS. Industry techniques for minimizing the effect of high loads infrequently incurred were applied. The first step is to separate cycles with and without engine shutdowns. Step two is to determine the percentage of damage based on time in the spectrum for the most damaging regimes. This method was found to be erratic, with some parts being too heavily penalized and others having safe-lives calculated that are much too long. This approach is not recommended.

The OEM method A sorts regimes from highest load to lowest maximum load, and then from lowest to highest minimum load. The sorted regimes are paired up based on the occurrences of each in the spectrum. The first 6000 paired occurrences (for a 1000-hour spectrum) are counted for damage. This approach was found to be fairly effective. A very long life part had its life significantly reduced, but even the reduced life was 10 times longer than the aircraft life. In addition, the 6000 occurrences used by the OEM could possibly be reduced to 5000 with more flight data, which might reduce the statistical variation.

Equivalent cycle methods involve choosing a load and determining how many cycles should be applied to match the virtual flight MTM damage. The loads used were from the OEM method A pairs at intervals of 1000 occurrences. This approach provided fairly consistent results across parts; however, there are two issues that make it problematic. First, it is purely empirical. No general determinations can be made across platforms, and it is driven by the part that is most sensitive to MTM damage. This means the same study would have to be repeated for each platform and should include all parts. Second, there is some sensitivity for MTM-driven parts to changes in load and cycles. This means that damage would have to be calculated across all parts and the equivalent cycle value carefully chosen. Therefore, though it is possible to get good results, the sensitivities and effort required for this method would encourage use of a different approach.

Equivalent loads methods involve picking a number of cycles and evaluating what load is needed to match the virtual flight damage. It is similar to OEM method B. This approach was bounded at the lowest number of cycles with 3.4 takeoffs (TO)/hr and at the highest number of cycles with 168 recognized regimes/hr. Load comparisons were made to the maximum GAG load from the FLS and the endurance limit for each part from the load vs. cycles to failure (SN) curve. This approach was found to have very inconsistent results and is not recommended for use.

Regression was conducted when the regime occurrences were independent variables and the amount of MTM damage from the virtual flights were dependent variables. Regression using just traditional GAG counters (TO, shutdowns, etc.) was a poor predictor of MTM damage. This is further confirmation that OEM method B and equivalent cycles methods are not valid. Using many regimes in the regression initially looked promising; however, life calculations using all regimes were found to be inconsistent. The major issue is that the quality of the regression was part dependent. It was also found that MTM-driven parts were the most sensitive. Trying to apply regression coefficients directly to damage SUMS is also complicated by negative coefficients. Regression methods applied to regimes are not recommended.

None of the previous methods are suitable for a full probabilistic approach to determine a reliability-based part life. To provide that, a SUMS-based loads model was used when the occurrences per hour were sorted into load bins. Each bin then has a statistical distribution across aircraft that can be part of a reliability assessment. Though the mechanics of the calculations are a bit involved for deterministic- or spectrum-based methods, the binning of loads demonstrated a consistently valid approach. There was some inconsistency for a small number of large bins, but results were very good when there were at least 20 bins.

Based on the results of this study, OEM method B, equivalent cycles, equivalent loads, and regression approaches are not recommended. Virtual Flights or max-min approaches could be used directly for tracking the damage of parts on a serial-number basis or for applying an MTM damage rate to a spectrum-based safe-life calculation. OEM method A was found to be fairly effective for spectrum-based safe-life calculations. In addition, binning of cycles by load is an accurate method for providing a statistical SUMS-based loads model.

1. INTRODUCTION

1.1 PURPOSE

There is an ongoing partnership between the FAA and Army Aviation Engineering Directorate (AED) to support the enhancement of FAA AC-29-2C, MG-15 for the use of structural usage monitoring system- (SUMS-) based data. As part of this partnership, AED evaluated methods of incorporating SUMS-based maneuver-to-maneuver (MTM) damage in determining the life of fatigue-critical parts.

1.2 BACKGROUND

The task collected 2198 usable regime recognition algorithm (RRA) files for 24 aircraft from three continental United States (CONUS) locations with 3362 flight hours. The aircraft were flown as part of CONUS operations and pre-deployment training. The RRA files identify the maneuvers as they were flown. An additional 3263 RRA files were accessed, but they consisted only of auxiliary power time and were discarded because they did not include a rotor start.

Flight load survey (FLS) time histories of all the relevant maneuvers for five selected parts were also collected. These were combined using the information from the RRA files to generate virtual flight histories. They were also processed to provide maximum and minimum loads and to determine which occurred first.

The load versus cycles to failure (SN) curves for the five parts were the same as those used by the original equipment manufacturer (OEM). Damage calculations were completed both manually, using Microsoft® Excel®, and by entering the SN curves into HBM nCode. The two approaches agreed closely.

In general, the methods were compared by determining the total damage for each part and then subtracting out the sum of the within-regime damage from each individual maneuver, with the remainder being the MTM damage.

One comparison was between simplified load pair sequences [1], in which the MTM loads were modeled based on the maximum and minimum load within each regime. Based on the sequence of regimes, they were paired either with the maximum first (referred to as max-min), with the minimum first (referred to as min-max), or in the actual order as seen in the time history (sequenced). The calculated damage was compared between each method of sequencing the load pairs and against virtual flights.

Methods for calculating the MTM damage contribution to the overall damage of a part were compared. These methods included two different OEM-based methods, several variations using equivalent loads (given a number of cycles), variations of equivalent cycles (given a load), load pairing sequences, regression, and a method in which the loads were binned. In every case, the comparisons were against lives based on the virtual flights and biased by the mean + 2* standard deviation (M+2) to maintain reliability in a way consistent with U.S. Army guidelines for spectrum regime time described in ADS-79 [2].

1.3 LEGACY SAFE-LIFE FATIGUE METHOD

The legacy method of determining the safe life of fatigue-critical parts has three inputs: the SN curve, the flight loads, and the usage spectrum. The spectrum and flight loads define the number of cycles at each load. Each load cycle is compared to the SN curve to determine the amount of damage, and the damage from all cycles is combined through Miner’s rule. The life of the part is the inverse of the accumulated damage rate.

The shape of the SN curve is typically determined by numerous coupon tests of the specific material. The magnitude of the curve is then adjusted based on a limited number of tests of the actual component.

The flight loads are determined for each regime from the FLS of a heavily instrumented aircraft. Steady-state maneuvers typically use the Top-of-Scatter load or the highest load observed during that maneuver. Transient maneuvers often use the cycle-counted damage of the most damaging instance of that particular regime.

The spectrum defines how many times a transient regime occurs or how long the aircraft is in each steady-state regime. There is also a definition of how many Ground-Air-Ground (GAG) cycles the aircraft will experience during flight. Two methods of applying GAG damage are demonstrated in this report, but the intent is to use the extreme loads the aircraft will see to account for the large cycles that occur between maneuvers.

The amount of damage for time/occurrences of each regime in the spectrum time frame is added to the damage calculated based on GAG cycles to determine the life of the part.

2. DISCUSSION

2.1 CONCEPTS

2.1.1 Load Pair Sequences

Three load pair sequencing methods were compared in this study. They are all based on the maximum and minimum peak loads for each given regime. Once the load pairs are arranged in the defined sequence, rainflow cycle counting is used for each given flight to determine damage. Rainflow cycle counting is used to reduce a spectrum of varying stress into a set of simple stress reversals. It allows the application of Miner’s rule to assess the fatigue life of a structure subject to complex loading.

The sequenced load pair method (S) uses the peak loads in the order in which they actually occur within the regime. If the minimum load comes first in the regime, it is used first in the sequence. The max-min load pair method (X) always puts the maximum load first and the min-max method (N) always puts the minimum load first, as shown in tables 1 and 2.

Table 1. Load pair example regimes

Regime	Max	Min	First
1	10	-10	Max
2	9	-9	Min
3	8	-8	Min

Table 2. Load pair sequence example

Load Step	X	N	S	Regime
1	10	-10	10	1
2	-10	10	-10	1
3	9	-9	-9	2
4	-9	9	9	2
5	8	-8	-8	3
6	-8	8	8	3

2.1.2 M+2 and Life Comparisons

ADS-79 states that when developing a new spectrum, reliability can be assumed to be maintained if the SUMS-based spectrum is biased by using the M+2 for each damaging regime. Nominally, each data point for calculation of the statistical parameters is one aircraft with a significant number of flight hours (approximately 200 hours). Statistically, there should also be at least 25 aircraft so that the confidence interval can be kept relatively tight.

For example, assuming the mean of the 25 aircraft for time in regime N is 100 seconds and the standard deviation is 20 seconds, without doing additional reliability studies, the SUMS-based spectrum time in regime N would be 140 seconds. The 40 seconds added to regime N would be subtracted out of a regime that is non-damaging for all fatigue-critical parts to maintain 100% spectrum time.

Though MTM damage is not the same as regime damage, for consistency (and because the statistical reasoning would be the same), the M+2 is retained as the appropriate bias.

Data were collected on 24 aircraft ranging from 14–245 hours of flight time, with an average of 129 hours. This is somewhat lower than the desired amount of data, though the damage rates appear to have a reasonable distribution. The 14-hour aircraft did have some of the highest damage for several of the gages, but it was not excessively outside the population and was retained in the calculations.

Calculated lives are used as a basis for comparison of the different methods. In most cases, MTM damage is the difference between calculated total damage and the sum of the cycle counted within-regime damage. For consistency of results, the same within-regime damage is used for all methods when calculating life. There is a very slight difference between the lives based on the

M+2 total damage and the sum of M+2 regime and M+2 MTM damage. The sum of regime and MTM damage is used as the ideal reference for MTM calculation methods. The better methods are under the reference life to ensure conservatism, but not so far below that the conservatism becomes excessive.

2.2 PARTS STUDIED

Five components are studied in this report, and they are identified throughout by the numerical identifiers for the FLS gages that serve as their substantiating parameter. The parts are listed in table 3.

Table 3. Study components

Component Name	Measurement ID	SN Curve Type/Corrected	Unit
Lead-Lag Damper	<1021>	Mean Stress Curve/No Correction	LB
Drive Shaft	<1023>	R Ratio Curve	IN-LB
Collective Bellcrank	<1407>	R Ratio Curve	LB
TR Gearbox Housing	<1913>	Mean Stress Curve	PSI
Pitch Housing Lug	<71851>	R Ratio Curve/No Correction	LB

Each part has a matching SN curve, as shown in section 3.3. The Goodman correction is used by the OEM on three of the parts, but not the other two. The equation used for the Goodman correction is based on the curve type.

For mean stress curves:

$$Fma = (Fu-Fms)/(Fu-Fs)*Fa \tag{1}$$

For R ratio curves:

$$Fra= (Fa*Fu)/[Fu - Fs + Fa*(1+R)/(1-R)] \tag{2}$$

where Fma is alternating load at specified mean load, Fms is specified mean load, Fra is alternating load at specified R, Fu is ultimate load for the component, Fs is steady load, Fa is alternating load, and R is specified load ration (min load/max load).

These parts were selected as part of an earlier study [3] that tracked part damage through actual SUMS-based usage. This study found that this was a very good subset of parts consisting of long- and short-life parts and parts with lives dominated by GAG damage and parts dominated by regime damage.

2.3 LOAD PAIR METHODS

The first part of the study was to evaluate the effectiveness and differences of the load pairing methods.

For specific review, the most damaging flights for each of the measurements were evaluated for max-min damage (X), min-max damage (N), sequenced damage (S), and then compared with the virtual flights. The methods of damage calculation are discussed in section 3.4. The damage calculation results for these five flights are shown in tables 4–8. Note that in these comparisons, the paired load damage is based on a rainflow count of all the maximum and minimum points from the regimes in the RRA file and no within-regime damage has been subtracted. Therefore, all of the load pair methods shown here are overpredicting the total damage. The flights are identified in each column by date. The Regime row is the summed damage from the regime full-time histories. The X total is the damage calculated from the max-min time history plus the regime damage. The virtual flight total is the total damage from the rainflow-counted virtual flights.

Table 4. The <1021> load pair comparison

	2010-0617	2010-0630	2010-0706	2010-0720	2011-0504
<1021>X	249.10E-6	919.70E-6	841.23E-6	1.47E-3	178.98E-6
<1021>N	246.33E-6	918.28E-6	844.34E-6	1.47E-3	179.86E-6
<1021>S	231.17E-6	856.16E-6	804.76E-6	1.41E-3	178.98E-6
<1021>V	63.06E-6	137.45E-6	135.93E-6	238.92E-6	88.95E-6
Regime	1.19E-3	4.83E-3	3.70E-3	8.19E-3	185.50E-6
X Total	1.44E-3	5.75E-3	4.54E-3	9.66E-3	364.48E-6
V Total	1.26E-3	4.96E-3	3.84E-3	8.42E-3	274.45E-6

Table 5. The <1023> load pair comparison

	2010-0617	2010-0630	2010-0706	2010-0720	0211-0504
<1023>X	17.74E-6	5.92E-6	5.92E-6	8.32E-6	000.00E+0
<1023>N	17.74E-6	6.26E-6	5.92E-6	8.32E-6	000.00E+0
<1023>S	17.74E-6	5.92E-6	5.92E-6	8.32E-6	000.00E+0
<1023>V	17.74E-6	5.40E-6	5.64E-6	8.32E-6	000.00E+0
Regime	000.00E+0	339.30E-9	000.00E+0	000.00E+0	000.00E+0
X Total	17.74E-6	6.26E-6	5.92E-6	8.32E-6	000.00E+0
V Total	17.74E-6	5.74E-6	5.64E-6	8.32E-6	000.00E+0

Table 6. The <1407> load pair comparison

	2010-0617	2010-0630	2010-0706	2010-0720	2011-0504
<1407>X	27.94E-6	3.78E-3	3.21E-3	1.47E-3	549.46E-9
<1407>N	27.94E-6	3.73E-3	3.21E-3	1.49E-3	549.46E-9
<1407>S	27.94E-6	3.75E-3	3.21E-3	1.47E-3	549.46E-9
<1407>V	27.82E-6	869.37E-6	644.85E-6	400.48E-6	549.46E-9
Regime	121.40E-9	11.48E-3	10.64E-3	4.62E-3	000.00E+0
X Total	28.06E-6	15.26E-3	13.85E-3	6.09E-3	549.46E-9
V Total	27.94E-6	12.35E-3	11.28E-3	5.02E-3	549.46E-9

Table 7. The <1913> load pair comparison

	2010-0617	2010-0630	2010-0706	2010-0720	2011-0504
<1913>X	218.83E-6	779.07E-6	1.05E-6	1.30E-3	3.66E-3
<1913>N	218.83E-6	780.54E-6	1.05E-3	1.30E-3	3.66E-3
<1913>S	218.83E-6	778.55E-6	1.05E-3	1.30E-3	3.66E-3
<1913>V	194.58E-6	724.34E-6	981.73E-6	1.17E-3	3.65E-3
Regime	62.04E-6	85.55E-6	146.70E-6	330.20E-6	000.00E+0
X Total	280.87E-6	864.62E-6	1.20E-3	1.63E-3	3.66E-3
V Total	256.62E-6	809.89E-6	1.13E-3	1.50E-3	3.65E-3

Table 8. The <71851> load pair comparison

	2010-0617	2010-0630	2010-0706	2010-0720	2011-0504
<71851>	15.64E-6	135.37E-6	195.65E-6	156.79E-6	67.28E-6
<71851>	15.64E-6	135.37E-6	195.65E-6	156.79E-6	67.28E-6
<71851>	15.64E-6	135.37E-6	195.65E-6	156.79E-6	67.28E-6
<71851>	7.84E-9	-11.99E-9	-2.61E-9	39.31E-9	-29.25E-9
Regime	59.94E-6	724.10E-6	489.30E-6	592.90E-6	101.50E-6
X Total	75.58E-6	859.47E-6	684.95E-6	749.69E-6	168.78E-6
V Total	59.95E-6	724.09E-6	489.30E-6	592.94E-6	101.47E-6

Histograms of damaging cycles for two of the flights for <1407> are shown in figures 1 and 2. Figure 1 is flight 2010-0630, which is dominated by within-regime damage. Figure 2 is flight 2010-0617, which is dominated by MTM damage. In these charts, only the damaging cycles are shown to reduce visual clutter. Loads are divided into 50 bins for display, and the color scale is a log scale of the damage.

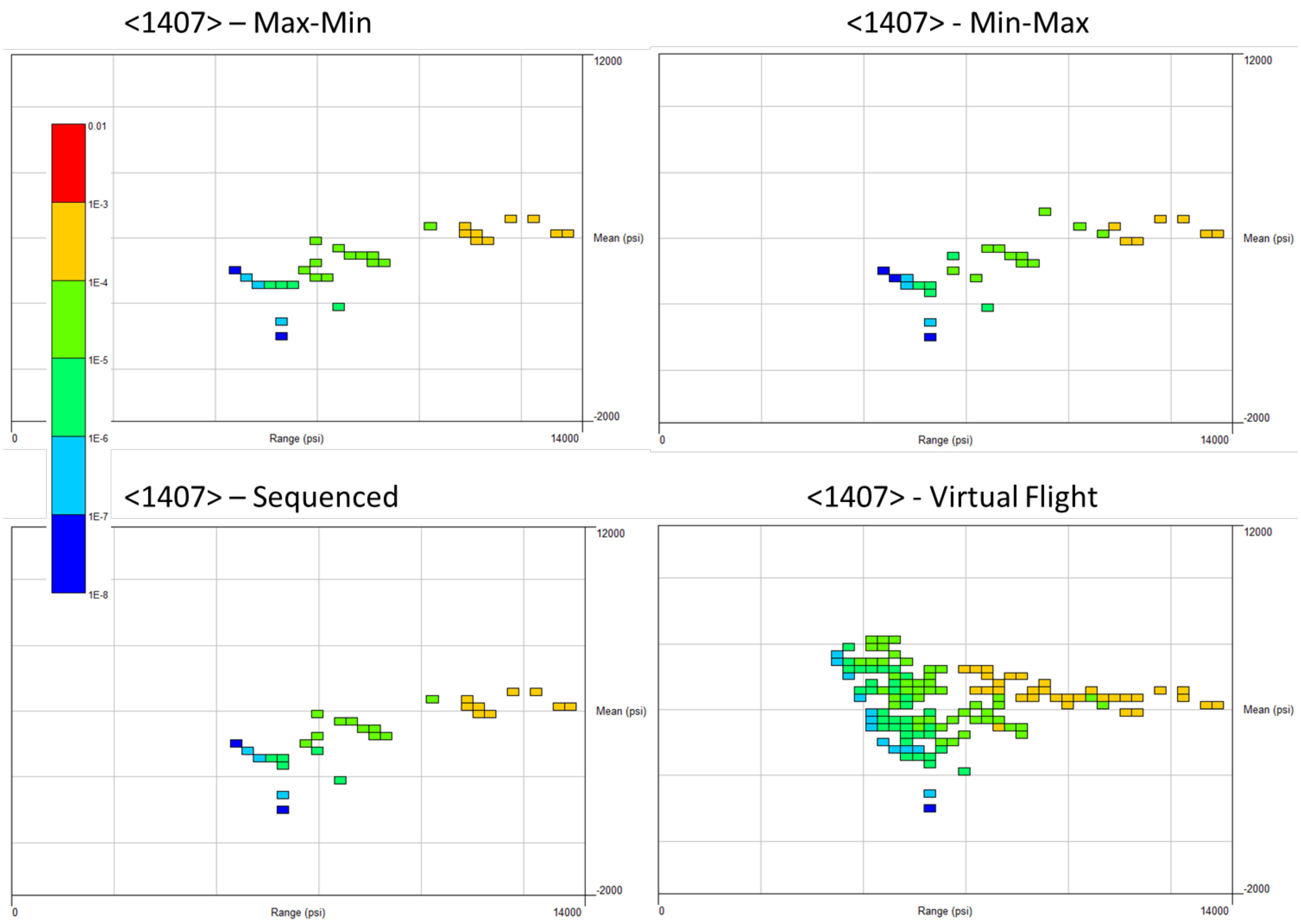


Figure 1. The 2010_0630 damage histograms for <1407>

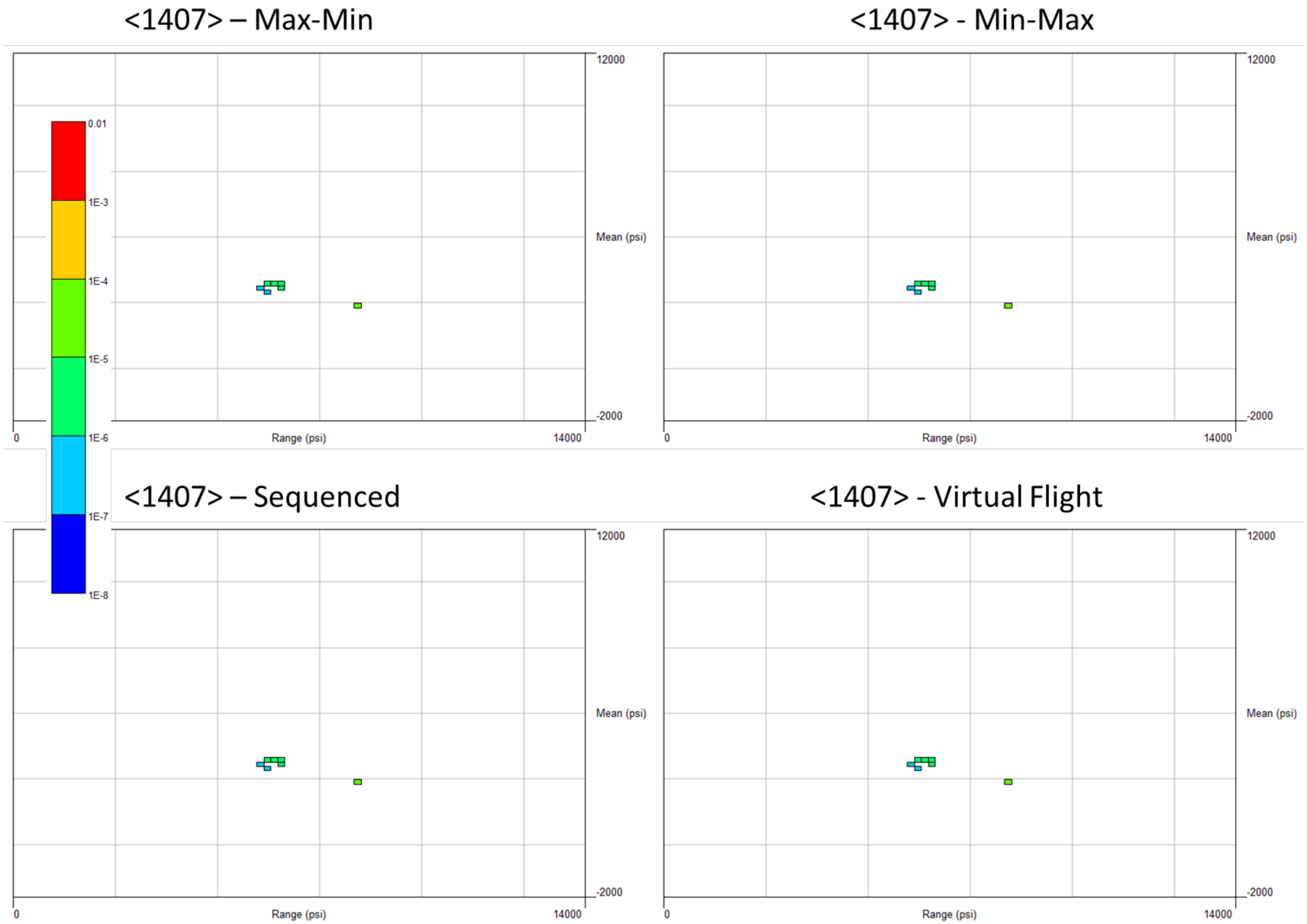


Figure 2. The 2010_0617 damage histograms for <1407>

It is notable from the tables that max-min vs. min-max vs. sequenced load pairs makes very little difference in the damage calculation.

It is also notable that for parts and flights with little or no within-regime damage, the virtual flight generated almost the same damage result. For parts/flights with a significant amount of regime damage, the virtual flight generated far less MTM damage than the load pairing methods.

For load <1021>, most of the high-load maneuvers are related (mostly rolling pull outs and pull ups), which means that most of the peak loading occurs within maneuvers rather than from MTM. Load <71851> is a derived load with a squared term, so almost all of the min loads are near 0. Because each individual maneuver goes from a max to 0, there is very little additional damage to come between maneuvers. For<1023> and <1913>, the max and min loads occur in different collections of maneuvers. Many of the min loads for <1023> are from shutdown; most of the max loads for <1913> are hovers. Because these are largely a string of maneuvers with low damage, MTM dominates with similar results between the MTM methods and the virtual flight. Load <1407> depends on the flight; some flights exhibit low regime damage, such as <1023>, and others have high regime damage, such as <1021>.

The consistently larger damage in the flights with high regime damage indicates that the damage from the half cycles within the regimes must be accounted for.

A review of the rainflow histograms helps make these results clear. For flight 2010_0630, there are numerous MTM bins in the damaging range, as can be seen in the very similar plots for max-min, min-max, and sequenced. However, in the virtual flight, there are many other damaging bins that overwhelm the damage from the MTM bins. In flight 2010_0617, which is MTM dominated, all four approaches have the identical damaging bins.

The first conclusion from these data is that there is no functional difference between the three load pairing methods. These data also indicate that damage from the half cycles within the load paired regimes must be accounted for to provide a good MTM damage estimate when there is significant within-regime damage.

2.4 MAX-MIN MTM DAMAGE

The same five flights were processed using the max-min method and accounting for the half cycles of within-regime damage. The results are shown in tables 9–13. The flight repeats rows are 1/damage for the max-min method and the virtual flight—essentially a life based on a single flight. In every case, the max-min damage is equal to or slightly higher than the virtual flight damage. This results in the flight repeats/lives for the max-min method being consistently equal or slightly lower.

Table 9. The <1021> max-min MTM damage

	2010-0617	2010-0630	2010-0706	2010-0720	2011-0504
<1021>X MTM	151.05E-6	492.45E-6	467.03E-6	819.73E-6	90.18E-6
<1021>V MTM	63.06E-6	137.45E-6	135.93E-6	238.92E-6	88.95E-6
Regime	1.19E-3	4.83E-3	3.70E-3	8.19E-3	185.50E-6
X Total	1.34E-3	5.32E-3	4.17E-3	9.01E-3	275.68E-6
V Total	1.26E-3	4.96E-3	3.84E-3	8.42E-3	274.45E-6
X life, flight repeats	745	188	240	111	3627
V life, flight repeats	797	201	261	119	3644

Table 10. The <1023> max-min MTM damage

	2010-0617	2010-0630	2010-0706	2010-0720
<1023>X	17.74E-6	5.75E-6	5.92E-6	8.32E-6
<1023>V	17.74E-6	5.40E-6	5.64E-6	8.32E-6
Regime	000.00E+0	339.30E-9	000.00E+0	000.00E+0
X Total	17.74E-6	6.09E-6	5.92E-6	8.32E-6
V Total	17.74E-6	5.74E-6	5.64E-6	8.32E-6
X live, flight repeats	56382	164171	168875	120256
V life, flight repeats	56382	174217	177456	120256

Table 11. The <1407> max-min MTM damage

	2010-0617	2010-0630	2010-0706	2010-0720	2011-0504
<1407>X	27.88E-6	2.30E-3	1.83E-3	907.44E-6	549.46E-9
<1407>V	27.82E-6	869.37E-6	644.85E-6	400.48E-6	549.46E-9
Regime	121.40E-9	11.48E-3	10.64E-3	4.62E-3	000.00E+0
X Total	28.00E-6	13.78E-3	12.47E-3	5.52E-3	549.46E-9
V Total	27.94E-6	12.35E-3	11.28E-3	5.02E-3	549.46E-9
X life, flight repeats	35710	73	80	181	1819962
V life, flight repeats	35790	81	89	199	1819963

Table 12. The <1913> max-min MTM damage

	2010-0617	2010-0630	2010-0706	2010-0720	2011-0504
<1913>X	195.41E-6	755.61E-6	994.05E-6	1.18E-3	3.66E-3
<1913>V	194.58E-6	724.34E-6	981.73E-6	1.17E-3	3.65E-3
Regime	62.04E-6	85.55E-6	146.70E-6	330.20E-6	000.00E+0
X Total	257.45E-6	841.16E-6	1.14E-3	1.51E-3	3.66E-3
V Total	256.62E-6	809.89E-6	1.13E-3	1.50E-3	3.65E-3
X life, flight repeats	3884	1189	877	662	273
V life, flight repeats	3897	1235	886	668	274

Table 13. The <71851> max-min MTM damage

	2010-0617	2010-0630	2010-0706	2010-0720	2011-0504
<71851>X	7.82E-6	67.67E-6	97.80E-6	78.39E-6	33.64E-6
<71851>V	7.84E-9	-11.99E-9	-2.61E-9	39.31E-9	-29.25E-9
Regime	59.94E-6	724.10E-6	489.30E-6	592.90E-6	101.50E-6
X Total	67.76E-6	791.77E-6	587.10E-6	671.29E-6	135.14E-6
V Total	59.95E-6	724.09E-6	489.30E-6	592.94E-6	101.47E-6
X life, flight repeats	14757	1263	1703	1490	7400
V life, flight repeats	16681	1381	2044	1687	9855

The conclusion from this is that the max-min method (or either of the other load pairing methods) is a simple, accurate, and consistently slightly conservative approach for determining MTM damage.

2.5 MTM DAMAGE CALCULATION

2.5.1 Reference Damage

As discussed in section 2.1.2, an M+2 is suggested in ADS-79 for time/occurrences of individual regimes. The damages from the virtual flights, as described in section 3.4, are collected by aircraft ID and the mean and standard deviation are then calculated. The data and calculation for <1021> are shown in table 14, and this was repeated for each of the other gages.

Table 14. The <1021> virtual flight damage statistics

ID	Total Damage	Regime Damage	MTM Damage	Total Damage/hr	Regime Damage/hr	MTM Damage/hr
178	0.0302	0.0287	1.42E-3	216.73E-6	206.53E-6	10.20E-6
216	0.0007	0.0007	44.69E-6	9.41E-6	8.84E-6	575.17E-9
230	0.0214	0.0203	1.11E-3	200.92E-6	190.50E-6	10.41E-6
233	0.0274	0.0262	1.20E-3	195.83E-6	187.28E-6	8.55E-6
243	0.0298	0.0284	1.41E-3	184.40E-6	175.70E-6	8.70E-6
250	0.0406	0.0387	1.89E-3	192.31E-6	183.37E-6	8.94E-6
253	0.0104	0.0099	494.51E-6	228.04E-6	217.22E-6	10.82E-6
273	0.0168	0.0160	796.47E-6	288.61E-6	274.94E-6	13.66E-6
274	0.0248	0.0236	1.15E-3	297.39E-6	283.59E-6	13.80E-6
7	0.0373	0.0358	1.50E-3	288.03E-6	276.42E-6	11.61E-6
9	0.0069	0.0066	291.93E-6	473.63E-6	453.52E-6	20.12E-6
11	0.0290	0.0277	1.33E-3	173.34E-6	165.38E-6	7.96E-6
15	0.0337	0.0320	1.65E-3	234.73E-6	223.24E-6	11.49E-6
18	0.0320	0.0306	1.36E-3	195.79E-6	187.44E-6	8.35E-6
20	0.0531	0.0510	2.14E-3	266.07E-6	255.36E-6	10.72E-6
21	0.0365	0.0347	1.83E-3	177.59E-6	168.71E-6	8.88E-6
22	0.0262	0.0249	1.30E-3	266.47E-6	253.30E-6	13.17E-6
33	0.0134	0.0127	679.49E-6	294.93E-6	279.94E-6	14.99E-6
67	0.0238	0.0227	1.04E-3	417.93E-6	399.58E-6	18.35E-6
109	0.0500	0.0480	1.91E-3	302.38E-6	290.82E-6	11.56E-6
114	0.0693	0.0664	2.84E-3	281.80E-6	270.23E-6	11.57E-6
126	0.0365	0.0345	1.93E-3	191.20E-6	181.10E-6	10.10E-6
139	0.0415	0.0399	1.58E-3	304.57E-6	292.98E-6	11.59E-6
143	0.0641	0.0618	2.30E-3	556.94E-6	537.01E-6	19.93E-6
			mean	259.96E-6	248.46E-6	11.50E-6
			stdev	109.29E-6	105.32E-6	4.14E-6
			mean+2	478.53E-6	459.10E-6	19.79E-6

Table 15 shows the mean and M+2 damage rates for each of the gages. The mean life is the inverse of the mean damage. The total M+2 life is the inverse of the mean life biased by M+2. The last life is the inverse of the sum of the M+2 regime damage and the M+2 MTM damage. Because this is slightly more conservative than the M+2 total damage, it is used as the reference life. Any method with a calculated life higher than this value is considered non-conservative and should not be used. A method that calculates lives that are only a small fraction of the total damage is considered overly-conservative and should not be used.

Table 15. Virtual flights damage and reference lives

	<1021>	<1023>	<1407>	<1913>	<71851>
VF Total Dam/hr mean	259.96E-6	627.55E-9	147.62E-6	257.32E-6	25.42E-6
VF Reg Dam/hr mean	248.46E-6	2.32E-9	127.46E-6	4.99E-6	25.42E-6
VF MTM Dam/hr mean	11.50E-6	625.23E-9	20.16E-6	252.32E-6	84.43E-12
VF Total Dam/hr M+2	478.53E-6	1.35E-6	287.49E-6	375.73E-6	38.97E-6
VF Reg Dam/hr M+2	459.10E-6	12.34E-9	255.34E-6	10.33E-6	38.97E-6
VF MTM Dam/hr M+2	19.79E-6	1.34E-6	34.86E-6	368.26E-6	181.28E-12
VF Life, total mean	3,847	1,593,499	6,774	3,886	39,336
VF Life, total M+2	2,090	739,759	3,478	2,661	25,663
VF Life, (reg M+2 + MTM M+2)	2,088	738,317	3,446	2,641	25,663

VF = virtual flight

2.5.2 Max-Min Flight Damage

The max-min method discussed in section 2.4 was applied to all flights. It was also processed in the same way as the virtual flights, except with the regime time histories being the maximum and minimum points only. Damage results were collected in the same way and are shown in table 16. In four of the parts, the lives for the max-min method are slightly less than the reference lives. The last part is the long life <1023> part and, because there is such a small amount of damage occurring in the very flat section of the SN curve, this is presumably just a round-off error. This confirms that the max-min method, accounting for half cycles of within-regime damage, is a valid and slightly conservative approach to calculating MTM damage directly from SUMS data.

Table 16. Max-min damage and lives

	<1021>	<1023>	<1407>	<1913>	<71851>
X MTM Dam/hr mean	33.07E-6	623.89E-9	28.68E-6	253.50E-6	7.52E-6
X MTM Dam/hr M+2	56.29E-6	1.32E-6	50.70E-6	367.89E-6	11.48E-6
X Life, total mean	3,552	1,596,915	6,404	3,869	30,356
VF Life, (reg M+2 + MTM M+2)	2,088	738,317	3,446	2,641	25,663
X life, total M+2	1,940	748,851	3,268	2,644	19,824

VF = virtual flight

2.5.3 OEM Methods

Though every platform addresses GAG damage uniquely, there are two fundamental approaches. The first, referred to as OEM method A, is to assume a certain rate of regime pairings in which the loads are determined by matching high- and low-load regimes the appropriate number of times, as determined by the spectrum. The second approach, OEM method B, assumes a specified rate of GAG cycles matched with extreme loads.

The platforms typically have prorates or combinations of different spectrums that vary in configuration and mission. The assumed number of GAG cycles or regime pairings is also distributed between these spectra. The aircraft used in this study were all selected from CONUS locations to match a training spectrum as closely as possible. Configurations were not tracked because they are not relevant for making comparisons between methods. According to the OEM fatigue substantiation report, all five components in this study received the most damage from GAG cycles during training.

Loads and the number of occurrences are based on the data collected for this study, as discussed in section 3.2. The peak loads for each regime are from the collected FLS time histories, and the occurrences and spectra are based on the M+2 occurrences across the aircraft.

2.5.3.1 OEM Method B, Assumed GAG Cycles, and Extreme Loads

OEM method B is simpler than OEM method A because it assumes there are six cycles of Rotor Startup and Shutdown (RSS) per hour. Because this sometimes produces high damage for some parts, it can be reduced to two cycles per hour of RSS and four cycles per hour of flight-to-flight idle on the ground, No Rotor Startup and Shutdown (No-RSS). That is, two times per flight hour the aircraft is shut down and four times per flight hour the aircraft lands, but the rotors are kept turning until the next TO.

A further reduction in severity can be accomplished by taking a ratio of flight time, based on the spectrum, for several categories of severe maneuver. In this case, the severity categories are based on speed and G loading, as shown in table 17. Details of the calculation are shown in section 3.5.1.1.

Table 17. OEM method B cycles by category

Category		Cycles/hr	% time	Cycles/1000 hr	Cycles cumulative
1.1 VH 2 G	RSS	2	0.0014	2.8	2.8
	No-RSS	4	0.0014	5.7	8.5
1.1 VH 1.5 G	RSS	2	0.0622	124.5	133.0
	No-RSS	4	0.0622	249.0	382.0
.9 VH Max G	RSS	2	0.1041	208.1	590.1
	No-RSS	4	0.1041	416.2	1006.3
.9 VH 2 G	RSS	2	0.1110	222.1	1228.4
	No-RSS	4	0.1110	444.2	1672.6
.9 VH 1.5 G	RSS	2	0.4819	963.8	2636.4
	No-RSS	4	0.4819	1927.6	4564.0
0.7 VH Max G	RSS	2	0.0415	83.0	4647.0
	No-RSS	4	0.0415	166.1	4813.1
0.7 VH 2 G	RSS	2	0.0493	98.7	4911.8
	No-RSS	4	0.0493	197.4	5109.1
0.7 VH 1.5 G	RSS	2	0.1485	297.0	5406.1
	No-RSS	4	0.1485	593.9	6000.0

The resulting damage and life are shown in table 18. The <1021> is slightly less than the virtual flight life, as desired, and <71851> is also fairly close. The <1023> is much lower, but, because it is such a long life part, the large reduction is not necessarily meaningful. The parts to focus on are <1407> and <1913>. The <1407> starts as a medium life part, but its life is cut in half using this method. The <1913> is a low-medium life part, but using this method results in a life over twice as long. For <1407>, the method is overly conservative, resulting in an economic impact of having to replace parts too often. For <1913>, the method is non-conservative, resulting in a safety issue.

OEM method B provides erratic results based only on MTM damage. Because this causes a factor of two changes in life, its use is not recommended.

Table 18. OEM method B life results

	<1021>	<1023>	<1407>	<1913>	<71851>
OEM-B Damage/1000 hrs	0.060660	0.003726	0.364541	0.176679	0.014593
VF Regime Damage/hr M+2	459.10E-6	12.34E-9	255.34E-6	10.33E-6	38.97E-6
OEM-B Life	1,924	267,475	1,613	5,347	18,671
VF Life	2,088	738,317	3,446	2,641	25,663

VF = virtual flight

2.5.3.2 OEM-A, Occurrences of Regime Pairings

The procedure of OEM method A is detailed in section 3.5.1.2. In short, the method sorts all the regimes from highest peak load to lowest, then sorts them again from lowest peak load to highest, and finally pairs them up based on the number of occurrences of that regime in the spectrum. The max and min load produce an oscillatory load, which generates the number of cycles from the SN curve. Damage is calculated from the number of occurrences of the regime pair, divided by the number of allowable cycles, and summed up. Per the OEM method in the fatigue substantiation report, the first 6000 occurrences are summed up for a 1000-hour spectrum (i.e., six significant MTM cycles per hour). The spectrum used here is the SUMS-based spectrum described in section 3.2.

The damage calculations were also used to evaluate whether 6000 occurrences in 1000 hours of flight was a valid number. The damage versus load pair occurrences for each part was plotted to determine if there was consistency in figures 3–7. Note that <1023> and <71851> have a vertical scale more than one order of magnitude smaller than the other charts. To try and evaluate any correlations, both the mean and M+2 spectra were used. The horizontal “Mean Usage” and “M+2 Usage” are the MTM damage rates from the virtual flights. The “Mean OEM” and “M+2 OEM” both use OEM method A and the M+2 occurrence spectrum, as defined in section 3.2, and the mean values of occurrences. Any consistency pertaining to where the usage lines crossed the OEM lines would have been an indicator that that number of occurrences was a valid choice across all the parts. However, there is a wide range of crossings from virtually 0 for <71851> (the usage curves are indistinguishable from the *x*-axis) to nearly 7000 for the <1913> mean curves.

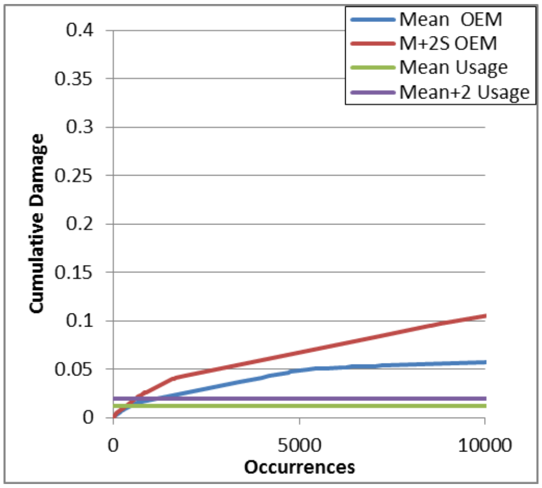


Figure 3. The <1021> damage vs. occurrences

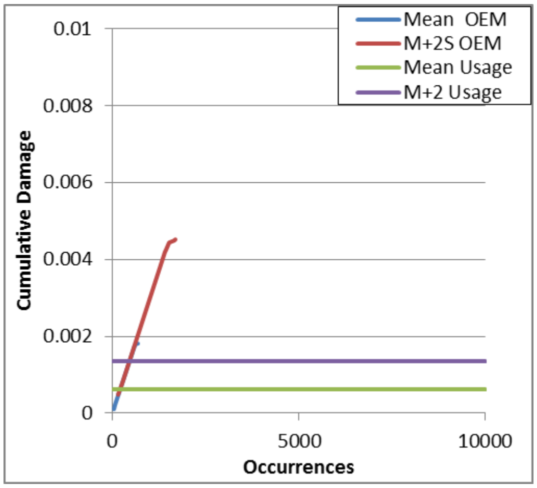


Figure 4. The <1023> damage vs. occurences

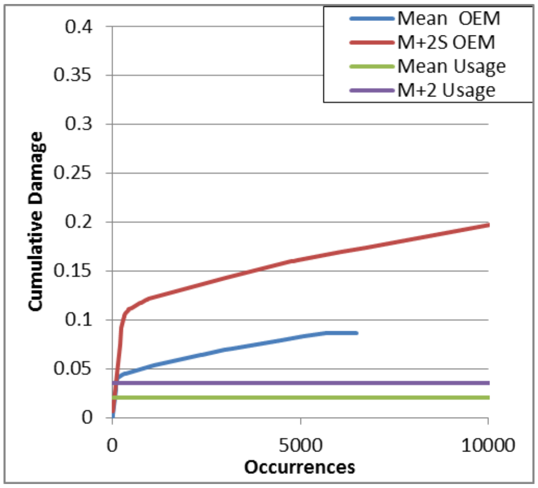


Figure 5. The <1407> damage vs. occurrences

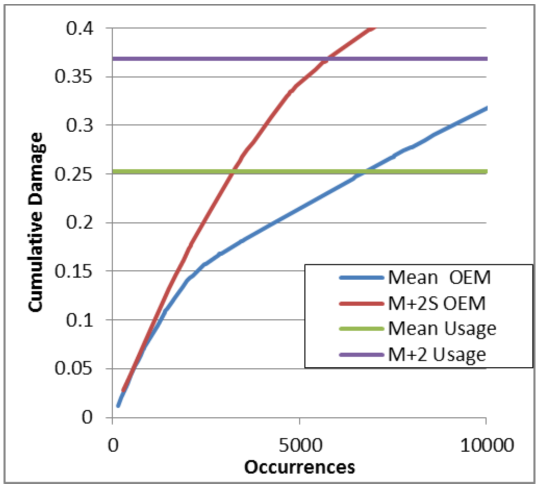


Figure 6. The <1913> damage vs. occurrences

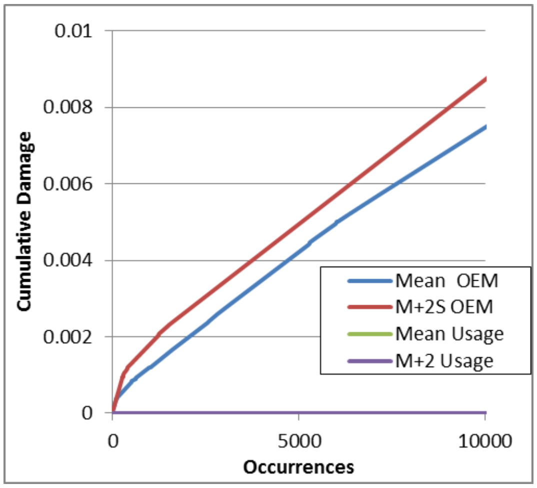


Figure 7. The <71851> damage vs. occurrences

For a life comparison, the lives were calculated for load pair occurrences from 1000–6000 and for all pairs that induced any damage. These results are shown in table 19. As for OEM method B, the life for <1023> is greatly reduced but is still extremely high. The column for <1913> shows that 6000 occurrences predict a life only slightly less than the target Virtual Flight-based life. As soon as the occurrences drop to 5000, the target life is exceeded. The lives for <1021> and <71851> at 6000 occurrences are very reasonable. The life for <1407> does have a significant drop for 6000 occurrences from the target life, but still provides a reasonable part life.

Table 19. OEM method A life results

	<1021>	<1023>	<1407>	<1913>	<71851>
Damage, all damaging pairs	0.134641	0.004514	0.215244	1.227978	0.02661
Damage, 6,000 occs	0.074872	0.004514	0.168854	0.374624	0.005695
Damage, 5,000 occs	0.067047	0.004514	0.161644	0.342998	0.004939
Damage, 4,000 occs	0.059221	0.004514	0.159724	0.296168	0.004183
Damage, 3,000 occs	0.051396	0.004514	0.142814	0.237513	0.003428
Damage, 2,000 occs	0.04357	0.004514	0.132216	0.170655	0.002672
Damage, 1,000 occs	0.028668	0.002958	0.121619	0.089662	0.001813
Regime Dam/hr M+2	459.10E-6	12.34E-9	255.34E-6	10.33E-6	38.97E-6
Life, hr, VF	2,088	738,317	3,446	2,641	25,663
Life, hr, all damage	1,684	220,923	2,125	808	15,249
Life, hr, 6,000 occs	1,873	220,923	2,357	2,598	22,390
Life, hr, 5,000 occs	1,901	220,923	2,398	2,830	22,776
Life, hr, 4,000 occs	1,929	220,923	2,409	3,263	23,175
Life, hr, 3,000 occs	1,959	220,923	2,512	4,035	23,588
Life, hr, 2,000 occs	1,989	220,923	2,580	5,525	24,016
Life, hr, 1,000 occs	2,050	336,658	2,653	10,001	24,522

VF = virtual flight; occs = occurrences

The difference in the plots between <1407> (see figure 5) and <1913> (see figure 6) is notable and explains the effect on part life. For <1913>, the loads do not change significantly for many occurrences so that there is little relief from the most damaging load pair as the occurrences increase. For <1407>, there are occurrences with much higher loads/damage. However, there are only a few of the very damaging loads before the amount of damage drops off significantly. These two parts are a clear indicator of why it is difficult to use overall max and min loads (as in OEM method B) as references for determining MTM damage. By selecting an appropriate number of cycles, MTM damage for <1913> could be modeled well because it is nearly linear. However, that method becomes extremely conservative for <1407> because of the sharp bend in the curve.

Also note that the target life is based on slightly fewer aircraft than desired, mostly with fewer flight hours than desired. Sufficient data could reduce standard deviations and generate small increases in the target life. Because the life for <1913> with 5000 occurrences is only slightly above the target life, it could become viable with more SUMS data.

The conclusion is that the use of OEM method A using sorted regime load pairs at 6000 (and possibly 5000) occurrences per 1000 hours is a reasonable approach. A key observation is that the differences in damage versus occurrences for various parts make the use of a traditional max-min GAG load problematic.

2.5.4 Equivalent Load Methods

The equivalent load methods assume a specified number of cycles and then determine what load is required to match the damage from the virtual flights. The same approach is applied to all five parts to see if it is generally applicable.

The approach is bounded using the rate of all recognized regimes and the rate of takeoffs (TOs). The rate of TO would match the conventional definition of a GAG. In the M+2 occurrence spectrum from section 3.2, there are 3.4 TO/hr. The M+2 total number of recognized regimes/hr is 168. The results are shown in table 20.

Table 20. Equivalent loads, TO/hr, and reg/hr

	<1021>	<1023>	<1407>	<1913>	<71851>
MTM Damage, VF M+2	19.79E-6	1.34E-6	34.86E-6	368.26E-6	181.28E-12
Cycles, TO/hr	3.4	3.4	3.4	3.4	3.4
Cycles, Reg/hr	168	168	168	168	168
N = Cyc/Dam, TO/hr	171,808	2,533,353	97,545	9,233	18.755E9
N = Cyc/Dam, Reg/hr	8,489,327	125,177,433	4,819,868	456,197	926.745E9
Load to match N, TO/hr	4,844	356,710	4,833	6,678	4,817
Load to match N, Reg/hr	3,471	348,000	3,715	1,952	4,817
EL	3,463	348,000	3,560	1,722	4,817
Max Load	9,549	384,695	11,366	6,339	8,421
Load/EL, TO/hr	1.399	1.025	1.358	3.878	1.000
Load/EL, Reg/hr	1.002	1.000	1.043	1.134	1.000
Load/Max Load, TO/hr	0.507	0.927	0.425	1.053	0.572
Load/Max Load, Reg/hr	0.363	0.905	0.327	0.308	0.572
3.9*EL, TO/hr	13,506	1,357,200	13,884	6,716	18,786
1.14*EL, Reg/hr	3,948	396,720	4,058	1,963	5,491
1.06*ML, TO/hr	10,122	407,776	12,048	6,719	8,926
.91*ML, Reg/hr	8,689	350,072	10,343	5,768	7,663
N, 3.9*EL	13,506	1,357,200	13,884	6716	18,786
N, 1.14*EL	498,867	202,243	705,570	439,188	1,089,552
N, 1.06*ML	7,453	154,585	505	9,077	158,951
N, .91*ML	15,313	19,025,059	1,779	13,379	271,541
Dam, 3.4 Cyc, 3.9*EL	251.75E-6	2.51E-6	244.89E-6	506.27E-6	180.98E-6
Dam, 168 Cyc, 1.14*EL	336.76E-6	830.68E-6	238.11E-6	382.52E-6	154.19E-6
Dam, 3.4 Cyc, 1.06*ML	456.20E-6	21.99E-6	6.73E-3	374.57E-6	21.39E-6
Dam, 168 Cyc, .91*ML	10.97E-3	8.83E-6	94.43E-3	12.56E-3	618.69E-6
Regime Dam/hr mean+2	459.10E-6	12.34E-9	255.34E-6	10.33E-6	38.97E-6
Life, 3.4 Cyc, 3.9*EL	1,407	397,220	1,999	1,936	4,546
Life, 168 Cyc, 1.14*EL	1,257	1,204	2,027	2,545	5,177
Life, 3.4 Cyc, 1.06*ML	1,093	45,441	143	2,598	16,568
Life, 168 Cyc, .91*ML	87	113,086	11	80	1,521
Life, hr, VF	2,088	738,317	3,446	2,641	25,663

VF = virtual flight

The first block of rows in the table has the MTM damage target based on the virtual flights; the TO and recognized regime rates; and the number of cycles on the SN curve to match the applied cycles and damage.

The second block of numbers is the load needed to match the MTM damage for the given number of cycles. These values were determined using Excel's Goal Seek on the SN curve tables using log-linear interpolation. For comparison, the endurance limit (EL) and maximum (GAG) load are shown for each part. The matching load for TO/hr for <71851> is right at the EL because the number of TO cycles and amount of damage is so low. However, the matching load for <1913> is well above the maximum GAG load the part experiences. The other three parts fall somewhere between the EL and GAG load. There is clearly no general relationship between the equivalent loads and a part-specific load. Regressions were attempted using the EL and max load because no independent variables with reasonable damage relationships were found.

The possibility that accounting for the worst-case part might be reasonable was investigated. The next block is the ratio of the matching loads for both cases to the EL and the max load. For the first three cases, <1913> has the worst case ratio. For the last case, the highest load ratio is for part <1023>. Based on the four loads obtained for each part, the number of allowable cycles, N, is determined for each, followed by the appropriate damage.

Finally, the lives for each part are calculated as 1/(regime damage + MTM damage) and compared to the target lives. For the first three cases, the lives for <1913> are not unacceptable, but the other parts have significantly reduced lives. The last case is driven by <1023> and makes the other part lives very short.

The conclusion is that trying to relate a fixed number of cycles to either the EL or max load is so inconsistent as to be meaningless. This approach is not recommended.

2.5.5 Equivalent Cycles Methods

Equivalent cycles methods take a given load and determine how many cycles are needed at that load. After observing the significant differences in the curves of damage versus load pair occurrences from OEM method A in section 2.5.3.2, the loads selected were based on load pairs that started with the first occurrence, or the maximum GAG load, and progressed from the 1000th occurrence to the 6000th occurrence. The goal was to balance the excessive damage calculated for parts with only a few cycles at a very high GAG load and parts with loads that decrease slowly as the occurrences increase. The results are shown in table 21. The first and second blocks of rows are the load and the number of cycles from the given occurrence taken directly from the OEM method A calculations for each part. The next block is how many cycles are needed for each part to match the MTM damage from the virtual flights (Cycles = MTM Damage/N). At every load level, the maximum number of cycles comes from <1913>. The next block calculates the damage using the cycles determined by <1913> divided by N for each part. The last block calculates lives when the life is 1/(Regime damage + MTM damage).

Table 21. Equivalent cycles given load

	<1021>	<1023>	<1407>	<1913>	<71851>
1st occurrence load	9,549	384,695	11,366	6,339	8,421
1,000th occurrence load	6,331	383,645	4,861	6,131	5,611
2,000th occurrence load	5,169	354,883	4,861	5,801	5,352
3,000th occurrence load	5,169	354,883	4,861	5,448	5,352
4,000th occurrence load	5,169	354,883	4,795	4,931	5,352
5,000th occurrence load	5,169	354,883	4,646	4,136	5,352
6,000th occurrence load	5,169	354,883	4,646	3,685	5,352
N at 1st occurrence load	10,183	326,539	836	10,601	191,556
N at 1,000th occurrence load	53,736	340,484	94,364	11,539	957,157
N at 2,000th occurrence load	127,788	3,540,775	94,364	13,200	1,323,086
N at 3,000th occurrence load	127,788	3,540,775	94,364	15,250	1,323,086
N at 4,000th occurrence load	127,788	3,540,775	103,488	18,826	1,323,086
N at 5,000th occurrence load	127,788	3,540,775	138,693	28,737	1,323,086
N at 6,000th occurrence load	127,788	3,540,775	138,693	36,998	1,323,086
MTM Damage, VF M+2	19.79E-6	1.34E-6	34.86E-6	368.26E-6	181.28E-12
Equiv Cycles at 1st occ load	0.202	0.438	0.0291	3.904	0.000
Cycles at 1,000th occ load	1.06	0.46	3.29	4.25	0.00
Cycles at 2,000th	2.53	4.75	3.29	4.86	0.00
Cycles at 3,000th	2.53	4.75	3.29	5.62	0.00
Cycles at 4,000th	2.53	4.75	3.61	6.93	0.00
Cycles at 5,000th	2.53	4.75	4.83	10.58	0.00
Cycles at 6,000th	2.53	4.75	4.83	13.62	0.00
Dam, 4 cycles, 1st load	392.83E-6	12.25E-6	4.79E-3	377.31E-6	20.88E-6
Dam, 4.25 cycles, 1,000th load	79.09E-6	12.48E-6	45.04E-6	368.30E-6	4.44E-6
Dam 4.9 cycles, 2,000th load	38.34E-6	1.38E-6	51.93E-6	371.20E-6	3.70E-6
Dam 5.7 cycles, 3,000th load	44.61E-6	1.61E-6	60.40E-6	373.77E-6	4.31E-6
Dam 7 cycles, 4,000th load	54.78E-6	1.98E-6	67.64E-6	371.82E-6	5.29E-6
Dam 11 cycles, 5,000th load	86.08E-6	3.11E-6	79.31E-6	382.78E-6	8.31E-6
Dam 14 cycles, 6,000th load	109.56E-6	3.95E-6	100.94E-6	378.40E-6	10.58E-6
Regime Dam/hr M+2	459.10E-6	12.34E-9	255.34E-6	10.33E-6	38.97E-6
Life, 4 at 1st	1,174	81,553	198	2,580	16,709
Life, 4.25 at 1,000th	1,858	80,035	3,329	2,641	23,038
Life, 4.9 at 2,000th	2,010	716,222	3,255	2,621	23,435
Life, 5.7 at 3,000th	1,985	616,464	3,167	2,603	23,108
Life, 7 at 4,000th	1,946	502,688	3,096	2,617	22,595
Life, 11 at 5,000th	1,834	320,615	2,988	2,544	21,150
Life, 14 at 6,000th	1,759	252,126	2,807	2,572	20,182
Life, Virtual Flight	2,088	738,317	3,446	2,641	25,663

For <1913>, the lives at each load level are very close to the target life because <1913> drove the number of cycles. The other parts had more cycles used than were needed to match the desired MTM damage, so they were all less than the target lives, as desired. The question, therefore, is how overly conservative is this method? At the maximum load (the first load occurrence), all of the other parts have significantly reduced lives, with <1407> being reduced the most. At the 1000th occurrence, most of the parts have reasonable lives in relation to the target lives with the exception of <1023>, though its life is still long. The 2000th load cycle, in which all of the part lives are getting close to the target lives, appears to be the best choice. Because this is an empirical approach, there is the question of how sensitive the results are to changes in the assumptions. Figures 8–13 show variations in life versus the occurrence load while at 5 cycles/hr and at the 2000th occurrence load pair. Parts <1021>, <1407>, and <71851> are fairly insensitive to changes in both cycles and load pair.

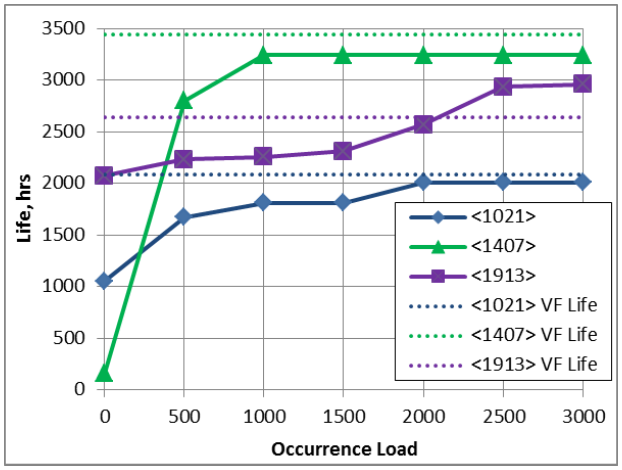


Figure 8. Life at 5 cycles

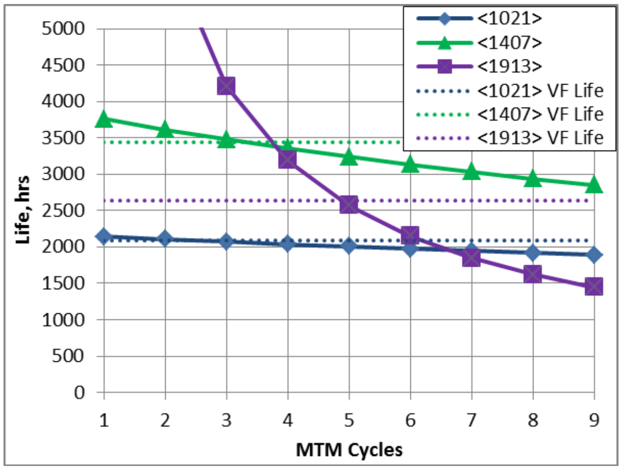


Figure 9. Life at 2000th load

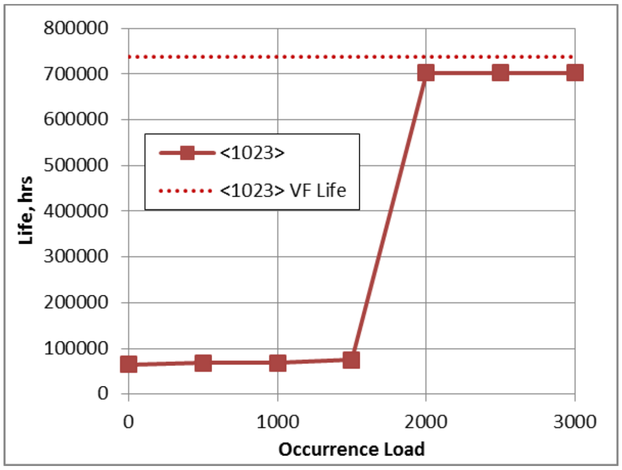


Figure 10. The <1023> life at 5 cycles

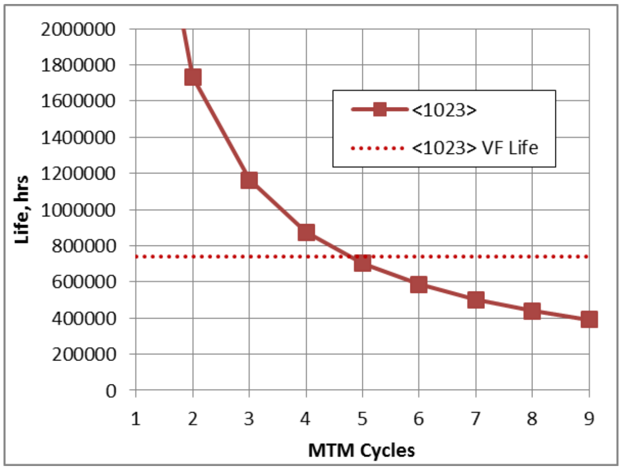


Figure 11. The <1023> life at 2000th load

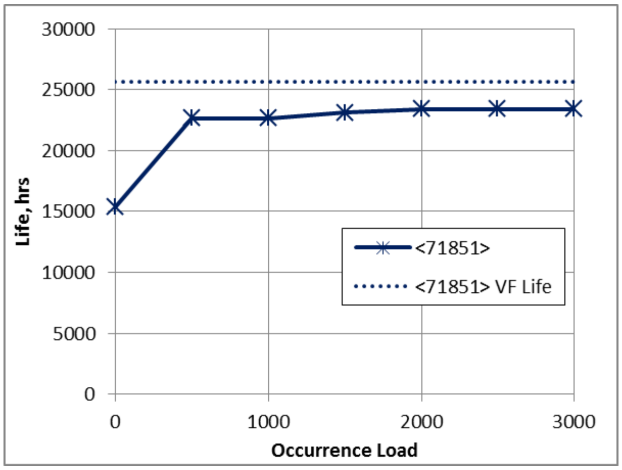


Figure 12. The <71851> life at 5 cycles

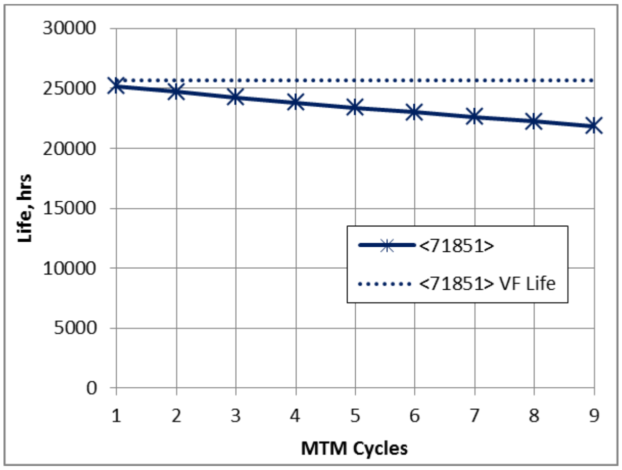


Figure 13. The <71851> life at 2000th load

The large jump in life for <1023> is the result of there being only 1701 damaging load pairs. All life calculations above the 1701st occurrence are based on the last damaging load pair, the 1701st, which is the smallest load that does any damage. The <1913>, which is the driver for the number of cycles, shows the highest sensitivity.

This approach provides valid damage results without being excessively conservative. However, it is empirical, meaning it cannot be generally applied across platforms. It is also fairly involved, with enough sensitivity in the critical part that all parts would need to be checked. This requires a significant amount of calculation, which produces results equivalent to, but not quite as good as, simply applying the virtual flight damage rate. The conclusion is that, though the approach provides reasonable results, it is too much calculation for not enough benefit.

2.5.6 Regression Methods

Linear regression was applied to the virtual flight MTM data to determine if a relationship could be found between MTM damage and the number of occurrences of various regimes. The procedures for the regression are discussed in section 3.5.2. The occurrences from each RRA file, and in some cases the loads, were used to generate linear equations for the MTM damage.

The first regression was based on the regimes that would typically be associated with GAG cycles: TO (regimes 201 and 202), shutdown (103 and 104), and flight-to-ground idle (107), and the total number of regimes and maximum and minimum loads. All two-way interactions were also included. The results of the regression are shown in figure 14. A perfect correlation would be a straight line with a slope of 1. The plot shows a general relationship, but not a very strong one. The correlation coefficient is only 82%. Similar results occurred for the other parts.

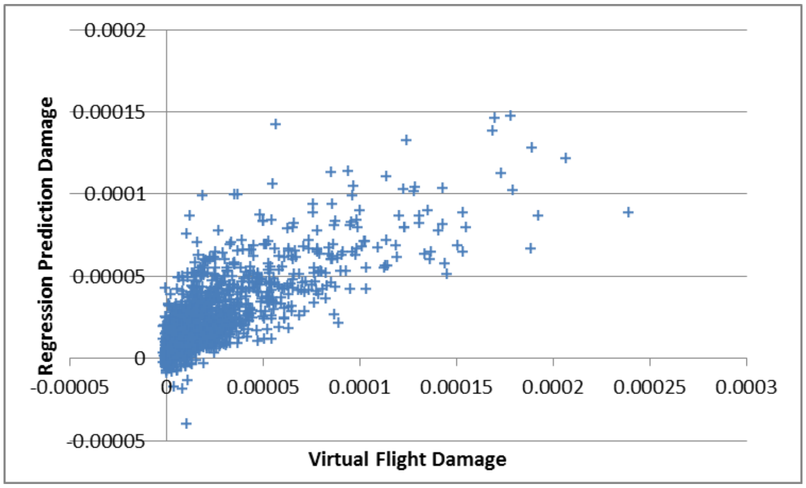


Figure 14. The <1021> GAG regimes with max-min load regression

Allowing for the fact that damage is (occurrences)/(SN curve cycles, N), the max and min loads were replaced with 1/N. A worse case result, with a correlation of 70%, is shown in figure 15. Several other combinations of independent variables were tried in both cases, with no significant improvement.

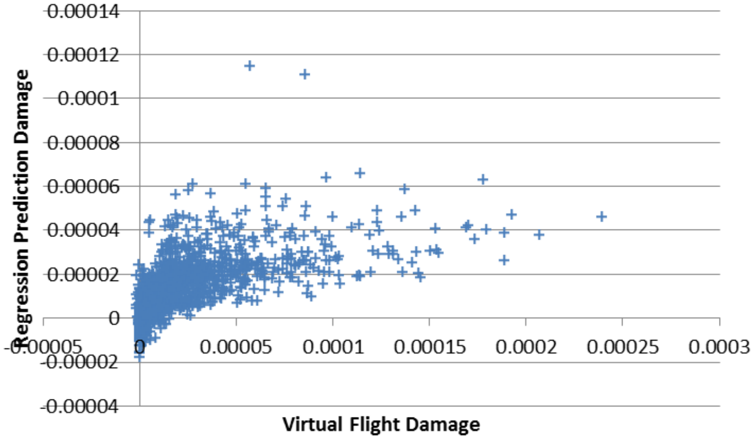


Figure 15. The <1021> GAG regimes with 1/N regression

The five regimes with the highest maximum loads and five regimes with the lowest minimum loads were used as the independent variables, with only a 60% correlation (see figure 16). Using the regimes that had an individual correlation with damage of greater than 50% (11 regimes for <1021>) has a correlation of 96%, but with some significant outliers (see figure 17). Finally, using the number of occurrences of all regimes in the regression resulted in a fairly good (98.7%) correlation (see figure 18).

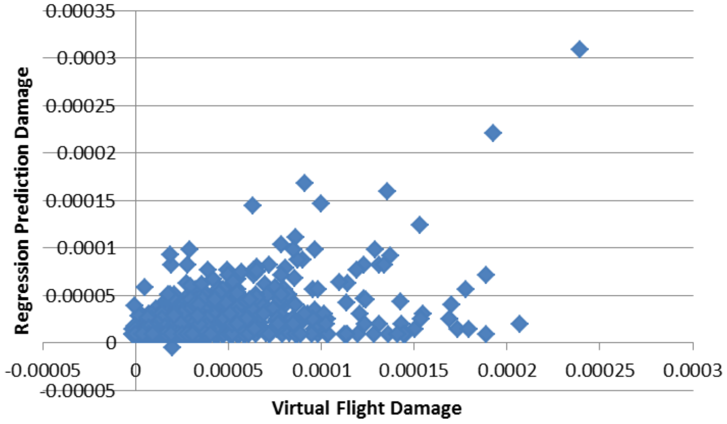


Figure 16. The <1021> top 5 max load and top 5 min load

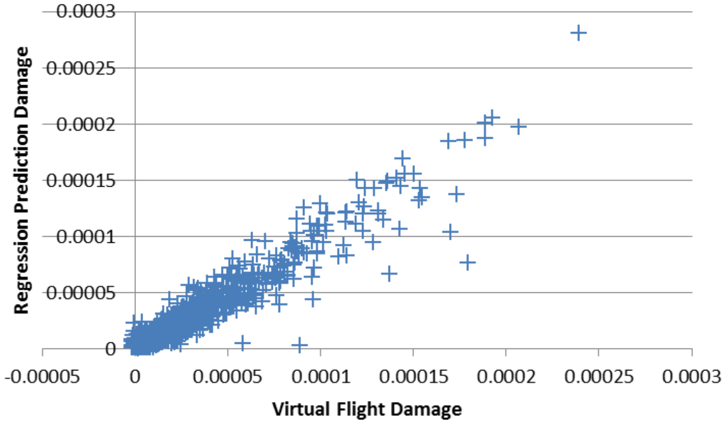


Figure 17. The <1021> individual correleations >50%

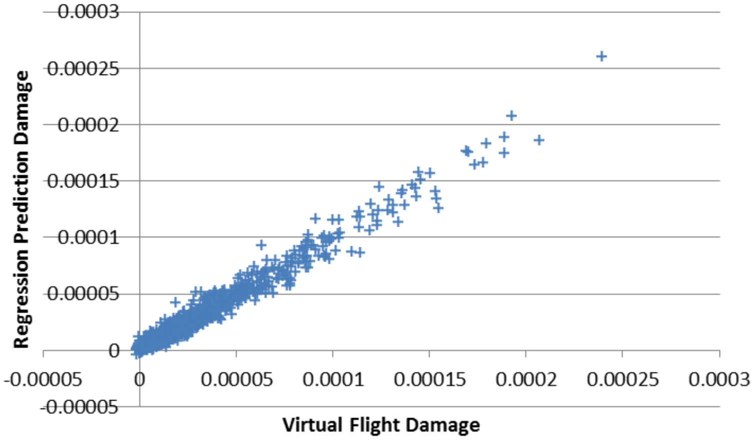


Figure 18. The <1021> all regimes

The strong correlation for <1021> using all regimes allows for the possibility of using the coefficients of the regression as damage deltas for each occurrence of the regime, either by spectrum or by serial-number-tracked parts. Therefore, the regression was repeated for the other four parts (see figure 19). The regression coefficient for each regime was multiplied by the number of occurrences from the SUMS M+2 spectrum, summed, and used in a life calculation (see table 22). No biasing was included on the regression coefficients because the spectrum already biases the usage.

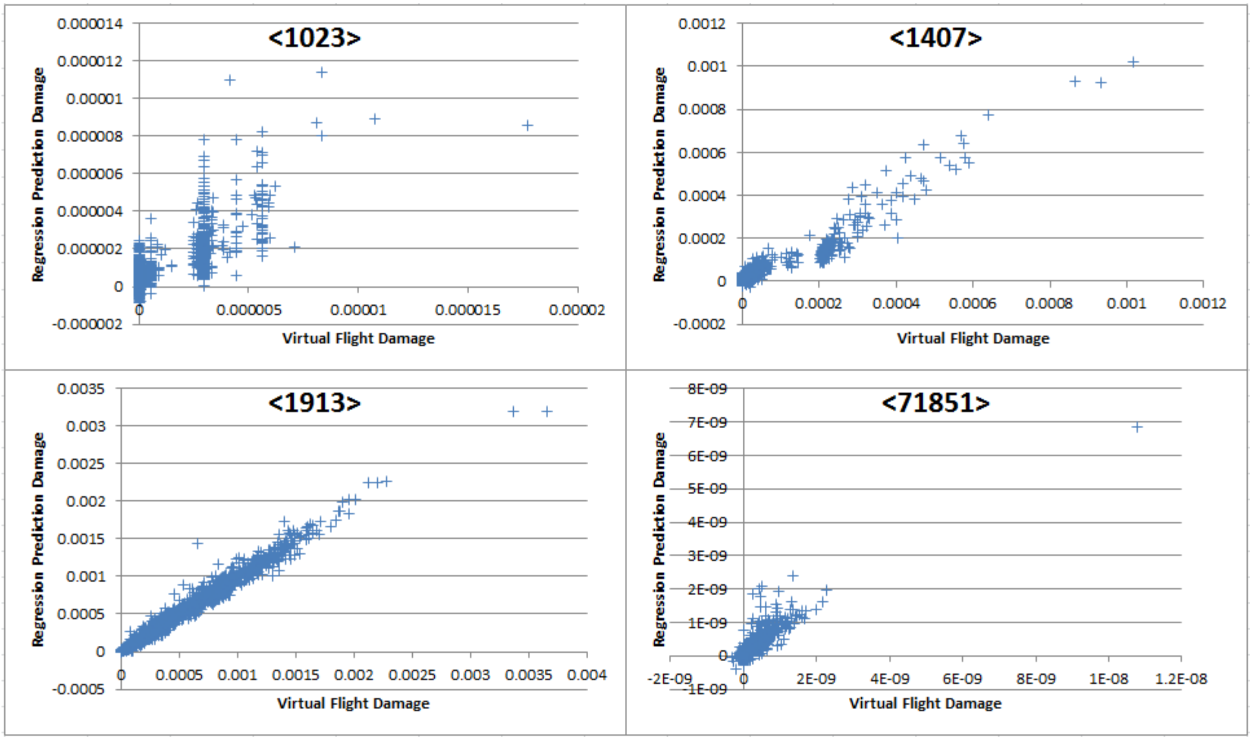


Figure 19. All regime regression for other parts

Table 22. Regression life results

	<1021>	<1023>	<1407>	<1913>	<71851>
Regime Dam/hr M+2	459.10E-6	12.34E-9	255.34E-6	10.33E-6	38.97E-6
Regression Dam/1,000 hr, SUMS M+2 spectrum	23.30E-3	1.16E-3	49.30E-3	578.96E-3	-10.67E-9
Regression Damage/1,000 hr, +coefficients only	36.20E-3	3.95E-3	127.23E-3	756.94E-3	346.97E-9
Life, hr, Virtual Flight	2,088	738,317	3,446	2,641	25,663
Life, hr, Regression	2,073	855,676	3,283	1,697	25,663
life, hr, + coefficients only	2,019	252,315	2,614	1,303	25,662

2.5.7 Binning—Max-Min

All of the methods previously discussed in this report use a fixed set of loads and are suitable for variations on the legacy safe-life method or serial-number-based damage monitoring. However, because of the fixed loads values, they do not extend well into a fully probabilistic reliability analysis. To allow for statistical modeling of loads, a method in which the loads are binned is demonstrated. Statistical parameters (mean and standard deviation) can then be calculated across aircraft and manipulated for a reliability analysis. The procedures used in this method are discussed in section 3.5.3.

In this approach, the min-max method was applied to all the RRA files, one aircraft at a time. The cycles are rainflow counted and the loads sorted into bins. The same RRA files are then used to sum up how many occurrences there are of each regime. The number of MTM occurrences is the difference between the total and the number of regimes. If the number of occurrences within a bin is small enough, it is possible to get a negative number of MTM occurrences. This is acceptable and should be processed normally even though it calculates a negative damage. The reason is that rainflow counting can pair max and min loads from different parts of the time history, but the regime occurrences are always two consecutive points. Because this can result in changes to where a load is binned based on the size of the bins, the MTM occurrences can become negative. However, it is just a mathematical construct to be able to arrive at a statistical model, and the negative values act to prevent cycles from being double booked in different bins.

Given the MTM occurrences/hr for each aircraft, the mean and standard deviation can be determined and then used in a probabilistic model. For verification of the approach, the M+2 occurrences are used to calculate damage in table 23. For this case, because it is intended to be probabilistic in nature, both the mean and M+2 conditions are shown. Small, medium, and large bins were compared and the size of the load, and the resultant number of non-zero bins, are shown.

Table 23. Bin and damage results for binned approach

	<1021>	<1023>	<1407>	<1913>	<71851>
Regime Damage Rates					
VF, Dam/hr, mean	248.46E-6	2.32E-9	127.46E-6	4.99E-6	25.42E-6
VF, Dam/hr, M+2	459.10E-6	12.34E-9	255.34E-6	10.33E-6	38.97E-6
Load Bin Sizes					
Small Bin Size	250	7,500	250	250	250
Mid Bin Size	500	15,000	500	500	500
Large Bin Size	1,000	30,000	1,000	1,000	1,000
Number of Bins					
Small Bin Size	39	52	46	27	34
Mid Bin Size	20	26	23	14	17
Large Bin Size	10	13	12	7	9
MTM Damage Rates, Mean					
VF MTM Dam/hr	11.50E-6	625.23E-9	20.16E-6	252.32E-6	84.43E-12
X MTM Dam/hr	33.07E-6	623.89E-9	28.68E-6	253.50E-6	7.52E-6
Small Bin MTM Dam/hr	32.29E-6	681.54E-9	29.01E-6	255.06E-6	7.41E-6
Medium Bin MTM Dam/hr	34.73E-6	627.04E-9	27.63E-6	263.46E-6	7.31E-6
Large Bin MTM Dam/hr	39.39E-6	505.13E-9	23.29E-6	270.54E-6	10.15E-6
MTM Damage Rates, M+2					
VF MTM Dam/hr	19.79E-6	1.34E-6	34.86E-6	368.26E-6	181.28E-12
X MTM Dam/hr	56.29E-6	1.32E-6	50.70E-6	367.89E-6	11.48E-6
Small Bin MTM Dam/hr	79.09E-6	1.65E-6	91.94E-6	433.05E-6	11.88E-6
Medium Bin MTM Dam/hr	77.09E-6	1.44E-6	80.98E-6	425.34E-6	11.26E-6
Large Bin MTM Dam/hr	76.35E-6	1.08E-6	58.42E-6	416.96E-6	15.42E-6

VF = virtual flight

The mean and M+2 damage rates are combined into lives, shown in table 24. The lives in general match very well. The most erratic is for <1023>, but because it is such a long life part, all of the loads are in the very flat part of the SN curve, where small loads changes result in large life changes. Other than that, the small and medium bins are a consistently good match for the min-max calculated lives. The large bin is starting to show some erratic behavior, with the <1023> increasing significantly, though the <71851> life drops. As noticed with the other methods, <1913> is particularly susceptible to changes in MTM damage. That can be seen in the M+2 lives, where <1913> does show the steepest drop using the binning method, but the mean lives drop very little. However, it is not excessively conservative.

Table 24. Life results for binned approach

	<1021>	<1023>	<1407>	<1913>	<71851>
Lives, mean					
VF Life	3,847	1,593,499	6,774	3,886	39,336
X Life	3,552	1,596,915	6,404	3,869	30,356
Small Bin Life	3,562	1,462,281	6,391	3,845	30,458
Med Bin Life	3,531	1,588,915	6,448	3,725	30,547
Large Bin Life	3,474	1,970,656	6,634	3,629	28,113
Lives, M+2					
VF Life	2,088	738,317	3,446	2,641	25,663
X Life	1,940	748,851	3,268	2,644	19,824
Small Bin Life	1,858	602,406	2,880	2,255	19,667
Med Bin Life	1,865	688,517	2,973	2,295	19,911
Large Bin Life	1,868	918,404	3,187	2,340	18,388

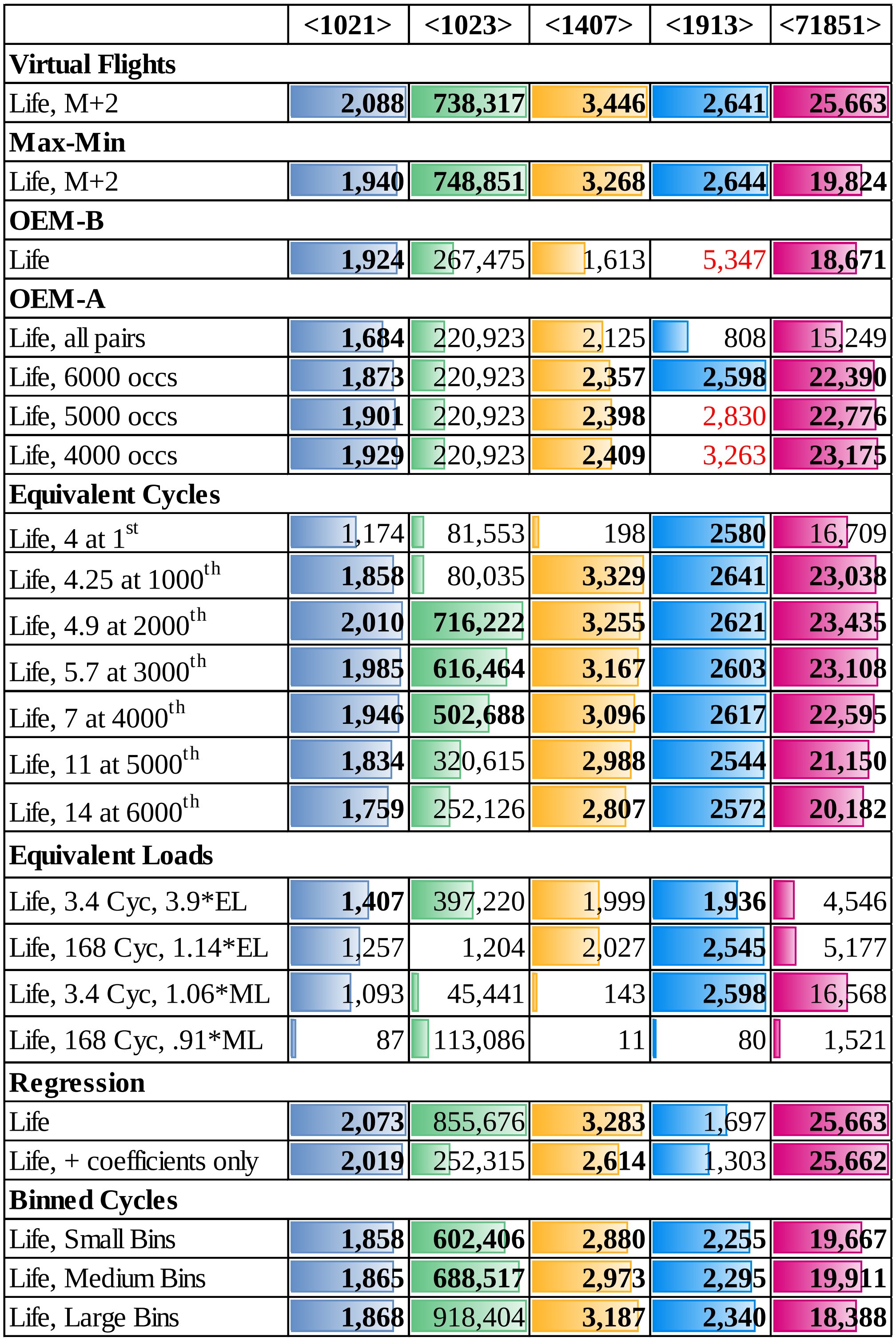
The conclusion is that using load bins of MTM occurrences is a valid approach for determining MTM damage and provides a statistical model for loads suitable for probabilistic reliability analysis.

2.6 SUMMARY OF METHOD RESULTS

Summaries of the damage and lives for each of the methods discussed are shown in tables 25 and figure 20. In these tables, unless otherwise specified, all damage rates are per hour, all damage is MTM only, and all lives and damages are M+2.

Table 25. Damage summary for each method

	<1021>	<1023>	<1407>	<1913>	<71851>
Virtual Flights					
Total Damage, mean	2.60E-04	6.28E-07	1.48E-04	2.57E-04	2.54E-05
Regime Damage, mean	2.48E-04	2.32E-09	1.27E-04	4.99E-06	2.54E-05
MTM Damage, mean	1.15E-05	6.25E-07	2.02E-05	2.52E-04	8.44E-11
Total Damage, M+2	4.79E-04	1.35E-06	2.87E-04	3.76E-04	3.90E-05
Regime Damage, M+2	4.59E-04	1.23E-08	2.55E-04	1.03E-05	3.90E-05
MTM Damage, M+2	1.98E-05	1.34E-06	3.49E-05	3.68E-04	1.81E-10
Max-Min					
Damage, mean	3.31E-05	6.24E-07	2.87E-05	2.54E-04	7.52E-06
Damage, M+2	5.63E-05	1.32E-06	5.07E-05	3.68E-04	1.15E-05
OEM Method B					
Damage	6.07E-05	3.73E-06	3.65E-04	1.77E-04	1.46E-05
OEM Method A					
Damage, all pairs	1.35E-04	4.51E-06	2.15E-04	1.23E-03	2.66E-05
Damage, 6,000 occurrences	7.49E-05	4.51E-06	1.69E-04	3.75E-04	5.70E-06
Damage, 5,000 occurrences	6.71E-05	4.51E-06	1.62E-04	3.43E-04	4.94E-06
Damage, 4,000 occurrences	5.92E-05	4.51E-06	1.60E-04	2.96E-04	4.18E-06
Equivalent Cycles					
Damage, 4 cycles, 1st load	3.93E-04	1.23E-05	4.79E-03	3.77E-04	2.09E-05
Damage, 4.25 cycles, 1,000th load	7.91E-05	1.25E-05	4.50E-05	3.68E-04	4.44E-06
Damage, 4.9 cycles, 2,000th load	3.83E-05	1.38E-06	5.19E-05	3.71E-04	3.70E-06
Damage, 5.7 cycles, 3,000th load	4.46E-05	1.61E-06	6.04E-05	3.74E-04	4.31E-06
Damage, 7 cycles, 4,000th load	5.48E-05	1.98E-06	6.76E-05	3.72E-04	5.29E-06
Damage, 11 cycles, 5,000th load	8.61E-05	3.11E-06	7.93E-05	3.83E-04	8.31E-06
Damage, 14 cycles, 6,000th load	1.10E-04	3.95E-06	1.01E-04	3.78E-04	1.06E-05
Equivalent Loads					
Damage, 3.4 cycles, 3.9*EL	2.52E-04	2.51E-06	2.45E-04	5.06E-04	1.81E-04
Damage, 168 cycles, 1.14*EL	3.37E-04	8.31E-04	2.38E-04	3.83E-04	1.54E-04
Damage, 3.4 cycles, 1.06*ML	4.56E-04	2.20E-05	6.73E-03	3.75E-04	2.14E-05
Damage, 168 cycles, .91*ML	1.10E-02	8.83E-06	9.44E-02	1.26E-02	6.19E-04
Regression					
Damage	2.33E-05	1.16E-06	4.93E-05	5.79E-04	-1.07E-11
Damage, +coefficients only	3.62E-05	3.95E-06	1.27E-04	7.57E-04	3.47E-10
Binned Cycles					
Damage, Small Bins	7.91E-05	1.65E-06	9.19E-05	4.33E-04	1.19E-05
Damage, Medium Bins	7.71E-05	1.44E-06	8.10E-05	4.25E-04	1.13E-05
Damage, Large Bins	7.64E-05	1.08E-06	5.84E-05	4.17E-04	1.54E-05



	<1021>	<1023>	<1407>	<1913>	<71851>
Virtual Flights					
Life, M+2	**2,088**	**738,317**	**3,446**	**2,641**	**25,663**
Max-Min					
Life, M+2	**1,940**	**748,851**	**3,268**	**2,644**	**19,824**
OEM-B					
Life	**1,924**	267,475	1,613	5,347	**18,671**
OEM-A					
Life, all pairs	**1,684**	220,923	2,125	808	15,249
Life, 6000 occs	**1,873**	220,923	**2,357**	**2,598**	**22,390**
Life, 5000 occs	**1,901**	220,923	**2,398**	2,830	**22,776**
Life, 4000 occs	**1,929**	220,923	**2,409**	3,263	**23,175**
Equivalent Cycles					
Life, 4 at 1st	1,174	81,553	198	**2580**	16,709
Life, 4.25 at 1000th	**1,858**	80,035	**3,329**	**2641**	**23,038**
Life, 4.9 at 2000th	**2,010**	**716,222**	**3,255**	**2621**	**23,435**
Life, 5.7 at 3000th	**1,985**	**616,464**	**3,167**	**2603**	**23,108**
Life, 7 at 4000th	**1,946**	**502,688**	**3,096**	**2617**	**22,595**
Life, 11 at 5000th	**1,834**	320,615	**2,988**	**2544**	**21,150**
Life, 14 at 6000th	**1,759**	252,126	**2,807**	**2572**	**20,182**
Equivalent Loads					
Life, 3.4 Cyc, 3.9*EL	**1,407**	397,220	1,999	**1,936**	4,546
Life, 168 Cyc, 1.14*EL	1,257	1,204	2,027	**2,545**	5,177
Life, 3.4 Cyc, 1.06*ML	1,093	45,441	143	**2,598**	16,568
Life, 168 Cyc, .91*ML	87	113,086	11	80	1,521
Regression					
Life	**2,073**	855,676	**3,283**	1,697	**25,663**
Life, + coefficients only	**2,019**	252,315	**2,614**	1,303	**25,662**
Binned Cycles					
Life, Small Bins	**1,858**	**602,406**	**2,880**	**2,255**	**19,667**
Life, Medium Bins	**1,865**	**688,517**	**2,973**	**2,295**	**19,911**
Life, Large Bins	**1,868**	918,404	**3,187**	**2,340**	**18,388**

Figure 20. Part life summary for each method

In figure 20, color bars are included as a visual indicator of the life calculations, and the lives that are in bold are (arbitrarily) between 66% and 102% of the target virtual flight lives. Note that for every part except <1913>, the Virtual Flight life is the highest (or very close to the highest) value in the figure. The color bars for <1913> exclude the three higher lives, which are in red. This figure helps to emphasize that the max-min and Small/Medium bin methods are consistently good representations of MTM damage. OEM method A is good for all of the shorter life parts and the sharp reduction in the longer life part could simply be due to the flatness of the SN curve at long lives. Some of the ranges of the equivalent cycles methods look promising, though it is a purely empirical determination of the correct values, and some parts can be sensitive to changes in the number of cycles or loads. OEM method B and the equivalent load method give extremely inconsistent results and are not recommended. Finally, regression methods have problems with parts dominated by MTM damage.

The relevancy of the various methods to different applications is shown in table 26. Because OEM method B, equivalent cycles, equivalent Loads, and regression were all found to be inconsistent, they are not recommended for any application. Virtual Flights or the less numerically intensive max-min could be used directly for tracking damage of parts on a serial-number basis. They could also be used in a deterministic safe-life approach by using SUMS data to determine the statistics of the part and directly applying the M+2 damage rate. OEM method A was found to be reasonable for determining MTM damage when given a spectrum (though the evaluation should be repeated with more data). Finally, collecting cycles by load bins allows a statistical model to be used, which could be applied to reliability approaches for safe-life calculations. It is marked as usable for a SUMS-based spectrum because it could be used in the same way as Virtual Flights and max-min to determine a damage rate to apply to the safe life, though the other methods are more direct.

Table 26. Applicability of each method

Method	Legacy	SUMS Spectrum	Damage Tracking	Reliability
Virtual Flights	X	✓	✓	X
Max-Min	X	✓	✓	X
OEM Method B	X	X	X	X
OEM Method A	✓	✓	X	X
Equivalent Cycles	X	X	X	X
Equivalent Loads	X	X	X	X
Regression	X	X	X	X
Binned Cycles	X	✓	X	✓

3. EVALUATION APPROACH

Data was processed using four tools:

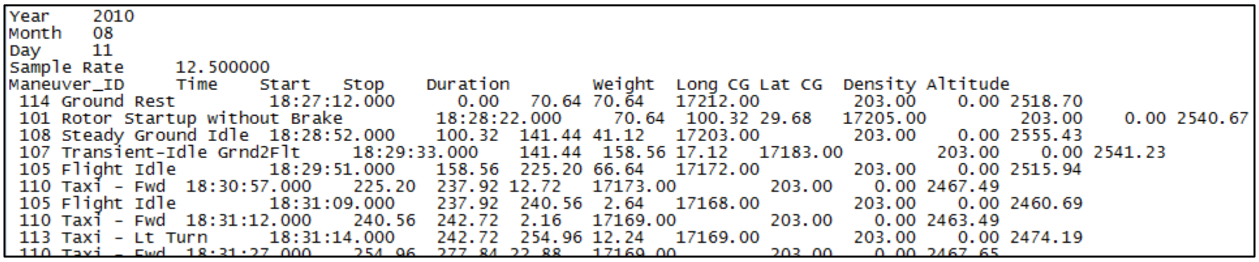
1. HBM nCode v7.0
2. Microsoft Excel 2010
3. C code compiled with Microsoft Visual C++ 2010 Express
4. ASRI PC-Signal® 1.0.3874.11879

The nCode software performed all of the rainflow counting and was also used for damage calculations. The nCode damage calculations agreed closely with the damage calculated by Excel using a log-linear interpolation. C code was written to extract and reformat data in text files to put it into usable formats for Excel and nCode. PC-Signal was used to extract regime flight data into a Comma Separated Variable (csv) file format.

3.1 USAGE DATA

The AED Condition Based Maintenance office provided AED Structures with appropriate aircraft and dates. The goal was to collect RRA files for approximately 30 aircraft for approximately 1 year, each ideally with 250 flight hours or more. RRA files are a SUMS program output of regimes and times in sequence in a tab delimited file.

Once the aircraft and locations were identified, only the CONUS flights were used to match the training mission scenario more closely, which has the most damage for the identified components. A total of 5461 RRA files were collected for 24 aircraft from three CONUS locations. From these files, 3263 had only a single regime entry of "APU Time." Because inclusion of these files would have drastically distorted the amount of time on each aircraft, and they did not include an engine start, they were eliminated. This left 2198 files totaling 3362 hours. A sample RRA file is shown in figure 21.



```
Year     2010
Month    08
Day      11
Sample Rate      12.500000
Maneuver_ID      Time     Start    Stop     Duration         Weight   Long CG Lat CG   Density Altitude
 114 Ground Rest          18:27:12.000     0.00    70.64 70.64    17212.00         203.00     0.00 2518.70
 101 Rotor Startup without Brake         18:28:22.000     70.64  100.32 29.68   17205.00         203.00     0.00 2540.67
 108 Steady Ground Idle  18:28:52.000     100.32  141.44 41.12    17203.00         203.00     0.00 2555.43
 107 Transient-Idle Grnd2Flt     18:29:33.000     141.44  158.56 17.12    17183.00         203.00     0.00 2541.23
 105 Flight Idle          18:29:51.000     158.56  225.20 66.64    17172.00         203.00     0.00 2515.94
 110 Taxi - Fwd  18:30:57.000     225.20  237.92 12.72    17173.00         203.00     0.00 2467.49
 105 Flight Idle          18:31:09.000     237.92  240.56  2.64    17168.00         203.00     0.00 2460.69
 110 Taxi - Fwd  18:31:12.000     240.56  242.72  2.16    17169.00         203.00     0.00 2463.49
 113 Taxi - Lt Turn       18:31:14.000     242.72  254.96 12.24    17169.00         203.00     0.00 2474.19
 110 Taxi - Fwd  18:31:27.000     254.96  277.84 22.88    17169.00         203.00     0.00 2467.65
```

Figure 21. Sample RRA file

The flight hours per aircraft ranged from 14–245, with an average of 129. This is far less than the 250 desired; however, the distributions seem reasonable. The lowest time aircraft had 14 hours, and though it did generally have more damage (especially for <1023>), it was not extremely out of bounds and was retained as a data point. The hours and damage (determined by virtual flights) is shown in table 27.

Table 27. Damage and hours by aircraft

	<1021>	<1021>	<1023>	<1023>	<1407>	<1407>	<1913>	<1913>	<71851>	<71851>	
ID	Total Dam/hr	MTM Dam/hr	Total Dam/hr	MTM Dam/hr	Total Dam/hr	MTM Dam/hr	Total Dam/hr	MTM Dam/hr	Total Dam/hr	MTM Dam/hr	Flight Hours
178	216.7E-6	10.2E-6	796.1E-9	791.2E-9	135.4E-6	18.4E-6	267.3E-6	261.5E-6	25.8E-6	79.5E-12	139.2
216	9.4E-6	575.2E-9	38.0E-9	38.0E-9	178.2E-9	178.2E-9	35.9E-6	35.4E-6	1.4E-6	-132.5E-15	77.7
230	200.9E-6	10.4E-6	639.4E-9	639.4E-9	250.9 E-6	30.8E-6	261.6E-6	257.0E-6	24.2E-6	67.0E-12	106.8
233	195.8E-6	8.6E-6	359.8E-9	352.5E-9	76.6 E-6	14.3E-6	249.8E-6	246.3E-6	20.8E-6	87.8E-12	139.8
243	184.4E-6	8.7E-6	401.3E-9	399.2E-9	167.6 E-6	24.9E-6	293.0E-6	290.1E-6	25.0E-6	104.0E-12	161.8
250	192.3E-6	8.9E-6	519.3E-9	519.3E-9	156.6 E-6	19.5E-6	251.3E-6	247.5E-6	23.3E-6	83.5E-12	211.0
253	228.0E-6	10.8E-6	473.4E-9	473.4E-9	76.3 E-6	17.6E-6	317.9E-6	314.0E-6	22.0E-6	40.2E-12	45.7
273	288.6E-6	13.7E-6	812.3E-9	812.3E-9	105.2 E-6	19.7E-6	265.2E-6	261.7E-6	27.5E-6	260.9E-12	58.3
274	297.4E-6	13.8E-6	226.4E-9	226.4E-9	98.9 E-6	20.0E-6	293.0E-6	291.2E-6	31.4E-6	111.1E-12	83.3
7	288.0E-6	11.6E-6	882.9E-9	880.3E-9	175.2 E-6	22.2E-6	214.7E-6	205.6E-6	28.2E-6	82.9E-12	129.5
9	473.6E-6	20.1E-6	2.0E-6	2.0E-6	232.9 E-6	40.4E-6	376.4E-6	362.4E-6	36.9E-6	9.5E-12	14.5
11	173.3E-6	8.0E-6	501.4E-9	501.4E-9	157.1 E-6	18.3E-6	198.9E-6	194.4E-6	20.4E-6	63.3E-12	167.5
15	234.7E-6	11.5E-6	770.7E-9	766.0E-9	56.3 E-6	11.8E-6	219.9E-6	214.6E-6	22.8E-6	56.3E-12	143.4
18	195.8E-6	8.4E-6	545.0E-9	538.8E-9	21.8 E-6	24.5E-6	270.3E-6	265.9E-6	21.0E-6	99.8E-12	163.4
20	266.1E-6	10.7E-6	563.9E-9	562.2E-9	220.9 E-6	23.1E-6	261.2E-6	254.7E-6	28.9E-6	98.2E-12	199.5
21	177.6E-6	8.9E-6	438.2E-9	438.2E-9	181.1 E-6	20.8E-6	263.0E-6	259.2E-6	25.0E-6	103.6E-12	205.7
22	266.5E-6	13.2E-6	419.0E-9	419.0E-9	76.6 E-6	12.8E-6	231.4E-6	228.0E-6	24.0E-6	69.3E-12	98.4
33	294.9E-6	15.0E-6	794.2E-9	794.2E-9	98.4 E-6	15.1E-6	289.0E-6	284.2E-6	28.9E-6	30.1E-12	45.3
67	417.9E-6	18.4E-6	1.1E-6	1.1E-6	99.8 E-6	18.7E-6	251.9E-6	245.7E-6	31.4E-6	107.1E-12	56.9
109	302.4E-6	11.6E-6	532.7E-9	532.7E-9	185.0 E-6	22.7E-6	272.7E-6	266.7E-6	26.9E-6	82.7E-12	165.2
114	281.8E-6	11.6E-6	603.6E-9	600.8E-9	190.7 E-6	22.6E-6	295.2E-6	287.6E-6	28.4E-6	99.0E-12	245.8
126	191.2E-6	10.1E-6	574.4E-9	574.4E-9	149.0 E-6	22.0E-6	281.0E-6	276.9E-6	22.8E-6	94.0E-12	190.7
139	304.6E-6	11.6E-6	611.2E-9	611.2E-9	140.5 E-6	16.9E-6	249.1E-6	242.4E-6	26.7E-6	87.9E-12	136.1
143	556.9E-6	19.9E-6	507.3E-9	507.3E-9	309.6 E-6	26.4E-6	266.0E-6	262.7E-6	36.5E-6	108.9E-12	115.2

3.2 REGIME DATA AND SUMS OCCURRENCE SPECTRUM

The FLS time histories for each regime were collected from the AED server. Because data collected during an FLS are not always 100%, the goal was to have a complete set of regime data rather than using the highest load from each maneuver. OEM documentation includes a list of which test maneuvers gave the maximum load, the minimum load, and the maximum oscillatory load for each measurement. These specific test maneuvers were targeted for collection first.

The FLS data on the AED server are stored in ASRI format for use by the PC-Signal software. That software was used on each flight maneuver to extract the specific gages and convert the time histories into a .csv format suitable for processing by Excel, nCode, and compiled C code. For these data, there was a good, but not perfect, correspondence between the regimes identified by SUMS in the RRA file and the regimes in the FLS. In addition, in the processing of time histories, some had to be processed by hand because of the length of recorded time. Table 28 lists the regimes along with any processing comments associated with that regime.

Table 28. List of regimes

RRA ID	FLS ID	Description	Flight-Point	Comments	Mean Occ/ 1,000 hr	M+2 Occ/ 1,000 hr
0		UNRECOGNIZED TIME		(0,0), (.5,1), (1,-1) dummy time series		
2		GROUND MAINTENANCE TIME		(0,0), (.5,1), (1,-1) dummy time series		
101	101	ROTOR START UP BRAKE OFF	776-5	hand processed, > 36,000 points	531	956
102	102	ROTOR START UP BRAKE ON	777-5	1st 130s truncated	1	6
103	103	ROTOR SHUT DOWN WITHOUT BRAKE	776-110	truncated at 170 s	35	161
104	104	ROTOR SHUT DOWN WITH BRAKE	777-85	hand processed, > 36,000 points	655	1,215
105		FLIGHT IDLE		last 1/2 s of 107	4,258	7,883
107	107	GROUND IDLE TO FLIGHT IDLE	776-8		759	1,355
108	108	GROUND IDLE (60%)	776-7		1,484	2,667
109	109	FLIGHT IDLE TO GROUND IDLE	776-6	truncated at 36,000 points	724	1,313
110	110	TAXI FORWARD	776-10	hand processed, > 36,000 points	5,145	10,666
111	111	TAXI AFT	776-11	hand processed, > 36,000 points	164	322
112	112	TAXI TURN RIGHT	776-12		1,811	4,113
113	113	TAXI TURN LEFT	776-13		2,531	5,604
114	114	CONTROL SWEEP	776-4		1,018	1,842
201	201	NORMAL TAKEOFF	776-90		2,448	4,758
202	202	JUMP TAKEOFF	776-92	Min <1407> 776-92	7	31
203	203	NORMAL APPROACH/LANDING	779-17		2,805	5,912
204	204	RUN ON LANDING	778-51	truncated at 36,000 points	75	164
205	205	1 ENG. OUT LDG VY-0	777-71		212	684
301	301	STEADY HOVER IGE	776-14		4,866	10,134
302	302	HOVER HOGE	777-72		5,099	10,487
303	303	IGE HOVER TURN RT	776-15	hand processed, > 36,000 points	1,252	2,574
304	304	IGE HOVER TURN LT	776-16	hand processed, > 36,000 points	1,366	3,090
305	305	OGE HOVER TURN RT	777-73	hand processed, > 36,000 points	957	2,139
306	306	OGE HOVER TURN LT	777-74	hand processed, > 36,000 points	1,035	2,246
307	307	IGE CONTROL REVERSAL DIR LEFT	776-20		104	310
308	308	IGE CONTROL REVERSAL DIR RIGHT	776-18		88	277
309	309	IGE CONTROL REVERSAL LONG FWD	776-21		238	502
310	310	IGE CONTROL REVERSAL LONG AFT	776-22		283	686
311	311	IGE CONTROL REVERSAL LAT LEFT	776-23		379	776
312	312	IGE CONTROL REVERSAL LAT RIGHT	776-24		285	607
313	313	IGE CONTROL REVERSAL COLL UP	776-25		109	227
314	314	IGE CONTROL REVERSAL COLL DWN	776-26		99	195
315	315	OGE CONTROL REVERSAL DIR LEFT	777-76		61	131
316	316	OGE CONTROL REVERSAL DIR RIGHT	777-75		71	163
317	317	OGE CONTROL REVERSAL LONG FWD	777-77		281	555
318	318	OGE CONTROL REVERSAL LONG AFT	777-78		204	429
319	319	OGE CONTROL REVERSAL LAT LEFT	777-79		68	152
320	320	OGE CONTROL REVERSAL LAT RIGHT	777-80		152	321
321	321	OGE CONTROL REVERSAL COLL UP	777-81		173	317
322	322	OGE CONTROL REVERSAL COLL DWN	777-82	Max <1913> 777-82	142	306
323	323	SIDEWARD FLT RT 45 KTS	776-27		395	1,215
324	324	SIDEWARD FLT LT 45KTS	776-28		27	253
325	325	REARWARD FLT 45 KTS	776-29		2,257	4,633
326	326	SIDEWARD ACCL LT MOD 0-45-0 KTS	776-30	hand processed, > 36,000 points	0	0
327	327	SIDEWARD ACCL LT MAX 0-45-0 KTS	776-31	hand processed, > 36,000 points	0	0
328	328	SIDEWARD ACCL RT MOD 0-45-0 KTS	776-32	hand processed, > 36,000 points	0	0
329	329	SIDEWARD ACCL RT MAX 0-45-0 KTS	776-33	truncated at 36,000 points	0	0
401	401	FULL POWER CLIMB SCS AT IRP	766-44		0	0
402	402	FULL POWER CLIMB SCS AT 0.9 IRP	766-44		172	376
403	403	PARTIAL POWER DESCENT AT .5VH	776-45		10	32
404	404	PARTIAL POWER DESCENT AT .7VH	766-45		8	31
405	405	POWER DIVE AT VNE	766-35		0	0
406	406	POWER DIVE @ 1.1VH	766-35		0	0

Table 28. List of regimes (continued)

RRA ID	FLS ID	Description	Flight-Point	Comments	Mean Occ/ 1,000 hr	M+2 Occ/ 1,000 hr
407	407	UNMASK	776-56		1	5
408	408	REMASK	776-57		3	12
501	501	MODERATE ACCELERATION 0-100 KTS	776-34	hand processed, > 36,000 points	732	1,570
502	502	MAX RATE ACCELERATION 0-100 KTS	776-36	truncated at 36,000 points	1,889	3,873
503	503	MODERATE DECELERATION 100-0 KTS	776-35	truncated at 36,000 points	28	83
504	504	MAX RATE DECELERATION 100-0 KTS	776-37		14	45
505	505	DCL TO HVR LNDG RAPID 85-0 KTS	776-91	truncated at 36,000 points	0	0
601	601	LVL FLT AT .1 VH	765-17		116	242
602	602	LVL FLT AT .2 VH	765-17		1,911	3,975
603	603	LVL FLT AT .4 VH	765-17		4,346	9,059
604	604	LVL FLT AT .4 VH	765-16		4,751	9,805
605	605	LVL FLT AT .5 VH	765-15		4,185	8,911
606	606	LVL FLT AT .6 VH	765-14		3,906	8,442
607	607	LVL FLT AT .7 VH	765-13		4,170	9,797
608	608	LVL FLT AT .8 VH	765-12		2,659	7,561
609	609	LVL FLT AT .9 VH	765-11		110	451
610	610	LVL FLT AT VH	765-10		7	39
611	611	SIDESLIP RIGHT AT .8VH	765-22		13,166	26,300
612	612	SIDESLIP RIGHT AT 1.0VH	765-31		2,901	6,618
613	613	SIDESLIP LEFT AT .8VH	765-27		9	45
614	614	SIDESLIP LEFT AT 1.0VH	765-35		14	147
615	615	CONTROL RVSL DIR LEFT AT .9VH	768-23		279	640
616	616	CONTROL RVSL DIR RIGHT AT .9VH	768-25		292	578
617	617	CONTROL RVSL LONG FWD AT .9VH	765-40		611	1,177
618	618	CONTROL RVSL LONG AFT AT .9VH	765-41		509	1,179
619	619	CONTROL RVSL LAT LEFT AT .9VH	765-42		273	534
620	620	CONTROL RVSL LAT RIGHT AT .9VH	765-43		401	806
621	621	CONTROL RVSL COLL UP AT .9VH	765-44		548	1,013
622	622	CONTROL RVSL COLL DWN AT .9VH	765-45		366	677
701	701	RIGHT TURN AT .5VH 1.5G	765-46		4,714	9,976
702	702	RIGHT TURN AT .5VH 2.0G	765-48		1	7
703	703	RIGHT TURN AT .8VH 1.5G	766-10		5,818	11,554
704	704	RIGHT TURN AT .8VH 2.0G	766-12		7	26
705	705	RIGHT TURN AT VH 1.5G	850-54	Max <1023> 850-54	650	1,561
706	706	RIGHT TURN AT VH 2.0G	766-16		1	6
707	707	LEFT TURN AT .5VH 1.5G	765-47		6,003	12,437
708	708	LEFT TURN AT .5VH 2.0G	765-49		2	9
709	709	LEFT TURN AT .8VH 1.5G	766-11		6,872	13,365
710	710	LEFT TURN AT .8VH 2.0G	766-13	Max Cyc <1033> 766-13	8	24
711	711	LEFT TURN AT VH 1.5G	766-15		808	1,871
712	712	LEFT TURN AT VH 2.0G	766-17		1	10
713	713	RPO RIGHT .8VH 1.5G	766-21		210	469
715	715	RPO RIGHT .8VH 2.0G	766-23		99	236
716	716	RPO RIGHT .8VH 2.5G	766-23		11	44
717	717	717 RPO Rt 0.8 Vh, 3.0 g	766-23		14	40
718	718	RPO RIGHT 1.0VH 1.5G	766-27		7	24
720	720	RPO RIGHT 1.0VH 2.0G	766-29		2	7
721	721	RPO RIGHT 1.0VH 2.5G	766-29		0	0
722	722	722 RPO Rt Vh, 3.0 g	735-40	Max Cyc <1021> 735-40	0	0
723	723	RPO RIGHT 1.1VH 1.5G	766-33		276	590
724	724	RPO RIGHT 1.0VNE 1.4G	766-37	OEM 724 moved to 760 for LP3 configuration only	102	235
725	725	RPO LEFT .8VH 1.5G	766-22		2	11
727	727	RPO LEFT .8VH 2.0G	750-15	Max <1033> 766-24, Max Cyc <1407> 750-15	24	64
728	728	RPO LEFT .8VH 2.5G	766-24		13	49
729	729	729 RPO Lt 0.8 Vh, 3.0 g	766-24		1	5

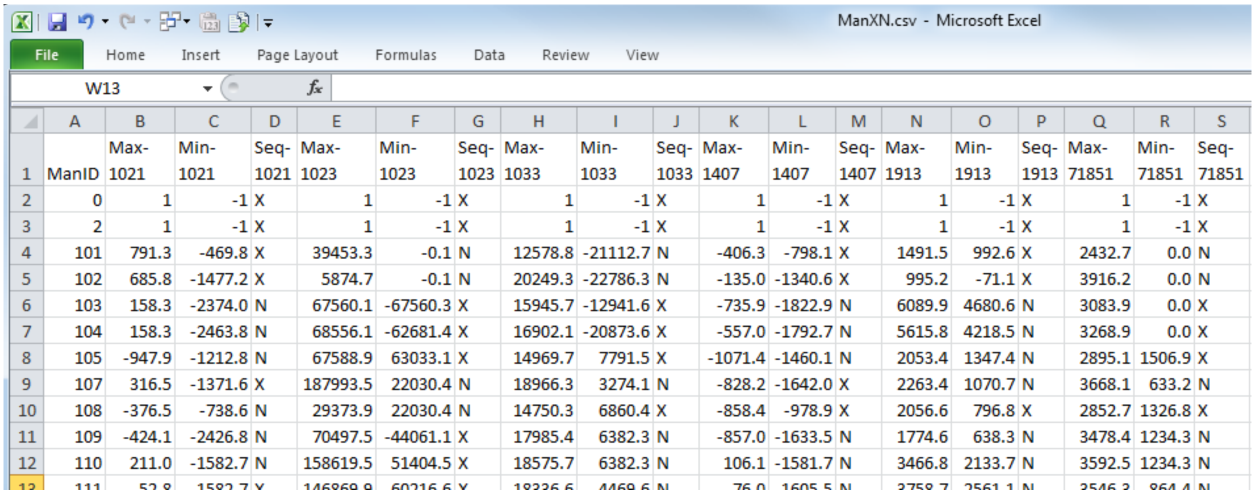
Table 28. List of regimes (continued)

RRA ID	FLS ID	Description	Flight-Point	Comments	Mean Occ/ 1,000 hr	M+2 Occ/ 1,000 hr
730	730	RPO LEFT 1.0VH 1.5G	766-28		0	0
732	732	RPO LEFT 1.0VH 2.0G	761-13	Min <1913> 761-13	0	0
733	733	RPO LEFT 1.0VH 2.5G	739-22	Max <1021>, <1407> 739-22	2	13
734	734	734 RPO Lt Vh, 3.0 g	766-30		4,207	7,974
735	735	RPO LEFT 1.1VH 1.5G	766-34		53	124
736	736	RPO LEFT 1.0VNE 1.4G	766-38	OEM 736 moved to 761 for LP3 configuration only	8	25
737	737	SYMM PULLOUT .5VH 2.5G	766-18		0	3
738	738	SYMM PULLOUT .8VH 1.5G	766-19		808	2,118
740	740	SYMM PULLOUT .8VH 2.0G	766-20		15	59
741	741	SYMM PULLOUT .8VH 2.5G	766-20		2	9
742	742	SYMM PULLOUT .8VH 3.0G	766-20		0	0
744	744	SYMM PULLOUT 1.0VH 1.5G	766-25		2	9
746	746	SYMM PULLOUT 1.0VH 1.5G	766-26		0	0
747	747	SYMM PULLOUT 1.0VH 2.5G	766-26		1	7
748	748	SYMM PULLOUT 1.0VH 3.0G	753-14	Min <1021> 753-14	5,818	11,554
750	750	SYMM PULLOUT 1.1VH 1.5G	766-31		7	26
751	751	SYMM PULLOUT 1.1VH 2.0G	766-32		650	1,561
752	752	SYMM PULLOUT VNE 1.75G	766-36		1	10
753	753	PUSHOVER .5VH .5G	766-39		1,139	2,497
754	754	PUSHOVER .5VH 0G	766-40		2	12
755	755	PUSHOVER .8VH 0G	761-27		7	25
756	756	PUSHOVER .8VH .5G	766-42		217	392
757		PUSHOVER .8VH .75G		copy of 758	2,861	5,458
758	758	PUSHOVER 1.0VH .5G	766-43		667	1,678
760		RPO RIGHT 1.0VNE 1.3G		249_30 not available, copy of 724	0	0
761		RPO LEFT 1.0VNE 1.3G		249_29 not available, copy of 736	0	0
762		SYMM PULLUP 0.8VH 1.5G		copy of 738	0	0
786		Symm. Pullup 0.5VH 1.5G		FLS not available, copy of 738	159	377
787		Symm. Pullup 0.5VH 2.0G		FLS not available, copy of 740	16	42
801	801	TWIN TO SINGLE .8VH	853-13	truncated at 36,000 points	68	164
802	802	TWIN TO SINGLE 1.0VH	853-13	truncated at 36,000 points	2	9
803	803	SINGLE TO TWIN .8VH	853-14	hand processed, > 36,000 points	608	1,285
804	804	SINGLE TO TWIN 1.0VH	853-14	hand processed, > 36,000 points	5	19
805	805	TWIN TO AUTOROT 120 KTS	861-11		618	1,297
806	806	TWIN TO AUTOROT VH	861-12	truncated at 36,000 points, Max Cyc <1023> 861-12	14	45
807	807	AUTOROT TO TWIN .8VH	853-15	hand processed, > 36,000 points	27	78
808	808	AUTOROT TO TWIN 1.0VH	853-15	hand processed, > 36,000 points	0	0
809	809	SINGLE TO AUTOROT VH	857-23		0	0
901	901	AUTOROTATION STABILIZED FLIGHT	753-43		0	0
902	902	AUTOROT TURN RIGHT .8VMA 1.5G	743-43		0	0
903	903	AUTOROT TURN RIGHT 1.0VMA 1.5G	750-16		0	0
904	904	AUTOROT TURN LEFT .8VMA 1.5G	743-44		0	0
905	905	AUTOROT TURN LEFT 1.0VMA 1.5G	748-50		0	0
906	906	AUTOROT P/U 1.5G 100KTS	856-31	Min <1023> 853-31	0	0
1001	1001	LAT AGILITY RIGHT 45 KT TO 0	776-38		0	3
1002	1002	LAT AGILITY LEFT 45 KT TO 0	778-46		1	6
1003	1003	LAT AGILITY RT 45 KT KICKOUT/ACCEL	776-40		17	50
1004	1004	LAT AGILITY LT 45 KT KICKOUT/ACCEL	776-41		7	25
1005	1005	POP UP AT 20 KTS	776-42		6	22
1006	1006	POP UP AT 40 KTS	776-43		6	21
1007	1007	SIDEFLARE/KICKOUT RT .4VH	749-46		0	3
1008	1008	SIDEFLARE/KICKOUT RT .8VH	749-46		0	0
1009	1009	SIDEFLARE/KICKOUT LT .4VH	749-47	truncated at 36,000 points	85	248
1010	1010	SIDEFLARE/KICKOUT LT .8VH	749-47	truncated at 36,000 points	117	377
1011	1011	SIDESLIP TO RIGHT 60 KTS	777-19		0	0

Table 28. List of regimes (continued)

RRA ID	FLS ID	Description	Flight-Point	Comments	Mean Occ/ 1,000 hr	M+2 Occ/ 1,000 hr
1012	1012	SIDESLIP TO RIGHT 90 KTS	777-32		0	3
1013	1013	SIDESLIP TO LEFT 60 KTS	777-26		188	411
1014	1014	SIDESLIP TO LEFT 90 KTS	777-38		1	10
1015	1015	TERRN TURN RIGHT 30 KTS	776-44		1,139	2,497
1016	1016	TERRN TURN RIGHT 60 KTS	776-48		286	702
1017	1017	TERRN TURN LEFT 30 KTS	776-45		199	448
1018	1018	TERRN TURN LEFT 60 KTS	776-49		363	850
1019	1019	PEDAL TURN RIGHT 20 KTS	776-46		3,153	6,645
1020	1020	PEDAL TURN RIGHT 40 KTS	776-50		25	78
1021	1021	PEDAL TURN LEFT 20 KTS	776-47		3,165	6,469
1022	1022	PEDAL TURN LEFT 40 KTS	776-51		4	16
1023	1023	TERRN PULLUP 1.25G 40KT	776-52		150	425
1024	1024	TERRN PULLUP 1.25G 80KT	776-53		123	278
1025	1025	DASH ACCEL TO 60KT/STOP	776-54	hand processed, > 36,000 points	399	807
1026	1026	DASH ACCEL TO VH/STOP	776-55	hand processed, > 36,000 points	47	106
1027	1027	TERRN PUSHOVER -0.25G 40KT	776-58		66	239
1028	1028	TERRN PUSHOVER -0.25G 80KT	776-48		44	105
1031	1031	CYCCLMB PO BREAK 60 KTAS (TAR) L	767-23		0	0
1032	1032	CYCCLMB PO BREAK 60 KTAS (TAR) R	767-24		0	0
1033	1033	CYCCLMB PO BREAK 100 KTAS (TAR) L	768-11		0	0
1034	1034	CYCCLMB PO BREAK 100 KTAS (TAR) R	768-10		0	0
1035	1035	CYCLIC CLIMB TO A PUSH-OVER BREAK, VH, LT	774-16	Max Cyc <1913> 774-16	0	0
1036	1036	CYCLIC CLIMB TO A PUSH-OVER BREAK, VH, RT	767-28		0	0
1037	1037	ALT DIVE RCVRY 60 KTAS (TAR) L	767-29		0	0
1038	1038	ALT DIVE RCVRY 60 KTAS (TAR) R	767-30		0	0
1039	1039	ALT DIVE RCVRY 100 KTAS (TAR) L	768-14		0	0
1040	1040	ALT DIVE RCVRY 100 KTAS (TAR) R	767-32		0	0
1041	1041	ALTERNATE DIVE RECOVERY, VH, LT	768-15	hand processed, > 36,000 points	0	0
1042	1042	ALTERNATE DIVE RECOVERY, VH, RT	767-34	truncated at 36,000 points	0	0
1043	1043	PITCHBACK ATTACK 60 KTAS (TAR) L	767-35	Min <1033> 767-35	0	0
1044	1044	PITCHBACK ATTACK 60 KTAS (TAR) R	767-36		0	0
1045	1045	PITCHBACK ATTACK 100 KTAS (TAR) L	768-16		0	0
1046	1046	PITCHBACK ATTACK 100 KTAS (TAR) R	767-38		0	0
1047	1047	PITCH BACK ATTACK, VH, LT	768-17	truncated at 36,000 points	0	0
1048	1048	PITCH BACK ATTACK, VH, RT	767-40		0	0
1049	1049	DECELERATING TURN 80 KTAS (TAR) L	767-41		0	0
1050	1050	DECELERATING TURN 80 KTAS (TAR) R	767-42		0	0
1051	1051	DECELERATING TURN 100 KTAS (TAR) L	768-18		0	0
1052	1052	DECELERATING TURN 100 KTAS (TAR) R	767-44		0	0
1053	1053	DECELERATING TURN, VH, LT	768-19		0	0
1054	1054	DECELERATING TURN, VH, RT	767-46		0	0
1055	1055	BREAK TURN 60 KTAS (TAR) L	767-47		0	0
1056	1056	BREAK TURN 60 KTAS (TAR) R	767-48		0	0
1057	1057	BREAK TURN 100 KTAS (TAR) L	768-20		0	0
1058	1058	BREAK TURN 100 KTAS (TAR) R	767-50		0	0
1059	1059	BREAK TURN, VH, LT	768-21		0	0
1060	1060	BREAK TURN, VH, RT	767-52		0	0
1061	1061	Pedal Turn Right, 40 KTAS	770-36	hand processed, > 36,000 points	0	0
1062	1062	Pedal Turn Right, 60 KTAS	770-13	hand processed, > 36,000 points	0	0
1063	1063	Pedal Turn Right, 80 KTAS	770-60	hand processed, > 36,000 points	0	0
1064	1064	Pedal Turn Right, 0.8Vh	769-90	hand processed, > 36,000 points	0	0
1065	1065	Pedal Turn Right, Vh	769-112	hand processed, > 36,000 points	0	0
1066	1066	Pedal Turn Left, 40 KTAS	770-37	hand processed, > 36,000 points	0	0
1067	1067	Pedal Turn Left, 60 KTAS	770-14	hand processed, > 36,000 points	0	0
1068	1068	Pedal Turn Left, 80 KTAS	770-61	hand processed, > 36,000 points	0	0
1069	1069	Pedal Turn Left, 0.8Vh	771-39	hand processed, > 36,000 points	0	0
1102	1102	Cyc. Climb PO Break 100kts R	777-41		0	3
1110	1110	Decelerating Turn 80Kts L	778-25		0	3

Each regime time history csv file was processed by the C program code to generate a columnar format usable by nCode. At the same time, the maximum, minimum, and sequence of loads were extracted into a file called ‘MaxXN.csv’ so that it could be used for calculating load time histories using the sequenced load pairings. The format of this file is shown in figure 22.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	ManID	Max-1021	Min-1021	Seq-1021	Max-1023	Min-1023	Seq-1023	Max-1033	Min-1033	Seq-1033	Max-1407	Min-1407	Seq-1407	Max-1913	Min-1913	Seq-1913	Max-71851	Min-71851	Seq-71851
2	0	1	-1	X	1	-1	X	1	-1	X	1	-1	X	1	-1	X	1	-1	X
3	2	1	-1	X	1	-1	X	1	-1	X	1	-1	X	1	-1	X	1	-1	X
4	101	791.3	-469.8	X	39453.3	-0.1	N	12578.8	-21112.7	N	-406.3	-798.1	X	1491.5	992.6	X	2432.7	0.0	N
5	102	685.8	-1477.2	X	5874.7	-0.1	N	20249.3	-22786.3	N	-135.0	-1340.6	X	995.2	-71.1	X	3916.2	0.0	N
6	103	158.3	-2374.0	N	67560.1	-67560.3	X	15945.7	-12941.6	X	-735.9	-1822.9	N	6089.9	4680.6	N	3083.9	0.0	X
7	104	158.3	-2463.8	N	68556.1	-62681.4	X	16902.1	-20873.6	X	-557.0	-1792.7	N	5615.8	4218.5	N	3268.9	0.0	X
8	105	-947.9	-1212.8	N	67588.9	63033.1	X	14969.7	7791.5	X	-1071.4	-1460.1	N	2053.4	1347.4	N	2895.1	1506.9	X
9	107	316.5	-1371.6	X	187993.5	22030.4	N	18966.3	3274.1	N	-828.2	-1642.0	X	2263.4	1070.7	N	3668.1	633.2	N
10	108	-376.5	-738.6	N	29373.9	22030.4	N	14750.3	6860.4	X	-858.4	-978.9	X	2056.6	796.8	X	2852.7	1326.8	X
11	109	-424.1	-2426.8	N	70497.5	-44061.1	X	17985.4	6382.3	N	-857.0	-1633.5	N	1774.6	638.3	N	3478.4	1234.3	N
12	110	211.0	-1582.7	N	158619.5	51404.5	X	18575.7	6382.3	N	106.1	-1581.7	N	3466.8	2133.7	N	3592.5	1234.3	N

Figure 22. File ManXN.csv

The csv file for each regime was then run through nCode to be simplified into peak/valley points to simplify processing, in which only the load reversal points are retained, rather than a point for every time segment that was initially recorded. The amount of within-regime damage was calculated using the nCode stress-life glyph for each measurement. The peak/valley points, along with the damage metadata, were saved in an nCode time history S3T format for processing in the virtual flights.

A second set of regime time history files—in which there were only two points, the maximum and the minimum—was also generated. These files were used in the calculation of damage using the max-min method.

Also listed in table 28 are columns for Mean Occurrences/1,000 hr and M+2 Occurrences/1,000 hr. The RRA files were processed for each aircraft to provide the number of occurrences and time in each regime—data suitable as input for the generation of a SUMS-based spectrum. Because all the MTM damage calculations are occurrence-based, the occurrence data were used to generate the mean and standard deviation for each regime across the 24 aircraft. This was used to generate an M+2 pseudo-spectrum that relates only to number of occurrences. No attempt was made to subtract occurrences from non-damaging regimes because they would have no effect on damage accumulation. The M+2 occurrence rates were used in all the methods that depend on a spectrum.

3.3 SN CURVES AND DAMAGE CALCULATION

The OEM of the parts being studied provided SN curves in the form of tables. These tables were entered into nCode for use by the stress-life glyph when calculating damage. They were also used in Excel where damage was calculated using log-linear interpolation between the points.

Excel and nCode did not produce exactly equivalent damage values, but they were very close and allow for reasonable comparison.

Figures 23–27 show the SN curves as captured in nCode. The stress-life glyph requires the units of measurement to be stress, so all of the SN curves are listed as psi regardless of their actual physical units. Flight data for <1023> are recorded in in-lb and the SN curve is reported in in-kip, so conversions are applied when necessary. The nCode software also requires that Mean stress curves have a curve with Mean = 0 and that R ratio curves have a curve with R = -1.0. The Goodman correction, as defined in section 2.2, was used to generate the needed curves for <1023>, <1913>, and <71851> because they were defined by the OEM at other values.

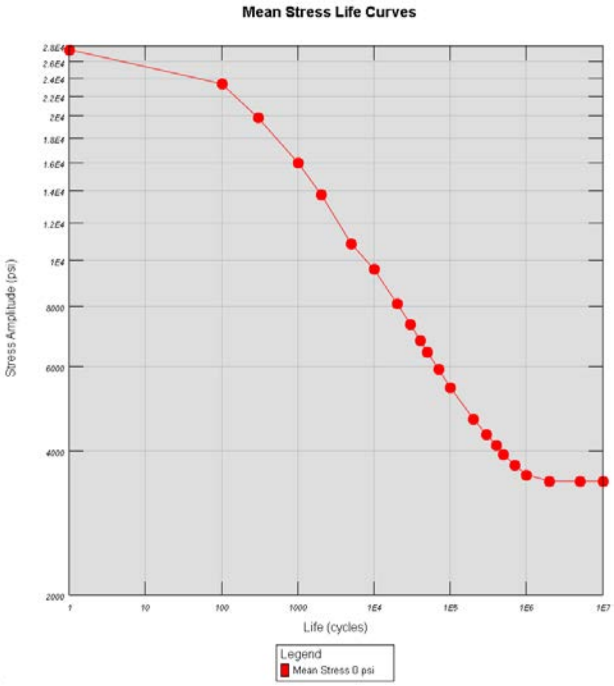


Figure 23. The <1021> SN curve

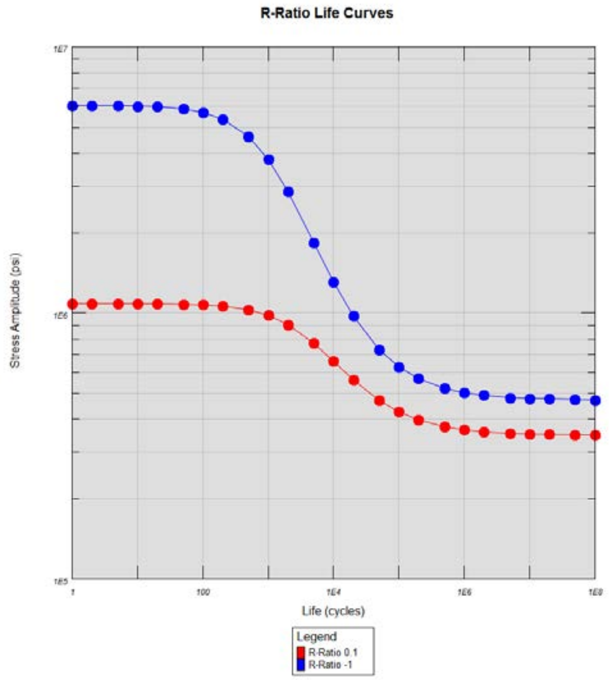


Figure 24. The <1023> SN curve

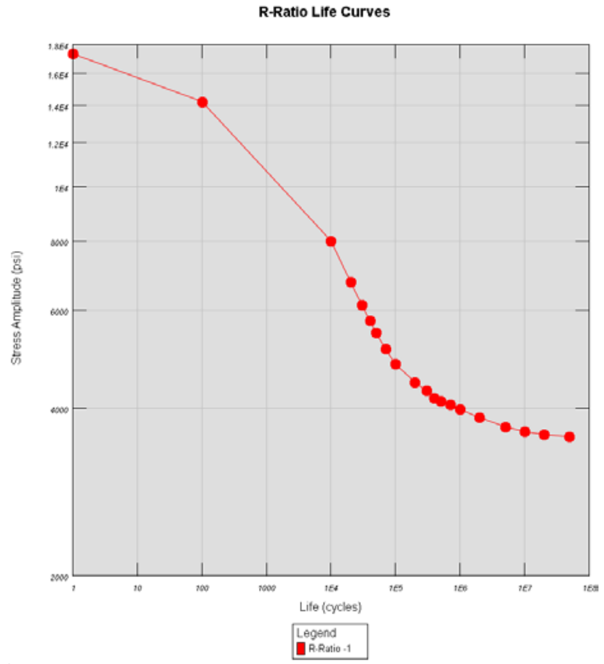


Figure 25. The <1407> SN curve

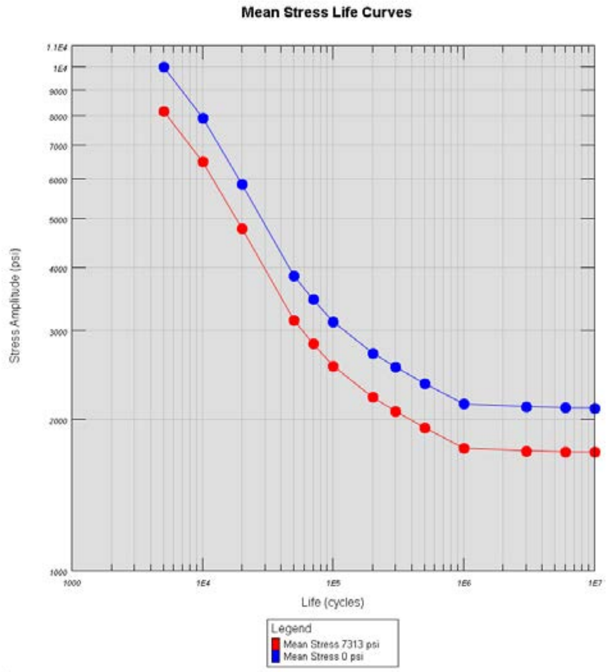


Figure 26. The <1913> SN curve

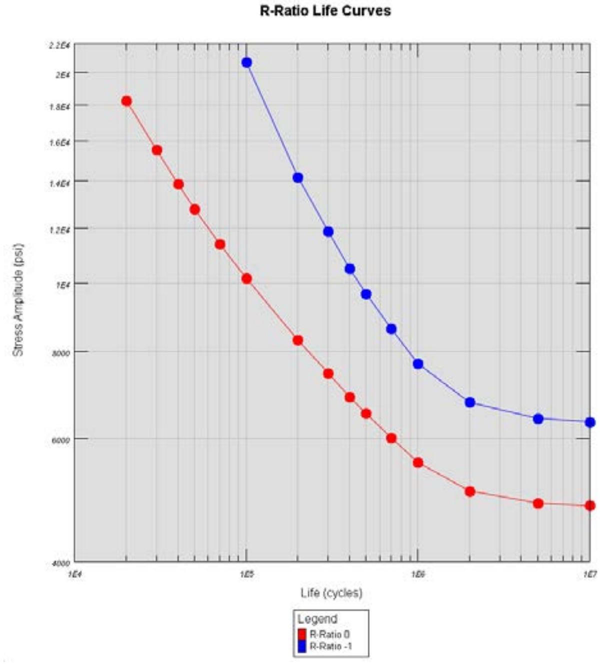


Figure 27. The <71851> SN curve

Table 29 shows the SN curve data points for <1021> showing cycles, N, at a given load, and S. The slope and intercept columns are based on the two points defined by S and Log(N). The row that follows is used for the log-linear interpolation. The equivalent table is repeated for each part. To calculate the number of cycles at a given load:

$$N = 10^{(slope*load+intercept)} \tag{3}$$

e.g., at $S = 6000, N = 10^{(-0.00030*6000+6.6144)} = 67,411 \text{ (incl. roundoff)}$.

Table 29. <1021> SN curve data points

N	S	Log(N)	Slope	Intercept
1E+07	3,463	7.00	-0.00917	38.7706
1E+06	3,572	6.00	-0.00092	9.2740
700,000	3,741	5.85	-0.00071	8.5118
500,000	3,946	5.70	-0.00054	7.8353
400,000	4,125	5.60	-0.00060	8.0680
300,000	4,334	5.48	-0.00051	7.7021
200,000	4,677	5.30	-0.00040	7.1487
100,000	5,439	5.00	-0.00031	6.6650
70,000	5,945	4.85	-0.00030	6.6144
50,000	6,436	4.70	-0.00026	6.3403
40,000	6,816	4.60	-0.00023	6.1448
30,000	7,368	4.48	-0.00023	6.1865
20,000	8,127	4.30	-0.00021	5.9767
10,000	9,587	4.00	-0.00024	6.2886
5,000	10,848	3.70	-0.00014	5.1704
2,037	13,723	3.31	-0.00014	5.1696
1,000	16,002	3.00	-0.00014	5.1699
300	19,858	2.48	-0.0001	5.171086
100	23,375	2.00		

3.4 PROCESSING FLIGHTS

The RRA files were used as the source to generate schedule files in nCode using a C program. The schedule files list the sequence in which individual regimes are flown, with an option to either concatenate all of the regime files into a single time history or manage each one separately. By concatenating all the files into a single time history, the virtual flights were generated. Rainflow counting the virtual flights and calculating damage based on the counted cycles provide the total damage for each flight/RRA file. Summing up the damage from the individual regimes provides the within-regime damage for each flight. The MTM damage is simply taken as the difference.

Processing the full-time history regime files gives results for the virtual flights. Performing the identical process with the simplified 2-point max-min regimes gives MTM results using the max-min method. When calculating the max-min within-regime damage, it is important to remember that each regime only has half of a cycle. When processed by nCode, the damage for the regimes assumes a full cycle and the results must be divided by two.

For each aircraft, all of the RRA files were processed for the total damage, within-regime damage, and MTM damage. The sums were then normalized by the flight time for that aircraft. Given the damage rates for each aircraft, the mean and standard deviation of the population was determined.

To clarify, figures 28–31 show the processing of a sample series of maneuvers for part <1021>. Regimes 302 (hover), 402 (climb), 607 (Level flight 0.7 VH), and 747 (Symm. Pullout 1.0VH 2.5G) were concatenated together. The raw FLS time history data are shown in figure 28. In this case, 36.5 seconds of data are represented in 36,429 data points. The changes between regimes are clearly visible at times of approximately 6.5s, 13s, and 23s.

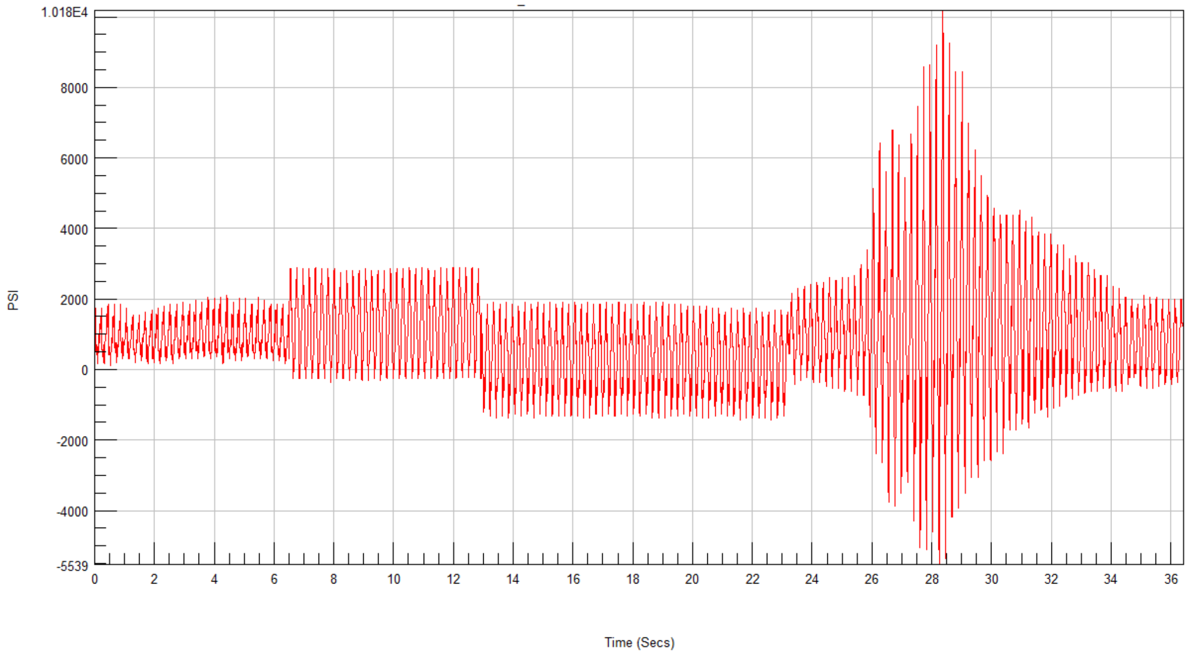


Figure 28. The <1021> sample FLS time history

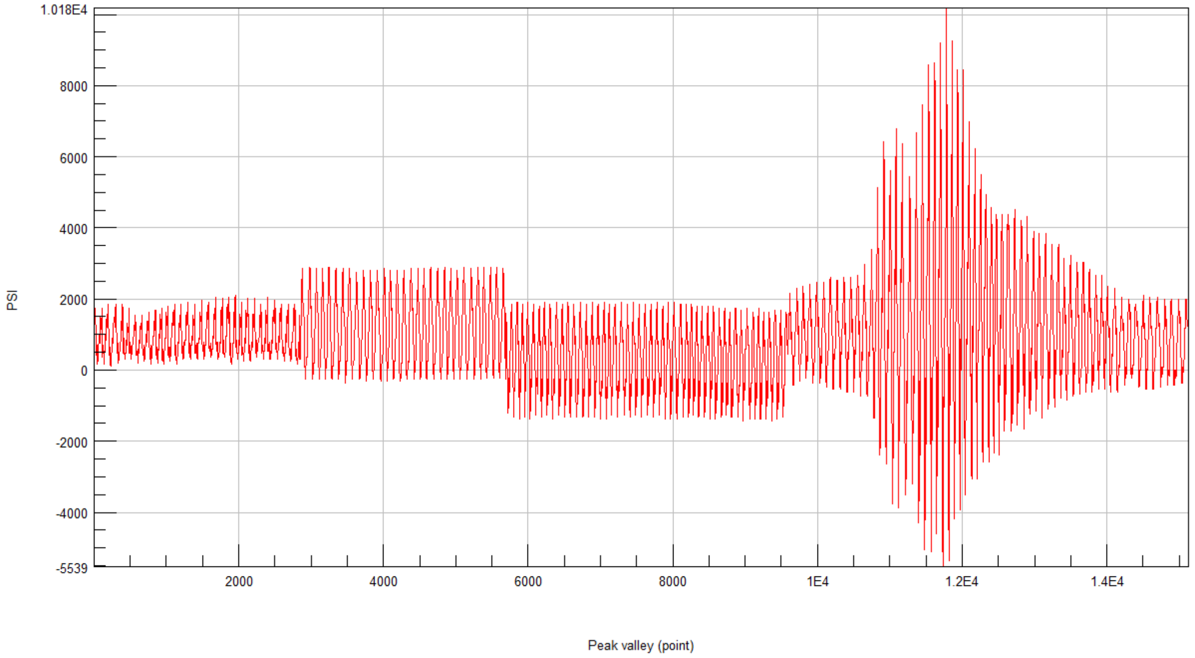


Figure 29. The <1021> sample peak valley time history

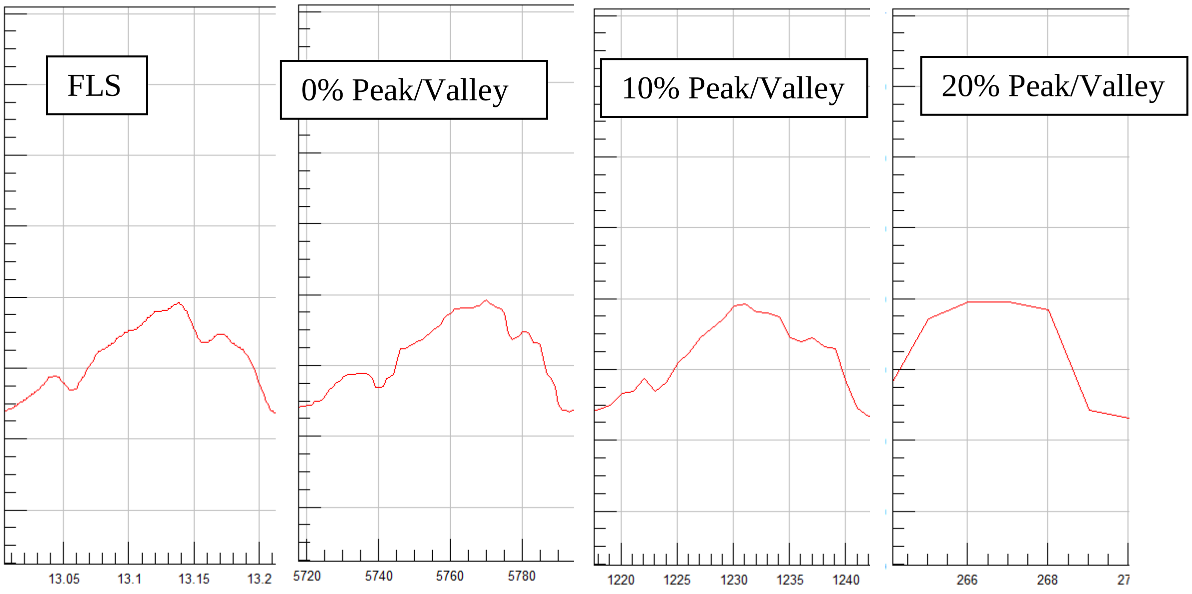


Figure 30. Single cycle peak valley comparison

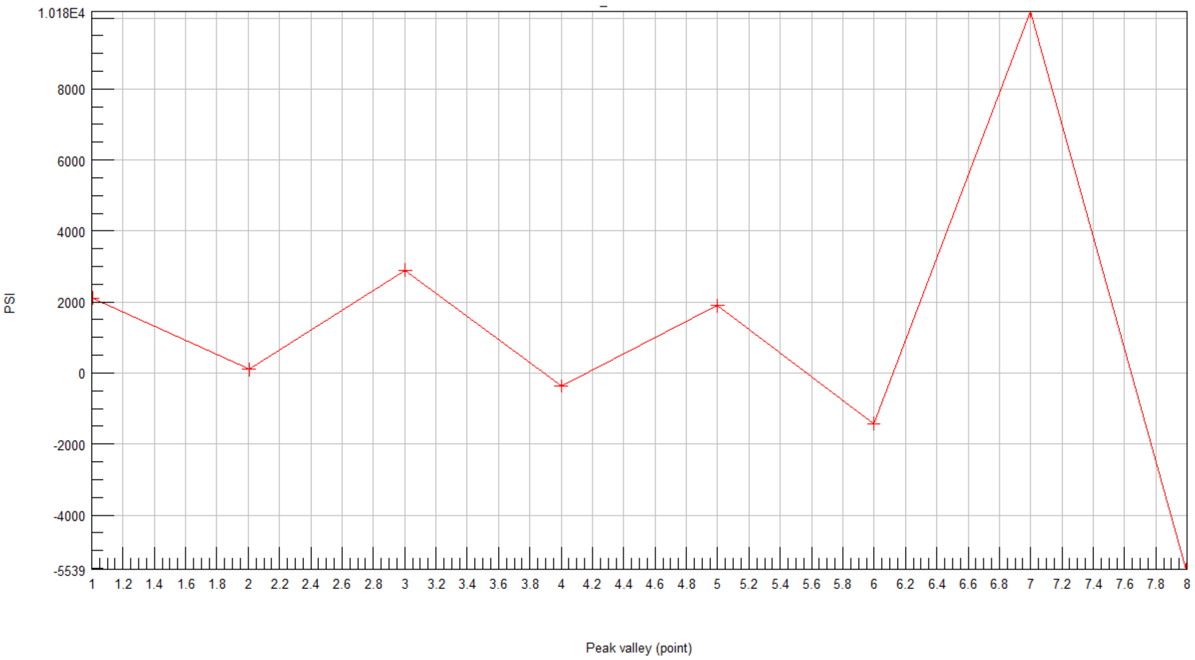


Figure 31. The <1021> sample max-min time history

In figure 29, the FLS data have been passed through the peak/valley filter in nCode with a 0% gate, meaning every load reversal is retained no matter how small. Only 15,130 points, approximately half the data, are needed.

Though the 0% gate was used in this study, figure 30 shows the effect of increasing the gate percentage on a single cycle at the beginning of the third regime. Moving from left to right, the curves are the full FLS data with 36,429 points, 0% peak/valley with 15,130 points, 10% peak/valley with 4,268 points, and 20% peak/valley with 1,829 points. A major loss of resolution is not apparent until the 20% filter, but even then the overall cycle loads are retained while having only 5% of the data to process.

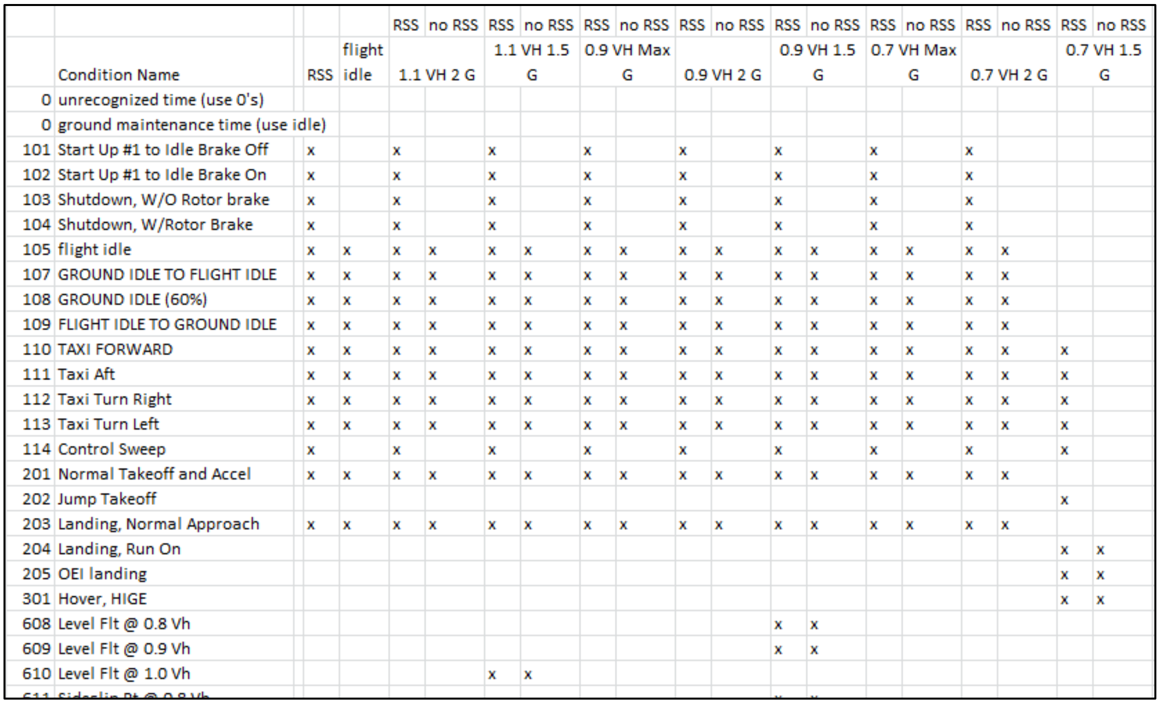
The max-min method time history, which results in the minimum amount of data possible, is shown in figure 31. In this figure, there are only the two points for each of the regimes.

3.5 MTM METHODS

3.5.1 OEM Methods

3.5.1.1 OEM Method B Procedure, Assumed GAG Cycles, and Extreme Loads

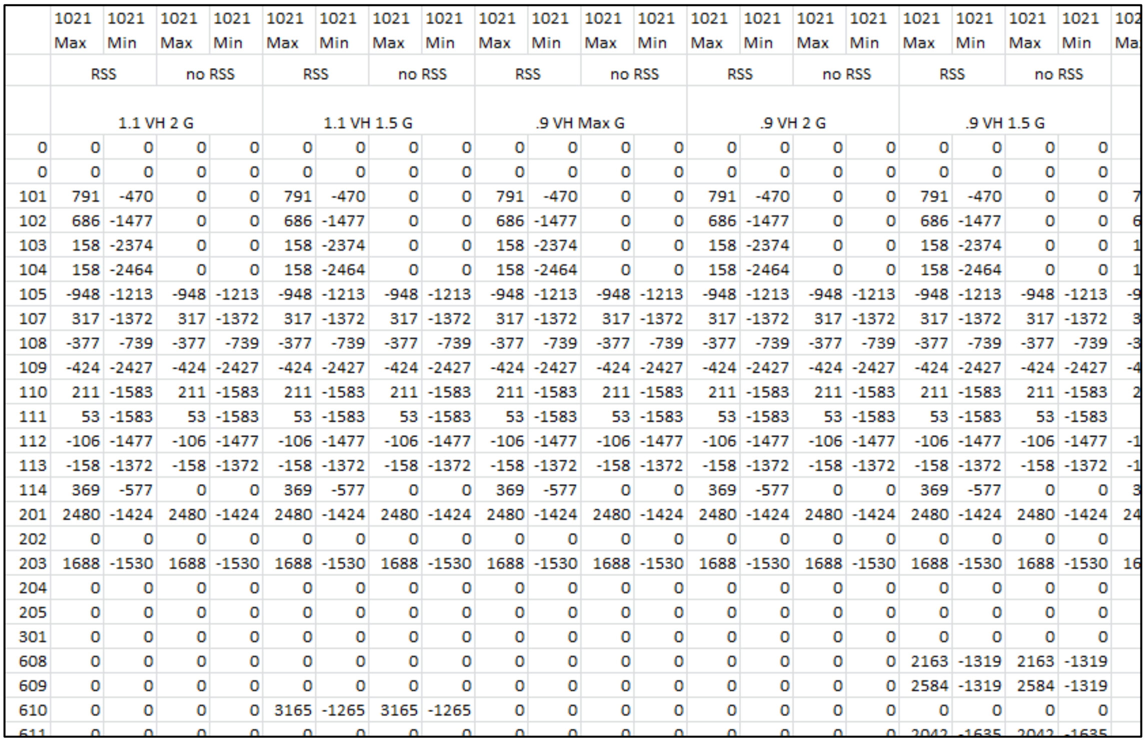
The OEM method B begins by identifying each regime into the appropriate categories. Flight regimes typically fall into a single category for either RSS or No-RSS. Most ground regimes fall into both the RSS and No-RSS divisions. The major difference is that the startup and shutdown regimes are not included in the No-RSS division. For parts <1021> and <71851>, RSS versus No-RSS makes no difference, but it is relevant to the other parts. The start of the identification matrix is shown in figure 32.



				RSS	no RSS	RSS	no RSS	RSS	no RSS	RSS	no RSS	RSS	no RSS	RSS	no RSS	RSS	no RSS	RSS	no RSS
	Condition Name	RSS	flight idle	1.1 VH 2 G		1.1 VH 1.5 G		0.9 VH Max G		0.9 VH 2 G		0.9 VH 1.5 G		0.7 VH Max G		0.7 VH 2 G		0.7 VH 1.5 G	
0	unrecognized time (use 0's)																		
0	ground maintenance time (use idle)																		
101	Start Up #1 to Idle Brake Off	x		x		x		x		x		x		x		x			
102	Start Up #1 to Idle Brake On	x		x		x		x		x		x		x		x			
103	Shutdown, W/O Rotor brake	x		x		x		x		x		x		x		x			
104	Shutdown, W/Rotor Brake	x		x		x		x		x		x		x		x			
105	flight idle	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		
107	GROUND IDLE TO FLIGHT IDLE	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		
108	GROUND IDLE (60%)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		
109	FLIGHT IDLE TO GROUND IDLE	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		
110	TAXI FORWARD	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
111	Taxi Aft	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
112	Taxi Turn Right	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
113	Taxi Turn Left	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
114	Control Sweep	x		x		x		x		x		x		x		x		x	
201	Normal Takeoff and Accel	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		
202	Jump Takeoff																	x	
203	Landing, Normal Approach	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		
204	Landing, Run On																	x	x
205	OEI landing																	x	x
301	Hover, HIGE																	x	x
608	Level Flt @ 0.8 Vh											x	x						
609	Level Flt @ 0.9 Vh											x	x						
610	Level Flt @ 1.0 Vh					x	x												

Figure 32. The OEM method B regimes by category

Once the regimes appropriate to each category are identified, the maximum and minimum loads, as determined from the FLS data, are extracted, as shown in figure 33.



	1021 Max	1021 Min	1021 Max	1021 Min	1021 Max	1021 Min	1021 Max	1021 Min	1021 Max	1021 Min	1021 Max	1021 Min	1021 Max	1021 Min	1021 Max	1021 Min	1021 Max	1021 Min	1021 Max	1021 Min
	RSS		no RSS		RSS		no RSS		RSS		no RSS		RSS		no RSS		RSS		no RSS	
	1.1 VH 2 G				1.1 VH 1.5 G				.9 VH Max G				.9 VH 2 G				.9 VH 1.5 G			
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
101	791	-470	0	0	791	-470	0	0	791	-470	0	0	791	-470	0	0	791	-470	0	0
102	686	-1477	0	0	686	-1477	0	0	686	-1477	0	0	686	-1477	0	0	686	-1477	0	0
103	158	-2374	0	0	158	-2374	0	0	158	-2374	0	0	158	-2374	0	0	158	-2374	0	0
104	158	-2464	0	0	158	-2464	0	0	158	-2464	0	0	158	-2464	0	0	158	-2464	0	0
105	-948	-1213	-948	-1213	-948	-1213	-948	-1213	-948	-1213	-948	-1213	-948	-1213	-948	-1213	-948	-1213	-948	-1213
107	317	-1372	317	-1372	317	-1372	317	-1372	317	-1372	317	-1372	317	-1372	317	-1372	317	-1372	317	-1372
108	-377	-739	-377	-739	-377	-739	-377	-739	-377	-739	-377	-739	-377	-739	-377	-739	-377	-739	-377	-739
109	-424	-2427	-424	-2427	-424	-2427	-424	-2427	-424	-2427	-424	-2427	-424	-2427	-424	-2427	-424	-2427	-424	-2427
110	211	-1583	211	-1583	211	-1583	211	-1583	211	-1583	211	-1583	211	-1583	211	-1583	211	-1583	211	-1583
111	53	-1583	53	-1583	53	-1583	53	-1583	53	-1583	53	-1583	53	-1583	53	-1583	53	-1583	53	-1583
112	-106	-1477	-106	-1477	-106	-1477	-106	-1477	-106	-1477	-106	-1477	-106	-1477	-106	-1477	-106	-1477	-106	-1477
113	-158	-1372	-158	-1372	-158	-1372	-158	-1372	-158	-1372	-158	-1372	-158	-1372	-158	-1372	-158	-1372	-158	-1372
114	369	-577	0	0	369	-577	0	0	369	-577	0	0	369	-577	0	0	369	-577	0	0
201	2480	-1424	2480	-1424	2480	-1424	2480	-1424	2480	-1424	2480	-1424	2480	-1424	2480	-1424	2480	-1424	2480	-1424
202	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
203	1688	-1530	1688	-1530	1688	-1530	1688	-1530	1688	-1530	1688	-1530	1688	-1530	1688	-1530	1688	-1530	1688	-1530
204	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
205	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
301	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
608	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2163	-1319	2163	-1319
609	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2584	-1319	2584	-1319
610	0	0	0	0	3165	-1265	3165	-1265	0	0	0	0	0	0	0	0	0	0	0	0

Figure 33. The OEM method B loads by regime and category

Finally, the damage calculations are shown in table 30 using <1021> as an example. The first column is for the severity categories, the second identifies RSS versus No-RSS, and the third shows the number of cycles per hour within each division. The "% Time" column is the fraction of the spectrum spent in the regimes that are part of that category. Note that the OEM spectrum is used in this example rather than the SUMS spectrum. "GAG/hr" x "% Time" x 1000 gives the number of cycles experienced in 1000 hours of flight. The "Max" and "Min" columns are the peak loads extracted from figure 33. "Load" is the load based on the Max and Min values, Goodman-corrected if appropriate for that part. "N" is the number of cycles on the SN curve given the load, based on log-linear interpolation of the SN curve points. The damage column is the cycles in 1000 hours divided by N. The damage is summed up to give the total GAG/MTM damage for that spectrum.

Table 30. The OEM method B damage calculations for <1021>

Category		GAG/hr	% Time	Cycle/ 1,000 hrs	Max	Min	Load	N	Damage/ 1,000 hrs
1.1 VH 2 G	RSS	2	0.0014	2.8	12,665	-11,408	12,037	3,449	0.00082
	no RSS	4	0.0014	5.7	12,665	-11,408	12,037	3,449	0.00165
1.1 VH 1.5 G	RSS	2	0.0622	124.5	8,337	-5,428	6,882	38,640	0.00322
	no RSS	4	0.0622	249.0	8,337	-5,428	6,882	38,640	0.00644
.9 VH Max G	RSS	2	0.1041	208.1	6,067	-5,698	5,882	73,165	0.00284
	no RSS	4	0.1041	416.2	6,067	-5,698	5,882	73,165	0.00569
.9 VH 2 G	RSS	2	0.1110	222.1	6,182	-6,182	6,182	59,521	0.00373
	no RSS	4	0.1110	444.2	6,182	-6,182	6,182	59,521	0.00746
.9 VH 1.5 G	RSS	2	0.4819	963.8	5,164	-4,674	4,919	160,496	0.00601
	no RSS	4	0.4819	1927.6	5,164	-4,674	4,919	160,496	0.01201
0.7 VH Max G	RSS	2	0.0415	83.0	3,113	-6,278	4,695	196,707	0.00042
	no RSS	4	0.0415	166.1	3,113	-6,278	4,695	196,707	0.00084
0.7 VH 2 G	RSS	2	0.0493	98.7	5,855	-4,695	5,275	116,070	0.00085
	no RSS	4	0.0493	197.4	5,855	-4,695	5,275	116,070	0.00170
0.7 VH 1.5 G	RSS	2	0.1485	297.0	6,014	-4,322	5,168	127,940	0.00232
	no RSS	4	0.1485	593.9	6,014	-4,322	5,168	127,940	0.00464
Total Damage 1,000 hrs									0.06066

3.5.1.2 OEM Method A Procedure, Occurrence of Regime Pairings

The first step in the OEM Method A procedure is to take all of the regimes and sort them in descending order by maximum load. Then, the regimes are taken again and sorted in ascending order by minimum load. Each regime carries with it the number of times it occurs based on the spectrum (the M+2 SUMS-based spectrum is used here). The loads from the regimes are then paired up, using all of the occurrences.

An example of this method using <1023> is shown in table 31, in which the maximum observed load comes from regime 705 and occurs 1509 times in the spectrum. The minimum observed load comes from regime 103 and occurs 158 times in the spectrum. Therefore, the first load pairing comes from regimes 705 and 103 and has 158 occurrences. That leaves 1351 occurrences of regime 705. The minimum load list is moved down, generating load pairs through regimes 1026, 104, and 806. Minimum load regime 805 uses the last of the 1509 occurrences from maximum load regime 705 and still has 1168 occurrences left. The maximum load regimes are then stepped through until all of the regime 805 occurrences are used up. For legacy OEM method A, this would continue for a specified 6000 occurrences in total.

Table 31. The <1023> sorted load pairings

Man ID	Max <1023>	Occs	Condition Name	Man ID	Min <1023>	Occs	Condition Name	Used Occs	Total Occs
705	778638	1509	Turn Rt, @ VH, 1.5 g	103	-67560	158	Shutdown, w/o Rotor brake	158	158
705	778638	1509	Turn Rt, @ VH, 1.5 g	1026	-63154	102	Dash Accel to VH/Stop	102	260
705	778638	1509	Turn Rt, @ VH, 1.5 g	104	-62681	1162	Shutdown, w/ Rotor brake	1162	1422
705	778638	1509	Turn Rt, @ VH, 1.5 g	806	-55828	19	Twin to Auto VH	19	1441
705	778638	1509	Turn Rt, @ VH, 1.5 g	805	-51421	1236	Twin to Auto 120 KTAS	68	1509
803	724280	159	Single to Twin 0.8 VH	805	-51421	1236	Twin to Auto 120 KTAS	159	1668
804	724280	9	Single to Twin VH	805	-51421	1236	Twin to Auto 120 KTAS	9	1677
733	719037	5	RPO Lt VH, 2.5 g	805	-51421	1236	Twin to Auto 120 KTAS	5	1682
806	718404	19	Twin to Auto VH	805	-51421	1236	Twin to Auto 120 KTAS	19	1701

The max and min load pairings give the mean and oscillatory loads, shown in table 32, which can then be Goodman-corrected if appropriate for the part. The corrected oscillatory load is applied to the SN curve by log-linear interpolation to get the number of cycles, N. Damage for each load pair is then determined by dividing used occurrences by the number of cycles. Total damage is summed over the desired number of occurrences. For <1023>, all the load pairings that cause damage are shown.

Table 32. The <1023> load pairing damage calculations

Used Occs	Total Occs	Max	Min	Mean	Osc	Goodman	N	Damage
158	158	778,638	-67,560	355,539	423,099	384,695	326,539	483.86E-6
102	260	778,638	-63,154	357,742	420,896	383,747	339,103	300.79E-6
1,162	1,422	778,638	-62,681	357,978	420,660	383,645	340,484	3.41E-3
19	1,441	778,638	-55,828	361,405	417,233	382,159	361,241	52.60E-6
68	1,509	778,638	-51,421	363,609	415,029	381,197	375,355	181.16E-6
159	1,668	724,280	-51,421	336,430	387,850	357,459	2,208,381	72.00E-6
9	1,677	724,280	-51,421	336,430	387,850	357,459	2,208,381	4.08E-6
5	1,682	719,037	-51,421	333,808	385,229	355,161	3,364,928	1.49E-6
19	1,701	718,404	-51,421	333,491	384,912	354,883	3,540,775	5.37E-6
Total Damage, 1,000 hrs								4.51E-3

Osc = oscillatory

3.5.2 Regression Procedures

The equation to determine the coefficients, *C*, of a linear regression is:

$$\{C\} = \left([M]^T * [M]\right)^{-1} * \left([M]^T * \{A\}\right) \tag{4}$$

Which is implemented in Excel by:

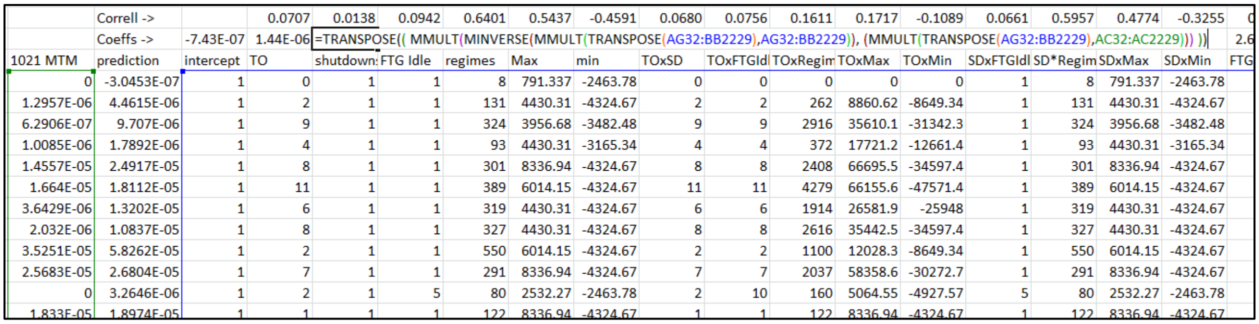
Coefficient array = (MMULT(MINVERSE(MMULT(TRANSPOSE(independent matrix), independent matrix)), (MMULT(TRANSPOSE(independent matrix),dependent array))))

The MTM damage from the virtual flights for each RRA file was taken as the dependent variable array, *A*. The independent variable matrix, *M*, represented the occurrences of each regime in each RRA file.

A prediction of MTM damage, *D*, for each RRA file is then calculated by:

$$D_i = C_1 * M_{i,1} + C_2 * M_{i,2} \ldots \tag{5}$$

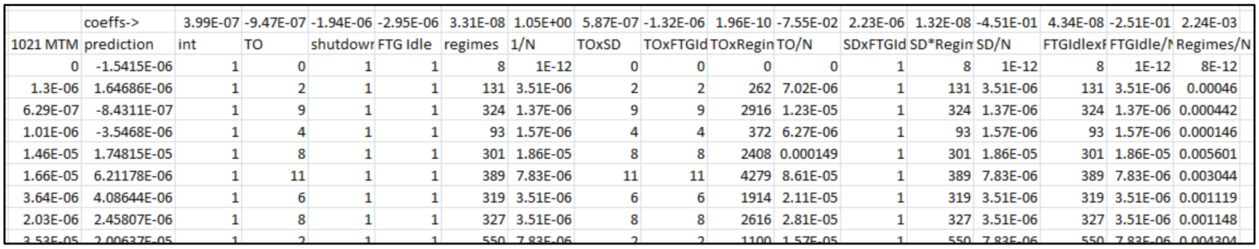
The Excel setup for regression and prediction for cases using the typical GAG regimes and the Max/Min loads, with two-way interactions, is shown in figure 34. The top row shows the correlation coefficient for each individual regime column with the MTM column using the CORRELL() Excel function. This was the value used when selecting those regimes with a correlation greater than 50%.



	Correll ->		0.0707	0.0138	0.0942	0.6401	0.5437	-0.4591	0.0680	0.0756	0.1611	0.1717	-0.1089	0.0661	0.5957	0.4774	-0.3255	0
	Coeffs ->	-7.43E-07	1.44E-06	=TRANSPOSE((MMULT(MINVERSE(MMULT(TRANSPOSE(AG32:BB2229),AG32:BB2229)), (MMULT(TRANSPOSE(AG32:BB2229),AC32:AC2229)))))														2.6
1021 MTM	prediction	intercept	TO	shutdown:	FTG Idle	regimes	Max	min	TOxSD	TOxFTGIdl	TOxRegim	TOxMax	TOxMin	SDxFTGIdl	SD*Regim	SDxMax	SDxMin	FTG
0	-3.0453E-07	1	0	1	1	8	791.337	-2463.78	0	0	0	0	0	1	8	791.337	-2463.78	
1.2957E-06	4.4615E-06	1	2	1	1	131	4430.31	-4324.67	2	2	262	8860.62	-8649.34	1	131	4430.31	-4324.67	
6.2906E-07	9.707E-06	1	9	1	1	324	3956.68	-3482.48	9	9	2916	35610.1	-31342.3	1	324	3956.68	-3482.48	
1.0085E-06	1.7892E-06	1	4	1	1	93	4430.31	-3165.34	4	4	372	17721.2	-12661.4	1	93	4430.31	-3165.34	
1.4557E-05	2.4917E-05	1	8	1	1	301	8336.94	-4324.67	8	8	2408	66695.5	-34597.4	1	301	8336.94	-4324.67	
1.664E-05	1.8112E-05	1	11	1	1	389	6014.15	-4324.67	11	11	4279	66155.6	-47571.4	1	389	6014.15	-4324.67	
3.6429E-06	1.3202E-05	1	6	1	1	319	4430.31	-4324.67	6	6	1914	26581.9	-25948	1	319	4430.31	-4324.67	
2.032E-06	1.0837E-05	1	8	1	1	327	4430.31	-4324.67	8	8	2616	35442.5	-34597.4	1	327	4430.31	-4324.67	
3.5251E-05	5.8262E-05	1	2	1	1	550	6014.15	-4324.67	2	2	1100	12028.3	-8649.34	1	550	6014.15	-4324.67	
2.5683E-05	2.6804E-05	1	7	1	1	291	8336.94	-4324.67	7	7	2037	58358.6	-30272.7	1	291	8336.94	-4324.67	
0	3.2646E-06	1	2	1	5	80	2532.27	-2463.78	2	10	160	5064.55	-4927.57	5	80	2532.27	-2463.78	
1.833E-05	1.8974E-05	1	1	1	1	122	8336.94	-4324.67	1	1	122	8336.94	-4324.67	1	122	8336.94	-4324.67	

Figure 34. The <1021> GAG regimes regression

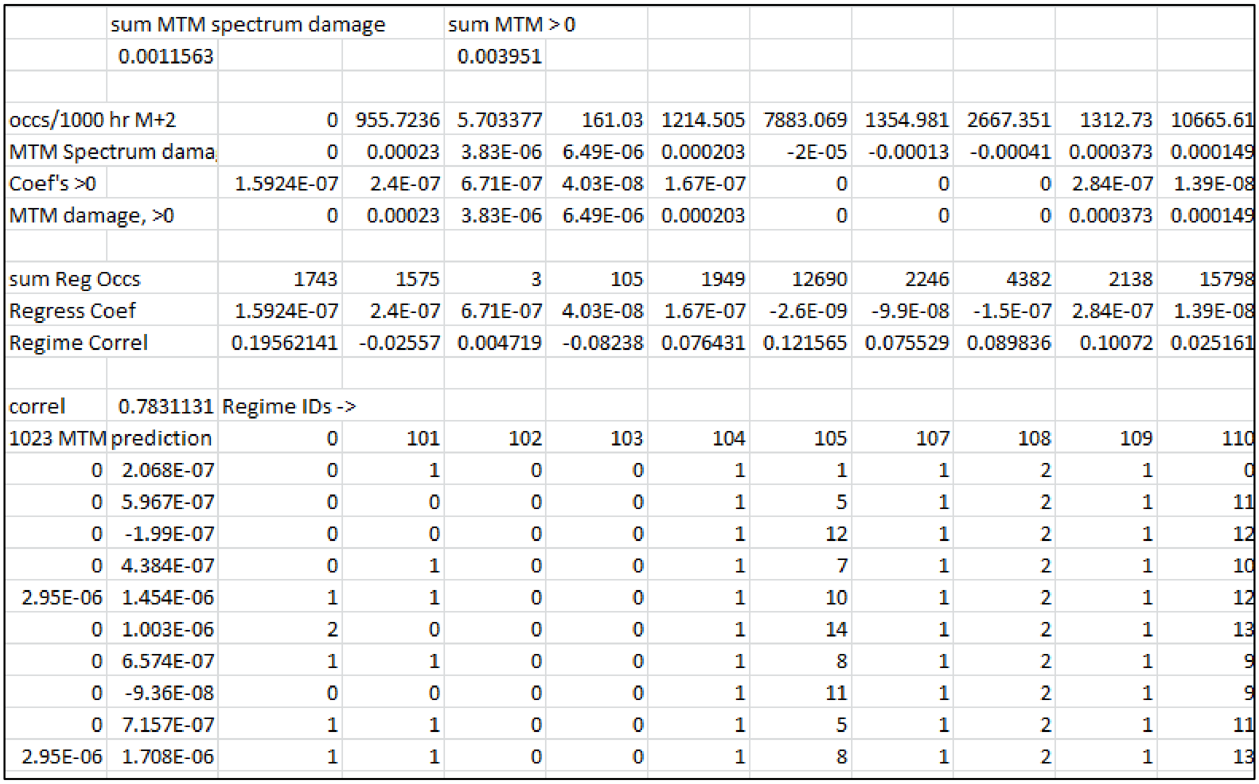
Cases using 1/N in the regression determined N from the Max and Min loads, Goodman-corrected as appropriate, and then the log-linear lookup on the SN curve tables are shown in figure 35. This is the same approach as described for OEM method B in section 3.5.1.1.



	coeffs->	3.99E-07	-9.47E-07	-1.94E-06	-2.95E-06	3.31E-08	1.05E+00	5.87E-07	-1.32E-06	1.96E-10	-7.55E-02	2.23E-06	1.32E-08	-4.51E-01	4.34E-08	-2.51E-01	2.24E-03
1021 MTM	prediction	int	TO	shutdowr	FTG Idle	regimes	1/N	TOxSD	TOxFTGId	TOxRegin	TO/N	SDxFTGId	SD*Regin	SD/N	FTGIdlexF	FTGIdle/	Regimes/N
0	-1.5415E-06	1	0	1	1	8	1E-12	0	0	0	0	1	8	1E-12	8	1E-12	8E-12
1.3E-06	1.64686E-06	1	2	1	1	131	3.51E-06	2	2	262	7.02E-06	1	131	3.51E-06	131	3.51E-06	0.00046
6.29E-07	-8.4311E-07	1	9	1	1	324	1.37E-06	9	9	2916	1.23E-05	1	324	1.37E-06	324	1.37E-06	0.000442
1.01E-06	-3.5468E-06	1	4	1	1	93	1.57E-06	4	4	372	6.27E-06	1	93	1.57E-06	93	1.57E-06	0.000146
1.46E-05	1.74815E-05	1	8	1	1	301	1.86E-05	8	8	2408	0.000149	1	301	1.86E-05	301	1.86E-05	0.005601
1.66E-05	6.21178E-06	1	11	1	1	389	7.83E-06	11	11	4279	8.61E-05	1	389	7.83E-06	389	7.83E-06	0.003044
3.64E-06	4.08644E-06	1	6	1	1	319	3.51E-06	6	6	1914	2.11E-05	1	319	3.51E-06	319	3.51E-06	0.001119
2.03E-06	2.45807E-06	1	8	1	1	327	3.51E-06	8	8	2616	2.81E-05	1	327	3.51E-06	327	3.51E-06	0.001148
3.53E-05	2.00637E-05	1	2	1	1	550	7.83E-06	2	2	1100	1.57E-05	1	550	7.83E-06	550	7.83E-06	0.004304

Figure 35. The 1/N regression calculations

The spectrum-based summation of damage is shown in figure 36. The regression using all regimes is repeated, as previously, though the intercept column has been removed. This had a negligible effect on the results. The “Regress Coef” row is the array of coefficients. The “occs/1000 hr M+2” row represents the number of occurrences of each regime in the SUMS M+2 spectrum from section 3.2. The “MTM Spectrum damage” row is the regression coefficient times the spectrum occurrences for each regime, which is summed up under “sum MTM spectrum damage.” These rows are repeated but with the coefficients with negative values replaced by 0. Combining the summed damage with the virtual flight regime damage allows a life to be calculated from 1/(regime damage + MTM Damage/1000).

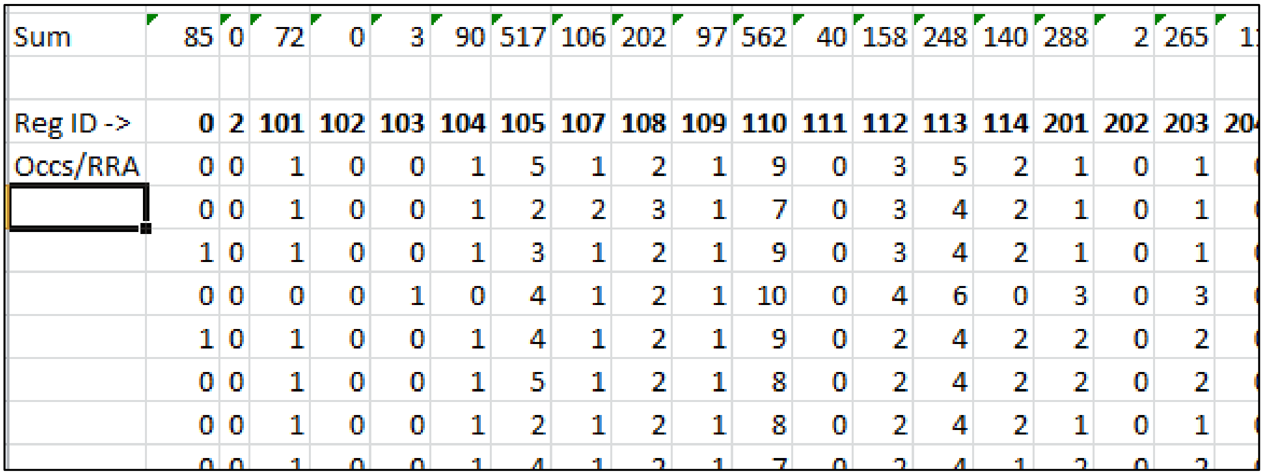


	sum MTM spectrum damage			sum MTM > 0							
	0.0011563			0.003951							
occs/1000 hr M+2		0	955.7236	5.703377	161.03	1214.505	7883.069	1354.981	2667.351	1312.73	10665.61
MTM Spectrum dama		0	0.00023	3.83E-06	6.49E-06	0.000203	-2E-05	-0.00013	-0.00041	0.000373	0.000149
Coef's >0		1.5924E-07	2.4E-07	6.71E-07	4.03E-08	1.67E-07	0	0	0	2.84E-07	1.39E-08
MTM damage, >0		0	0.00023	3.83E-06	6.49E-06	0.000203	0	0	0	0.000373	0.000149
sum Reg Occs		1743	1575	3	105	1949	12690	2246	4382	2138	15798
Regress Coef		1.5924E-07	2.4E-07	6.71E-07	4.03E-08	1.67E-07	-2.6E-09	-9.9E-08	-1.5E-07	2.84E-07	1.39E-08
Regime Correl		0.19562141	-0.02557	0.004719	-0.08238	0.076431	0.121565	0.075529	0.089836	0.10072	0.025161
correl	0.7831131	Regime IDs ->									
1023 MTM	prediction	0	101	102	103	104	105	107	108	109	110
0	2.068E-07	0	1	0	0	1	1	1	2	1	0
0	5.967E-07	0	0	0	0	1	5	1	2	1	11
0	-1.99E-07	0	0	0	0	1	12	1	2	1	12
0	4.384E-07	0	1	0	0	1	7	1	2	1	10
2.95E-06	1.454E-06	1	1	0	0	1	10	1	2	1	12
0	1.003E-06	2	0	0	0	1	14	1	2	1	13
0	6.574E-07	1	1	0	0	1	8	1	2	1	9
0	-9.36E-08	0	0	0	0	1	11	1	2	1	9
0	7.157E-07	1	1	0	0	1	5	1	2	1	11
2.95E-06	1.708E-06	1	1	0	0	1	8	1	2	1	13

Figure 36. Regression and SUMS spectrum

3.5.3 Binning—Max-Min

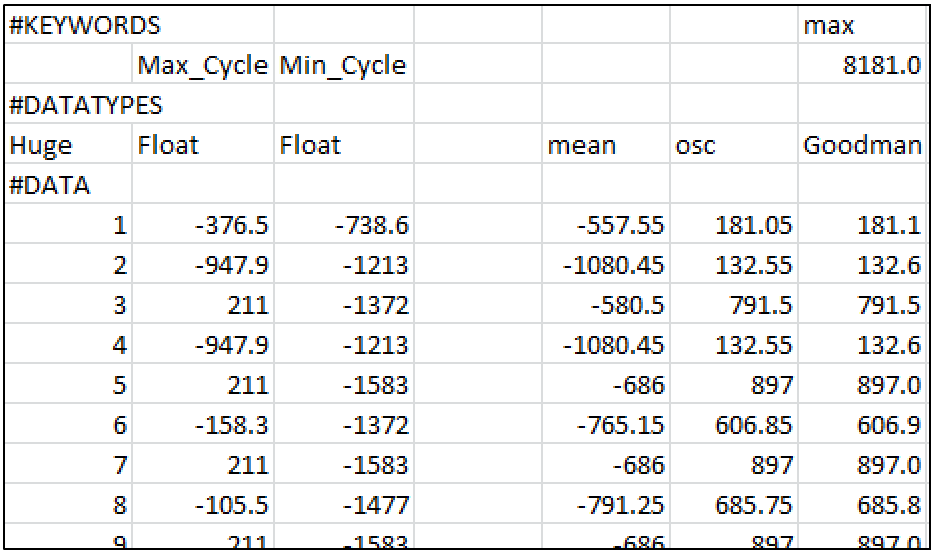
The process for binning the loads began with collecting the number of occurrences of each regime for each RRA file, which were then summed up for each aircraft, as shown in figure 37.



Sum	85	0	72	0	3	90	517	106	202	97	562	40	158	248	140	288	2	265	1
Reg ID ->	**0**	**2**	**101**	**102**	**103**	**104**	**105**	**107**	**108**	**109**	**110**	**111**	**112**	**113**	**114**	**201**	**202**	**203**	**20**
Occs/RRA	0	0	1	0	0	1	5	1	2	1	9	0	3	5	2	1	0	1	
	0	0	1	0	0	1	2	2	3	1	7	0	3	4	2	1	0	1	
	1	0	1	0	0	1	3	1	2	1	9	0	3	4	2	1	0	1	
	0	0	0	0	1	0	4	1	2	1	10	0	4	6	0	3	0	3	
	1	0	1	0	0	1	4	1	2	1	9	0	2	4	2	2	0	2	
	0	0	1	0	0	1	5	1	2	1	8	0	2	4	2	2	0	2	
	0	0	1	0	0	1	2	1	2	1	8	0	2	4	2	1	0	1	
	0	0	1	0	0	1	4	1	2	1	7	0	2	4	1	2	0	2	

Figure 37. Occurrences/RRA for aircraft 143

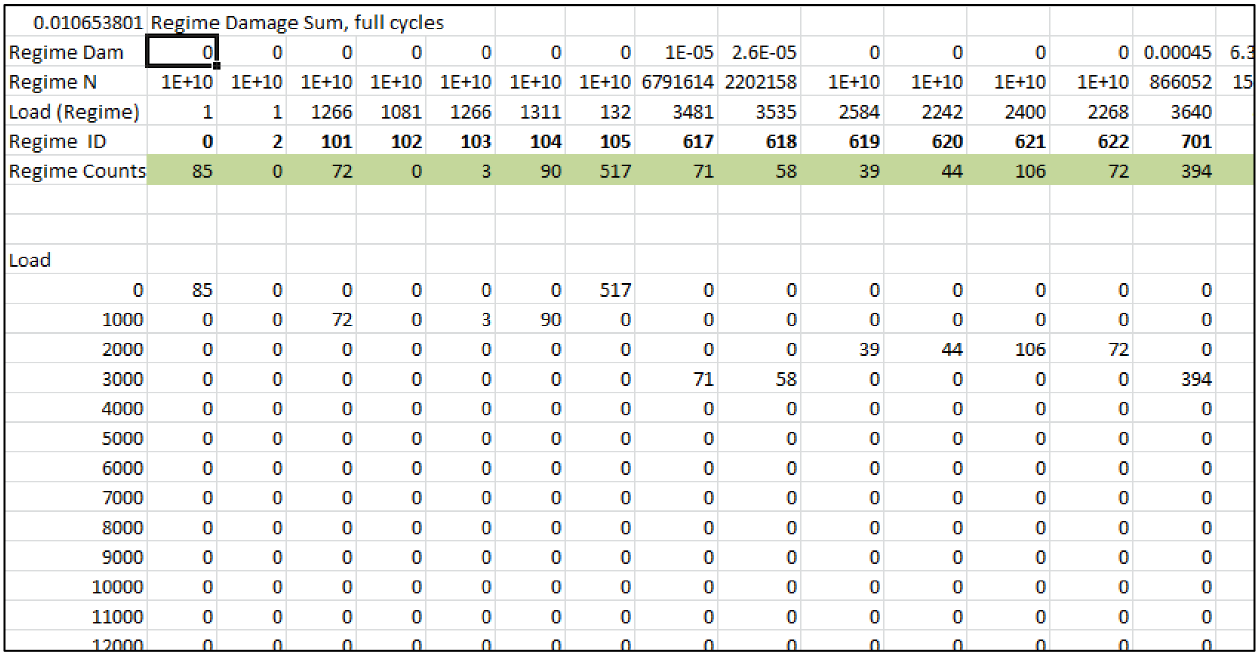
Every RRA file was processed through nCode, using the max-min method of section 2.5.2, with the output shown in figure 38. The max-min method was used because within-regime damage could be calculated easily from the number of regime occurrences. The virtual flight approach should work just as well but will require tracking and binning of all the load cycles within regimes. The nCode output includes, for each counted cycle, the maximum load (Max_Cycle) and minimum load (Min_Cycle). The max and min loads are used to determine the oscillatory load to be used for that part, Goodman-corrected where appropriate.



#KEYWORDS						max
	Max_Cycle	Min_Cycle				8181.0
#DATATYPES						
Huge	Float	Float		mean	osc	Goodman
#DATA						
1	-376.5	-738.6		-557.55	181.05	181.1
2	-947.9	-1213		-1080.45	132.55	132.6
3	211	-1372		-580.5	791.5	791.5
4	-947.9	-1213		-1080.45	132.55	132.6
5	211	-1583		-686	897	897.0
6	-158.3	-1372		-765.15	606.85	606.9
7	211	-1583		-686	897	897.0
8	-105.5	-1477		-791.25	685.75	685.8
9	211	-1583		-686	897	897.0

Figure 38. The <1021>, aircraft 143, rainflow counted cycles

The number of regime occurrences in each bin is shown in figure 39. In this example, the large bins for <1021> of 1000 lb are used. The load for each regime is in the "Load (Regime)" row. If that load falls within the bin (0–1000 for the first load row), the number of occurrences of that regime is added to the bin for that aircraft. This figure also shows the number of cycles for the regime load from the SN curve (Regime N) and the damage from that regime (Regime Dam = Regime Counts/Regime N). The summation of all the regime damage is at the top. Note that, as shown, this assumes a full amount of damage for each regime, and per the max-min method, must be divided by two because they are all actually half cycles.



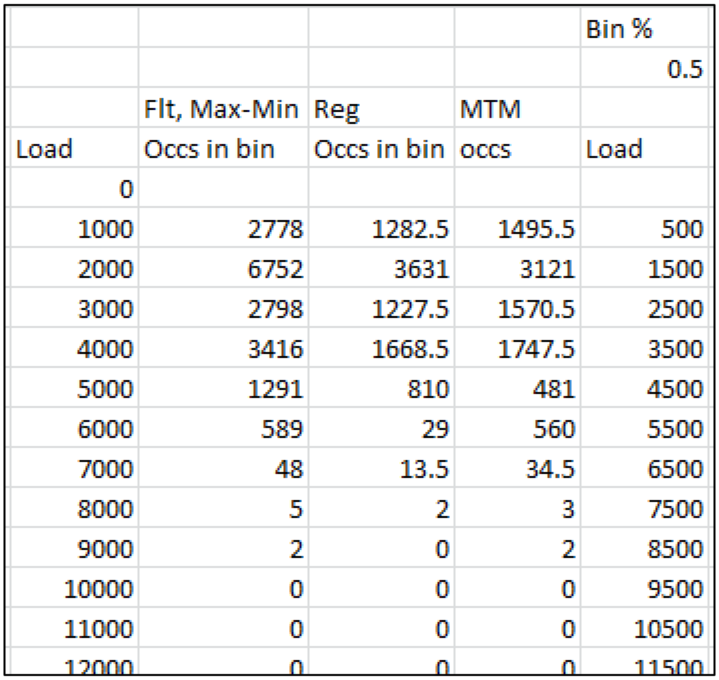
0.010653801	Regime Damage Sum, full cycles														
Regime Dam	0	0	0	0	0	0	0	1E-05	2.6E-05	0	0	0	0	0.00045	6.3
Regime N	1E+10	1E+10	1E+10	1E+10	1E+10	1E+10	1E+10	6791614	2202158	1E+10	1E+10	1E+10	1E+10	866052	15
Load (Regime)	1	1	1266	1081	1266	1311	132	3481	3535	2584	2242	2400	2268	3640	
Regime ID	**0**	**2**	**101**	**102**	**103**	**104**	**105**	**617**	**618**	**619**	**620**	**621**	**622**	**701**	
Regime Counts	85	0	72	0	3	90	517	71	58	39	44	106	72	394	
Load															
0	85	0	0	0	0	0	517	0	0	0	0	0	0	0	
1000	0	0	72	0	3	90	0	0	0	0	0	0	0	0	
2000	0	0	0	0	0	0	0	0	0	39	44	106	72	0	
3000	0	0	0	0	0	0	0	71	58	0	0	0	0	394	
4000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
5000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
6000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
7000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
8000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
9000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
10000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
11000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
12000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Figure 39. The <1021>, aircraft 143, binned regime occurrences

Finally, the results of the occurrences sorted into bins for the aircraft is shown in figure 40. The total number of occurrences in each bin is summed up from the max-min rainflow counted loads of figure 38. This is done using the Excel function:

COUNTIFS((load array),”<=”&Q23,(load array),”>”,&Q22)

where (load array) is the set of cells with the loads and Q22 and Q23 are the lower and upper bounds of the bin.



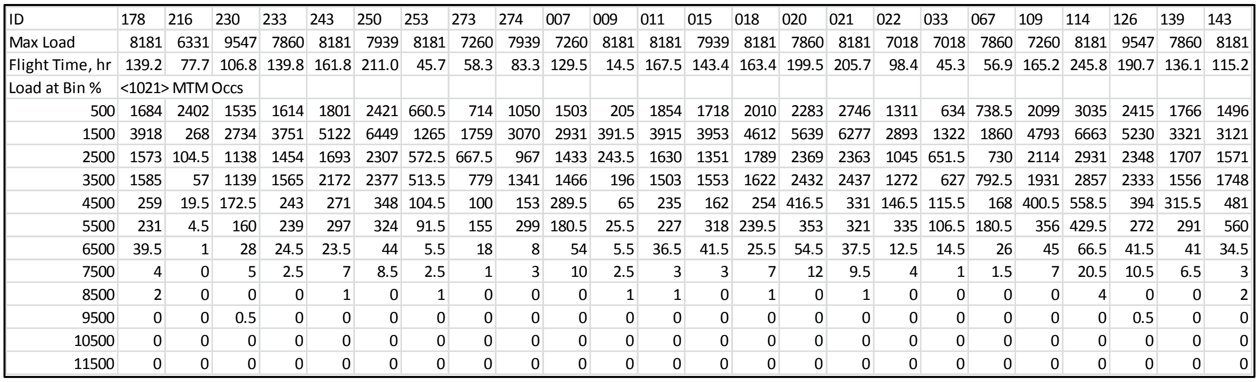
				Bin %
				0.5
	Flt, Max-Min	Reg	MTM	
Load	Occs in bin	Occs in bin	occs	Load
0				
1000	2778	1282.5	1495.5	500
2000	6752	3631	3121	1500
3000	2798	1227.5	1570.5	2500
4000	3416	1668.5	1747.5	3500
5000	1291	810	481	4500
6000	589	29	560	5500
7000	48	13.5	34.5	6500
8000	5	2	3	7500
9000	2	0	2	8500
10000	0	0	0	9500
11000	0	0	0	10500
12000	0	0	0	11500

Figure 40. The <1021>, aircraft 143, binned load occurrences

The regime occurrences with each bin are the summation of each load row of figure 39. The MTM Occurrences is the difference between the flight and regime occurrences. The load that will be used in damage calculations and used throughout at 50% of the bin is also shown. This means the damage for the occurrences within that bin will be calculated at the midpoint. Using a higher percentage of the bin size would result in more conservative results.

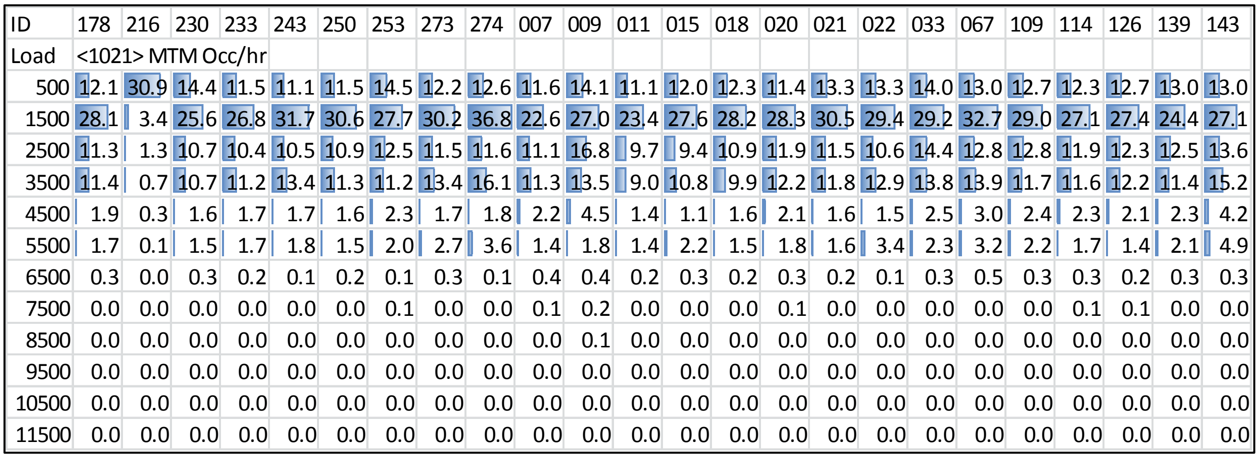
It is important to note that the regime occurrences and MTM occurrences are really pseudo-cycles used to give an accurate mathematical representation of the damage rather than a true physical representation. This is important because as the size of the bins gets smaller, and when the number of occurrences in the bins is small, it is quite possible to get negative MTM occurrences. These should be carried forward and calculated as negative damage because they are essentially corrections of occurrences in other bins that would otherwise be double booked.

Once the occurrences within the MTM bins have been determined for each part and each aircraft, they can be collected, as shown in figure 41, and normalized by flight hours, as shown in figure 42. The statistics across aircraft for each bin are shown in figure 43. For a life comparison with the other methods, the mean and M+2 damage for each bin are calculated and summed. Loads below the EL default to an SN curve, N, of 10E10 and a damage of 0.



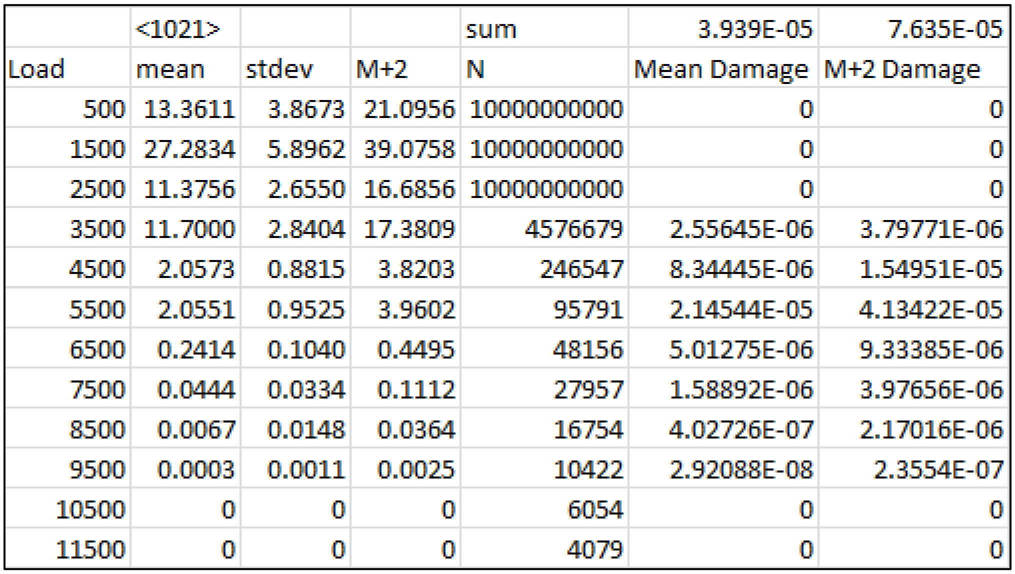
ID	178	216	230	233	243	250	253	273	274	007	009	011	015	018	020	021	022	033	067	109	114	126	139	143
Max Load	8181	6331	9547	7860	8181	7939	8181	7260	7939	7260	8181	8181	7939	8181	7860	8181	7018	7018	7860	7260	8181	9547	7860	8181
Flight Time, hr	139.2	77.7	106.8	139.8	161.8	211.0	45.7	58.3	83.3	129.5	14.5	167.5	143.4	163.4	199.5	205.7	98.4	45.3	56.9	165.2	245.8	190.7	136.1	115.2
Load at Bin %	<1021> MTM Occs																							
500	1684	2402	1535	1614	1801	2421	660.5	714	1050	1503	205	1854	1718	2010	2283	2746	1311	634	738.5	2099	3035	2415	1766	1496
1500	3918	268	2734	3751	5122	6449	1265	1759	3070	2931	391.5	3915	3953	4612	5639	6277	2893	1322	1860	4793	6663	5230	3321	3121
2500	1573	104.5	1138	1454	1693	2307	572.5	667.5	967	1433	243.5	1630	1351	1789	2369	2363	1045	651.5	730	2114	2931	2348	1707	1571
3500	1585	57	1139	1565	2172	2377	513.5	779	1341	1466	196	1503	1553	1622	2432	2437	1272	627	792.5	1931	2857	2333	1556	1748
4500	259	19.5	172.5	243	271	348	104.5	100	153	289.5	65	235	162	254	416.5	331	146.5	115.5	168	400.5	558.5	394	315.5	481
5500	231	4.5	160	239	297	324	91.5	155	299	180.5	25.5	227	318	239.5	353	321	335	106.5	180.5	356	429.5	272	291	560
6500	39.5	1	28	24.5	23.5	44	5.5	18	8	54	5.5	36.5	41.5	25.5	54.5	37.5	12.5	14.5	26	45	66.5	41.5	41	34.5
7500	4	0	5	2.5	7	8.5	2.5	1	3	10	2.5	3	3	7	12	9.5	4	1	1.5	7	20.5	10.5	6.5	3
8500	2	0	0	0	1	0	1	0	0	0	1	1	0	1	0	1	0	0	0	0	4	0	0	2
9500	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0
10500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 41. The <1021> binned MTM occurrences by aircraft



ID	178	216	230	233	243	250	253	273	274	007	009	011	015	018	020	021	022	033	067	109	114	126	139	143
Load	<1021> MTM Occ/hr																							
500	12.1	30.9	14.4	11.5	11.1	11.5	14.5	12.2	12.6	11.6	14.1	11.1	12.0	12.3	11.4	13.3	13.3	14.0	13.0	12.7	12.3	12.7	13.0	13.0
1500	28.1	3.4	25.6	26.8	31.7	30.6	27.7	30.2	36.8	22.6	27.0	23.4	27.6	28.2	28.3	30.5	29.4	29.2	32.7	29.0	27.1	27.4	24.4	27.1
2500	11.3	1.3	10.7	10.4	10.5	10.9	12.5	11.5	11.6	11.1	16.8	9.7	9.4	10.9	11.9	11.5	10.6	14.4	12.8	12.8	11.9	12.3	12.5	13.6
3500	11.4	0.7	10.7	11.2	13.4	11.3	11.2	13.4	16.1	11.3	13.5	9.0	10.8	9.9	12.2	11.8	12.9	13.8	13.9	11.7	11.6	12.2	11.4	15.2
4500	1.9	0.3	1.6	1.7	1.7	1.6	2.3	1.7	1.8	2.2	4.5	1.4	1.1	1.6	2.1	1.6	1.5	2.5	3.0	2.4	2.3	2.1	2.3	4.2
5500	1.7	0.1	1.5	1.7	1.8	1.5	2.0	2.7	3.6	1.4	1.8	1.4	2.2	1.5	1.8	1.6	3.4	2.3	3.2	2.2	1.7	1.4	2.1	4.9
6500	0.3	0.0	0.3	0.2	0.1	0.2	0.1	0.3	0.1	0.4	0.4	0.2	0.3	0.2	0.3	0.2	0.1	0.3	0.5	0.3	0.3	0.2	0.3	0.3
7500	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0
8500	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9500	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10500	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11500	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Figure 42. The <1021> binned MTM occurrences/hr



	<1021>			sum	3.939E-05	7.635E-05
Load	mean	stdev	M+2	N	Mean Damage	M+2 Damage
500	13.3611	3.8673	21.0956	10000000000	0	0
1500	27.2834	5.8962	39.0758	10000000000	0	0
2500	11.3756	2.6550	16.6856	10000000000	0	0
3500	11.7000	2.8404	17.3809	4576679	2.55645E-06	3.79771E-06
4500	2.0573	0.8815	3.8203	246547	8.34445E-06	1.54951E-05
5500	2.0551	0.9525	3.9602	95791	2.14544E-05	4.13422E-05
6500	0.2414	0.1040	0.4495	48156	5.01275E-06	9.33385E-06
7500	0.0444	0.0334	0.1112	27957	1.58892E-06	3.97656E-06
8500	0.0067	0.0148	0.0364	16754	4.02726E-07	2.17016E-06
9500	0.0003	0.0011	0.0025	10422	2.92088E-08	2.3554E-07
10500	0	0	0	6054	0	0
11500	0	0	0	4079	0	0

Figure 43. The <1021> statistics by bin

4. CONCLUSIONS

The first part of this study compared load pair methods. It was found that there is no functional difference between using the max-min, min-max, or sequenced load pairs for the determination of maneuver-to-maneuver (MTM) damage. A comparison against MTM damage determined by Virtual Flights showed that the sequenced load pairs are accurate, though it is not adequate to simply rainflow count and determine damage from the series of load pairs. The damage induced by the half cycles of the load pairs must be subtracted out.

The second part of this study was the evaluation of different methods of MTM calculation. In all cases, the methods were compared to virtual flights using a biasing of mean + 2* standard deviation (M+2) across aircraft.

The max-min load pairing method was studied in more detail. This essentially repeated the virtual flights calculations, but with each regime represented by only two load points, with the maximum load first. With the half cycles of within-regime damage removed, the max-min approach was found to agree well with the virtual flight damage calculations, verifying that use of sequenced load pairs is a valid approach to determining MTM damage.

The original equipment manufacturer (OEM) method B, in which a specified number of cycles is applied to the maximum and minimum overall loads, was found to be erratic. Some parts are too heavily penalized and others have safe lives calculated that are far too long. This approach is not recommended.

The OEM method A, in which loads are paired up based on sorted occurrences of regimes within the spectrum, was found to be fairly effective. A very long life part had its life significantly reduced, but even the reduced life was 10 times longer than the aircraft life. The sensitivity is presumed to be caused by the long life means damage accruing in the very flat, and therefore very sensitive, part of the SN curve. In addition, the 6000 occurrences used by the OEM could possibly be reduced to 5000 with more structural usage monitoring system (SUMS) data.

Equivalent cycles methods, choosing a load, and determining how many cycles should be applied at that load provided fairly consistent results across parts. However, there are a couple of issues that make it problematic. The first is that it is purely empirical. No general determinations can be made across platforms; rather, it is driven by the part that is most sensitive to MTM damage. This means the same study would have to be repeated for each platform and should include all parts. The second issue is that there is some degree of sensitivity for MTM-driven parts. This means that damage would have to be calculated across all parts and the equivalent cycle value carefully chosen. Though it is possible to get good results, this approach is not recommended. This is because the sensitivities and effort required for this method would encourage use of a different method.

Equivalent loads methods, trying to relate a fixed number of cycles to a reference load (similar to OEM method B) was found to be very inconsistent across parts. This approach is not recommended.

Use of regression on the occurrences of regimes was found to have validity only if many regimes were used in the regression. It was also found that the traditional GAG counters (e.g., take offs, shutdowns) were unable to provide any reasonable estimate of MTM damage. Regression using all of the regimes generally produced a reasonable prediction of MTM damage, though its quality was part dependent. The MTM-driven parts were found to be most inconsistent when using regression to calculate lives. Use of the regression coefficients to determine damage was also complicated by negative coefficients. Regression methods on regimes are not recommended.

None of the methods described up to this point are suitable for a full probabilistic approach to determining a reliability-based part life. To provide such a determination, a SUMS-based loads model was used in which the occurrences per hour were sorted into load bins. Each bin then has a statistical distribution that can be part of a reliability assessment. Though involved for deterministic or spectrum-based methods, the binning of loads is a consistently good approach. There is a level of inconsistency for small numbers of large bins, but results are very good when there are at least 20 bins spanning the load range.

Based on the results of this study, OEM method B, equivalent cycles, equivalent loads, and regression approaches are not recommended. Virtual Flights or max-min approaches could be used directly for tracking damage of parts on a serial-number basis or for applying an MTM damage rate directly to a spectrum-based safe-life calculation. OEM method A was found to be fairly effective for spectrum-based safe-life calculations. The binning of cycles by load is an accurate method for providing a statistical SUMS-based loads model.

5. REFERENCES

1. Benton, R., Dudley, R., and Chang, J. (2009, May 2729). *Maneuver-to-Maneuver Load Cycle Case Study*. American Helicopter Society 65th Annual Forum, Grapevine, Texas.

2. *Aeronautical Design Standard Handbook for Condition Based Maintenance Systems for U.S. Army Aircraft* (2012, January 12). ADS-79C-HDBK.

3. FAA Report (2016). *Results of health and usage monitoring system fleet data analysis for usage credits*. DOT/FAA/TC-15/15.

Note: a variety of proprietary sources were used for this report, including resources that were used for fatigue substantiation reports; flight load survey reports and data; and fatigue methodology reports from multiple original equipment manufacturers. Because this material is not publically available, the sources are not included as references in this report.