

# **Component Fatigue Life Reliability with Usage Monitor**

**Suresh Moon**

TITAN, an L-3 Communications Company, Lexington Park, MD

and

**Nam Phan**

Structures Division, NAVAIR, Patuxent River, MD

## **Abstract**

The helicopter industry has tried to quantify the probability of component failure during service life considering the variability of loads, material strength, and usage. The specified goal is to provide safe retirement times with six nines reliability. One component failure in the lifetime of the fleet equals to six nines reliability or, put another way, one in a million failure probability. Manufacturers have computed component life according to their own fatigue life methodology. Though different in detail, each methodology generally derives three nines from treatment of material strength variation, two nines from conservative treatment of applied load, and one nine from conservative usage assumption. With advanced recorder technology, the industry is poised for the implementation of Condition Based Maintenance (CBM) of gearbox and transmission systems and for automated rotor track and balance. Dynamic component retirement based on actual, rather than assumed usage is now possible. Life tracking by regime recognition algorithm means dynamic component life will no longer be assigned as a single value to every aircraft, but will vary with the individual aircraft. The assigned (assumed) conservative fleet usage spectrum will be replaced by individual aircraft usage spectrum. The consequence of this change on reliability is unknown. Some in the industry believe replacement of the assumed spectrum with the actual spectrum will result in decreases in reliability, while others think it will result in an increase in reliability. The American Helicopter Society (AHS) Fatigue and Damage Tolerance Subcommittees conducted a round robin in 2006 on the reliability of usage monitored based component retirement.

The author's approach to compute reliability for the AHS round robin 2006 problem is presented herein. The component life increases with reduced severity in the usage spectrum from 95th percentile to 5th percentile. It has been shown that increased life can be obtained while maintaining six nines reliability. However, the contributions to overall reliability come more from severe loads and reduced fatigue strength combination and are not unique. It has been identified that the multivariate standard deviation value is responsible for providing adequate reliability. The severity of load in the distribution shall be within the helicopter capability, and fatigue strength shall be greater than a value that provides required reliability. In addition, the effect of cycle counting and constant fatigue strength on reliability has been discussed. This approach will help to compute and ensure desired reliability with usage based component replacement.

## Background

General guidelines for rotorcraft dynamic component life determination methodologies are outlined in MIL, FAR, and AR-56 documents. The component life calculations to satisfy these guidelines must utilize conservative material fatigue strength, severe loads, and severe usage spectrum. However, detailed methodology for computing fatigue life is left to the discretion of the helicopter manufacturer as approved by certification authorities such as FAA, U.S. Army, U.S. Navy, U.S. Air Force. To understand the effect on computed life due to details in methodologies, AHS conducted a specialist meeting on helicopter fatigue methodology in March 1980 (Reference 1). A hypothetical fatigue life problem was posed to the industry with measured loads, usage spectrum, and component fatigue test data. Each manufacturer was asked to compute the resulting fatigue life accordingly. The lives varied from 9 to 2,504 hours based on peak value flight loads and 58 to 27,816 hours with cycle counted loads. This variation in calculated fatigue life was solely due to detail buried in the methodology of each helicopter manufacturer. Differences in S-N curve shapes, derivation of mean S.N curve from material test data, reduction factors for determining working S.N curves, GAG cycle determination, and cycle counting methods were factors influencing the wide variation in computed fatigue life.

This variation in computed component life cast doubts on the assumed reliability of assigned fatigue lives. To ensure reliability, the U.S. Army began requiring (Reference 2) a demonstrated six nines reliability (0.999999). This equates to less than one failure in the fleet of 100 aircraft having a dynamic component with 10,000 hours safe fatigue life. AHS hosted another specialist

meeting on reliability of rotorcraft structures in 1989. The manufacturers presented their reliability computations and ensured the certification authorities that their computed fatigue lives met the requirements. The approaches for reliability computation are outlined in References 3 through 7.

With advances in microprocessor based technology, CBM is becoming a reality. Dependable regime recognition and consequent usage based component retirement is on the horizon. The U.S. Navy has previously developed and fielded usage monitors in their AH-1W fleet and instituted individual dynamic component tracking on a limited scale as discussed in References 8 and 9. Actual usage gathered from 60 aircraft was used to develop the revised usage spectrum discussed in Reference 10. Similar processes were carried out for H-46, H-60, and H-3 aircraft. Usage spectra developed and assigned for use in component fatigue life calculation were severe with respect to the individual aircraft spectrum (References 10 and 11).

In the year 2000, the U.S. Navy began installing the Health and Usage Monitoring System (HUMS) on H-53 and H-60 (Reference 12). The V-22 has entered Marine and Air Force service with onboard HUMS (Reference 13) capable of providing individual aircraft usage data. Likewise, the US Army is aggressively pursuing HUMS installations for CBM. A common assumption is that one benefit of HUMS incorporation will be increased fatigue lives for most aircraft components. Retirement life will be significantly higher for those aircraft flying a benign spectrum (assumed to be a majority of the fleet), than for those currently assigned with the assumed spectrum. The assumed conservatism of an assigned usage spectrum has been removed and replaced with actual monitored usage.

Some in industry believe, as discussed in Reference 14, that replacement of conservative usage spectrum with actual usage spectrum will decrease the component life reliability. However, others in industry and government believe reliability will actually increase. To investigate the problem, the AHS fatigue and damage tolerance sub-committee conducted a round robin exercise in 2006. The author participated in the round robin and explains his approach and findings in this paper.

**Problem Definition**

A 100-hour usage spectrum consisting of six flight conditions was supplied to all participants. The usage in each flight condition follows Weibull distribution with slope ( $\beta$ ) = 2 and 95th percentile usage for each flight condition as indicated in Table 1.

Loads in six flight conditions have Weibull distribution with slope ( $\beta$ ) = 4. The 95th percentile load for each flight condition is indicated in Table 2. In addition, cycle counted loads are 0.2, 0.4, 0.6, 0.8, 1.0 fraction of peak load and corresponding number of cycles at these load levels is 0.35, 0.25, 0.20, 0.15, 0.05 fraction of total cycles in the regime, respectively. The predominant load frequency is 5 cycles/sec.

The shape of S.N curve is defined in the following equation:

$$S/Se = 0.92 + 0.8/N^{1/2}$$

Where: S = Stress level  
 Se = Stress at endurance ( $10^8$  cycles)  
 N = Number of cycles in millions

The component mean fatigue strength is 1,000 psi at  $10^8$  cycles with standard deviation of 100 psi.

**Table 1. Usage Monitor Measured Usage Spectrum, and Weibull Parameters**

Maneuvers	Flight Condition	Slope	Eta	95th percentile Severity Usage	50th percentile Severity Usage	5th percentile Severity Usage
Pull-up	1	2	0.577	1	0.48	0.13
Turn	2	2	2.31	4	1.92	0.52
Climb	3	2	4.622	8	3.85	1.05
Descent	4	2	8.08	14	6.73	1.83
Hover	5	2	12.71	22	10.58	2.88
Forward Flight	6	2	29.465	51	76.44	93.59

**Table 2. Flight Loads with Weibull Distribution Values**

Flight Condition	Maneuver	Slope	Eta	50th percentile Peak Load (psi)	95th percentile Peak Load (psi)	99th percentile Peak Load (psi)
1	Pull-up	4	1748	1595	2300	2561
2	Turn	4	1330	1214	1750	1949
3	Climb	4	988	902	1300	1450
4	Descent	4	684	625	900	1002
5	Hover	4	456	417	600	668
6	Forward Flight	4	380	347	500	557

## Weibull Distribution

The three parameter Weibull distribution is the most versatile statistical distribution that can characterize load, usage, and material strength. The application of Weibull distribution with respect to these variables has been demonstrated in References 7, 15, and 16. These references also provide limitations and approaches to characterize them appropriately.

The three parameter Weibull distribution with probability density function (PDF) is given by Reference 17:

$$f(u, u_0, b) = \frac{b}{(\theta - u_0)} \left( \frac{u - u_0}{\theta - u_0} \right)^{b-1} \exp \left[ - \left( \frac{u - u_0}{\theta - u_0} \right)^b \right] \quad (1)$$

Where:

- u = regime usage/load/strength in percentage (variable)
- u<sub>0</sub> = location parameter (minimum possible regime usage/load/strength in percentage)
- b = Weibull slope
- θ = characteristic regime usage/load/strength in percentage (θ is defined as regime usage in percentage corresponding to a 63.2 percentile probability of occurrence)

The cumulative probability distribution (CPD) function of the Weibull distribution is given by:

$$F(u, u_0, b) = 1 - \exp \left[ - \left( \frac{u - u_0}{\theta - u_0} \right)^b \right] \quad (2)$$

## Usage Distribution Model

The six flight condition Weibull probability distribution is shown in Figure 1. It is evident from the distribution that severe usage probability distribution is highly

peaked as compared to benign usage. At the same time, and as expected, the distribution of severe flight condition range is small as compared to the benign flight condition. Characteristics of distribution are comparable to actual usage distribution created from the recorded data and published in References 7 and 10 for the AH-1W helicopter and unpublished distribution of H-60 and H-46 usages. From the usage probability distribution, Weibull cumulative probability distributions shown in Figure 2 were created. Cumulative distributions are useful for selecting specified probability of occurrence and varying percent usage to create usage spectra with respect to various severities. This reduces the distribution of usages in various regimes to a single variable specified in terms of usage severity.

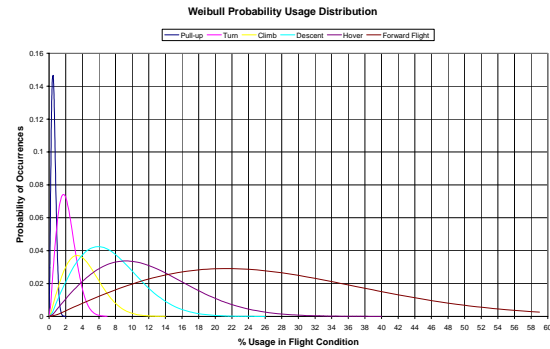


Figure 1. Weibull probability usage distribution

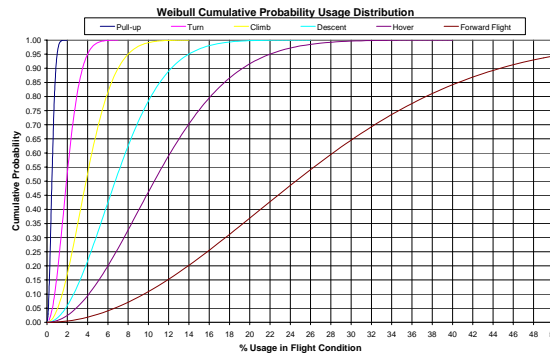
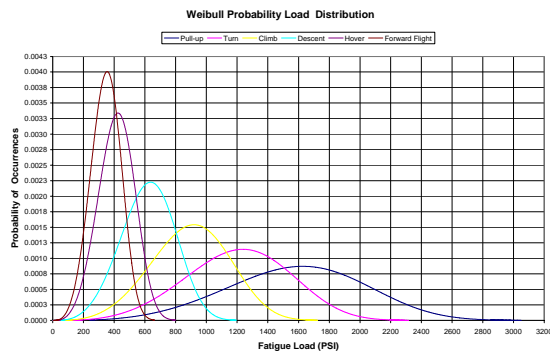


Figure 2. Weibull cumulative probability usage distribution

## Load Distribution Model

Load Weibull distribution parameter values are provided in Table 2. These values are comparable to published values for rotorcraft component loads distribution in References 7, 15, and 16. The probability density plot in Figure 3 illustrates the nature of load variability in various maneuvers. The benign conditions (forward flight and hover) have less variability characterized by peaked distribution with smaller load range as compared to pull-up and turns having flat distribution shape and wide load range. The coefficient of variations provided in References 7, 15, and 16 demonstrate the nature of load variability. From Figure 3, it can be inferred that dynamic component load should not be characterized with single distribution but load distribution shall be fitted for each regime. It also helps to compute damage based on percent usage of this regime and associated load. This helps to explain component failure on one helicopter with no sign of degradation on another helicopter. The difficulty arises while computing reliability, as the load is not represented by unique distribution. The problem becomes one of multiple variable reliability computations.



**Figure 3. Weibull load probability load distribution**

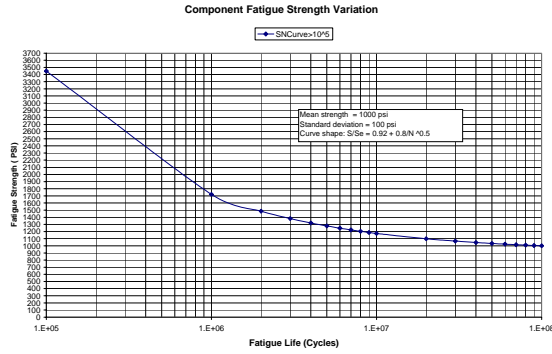
To reduce it to a single load variable, the concept of specified load severity based on cumulative probability has been proposed. Figure 4 shows the load cumulative probability distribution for various regimes. From these distributions, loads in various regimes can be obtained for specified load severity in terms of cumulative probability of occurrence. This reduces loads from various regimes to a single variable for reliability computations.



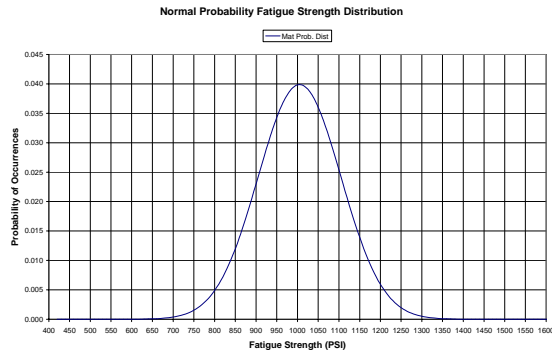
**Figure 4. Weibull cumulative probability load distribution**

## Component Fatigue Strength Distribution

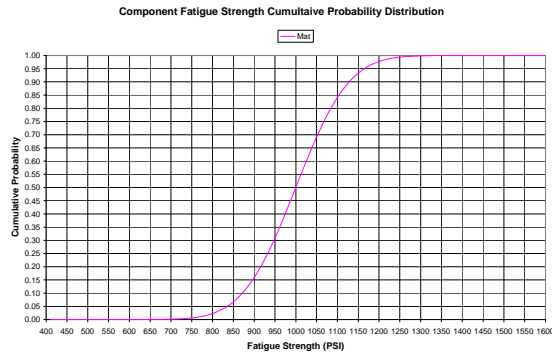
The mean component fatigue strength described by S.N. curve equation is graphically represented by the curve shown in Figure 5. Mean fatigue strength at  $10^8$  cycles is 1,000 psi with a standard deviation of 100 psi. Fatigue strength at  $10^8$  cycles follows a normal distribution and cumulative probability distribution illustrated in Figures 6 and 7.



**Figure 5. Component fatigue strength variation**



**Figure 6. Normal probability fatigue strength distribution**



**Figure 7. Component fatigue strength cumulative probability distribution**

## Reliability Computation Approach

The Weibull load distributions (Table 2), created using alternating load cycles in each regime, were utilized for reliability computations. As discussed earlier, the usage ( $u$ ), load ( $l$ ), and component strength ( $s$ ) can be distributed using Weibull distributions. Therefore, the component failure probability is a multivariable probability of the distributed usage, load, and strength occurrence. The probability that the usage, load, and strength exist in a particular interval at the same time is given by the following joint PDF, as discussed in Reference 7:

$$P \left[ u - \frac{du}{2} < u < u + \frac{du}{2}, l - \frac{dl}{2} < l < l + \frac{dl}{2} \text{ and } s - \frac{ds}{2} < s < s + \frac{ds}{2} \right] = \int_{u-dl/2}^{u+dl/2} \int_{l-dl/2}^{l+dl/2} \int_{s-ds/2}^{s+ds/2} f(u, l, s) du dl ds \quad (3)$$

Usage ( $u$ ), load ( $l$ ), and component strength ( $s$ ) are statistically independent random variables, which reduce the joint PDF expression (3) as the multiplication of individual incremental PDF given by the following expression:

$$P \left[ u - \frac{du}{2} < u < u + \frac{du}{2}, l - \frac{dl}{2} < l < l + \frac{dl}{2} \text{ and } s - \frac{ds}{2} < s < s + \frac{ds}{2} \right] = \int_{u-dl/2}^{u+dl/2} f(u) du \int_{l-dl/2}^{l+dl/2} f(l) dl \int_{s-ds/2}^{s+ds/2} f(s) ds \quad (4)$$

The integrals in equation (4) are evaluated numerically with the following approximation:

$$\Delta P_{ijk}(u, l, s) = \Delta P_i(u) \cdot \Delta P_j(l) \cdot \Delta P_k(s) \quad (5)$$

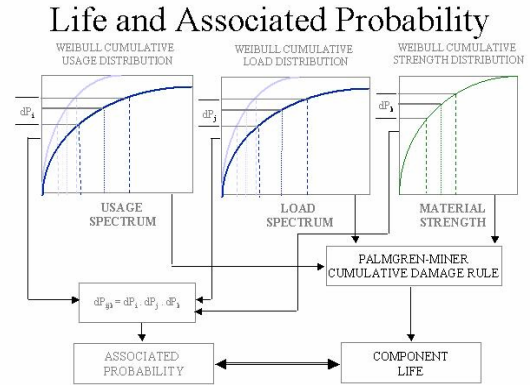
The incremental probability of occurrence ( $\Delta P$ ) is the area under the probability distribution curve for incremental change ( $du$ ,  $dl$ ,  $ds$ ) in variables  $u$ ,  $l$ , and  $s$ . Therefore,  $\Delta P$  is computed using the Weibull CPD's of the variables usage ( $u$ ), load ( $l$ ), and strength ( $s$ ) as follows:

$$\Delta P_i = F(u+du/2)-F(u-du/2) \text{ for usage}$$

$$\Delta P_j = F(l+dl/2)-F(l-dl/2) \text{ for loads}$$

$$\Delta P_k = F(s+ds/2)-F(s-ds/2) \text{ for strength} \quad (6)$$

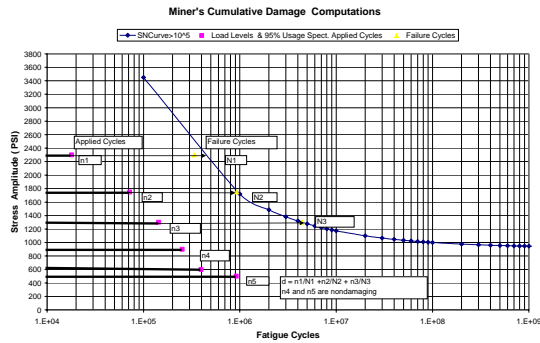
Usage and loads have distinct Weibull distributions for each regime with associated Weibull parameter values, which results in different loads and percentage usage for the regimes in the spectrum corresponding to a single CPD value. To simulate a problem to three variables (usage, loads, and strength), one incremental PDF ( $\Delta P_j$ ) is required to represent the loads from all regimes, another PDF ( $\Delta P_i$ ) to represent the percent usage from all regimes, and a third PDF ( $\Delta P_k$ ) to represent strength. To achieve these objectives, the load and usage distribution variable range above the 50th percentile and the component strength range below the 50th percentile were divided into segments. The Weibull parameters presented in Tables 1 and 2 and the upper and lower bounds of each segment were utilized to compute the Weibull CPD using equation (2). CPD's thus evaluated were employed in equation (6) to obtain equal incremental PDF ( $\Delta P_i$ ) for usage in all regimes, another incremental PDF ( $\Delta P_j$ ) for loads in different regimes, and a third incremental PDF ( $\Delta P_k$ ) for strength (Figure 8).



**Figure 8. Fatigue life and associated probability computations with usage monitor**

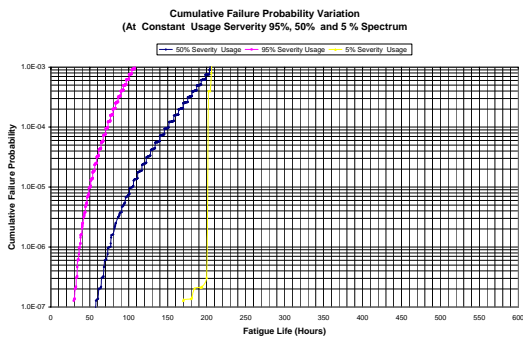
Individual regimes in the usage spectrum have Weibull distribution. However, as explained in the reliability computation approach, the single spectrum severity can be specified using cumulative probability distribution. In the AHS round robin problem, the usage spectrum severity was specified as constant at 95th percentile, 50th percentile, and 5th percentile. For reliability computation, fatigue strength was varied from 50th percentile to 0.0000001th percentile in steps of 10 psi. This variation included very low component strength that can occur with probability less than  $10^{-6}$ . The load severity was varied from 50th percentile to 99.99999<sup>th</sup> percentile. This resulted in 103 variable load increments/segments from 5 to 200 psi for reliability computation. The high load severity level includes load with probability of occurrence less than  $10^{-6}$ . The high loads included in the spectrum shall not exceed the capability of aircraft. For constant usage, all load segments ( $j=1,103$ ) were selected one by one while varying the fatigue strength ( $k= 1, 60$ ). The average value of each segment from load and strength was utilized to compute component life using Miner's cumulative damage theory as illustrated in Figure 9. The process was repeated until all segments of load and fatigue strength

distribution were considered. For each iteration, component fatigue life and associated incremental joint PDF were calculated. Fatigue lives thus computed were arranged in ascending order of magnitude along with associated PDF. The probability that fatigue life is less than a certain value is an addition of incremental joint probability of failures (i.e., cumulative probability of failure). The reliability corresponding to this fatigue life is one minus the cumulative probability of failure.



**Figure 9. Miner cumulative damage computation illustration**

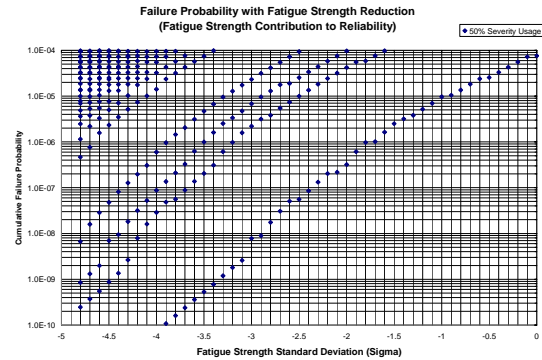
Figure 10 shows the variation of reliability computed using this approach at constant usage severity of 95th percentile, 50th percentile, and 5th percentile. As expected, reliability decreases with an increase in component life. At six nines reliability, component life increases with a decrease in usage severity from 95th percentile to 5th percentile.



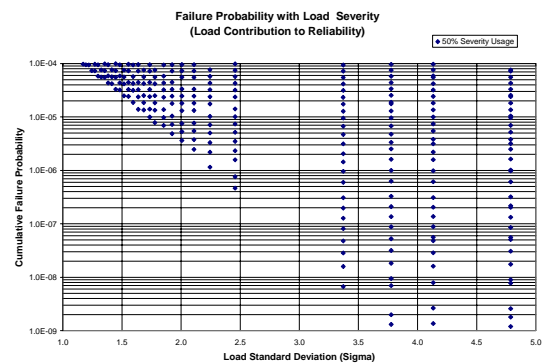
**Figure 10. Cumulative failure probability (reliability 1-CFP) variation with fatigue life**

## Fatigue Strength and Load Contribution to Reliability

Figure 10 shows an increase in life with a decrease in usage severity for constant reliability values. At constant usage, the contribution to reliability is from fatigue strength variations and load variation. From Figure 11, it can be inferred that six nines reliability (failure probability of  $10^{-6}$ ) can be obtained with -1.7, -1.8, -3.2, -3.5, -3.9, and -4.8  $\sigma$  reduction in fatigue strength. Therefore, reduction in fatigue strength is not unique and it needs to be combined with load severity to failure probability. Similarly, six nines reliability can be obtained with 2.25, 2.45, 3.3, 3.7, 4.25, and 4.75  $\sigma$  increase in load severity (Figure 12). It is necessary to find the combination that provides the desired reliability.



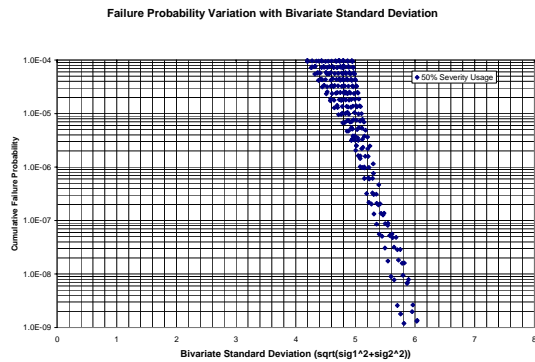
**Figure 11. Fatigue strength contribution to reliability**



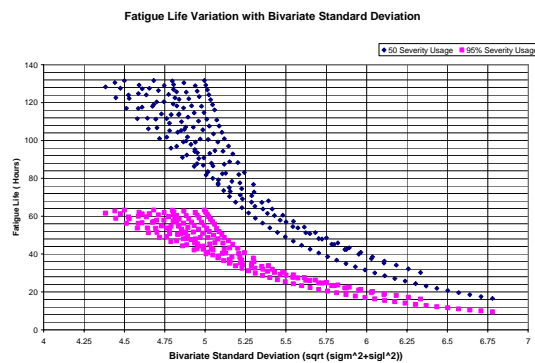
**Figure 12. Load contribution to reliability**



To obtain higher reliability, strength lower than mean, and loads greater than mean, that is difference in load and strength distributions, is required. If fatigue strength and load are independent normal distributions, the difference is also normally distributed with variance equal to the sum of their variances. From Figure 13, it is evident that, with an increase in bivariate standard deviation, the cumulative failure probability failure decreases. Six nines reliability is obtained with bivariate standard deviation ( $\sqrt{\text{strength}^2 + \text{load}^2}$ ) varying from 5.08 to 5.22, its value for bivariate normal distribution is 4.8. As expected for a constant value of bivariate standard deviation, the reliability is approximately the same, but the life increases due to a reduction in usage severity from 95th percentile to 50th percentile (Figures 13 and 14).



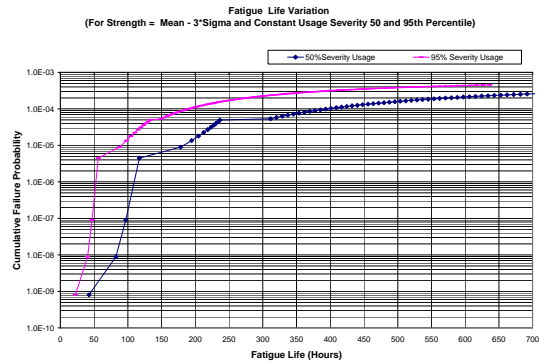
**Figure 13. Cumulative failure probability variation with bivariate standard deviation**



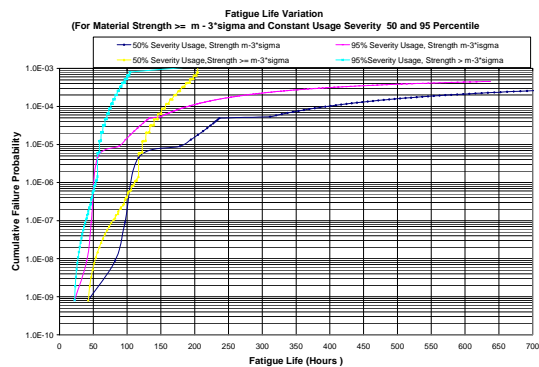
**Figure 14. Fatigue life variation with bivariate standard deviation**

## Fatigue Strength Contribution to Reliability

For a constant mean- $3\sigma$  fatigue strength and constant usage severity of 95th percentile and 50th percentile, the reliability variation is due to a load variation from 99.99999th percentile to 50th percentile. To obtain reliability greater than six nines, it is necessary to include loads with a probability of occurrence less than  $10^{-6}$ . In this situation, the 50th percentile usage severity fatigue life is greater than 95th percentile while maintaining the same reliability (Figure 15). However, for the same life, increases in fatigue strength  $> \text{mean}-3\sigma$ , load variation from 99.99999th percentile to 50th percentile, and constant usage severity, result in a decrease in the reliability (Figure 16).



**Figure 15. Fatigue life variation for fatigue strength = mean- $3\sigma$**



**Figure 16. Fatigue life variation for fatigue strength  $\geq \text{mean}-3\sigma$**

## Fatigue Life with Cycle Counting

The application of cycle counting in calculating dynamic component fatigue life varies by manufacturer. Some helicopter manufacturers cycle count the transient maneuvers all the time. Others perform cycle counting only when the fatigue life computed using peak counting method is viewed as overly penalizing. In addition, methods of cycle counting (rain flow counting, range pair counting, peak-valley within a rotor cycle) also differ from company to company. Transient maneuver cycle counting results in a significant increase in component fatigue life. It is difficult to assign probability of occurrence to cycle counted load. However, if cycle counted loads are included to create Weibull load distribution as outlined in References 7, 15, and 16, then each regime Weibull load distribution includes its effect on fatigue life and reliability.

In the AHS round robin problem, regime Weibull load distribution parameters were specified. In addition, load variation for cycle counting, as indicated in Figure 17, was provided. The cumulative probability of cycle counted load level is indicated in Figure 18. The incremental probability of occurrence for each cycle counted load with this approach will be equal. When peak load occurrences are varied from 99.9999th percentile to 50th percentile, the incremental probability of peak counted load varies in steps and is equal to the cycle counted load. However, the damage, due to cycle counting will be lower, resulting in higher fatigue life as displayed in Figure 19 for the same cumulative failure probability. With the cycle counting method, significant increase in fatigue life is observed with decrease in usage severity from 95th percentile to 5th

percentile while maintaining the same reliability (Figure 20).

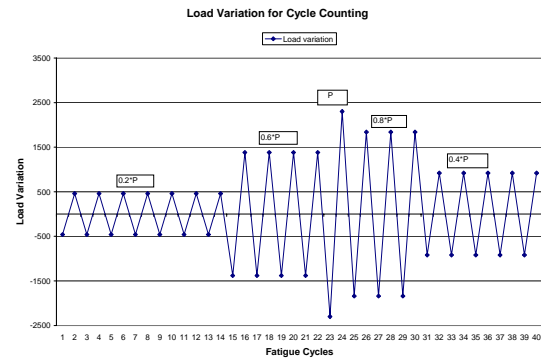


Figure 17. Cycle counted load variation

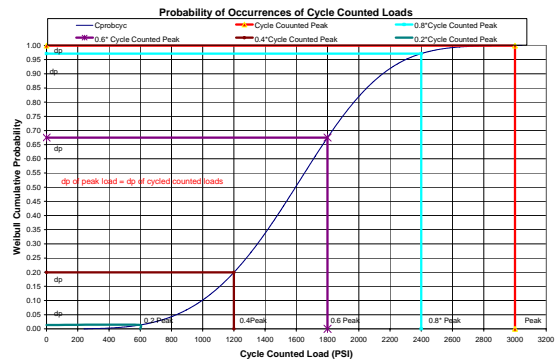


Figure 18. Probability of occurrences of cycle counted loads

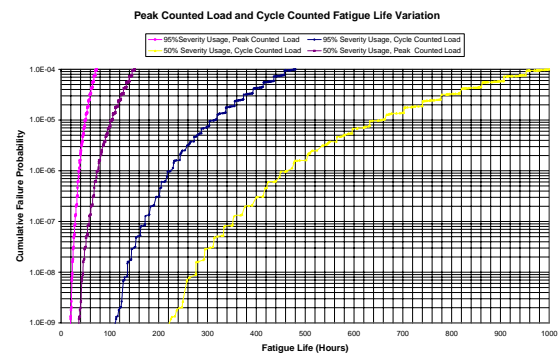
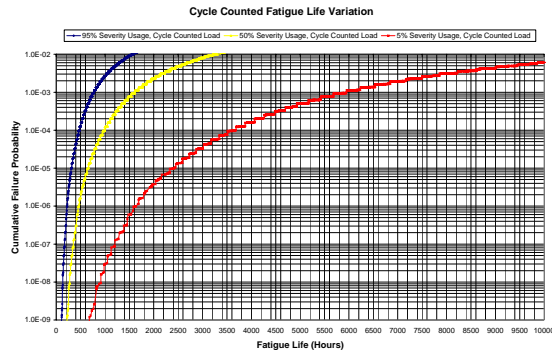


Figure 19. Fatigue life variation with peak counted and cycle counted loads



**Figure 20. Reliability of fatigue life with cycle counted loads**

## Conclusions

1. As expected, fatigue life increases with a decrease in usage severity from 95<sup>th</sup> percentile to 5<sup>th</sup> percentile while maintaining the same reliability.
2. Six nines reliability is obtained with bivariate standard deviation varying from 5.08 to 5.22. For bivariate normal distribution, the standard deviation is 4.8.
3. For a constant mean- $3\sigma$  fatigue strength, the 50<sup>th</sup> percentile usage severity fatigue life is greater than 95<sup>th</sup> percentile usage severity fatigue life while maintaining the same reliability. However, for the same life, increases in fatigue strength  $>$  mean- $3\sigma$  result in a decrease in the reliability.
4. The methodology proposed is based on mathematical probability theory and produces consistent results. When the problem of three variables is reduced to two variables, results are comparable with normal distribution of two variables.

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