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Certification of Composite-Metal Hybrid Structures using Load-Enhancement Factors

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ABSTRACT

The primary goal in a damage-tolerance certification program is to avoid catastrophic failure due to fatigue, corrosion, or accidental damage throughout the operational life of the aircraft. The damage-tolerance philosophy is well established for metallic airframes, where proven methods (structural analysis and inspection procedures) and supporting databases exist to detect damage and predict crack growth and residual strength. Damage growth mechanics and load spectra for composite and metal structure have significant differences that make the certification of composite-metal hybrid structures challenging, costly and time consuming. Several test substantiation approaches such as two separate full-scale test articles—one focusing metal certification and the other focusing composites certification, or substantiation of metal parts at lower level of building-blocks of testing can be used for certification of hybrid structures. The primary goal of this research is to provide guidance and examples validated through testing for certification of composite-metal hybrid structures. Often composite structural certification uses load-enhancement factor(s) to reduce the test duration. In certain cases this causes the enhanced load spectrum to have loads beyond the clipping level of metal structural details. A technique called a LEF-Hybrid is introduced so that different combinations of life-load factors can be used for different parts of the spectrum so that the high loads (that potentially can go beyond clipping level after LEF application) can have a higher life factor and a lower or no LEF. Second concept called Load-Life Shift (LLS) is introduced so that a single test article can be used to substantiate both metal and composites as a two-phase certification methodology with different LEFs, i.e., first phase with LEF=1 for metal and second phase LEF>1 for composite. The LLS approach provides a mechanism to obtain credit for the loads applied during first phase (focusing metal) so that the composite certification phase can be reduced. The goal of the program is to provide an efficient certification approach that weighs both the economic aspects of certification and the time frame required for certification testing, while ensuring that safety is the key priority. In order to accommodate the use of multiple LEF values for different parts of the full-scale substantiation phases, a concept called load-life shift, which was previously introduced by the authors, was used to show equivalent level of reliability for the cumulative full-scale substantiation test.

KEY WORDS: load enhancement factor, life factor, certification, composite, fatigue

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1. INTRODUCTION

Over the past 25 years, the use of advanced composite materials in aircraft primary structures has increased significantly. In 1994, with the Advanced General Aviation Transport Experiments (AGATE) program, the National Aeronautics and Space Administration (NASA) and the Federal Aviation Administration (FAA) revitalized the use of composites in general and commercial aviation. Driven by the demand for fuel-efficient, light-weight, and high-stiffness structures that have fatigue durability and corrosion resistance, modern large commercial aircraft are designed with more than 50 percent composite materials. Although there are key differences between metal and composite damage mechanics and durability concerns, the certification philosophy for composites must meet structural integrity, safety, and durability requirements. Despite the many advantages, composite structural certification becomes challenging due to the lack of experience in large-scale structures, complex interactive failure mechanisms, sensitivity to temperature and moisture, and scatter in the data, especially in fatigue. The overall objective of this research was to provide guidance into structural substantiation of composite-metal hybrid airframe structures through an efficient approach that weighs both the economic aspects of certification and the timeframe required for testing, while ensuring safety.

2. RELIABILITY ANALYSIS

2.1 Reliability (Scatter) Analysis for Fatigue Life Determination

Over the years, composite and hybrid structural certification programs have adopted methodologies utilized for metal structures that are based on several decades of experience in full-scale structural certification and service. Despite the advantages, such as high specific weight, tailorability, and fatigue resistance, composite structural certification becomes challenging due to the lack of experience with large-scale structures, complex interactive failure mechanisms, sensitivity to temperature and moisture, and scatter in the data, especially relative to fatigue. Despite the superior fatigue properties, the heterogeneous nature due to the presence of multiple constituents and the notch sensitivity of composites resulted in special requirements for durability and damage tolerance (DaDT) substantiation of composite structures. The data scatter in composites is related to the reliability of composite structure through a concept known as the scatter factor, which signifies the relation between the central tendency of a data set (mean) and the extreme statistics (allowables). In order to develop a certification methodology for composite structures that has the same level of reliability as observed in metal certification approaches, accounting for the inherent difference between metal and composites, the FAA and U.S. Navy developed a certification approach for bolted composite structures [1,2] as part of the F/A-18 certification. This methodology was formulated to account for the uncertainties of applied loads as well as the scatter in static strength and fatigue life related to composite structures. This approach analyzes the data scatter in the static (residual) strength and fatigue life of composites to establish a certification methodology that has the same level of reliability as for metal structures. Furthermore, this approach attempts to address the issues related to hybrid (composite and metallic) structures through a combined approach referred to as the load-life approach, which will be further discussed in this paper. This approach was developed for what, at that time, was current composite usage and did not explicitly account for the damage in composite structures or adhesively bonded structural details. Over the years, several composite structural certification programs employed this certification methodology, which was developed for materials and test methods that were considered current at the time. Since then, materials and

process techniques as well as test methods for evaluating composites have evolved. Consequently, test data often display significantly less scatter with high reliability. Thus, the probabilistic approach employed by Whitehead, et al., [1] can be reevaluated for newer material forms and to represent structural details of current aircraft structures to obtain improved life and load-enhancement factors [3,4,5].

2.2 Data Scatter Analysis

The primary goal in scatter analysis of composites is to interpret the variability in data in lower levels of the building blocks of testing and translate the statistical significance of such phenomenon into full-scale test substantiation. In order to determine the shape parameters for static strength and fatigue life for the purpose of full-scale test substantiation, test matrices must be designed so that at least the design details and loading modes of critical locations of the structure are represented by coupon and/or element tests. The influence of material, layup sequence, loading mode, sandwich construction, joints, environmental effects, etc., is typically considered during static strength scatter analysis. Fatigue analysis includes the influence of the stress ratio in addition to the above-mentioned design details.

Static data scatter analysis was conducted using Weibull analysis. Fatigue data scatter analysis was conducted using Individual Weibull analysis, i.e., Weibull analysis was conducted at each (fatigue) stress level and the shape parameters were arithmetically averaged. Weibull distribution is used in statistical analysis of composites, especially for small samples, due to its simple functionality and ease of interpretation. The commonly used two-parameter Weibull distribution expressed by the cumulative survival probability function is shown as

$$P(X \leq x) = e^{-\left(\frac{x}{\hat{\beta}}\right)^{\hat{\alpha}}} \quad (1)$$

where, x is the random variable, $\hat{\alpha}$ is the shape parameter, and $\hat{\beta}$ is the scale parameter. The population mean, μ , and standard deviation, σ , are calculated with the Gamma (Γ) distribution function in equations (2) and (3), respectively.

$$\mu = \hat{\beta} \cdot \Gamma\left(\frac{\hat{\alpha} + 1}{\hat{\alpha}}\right) \quad (2)$$

$$\sigma = \hat{\beta} \sqrt{\Gamma\left(\frac{\hat{\alpha} + 2}{\hat{\alpha}}\right) - \Gamma^2\left(\frac{\hat{\alpha} + 1}{\hat{\alpha}}\right)} \quad (3)$$

The shape parameter and scale parameter are estimated in an iterative process using either the maximum likelihood estimation (MLE) or rank regression.

During the individual Weibull analysis of fatigue data, each stress level is analyzed, and then the shape parameters are arithmetically averaged to define life scatter. Since Weibull analysis considers only the data at a certain stress level at a time, six or more data points must be included in each stress level.

2.3 Life Factor Approach

The life factor test approach has been successfully used for metal to assure structural durability. In this approach, the structure is tested for additional fatigue life to achieve the desired level of reliability. Underlying objective of life factor is to ensure that the design life is representative of the condition of the weakest member of the population after a specified life in service.

The ratio of the mean repeated load life to B-basis repeated life is defined as life factor, N_F , and given by equation (4).

$$N_F = \Gamma\left(\frac{\alpha_L + 1}{\alpha_L}\right) / \left\{ \left[\frac{\chi_\gamma^2(2n)}{2n} \right] \right\}^{1/\alpha_L} \quad (4)$$

α_L – (modal) fatigue life scatter factor

n – number of articles

p – required reliability at γ level of confidence
($p = 0.99$ for A-basis; $p = 0.9$ for B-basis)

$\chi_\gamma^2(2n)$ – Chi-square distribution with $2n$ degrees of freedom at γ level confidence

This is graphically illustrated in Figure 1, in terms of B-basis statistics, i.e. successful repeated load test to mean fatigue life (N_F) would demonstrate B-basis reliability on design lifetime (DLT).

Figure 1 shows the influence of shape parameter on life factor, which is the ratio between mean repeated life to B-basis life. The life factor becomes insensitive to small changes in the life shape parameter beyond a value of 4, which is considered to be the life shape parameter for some metallic structures. The composite modal life shape parameter of 1.25 in Reference 1 lies within the highly sensitive region of life factor vs. shape parameter curve as shown in Figure 1. Therefore, even a small improvement in fatigue data scatter will result in a dramatic reduction of life factor, which reflects the required number of test durations to achieve a certain level of reliability in the design life [4].

Due to large scatter in composite data, composite structure is required to test additional fatigue life to achieve the desired level of reliability, i.e. test duration of over 13 DLT for composite in contrast to 2 DLT for metal. As can be seen in Figure 1, life factor is a function of fatigue life scatter. Thus, improvements in fatigue life shape parameters for newer forms of materials that exhibit less scatter can significantly reduce the life factor.

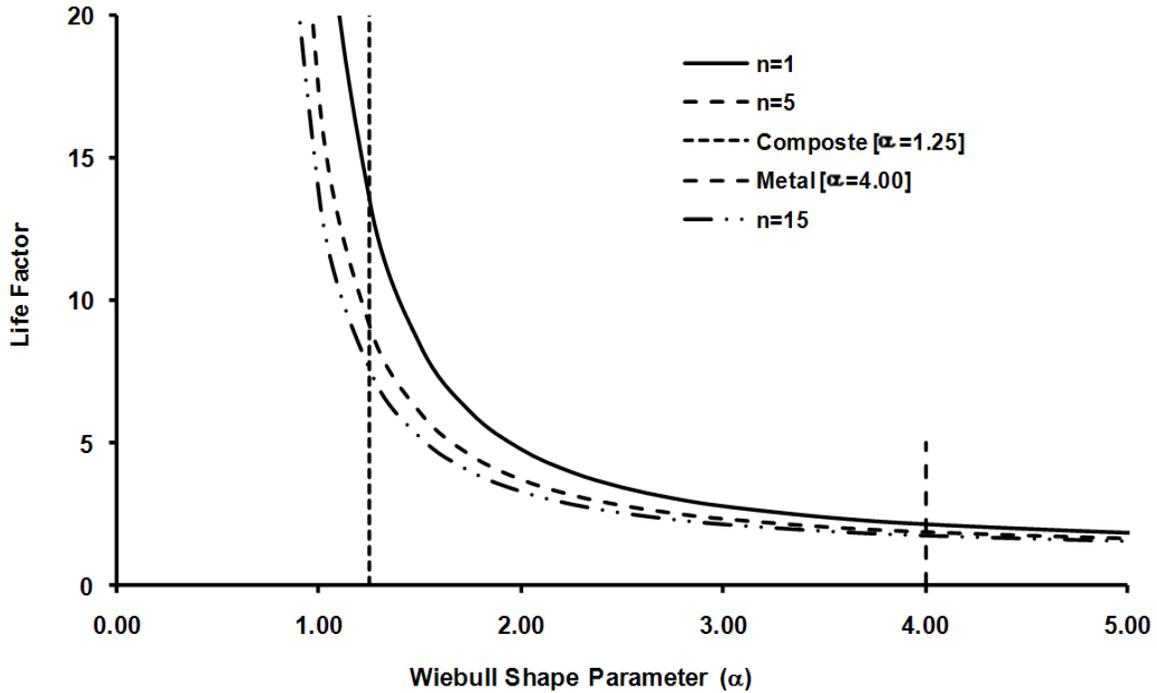


Figure 1. Life factor approach

2.4 Load-Enhancement Factor Approach

An alternative approach to the life factor (N_F) approach, which requires an excessive test duration for composite due to historically observed data scatter, is to increase the applied loads in the fatigue spectrum so that the same level of reliability can be achieved with a shorter test duration [1]. This approach is referred to as the load enhancement factor (LEF) approach. This approach is also known as combined load-life approach, because of the formal relationship between LEF and the test duration. Assuming that both the fatigue life and residual strength distributions can be described by two-parameter Weibull distribution, then the LEF in terms of test duration, N , is calculated using equation (5).

$$LEF = \Gamma\left(\frac{\alpha_L + 1}{\alpha_L}\right)^{\frac{\alpha_L}{\alpha_R}} \left/ \left\{ \frac{-\ln(p) \cdot N^{\alpha_L}}{\left[\frac{\chi^2_{\gamma}(2n)}{2n} \right]} \right\}^{\frac{1}{\alpha_R}} \right. \quad (5)$$

where α_R and α_L is the (modal) strength shape parameter (MSSP) and modal life shape parameter (MLSP), respectively, n is the number of test articles, and R is the reliability (for $\gamma=0.95$, A- and B-basis reliabilities are 0.99 and 0.90, respectively). $\chi^2_{\gamma}(2n)$ is the Chi-square distribution with $2n$ degrees of freedom at γ -level confidence.

As shown in Figure 2, a significant reduction in LEF is achieved simply by increasing the test duration to 1.5 DLT. Furthermore, the influence of strength and life shape parameter on LEF changes as the test duration is increased. For example, as the test duration is increased, the influence of the fatigue-life shape parameter on LEF increases. This is understood, as N_F is only influenced by MLSP. Also, note for small test durations, the influence of MSSP on LEF is significant due to the increased influence of load factor.

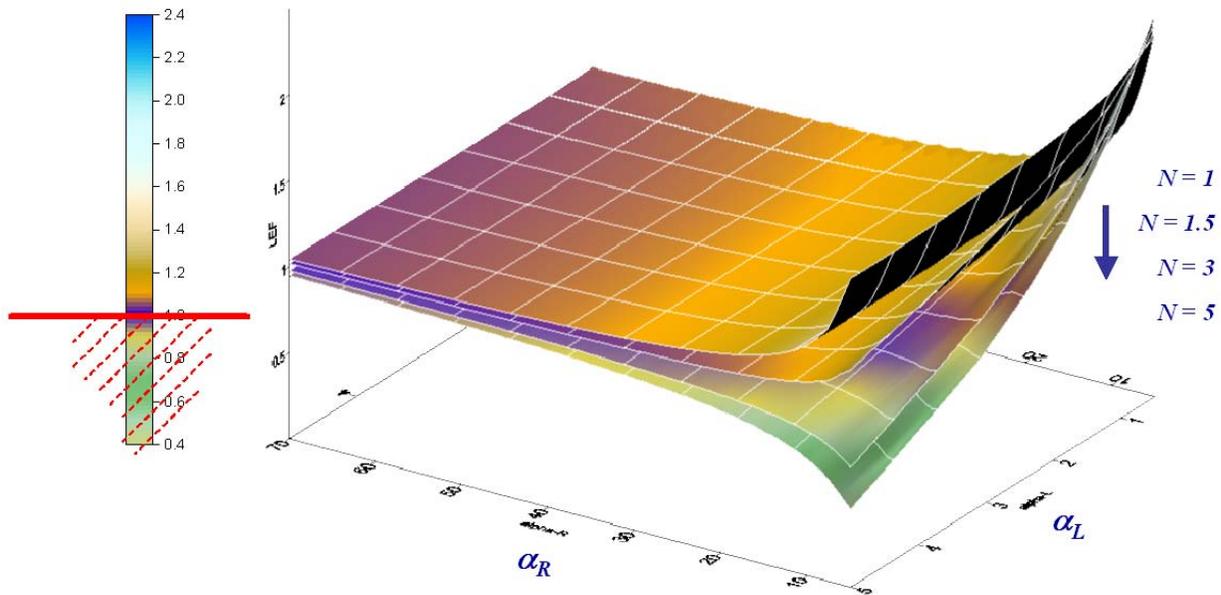


Figure 2. Influence of MSSP and MLSP on LEF [4]

Application of the combined load-life approach is illustrated in Figure 3. The LEF is calculated as the ratio of the maximum applied load to the design maximum fatigue stress. This curve is generated by calculating LEF for several different test durations. Note that the LEF required for the test duration that is equal to the life factor, N_F , is one, and N_F is obtained from equation (4) for the corresponding fatigue-life shape parameter. If the design maximum load in the repeated load test (P_F) is increased to the mean residual strength at one lifetime (P_T), then the A- or B-basis residual strength of the structure would be equivalent to the design maximum fatigue stress. Thus, a successful repeated load test to one lifetime at applied stress, P_T , or a repeated test to N_F at applied stress P_F (no LEF) would both demonstrate the corresponding reliability. Furthermore, a successful repeated load test to a test duration (less than N_F) with the corresponding LEF would demonstrate the same level or reliability on the design lifetime.

Figure 4 shows the B-basis LEF requirements based on the number of test specimens using equation (5) for the shape parameters reported in reference [6], $\alpha_R = 20$ and $\alpha_L = 1.25$. It shows that the increased number of test specimens reduces the LEF requirements. However, in large-scale testing only a single fatigue test ($n=1$) is conducted due to high cost and long test duration. This figure also shows that conducting the test for additional test durations is more practical than testing more articles, i.e., $N=1.5$ for $n=1$ and $N=1$ for $n=5$ require the same $LEF=1.148$. For full-

scale fatigue testing, minimum of B-basis reliability must be demonstrated with an appropriate combination of LEF and N.

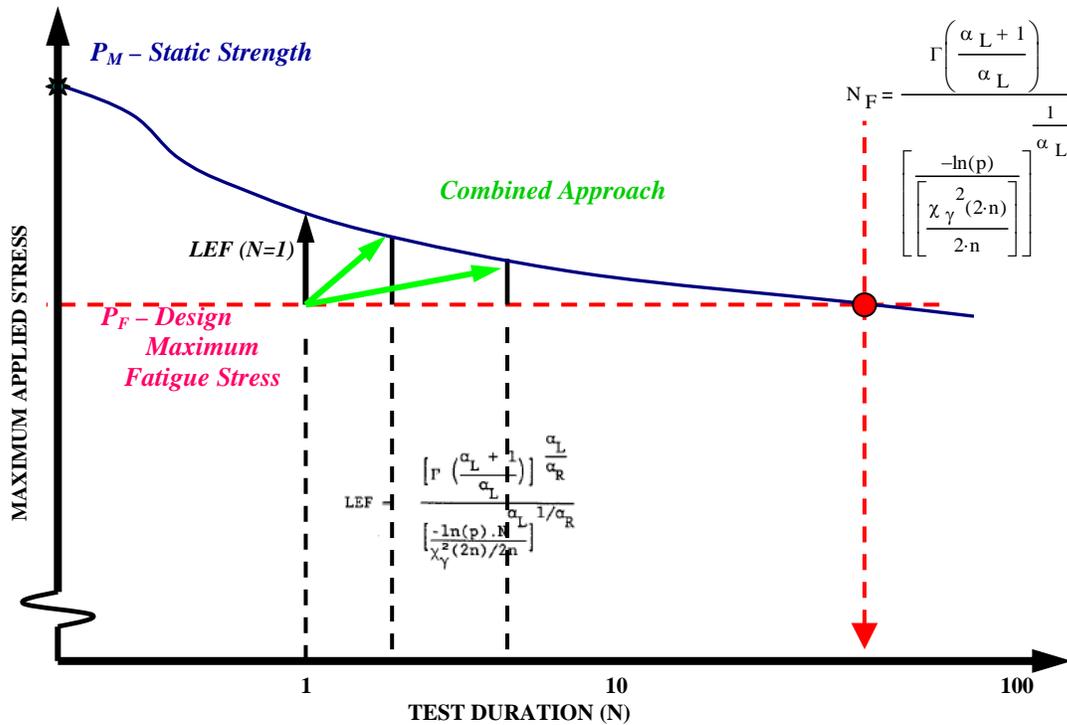


Figure 3. Combined load-life approach for composite structures

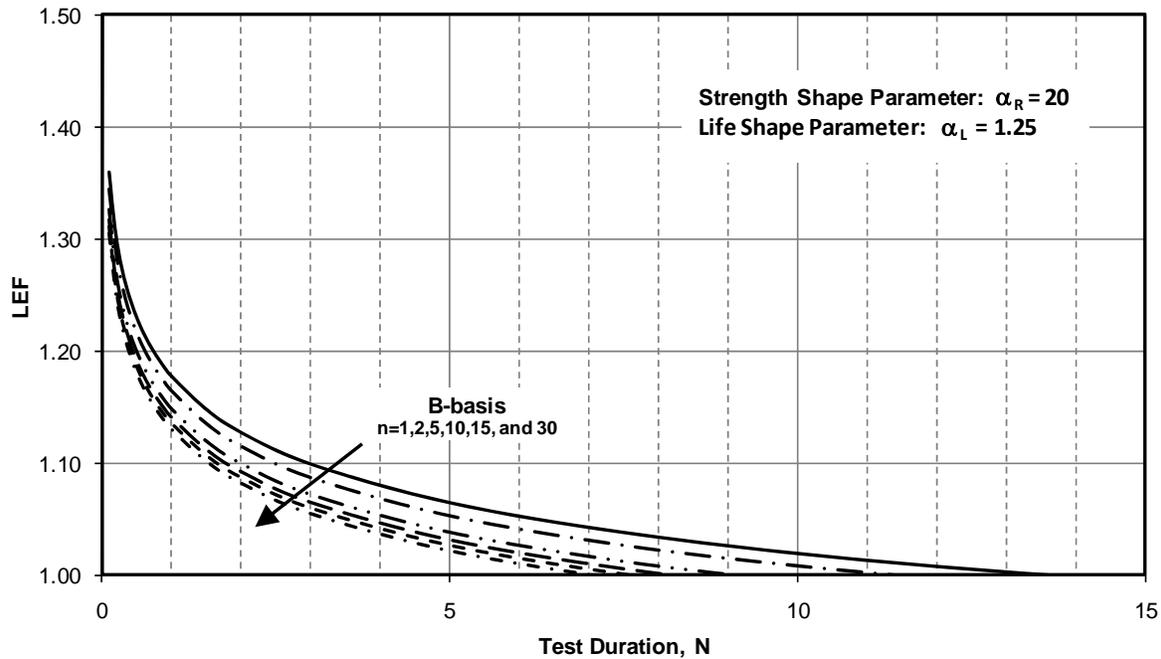
3. SCATTER ANALYSIS OF NIAR DATA

A statistical analyses and derivation of Life Factor and Load Enhancement Factor for several composite material systems used in current aircraft applications are performed following the procedures outlined in references [1] and [4] through [6]. The modal strength parameter (MSSP or α_R) was determined by evaluating the shape parameter and scale parameter of the distribution of static strength scatter. Similarly, the modal life parameter (MLSP or α_L) was determined by evaluating the shape parameter and scale parameter of the distribution of S-N data scatter.

3.1 Load Enhancement Factors for NIAR Data

The required load enhancement and test life depend on the statistical distributions of both the fatigue life and the residual strength. Assuming that both the fatigue life and residual strength distributions can be described by two-parameter Weibull distribution, the load enhancement factor (LEF) in terms of test duration, N, is calculated using equation (5). In order to compare the LEF requirements for different test durations (N), MSSP of 26.310 and MLSP of 2.131 were selected and the corresponding B-basis LEFs are included in Table 1 [4,5]. Further, the B-Basis LEF curve is compared with the LEF curves for Whitehead data (MSSP=20 and MLSP=1.25

[1]). These data are graphically illustrated in Figure 5. Note that any combination of LEF and N that lies on a particular curve demonstrates B-basis reliability for a combination of strength and life shape parameters (MSSP and MLSP).



Sample Size	LEF		
	N=1	N=1.5	N=2
1	1.177	1.148	1.127
2	1.163	1.134	1.114
5	1.148	1.120	1.100
10	1.140	1.111	1.091
15	1.135	1.107	1.087
30	1.130	1.101	1.082

Figure 4. Illustration of B-basis LEF requirements for Whitehead Data

NIAR data indicate there are significant improvements in static and fatigue data scatter compared to Whitehead data (referred to as NAVY). These can be attributed to the improvements in material and process techniques as well as due to the improvements in test methodologies. The static strength modal shape parameter (MSSP) improved from 20.000 to 32.193 while the fatigue life modal shape parameter (MLSP) improved from 1.25 to 1.88. The improvements in MLSP resulted in a reduction of life factor from 13.558 to 5.267. The reductions in the LEFs for different test durations are shown in Table 1.

Table 1. Comparison of LEF for Whitehead [1] and NIAR [5] data

	NAVY	NIAR
MSSP	20.000	32.193
MLSP	1.250	1.880
N	Load-Enhancement Factor (B-Basis)	
1.0	1.177	1.102
1.5	1.148	1.076
2.0	1.127	1.058
2.5	1.111	1.044
3.0	1.099	1.033
3.5	1.088	1.024
4.0	1.079	1.016
5.0	1.064	1.003
6.0	1.052	
8.0	1.034	
9.0	1.026	
14.0		
N_F	13.558	5.267

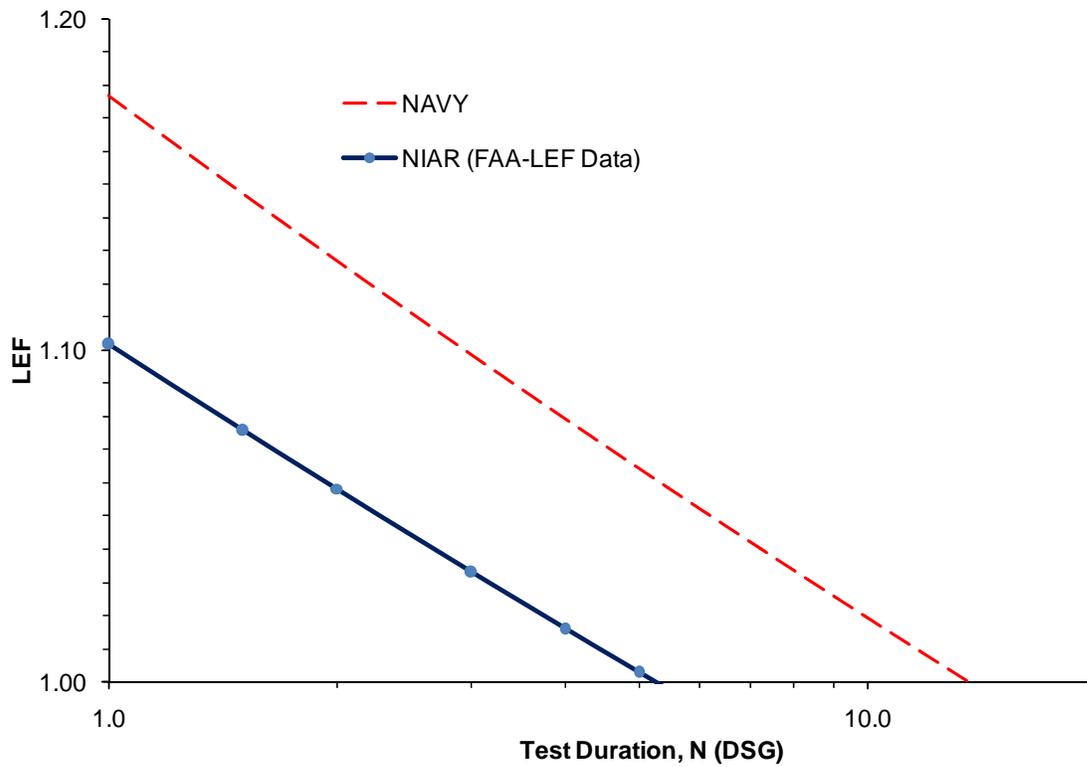


Figure 5. Comparison of LEF for B-Basis

4. APPLICATION OF LOAD ENHANCEMENT FACTOR

The combined load-life approach can be used in two different ways: (1) apply the same LEF, which is calculated for a certain test duration, to the entire spectrum or (2) apply a different LEF for different load blocks in the spectra based on the severity of enhanced load, i.e., cycles that have high loads are repeated for a longer test duration (with lower LEF) than the rest of the spectrum [4]. This approach is particularly useful for hybrid structures that exhibit metallic component failure due to high LEF (overloads) and to avoid premature failure due to buckling. Both of these applications are illustrated in Figure 6. In Figure 6, dark and light gray colors represent the original and enhanced load blocks with LEF, respectively. For example, if this block is repeated once ($N=1$) for B-basis reliability demonstration, the required LEF of 1.102 (Table 1) is applied. Since, the high load block with LEF is above the clipping level, only this block is repeated 3 times with $LEF=1.033$ (Table 1). Typically, such high load blocks have fewer occurrences compared to low load blocks. Therefore, repeating high load blocks with a life factor rather than a load factor has minimal impact on the test duration. Similarly, any combinations of load and life from Table 1 can be applied to individual blocks to demonstrate the required B-basis reliability. Note that the high load block with $LEF=1.033$ ($N=3$) is repeated 3 times by rearranging the smaller load blocks with $LEF=1.102$ ($N=1$) with original number of occurrences so that the high load blocks are not repeated one after the other. This example of LEF-Hybrid approach is illustrated in Figure 6(b).

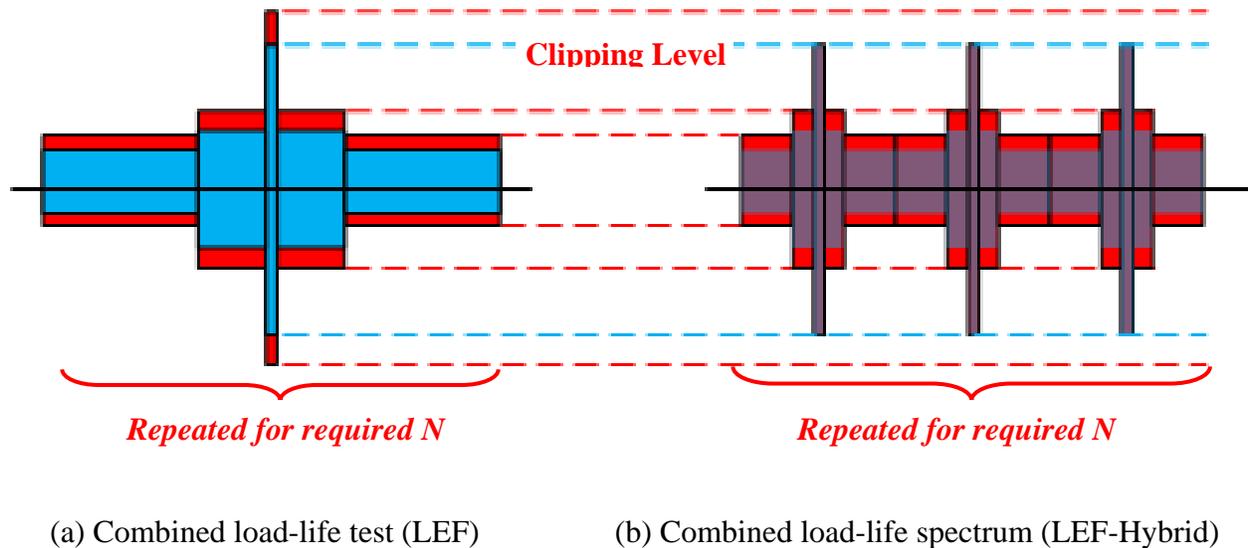


Figure 6. Application of combined load-life approach

One common practice for composite full-scale test substantiation is a two-lifetime test, which is adopted from metallic structural certification (Figure 1) using the design spectrum with the corresponding LEF under room temperature ambient test conditions. Often times for composites, the test duration of 1.5 DLT is used with the corresponding LEF. The LEF approach accounts for the variability in design details and loading modes. In order to account for the

service environmental effects on composite, additional factors are calculated from the design allowable tests for application during full-scale residual strength test. These additional factors for composite structures account for the difference between composite and metallic structure during design and analysis, and are beyond what is normally done for metallic certifications. Such factors, accounting for both moisture and temperature effects on composites, depend significantly on the material system and the layup configuration.

In metallic structures, severe flight loads result in crack growth retardation. Therefore, it is common practice to clip the peak loads (i.e., reduce the peak loads to the clipping level, no loads are omitted) after careful consideration of the appropriate clipping levels. In contrast, such severe flight loads significantly contribute to flaw growth in composite structures and reduce the fatigue life. Therefore, clipping of high fatigue spectrum loads must be avoided during structural testing of composite structures. When load enhancement factors are applied to composite load spectrum, the test loads can be significantly higher than the clipping levels for metallic components. For hybrid structures, this can be addressed through the LEF-Hybrid approach shown in Figure 6(b).

In order to reduce the test duration, the fatigue test spectrum is truncated by eliminating the segments with stress levels below an endurance limit (stress level corresponds to an infinite life). The endurance limit of a particular composite material varies based on parameters such as the layup configuration, test environment, and stress ratio. The S-N curves that are generated to obtain the life shape parameters can be used to determine the endurance limit for different design details of a composite structure. The life factor and/or load-enhancement factor are to be applied after truncation of the load spectrum.

The application of load enhancements must preserve the stress ratio of each load cycle throughout the spectrum so that the fatigue damage mechanism and the life are not artificially influenced. The LEF must be applied to the minimum/maximum load in the fatigue spectrum as shown in equation (6).

$$P_{Min/Max} = \left[(Load_{1-g}) + \left(\frac{\Delta Load}{\Delta g} \right) \cdot \Delta g \right] \cdot LEF \quad (6)$$

$(Load_{1-g})$ = mean fatigue load (i.e., 1-g maneuver) of a load block

Δg = amplitude with respect to 1-g fatigue load

$\left(\frac{\Delta Load}{\Delta g} \right)$ = load (shear/moment/torque) per Δg

The LEFs should not be applied to the mean fatigue loads as it offsets the spectrum in either the positive (for positive mean loads) or negative (for negative mean loads) direction (Figure 7). For cycles with load reversal (stress ratio $R < 0$), this causes a reduction in load magnitudes in the opposite loading direction, i.e., shifts the mean load [4]. Consequently, this alters the damage growth caused by reversible loads to the composite structure. Furthermore, for higher LEF values, this may convert a tension-compression cycle to a tension-tension cycle or compression-compression cycle for positive and negative enhanced mean loads, respectively. Specimen-level

data for composite materials show that reversible load cases ($R < 0$) are critical and have a significantly lower fatigue life than that of tension-tension or compression-compression ($R > 0$) cases (Figure A-9). Therefore, full-scale fatigue test spectrum loads are generated by applying the LEF to the minimum and maximum shear-moment-torque (SMT) loads so that the reversible loads are not shifted but rather enhanced, depending on the sign of the maximum or minimum SMT load, and the stress ratio of each cycle/segment is maintained after load enhancement.

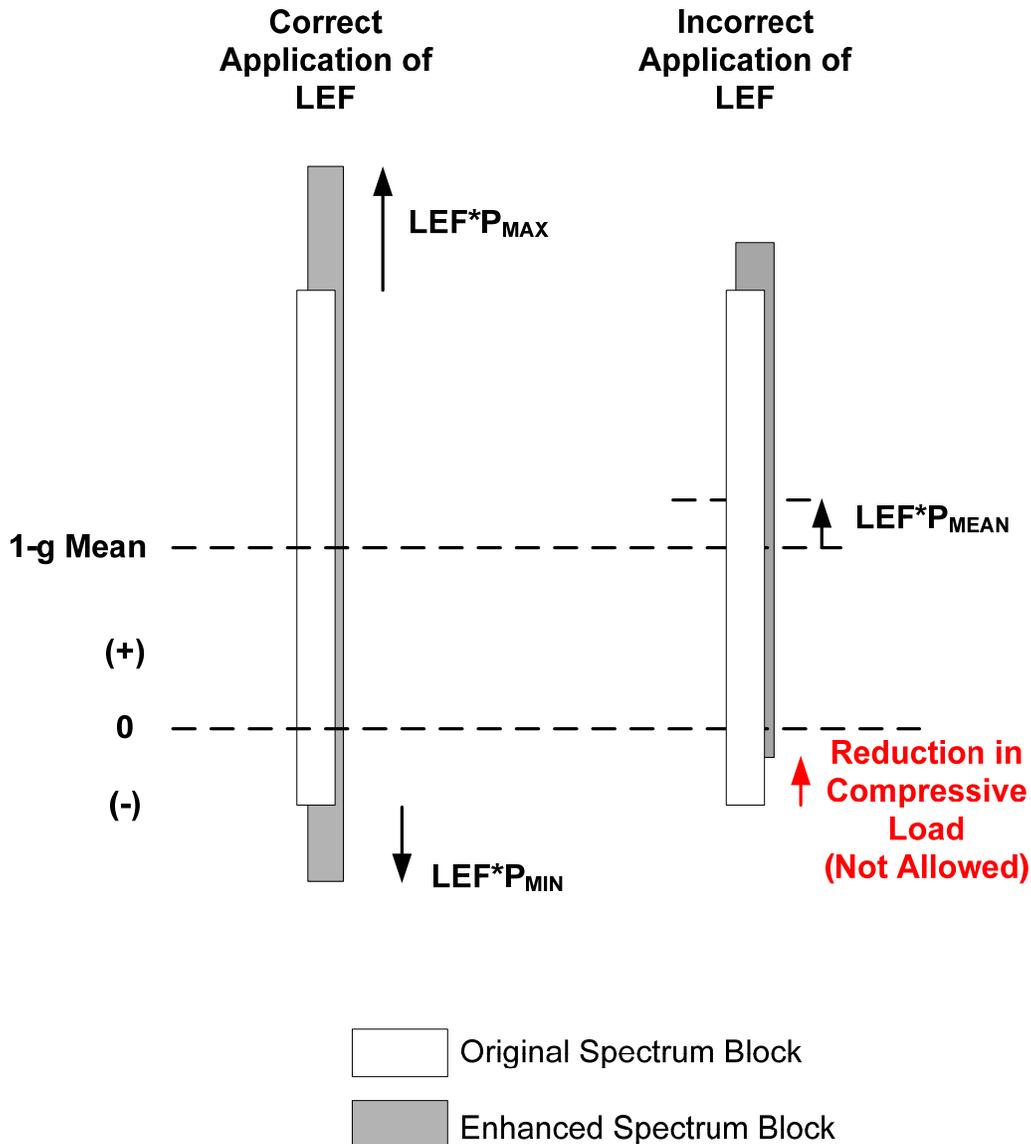


Figure 7. Application of LEF

5. CERTIFICATION OF COMPOSITE-METAL HYBRID STRUCTURES

The primary goal in a damage-tolerance certification program is to avoid catastrophic failure due to fatigue, corrosion, or accidental damage throughout the operational life of the aircraft. The damage-tolerance philosophy is well established for metallic airframes, where proven methods (structural analysis and inspection procedures) and supporting databases exist to detect damage and predict crack growth and residual strength. Damage growth mechanics and load spectra for composite and metal structure have significant differences that make the certification of composite-metal hybrid structures challenging, costly and time consuming. Composite damage growth mechanics are influenced by high loads, while low-loads can be truncated based on endurance limit. Conversely, the metal damage accumulation is influenced by low loads, while high loads must be truncated to prevent crack growth retardation and plastic deformation as shown in Figure 8.

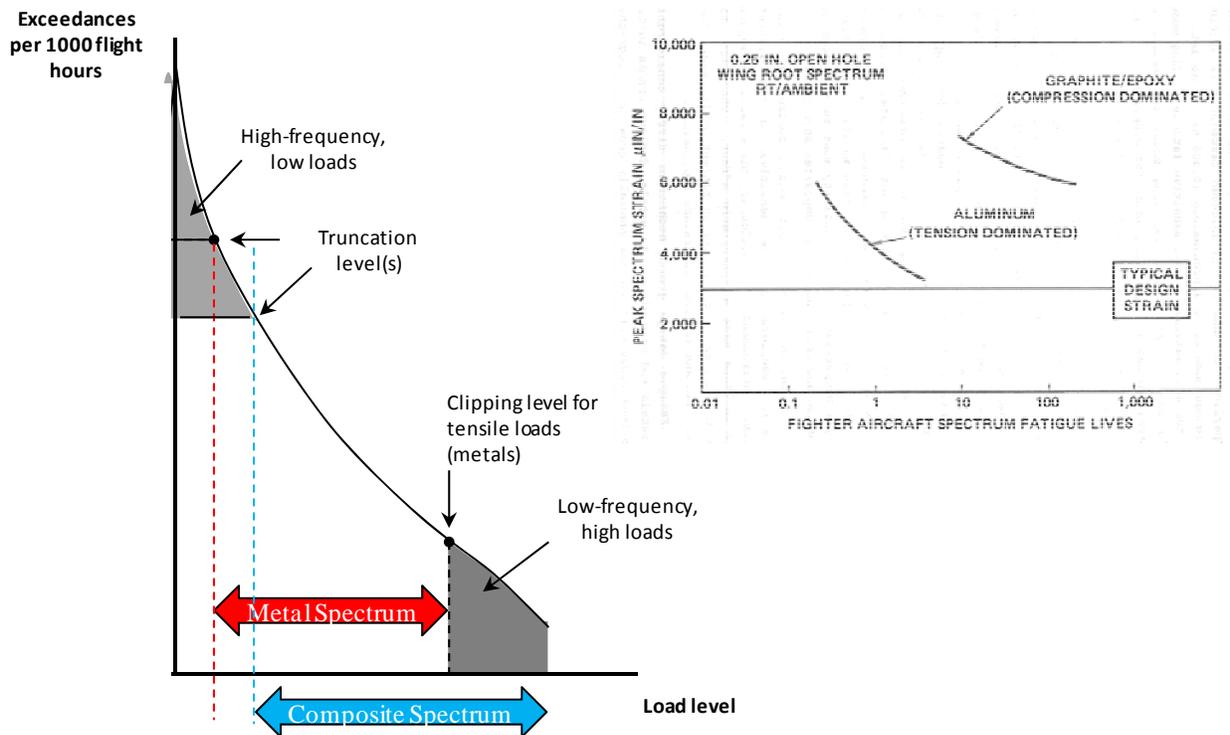


Figure 8. Composite and metal spectrum requirements

5.1 Load-Life Hybrid (LEF-H) Approach

The data scatter in composites compared to metal is significantly higher requiring large test duration to achieve a particular reliability that a metal structure would demonstrate with significantly low test duration. In order to reduce the test duration of composite structures, a load-enhancement factor (LEF) is applied to the composite spectrum. Such load enhancement factors on the test spectrum of a hybrid structure may adversely affect the metal certification, i.e.,

loads above clipping level(s) resulting metal crack growth retardation. A technique called a LEF-Hybrid is introduced such that different combinations of life-load factors can be used for different parts of the spectrum so that the high loads (that potentially can go beyond clipping level after LEF application) can have a higher life factor and a lower or no LEF as shown in Figure 6(b). This is further elaborated in Figure 9

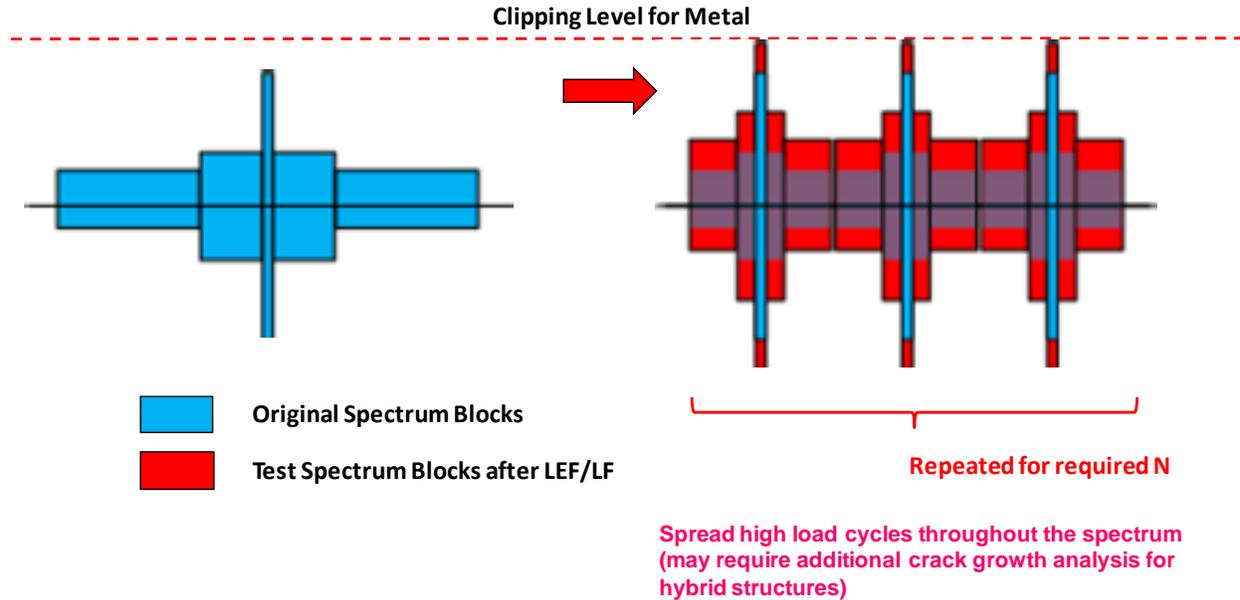


Figure 9. Application of combined load-life hybrid approach for composite-metal hybrid structures

5.2 Load-Life Shift (LLS) Approach

Second concept called Load-Life Shift (LLS) is introduced from authors' previous research work [4] so that a single test article can be used to substantiate both metal and composites as a two-phase certification methodology with different LEFs, i.e., first phase with LEF=1 for both metal and composite, and the second phase with LEF>1 for composite as shown in Table 2 (Figure 10) [7]. The load-life shift given in equation (6) calculates the remaining test duration based on the percentage of unsubstantiated design life in the previous test phase.

$$N_2^T = \left(1 - \frac{N_1^T}{N_1^R}\right) \cdot N_2^R \quad (7)$$

In equation (7), the subscripts 1 and 2 correspond to the test phase, and the superscripts R and T denote the corresponding repeated life for a particular LEF and the actual test duration, respectively, to demonstrate the reliability of design lifetime. The LLS approach provides a mechanism to obtain credit for the loads applied during first phase (focusing metal) so that the test duration for the composite certification phase can be reduced. The LLS approach provides a mechanism for an efficient certification approach that weighs both the economic aspects of certification and the time frame required for certification testing, while ensuring that safety is the

key priority. The LLS approach for full-scale test substantiation with LEF can also be written as the general form (analogous to Minor's rule for damage accumulation) shown in equation (8).

$$\frac{N_{LEF_1}^T}{N_{LEF_1}^R} + \frac{N_{LEF_2}^T}{N_{LEF_2}^R} + \dots + \frac{N_{LEF_n}^T}{N_{LEF_n}^R} = \sum_{i=1}^n \frac{N_{LEF_i}^T}{N_{LEF_i}^R} \geq 1.0 \quad (8)$$

In equation (8), the subscripts LEF_i correspond to the test phase i with the corresponding LEF, and the superscripts R and T denote the corresponding repeated life (required test duration) for a particular LEF and the actual test duration, respectively, to demonstrate the reliability of design lifetime. In order to show the desired level of reliability on the design lifetime, the cumulative ratio of test duration for required repeated life for each corresponding LEF must be equal (or greater than 1.0).

In order to apply the LLS approach, the load spectrum must include both metal and composite load spectra during phase 1. If the composite-critical loads are beyond clipping levels for metals after application of LEF, the LEF-Hybrid approach (Figure 6) must be implemented. If any of the loads are beyond clipping levels for metal prior to application of LEF, such loads must be included during the second phase so that the total required number of occurrences for such loads are applied by the end of second phase.

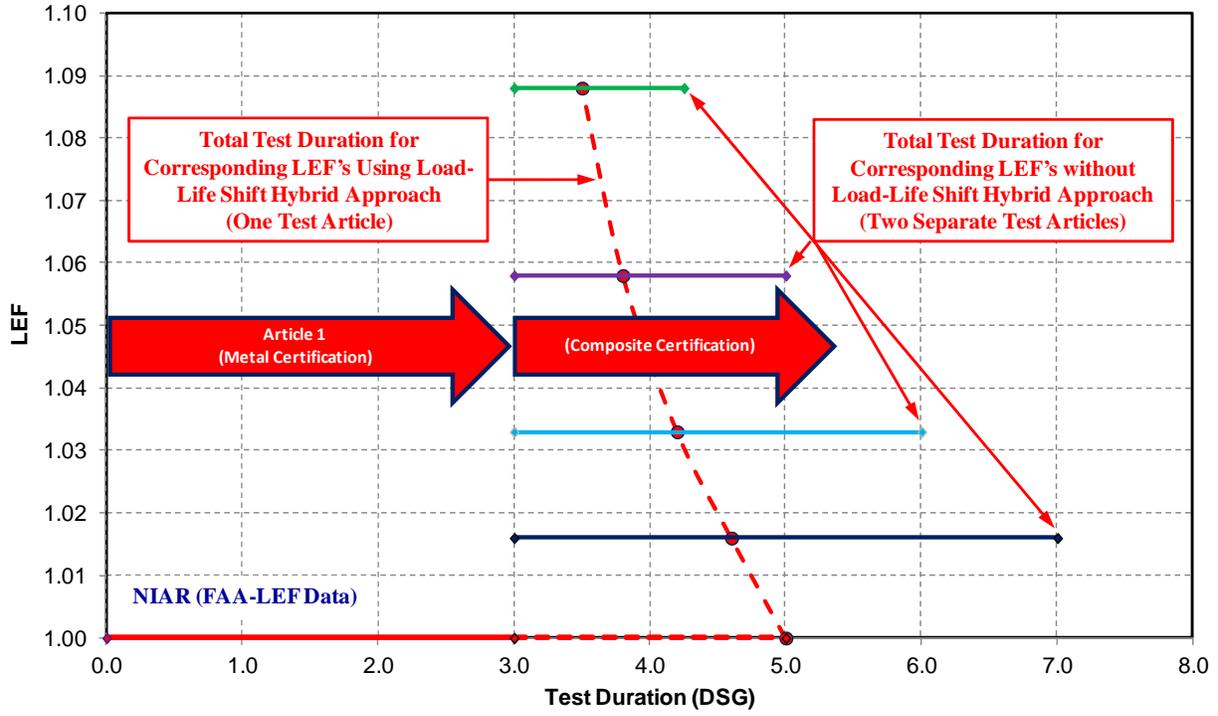
The example in Table 2 shows the B-basis load-life test requirements for a hybrid test article that has completed 3 DLT with LEF=1.0, primarily focusing on metal substantiation. This is equivalent to about 36 percent of the life factor. In order to continue the second phase to complete the composite substantiation, several options were given in Table 2 (and illustrated in Figure 10) with corresponding LEF and the remaining (LLS) test duration. For example, if 3 DLT test with LEF=1 is completed in phase one, the second phase can be completed with an LEF of 1.016 for approximately 1.6 additional DLT to demonstrate the B-basis reliability on the design life for the hybrid structure. Figure 10(b) shows the test time reduction with the use of LLS approach for different LEF requirements.

Note that high-load cycles that are clipped in the metal+composite portion of the sequence will need to be added to the composite cycles. These high load cycles should be interspersed in the spectrum and be chosen such that the stress ratio is maintained.

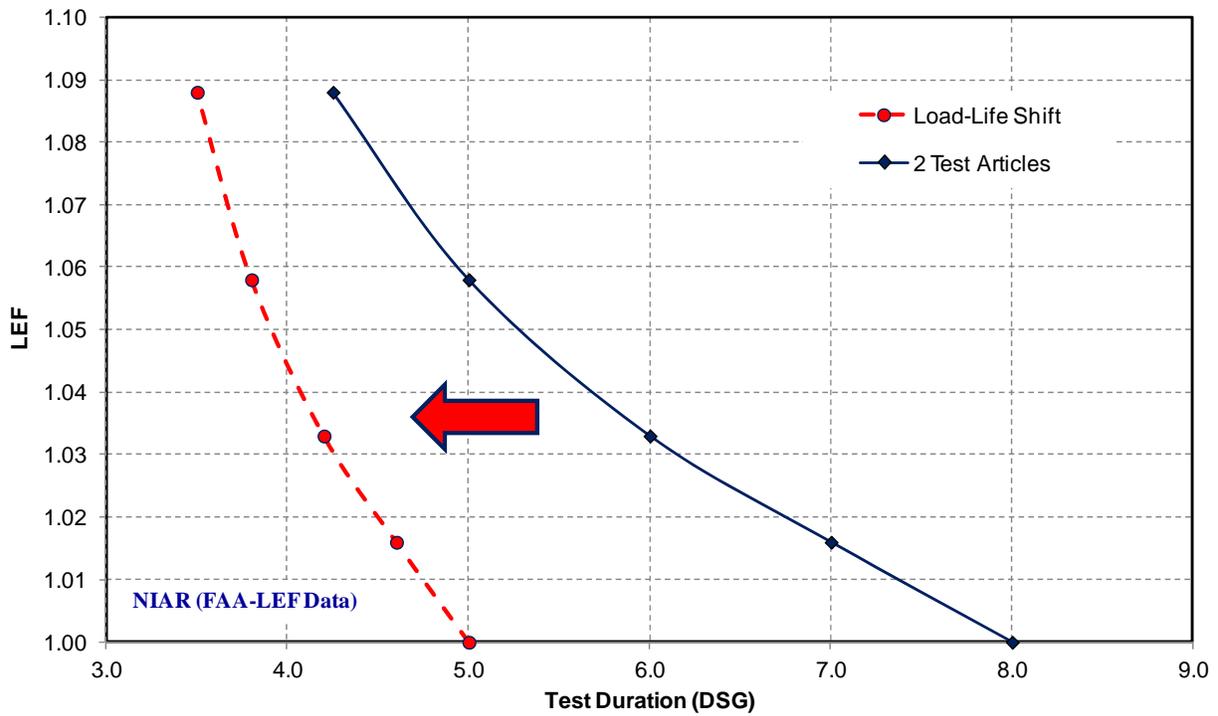
Table 2. Load-Life Shift Test Requirements in Composite Phase for NIAR Data*

Option	LEF	Required Test Duration without LLS	Required Test Duration with LLS	Total Test Duration
1	1.000	5.0	2.0	5.0
2	1.016	4.0	1.6	4.6
3	1.033	3.0	1.2	4.2
4	1.058	2.0	0.8	3.8
5	1.088	1.3	0.5	3.5

NOTE: * - After 3 DLT test with LEF=1 for metal certification phase



(a) Application of LLS



(a) Reduction in test duration due to LLS

Figure 10. Certification of composite-metal hybrid structures using LEF and LLS

Figure 11 shows an example test sequence for full-scale test substantiation of a composite-metal hybrid structure using LEF and LLS. The example illustration shows that the first two phases are carried out with primarily focusing the durability and damage tolerance of metal structure with an LEF = 1.0. Then, the third phase is carried out with an appropriate LEF and LLS test duration as shown in Table 2 primarily focusing composite structure. For the loads in composite spectrum that are beyond the clipping level for metal (prior to applying LEF) must be applied during the third phase so that such loads will not affect the metal damage growth, i.e., crack growth retardation and plasticity.

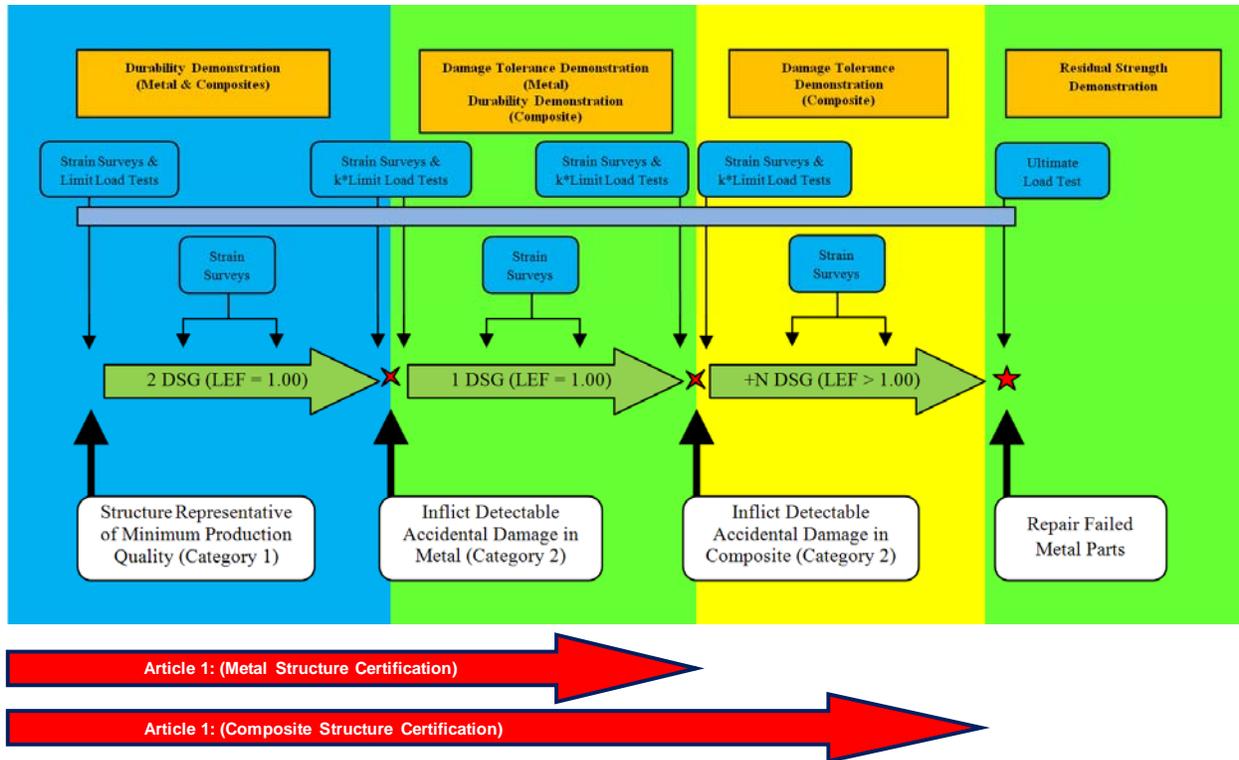


Figure 11. Example test sequence for full-scale test substantiation using load-life shift hybrid approach [7]

6. CONCLUSIONS

Damage growth mechanics and load spectra for composite and metal structure have significant differences that make the certification of composite-metal hybrid structures challenging, costly and time consuming. Composite damage growth mechanics are influenced by high loads, while low-loads can be truncated based on endurance limit. Conversely, the metal damage accumulation is influenced by low loads, while high loads must be truncated to prevent crack growth retardation and plastic deformation. Two techniques for application of LEF for composite-metal hybrid structures are introduced; (1) LEF-Hybrid (LEF-H) approach, and (2) load-life shift (LLS) approach.

LEF-Hybrid is introduced such that different combinations of life-load factors can be used for different parts of the spectrum so that the high loads (that potentially can go beyond clipping level after LEF application) can have a higher life factor and a lower or no LEF, while LEF can be applied to the rest the loads.

The LLS approach provides a mechanism to obtain credit for the loads applied during first phase (focusing metal) so that the test duration for the composite certification phase can be reduced. The LLS approach provides a mechanism for an efficient certification approach that weighs both the economic aspects of certification and the time frame required for certification testing, while ensuring that safety is the key priority. Once the test article has completed a phase, the remaining test duration is calculated using LLS approach. The example discussed in this paper showed that this approach significantly reduce the required test duration.

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