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CERTIFICATION OF DAMAGE TOLERANT COMPOSITE STRUCTURE[1]

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ABSTRACT

A reliability based certification testing methodology for impact damage tolerant composite structure was developed. Cocured, adhesively bonded, and impact damaged composite static strength and fatigue life data were statistically analyzed to determine the influence of test parameters on the data scatter. The impact damage resistance and damage tolerance of various structural configurations were characterized through the analysis of an industry wide database of impact test results. Realistic impact damage certification requirements were proposed based on actual fleet aircraft data. The capabilities of available impact damage analysis methods were determined through correlation with experimental data. Probabilistic methods were developed to estimate the reliability of impact damaged composite structures.

INTRODUCTION

A reliable certification testing procedure has evolved, over a period of many years, for metallic aircraft structures. The procedure encompasses two key requirements: (1) the full scale static test article must demonstrate a strength which equals or exceeds 150% design limit load (DLL), and (2) the full scale fatigue test article must demonstrate a life which equals or exceeds two times the design service life. These requirements are accepted measures of assuring structural integrity, developed mainly through experience.

These same full scale test requirements have been applied to the certification of composite structure by the aircraft industry. The Navy previously funded two certification programs [1,2] to address

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bolted composite and mixed composite/metal structures. Significant changes and additions were made in the certification process to account for special characteristics inherent to composites. A Navy certification methodology was thus formulated for what, at the time, was current composite usage. In this program, the methodology was extended to include integral (cocured or adhesively bonded) and impact damaged composite structure.

SCATTER ANALYSIS RESULTS

The analysis of static strength and fatigue life data scatter is an intrinsic part of the certification process. Scatter affects the minimum strength or life a structure must exhibit to attain a specific level of reliability. Scatter in strength and life data was analyzed in previous certification programs [1,2] for composite structures whose principal means of attachment was mechanical fastening. No tests were performed in those programs. The selected sources provided a database of over 6,000 static strength tests and 700 fatigue life tests. Several material systems, specimen types, and environmental conditions were included in the database. Several important observations were made in the previous programs concerning scatter in bolted composite test data.

The strength scatter was characterized by the coefficient of variation, CV, which is the standard deviation divided by the mean value. The strength scatter for bolted composites was found to be over one and one half times that for metals, and is independent of material system, environment, and loading direction (tension or compression). Strength specimens with holes produce approximately one third less scatter than unnotched specimens. Specimens with unloaded or loaded holes have nearly identical static strength scatter, and the scatter is independent of thickness/hole diameter and edge distance/hole diameter ratios.

The fatigue life scatter for bolted composites, as characterized by the standard deviation in the logarithm of life, can be up to ten times the life scatter of metals. The life scatter for specimens with no load transfer through the fastener is less than that for specimens with load transfer. Life scatter increases with the applied stress level for no load transfer specimens, but has little effect on the life scatter for load transfer specimens. Environmental conditions have little effect on bolted composite life scatter.

The integrally stiffened and impact damaged composite strength and life data available in the literature were far less abundant than that available for the bolted composite scatter analysis. Only twelve data sources were obtained through personal contacts and a review of more than twenty five sources. The data obtained included 373 strength and 59 fatigue tests. Although the database was limited, several important observations can still be made.

The strength scatter of integral composite specimens is slightly higher than that of bolted composites, and appears to be independent of material system and environment. Impact damaged composite specimens, with an in plane failure mode, exhibit strength scatter that is nearly that of metal specimens, and appears to be independent of material system, environment, laminate layup, and impact energy normalized by the specimen thickness. The fatigue life scatter of integral and impact damaged composite specimens appears to be similar to that observed for bolted composites. A summary of the scatter analysis results of all of the composite data is given in Figure 1.

IMPACT DAMAGE REQUIREMENTS

To set guidelines for development testing, the threat of impact damage to composite structure must be known. Impact test data were analyzed to identify the parameters that affect the damage resistance and damage tolerance of composite structures. A summary of the database used to characterize impact damage is given in Figure 2. Damage resistance is the ability of a structure to resist damage, and is related to parameters of the impact event. Damage tolerance is the ability of a structure to perform as intended with damage present, such as retain adequate residual strength, and is related to the loading and structural configuration. The following observations were made concerning impact damage resistance and tolerance of composite structures.

Simple coupons accurately represent the midbay damage resistance and damage tolerance of more complex integral and bolted composite structures. Damage resistance is independent of laminate layups commonly used in fighter aircraft, but matrix dominated layups are more damage tolerant than fiber dominated layups. Stitching through the laminate thickness improves damage resistance, but the subsequent damage tolerance (strength) is related only to the amount of damage present; stitching provides no further benefits. Adverse environmental conditions and impact damage both reduce the damage tolerance of composites. However, their combined effect appears to be less detrimental than the effects of each taken separately.

The susceptibility of composite structures to impact damage needs to be considered in the certification process, along with the damage resistance and tolerance characteristics. Surveys of fleet aircraft impact damage were performed by MCAIR [3]. Impact damage was measured and recorded for nine F/A-18, eighteen F-4, three A-10, and three F-111 aircraft. Indentation depth exceedances per aircraft for each aircraft type are shown in Figure 3. The largest indentation depth recorded was 0.09 inch, of the more than 3,000 visible occurrences. Indentation depths of 0.01 inch deep were readily visible during the walk around surveys, making a visibility threshold of a 0.05 inch deep indentation a conservative requirement. These indentation depth data were compared to impact test data (Figure 4), and a conservative estimate of the impact energy causing the maximum indentation depth was found to be 50 ft-lbs.

IMPACT DAMAGE ANALYSES

Verified strength and life analysis capabilities reduce the amount of testing required to characterize the behavior of the myriad of configurations found in aircraft structure. Analyses also permit element test results to be related to subcomponents and full scale article tests. Promising impact damage resistance and tolerance analyses were identified through a literature search. The capabilities of each available method were evaluated through comparison with experimental data. Although some of the residual strength analyses appear promising, the complexity of integral composite structure precludes their use as a means of significantly reducing the amount of testing required to demonstrate impact damage tolerance. The current analyses may be applied within a particular development test program to identify parameters that affect strength significantly, or as a basis for empirical correlations between development and full scale test results to guide any redesigns.

CERTIFICATION METHODOLOGIES

Bolted Composite or Mixed Composite/Metal Structure

The certification methodology for these structural types can be summarized as follows:

(1) Static strength and fatigue life design allowables are developed using coupon specimens. A sufficient number of coupons are tested to obtain B-basis strain allowables for the range of expected service environmental conditions. B-basis implies that 90% of future values will be greater than the B-basis value, and that the estimate of this value will be correct 95% of the time. Fatigue life behavior is characterized using spectrum loading.

(2) The structural analysis and design of the airframe are used to select areas deemed critical for static and fatigue test verification. A series of low complexity specimens representing these critical areas are tested. Specimens simulating progressively greater design complexity, including large scale components, are then tested, usually in the critical environment for the anticipated failure mode. These specimens are strain gaged for correlation with the full scale test results.

(3) A full scale static test to failure of the entire airframe is performed, in most cases, under room temperature/ambient (RTA) conditions. For a successful static test, the measured strains at 150% design limit load (DLL) must not exceed the B-basis allowables for the most critical environmental condition. Also, the failure load of the composite structure must exceed 150% DLL by a factor equal to the RTA allowable divided by the environment allowable. Moreover, the load-strain response in critical areas of the full scale article must agree with that of the supporting element and component tests.

(4) A full scale fatigue test of the entire airframe is performed under RTA conditions using a severe load spectrum. The full scale article must not suffer a catastrophic failure during a test to two times the design service life.

Integral or Impact Damaged Composite Structure Static Strength Certification

Two reliability based approaches to static strength certification of integral or impact damaged composite airframes were developed: the demonstrated strength approach and the measured strains approach. The methods were used to determine the required structural performance of an impact damaged composite airframe, including environmental effects, so as to achieve the same reliability as that of an all metal airframe with a demonstrated strength of 150% DLL.

Using the demonstrated strength approach, variations in strength, peak load, and structural response are accommodated by testing the full scale article to a load level above that expected in the service life of the aircraft. Again, the traditional load level increase has been to 150% DLL. Variation in expected peak load was estimated from load factor exceedance data, from aircraft exhibiting nominally identical usage. Variation in structural response includes variations in manufacturing and design tolerances, and was estimated from strain gage data [2].

Summarized in Figure 5 are the reliabilities at 100% DLL for a composite full scale article tested to 150% DLL, and the demonstrated strength needed to achieve the reliability of a metal full scale article. Reliabilities are given for a composite full scale article, with impact damage, tested under the critical environmental condition, and for an undamaged composite full scale article tested under RTA conditions. Reliabilities for in plane and out of plane failure modes are strongly affected by their respective static strength variations, as shown in Figure 5.

The damaged/environment reliability is calculated for the undamaged/RTA full scale article using either of two knockdown (reduction factor) approaches. One approach, the combined K_{DE} approach, is to derive strength knockdowns from specimens tested damaged, at environment, and compare these results to similar undamaged/RTA tests. The other approach, the separate $K_D K_E$ approach, uses damage and environment strength knockdowns that are derived from separate supporting element tests. The reliabilities in Figure 5 were calculated under the assumption that the critical area of the structure was subject to impact damage with the lowest failure load occurring at an environment other than RTA. It is recognized that this may not always be the case, and that the values given in Figure 5 are conservative estimates.

The estimated metal reliability decreases if the variation in expected peak load is included in the reliability calculation. With no peak load variation, the metal reliability is 99.9997%, while if the peak load variation is included, the metal reliability decreases to 99.995%. From Figure 5, the metal reliabilities are not reached with a composite full scale test to 150% DLL. Only testing the composite full scale with impact damage at environment results in achievable demonstrated strengths; using either knockdown approach with an undamaged/RTA composite test requires unreasonably high strengths to be demonstrated. The demonstrated strength approach may not be a viable approach for certifying the static strength of an airframe subject to impact damage because of the cost and time required to environmentally condition the structure.

The recommended approach is to demonstrate that the measured strains at 100% DLL are less than the damaged/environment ultimate strain estimate by a sufficient margin so as to achieve the desired reliability. The full scale article is tested undamaged/RTA and supporting elements are tested either damaged/environment, or undamaged/RTA with one of the knockdown approaches used to accommodate damage/environment strength reductions. The required element margins are given in Figure 6, and indicate that, although in some cases somewhat high, they are nevertheless achievable.

A difficulty is anticipated when the failure mode is out of plane using the measured strains approach. Measuring out of plane strains on the full scale article are nearly impossible. Therefore, in plane strains from the full scale article and supporting element tests must be correlated with out of plane failure loads.

Integral or Impact Damaged Composite Structure Fatigue Life Certification

Three reliability based approaches to fatigue life certification of integral or impact damaged composite airframes were developed: the scatter factor approach, the increased loads factor approach, and the ultimate strength/measured strains approach. These approaches were used to determine the required structural performance of an impact damaged composite airframe, including environmental effects. The goal was to achieve the same reliability as that of a metal airframe with a demonstrated life of two times the design service life.

Using the scatter factor approach, variations in life and expected usage are accommodated by demonstrating a test life that is greater than the design service life. Traditionally, this has been two times the design service life. Shown in Figure 7 are reliabilities of damaged composite full scale articles, with either a critical in plane or out of plane failure mode, as a function of the life demonstrated in test. Clearly, the demonstrated lives necessary to achieve the same reliability as a metal airframe are unreasonably high, ten to twenty times the design service life. This, coupled with the fact that the full scale article must be impact damaged, precludes the use of the scatter factor approach to fatigue life certification of impact damaged composite structures.

However, through modest increases in the spectrum fatigue loads, the desired reliability level may be attained with lower demonstrated lives. The necessary load increases for test durations of one, two, and four times the design service life are summarized in Figure 8, for various material and specimen configurations. An impact damaged composite full scale article, whose critical failure mode is in plane, must accommodate an 8% increase in loads with the traditional two lifetime test. If the failure mode is out of plane, the full scale article must accommodate a 20% load increase for the same two lifetime test. A 20% increase in loads is not practical for metallic structure, making this approach viable for all composite structure only.

The recommended approach is to compare measured strains, from the full scale static article test, to allowable strains from fatigue element tests. The advantages of this ultimate strength/measured strains approach are twofold. Only a static test of a full scale article need be performed to certify the composite structure. Also, the full scale article is undamaged. Damaging the full scale article will at best be controversial, and results could possibly be compromised should unrealistic damage be introduced in the structure. The traditional two lifetime fatigue test is still performed to certify any metallic components.

Results of this fatigue certification approach are shown in Figure 9. The supporting elements, representative of each fatigue critical area, should be impact damaged. Typically, five spectrum fatigue tests should be performed at each of two different limit load levels. These load levels should be chosen to be as different as the economics of testing will allow. If the load level is too low, life to failure will be prohibitively long. Conversely, load levels that are too high could cause quasistatic failures. From Figure 9, adequate fatigue reliability is achieved with element B-basis fatigue strain allowables that are 17% greater than the measured strain in the fatigue critical area, when the failure mode is out of plane. Only an 11% margin is necessary when the failure mode is in plane.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are made based on this work:

(1) The static strength variation of integral composite construction appears to be independent of test conditions and specimen configuration. Population scatter estimates can then be made using generic test configurations, permitting design allowables to be determined from smaller samples, as compared to standard handbook methods. Within the test budget, more structural details can be interrogated and more accurate reliability estimations made.

(2) Coupons and elements can accurately represent the damage resistance and damage tolerance behavior of full scale composite structure. These less expensive specimens can be used to characterize static strength and fatigue life behavior of damaged composite

structure, including environmental effects. Larger, and more expensive, subcomponent tests can still be performed and increase confidence and more accurately simulate secondary effects due to damage.

(3) A good start has been made in defining the real threat of impact damage to aircraft structure through surveys of fleet aircraft. The threat does not appear to be as severe as previously conjectured, but appears to be highly dependent on maintenance actions and detail design.

(4) The multiplicity of failure modes present within the composite during the impact event has precluded the development of a quick and accurate damage resistance analysis. This portion of the impact problem is best left to empirical characterization. The damage tolerance analyses are more developed but still rest on the same semi-empirical foundation as undamaged strength and life.

Recommendations for future work are

(1) Integral and impact damaged composite fatigue life database was very limited. Not enough data existed or were published to make well supported conclusions about fatigue life scatter. Future efforts could be directed at this apparent gap in the knowledge of scatter.

(2) Impact damage on fleet aircraft with primary composite structures should be more thoroughly assessed. The threat of impact damage to current designs has been given an initial assessment and is not expected to be greater through changes in material systems. However, newer aircraft may have special servicing conditions which cause those aircraft to be subjected to a higher incidence of damage.

(3) A composite damage tolerance design guide is needed that combines the results from research efforts, production experience, and service experience. This guide should include assessments of manufacturing actions, design practice, and testing requirements.

SUMMARY

To achieve the computed reliability of metallic structures, significant changes in composite certification procedures are required; composites have comparatively large strength and life scatter, are susceptible to impact damage, and are environmentally sensitive. As summarized in Figure 10, a straightforward modification of metallic procedures would result in unrealistically large load and life increases for composite structures. Alternatives are to demonstrate that airframe strains are conservative, either by comparison to element and component test results or by modest increases in fatigue loads.

The certification process for composite structures requires a level of planning significantly greater than that used for all metal structures. The airframe contractor and contracting agency must preplan development tests and coordinate them with the full scale tests. With careful planning, all composite and mixed composite/metal aircraft structures can be reliably certified.

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Material/Specimen	Static Strength		Fatigue Life	
	Coefficient of Variation	Weibull Shape Parameter	Standard Deviation of Log Life	Weibull Shape Parameter
Metal	0.040	31	0.10	5.0
Composites				
Out of Plane Failure	0.078	16	0.42	1.0
Damaged In Plane Failure	0.043	29	0.32	1.4
Fastener Specimens				
No Load Transfer	0.065	19	0.30	1.5
Intermediate Load Transfer	0.064	19	0.72	0.81
Pin Bearing	0.062	20	0.55	0.66

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Figure 1. Summary of Static Strength and Fatigue Life Scatter Analyses

Author	Material	Specimen Description	Layup/ Thickness	Impactor	Damage Resistance Effects	Damage Tolerance Effects
McCarty, et. al. [4]	AS4/3501-6 AS4/APC-2 AS6/5245C C12000/5245C T300/V378A	Panels Stiffened With Mechanically Attached Titanium Channels (Multispar Panels)	42/50/8 0.25 in. Thickness	1 in. Dia Steel	• Impact Energy Level • Material System	• Damage Area • Multiple Impacts • Peak Spectrum Load
McCarty, et. al. [4]	AS4/3501-6	Coupons (Clamped Along Edges)	42/50/8 0.25 in. Thickness	1 in. Dia Steel	• Impact Energy Level	• Damage Area
McCarty, et. al. [4]	AS6/2220-3	Cocured Multirib Panels (With and Without Stitching Through Rib Flange)	4/28/4 0.27 in. Thickness	1 in. Dia Steel	• Impact Location • Stitching	
Dominguez [5]	AS4/3501-6	F/A-18 Wing Fully Assembled and Attached to Aircraft (Aluminum Substructure)	Various	1 in. Dia Steel	• Impact Location • Laminate Layup and Thickness	
Ramkumar [6]	AS4/3501-6	Coupons (Steel Bars Bolted Along All Edges)	42/50/8 0.25 in. Thickness 42/50/8 0.50 in. Thickness	1/8 in. Dia Steel 1/2 in. Dia Steel	• Impact Location • Laminate Layup and Thickness	
Bhatia [7]	AS4/3501-6	Coupons (Aluminum Channels Bolted Along Two Edges)	42% 0° Plies 0.44 in. Thickness 21% 0° Plies 0.50 in. Thickness	5/8 in. Dia Steel	• Laminate Layup and Thickness	• Laminate Layup
Ashford [8]	AS4/3501-6 T300/V378A	Coupons (Clamped Along All Edges)	25/50/25 0.112 in. Thickness	1/2 in. Dia Steel	• Temperature	• Temperature • Peak Spectrum Load
Dexter and Funk [9]	T300/3501-6	Coupons (Clamped Along All Edges; Various Stitch Spacings/Pitches)	Quasi-Isotropic 0.30 in. Thickness	1/2 in. Dia Aluminum	• Stitching	• Stitching

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Figure 2. Summary of Impact Damage Characterization Data

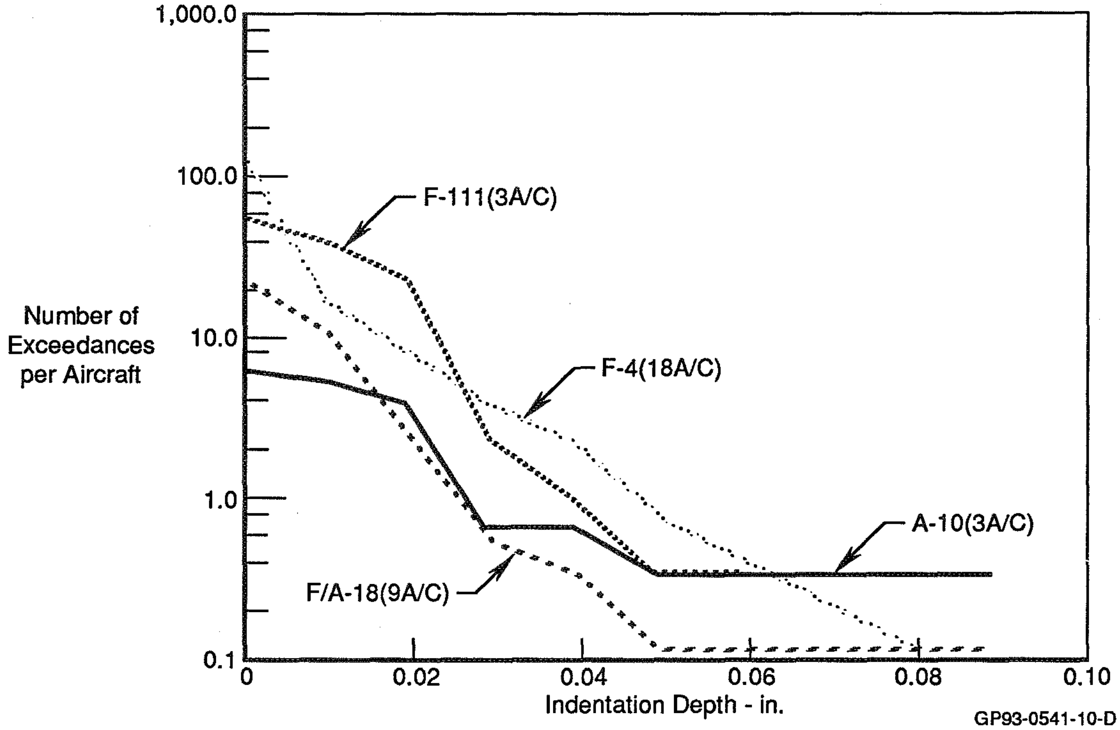

Figure 3. Indentation Depth Exceedances for Fleet Survey Aircraft

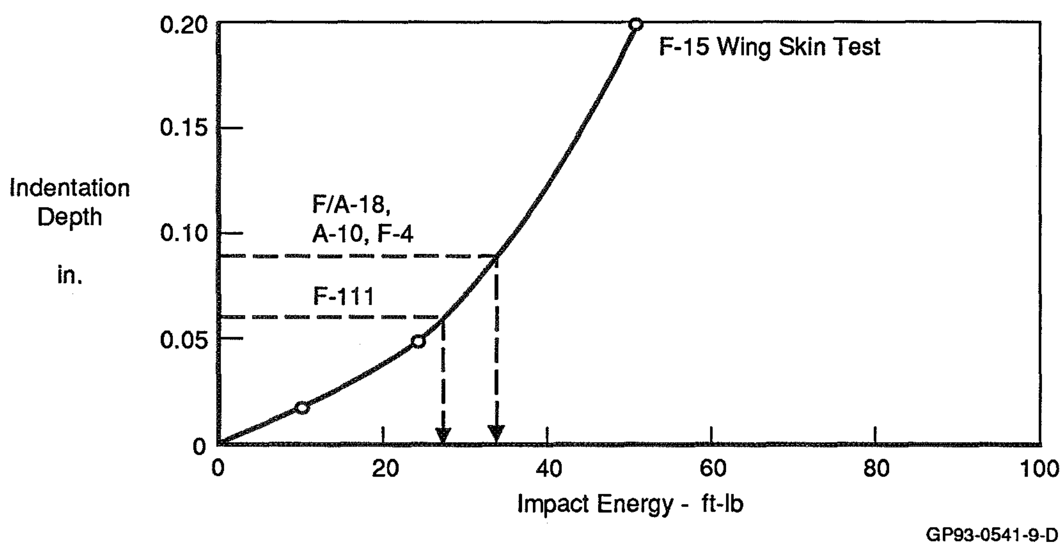

Figure 4. Maximum Damage to Fleet Aircraft Are Caused by Impact Energies of Less Than 40 ft-lb

Composite Full Scale Article and Knockdown Approach		No Peak Load Variation		Nominally Identical Usage Peak Load Variation	
		%R at 100% DLL(1)	R = 99.9997(2) (%DLL)	%R at 100% DLL(1)	R = 99.995%(2) (%DLL)
In Plane Failure Mode	Damaged/Environment	99.999	151.4	99.989	152.1
	Undamaged/RTA Combined K_{DE}	0.135	360.5	0.487	342.8
	Undamaged/RTA Separate K_D K_E	0.017	408.4	0.099	383.7
Out of Plane Failure Mode	Damaged/Environment	98.921	200.7	98.344	190.6
	Undamaged/RTA Combined K_{DE}	0.786	950.6	1.255	686.2
	Undamaged/RTA Separate K_D K_E	0.265	1,377.8	0.485	878.1

(1) Composite reliabilities are for full scale tests to 150% DLL.
(2) Reliability of metal full scale article tested to 150% DLL.

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Figure 5. Summary of Demonstrated Strength Approach to Impact Damaged Composite Certification

Composite Element and Knockdown Approach		Damaged and Environment Ultimate Strain/Measured Strain at 100% DLL	
		No Peak Load Variation R = 99.9997%(1)	Nominally Identical Usage Peak Load Variation R = 99.995%(1)
In Plane Failure Mode	Damaged/Environment	167.0%	166.1%
	Undamaged/RTA Combined K_{DE}	170.7%	169.6%
	Undamaged/RTA Separate K_D K_E	174.2%	172.9%
Out of Plane Failure Mode	Damaged/Environment	225.6%	209.4%
	Undamaged/RTA Combined K_{DE}	233.9%	216.2%
	Undamaged/RTA Separate K_D K_E	242.0%	222.9%

(1) Reliability of metal full scale article tested to 150% DLL

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Figure 6. Summary of Measured Strains Approach to Impact Damaged Composite Certification

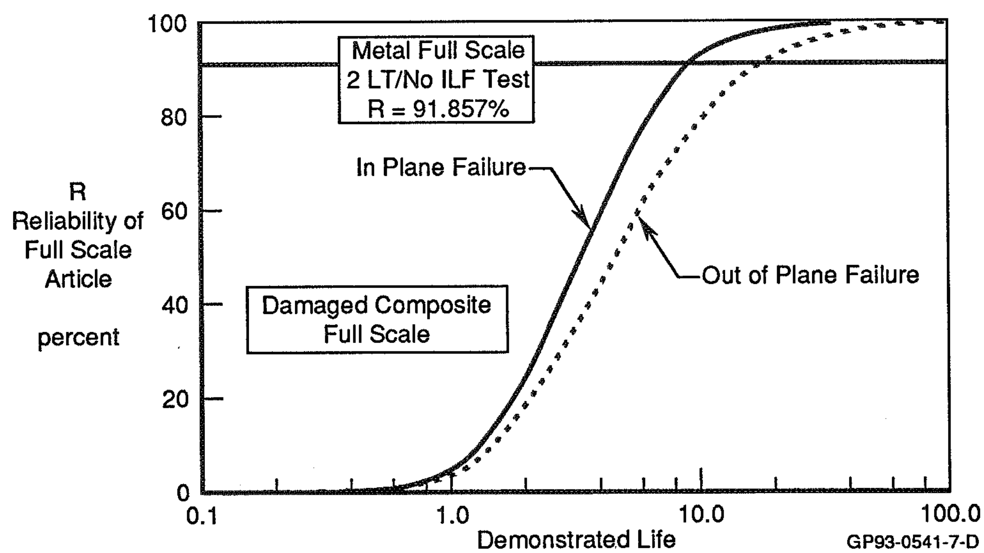

Figure 7. Required Demonstrated Lives for Composite Certification Are Unrealistic Using Scatter Factor Approach

Material/Specimen	ILF Required to Achieve Metal 2LT/ No ILF Test Reliability of 91.857%		
	$N_L = 1$	$N_L = 2$	$N_L = 4$
Metal	1.141	1.000	0.878
Composites			
Out of Plane Failure	1.263	1.196	1.132
Damaged In Plane Failure	1.119	1.081	1.045
Fastener Specimens			
No Load Transfer	1.080	1.053	1.027
Intermediate Load Transfer	1.200	1.170	1.141
Pin Bearing	1.390	1.310	1.235

1. ILF denotes increased loads factor
2. LT denotes lifetimes
3. N_L denotes demonstrated life in test

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Figure 8. Increased Loads Factor to Achieve the Reliability of a Metal Two Lifetime/No Increased Loads Factor Test

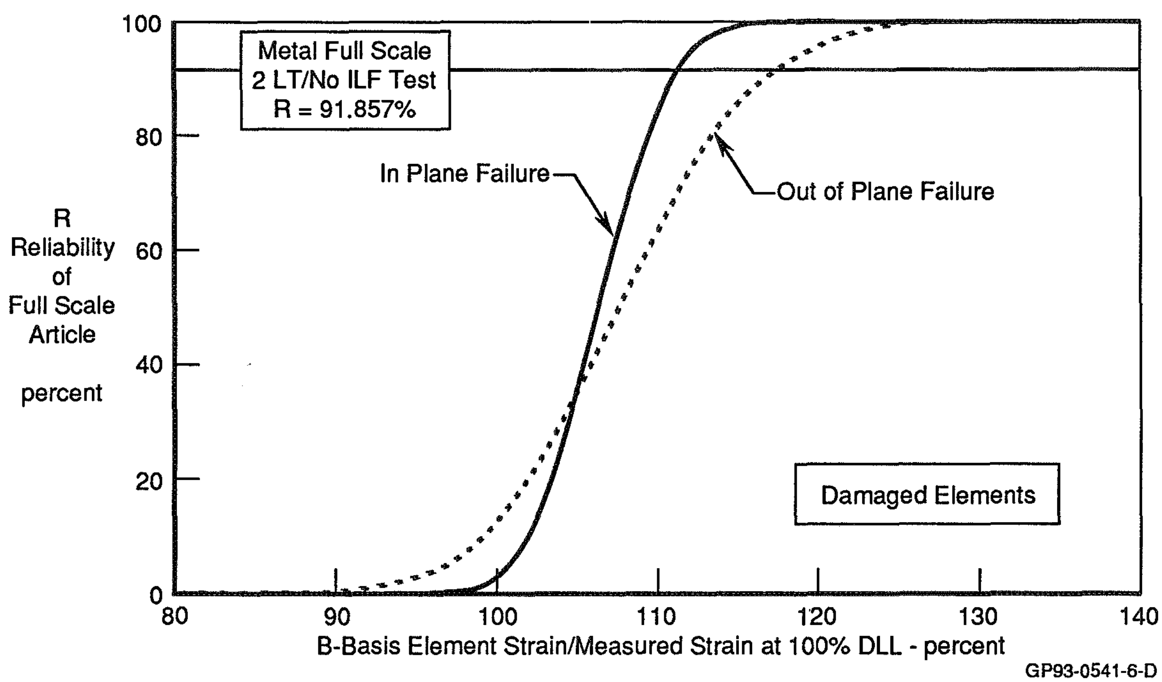

Figure 9. Fatigue Certification With Damaged Supporting Elements Using Ultimate Strength/Measured Strains Approach

Material/Specimen	Static Strength Approaches		Fatigue Life Approaches		
	Demonstrated Strength (DLL)(2)	Measured Strains at DLL/B-Basis Allowable (2)	Test Duration (LT) (3)	ILF With 2 LT Test(3)	Measured Strains at DLL/B-Basis Allowable(3)
Metal	150%	65%	2	0%	88%
Composites					
Out of Plane Failure	200%	49%	20	20%	85%
Damaged In Plane Failure	151%	64%	10	8%	90%
Fastener Specimens					
No Load Transfer	180%	55%	5	5%	91%
Intermediate Load Transfer	178%	56%	43	17%	88%
Pin Bearing	175%	57%	34	28%	84%

(1) Composite elements tested damaged/environment

(2) Required to achieve baseline metal reliability of 99.9997%

(3) Required to achieve baseline metal reliability of 91.857%

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Figure 10. Summary of Certification Approaches