Fatigue Sensitivity of Composite Structure for Fighter Aircraft

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A spectrum sensitivity study was conducted on chordwise splices in a fighter aircraft composite wing. Composite-to-metal bolted and bonded joints were used to experimentally determine their fatigue sensitivity to spectrum loading and environmental content. Fiber-dominated bolted joints were not sensitive to any of the parametric spectrum load variations in any of the environments used. By contrast, the step-lap bonded joints were sensitive to many of the parametric spectrum load variations and environmental exposures used. However, the bolted joints were significantly heavier than the bonded joints. Control and monitoring of materials and processes variables through an extensive quality assurance program was found to be indispensible for isolating parametric effects.

Introduction

DESIGN development, life prediction, and testing of primary composite structure has long been hampered by the lack of available information on composite fatigue performance in real-time flight environments. Decisions are generally made on the types of spectrum load, environment, and time simulation in the test laboratory for the sake of expediency and without a rational basis for measuring the effect of these decisions against actual fatigue performance in real flight time. In the case of high performance fighter aircraft, small amounts of moisture combined with high maneuver loads and flight temperatures (200°F or higher) may be detrimental to the strength of certain types of composites and loading modes. The way in which these life cycle fatigue parameters are represented in an accelerated laboratory environment can affect the composite laminate durability and strength in substantially different ways. It is desirable to know the sensitivity of composites to the manner in which the parameters may be truncated, accelerated, clipped, or otherwise simplified to produce a more cost-effective fatigue test.

A number of programs have been initiated in recent years to investigate various aspects of this sensitivity.[1-5] The program described in Ref. 3 was largely aimed at developing damage tolerance technology for composite fracture control. A number of schemes for environmental conditioning were also investigated, and another program[5] is a fairly recent advanced development program initiated to apply existing composite durability technology to more complex fighter aircraft structure, including major wing box and fuselage components. The complete results of this study are about three years away.

The study reported here evaluates the most frequent assumptions made in load truncation, rms load level, load frequency content, test temperatures, moisture contents, and mission mix, in development of test spectra to simulate actual flight-time fatigue effects. Both accelerated and real-flight-time tests were conducted on composite joints. Information was developed on the effects of spectrum power spectral density content and sustained load maneuvers on joint residual strength by varying the loading rates and peak load dwell times.

Statistical techniques were developed to account for the effects of censored fatigue testing (tests with only a partial number of fatigue failures). Some of the early work in this study[6,7] contains a number of preliminary conclusions based largely on the room temperature dry (RTD) data available at that time. Based on the larger data base available at the completion of the program, a few of these previously reported conclusions have been modified in this paper and are noted in the appropriate discussion.

The program test matrix is summarized in Table 1. Shown in this table is the test series number for each parametric test conducted. A total of 104 test series, including seven repeated fatigue tests and 12 static test series (without fatigue exposure), were completed; also, residual strength tests run on approximately 80% of the fatigue specimens that survived one or two lifetimes of fatigue (or 15 lifetimes in the case of the extended lifetime tests) were completed. All test series contained 20 specimens per series except the real-time tests and bolted joint extended lifetime tests, which were ten specimens each, and baseline test series 3 and 14, which were 40 specimens each. The 20-specimen large-scale joint test series 72 and 76 included ten fatigue and ten static specimens. Not included in this test matrix or in Table 1 are the approximately 400 specimens tested for the purpose of development and verification of the specimen designs, test machines, and test fixturing. Some of this checkout testing was fairly extensive owing to the complexity of the gang testing fixtures and the environmental conditioning equipment used.

The parameters investigated are grouped into six categories.

1) Loading frequency effects:
   a) constant frequency, 5 and 0.5 Hz
   b) constant load rate, 12 and 1.2 kips/s
   c) peak load dwell
   d) real time.
2) Load truncation effects:
   a) increased peak load
   b) reduced peak load
   c) increased low load occurrences.
3) Stress level effects
   a) spectrum severity variations about the standard baseline.
4) Extended lifetime
   a) fatigue failure or 15 lifetimes.
5) Loading direction
   a) bonded joint—tension and compression
   b) bolted joint—tension only.
6) Environment:
   a) room temperature dry (RTD)
   b) room temperature wet (RTW)
   c) mission profile temperature wet (MPTW).

All static testing was conducted either RTD, RTW, LTW (low temperature wet), or HTW (high temperature wet). The test program was structured so as to provide residual strength data as the primary means of measuring sensitivity of the spectrum parameters.

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Table 1 Test condition and test series matrix

				Static	Baseline[a]		Frequency effects					Truncation effects			Stress level effects[b]			Extended LT effects
															K_1X		K_2X	
	rms				Standard		Standard					Standard			Standard		Standard	Standard
	Truncation[c]				9/2		Standard (9/2)					7.33/2	10/2	9/1	Standard (9/2)		Standard (9/2)	Standard (9/2)
	Frequency, Hz				5		0.5		Variable (~5) Avg	(~0.5) Average	Real	5	5	5	5	0.5	5	5
	Load rate				Varied		Varied	$12 K/S$	$12 K/S$ dwell	$1.2 K/S$	Real	Varied	Varied	Varied	Varied	Varied	Varied	Varied
	Duration (LT)				1	2	2	2	2	2	1	2	2	2	2	2	2	until fatigue failure
Task	Environment																	
I	RTD	Bonded	T	1[e]	4	3	5	6	8	7	9	29	30	28	22	101	23	104
			C	2	11	10		12	12A		13	32	32A	31	24	102	25	105
		Bolted	T	14	16	15	17	18	20	19	21	34	35	33	26	103	27	106
IIA	LTW	Bonded	T	63														
			C	64														
		Bolted	T	65														
	RTW	Bonded	T	60	108	107	109		110		111T		124	123	120			128
			C	61	113	112			114		111C		126	125	121			129
		Bolted	T	62	116	115	117		118		119		127	127A	122			130
IIB	MPTW	Bonded	T	66[d]	132	131	132A		133		134T		145	145A	142			148
			C	67[d]	136	135			137		134C		146	146A	143			149
		Bolted	T	68[d]	139	138	139A		140		141		147	147A	144			150
	RTD,RTW, MPTW	Bonded and bolted as applicable			Batch effect characterization						Repeat test series 3-1, 107-1, 109-1, 131-1, 149-1, and 10A—repeat test series 15-1							
III	RTW,MPTW				Aircraft usage and specimen characteristics						Test series 77,78,79 and large-scale test series 76, large-scale test series 72							

[a] Baseline spectrum (same for all tasks). [b] See Ref. 9 for multiplication factors (K_1 and K_2). [c] Numbers shown denote upper and lower positive load factor range (e.g., 9/2 = 9g upper, 2g lower). [d] These specimens to be HTW only (no mission profile). [e] Denotes test series numbers; all test series 20 specimens per series except 9, 13, 21, 106, 111T, 111C, 119, 134T, 134C, 141, 150—10 specimens per series; 3, 15—40 specimens per series.

Test Specimen Selection

Two types of specimens were studied in this program: a bonded composite to metal step-lap and a bolted composite to metal joint. The basic design requirement was for joints to be generic to fighter wing application and capable of sustaining a specified ultimate design load and two lifetimes of realistic fatigue spectrum loading. This is consistent with current USAF requirements for certification testing of aircraft structures. Matrix- and adhesive-dominated tension and compression failure modes were represented by the bonded joint, and fiber-dominated ones by a bolted joint that exhibits net tension failure through a fastener hole.

An important consideration in the selection and design of these test specimens was that they be sufficiently realistic from the point of view of structural application. Thus the test specimen joints were configured for a simulated chordwise splice at the wing root area of the Northrop F-5E aircraft.

The program required a bonded joint and bolted joint configuration of substantially the same load carrying capacity. A chordwise root skin splice at approximately the 15 per chord location of the F-5E wing was used for these two specimens. The ultimate spanwise load intensity at that location is 9000 lb/in. The basic skin layup required to meet the joint strength and stiffness requirements is a 27-ply graphite/epoxy laminate with 59% 0-deg plies, 30% ±45-deg plies, and 11% 90-deg plies. In an actual wing design, the upper and lower skin joint configurations (i.e., compression and tension skins) would not necessarily have exactly the same geometry. However, the same joint configuration was used for both tension- and compression-dominated testing in the program for ease in comparing the data. Testing was carried out on four specimen configurations: 1) standard size bolted joint (Fig. 1); 2) standard size step-lap bonded joint (Fig. 2); 3) large-scale bonded joint (Fig. 3); and 4) large-scale bolted joint (Fig. 3). The large-scale joints have about twice the load carrying capacity of the standard size joints. About 25% of the standard size step-lap joints were of "double-end joint" configuration with an identical joint at each end of the specimen. Since only one joint failed in test, these data were treated as censored and analyzed by different methods discussed later.

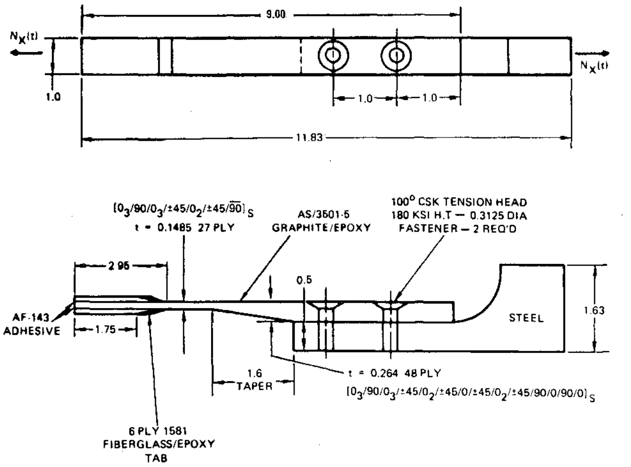

Fig. 1 Standard bolted joint test specimen.

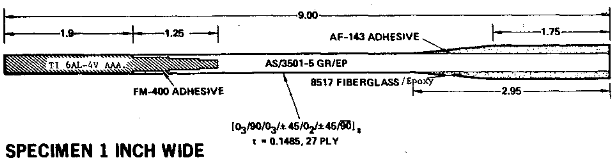

Fig. 2 Standard bonded joint test specimen—type C.

The composite material is Hercules AS/3501-5 graphite/epoxy prepreg and the modified epoxy film adhesive in the step-lap bonded joint is American Cyanamid FM-400 (with nylon scrim). The particular composite material was selected because it had been fairly well characterized.[3]

The study was primarily concerned with structural joint effects rather than fatigue effects in the basic laminate. Thus,

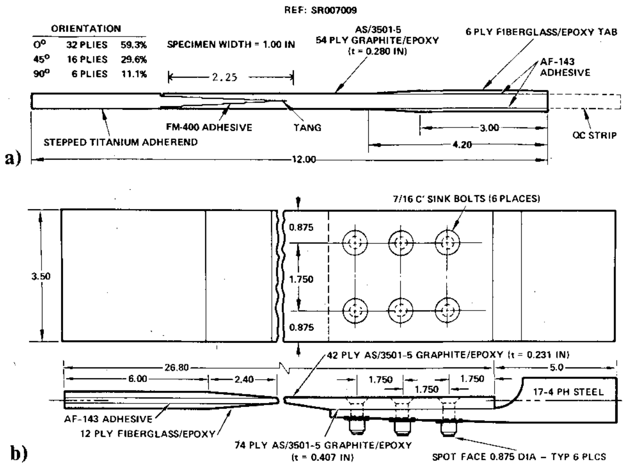

Fig. 3 a) Large-scale bonded joint and b) large scale bolted joint.

in designing both the bonded and bolted joints, primary consideration was given to producing failure modes in the joint itself. However, the resulting strain levels in the basic 27-ply laminate at the maximum spectrum loads were in the range of what might be considered nominal to slightly on the high side of accepted design practice, or about 2600-4000 μin./in. for the peak spectrum loads of from 5000 to 6500 lb/in. used in fatigue testing.

Bolted joint static and residual strength failure modes were, without exception, the same. Failure of these tensile loaded specimens occurred in net section tension across the first bolt hole next to the tabs with a varying degree of secondary delamination. No fatigue failures were observed. No residual strength bearing or shear out failure modes were observed, even secondarily.

The predominant primary failure mode of bonded joints, regardless of loading types or environment, appears to be cohesive fracture of the bondline at the first step (tang) with secondary multiple mode failure occurring. Some of the test series specimens with the higher moisture contents exhibited almost 100% cohesive fracture of the bondline. Primary failures in the laminate (delamination and fracture) occurred most frequently in compression dominated fatigue at RTD and RTW conditions; however, such failure modes were observed only in a small percentage of these test series.

Load and Temperature Spectra

Since the program was a study of the effects of various spectrum changes on residual strength and fatigue life, the requirements for test spectrum generation were fairly rigorous. The spectrum parameters were investigated for the purpose of assessing the degree of realism required in the spectrum testing compared to actual usage typical of a multimission fighter aircraft. Therefore the simulated usage was described in considerable detail with respect to mission types, mission mix, mission temperature profiles, mission exceedance data, and the load time histories. The reference test spectrum derived from this usage was described with respect to peak load exceedance data, load frequency content, random load/temperature sequences, random mission sequences, ground-air-ground cycles, load truncation, and individual flight length. From this reference spectrum, all other spectra for the various parametric studies were derived.

The reference spectrum was not only highly detailed in the definition of a flight load sequence, but also simulated real-time load cycle frequency on a cycle-by-cycle basis. This was accomplished by use of a computer program that simulates real-time loading spectrum cyclic frequency by one-dimensional narrow-band frequency distributions (bandwidth limited white noise) with mission profile data.[8] The "real-time" load factor spectral output from this program served as input to another computer program which converts the load factor amplitudes to specimen stress or load amplitude based on transfer functions and subsequently to a test machine language tape. A baseline spectrum was defined (5-Hz constant frequency, standard truncation, RTD) and other parametric studies were compared to this. The test spectra generation methodology is discussed in more detail elsewhere.[6,7]

Table 2 Summary of bonded specimen peak spectrum loads and percentages of "B-basis" static

	Environment		
Loading mode	RTD	RTW	MPTW
Tension	5850 (65%)	5000 (80%)	5000 (90%)
Compression	−5850 (57%)	−5850 (71%)	−5850 (80%)

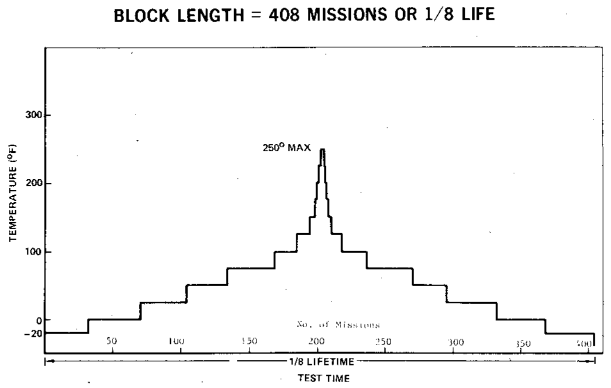

Fig. 4 Temperature vs number of missions for accelerated spectrum.

The approach to selecting the severity level of the spectrum for fatigue testing was to achieve at least two lifetimes of simulated fatigue test exposure, followed by residual static strength tests to failure. Also, the baseline maximum spectrum load was not to exceed an upper limit of 70% of the specimen "B basis" static strength $[\check{N}_x(0)]$. The 70% factor was arrived at as follows.

It was determined from F-5 and F-4 aircraft air-to-air combat data that these aircraft experience operating at spectrum loads up to 5% above limit design. Thus the percentage of peak spectrum to ultimate design stress was established as

$$F_{\text{peak}}\,(\text{peak spectrum load}) = 1.05 \times 0.67 \times \check{N}_x(0) = 0.70\check{N}_x(0)$$

No serious consideration was given to exceeding this 0.70 factor to produce more fatigue failures (except in stress level and truncation effects studies) since the 0.70 factor was felt to be conservatively high in the first place, and higher spectrum loading relative to static strength could raise questions as to how representative such strength and failure mode data are.

The 70% value was generally maintained for bolted specimen testing. However, load levels were adjusted somewhat for bonded specimens as shown in Table 2. The peak spectrum load for bonded specimen tension testing RTW and MPTW was reduced to 5000 lb/in. Although this load appeared high relative to the static values in these environments, there was some evidence from preliminary data that the strength reduction from fatigue was somewhat less in these environments compared to RTD. Even so, this value turned out to be too high, producing a greater number of premature fatigue failures than desired in the RTW and MPTW environments.

The temperature spectrum varied from −20 to +250 °F, with the highest temperatures (150-250°F) placed in air-to-air combat segments of the real-time mission profiles. The remaining temperatures (−20 to +250°F) were distributed to various real-time mission segments to achieve a rational distribution of temperature occurrences and time at temperature. The problem of generating a typical fighter temperature spectrum is compounded when accelerated testing, with respect to real time, is considered. Details of the temperature spectrum construction were discussed in Ref. 9.

The primary correlation between the accelerated frequency temperature spectra and the real-time frequency spectrum is that both types of temperature spectra have the same number of simulated flying hours at each temperature value. An attempt was made to maintain approximately the same number of load occurrences at each temperature value for both spectrum types. The resulting temperature spectrum shown in Fig. 4 was made up of about ten temperature bands, with not every temperature band being of the same width.

Statistical Data Reduction

In this study, specimen design for fatigue life relied mainly on static (RTD) strength prediction methodology and checkout fatigue testing at RTD and MPTW conditions. If specimen checkout testing at maximum spectrum loads indicated inadequate life, then the loads were reduced in subsequent testing to achieve the required life. However, this was not an exact procedure since maintaining the test schedule frequently dictated that a decision be made on spectrum load levels before any or all checkout testing had been completed. This led to spectrum loads being too high in some cases, producing a large number of fatigue failures and presenting a problem of analysis of data sets consisting of both fatigue and residual strength data. This provided one of the greatest challenges in the program: how to do a meaningful statistical analysis of this type of mixed mode data in order to assess the effect of a particular type of spectrum parameter.

All static strength, fatigue life, and residual strength data were statistically reduced using a two-parameter Weibull distribution. The shape (α) and scale (β) parameters of the Weibull distribution were estimated for each test series. A 0.95 confidence lower limit of the scale parameter ($\check{\beta}$) and a 0.95 confidence, 0.90 probability design allowable [$\check{N}_x(t)$] were then determined for each test series.

Two methods were used to estimate the Weibull shape ($\hat{\alpha}$) and scale ($\hat{\alpha}$) parameters. These are, namely, the maximum likelihood estimate method (MLE) and the least-squares method (LS). For all static test series with the exception of double-end stepped-lap joint tests, the strength values from a test series were treated as a completed sample and the Weibull parameters were estimated by the MLE method. In the case of the double-end stepped-lap joint test data, since each specimen consists of two joints, each failure load provided two strength data points—one failure strength and one censored strength. Therefore, for such a test series, the failure loads were treated as a censored sample, using the MLE method to estimate the Weibull parameters.

All fatigue lives were analyzed using the MLE method. For test series where all specimens failed during fatigue test, the life data were considered as a completed sample. However, the fatigue life data were treated as a censored sample in the case of test series with survived specimens.

In analyzing the residual strength data, both the MLE and LS methods were used. For test series with no fatigue failures, the residual strength data were analyzed by the MLE method and the data were treated either as a complete or a censored sample depending upon the type of the joint (single- or double-end joint). In cases where fatigue failure occurred prior to test completion, the residual strength data were considered as a censored sample. In such cases, treating the residual strength data of the survived specimens as a complete sample would result in a biased estimate of the population distribution. Thus, to include the effects of the failed specimens in the statistical data reduction, a least-squares technique was developed. In the LS method, a strength-life equal rank assumption was made. That is, it was assumed that the originally weaker specimens failed earlier under identical fatigue loading. Based on this assumption, the residual strength data from the surviving specimens were treated as a censored sample. The sample is then divided into two groups, the first group consisting of n_f weaker (failed) specimens and having no residual data values, with a ranking of from 1 to n_f, and the second group consisting of n_s stronger (survived) specimens which have measured residual strengths with rankings from n_f+1 to n (total sample size). The stronger specimens are ranked according to their strength value and numbered from n_f+1 to n. The least-squares technique is then used to estimate the shape and scale parameters of the two parameter Weibull distribution using only the latter (censored n_s) sample of n_f+1 through n residual strength values, i.e., the surviving specimens.

Environmental Conditioning

Fatigue testing that includes the combined environmental effects of loads, temperature, and moisture will require consideration of three factors: 1) life cycle moisture model and moisture conditioning approach, 2) environmental test equipment, and 3) the means for monitoring moisture level throughout the test.

Moisture is generally absorbed in the laminate during aircraft ground storage, and is desorbed during flight, particularly if high temperatures are encountered. The first step in establishing an accelerated moisture model was to analytically predict the real-time moisture level during a 20-year life cycle. This required definition of the environmental ground storage spectrum based on a fighter aircraft stationed at a baseline Seymour-Johnson AFB in Goldsboro, N.C. with reference data[4] used to establish this spectrum. The hourly average annual ground temperature and humidity (corrected for precipitation and solar radiation) at the upper and lower wing surfaces are shown in this reference. The mean of each six-hour period was obtained from these values. The ground/flight cycle for the baseline case was assumed to be 41.7 h on the ground and 1.2 h of flight for a total cycle time of 42.9 h. Two ground storage environmental spectra were considered: one for the lower wing surface tension-dominated load spectrum, and one for the upper wing surface compression-dominated load spectrum. The lower wing surface spectrum was used throughout since the moisture contents were higher.

The real-time model was analytically simulated in 1/4-lifetime (LT) blocks by 1) seven different temperature/humidity blocks based on the average values of each daily six-hour interval covering the 41.7-h ground time, repeated 811 times, and 2) a real-time flight temperature spectrum simulating 811 flights of 1.2-h duration. This one lifetime, real-time model predicted moisture levels of 0.73%‡ prior to application of the last 1/4-LT flight temperature, and 0.65% afterward in the 27-ply graphite/epoxy laminate. These values represent equilibrium moisture levels which remain approximately the same up to two lifetimes.

The experimental procedure for the standard size joints was to do accelerated (laboratory) moisture conditioning to the first 1/4-LT level (defined as primary conditioning) followed by accelerated or real-time load/temperature testing and then accelerated (laboratory) moisture conditioning to the 3/4- or 7/4-lifetime level (defined as secondary conditioning) followed by (3/4-7/4)-LT§ of accelerated or real-time load/temperature testing. The primary conditioning of the composite specimens consisted of 28 days at 170°F, 95% R.H. followed by 12 days at 170°F, 65% R.H. The secondary conditioning consisted of 20 days at 170°F, 80% R.H.

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‡Maximum moisture level.

§In the case of extended lifetime test this value would be 14¾ lifetimes. Such longer accelerated testing did not affect moisture levels significantly.

Environmental Test Equipment

Most of the fatigue test frames and environmental control equipment were constructed specifically for this program because of the unique requirements for gang fatigue testing of from 10 to 20 specimens at a time, and because of the particular type of thermal cycling necessary for simultaneous fatigue loading of multiple specimens. The only exception to gang fatigue testing was with the large-scale bolted joint specimens which were tested one-at-a-time in a single frame machine because limited numbers of these specimens did not warrant modification of a multiple specimen test frame.

Ambient fatigue testing of bolted and bonded joints, either RTD or RTW, was accomplished on the 10-channel test frame. All MPTW testing, real-time and accelerated, of both bonded and bolted joint specimens was carried out in the same 10-channel loading frame, fitted with a temperature chamber for each two loading channels. This equipment was designed to run a 20 bonded (10 bolted) specimen fatigue load test while exposing the specimens to a fighter temperature spectrum that varies from mission segment to mission segment with a heat up/cool down rate of 50°F/min. The heating/cooling system used heating elements and blowers for heating and mechanical refrigeration for cooling and an LN_2 boost system to help maintain the temperature change rate. Load and temperature control were synchronized by a temperature controller which cycled the heating elements and blowers on and off and positioned the air dampers for diverting cool air over the specimen on signal from a thermocouple bonded to the surface of a specimen in one of the five chambers, for closed-loop feedback and control of the temperature extremes. This temperature system had an operational range of from $+300$ to -50°F. Refrigerated air distribution among the five chambers was controlled by adjustment of manual control valves. Temperature accuracy within a chamber was ± 3°F and between chambers the variation was 5-7°F total.

Moisture Absorption Records

For each RTW and MPTW test series (including some RTD test series) moisture control travelers (MCTs) were included in test series' makeup. At least one set of four is included with each test series. Also one set of travelers was placed in each of the five chambers of the mean profile temperature unit (MPTU). The four moisture control travelers are made up to represent the solid laminate and the three laminate-plus-bondline sections that occur in the bonded joints.

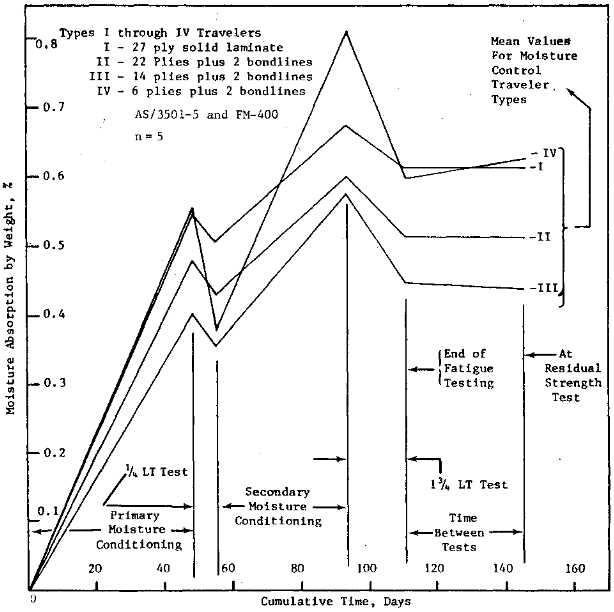

Fig. 5 Moisture absorption vs cumulative time for test series 135 (MPTW).

The moisture weight gain data on types I-IV MCTs for baseline MPTW test series No. 135 are plotted in Fig. 5 vs cumulative time from the first weighing at test series makeup to each subsequent weighing after certain planned moisture conditioning and testing events took place. This cumulative time is not the same as the time of moisture conditioning or testing but includes the time used in setup and the storage time in foil/plastic bags, i.e., the total elapsed time since test series makeup. Figure 6 presents the moisture absorption data on types I-IV MCTs for real-time MPTW bonded joint test series No. 134. Basic first weighing dates are different but MCTs and specimens are stored in foil/plastic bags when not being weighed, tested, or moisture conditioned. Thus the cumulative time at the end of test periods and at residual strength are different for each type of MCT.

Data Analysis and Discussion

Bonded Joint Data

A summary of the bonded joint tension-dominated fatigue residual strength data, including static tension data in bar graph form, is shown in Figs. 7-9 for each of the three test environments (RTD, RTW, MPTW). All statistical data in these bar charts are normalized to the appropriate baseline β value for each environment. Residual strength data were also normalized to the static quality control data that characterized the RTD tension strength of each fabrication panel from which specimens were selected for a given test series.[6] This enabled final data comparisons to isolate spectrum parametric effects to be made in such a way that the results were not influenced by specimen scatter due to fabrication batch effects and material variations.

Since a large number of fatigue failures occurred during tension spectrum testing of the bonded joints, especially in the RTW and MPTW environments, probability of survival plots vs lifetimes of selected test series data is presented in Figs. 10 and 11. Fatigue failure data are separated by materials and processing (M&P) groups. These groups represent different material batches and are explained elsewhere.[6] Although an

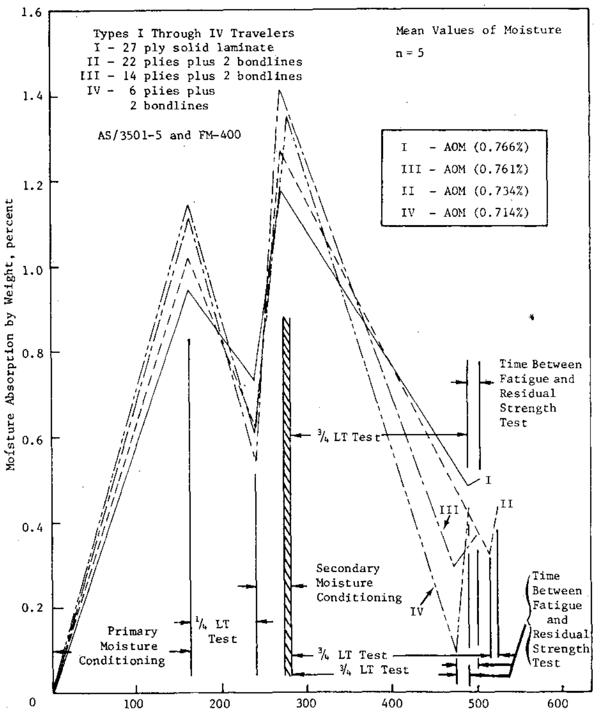

Fig. 6 Moisture absorption vs cumulative time for test series 134 (real-time MPTW).

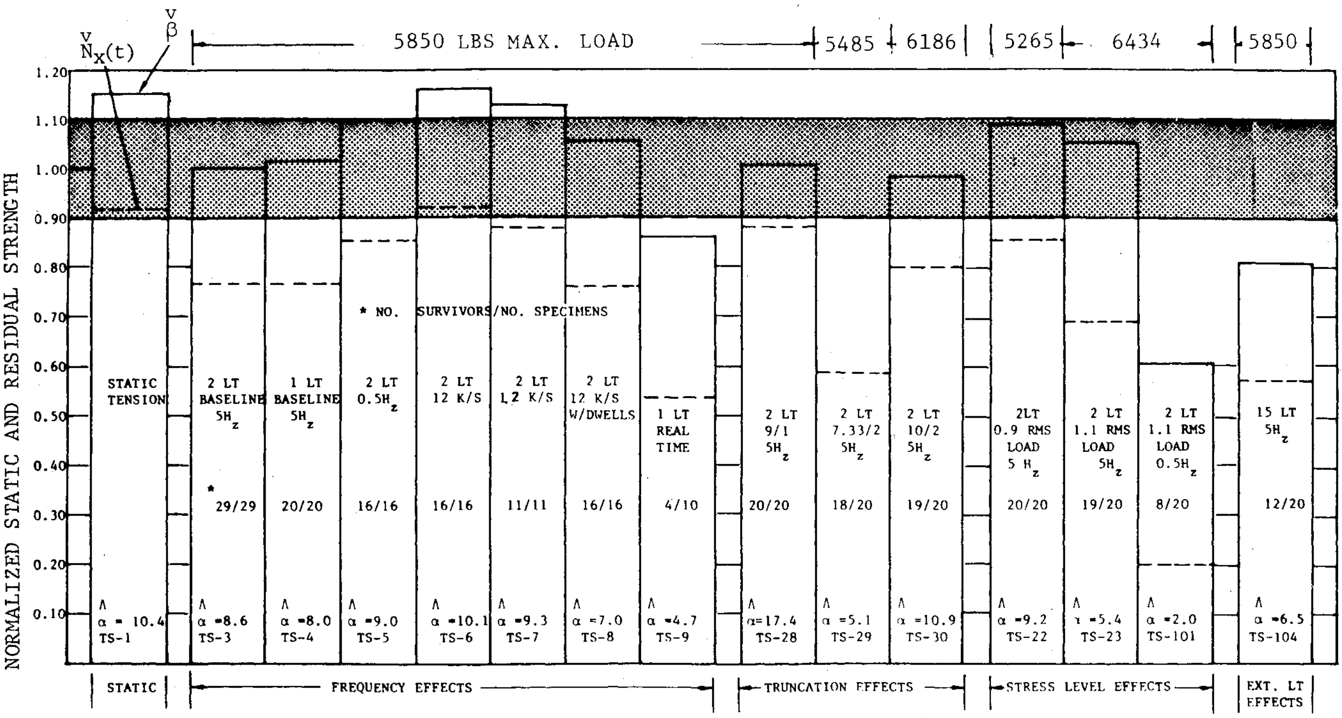

Fig. 7 Summary of parametric residual strength for the step-lap joints in tension (RTD).

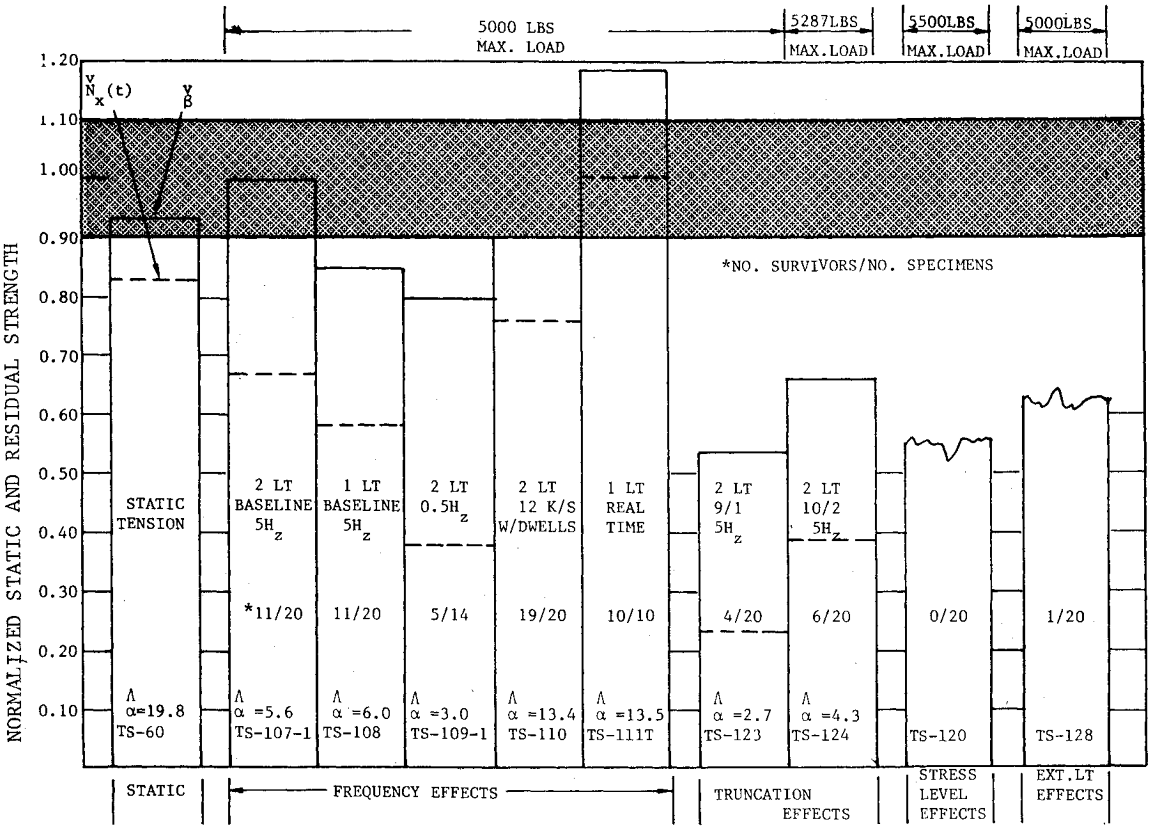

Fig. 8 Summary of parametric residual strength for the step-lap joints in tension (RTW).

equal amount of bonded joint compression fatigue data were generated, they are not included here because the parametric spectrum sensitivity trends observed were essentially the same as for the tension data. In general, fewer premature fatigue failures occurred in compression than in tension and residual strengths were somewhat higher, although the differences were less in the more severe environments.

A ±10% scatter band is used about the fatigue baseline $\check{\beta}$ values in all cases representing measured specimen scatter within a fabrication panel. Thus the measure of sensitivity is the position of the normalized value from any parametric test relative to this scatter band. Also, the moisture level has been a contributing factor to any relative data differences. Both residual strength and fatigue failure data were evaluated to determine if conclusions based on one failure mode are substantiated by the other. In every case they were consistent. Any effect observed in residual strength data was also observed in the fatigue failure data.

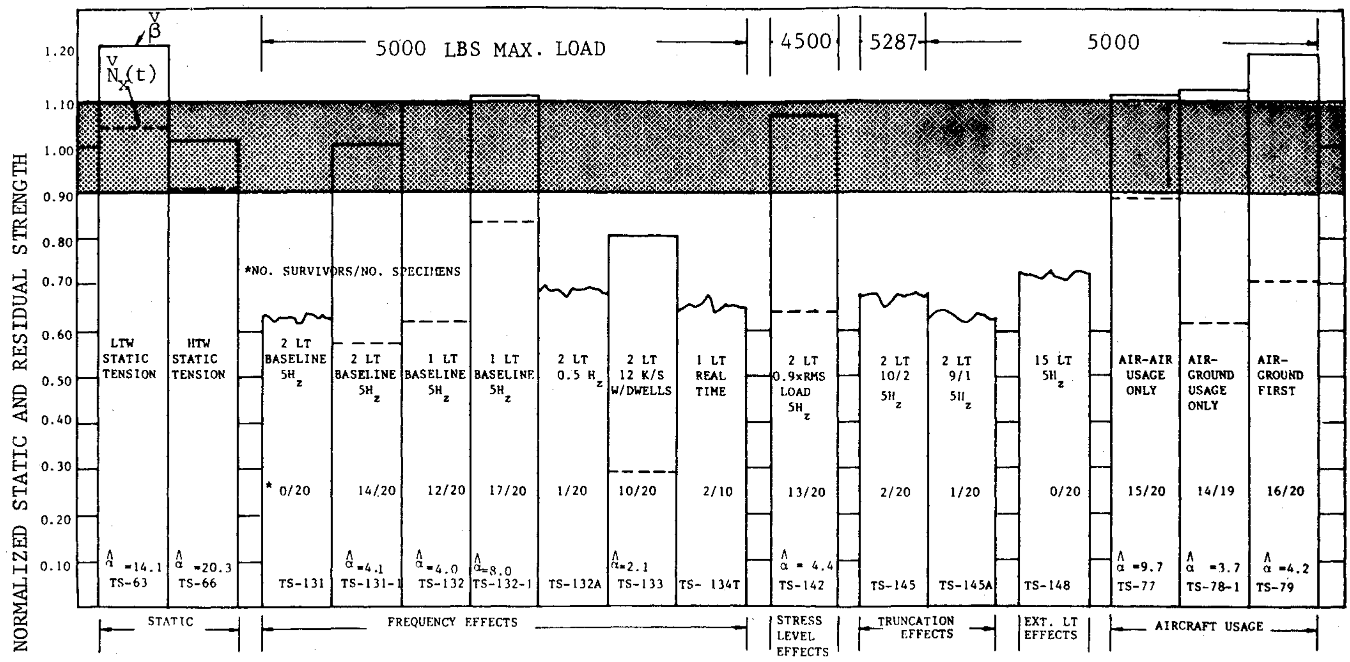

Fig. 9 Summary of parametric residual strength for the step-lap joints in tension (MPTW).

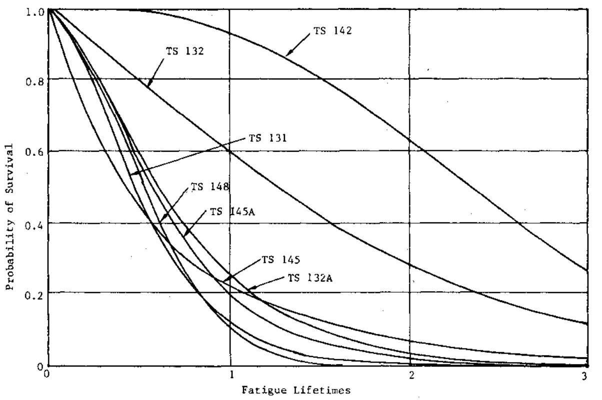

Fig. 10 Fatigue failure data for MPTW, M&P: A-bonded specimen in tension.

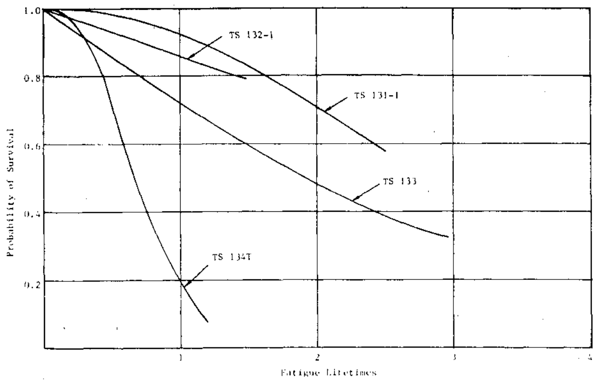

Fig. 11 Fatigue failure data for MPTW, M&P: B-bonded specimen in tension.

Bolted Joint Data

A summary of the tension fatigue residual strength data in bar graph form is shown in Fig. 12 for MPTW bolted joints. Similar data were also developed for the RTD and RTW environments; however, the results were essentially the same. Data in these bar charts are normalized to the appropriate fatigue baseline $\tilde{\beta}$ value, and to the quality control $\tilde{\beta}$ values¶ similar to the approach used in bonded joint data reduction, discussed above. Unlike the step-lap bonded joint experience, no fatigue failures occurred within the composite portion of the bolted joint specimens during the entire test program. Only an occasional steel loading block failed during the RTD and RTW 15-lifetime tests. This was not unexpected since composite bolted joints are known to be fairly insensitive to tension-dominated fatigue loading at normal operating loads. However, such joints had never previously been evaluated in the type of severe environments used in this program, i.e., real-flight-time load and temperature, and 15 lifetimes of accelerated fatigue at 70% of the "B-basis" static strength in a −20 to +250°F cold-hot wet environment. Specimen strength variation within a bolted joint fabrication panel gave a ±4% scatter band that was used about the baseline $\tilde{\beta}$ value.

Summary and Conclusions

Considerable data are available as a result of this study to aid in determining which spectrum parameters may be considered critical in developing an accelerated test scheme. Although it was not the purpose of this program to develop such a test scheme, the following summarizes the major conclusions regarding the effect of these parameters on spectrum testing and design of advanced composite joints representative of fighter aircraft composite structure.

Fiber-Dominated Bolted Joints

1) Net tension failure of fiber-dominated bolted joints (54% 0-deg fibers)** is not sensitive to accelerated testing in any of the environments investigated (RTD, RTW, MPTW). Thus this type of joint may be tested, accelerated, in any environment (up to 250°F).

2) A 10% knockdown factor applied to the 95% confidence scale parameter ($\tilde{\beta}$) for the B-basis static strength

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¶It should be noted that large strength scatter was observed in these quality control values resulting from a composite prepreg batch-to-batch fiber strength variation of ±16% from the mean.

**In the 48-ply built-up bolt hole section. There are 59% 0-deg fibers in the 27-ply laminate section.

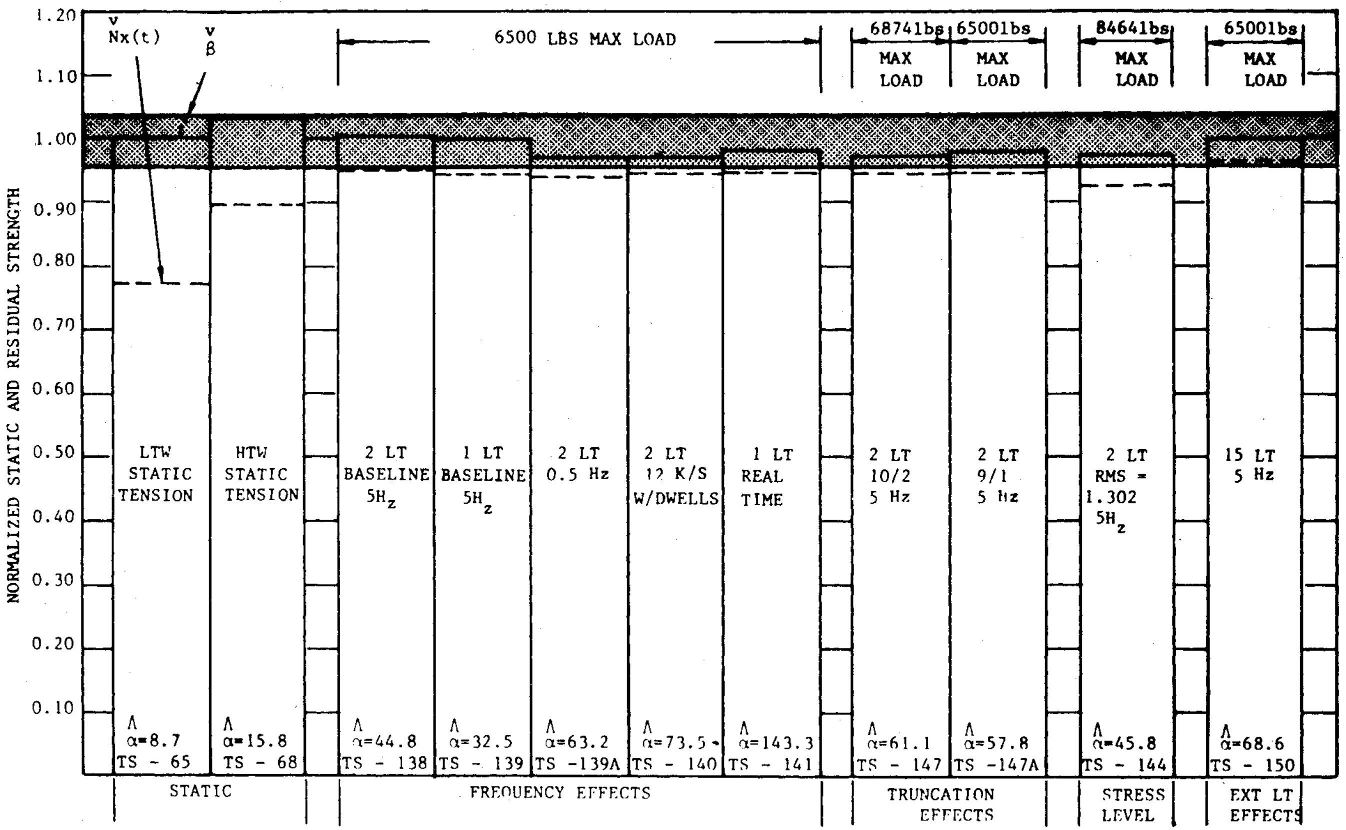

Fig. 12 Summary of parametric residual strength for bolted joints in tension (MPTW).

design is sufficient to account for all fatigue load and environmental effects for specimens fabricated from a single prepreg batch. When two or more prepreg batches are included, a factor of approximately 20% is required, unless it is definitely known that batch-to-batch prepreg strength, i.e., fiber strength, variations are equivalent to variations within a single batch.

3) No significant differences in parametric effects were observed on residual strength in scaled-up specimens when compared to similar effects in standard size specimens. No other detrimental effects due to scale-up were observed.

Matrix/Adhesive-Dominated Bonded Joints

The failure modes in the step-lap bonded joint were dominated by cohesive failure of the adhesive system. However, an appreciable percentage of the failure mode was interlaminar shear failure of the laminate (matrix failure). Also interlaminar shear in the laminate was the principal mechanism for axial load redistribution as the failure progressed through the joint. Thus the measured fatigue sensitivities of the joint reflect the combined influence of both the adhesive and laminate (matrix/fiber system).

Each of these two materials and their related failure modes would very likely display a different degree of spectrum sensitivity when evaluated individually. However, it would be reasonable and prudent to assume, in developing accelerated test methods for durability critical structure, that matrix-dominated laminates (less than 10% 0-deg fibers), will be sensitive to the same spectrum parameters as observed herein in the step-lap bonded joint.

Accelerated testing of the joint adhesive- and laminate-matrix-dominated composite joints may need to consider a fairly realistic representation of the following spectrum loading and environmental parameters.

1) *Time at load:* There are indications that load dwell (analogous to a sustained load flight maneuver), waveform, and/or real-flight-time-type loading effects may be more detrimental in this type of structure than accelerated sinusoidal fatigue loading. Real-flight-time fatigue life was reduced by factors of from 5 to 10 over 5-Hz accelerated testing.

2) *High load clipping:* Care should be exercised in selecting the maximum load in the test spectrum. When the peak load was increased from 12 occurrences of 9.0*g* per lifetime to one occurrence of 10.5 *g* per lifetime, both residual strength and fatigue life decreased substantially in the RTW environment.

3) *Moisture:* The addition of moisture (RTW) to the specimen reduced residual strength from 17 to 30% and increased the number of fatigue failures about 40% in tension- and compression-dominated fatigue testing.

4) *Stress level variations:* A 10-20% change in stress level will change the fatigue life by a factor of about 5. This is a fairly consistent ratio regardless of the environment.

Accelerated testing of adhesive- and laminate-matrix-dominated composite joints was found *not* to be particularly sensitive to the following:

1) *Linear frequency changes:* Varying the cyclic frequency linearly without changing loading waveform was not found to significantly effect residual strength or fatigue life except to a minor degree in the RTW condition.

2) *Low load truncation:* There is no clear indication of an effect from truncating low load factors in the range 0.5-2*g* in any of the environments investigated. An appreciable reduction in residual strength and fatigue life observed in the RTW environment was attributed to excessive moisture in these specimens.

3) *Aircraft usage:* There is no reduction in fatigue life or residual strength if the usage is all air-air, all air-ground, or all air-air flights occur first in a mixed usage. This assumes the design load is the same in all cases.

4) *Scale effects:* No significant differences were observed in residual strength or fatigue life effects in scaled up specimens when compared to similar effects in standard size specimens.

Design Certification Considerations

Although some substantial fatigue sensitivities were observed in the step-lap bonded joint spectrum parameters discussed above, there is not overwhelming evidence in favor of real-time certification testing of large complex adhesive- or matrix-dominated composite structure. The following are reasonable, standard design approaches that may be adequate to compensate for all or most of these effects.

1) The minimum design load levels indicated by the fatigue results were higher than those based on static strength criteria (in a given environment). Thus, designing to the static requirements may cover the fatigue requirements for the temperature/load combinations investigated in this program. For example, step-lap bonded joint average bondline stresses are rarely designed to exceed 1500 psi ultimate in practical applications. This is well under the 2150-psi fatigue design maximum indicated by this program.

2) The fatigue "knockdown factors" were fairly consistent and may be predictable with sufficient confidence to allow the demonstration of certification compliance to take place in an accelerated environment. The residual strengths measured at the completion of this accelerated test must then be sufficient to offset the design knockdown factors used to account for environment effects not represented in the test.

3) If real-time fatigue testing is deemed necessary, small specimen or element testing is sufficient to represent large complex structures.

Acknowledgment

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