JOURNAL OF AIRCRAFT
Vol. 30, No. 2, March–April 1993

Generation of MIL-HDBK-5 Design Allowables for Aramid/Aluminum Laminates

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ARALL® laminates are the first commercial members of a family of fibrous-metal structural laminates featuring high strength, low density, and high resistance to fatigue and fracture. (ARALL is a registered trademark for ALCOA and AKZO.) These materials are bonded arrangements composed of alternating layers of thin aluminum sheet and epoxy adhesive impregnated with strong aramid fibers. Consideration of ARALL laminates for aerospace applications will require the generation of basic strength property design allowables. This article presents results of a program conducted to establish ARALL laminate design allowable information based on modified MIL-HDBK-5 procedures. Experimental and analytical practices employed to obtain *S*-basis minimum properties for tension, compression, in-plane shear and bearing are described. Observations on specimen failure modes for the individual property determinations are presented.

I. Introduction

ARALL laminates are a new family of structural materials developed for fatigue critical applications requiring light-gauge sheet.[1-8] These materials are bonded arrangements of thin aluminum alloy sheets and alternating plies of epoxy-adhesive impregnated with unidirectional aramid fibers (Fig. 1). The principal benefit of the resulting hybrid composites is their ability to impede and arrest crack growth caused by the component of cyclic loading aligned with the fibers (generally also the direction of greatest tensile stress). Once a through-thickness fatigue crack develops in the aluminum layers, controlled delamination between the fiber/epoxy interfaces accommodates stress redistribution from the metal to unbroken fibers in the crack wake. The bridging provided by the strong aramid fibers constrains crack opening, thereby reducing the driving force for metal crack advance.[1,2,9] Effects of temperature and strain rate on the tensile properties of ARALL laminates have been extensively reported by Wu.[10-13]

Though originally developed for fatigue resistance, ARALL laminates display a range of impressive—albeit directional—property improvements over those of monolithic high-strength aluminum, and they feature performance traits that compete with those of advanced composites.[1-13] These attractive characteristics include 15–20% lower density than aluminum; up to 60% higher strength than 7075 and 2024 aluminum at comparable stiffness; fabricability comparable to metal (e.g., the material can be cut, sawed, drilled, joined, and inspected by conventional practices for metal); resistance of the outer metal layers to fiber-resin system damage by moisture, thermal attacks, lightning strike, and impacts; and damping ability superior to monolithic aluminum. Envisioned aircraft usages include tension-dominated fatigue and fracture critical structures (e.g., lower wing and fuselage skins), damping critical structures, lightning-strike areas, fire walls, and structure requiring resistance to impacts, where attendants trade studies have identified potential for significant (15–40%) weight savings over current designs.[3-6,14-20] Since October 1987, ARALL laminates have been utilized in the lower wing of a Fokker-50 prototype commercial transport aircraft,[17] and Fokker[20] and other airframers are evaluating the material for broader aircraft use. In addition, ARALL laminates have been applied to the large cargo door of the C-17 military transport developed by Douglas Aircraft Company.[21,22] The orthogonal properties of ARALL laminates are well-suited to handle the circumferentially oriented cabin pressurization stresses with a resultant 23% weight savings over an all-aluminum cargo door construction.

ARALL laminates exhibit the plasticity, inspectable damage (e.g., cracks and dents), and repair characteristics of metals. These characteristics, plus the economic considerations of a new material introduction, have led some airframe designers to conclude that ARALL laminates material qualification and structural integrity philosophies should align more closely with those of metals than those of traditional composites. As such, a design prerequisite for ARALL laminates introduction to service is development and presentation of minimum mechanical property allowables consistent with the format of the Military Standardization Handbook, MIL-HDBK-5.[23] This handbook is the primary source of design mechanical properties for metallic structural materials, and its use is mandated in the design of aerospace vehicles controlled or pro-

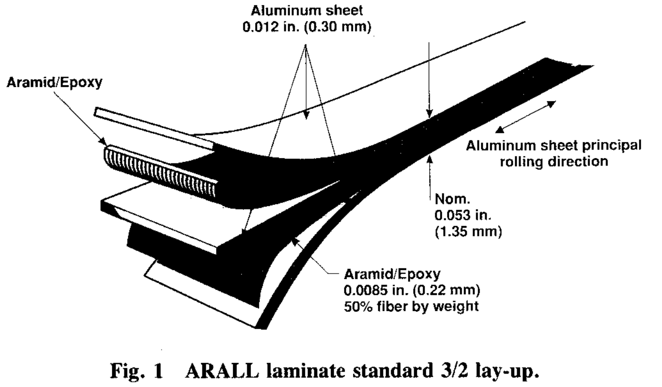

Fig. 1 ARALL laminate standard 3/2 lay-up.

Received Sept. 22, 1991; revision received Feb. 3, 1992; accepted for publication Feb. 18, 1992.

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cured by Department of Defense (DoD) agencies, the Federal Aviation Administration (FAA), and the National Aeronautics and Space Administration (NASA). This article describes the methodology and results from a pilot study conducted to produce ARALL laminates tension, compression, shear, and bearing property allowables in the statistical basis format required for MIL-HDBK-5 incorporation.

II. Material Statistical Design

ARALL laminates property combinations can be modified by varying the fiber-resin system, the aluminum alloy(s) or sheet gauge, ply arrangement, and the degree of post-cure mechanical stretch. ARALL 1 and 3 laminates are given a nominal 0.4% permanent stretch to reverse the residual stress state to compression in the aluminum layers and tension in the higher-strength aramid fibers. Although many possibilities exist, the four product variants listed in Table 1 have been standardized and are commercially available.[8] All are fatigue resistant with good static strength as compared to conventional aluminum alloy sheets. A 3/2 lay-up (i.e., three layers aluminum alloy sheet and two layers prepreg) is shown in Fig. 1; however, multiple lay-up possibilities (e.g., 2/1, 3/2, 4/3, 5/4, . . .) are available as commercial sheet products. Considering that individual aluminum plies are 0.012 in. (0.3 mm) nominal thickness and the prepreg nominal thickness is 0.0085 in. (0.2 mm), the nominal laminate gauges metal volume fraction and densities are as follows:

Lay-up	Laminate nominal gauge, in. (mm)	Metal volume fraction	Density, lb/in.^{3} (g/cm^3)
2/1	0.032 (0.81)	0.738	0.085 (2.35)
3/2	0.053 (1.35)	0.679	0.083 (2.30)
4/3	0.074 (1.88)	0.653	0.082 (2.27)
5/4	0.094 (2.39)	0.638	0.081 (2.24)

Density was determined using a micrometrics model HP1330 Accupyc pycnometer.

Volume fraction is the fractional quantity of aluminum alloy sheet per unit of laminate volume. For this pilot study, the development of ARALL laminate mechanical property allowables was confined to 2/1, 3/2, 4/3, and 5/4 lay-ups of the ARALL 3 product variant. The statistical effect of lot-to-lot variability on design allowable properties was addressed by the program experimental design, which consisted of 16 lots of production scale ARALL 3 laminate sheet, 90 in. × 52 in. (229 cm × 132 cm). A lot is defined as laminate(s) made from aluminum of one heat treated lot, one aluminum surface pretreatment lot, one aramid/epoxy prepreg lot, and one autoclave cure cycle. The 16 laminate lots were fabricated from three aluminum alloy sheet lots, five aramid/epoxy prepreg lots, two aluminum surface treatments (chromic acid and phosphoric acid anodizing), and four autoclave curing cycles according to the experimental design shown in Table 2.[20] Replicated specimens from each laminate sheet lot were tested for the purpose of developing *S*-basis MIL-HDBK-5 tension, compression, in-plane shear, and bearing design allowable properties.

Table 1 ARALL laminate commercial product forms[a]

Product variant	Description	Characteristics
ARALL 1	Alloy: 7475-T61[b] 250°F (121°C) cure prepreg[c] 0.4% permanent stretch	Superior fatigue High strength
ARALL 2	Alloy: 2024-T3[b] 250°F (121°C) cure prepreg[c]	Excellent fatigue Increased formability Damage tolerance
ARALL 3	Alloy: 7475-T761[b] 250°F (121°C) cure prepreg[c] 0.4% permanent stretch	Superior fatigue Controlled toughness Exfoliation resistance High strength
ARALL 4	Alloy: 2024-T8[b] 350°F (177°C) cure prepreg[c]	Excellent fatigue High temperature

[a]Also produced in a one or two surface clad condition for added corrosion protection.
[b]Aluminum bonding surfaces anodized and primed.
[c]Epoxy-adhesive prepreg 50% by weight unidirectional aramid fibers; bonded prepreg has fibers parallel to aluminum sheet principal rolling direction.

Table 2 Statistical design matrix for ARALL 3 laminate design allowable program

Panel no.[a]	Configuration	Surface treatment[b]	Lamination cycle[c]	Aluminum lot[d]	Prepreg lot[e]
1	2/1	C	1	1	5
2		C	2	2	4
3		P	3	1	1
4		P	4	3	3
5	3/2	C	2	1	2
6		C	3	3	5
7		P	4	2	1
8		P	1	2	4
9	4/3	C	3	1	3
10		C	4	3	1
11		P	1	2	2
12		P	2	3	4
13	5/4	C	4	1	4
14		C	1	3	2
15		P	2	2	3
16		P	3	2	5

[a]Each panel number represents a production scale lot.
[b]C, chromic acid anodizing; P, phosphoric acid anodizing.
[c]Panels from four time/temperature cycles.
[d]Three production lots of aluminum alloy used.
[e]Five aramid/epoxy prepreg lots used.

III. Testing Procedures

A. Primary Static Tests

In this program, the tension, compression, in-plane Iosipescu shear, and pin-type bearing tests were performed in sextuplet for each laminate lot/property/test direction/configuration. Ultimate strength, yield strength, elastic modulus, Poisson's ratio, and density measurements were made on each configuration and in each test direction. All of the testing procedures were based on ARALL laminate testing procedures as described in Ref. 24. The tension, compression, and bearing test procedures were consistent with conventional MIL-HDBK-5 test procedures used for aluminum sheet materials. The Iosipescu shear test[25,26] was considered to be more meaningful than the blanking shear test traditionally used for monolithic aluminum sheet.[24]

B. Fractography Study

The failures from each type of test were examined under the scanning electron microscope, and predominant failure modes were identified.

IV. Methodology for Determining *S*-Basis Design Allowables

A. Definitions of Design Allowables

MIL-HDBK-5E[23] has defined the following room-temperature design allowables:

1) At least 99% of the population of values is expected to equal or exceed the A-basis mechanical property allowable, with a confidence of 95%; (A-basis).

2) At least 90% of the population of values is expected to equal or exceed the B-basis mechanical property allowable, with a confidence of 95%; (B-basis).

3) The *S* value is the minimum value specified by the governing federal, military, or industry specification for the ma-

terial. Statistical assurance associated with this value is not known; (S-basis).

4) The typical property value is an average value and has no statistical assurance associated with it; (typical basis).

The mechanical properties presented as room-temperature design allowables are listed as follows:

Property	Minimum value	Typical value
Tensile ultimate strength, ksi	F_{tu}	TUS
Tensile yield strength, ksi	F_{ty}	TYS
Compressive yield strength, ksi	F_{cy}	CYS
Shear ultimate strength, ksi	F_{su}	SUS
Shear yield strength, ksi	F_{sy}	SYS
Bearing ultimate strength, ksi	F_{bru}	BUS
Bearing yield strength, ksi	F_{bry}	BYS
Total strain at failure	ε_t	Strain at failure

The mechanical property symbols listed above are followed by one of the following symbols: *L*, longitudinal direction (in this case parallel to the principal direction of the aramid fibers); or *LT*, long-transverse direction (in this case perpendicular to the principal direction of the aramid fibers) with fiber direction aligned parallel to the principal rolling direction of the aluminum sheet. In addition, the tensile modulus E_t, compressive modulus E_c, shear modulus G, Poisson's ratio μ, and laminate density ω are presented on a typical basis.

B. Computation of Design Allowable Properties

Direct computation of design allowables requires many tests for all properties. For instance, A and B allowables require adequate data to determine 1) the distribution form; and 2) reliable estimates of the population mean and standard deviation (if the data conform to a normal distribution) or reliable estimates of population threshold, shape, and scale parameters (if the data conform to a Weibull distribution). Determination of A and B allowable values in accordance with MIL-HDBK-5 requires at least 100 individual observations if the distribution is known, and 300 individual observations if the distribution is not known (i.e., nonnormal and nonWeibull). Because of these substantial data requirements, the current program focused only on the development of S-basis allowables. As additional data become available, the S-basis numbers will be upgraded to A- or B-basis allowable values.

In this study a modified reduced ratio computational procedure of MIL-HDBK-5 based on the metal volume fraction approach was used for the determination of design allowables. Each derived property was determined by its relationship to an established tensile property. S-basis minimum tensile properties, established in AMS 4302A, served as the established tensile properties.

The modified reduced ratio procedure involves pairing of individual SUS and BUS measurements with TUS measurements for which the S-basis F_{tu} has been established. It also involves pairing of individual CYS, SYS, and BYS measurements with TYS measurements for which the S-basis F_{ty} has been established. This technique is based on the premise that the mean ratio of paired observations of related properties estimates the ratio of corresponding population means. The ratio consists of individual measurements of property to be derived as the numerator and measurement of the established tensile property as the denominator. Thus, TUS or TYS in the specified testing direction always appears in the denominator of the ratio of observed values.

Three assumptions are required for the reduced ratio procedure as follows:

1) Both properties must be distributed according to a bivariate normal distribution.

2) The coefficient of variation must be the same for the two properties.

3) The average of the ratio of the two properties must be well-described by a linear function of the independent variable.

Regression analysis may be used to determine reduced ratios when an allowable for a property, such as CYS (LT), is computed indirectly from an already established allowable for TYS (LT) in the same test direction. The confidence level associated with allowables computed using the reduced ratio technique may be somewhat below 95%. To compute the reduced ratio at $x = x_0$, Eq. (1) is used

$$\text{Reduced Ratio} = a + bx_0 - t_{0.95}s_y\sqrt{(1 + \Delta)/n} \quad (1)$$

where Δ is defined as $\Delta = [(x_0 - \Sigma\, x/n)^2]/[\Sigma\, (x - \Sigma\, x/n)^2/n]$, n is number of ratios, s_y is the standard deviation of the ratios, a, b, and s_y are computed in regression of CYS (LT)/TYS (LT) data, and $t_{0.95}$ is selected from the statistical table of t-distribution corresponding to n-2 DOF.[23] In this case x_0 refers to a specific volume fraction rather than thickness. The allowable for CYS (LT), F_{cy} (LT) at x_0 is then computed as

$$F_{cy}\,(\text{LT}) = (\text{Reduced Ratio}) \times F_{ty}\,(\text{LT}) \quad (2)$$

V. Results and Discussion

A. Density

Due to the low density of the aramid prepreg layers, the net density of ARALL laminates is less than that of monolithic aluminum. The plot of Fig. 2 shows that increasing laminate thickness (or decreasing aluminum volume fraction) by increasing the number of plies reduces the density to an asymptotic limit of about 80% that of solid aluminum.

B. Tension

Typical tensile stress-strain behavior for the 3/2 configuration of the ARALL 3 laminate is plotted in Fig. 3. Figure 4 shows the relation between tensile strength and metal volume fraction for both the L and LT test directions. The ARALL 3 laminate tensile ultimate strength in the longitudinal fiber direction is significantly greater than that of its aluminum constituent [e.g., TUS = 79 ksi (545 MPa) and TYS = 69 ksi (476 MPa) for 0.063-in. (1.6-mm) thick 7475-T761 aluminum-alloy sheet]. In contrast, Fig. 4 shows that fibers contribute little to the transverse properties, revealing the anisotropic nature of ARALL laminates. The tensile yield properties are linked to the plastic strength of the metal layers. The higher longitudinal tensile yield strengths over the monolithic material are, in part, attributed to aluminum strain hardening during the postcure mechanical stretching and, in part, due to the poststretch residual compression in the metal layers.[7,8] Because the unidirectional fibers dominate the longitudinal tensile behavior, longitudinal tensile strength increases as the metal volume fraction decreases. Fibers contribute little to transverse tensile properties, and consequently trans-

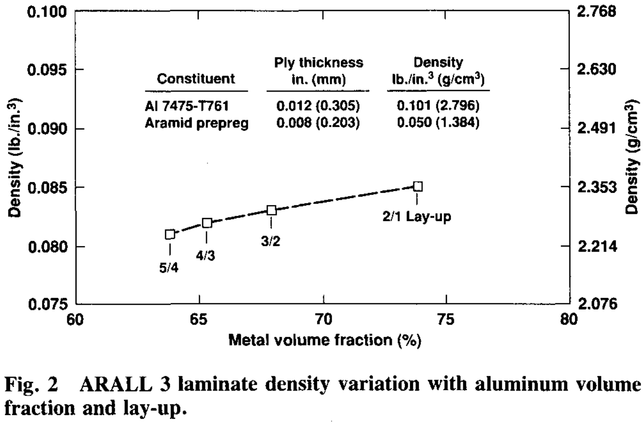

Fig. 2 ARALL 3 laminate density variation with aluminum volume fraction and lay-up.

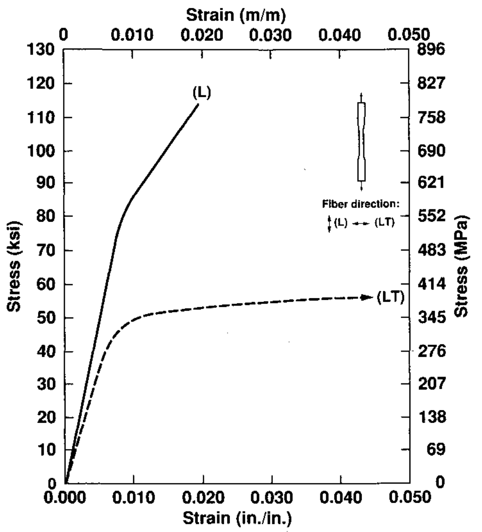

Fig. 3 Typical room temperature tensile stress-strain curves for 3/2 ARALL 3 laminate.

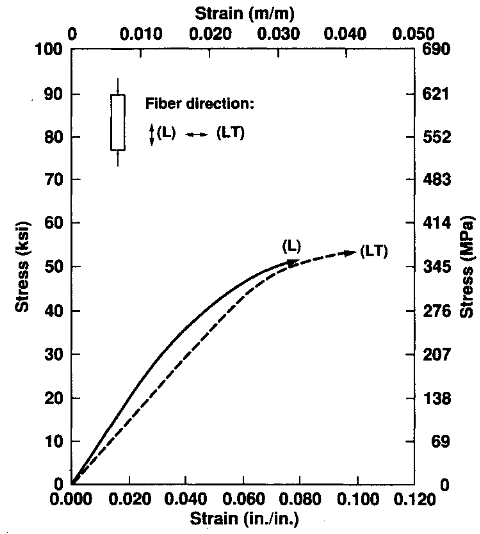

Fig. 5 Typical room temperature compressive stress-strain curves for 3/2 ARALL 3 laminate.

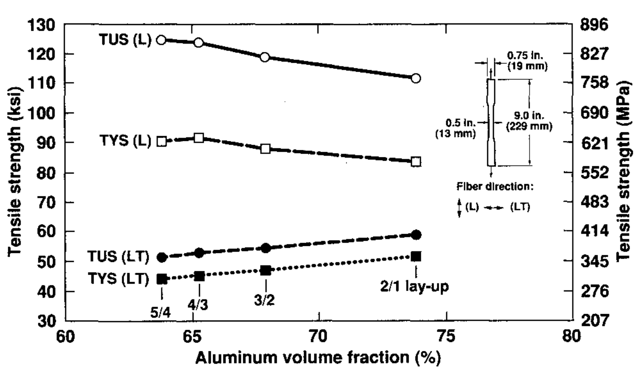

Fig. 4 ARALL 3 laminate tensile strength variation with aluminum volume fraction and lay-up.

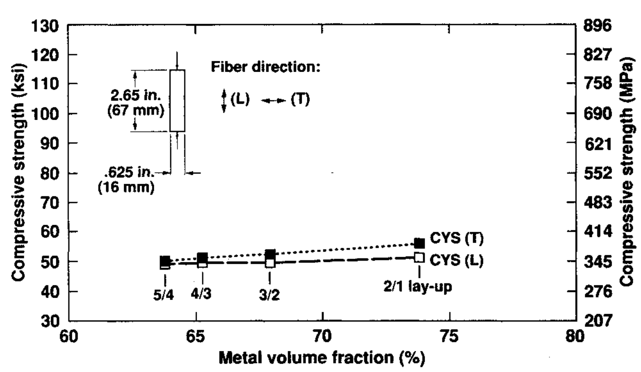

Fig. 6 ARALL 3 laminate compressive strength variation with aluminum volume fraction and lay-up.

verse tensile strength increases with increasing metal volume fraction. This is because the transverse properties are matrix or aluminum dominated.

C. Compression

Typical compressive stress-strain curves of the 3/2 configuration are given in Fig. 5. The longitudinal and transverse compressive yield strengths are comparable since the fibers contribute little in compression. The compressive yield strength in both the longitudinal and transverse directions increases as the metal volume fraction increases, as shown in Fig. 6. This indicates that the compressive properties are predominantly controlled by the metal.

D. Shear

Historically, much of the thin-aluminum-sheet data appearing in MIL-HDBK-5 was developed by the blanking (punch) shear test method. However, the in-plane Iosipescu shear test[25,26] is more meaningful than the punch test and has been used for the ARALL laminate shear mechanical property determinations. The longitudinal shear property is defined as the fibers running parallel to the long axis of the Iosipescu shear specimen which is perpendicular to the direction of loading. Consistent with this, the transverse shear property is defined as the fibers running parallel to the short axis of the specimen which is parallel to the loading direction. Typical in-plane shear stress-strain behavior for 3/2 ARALL 3 laminate is shown in Fig. 7. The shear yield strength in both the longitudinal and transverse directions increases as the

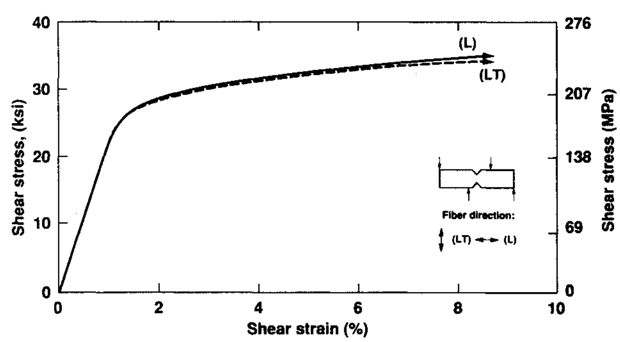

Fig. 7 Typical Iosipescu in-plane shear stress-strain curves for 3/2 ARALL 3 laminate.

metal volume fraction increases, as shown in Fig. 8. The shear ultimate strength in the transverse direction has the same trend also plotted in Fig. 8. The shear ultimate strength in the longitudinal direction is not reported since plastic buckling often preceded failure in shear. In other cases the test exceeded the range of travel of the test fixture. The shear yield strengths were determined as the shear yield strength at 0.2% offset from load-displacement curves.

E. Bearing

In the pin-loaded bearing tests, edge distance ratios (e/D) equal to 1.5 and 2.0 were performed. All bearing tests were

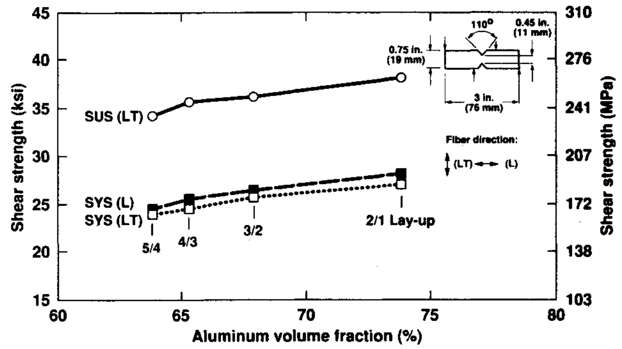

Fig. 8 ARALL 3 laminate in-plane shear strength variation with aluminum volume fraction and lay-up.

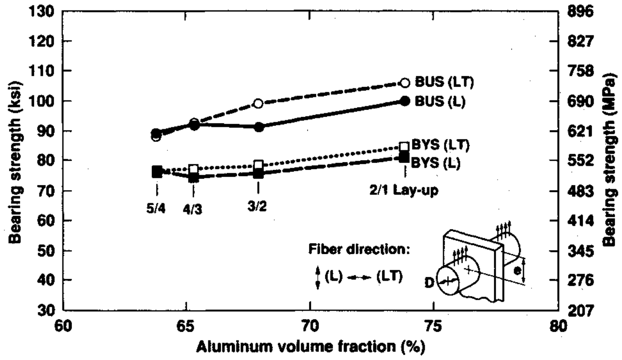

Fig. 9 ARALL 3 laminate pin-load bearing strength variation with aluminum volume fraction and lay-up (e/D = 1.5).

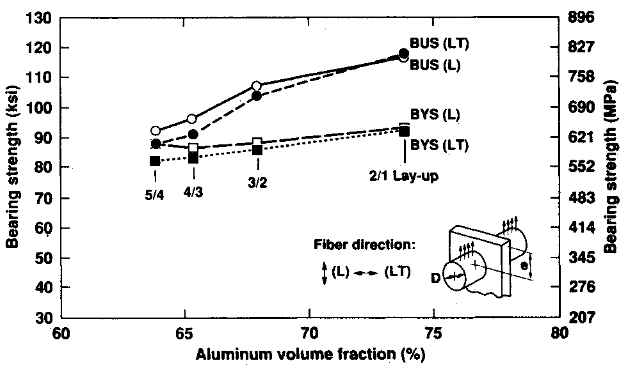

Fig. 10 ARALL 3 laminate pin-load bearing strength variation with aluminum volume fraction and lay-up (e/D = 2.0).

conducted in accordance with ASTM E 238-84,[27] which is applicable to conventional aluminum alloy products as described in MIL-HDBK-5.[23] The bearing strengths in both the longitudinal and transverse directions increase as the metal volume fraction increases. However, the bearing strengths decrease significantly from V_{AL} = 73.8% to V_{AL} = 67.9%. The bearing strengths remain almost constant from V_{AL} = 67.9% to V_{AL} = 63.8%. These plots are shown in Figs. 9 and 10.

F. Derived Property Allowables Determination

To determine if the mechanical property ratios were significantly influenced by sheet laminate thickness, linear-regression analyses were conducted. A computer program to perform this analysis was developed and linear-regression analyses of the mechanical property ratios vs volume fraction were conducted. All of the ratios except SUS(LT)/TUS(LT) and SYS(LT)/TYS(LT) were found to be significantly dependent on thickness. However, the hypothesis that the regression was linear was rejected for 8 of the 11 ratios that were significantly affected by thickness, as determined by analysis of variance tests to determine adequacy of the regression. Upon noting that relationship of sheet thickness to metal volume fraction is nonlinear, a metal volume fraction approach was presented and shown to be a better predictor of the mechanical property ratios than laminate thickness.

Typical mechanical property ratios vs aluminum volume fraction are shown in Figs. 11–14. All of the mechanical property ratios exhibited statistically significant regression (positive or negative) with increasing volume fraction. Regression was linear (hypothesis not rejected) for all of the compression

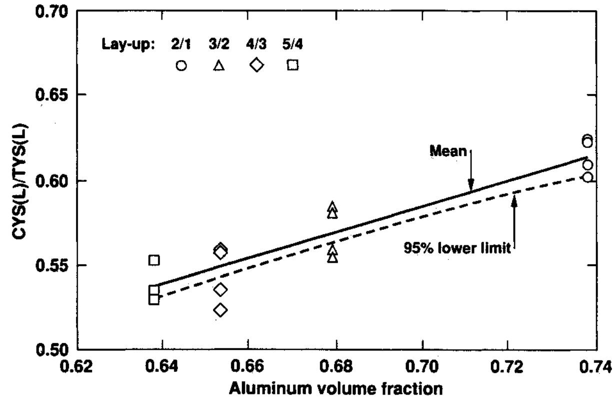

Fig. 11 ARALL 3 laminate compressive yield to tensile yield property ratios in the longitudinal direction.

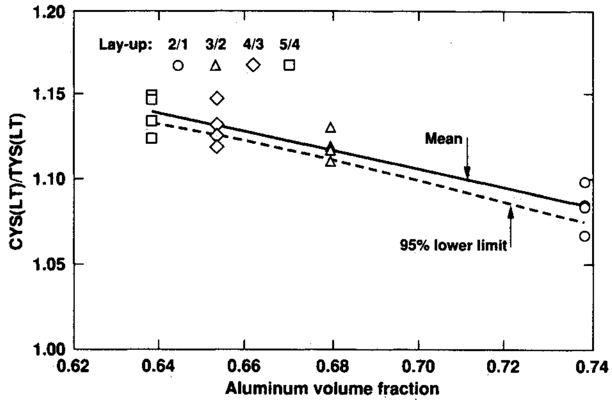

Fig. 12 ARALL 3 laminate compressive yield to tensile yield property ratios in the long-transverse direction.

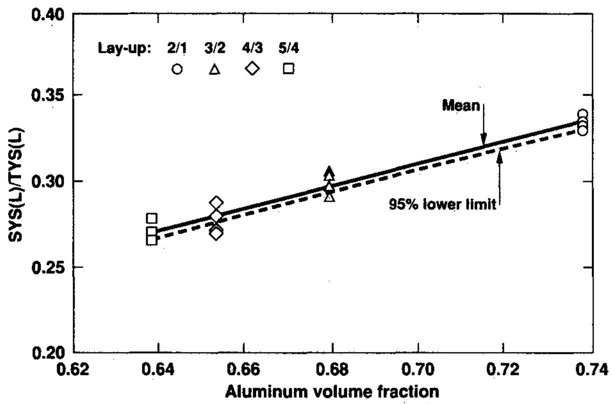

Fig. 13 ARALL 3 laminate shear yield to tensile yield property ratios in the longitudinal direction.

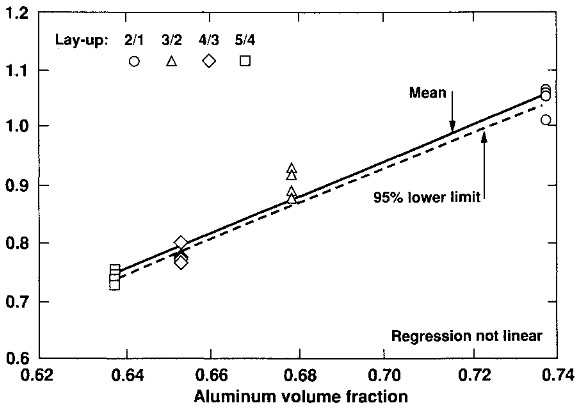

Fig. 14 ARALL 3 laminate bearing ultimate to tensile ultimate property ratios (e/D = 2.0) in the longitudinal direction.

and shear strength ratios but exhibited linearity for only two [BYS(LT)/TYS(LT), $e/D = 1.5$ and $e/D = 2.0$] of eight bearing ratios. Although volume fraction was a better predictor than thickness of bearing property ratios, design values determined by the reduced ratio method for the remaining six bearing strength conditions would have been in violation of MIL-HDBK-5 guidelines.

To generate a better fit to the bearing strength ratios, a second-order polynominal equation was used for regression of the reduced ratios as a function of metal volume fraction. A computer program was developed to perform the analyses. The results indicated that the quadratic equation did not significantly improve the fit of the curves for compression and shear strength ratios because these ratios still exhibited a linear regression as shown previously. Therefore, the analyses using the second-order polynominal equations defaulted to linear regression. Although the curves resulting from the quadratic equations did provide a better fit to the bearing strength data, the second-order polynominal equations were still rejected based on goodness of fit. Although design values computed using reduced ratios from the second-order polynominal equations would provide more reliable minimum properties than those from the linear regression, these design values when compared to actual bearing strength data were not acceptable. It is believed that higher (than second-order) polynominal equations would not provide realistic curves.

As a result, for establishing bearing property allowables, it was decided that the regression analysis procedure would be abandoned, and design allowables would be calculated for each lay-up. The only limitation to this approach was that mechanical property ratios were available for only four lots for each thickness (lay-up). Ten lots of material are normally required according to the guidelines of MIL-HDBK-5. However, preliminary design values computed from this direct analysis approach resulted in design values more consistent with average bearing strengths than those previously completed by regression.

The currently proposed design values for ARALL 3 laminates are presented in Table 3. Although some of the mechanical properties were based on regression analyses utilizing metal volume fraction, design values are listed according to the nominal thickness of the sheet laminate because this product will be specified and supplied by thickness.

Design values for compression and shear strengths were computed using the reduced ratios provided by linear regression. Design values for bearing strengths were calculated using the reduced ratios for each lay-up. Although the reduced ratios were determined from four lots compared to 10 required by the guidelines, it is believed that the reduced ratios are representative and reliable because the mechanical properties were determined from material which had been fabricated specifically for a test program scientifically designed to incorporate manufacturing variables such as surface treatment, lamination cycle, aluminum lot, and prepreg lot.[20] Also, six tests were conducted on each lot. Data for other thicknesses (lay-ups) were available so as to permit evaluation of the reasonableness of trends in the design properties.

Table 3 Design mechanical and physical properties of 7475-T761 aluminum alloy, aramid fiber reinforced, sheet laminate (ARALL 3 laminates)

Specification form	AMS 4302A Aramid fiber reinforced sheet laminate (ARALL 3 laminates)			
Laminate lay-up	2/1	3/2	4/3	5/4
Nominal thickness, in.	0.032	0.053	0.074	0.094
Basis	S	S	S	S
Mechanical properties:				
F_{tu}, ksi:	103	111	114	116
L	56	51	50	48
LT				
F_{ty}, ksi:				
L	76	82	82	84
LT	48	43	42	40
F_{cy}, ksi:				
L	46	46	44	44
LT	51	48	47	45
F_{su},[a] ksi:	35	33	33	32
F_{sy},[a] ksi:	24	23	22	21
F_{bru},[b] ksi:				
L (e/D = 1.5)	91	83	84	82
LT (e/D = 1.5)	96	85	86	80
L (e/D = 2.0)	104	87	88	84
LT (e/D = 2.0)	108	88	86	80
F_{bry},[b] ksi:				
L (e/D = 1.5)	73	70	66	69
LT (e/D = 1.5)	76	69	69	67
L (e/D = 2.0)	83	81	77	79
LT (e/D = 2.0)	84	76	75	72
ε_f,[c] %:				
L	1.5	1.8	1.7	1.8
LT	6.1	6.4	6.3	6.6
E, 10^3 ksi:				
L	9.8	9.9	10.0	9.8
LT	7.7	7.1	6.7	6.7
E_c, 10^3 ksi:				
L	9.6	9.6	9.6	9.7
LT	7.8	7.3	7.0	6.9
G, 10^3 ksi:				
L	2.8	2.6	2.3	2.3
LT	2.6	2.4	2.3	2.3
μ:				
L	0.35	0.35	0.35	0.35
LT	0.25	0.25	0.25	0.25
Physical properties:				
ω, lb/in.^{3}	0.085	0.083	0.082	0.081
C, K, and α	—	—	—	—

[a]Shear values determined from data obtained using Iosipescu shear specimens.
[b]Bearing values are "dry pin" values per section 1.4.7.1 determined in accordance with ASTM E 238.
[c]Total (elastic plus plastic) strain at failure determined from stress-strain curve.

The longitudinal bearing ratios are lower than those of conventional aluminum products, and longitudinal bearing strengths are lower than tensile strengths of conventional aluminum products. The predominant mode of failure for bearing specimens was "crushing," or out-of-plane deformation of the test hole. In a real structure the hole lateral constraint would be more than provided by the bearing fixture pin load arrangement. It is suggested that a modified bearing test procedure for aluminum sheet laminates be investigated with the goal of establishing a standard bearing test procedure representative of typical joined structural members. Perhaps the utilization of a washer or some type of confinement of the material adjacent to the test hole (similar to the composite bearing test procedure described in MIL-HDBK-17[28]) would provide higher bearing strengths and more nearly simulate production fastener installation (which normally provides constraint by a fastener head or washer) in sheet laminates. It is believed that the proposed longitudinal bearing design values (Table 3) which are based upon specimens tested in accordance with ASTM E 238-84 are conservative. Eriksson[29] has reported that using bearing specimens bolted laterally (with washers) can effectively distribute the bearing stress over a larger area than in a pin-loaded graphite/epoxy specimen, resulting in a higher bearing strength (2–4 times greater than pin-loaded results). Vogelesang[30] also used a modified ASTM D953-87 plastic bearing test procedure[31] to provide lateral side restraints for ARALL/GLARE grades. He found that using this set-up significantly increases bearing strengths.

For the shear design allowable properties, since the maximum difference in design values for F_{sy}(L) and F_{sy}(LT) was 1 ksi, design values for F_{sy} are not presented according to test direction. Design values for the grain direction (LT) exhibiting the lower strengths were used for F_{sy} design values.

G. Fractography Study

The photographs of failure modes encountered under the aforementioned property determinations are shown in Fig. 15. Longitudinal tension specimens typically show low ductility failure without the longitudinal splitting as to most other fibrous composites. Transverse tension specimens show epoxy tensile failure and fiber-matrix debonding/splitting. Very little kink band deformation[32] was observed from the compression test in the longitudinal direction. This is because the test only loaded to the 0.2% offset yield. In the in-plane Iosipescu shear test, fiber/matrix shear failures predominated in the transverse specimens. However, significant plastic deformations were observed in the longitudinal specimens which did not fail during test. Crushing failure is the predominant failure mode in the bearing test, however, evidence of shear failure and shear-tension failure are also exhibited in some longitudinal specimens. Bearing failure is caused primarily by the pin contact stress and occurs in the laminate immediately adjacent to the pin contact point. This pin-type loaded bearing test provided extremely conservative data.

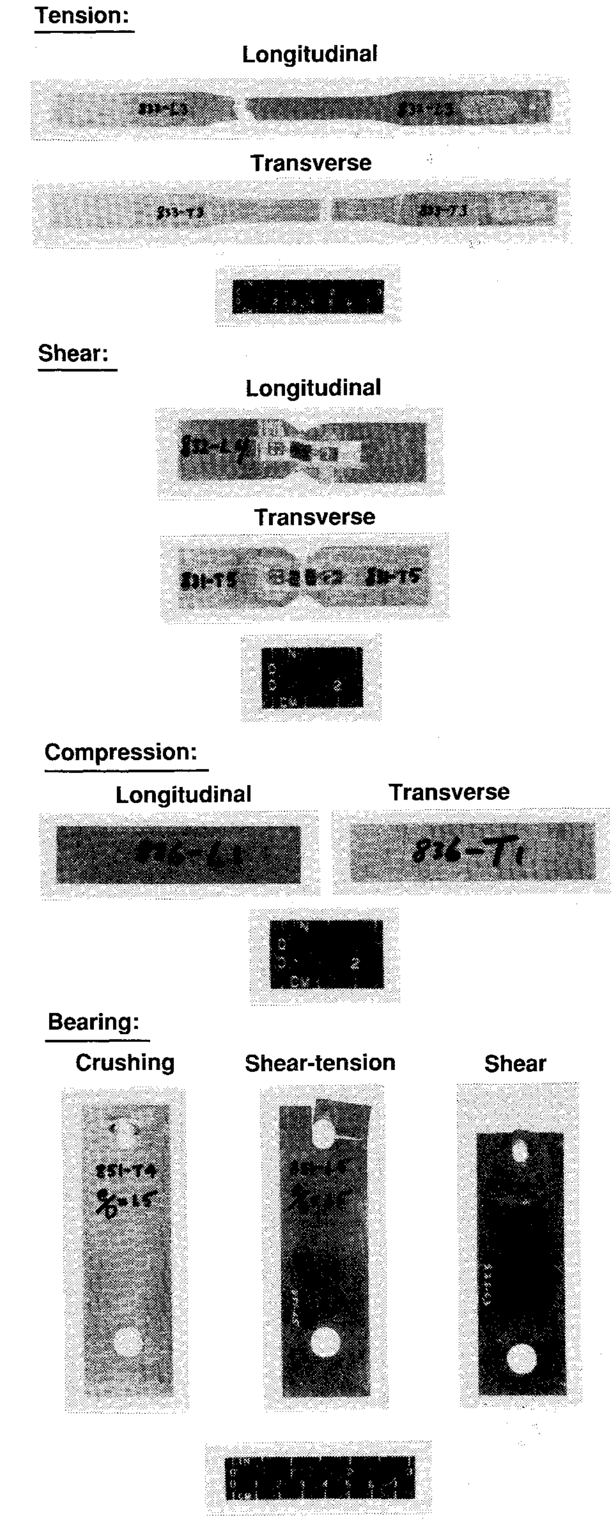

Fig. 15 Failure modes of MIL-HDBK-5 static strength test specimens.

VI. Conclusions

Previous investigators have amply shown the high fatigue resistance of the new fiber/metal laminates, ARALL. Application of ARALL requires the establishment of an allowable stress level for other mechanical properties. For that purpose a framework for generation of mechanical property *S*-basis allowables for ARALL laminates has been established. ARALL 3 laminate design allowables have been accepted for incorporation into a newly written Chapter 7 of MIL-HDBK-5, *Miscellaneous Alloys and Hybrid Materials*. This work sets precedent in that fiber/metal laminates represent the first emerging classes of hybrid materials to be incorporated into MIL-HDBK-5 as modified metals.

The present study also shows that a volume fraction approach is meaningful for the determination of future fiber-reinforced aluminum laminate property allowables. Failure mode observations corresponding to each type of mechanical tests conducted in the MIL-HDBK-5 design allowables test program are also reported.

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