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Pilot Study of Metal Volume Fraction Approach for Fiber/Metal Laminates

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This article presents results of a statistically designed program conducted to validate the feasibility of using the relationship of mechanical properties and metal volume fraction in fiber/metal laminates to make property predictions. Experimental and analytical practices employed to obtain these mechanical properties for tension, compression, in-plane shear, and bearing are described. Results from this pilot study conclude that the use of metal volume fraction may be useful for the prediction of strength mechanical properties in fiber/metal laminates. However, this needs further study to validate the concept. If the hypothesis is valid, the number of laminate configurations to be tested to qualify a fiber/metal laminate family can be minimized. The findings imply that a metal volume fraction approach using a rule-of-mixtures can be exploited to estimate design properties for a multitude of fiber/metal laminate variants, which is economically beneficial to preliminary stages of aircraft design.

I. Introduction

FIBER/METAL laminates are engineered materials composed of thin structural sheet metal plies alternatively bonded to plies of fiber-reinforced polymer. Such hybrid materials combine the best features of the metal and fiber-reinforced composite of which they are composed. Fiber/metal laminates retain the conventional workshop practices of metals, including damage inspectability.[1–12] These attributes alone dramatically reduce the implementation cost associated with the application of fiber/metal laminates. Fiber/metal laminates, ARALL (Kevlar® fiber-based aluminum laminates) or GLARE (S-2 glass fiber-based aluminum laminates), are particularly promising for aerospace structural applications, where the qualities of low weight,[13–15] high-strength/stiffness, and good damage tolerance are essential. In addition, fiber/metal laminates also exhibit good thermal stability in cryogenic and elevated temperature environments.[16–19]

Although ARALL 2 and ARALL 3 laminate design allowables[20–25] have currently been accepted for incorporation into a newly written chapter of MIL-HDBK-5, *Miscellaneous Alloys and Hybrid Materials*, the case of GLARE laminates is more complex due to their composite prepreg lay-up configurations. To enable the usage of GLARE laminates in multiple applications in aerospace industry, especially for fuselage application, it is necessary to qualify a broad family of fiber/metal laminates according to MIL-HDBK-5 requirements. However, if the qualification procedure is based on the testing of an individual configuration, financial constraints will limit the number of configurations that can be qualified. A possible solution for this dilemma is the applicability of the metal volume fraction approach using the rule-of-mixtures (ROM) to predict properties. If the hypothesis of this pilot study is correct, then the MIL-HDBK-5 design properties of different laminate configurations can be predicted as a function of their metal volume fraction, the qualification of fiber/metal laminate family only requires a minimum testing effort on a few laminate configurations.

II. Theoretical Model

The hypothesis considered is that mechanical properties of hybrid laminates, such as ultimate strength and modulus, can be predicted by the ROM. In carrying out the analysis, individual identities of fiber and matrix are ignored. Each individual layer of laminate (aluminum alloy or composite layer) is treated as a homogeneous, orthotropic sheet, and the laminated hybrid material is analyzed using the classical theory of laminated plates. In this case, we consider continuous fibers that are perfectly elastic up to their breaking points. The matrix is assumed to be elastic-perfectly plastic (for metal). From the previous design allowable study, Wu et al.[22] have shown most of the mechanical properties of fiber/metal laminates are metal- (aluminum-) dominated linear properties. In addition, Slagter,[28] Wu and Slagter,[33] and Verolme[30] have also shown that the bearing and compression properties of the fiber/metal laminates can be predicted by the ROM. Thus, these predicted strengths through the general ROM are

For ultimate strength

$$\sigma_{\text{lam}} = V_{\text{al}} \times \sigma_{\text{al}} + (1 - V_{\text{al}}) \times \sigma_p \tag{1}$$

For Young's moduli

$$E_{\text{lam},11} = V_{\text{al}} \times E_{\text{al}} + (1 - V_{\text{al}}) \times E_p \tag{2}$$

or

$$1/E_{\text{lam},22} = V_{\text{al}}/E_{\text{al}} + (1 - V_{\text{al}})/E_p \tag{3}$$

For in-plane shear modulus

$$1/G_{\text{lam},12} = V_{\text{al}}/G_{\text{al}} + (1 - V_{\text{al}})/G_p \tag{4}$$

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where

σ_{lam} = laminate ultimate strength
σ_{al} = aluminum alloy ultimate strength
σ_p = cured composite prepreg ultimate strength
$E_{lam,11}$ = Young's modulus of the laminate in the longitudinal fiber direction
$E_{lam,22}$ = Young's modulus of the laminate in the long-transverse fiber direction
E_{al} = Young's modulus of the aluminum alloy
E_p = Young's modulus of the cured composite prepreg
$G_{lam,12}$ = shear modulus of the laminate in the 1-2 plane
G_{al} = shear modulus of the aluminum alloy
G_p = shear modulus of the cured composite prepreg
V_{al} = aluminum alloy volume fraction

III. Material and Experimental Design

A. Material

Laminate configurations of 2/1, 3/2, and 5/4 were considered. In definition, e.g., 3/2 GLARE 4 consists of three layers of 0.012-in.- (or 0.016-in.-) thick aluminum alloy sheets and two layers of 70/30 glass prepreg (with 70% of fibers in 0-deg orientation and 30% of fibers in 90-deg orientation in each glass prepreg). Each prepreg layer (0 deg/90 deg/0 deg) has a 0.015 in. thickness. A GLARE 4 laminate schematic representation is shown in Fig. 1. The use of GLARE 4 laminates allows the evaluation of biaxial laminates and will give maximum information for the longitudinal L and long-transverse LT testing direction. To examine the variability of the metal volume fraction approach, five panels of different laminate configurations were evaluated. Two standard aluminum alloy sheet thickness, 0.012 and 0.016 in., were used for controlling desired metal volume fraction. Type of lay-up, total laminate thickness, and metal volume fraction are listed in Table 1.

B. Experimental Design and Test Procedures

In this pilot study, static design properties were evaluated using a simple statistically designed experiment as described in Ref. 26. Mechanical property determinations include the tensile ultimate and yield strengths, compressive yield strength, in-plane shear yield strength, and bearing ultimate and yield strengths. In addition, tensile, compressive, and in-plane shear moduli are also of interest. In this experimental program quadruplicate tests were performed in both the L and LT directions and executed according to the run order provided in Ref. 26. Two randomizations were involved in carrying out these experiments. The first was the random assignment of the treatment variables to the specimens cut from each panel. This was done to guard against systematic variations in the properties of the material with position on the panel. The second randomization involved testing the samples in a random time order. This guarded against a systematic drift in the testing system with time. Tension, compression, and bearing tests were carried out in Delft University, and in-plane shear tests were performed at the Alcoa Technical Center.

In this program, specimen dimensions and testing methods for the tension, compression, and in-plane Iosipescu shear tests were performed based on ARALL laminates testing procedures as described in Ref. 27. And the bearing tests were according to the bolt-type bearing test procedure as described in a previous publication.[28]

Table 1 Material descriptions of GLARE 4 laminates

Lay-up	Total metal thickness, in.	Total laminate thickness,[a] in.	Metal volume fraction, %
2/1	2 × 0.016	0.047	68.09
3/2	3 × 0.016	0.078	61.54
3/2	3 × 0.012	0.066	54.55
5/4	2 × 0.012 3 × 0.016	0.132	54.55
5/4	5 × 0.012	0.120	50.00

[a]Each cross-ply 0 deg/90 deg/0 deg glass prepreg has a 0.015-in. thickness.

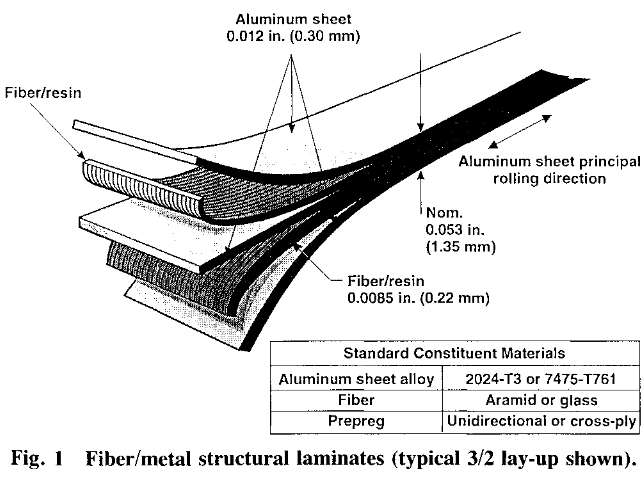

Fig. 1 Fiber/metal structural laminates (typical 3/2 lay-up shown).

IV. Results and Discussion

Metal volume fraction is the fractional quantity of aluminum alloy sheet per unit of laminate volume. A previous study[20–22] on the generation of MIL-HDBK-5 design allowables for fiber/metal laminates has shown the potential feasibility of laminate property as a function of volume fraction. In this study, metal volume fractions of 68.09, 61.54, 54.55 (with two different laminate configurations, 3/2 and 5/4), and 50.00% were considered.

A. Tension

Forty tensile specimens were tested to determine the values of the tensile ultimate strength, tensile yield strength, and tensile modulus. The data are summarized in Table 2. Results show that tensile strength and tensile modulus are linear functions of the aluminum alloy volume fraction. Tensile modulus can be predicted using the ROM, which is the addition of the tensile moduli of the constituents taking into account the thickness of the separate layers. Since the experimental data of cured glass prepreg are not available, the following back-calculated glass prepreg properties are used in this analysis (which assumes ROM applies): σ_p = 1507 MPa and E_p = 22.55 GPa in the L direction; and σ_p = 742 MPa and E_p = 12.43 GPa in the LT direction. For 2024-T3 aluminum alloy sheet, we use typical values of σ_{al} = 490 MPa and E_{al} = 73.5 GPa, taken from Ref. 29. A comparison between experimental and theoretical prediction from the ROM results of tensile strength and tensile modulus shows a good agreement as shown in Table 3. Typical tensile strength and modulus against metal (aluminum) volume fraction are plotted in Figs. 2–4.

B. Compression

Forty compressive specimens were tested to determine the values of the compressive yield strength and compressive modulus. In order to prevent buckling of compression specimen, several layers of GLARE were bonded together prior to testing. All the compression specimens including the unbonded ones were subjected to the same postcure thermal cycle. The data are summarized in Table 4. A good linear relationship has been shown to exist between the compressive yield strength and compressive modulus values and the aluminum alloy volume fraction. Compressive modulus can also be predicted by the ROM. The predicted values were obtained using the experimental data of compressive properties of aluminum alloy sheet and cured glass prepreg.[30] They are E_p = 38.7 GPa in the L direction and E_p = 25.4 GPa in the LT

Table 2 Summary of tension test results for GLARE 4 laminates

		Longitudinal			Long-transverse		
Lay-up	Metal volume fraction, %	TYS,[a] MPa	TUS,[b] MPa	E_t,[c] GPa	TYS,[a] MPa	TUS,[b] MPa	E_t,[c] GPa
5/4	50.00	324	965	51.31	227	616	43.35
	50.00	320	1019	49.69	229	619	40.92
	50.00	320	987	48.44	228	629	42.16
	50.00	318	1024	47.61	231	609	44.74
5/4	54.55	331	939	53.37	231	610	45.36
	54.55	325	958	50.54	235	609	50.07
	54.55	332	980	50.80	237	612	48.68
	54.55	345	960	48.40	231	604	45.82
3/2	54.55	315	924	53.78	231	623	43.73
	54.55	317	946	52.10	231	607	44.72
	54.55	317	961	48.68	[d]	[d]	[d]
	54.55	313	943	48.13	226	598	44.00
3/2	61.54	338	873	57.99	250	588	49.10
	61.54	334	884	51.23	244	596	49.19
	61.54	335	871	51.43	246	592	49.51
	61.54	330	885	51.78	246	[d]	59.65
2/1	68.09	338	817	55.19	252	566	52.05
	68.09	335	797	56.95	261	562	55.80
	68.09	348	830	55.76	254	558	51.25
	68.09	341	822	58.84	251	544	50.86

[a]TYS, tensile yield stength.
[b]TUS, tensile ultimate strength.
[c]E_t, tensile modulus.
[d]Extensometer was not activated during the test.

Table 3 Comparison between experimental and predicted tensile properties for GLARE 4 laminates

		Longitudinal					Long-transverse				
Lay-up	Metal volume fraction, %	TYS,[a] MPa	TUS_{exp},[b] MPa	TUS_{rom},[c] MPa	E_{exp},[d] GPa	E_{rom},[e] GPa	TYS,[a] MPa	TUS_{exp},[b] MPa	TUS_{rom},[c] MPa	E_{exp},[d] GPa	E_{rom},[e] GPa
5/4	50.00	321	999	998	49.26	48.03	229	618	616	42.79	42.97
5/4	54.55	333	959	952	50.78	50.34	233	609	605	47.48	45.74
3/2	54.55	316	944	952	50.34	50.34	229	609	605	44.15	45.74
3/2	61.45	334	878	881	53.11	53.90	247	592	587	51.86	50.01
2/1	68.09	341	817	815	56.69	57.24	255	558	570	52.49	54.01

[a]TYS, average experimental tensile yield strength.
[b]TUS_{exp}, average experimental tensile ultimate strength.
[c]TUS_{rom}, predicted tensile ultimate strength using ROM.
[d]E_{exp}, average experimental tensile modulus.
[e]E_{rom}, predicted tensile modulus using ROM.

Table 4 Summary of compression test results for GLARE 4 laminates

		Longitudinal		Long-transverse	
Lay-up	Metal volume fraction, %	CYS,[a] MPa	E_c,[b] GPa	CYS,[a] MPa	E_c,[b] GPa
5/4	50.00	315	55.70	265	51.47
	50.00	321	58.98	247	52.02
	50.00	306	58.47	262	51.03
	50.00	322	65.45	268	52.20
5/4	54.55	330	60.13	256	52.92
	54.55	321	59.71	263	54.36
	54.55	321	60.98	261	53.59
	54.55	329	54.66	263	50.86
3/2	54.55	312	60.11	272	57.14
	54.55	307	61.68	263	55.52
	54.55	307	59.16	272	54.32
	54.55	308	59.74	266	53.95
3/2	61.54	314	63.92	282	65.14
	61.54	316	67.00	280	61.93
	61.54	305	60.68	—	—
	61.54	300	65.66	277	57.60
2/1	68.09	306	70.32	294	63.29
	68.09	—	—	289	64.92
	68.09	297	73.18	291	63.45
	68.09	307	66.63	282	64.13

[a]CYS, compressive yield strength. [b]E_c, compressive modulus.

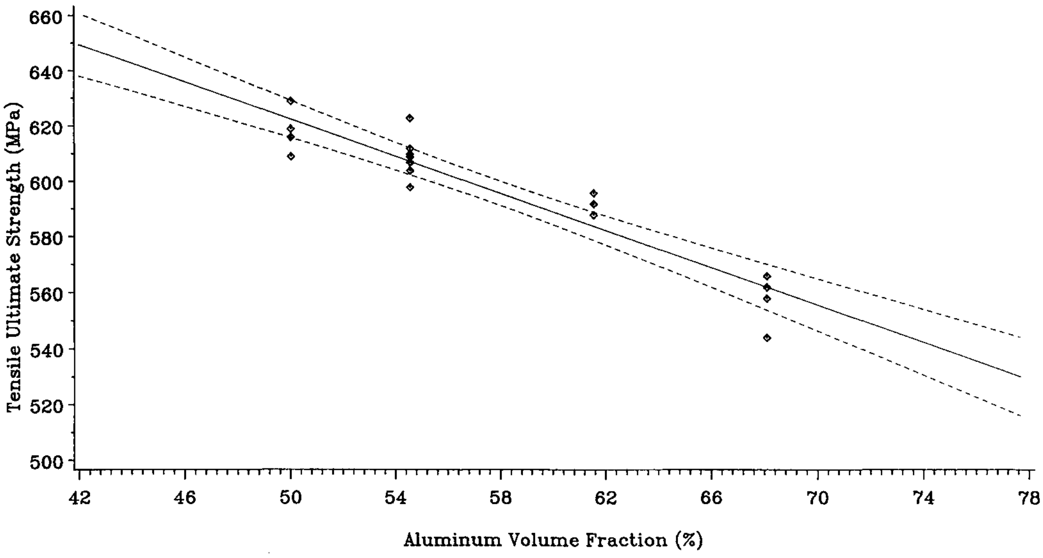

Fig. 2 Ninety-five percent confidence intervals for GLARE 4 laminate long-transverse tensile ultimate strength variation with aluminum volume fraction.

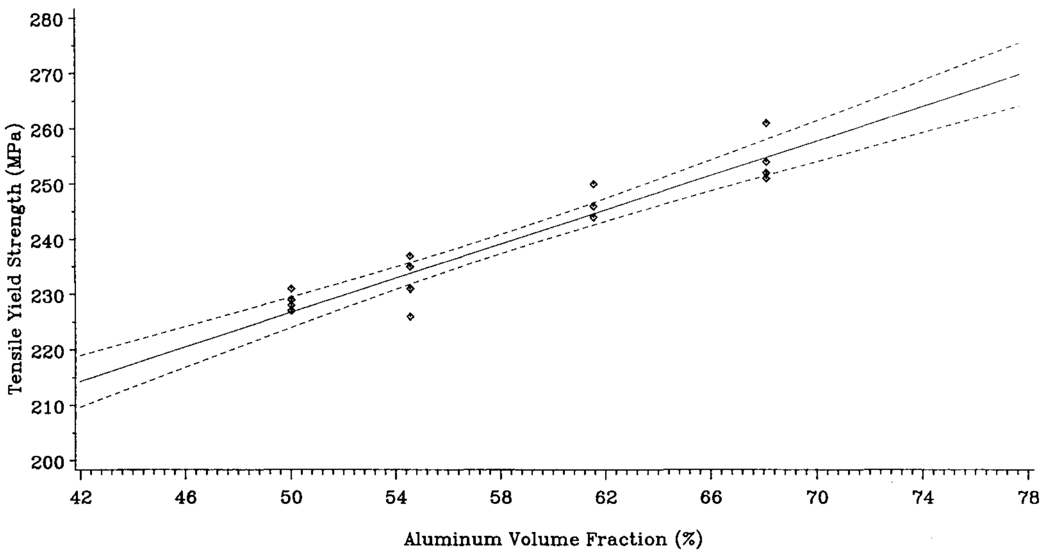

Fig. 3 Ninety-five percent confidence intervals for GLARE 4 laminate long-transverse tensile yield strength variation with aluminum volume fraction.

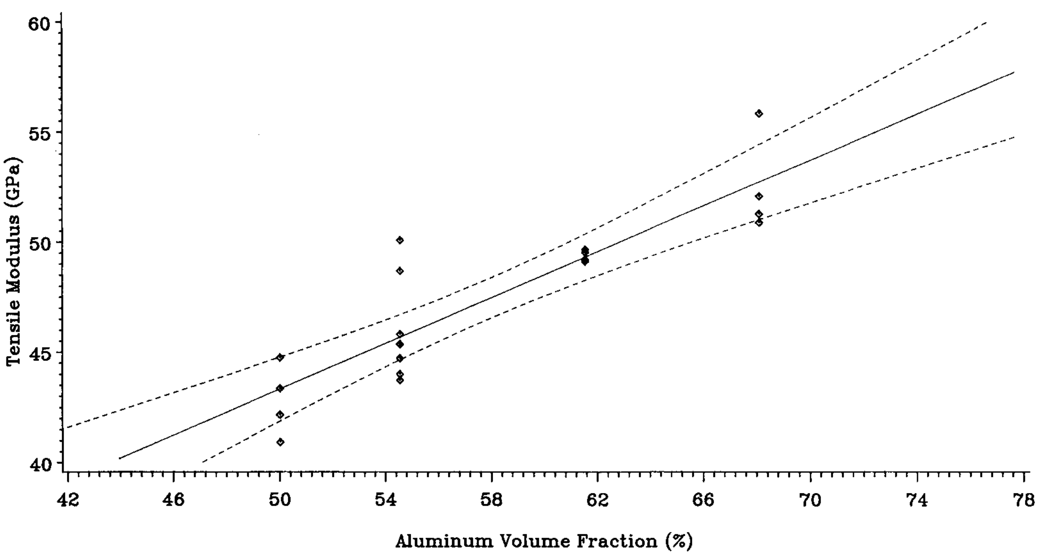

Fig. 4 Ninety-five percent confidence intervals for GLARE 4 laminate long-transverse tensile modulus variation with aluminum volume fraction.

direction for cross-ply cured glass prepreg; and $E_{al} = 75.8$ GPa for 2024-T3 aluminum alloy sheet. Experimental results are also in good agreement with the theoretical prediction except for results of the 2/1 lay-up as shown in Table 5. Typical compressive yield strength and modulus against metal (aluminum) volume fraction are plotted in Figs. 5 and 6.

C. In-Plane Shear

Forty Iosipescu in-plane shear[31,32] specimens were tested to determine the values of the shear yield strength and shear modulus. The data are summarized in Table 6. A linear relationship is present between shear modulus and aluminum alloy volume fraction. However, the shear yield strength data do not fit well with linear regression model. This suggests that the shear yield strength measured from the Iosipescu shear testing procedure may be underestimated, perhaps due to the shear specimen notch geometry and plasticity of aluminum alloy sheet. Since the experimental data of cured glass prepreg are not available, the following back-calculated glass prepreg properties (assuming ROM applies) are used in the analysis: $G_p = 8.16$ and 8.10 GPa for both the L and LT directions, respectively. For the 2024-T3 aluminum alloy sheet, we use

Table 5 Comparison between experimental and predicted compressive properties for GLARE 4 laminates

		Longitudinal			Long-transverse		
Lay-up	Metal volume fraction, %	CYS,[a] MPa	E_{exp},[b] MPa	E_{rom},[c] GPa	CYS,[a] MPa	E_{exp},[b] MPa	E_{rom},[c] GPa
5/4	50.00	314	59.87	57.25	261	51.68	50.60
5/4	54.55	309	59.67	58.94	268	55.23	52.89
3/2	54.55	327	58.59	58.94	261	52.93	52.89
3/2	61.54	306	63.42	61.53	280	61.56	56.42
2/1	68.09	303	70.04	63.96	289	63.95	59.72

[a]CYS, average compressive yield strength.
[b]E_{exp}, average experimental compressive modulus.
[c]E_{rom}, predicted compressive modulus using ROM.

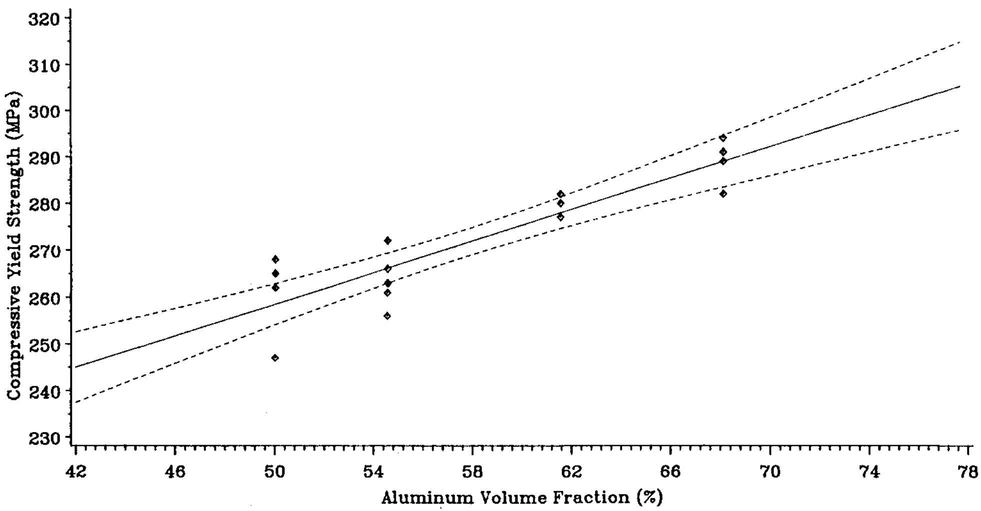

Fig. 5 Ninety-five percent confidence intervals for GLARE 4 laminate long-transverse compressive yield strength variation with aluminum volume fraction.

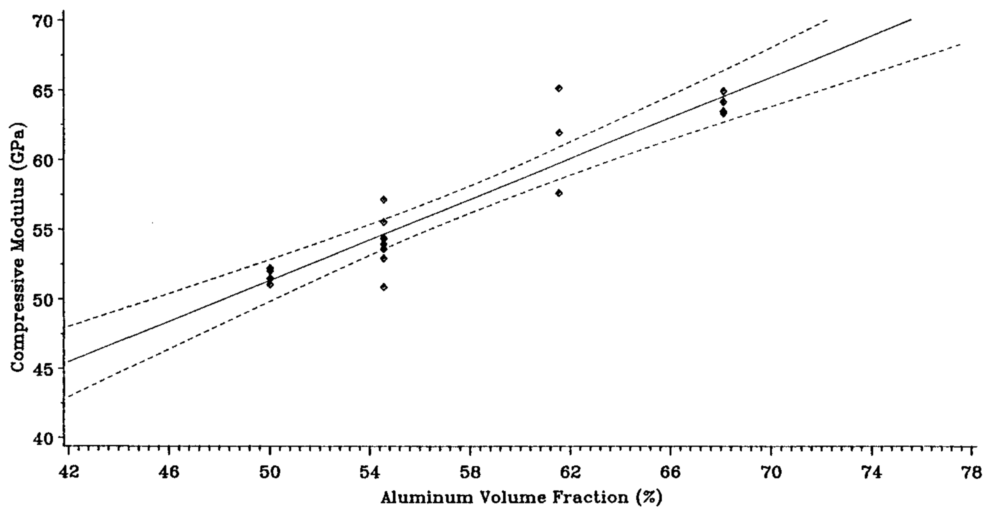

Fig. 6 Ninety-five percent confidence intervals for GLARE 4 laminate long-transverse compressive modulus variation with aluminum volume fraction.

Table 6 Summary of Iosipescu in-plane shear test results for GLARE 4 laminates

Lay-up	Metal volume fraction, %	Longitudinal		Long-transverse	
		SYS,[a] MPa	G_s,[b] GPa	SYS,[a] MPa	G_s,[b] GPa
5/4	50.00	95	11.38	94	11.17
	50.00	95	11.17	97	10.76
	50.00	95	11.51	93	11.24
	50.00	95	11.45	99	13.03
5/4	54.55	101	13.65	98	14.27
	54.55	100	13.58	96	13.93
	54.55	101	13.72	100	13.79
	54.55	101	13.72	99	13.38
3/2	54.55	103	11.79	97	12.07
	54.55	100	12.41	98	10.96
	54.55	99	11.79	96	11.17
	54.55	99	11.65	99	11.03
3/2	61.54	102	15.86	107	14.34
	61.54	105	16.20	106	15.24
	61.54	106	14.55	107	15.17
	61.54	106	14.41	109	12.55
2/1	68.09	118	16.89	116	16.82
	68.09	119	16.34	117	17.44
	68.09	119	17.38	118	17.79
	68.09	121	16.48	117	17.93

[a]SYS, shear yield strength. [b]G_s, shear modulus.

Table 7 Comparison between experimental and predicted in-plane shear properties for GLARE 4 laminates

Lay-up	Metal volume fraction, %	Longitudinal			Long-transverse		
		SYS,[a] MPa	G_{exp},[b] MPa	G_{rom},[c] GPa	SYS,[a] MPa	E_{exp},[b] MPa	G_{rom},[c] GPa
5/4	50.00	95	11.38	12.59	96	11.55	12.52
5/4	54.55	101	13.67	13.25	98	13.84	13.18
3/2	54.55	100	11.91	13.25	98	11.31	13.18
3/2	61.54	105	15.26	14.40	107	14.33	14.33
2/1	68.09	119	16.77	15.68	117	17.50	15.61

[a]SYS, average shear yield strength.
[b]G_{exp}, average experimental shear modulus.
[c]G_{rom}, predicted shear modulus using ROM.

Table 8 Summary of bearing[a] test results for GLARE 4 laminates

Lay-up	Metal volume fraction, %	Longitudinal			Long-transverse		
		BYS,[b] MPa	BUS[c]-4%, MPa	BUS[d]-max, MPa	BYS,[b] MPa	BUS[c]-4%, MPa	BUS[d]-max, MPa
5/4	50.00	631	706	884	571	677	951
	50.00	600	710	896	564	690	950
	50.00	598	692	913	593	709	945
	50.00	640	721	919	589	709	920
5/4	54.55	635	720	890	560	652	951
	54.55	634	741	919	554	635	930
	54.55	604	702	875	526	623	910
	54.55	627	713	899	526	635	920
3/2	54.55	647	751	936	593	716	980
	54.55	662	770	947	618	724	947
	54.55	657	746	953	601	713	981
	54.55	646	769	943	578	702	975
3/2	61.54	678	735	981	528	660	988
	61.54	[e]	[e]	[e]	612	726	1032
	61.54	672	[e]	1001	601	729	1020
	61.54	653	743	967	565	683	992
2/1	68.09	688	773	1014	633	734	1062
	68.09	651	759	1026	664	773	1095
	68.09	674	762	1027	594	703	1051
	68.09	654	759	1014	617	734	1037

[a]All bearing tests according to ASTM D-953 testing procedure (bolt-type).
[b]BYS, bearing yield strength determined at 2% of pin-hole deformation.
[c]BUS-4%, bearing ultimate strength determined at 4% of pin-hole deformation.
[d]BUS-max, bearing ultimate strength determined at final failure.
[e]Extensometer was not activated during the test.

G_{al} = 27.58 GPa taken from Ref. 29. Comparison between experimental and predicted in-plane shear properties, except for results of the 2/1 lay-up, are found to be in a good agreement and are listed in Table 7. Typical shear yield strength and modulus against metal (aluminum) volume fraction are plotted in Figs. 7 and 8.

D. Bearing

Forty bearing specimens having a constant edge distance to pin diameter ratio e/D of 3 and width to pin diameter ratio W/D of 6, recommended from previous research,[33-36] were tested. A modified ASTM D-953 bearing testing procedure with lateral constraint[28] was employed in this study. The bearing yield strength, bearing ultimate strength at 4% pin-hole deformation, and bearing ultimate strength at maximum load were recorded. The data are listed in Table 8. Results show that bearing strength is a function of aluminum alloy volume fraction, although some of scatter exists. Since we do not have the experimental bearing ultimate strength data for cured glass prepreg, back-calculated glass prepreg properties (assuming ROM applies) are used in this analysis. They are σ_p = 953 MPa in the L direction and σ_p = 1033 MPa in the LT direction. For the 2024-T3 aluminum alloy sheet, we use σ_{al} = 959 MPa obtained from Ref. 29. A comparison of the experimental and predicted bearing ultimate strength are presented in Table 9. Comparison between experimental and predicted values show a good agreement in bearing ultimate strength. Typical bearing strength against metal (aluminum) volume fraction is plotted in Fig. 9.

In general, for the above four tests, measured mechanical properties of the cured composite prepreg and aluminum alloy sheet used in the laminate should be used for theoretical prediction. In this text, due to budget and time constraints, we only used the back-calculated and typical values, respectively, for the work. In order to arrive at an accurate prediction, test work on laminate components (aluminum alloy sheet and cured prepreg) should be performed in the future.

E. Statistical Analysis

All the data populations fit a normal distribution well. This can be seen from the results of Kolmogorov–Smirnov goodness-of-fit listed in Table 10. Linear regression analysis has been used for determining the relationship between mechanical properties and aluminum alloy volume fraction. The experimental data show that most of the mechanical properties of fiber/metal laminates are a function of aluminum alloy volume fraction. Test hypothesis on linearity has been analyzed through lack-of-goodness-fit. Details of statistical anal-

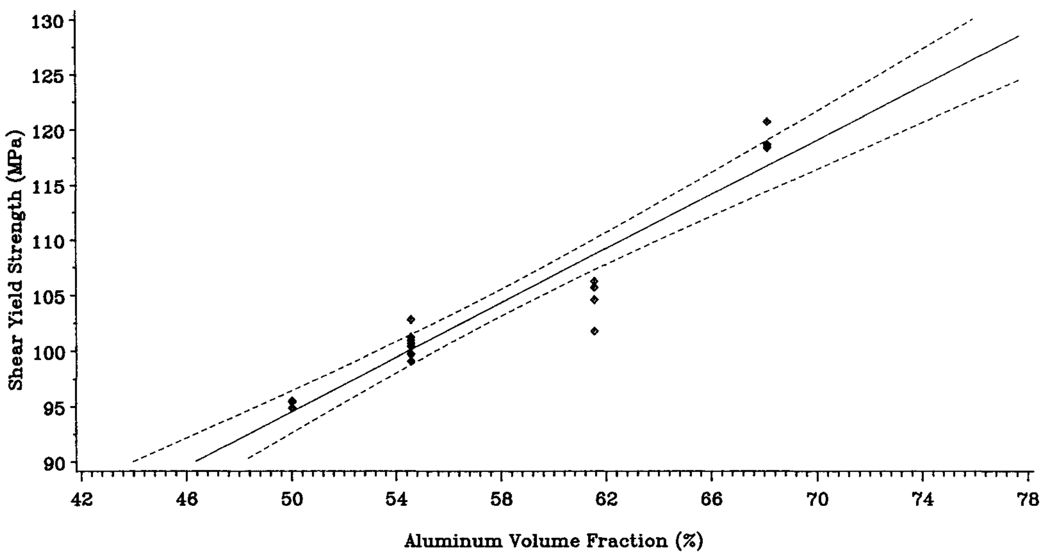

Fig. 7 Ninety-five percent confidence intervals for GLARE 4 laminate long-transverse shear yield strength variation with aluminum volume fraction.

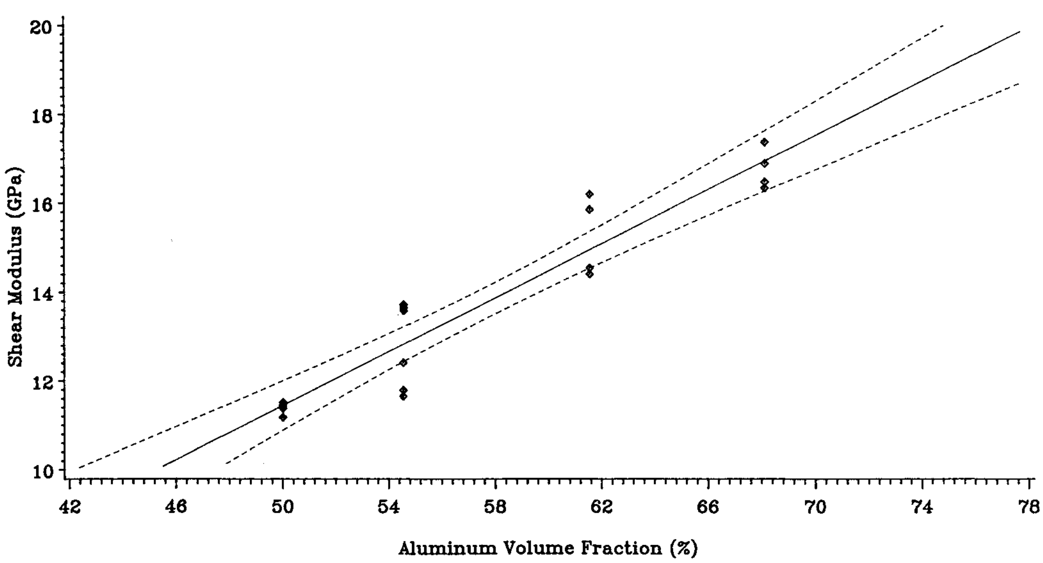

Fig. 8 Ninety-five percent confidence intervals for GLARE 4 laminate long-transverse shear modulus variation with aluminum volume fraction.

Table 9 Comparison between experimental and predicted bearing properties for GLARE 4 laminates

Lay-up	Metal volume fraction, %	Longitudinal BYS,[a] MPa	Longitudinal BUS_{exp}[b]-max, MPa	Longitudinal BUS_{rom},[c] MPa	Long-transverse BYS,[a] MPa	Long-transverse BUS_{exp}[b]-max, MPa	Long-transverse BUS_{rom},[c] MPa
5/4	50.00	617	903	956	579	942	996
5/4	54.55	625	896	956	542	928	993
3/2	54.55	653	945	956	598	971	993
3/2	61.54	668	983	957	577	1008	988
2/1	68.09	667	1020	957	627	1061	983

[a]BYS, average bearing yield strength.
[b]BUS_{exp}-max, average experimental ultimate strength determined at maximum failure.
[c]BUS_{rom}, predicted bearing ultimate strength using ROM.

Table 10 Test for adequacy of the simple regression analysis and distribution fitting function for GLARE 4 laminates

Property vs metal volume fraction	Probability level (lack-of-goodness-fit)	Linearity of relationship	Significant level of K-S[a] test for normal distribution	Normality of data
TYS, *L*	0.91785	Yes	0.76716	Yes
TUS, *L*	0.92905	Yes	0.6519	Yes
E_t, *L*	0.81278	Yes	0.75823	Yes
TYS, *LT*	0.09203	Yes	0.21529	Yes
TUS, *LT*	0.08348	Yes	0.65687	Yes
E_t, *LT*	0.75008	Yes	0.76675	Yes
CYS, *L*	0.92369	Yes	0.77935	Yes
E_c, *L*	0.58925	Yes	0.48434	Yes
CYS, *LT*	0.54426	Yes	0.88405	Yes
E_c, *LT*	0.17687	Yes	0.38086	Yes
SYS, *L*	0.00001	No	0.35648	Yes
G_s, *L*	0.66312	Yes	0.54822	Yes
SYS, *LT*	0.00652	No	0.17336	Yes
G_s, *LT*	0.38853	Yes	0.78237	Yes
BYS, *L*	0.30664	Yes	0.98868	Yes
BUS-4%, *L*	0.25612	Yes	0.898	Yes
BUS-max, *L*	0.48224	Yes	0.88176	Yes
BYS, *LT*	0.19931	Yes	0.98687	Yes
BUS-4%, *LT*	0.25785	Yes	0.49504	Yes
BUS-max, *LT*	0.24305	Yes	0.59557	Yes

[a]K-S, test of Kolmogorov–Smirnov for goodness-of-fit.

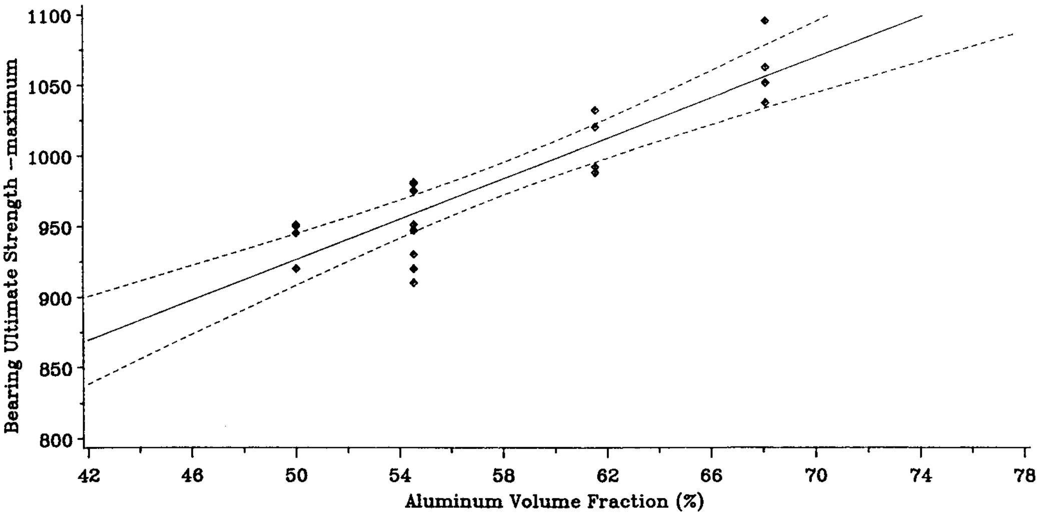

Fig. 9 Ninety-five percent confidence intervals for GLARE 4 laminate long-transverse bearing ultimate strength at maximum failure variation with aluminum volume fraction.

ysis show a good linearity at 95% confidence intervals for all properties except shear yield strength. Properties obtained from the same aluminum alloy volume fraction (54.55%), whose panels fabricated from lay-up of 3/2 (using 0.012-in. aluminum alloy sheet) or 5/4 (using 0.012- and 0.016-in. aluminum alloy sheets), are shown not to be statistically different. However, the power of statistical testing to discern differences is extremely low due to the small sample sizes involved. Box and whisker plots for each set of data with 95% confidence intervals for factor means show that, for many properties, differences do exist between the two lay-ups containing 54.55% volume fraction of aluminum.

V. Conclusions

This pilot study of research has concluded that metal volume fraction approach using the ROM may be able to predict most of the mechanical properties of fiber/metal laminates. However, more study is needed to completely verify this concept. If this hypothesis can be well-validated, qualifying a fiber/metal laminate family will only require evaluation of a few configurations.

VI. Future Work

Further study for verifying this concept is recommended. Before generating this research, mechanical properties of the cured composite prepreg and aluminum alloy sheet used in the laminates should be experimentally determined. Also, all the failure modes corresponding to different types of tests should be considered in the study. If we can carry out this test program, a validation on the MIL-HDBK-5 type design allowable property prediction will then be characterized and qualified.

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