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Use of rule of mixtures and metal volume fraction for mechanical property predictions of fibre-reinforced aluminium laminates

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This paper presents the results of a statistically designed programme conducted to validate feasibility of using the relationship of mechanical properties and metal volume fraction in fibre–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 show that use of the metal volume fraction may be useful for the prediction of strength mechanical properties in fibre–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 fibre–metal laminate family can be minimized. The findings imply that the metal volume fraction approach using a rule of mixtures can be exploited to estimate design properties for a multitude of fibre–metal laminate variants, which is economically beneficial to the preliminary stages of aircraft design.

1. Introduction

Fibre–metal laminates are engineered materials composed of thin structural sheet metal plies alternately bonded to plies of fibre-reinforced polymer. Such hybrid materials combine the best features of the metal and fibre–reinforced composite of which they are composed. Fibre–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 fibre-metal laminates. Fibre–metal laminates, ARALL (aramid fibre-based aluminium laminates) or GLARE (glass fibre-based aluminium laminates (ARALL or GLARE) 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, fibre–metal laminates also exhibit good thermal stability in cryogenic and elevated-temperature environments [16–18].

Although ARALL 2 and ARALL 3 laminate design allowables [19–23] have currently been accepted for incorporation into a newly written chapter of MIL-HDBK-5 [24], *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 the aerospace industry, especially for fuselage application, it is necessary to qualify a broad family of fibre–metal laminates according to MIL-HDBK-5 requirements. However, if the qualification procedure is based on the testing of individual configurations, 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, and the qualification of a fibre–metal laminate family only requires a minimum testing effort on a few laminate configurations.

2. 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 fibre and matrix are ignored. Each individual layer of laminate (aluminium alloy or composite layer) is treated as a homogeneous, orthotropic sheet and the laminated hybrid material is analysed using the classical theory of laminated plates. These are as follows:
for ultimate strength

$$\sigma_{\rm ult}^{\rm Lam} = V_{\rm f}^{\rm Al}\sigma_{\rm ult}^{\rm Al} + (1 - V_{\rm f}^{\rm Al})\,\sigma_{\rm ult}^{\rm p} \qquad (1)$$

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for Young's modulus

$$E_{11}^{\mathrm{Lam}} = V_{\mathrm{f}}^{\mathrm{Al}} E^{\mathrm{Al}} + (1 - V_{\mathrm{f}}^{\mathrm{Al}}) E^{\mathrm{P}} \qquad (2)$$

or

$$\frac{1}{E_{22}^{\mathrm{Lam}}} = \frac{V_{\mathrm{f}}^{\mathrm{Al}}}{E^{\mathrm{Al}}} + \frac{(1 - V_{\mathrm{f}}^{\mathrm{Al}})}{E^{\mathrm{P}}} \qquad (3)$$

and for in-plane shear modulus

$$\frac{1}{G_{12}^{\mathrm{Lam}}} = \frac{V_{\mathrm{f}}^{\mathrm{Al}}}{G^{\mathrm{Al}}} + \frac{(1 - V_{\mathrm{f}}^{\mathrm{Al}})}{G^{\mathrm{P}}} \qquad (4)$$

where $\sigma_{\mathrm{ult}}^{\mathrm{Lam}}$ = laminate ultimate strength, $\sigma_{\mathrm{ult}}^{\mathrm{Al}}$ = aluminium alloy ultimate strength, $\sigma_{\mathrm{ult}}^{\mathrm{P}}$ = cured composite prepreg ultimate strength, E_{11}^{Lam} = Young's modulus of the laminate in the longitudinal fibre direction, E_{22}^{Lam} = Young's modulus of the laminate in the long transverse fibre direction, E^{Al} = Young's modulus of the aluminium alloy, E^{P} = Young's modulus of the cured composite prepreg, G_{12}^{Lam} = shear modulus of the laminate in 1–2 plane, G^{Al} = shear modulus of the aluminium alloy, G^{P} = shear modulus of the cured composite prepreg and $V_{\mathrm{f}}^{\mathrm{Al}}$ = aluminium alloy volume fraction.

3. Experimental procedure

3.1. Materials

Laminate configurations of 2/1, 3/2 and 5/4 were considered. In definition, for example, 3/2 GLARE 4 consists of three layers of 0.012 or 0.016 in. (0.30 or 0.41 mm) thick aluminium alloy sheets and two layers of 70/30 glass prepreg (with 70% of fibres in 0° orientation and 30% of fibres in 90° orientation in each glass prepreg). Each prepreg layer (0°/90°/0°) has a 0.015 in. (0.38 mm) 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. The two standard aluminium alloy sheet thicknesses, 0.012 and 0.016 in. (0.30 and 0.41 mm), were used for controlling desired metal volume fraction. The type of lay-up, total laminate thickness and metal volume fraction are listed in Table I.

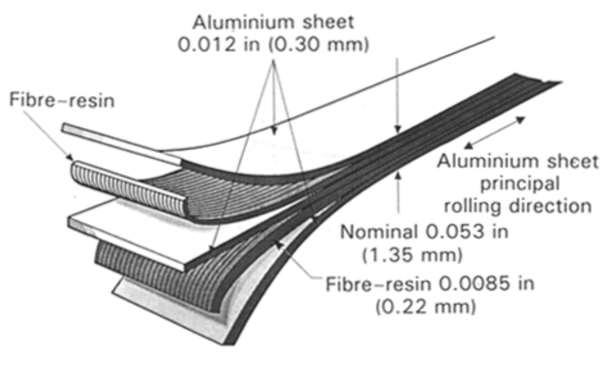

Figure 1 Fibre–metal structural laminates (typical 3/2 lay-up shown). Standard constituent materials: aluminium sheet alloy 2024 or 7475, aramid or glass fibre, unidirectional or cross-ply prepreg.

TABLE I Material descriptions of GLARE 4 laminates

Lay-up	Total metal thickness (in.)[a]	Total laminate thickness (in.)[b]	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 and 3 × 0.016	0.132	54.55
5/4	5 × 0.012	0.120	50.00

[a] 1 in. = 25.4 mm
[b] Each cross-ply 0°/90°/0° glass prepreg has a 0.015 in. thickness.

3.2. Experimental design

In this pilot study, static design properties were evaluated using a simple statistically designed experiment as described elsewhere [25]. 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 programme, quadruplicate tests were performed in both the L and LT directions, executed according to the run order provided [25]. 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.

4. Results and discussion

Metal volume fraction is the fractional quantity of aluminium alloy sheet per unit of laminate volume. A previous study [19] on the generation of MIL-HDBK-5 design allowables for fibre–metal laminates has shown the potential feasibility of obtaining laminate properties as a function of volume fraction. In this study, metal volume fractions of 68.09, 61.54 and 54.55% (with two different laminate configurations, 3/2 and 5/4) and 50.00% were considered.

4.1. 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 II and results are plotted in Figs 2 to 7. The results show that tensile strengths and tensile modulus are linear functions of the aluminium 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

TABLE II Summary of tension test results for GLARE 4 laminates

Lay-up	Metal volume fraction (%)	Longitudinal			Long-transverse		
		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] Tensile yield strength.
[b] Tensile ultimate strength.
[c] Tensile modulus.
[d] Extensometer not activated during test.

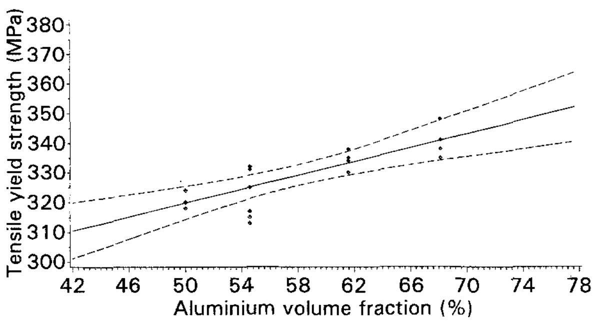

Figure 2 95% confidence intervals for GLARE 4 laminate longitudinal tensile yield strength variation with aluminium volume fraction.

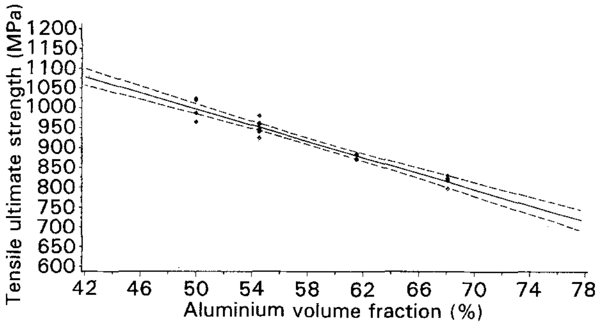

Figure 3 95% confidence intervals for GLARE 4 laminate longitudinal tensile ultimate strength variation with aluminium volume fraction.

data of cured glass prepreg are not available, the following back-calculated glass prepreg properties are used in this analysis (which assumes that the ROM applies): $\sigma_{ult}^{p} = 1507$ MPa and $E^{p} = 22.55$ GPa in the

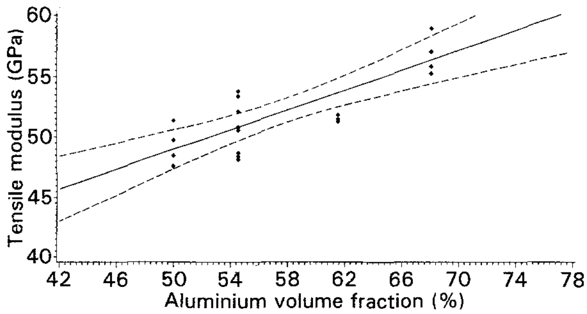

Figure 4 95% confidence intervals for GLARE 4 laminate longitudinal tensile modulus variation with aluminium volume fraction.

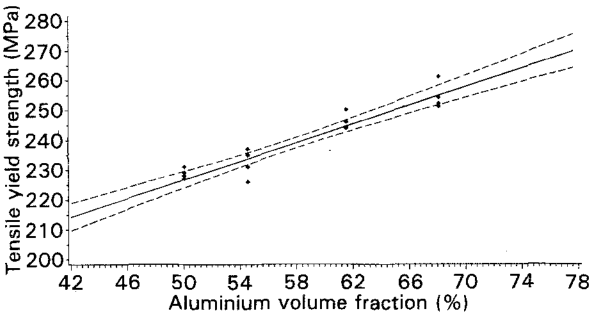

Figure 5 95% confidence intervals for GLARE 4 laminate long-transverse tensile yield strength variation with aluminium volume fraction.

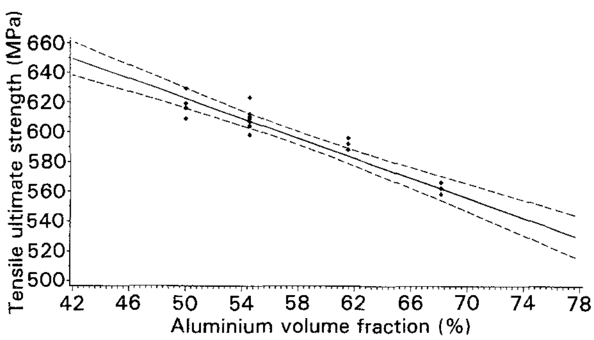

Figure 6 95% confidence intervals for GLARE 4 laminate long-transverse tensile ultimate strength variation with aluminium volume fraction.

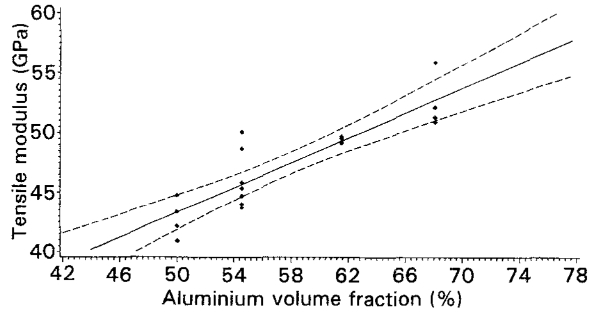

Figure 7 95% confidence intervals for GLARE 4 laminate long-transverse tensile modulus variation with aluminium volume fraction.

longitudinal direction, and $\sigma_{ult}^{p} = 742$ MPa and $E^{p} = 12.43$ GPa in the LT direction. For 2024-T3 aluminium alloy sheet, we use typical values of $\sigma_{ult}^{Al} = 490$ MPa and $E^{Al} = 73.5$ GPa, taken from Hatch

TABLE III Comparison between experimental and predicted tensile properties for GLARE 4 laminates

Lay-up	Metal volume fraction (%)	Longitudinal					Long-transverse				
		TYS[a] (MPa)	TUS^{b}_{exp} (MPa)	TUS^{c}_{rom} (MPa)	E^{d}_{exp} (GPa)	E^{e}_{rom} (GPa)	TYS (MPa)	TUS_{exp} (MPa)	TUS_{rom} (MPa)	E_{exp} (GPa)	E_{rom} (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] Average experimental tensile yield strength.
[b] Average experimental tensile ultimate strength.
[c] Predicted tensile ultimate strength using rule of mixtures.
[d] Average experimental tensile modulus.
[e] Predicted tensile modulus using rule of mixtures.

[26]. A comparison between experimental and the theoretical prediction from the ROM results for tensile strengths and tensile modulus shows good agreement, as shown in Table III.

4.2. 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 specimens, several layers of GLARE were bonded together prior to testing. All the compression specimens including the unbonded ones were subjected to the same post-cure thermal cycle. The data are summarized in Table IV and results are plotted in Figs 8 to 11. A good linear relationship has been shown to exist between the compressive yield

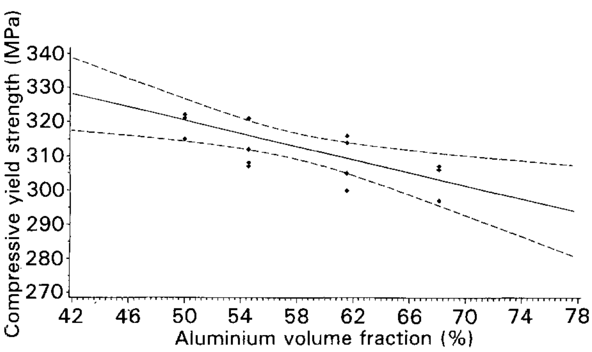

Figure 8 95% confidence intervals for GLARE 4 laminate longitudinal compressive yield strength variation with aluminium volume fraction.

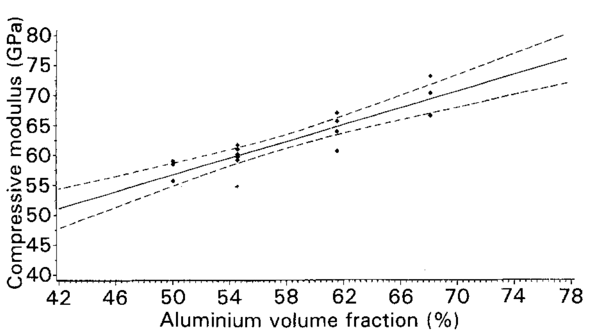

Figure 9 95% confidence intervals for GLARE 4 laminate longitudinal compressive modulus variation with aluminium volume fraction.

TABLE IV Summary of compression test results for GLARE 4 laminates

Lay-up	Metal volume fraction (%)	Longitudinal		Long-transverse	
		CYS[a] (MPa)	E^{b}_{c} (GPa)	CYS (MPa)	E_c (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] Compressive yield strength.
[b] Compressive modulus.

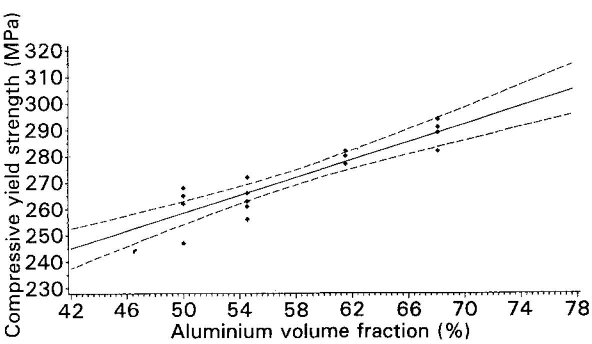

Figure 10 95% confidence intervals for GLARE 4 laminate long-transverse compressive yield strength variation with aluminium volume fraction.

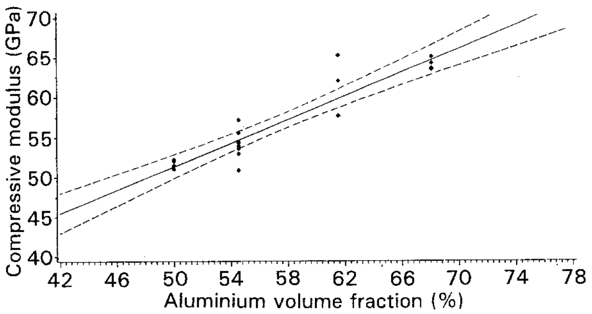

Figure 11 95% confidence intervals for GLARE 4 laminate long-transverse compressive modulus variation with aluminium volume fraction.

TABLE V Comparison between experimental and predicted compressive properties for GLARE 4 laminates

Lay-up	Metal volume fraction (%)	Longitudinal			Long-transverse		
		CYS[a] (MPa)	E^b_{exp} (MPa)	E^c_{rom} (GPa)	CYS (MPa)	E_{exp} (MPa)	E_{rom} (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] Average compressive yield strength.
[b] Average experimental compressive modulus.
[c] Predicted compressive modulus using rule of mixtures.

strength and compressive modulus values and the aluminium alloy volume fraction. The compressive modulus can also be predicted by the ROM. The predicted values were obtained using the experimental data of compressive properties of aluminium alloy sheet and cured glass prepreg [27]. They are: $E^p = 38.7$ GPa in the longitudinal direction and $E^p = 25.4$ GPa in the LT direction for cross-ply cured glass prepreg, and $E^{Al} = 75.8$ GPa for 2024-T3 aluminium alloy sheet. The experimental results are also in good agreement with the theoretical prediction except for results of the 2/1 lay-up, as shown in Table V.

4.3. In-plane shear

Forty Iosipescu in-plane shear [28, 29] specimens were tested to determine the values of the shear yield strength and shear modulus. The data are summarized in Table VI and results are plotted in Figs 12 to 15. A linear relationship is present between shear modulus and aluminium alloy volume fraction. However, the shear yield strength data do not fit well with a 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 the plasticity of aluminium alloy sheet. Since the experimental data of

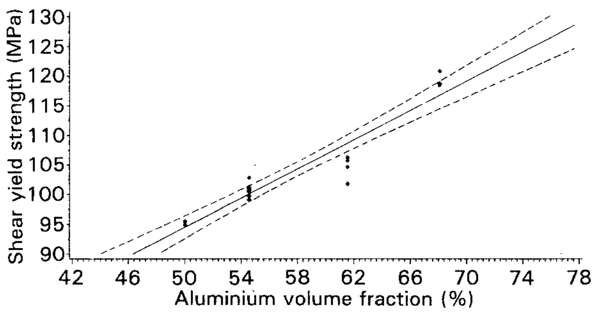

Figure 12 95% confidence intervals for GLARE 4 laminate longitudinal shear yield strength variation with aluminium volume fraction.

TABLE VI Summary of Iosipescu in-plane shear test results for GLARE 4 laminates

Lay-up	Metal fraction (%)	Longitudinal		Long-transverse	
		SYS[a] (MPa)	G^b_s (GPa)	SYS (MPa)	G_s (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] Shear yield strength.
[b] Shear modulus.

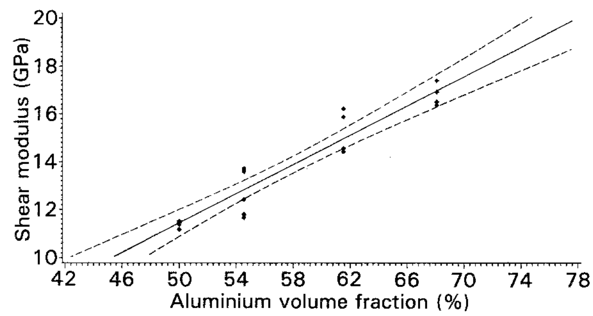

Figure 13 95% confidence intervals for GLARE 4 laminate longitudinal shear modulus variation with aluminium volume fraction.

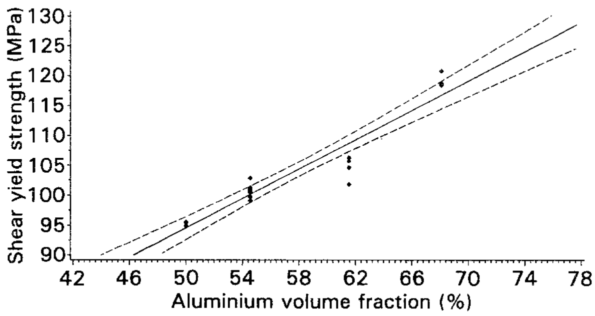

Figure 14 95% confidence intervals for GLARE 4 laminate long-transverse shear yield strength variation with aluminium volume fraction.

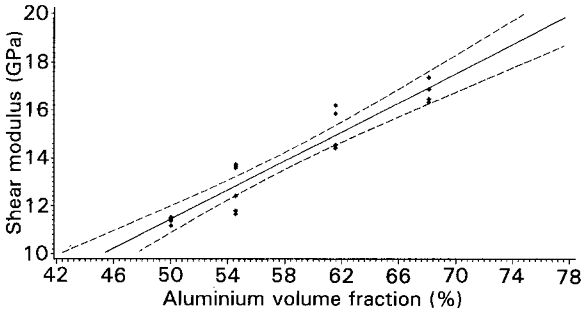

Figure 15 95% confidence intervals for GLARE 4 laminate long-transverse shear modulus variation with aluminium volume fraction.

cured glass prepreg are not available, the following glass prepreg properties (back-calculated assuming that the ROM applies) are used in the analysis: G^{p} = 8.16 and 8.10 GPa for L and LT directions, respectively. For 2024-T3 aluminium alloy sheet, we use G^{Al} = 27.58 GPa taken from Hatch [26]. Comparison shows that the experimental and predicted in-plane shear properties (except for the results for the 2/1 lay-up) are found to be in a good agreement, and are listed in Table VII.

TABLE VII 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^{b}_{exp} (MPa)	G^{c}_{rom} (GPa)	SYS (MPa)	E_{exp} (MPa)	G_{rom} (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] Average shear yield strength.
[b] Average experimental shear modulus.
[c] Predicted shear modulus using rule of mixtures.

4.4. 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 [30, 31] were tested. A modified ASTM D-953 bearing testing procedure with lateral constraint 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. All the data are listed in Table VIII and the results are plotted in Figs 16 to 21.

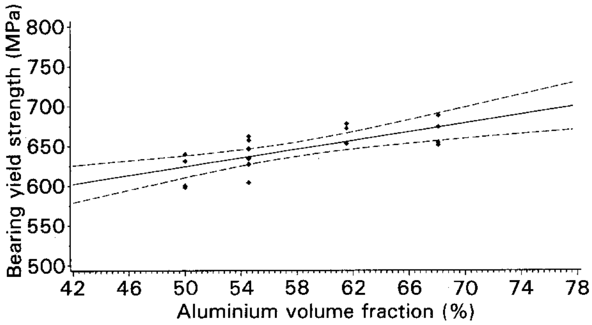

Figure 16 95% confidence intervals for GLARE 4 laminate longitudinal bearing yield strength variation with aluminium volume fraction.

TABLE VIII Summary of bearing test results for GLARE 4 laminates[a]

Lay-up	Metal volume fraction (%)	Longitudinal			Long-transverse		
		BYS[b] (MPa)	BUS (4%)[c] (MPa)	BUS (max)[d] (MPa)	BYS (MPa)	BUS (4%) (MPa)	BUS (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] Bearing yield strength determined at 2% of pin-hole deformation.
[c] Bearing ultimate strength determined at 4% of pin-hole deformation.
[d] Bearing ultimate strength determined at final failure.
[e] Extensometer not activated during test.

TABLE IX Comparison between experimental and predicted bearing properties for GLARE 4 laminates

Lay-up	Metal volume fraction (%)	Longitudinal			Long-transverse		
		BYS[a] (MPa)	BUS'_{exp} (max)[b] (MPa)	BUS^{c}_{rom}, (MPa)	BYS (MPa)	BUS_{exp} (max) (MPa)	BUS_{exp} (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] Average bearing yield strength.
[b] Average experimental bearing ultimate strength, determined at maximum failure.
[c] Predicted bearing ultimate strength using rule of mixtures.

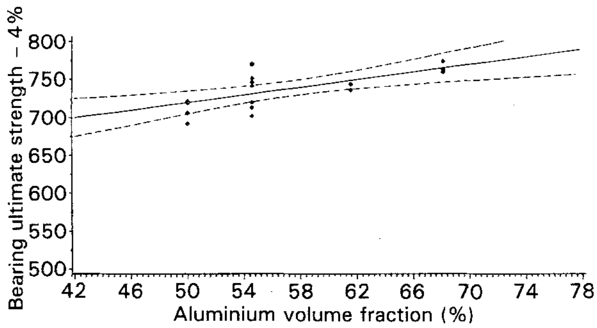

Figure 17 95% confidence intervals for GLARE 4 laminate longitudinal bearing ultimate strength at 4% pin-hole deformation variation with aluminium volume fraction.

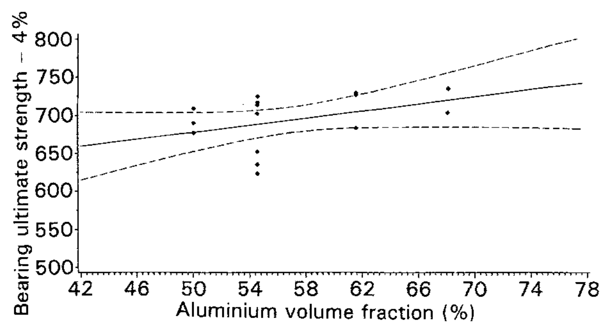

Figure 20 95% confidence intervals for GLARE 4 laminate long-transverse bearing ultimate strength at 4% pin-hole deformation variation with aluminium volume fraction.

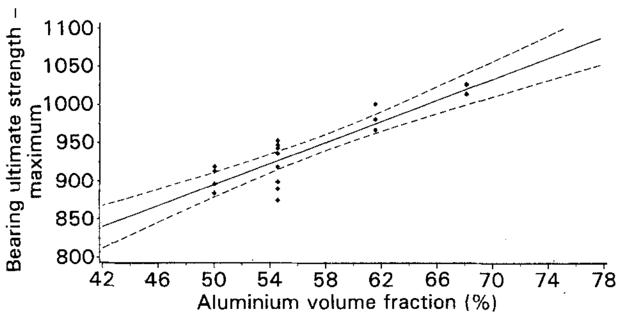

Figure 18 95% confidence intervals for GLARE 4 laminate longitudinal bearing ultimate strength at maximum failure variation with aluminium volume fraction.

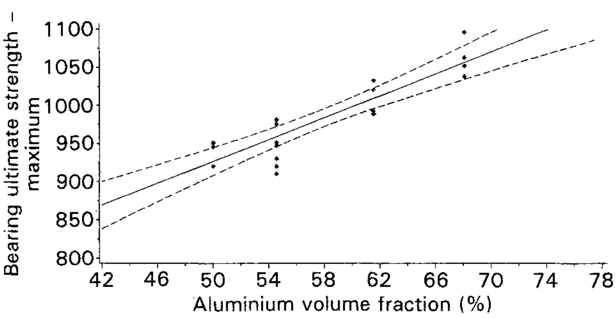

Figure 21 95% confidence intervals for GLARE 4 laminate long-transverse bearing ultimate strength at maximum failure variation with aluminium volume fraction.

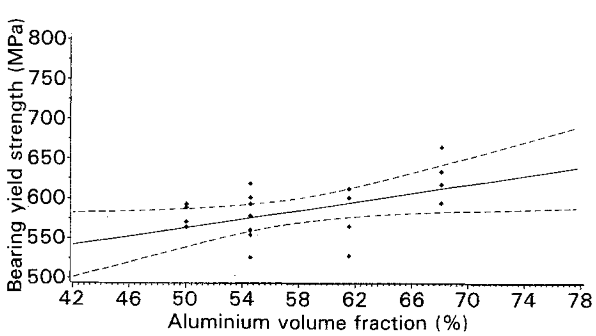

Figure 19 95% confidence intervals for GLARE 4 laminate long-transverse bearing yield strength variation with aluminium volume fraction.

The results show that bearing strength is a function of aluminium alloy volume fraction, although a great deal of scatter exists. Since we do not have the experimental bearing data for cured glass prepreg, back-calculated glass prepreg properties (assuming that the ROM applies) are used in this analysis. They are: $\sigma^{p}_{bus} = 953$ MPa in the longitudinal direction and $\sigma^{p}_{bus} = 1033$ MPa in the LT direction. For 2024-T3 aluminium alloy sheet, we use $\sigma^{Al}_{bus} = 959$ MPa obtained from Slagter [32]. A comparison of the experimental and predicted bearing ultimate strengths is presented in Table IX. The comparison shows good agreement.

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

TABLE X Test for adequacy of the simple regression analysis and distribution fitting function for GLARE 4 laminates

Property plotted versus metal volume fraction	TYS(L)	TUS(L)	E_t(L)	TYS(LT)	TUS(LT)	E_t(LT)	CYS(L)
Probability level (Lack of goodness-of-fit)	0.917 85	0.929 05	0.812 78	0.092 03	0.083 48	0.750 08	0.923 69
Linearity of relationship	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Significance level of KS[1] test[a] for normal distribution	0.767 16	0.6519	0.758 23	0.215 29	0.656 87	0.766 75	0.779 35
normality of data	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Property plotted versus metal volume fraction	E_c(L)	CYS(LT)	E_c(LT)	SYS(L)	G_s(L)	SYS(LT)	G_s(LT)
Probability level (Lack of goodness-of-fit)	0.589 25	0.544 26	0.176 87	0.000 01	0.663 12	0.006 52	0.388 53
Linearity of relationship	Yes	Yes	Yes	No	Yes	No	Yes
Significance level of KS[1] test[a] for normal distribution	0.484 34	0.884 05	0.380 86	0.356 48	0.548 22	0.173 36	0.782 37
normality of data	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Property plotted versus metal volume fraction	BYS(L)	BUS (4%) (L)	BUS (max) (L)	BYS (LT)	BUS (4%) (LT)	BUS (max) (LT)
Probability level (Lack of goodness-of-fit)	0.306 64	0.256 12	0.482 24	0.199 31	0.257 85	0.243 05
Linearity of relationship	Yes	Yes	Yes	Yes	Yes	Yes
Significance level of KS[1] test[a] for normal distribution	0.988 68	0.898	0.881 76	0.986 87	0.495 04	0.595 57
normality of data	Yes	Yes	Yes	Yes	Yes	Yes

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

4.5. Statistical analysis

All the data populations fit a normal distribution well. This can be seen from the results of Kolmogorov–Smirnov goodness-of-fit tests listed in Table X. Linear regression analysis has been used for determining the relationship between mechanical properties and aluminium alloy volume fraction. Figs 2 to 21 show that most of the mechanical properties of fibre–metal laminates are a function of aluminium alloy volume fraction. The hypothesis of linearity has been analysed by testing for lack of goodness-of-fit. Details of the statistical analysis show good linearity at 95% confidence intervals for all properties except shear yield strength.

Properties obtained from the same aluminium alloy volume fraction (54.55%) whose panels were fabricated from a lay-up of 3/2 (using 0.012 in. (0.30 mm) aluminium alloy sheet) or 5/4 (using 0.012 or 0.016 in. (0.30 or 0.41 mm) aluminium alloy sheet) 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 aluminium.

5. Conclusions

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

Further study for verifying this concept is recommended. Before generating this research, the mechanical properties of the cured composite prepreg and aluminium alloy sheet used in 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 programme, a validation of the MIL-HDBK-5 type design allowable property prediction will then be characterized and qualified.

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