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A study of tension test specimens of laminated hybrid composites

Part II *Size and alignment effects*

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This paper is a continuation of the research work reported on earlier in Part I: a study of tension test specimens for laminated hybrid composites. Effects of specimen size and alignment of the tensile testing machine were investigated. It is demonstrated that the variation of strength with size is significant, and alignment of the testing machine is critical. In summary, the use of a straight-sided specimen for tension testing of fibre–metal laminates is recommended. However, if one can maintain good control of alignment from the tensile testing machine, use of a dogbone-type test specimen is also applicable. The effect of specimen size on the strength of fibre–metal laminates is also examined in this study. The strength of fibre–metal laminates exhibits no size (width) effect over the range 6.4 to 38.1 mm, holding the strain rate constant.

1. Introduction

Aramid fibre-reinforced aluminium laminates (ARALL laminates) are a new family of hybrid structural composite materials developed for critical fatigue applications requiring light gauge sheets [1–6]. These materials are bonded arrangements of thin aluminium alloy sheets and alternating plies of epoxy adhesive, impregnated with unidirectional aramid fibres (see Fig. 1). The principal benefit of the resulting hybrid composites is the ability to impede and self-arrest crack growth attributed to the component of cyclic loading aligned with the fibres (generally also the direction of greatest tensile stress). Once a through-thickness fatigue crack develops in the aluminium layer, controlled delamination between the metal, epoxy and fibre interfaces accommodates stress redistribution from the metal to unbroken fibres in the crack wake. The bridging provided by the strong aramid fibres constrains crack opening, thereby reducing the driving force for metal crack advance [1, 2, 7]. ARALL laminates were pioneered at Delft University of Technology, the Netherlands, in the early 1980s [1–5]. Though originally developed for fatigue resistance, ARALL laminates display a range of impressive, albeit directional, property improvements over those of monolithic high strength aluminium, and they feature performance traits that compete with those of advanced composites [1–7]. These attractive characteristics, include 15–20% lower density than aluminium; up to 60% higher strength than 7075 and 2024 aluminium at comparable stiffness [8–11]; fabricability comparable to metal (e.g. it can be cut, sawed, drilled, joined and inspected by conventional metal practices); ability of the outer metal layers to protect against fibre–resin system damage by moisture, thermal attacks [10, 11], lightning, and impacts; and damping ability superior to monolithic aluminium. Envisioned aircraft usages include tension-dominated fatigue and fracture critical structure (e.g. lower wing and fuselage skins), damping critical structure, lightning strike areas, and structure requiring resistance to impacts, where attendant trade studies have identified potential for significant (15–40%) weight savings over current designs [12–17]. Since October 1987, ARALL laminates have been flying in the lower wing of a Fokker-50 prototype commercial transport aircraft, and Fokker and other airframers are evaluating the material for broaden aircraft use.

2. Background

In their research work, Wu and Wu [18] have reported that using a straight-sided tension test specimen is recommendable for fibre-reinforced aluminum laminates. They also suggest that considering the specimen size and maintaining better alignment with a slower testing machine speed may reduce the scatter of the test data.

Although, by and large, adequate methods have been developed for mechanical testing of high performance composites, there still remain many problems in the use of mechanical test data in the design of large structures. One of these problems is the adjustment of tensile strength data obtained from relatively small laboratory test coupons to values appropriate to large scale structures. The strength of a large structure is invariably lower than that of a small structure made from identical material, and as a general rule the

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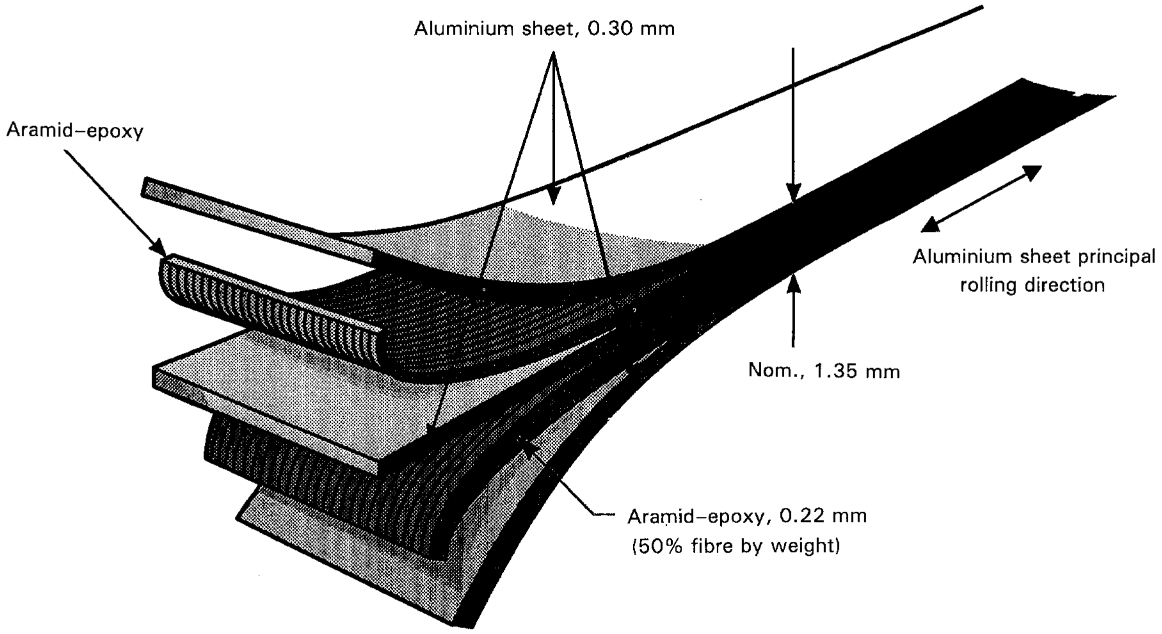

Figure 1 ARALL laminate standard 3/2 lay-up.

discrepancy in strengths increases with increasing brittleness of the material. Thus, the variation of strength with specimen size is much greater for brittle materials than for tough, ductile materials. At a fundamental micromechanical level, the scatter in strength is due to the distribution of flaws. The distribution of flaw sizes in flaw-sensitive materials can lead to a large scatter in strength of small test specimens, values of ~ 20% being very common. The treatment of this strength–size effect is clearly of considerable importance in the design of composite structures, and the development of an adequate treatment for taking it into account is a necessary stage in the development of composite technology. A treatment which has been particularly effective for homogeneous, isotropic materials is the use of so-called Weibull statistics [19]. In material sciences and engineering, Weibull statistics have been found to be an effective treatment for the strength of brittle materials, and recent work has sought to assess their validity in the prediction of the effect of specimen size on the strength of unidirectional fibre-reinforced aluminium laminates.

Manders and Kowalski [20] reported that small angular misalignments of the fibres in typical tensile coupons by as little as 1° are sufficient to dramatically reduce the measured strengths by over 30% for graphite–epoxy composites. This indicates that alignment of the load frame of the testing machine plays an important role in tensile testing. It was noted that the Tinus Olsen testing machine (testing horizontally) provides better alignment of the load frame than the Instron testing machine (testing vertically), reported previously by Wu and Wu [18]. A replication of the tests between straight-sided and dogbone-type specimens associated with an experimental design were performed in this study.

3. Experimental procedure

Details of specimen dimensions for the two types of tension test specimen are shown in Fig. 2a, b. All specimens were taken from the same 3/2 aramid fibre-reinforced aluminium laminate panel (SN 605063) which included three plies of 7075–T6 aluminium alloy sheet and two plies of aramid fibre–epoxy prepreg. The panel was 1.3 mm thick and was stretched to 0.4% residual longitudinal prestrain. The main objective of giving the 0.4% permanent stretch was to reverse the residual stress state to compression in the aluminium layer and tension in the higher strength aramid fibres.

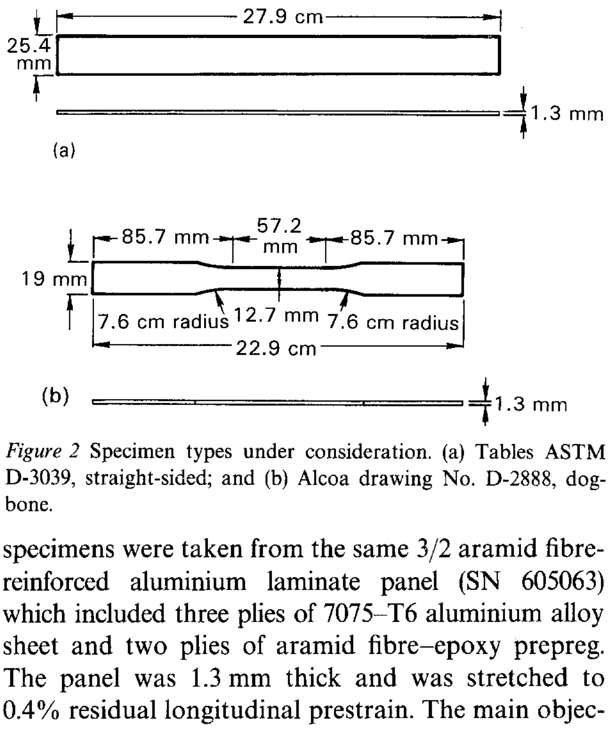

Figure 2 Specimen types under consideration. (a) Tables ASTM D-3039, straight-sided; and (b) Alcoa drawing No. D-2888, dogbone.

The fibres that are parallel to the tensile loading direction were designated as "longitudinal or (L)". The fibres that are perpendicular to the tensile loading direction were designated as "long-transverse or (LT)". Thirty longitudinal straight-sided specimens were tested for size effect study. In the investigation of the size effect, tensile specimen widths of 6.4, 12.7, 19, 31.8 and 38.1 mm were of interest. Tensile ultimate strength and tensile yield strength were recorded. In the study of alignment effect for the tensile testing machine, a Tinius Olsen testing machine (testing horizontally) was used. Thirty longitudinal and long-transverse straight-sided specimens and thirty longitudinal and long-transverse dogbone-type specimens

TABLE I Effect of specimen–testing machine alignment of tensile properties of longitudinal 3/2 ARALL 1 laminates

Specimen type	No. of specimens	TUS[a] (MPa) {CV%}	TYS[b] (MPa) {CV%}	Modulus (GPa) {CV%}	Probability of good or bad failure
Straight-sided	30	863 {1.5}	659 {2.6}	74 {2.4}	Good = 23/30 = 0.77 Bad = 7/30 = 0.23
Dogbone-type	30	858 {2.6}	667 {2.3}	74 {1.9}	Good = 15/30 = 0.50 Bad = 15/30 = 0.50

[a] TUS, tensile ultimate strength.
[b] TYS, tensile yield strength.

TABLE II ANOVA results for the means of tensile ultimate strength

Source of variation	Sum of squares	d.f.[a]	Mean square	F-ratio	Significance level
Shape	2.2427	1	2.2427	0.25	0.5731
Block (shape)	35.4680	8	8.8670	1.31	0.9962
Residual	337.6367	50	6.7527		

[a] d.f., degree of freedom.

were tension tested at a speed of 5.1 mm min^{-1} on the Tinius Olsen testing machine. Emery paper was used as a tabbing material for the straight-sided specimens tested. All the dogbone-type specimens were tested without tabbing material. In order to investigate the location of specimen failure during the test, failure distance is of interest; likewise as reported in the previous study by Wu and Wu [18]. Distance from the centre of the fractured edge to the centre-line of each specimen after failure, defined as "failure distance", was recorded. Failures that occurred nearest the top or right grip were designated as +, and failures that occurred nearest the bottom or left grip were designated as −. The measurement of the failure distance was used for statistical distribution fitting and may help indicate misalignment of the testing machines. The tensile ultimate strength, tensile yield strength and tensile modulus were determined.

3.1. Statistical treatments

Thirty longitudinal specimens were prepared for the size effect study, and sixty specimens in both the longitudinal and long-transverse directions were prepared for the alignment effect study. All specimens were selected at random for the static strength experiments, providing added insurance against biased results from sample preparation variabilities, or variabilities existing along the length or width of a laminated panel. The sixty specimens were divided into two groups having a random block experimental design (each block having six specimens). Two-way analysis of variance (ANOVA) and Levene's test were used for the data analysis of strength and failure distance. Of interest were the mean differences and variability between the two different specimen geometries and identification of the distribution of the failure distance.

4. Results and discussion

4.1. Mechanical properties

Table I summarizes the average room temperature tensile mechanical property data. The results of tensile ultimate strength, tensile yield strength and tensile modulus appear to be independent of the geometry of the specimen. The probability of failure from the straight-sided specimens shows a higher success rate of failure than that of the dogbone-type specimens.

4.2. Alignment effect

The expected mean squares in the experiment are

Source	Expected mean square
Shape	$30Q + 6\sigma_B^2 + \sigma^2$
Block	$6\sigma_B^2 + \sigma^2$
Error	σ^2

Here, Q is a quadratic term in the shape factor. σ_B^2 is the component of variability due to the block nested within shape factor, and σ^2 is the component of variability due to the within blocks variability. The "shape" factor is fixed, but the block within shape factor is random, hence the term "mixed model". In the analysis, the significance of the shape factor is tested by forming the ratio of the shape mean square to the blocks within shape mean square, i.e.

$$(30Q + 6\sigma_B^2 + \sigma^2)/(6\sigma_B^2 + \sigma^2)$$

The significance of the blocks within shape factor is found from the ratio $(6\sigma_B^2 + \sigma^2)/\sigma^2$.

The general plan for analysing the means is first to run the correct ANOVA procedure. Effects which are judged significant are then investigated further: if they are fixed effects, the means are compared; if they are random, the variance components are estimated. In analysing the variability, Levene's procedure is performed to determine significance. No means comparisons or variance components calculations are done, since such items really have no meaning in this procedure.

For the analysis of means of the tensile ultimate strength response, the ANOVA table in Table II is obtained, with significance probabilities for shape of 0.5731 and for block (shape) of 0.9962. Thus, both factors are significant at the 5% level. For the shape factor, the mean of level 1 (straight-sided specimen) is

863 MPa, while that of level 2 (dogbone-type specimen) is 858 MPa. The difference in means is 5 MPa (0.8 Ksi); a 95% confidence interval for this difference is

$$\begin{aligned} & d \pm t_8 * [(1/n_1 + 1/n_2) \mathrm{MS}_{\mathrm{BLOCK(SHAPE)}}] \\ &= 0.8 \pm 2.306[(1/30 + 1/30)(8.867)] \\ &= 0.8 \pm 1.77 \\ &= (-0.97, 2.57) \end{aligned}$$

Since this confidence interval does include the value zero, the difference is insignificant at the 5% level.

To obtain estimates of the variance components σ_B^2 and σ^2, equate the expected mean square to the observed mean square. This gives

$$6\sigma_B^2 + \sigma^2 = 8.867, \sigma^2 = 6.7527$$

Solving for σ_B^2 gives $\sigma_B^2 = 0.3524$. The 95% confidence intervals for the variance are $(-0.6196, 1.4036)$ for σ_B^2.

For Levene's test in Table III, the significance levels are 0.2784 for the shape factor and 0.5697 for the blocks within shape factor, so neither are significant.

As expected, the strength data fit a two-parameter Weibull distribution [19]. The statistical results show a consistent material behaviour as those obtained from a previous paper of Wu [8].

Going on to the analysis of failure distance, the significance levels in Table IV are 0.3599 for shape and 0.9488 for block within shape. Neither of these is significant. Then, the variance components can be estimated in the same way as before. This gives

$$\sigma^2 = 2.8171, \qquad \sigma_B^2 = 0.0185$$

The 95% confidence intervals are $(-1.6595, -0.5145)$ for σ_B^2.

For the variability analysis of failure distance, Levene's test in Table V gives significance probabilities of < 0.0000 for shape and 0.4469 for block within shape. This indicates that although the different shapes have distinguishable variabilities, different blocks within shape cells have indifferent variabilities.

4.3. Size effect

The size effect investigated here is holding constant specimen thickness by varying the specimen width. The size effect can be correlated to tensile ultimate strength by means of Weibull strength theory [19] in which the strength decreases with increasing specimen size. This supposes that the strength of a brittle material is controlled by flaws which are statistically distributed. The simple two-parameter model states that the probability of failure, F, under a stress or strain field, σ, is:

$$F(\sigma) = 1 - \left[- \int_V (\sigma/\sigma_0)^{\mathrm{m}} \times \mathrm{d}V \right] \qquad (1)$$

where σ_0 is the characteristic strength (a measure of the intrinsic tensile strength of the material) which may be expressed in terms of either stress or strain to failure, V is the volume and m is the Weibull modulus or shape parameter (a measure of the variability of the material). Both σ_0 and m are material constants.

TABLE III Levene's test results for the variability of tensile ultimate strength

Source of variation	Sum of squares	d.f.[a]	Mean square	F-ratio	Significance level
Shape	2.3050	1	2.3050	0.80	0.2784
Block (shape)	11.5464	8	2.8866	1.50	0.5697
Residual	95.9723	50	1.9194		

[a] d.f., degree of freedom.

TABLE IV ANOVA results for the means of failure distance

Source of variation	Sum of squares	d.f.[a]	Mean square	F-ratio	Significance level
Shape	2.5092	1	2.5092	0.86	0.3599
Block (shape)	11.7113	8	2.9278	1.04	0.9488
Residual	140.8510	50	2.8171		

[a] d.f., degree of freedom.

TABLE V Levene's test results for the variability of failure distance

Source of variation	Sum of squares	d.f.[a]	Mean square	F-ratio	Significance level
Shape	17.7235	1	17.7235	19.17	0.0000
Block (shape)	3.6983	8	0.9246	1.56	0.4469
Residual	29.6719	50	0.5934		

[a] d.f., degree of freedom.

For two tests on different specimens, for equal probability of failure

$$\int_{V_1} \sigma^{\mathrm{m}} \times \mathrm{d}V = \int_{V_2} \sigma^{\mathrm{m}} \times \mathrm{d}V \qquad (2)$$

The stress distribution can be normalized by expressing them in terms of a constant value, for example the maximum stress, σ, and a function of position x, y, z, A, giving the variation of stress over the body

$$\sigma = \sigma A(x, y, z) \qquad (3)$$

Substituting into Equation 2 yields

$$\sigma_1/\sigma_2 = (V_2/V_1)^{1/\mathrm{m}} \qquad (4)$$

Equation 4 tells us that the ratio of strengths depends on the relative volumes and the Weibull modulus, m. The measure of material variability is approximately related to the coefficient of variation (CV) of individual specimen strength by the relation

$$\mathrm{m} = 1.2/\mathrm{CV} \qquad (5)$$

A highly variable material will have a low value of m, and would be expected to give a high amount of scatter in specimen strengths and a large size effect.

Straight-sided tensile test specimen widths of 6.4, 12.7, 19, 31.8 and 38.1 mm were conducted for the size effect study. Each specimen size had five replications. The ANOVA results for size effect on tensile ultimate strength and tensile yield strength are summarized in Tables VI and VII. Statistical results show that the

TABLE VI ANOVA results for size effect of tensile ultimate strength

Source of variation	Sum of squares	d.f.[a]	Mean square	F-ratio	Significance level
Between groups	13.0016	4	3.2504	0.843	0.5143
Within groups	77.1120	20	3.8556		
Total (corrected)	90.1136	24			

[a] d.f., degree of freedom.

TABLE VII ANOVA results for size effect of tensile yield strength

Source of variation	Sum of squares	d.f.[a]	Mean square	F-ratio	Significance level
Between groups	3.4464	4	0.8616	0.869	0.4998
Within groups	19.8360	20	0.9918		
Total (corrected)	23.2824	24			

[a] d.f., degree of freedom.

size (width) effect is insignificant for mean tensile ultimate strength and tensile yield strength. The Cochran's C tests for homogeneity of variances for both tensile ultimate strength and tensile yield strength also show no differences in size effect (probabilities are equal to 0.2548 and 0.3664 for tensile ultimate strength and tensile yield strength, respectively).

5. Conclusions

In Part II of the study on tension test specimens, comparison of size and alignment effects between straight-sided and dogbone-type specimens was conducted. Based on the findings from this study, the following conclusions can be drawn:

1. The use of a straight-sided specimen of fibre-reinforced aluminium laminates for tension testing is recommended. However, if good alignment of the testing machine is achievable, a dogbone-type specimen may also be used.

2. The effect of size (width) on tensile strength in fibre–metal laminates is insignificant over the range of specimen widths investigated, from 6.4 to 38.1 mm, holding the strain rate constant.

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