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PERFORMANCE CHARACTERISTICS OF GFRP BASED ON FIBER ORIENTATION OF SECONDARY STRUCTURE

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ABSTRACT :

Woven E-glass/epoxy laminates are used in secondary aircraft structures, where the stacking sequence and any additive in the matrix can change strength. This paper reports how stacking symmetry and aluminium powder filler affect four 12-ply laminates made by hand lay-up from 350 GSM woven E-glass fabric, Araldite LY556 epoxy and HY951 hardener. Symmetric and unsymmetric stacking sequences were each made with and without 15 g of aluminium powder and tested in tension and three-point bending (one specimen per laminate). Tensile strength was 124.0 MPa (symmetric, filled), 121.2 MPa (symmetric, unfilled), 112.0 MPa (unsymmetric, unfilled) and 104.4 MPa (unsymmetric, filled). The symmetric laminates were stronger than the unsymmetric ones by 8.2 % (unfilled) and 18.8 % (filled) in tension, and by 4.3 % and 17.2 % in bending. Aluminium powder changed tensile strength by +2.3 % in the symmetric pair and by −6.8 % in the unsymmetric pair, so no consistent benefit was found. A separate linear static ANSYS model gave lower deformation for the symmetric stacking, in the same direction as the tests. In these laminates, stacking symmetry mattered more than the filler.

Keywords: GFRP; woven E-glass/epoxy; fibre orientation; symmetric and unsymmetric laminates; aluminium powder; hand lay-up; tensile test; three-point bending; ANSYS

INTRODUCTION

1.1 Background

Weight is the first concern in aircraft structures. Every kilogram removed from the airframe can be turned into payload, range or fuel saving, and for this reason fibre reinforced polymer (FRP) composites have taken over many parts that were once made of aluminium alloy [1]. Composites are used today in skins, control surfaces, fairings, radomes, floor panels and interior parts of civil, military and unmanned aircraft. A composite is made of two or more constituents that stay physically separate but together give properties that neither has alone. In an FRP, strong and stiff fibres carry most of the load, while the polymer matrix holds the fibres in place, passes load between them and protects them from the environment [2]. Since fibres are strong mainly along their length, the properties of the finished part depend very strongly on the direction in which the fibres are placed. This directional behaviour (anisotropy) is both the main advantage of composites and the main difficulty in designing with them.

Glass fibre reinforced polymer (GFRP) is the most widely used FRP because glass fibre is cheap, easy to get in many fabric forms and gives a good balance of strength, stiffness and electrical insulation. E-glass is the common grade. In aircraft, GFRP is mainly used in secondary structures, meaning parts whose failure would not immediately endanger the aircraft, such as fairings, access panels, wing-tip and tail-tip covers, radomes and interior panels [1]. The woven fabric used in this work contains yarns in two perpendicular directions (warp and weft), so a single ply already carries load in two directions, and it drapes easily during hand lay-up. Epoxy is the usual matrix

for such laminates because it bonds well to glass, shrinks little during curing and gives good mechanical properties. Mixed with its hardener, the liquid resin reacts to form a rigid, cross-linked network that cannot be melted again.

1.2 Fibre orientation, stacking and symmetry

A single ply is thin and is rarely used alone. Several plies are stacked and cured together as a laminate. The angle of a ply measured from a reference axis is its fibre orientation, and the order of the plies is the stacking sequence. When a ply is loaded along its fibres, the fibres carry most of the load and the ply is stiff and strong. When the load is at an angle to the fibres, more of it goes through the matrix and the fibre–matrix interface, and the ply becomes weaker and more flexible. A ply at 45° gives the best shear stiffness but a lower stiffness along the axis. A laminate therefore combines plies at several angles so that stiffness along the length, across the width and in shear are balanced [2,3].

Laminates are called symmetric when, for every ply above the mid-plane, there is an identical ply (same material, thickness and angle) at the same distance below it. In an unsymmetric laminate this mirror arrangement is absent. The difference is not only geometric. Classical laminate theory shows that a symmetric laminate has no coupling between in-plane stretching and out-of-plane bending, whereas an unsymmetric laminate has such coupling, so an in-plane load can bend or twist it. Unsymmetric laminates can also warp after curing, because the plies shrink by different amounts in different directions as the part cools [2,3]. This is why aircraft laminates are normally symmetric, and why it is useful to measure how much strength is lost when symmetry is removed.

1.3 Aluminium powder as a matrix filler

Fine particles can be added to the matrix of a composite to change its properties, reduce cost or help processing. In glass/epoxy composites, aluminium oxide, silicon oxide, titanium oxide, fly ash and metal powders have all been tried [4–7]. Aluminium powder is attractive because it is light, cheap and much stiffer than epoxy. When it is stirred into the resin, the particles sit between the fibres and can change the stiffness of the matrix, the way load is transferred and the way cracks grow. Too much powder, however, makes the resin thicker, which makes wetting of the fabric harder and can trap air. The net effect depends on the amount of filler, particle size, dispersion and bonding with the epoxy, and the published results do not always agree.

1.4 Hand lay-up and the aim of this paper

Hand lay-up is the simplest way of making a composite laminate. It needs only a flat mould, resin, a brush and a roller, so it is widely used in laboratories and small workshops. Its disadvantages are its dependence on the skill of the person doing the lay-up, a variable fibre-to-resin ratio and the chance of trapped air [1]. These factors cause scatter in test results and must be kept in mind when the laminates are compared.

This paper compares two variables on the same fabric and resin: stacking symmetry and the presence of aluminium powder. Four 12-ply woven E-glass/epoxy laminates (symmetric and unsymmetric, each with and without aluminium powder) were made by hand lay-up and tested in tension and in three-point bending. The same four configurations were also analysed in ANSYS under one common load. Experimental and ANSYS results are kept separate throughout the paper. The results are reported mainly as percentage differences between the laminates, since each value comes from a single specimen.

Literature Survey

1.5 Particulate fillers in glass/epoxy composites

Aveen et al. [4] added mother of pearl, fly ash and aluminium powder to glass/epoxy composites at 3, 6 and 9 % of the total volume and tested them in tension and flexure. The composite with aluminium powder gave the best tensile behaviour and the one with fly ash the best flexural behaviour. This shows that a filler can rank differently in different loading modes, which is why both tension and bending were measured in the present work.

Kazim et al. [5] made epoxy composites with 3 vol % glass fibre and 2, 4 and 6 vol % micro-powders of aluminium oxide, silicon oxide and titanium oxide. Hardness, flexural strength, density and water absorption increased with filler fraction, and hardness and flexural strength also increased as the particle size became smaller. Asi [6] studied the mechanical properties of glass-fibre reinforced epoxy filled with Al_2O_3 particles, and Megahed et al. [7] studied glass/epoxy composites enhanced with micro- and nano-sized aluminium particles. Particle size is not varied in the present work and is left for future study.

Hasan et al. [8] studied hybrid epoxy composites with glass fibre (20–60 %) and aluminium powder (5–15 %) under high-velocity impact, using a gas gun at velocities from 11.43 to 25 m/s. Higher glass fibre content improved tensile strength and impact resistance most, with the best result at 60 % fibre, and aluminium powder improved impact absorption to a smaller extent. Their finite element results agreed with the tests to within 10 % in residual velocity. The elastic constants given in that paper for epoxy, E-glass and aluminium powder are used in Table 2 of the present paper.

1.6 Fibre orientation and stacking sequence

Murugan et al. [9] studied how fibre orientation (45° and 90°) changes the effective stacking sequence of woven glass/carbon hybrid epoxy laminates made by hand lay-up, and measured tensile and flexural strength. Singh and Gupta [10] studied the effect of fibre orientation on a jute/carbon/glass hybrid composite. Both studies treat the ply angle as a design variable that changes the mechanical response even when the materials are the same, and the first one uses the same fabrication route as the present work.

1.7 Mechanics of laminates

The behaviour of symmetric and unsymmetric laminates, including extension–bending coupling, is described in classical laminate theory [2,3,11]. Mallick [1] covers constituents, hand lay-up and laminate design, and Daniel and Ishai [11] cover laminate analysis and the experimental testing of composites. These books are used here to explain the observed behaviour.

Table 1. Summary of the related research.

Ref.	Material / topic	Point relevant to this work
Aveen et al. [4]	Glass/epoxy; mother of pearl, fly ash, Al powder	Filler type changes tensile and flexural behaviour differently
Kazim et al. [5]	Glass/epoxy; Al_2O_3, SiO_2, TiO_2 micro-powders	Flexural strength and hardness rise with filler fraction and smaller particles
Asi [6]	Glass/epoxy filled with Al_2O_3	Ceramic particulate in a glass/epoxy laminate
Megahed et al. [7]	Glass/epoxy with micro and nano Al particles	Aluminium particles in glass/epoxy; particle size
Hasan et al. [8]	Glass fibre + Al powder in epoxy; high-velocity impact	Fibre content most effective; Al powder helps impact absorption less
Murugan et al. [9]	Woven glass/carbon hybrid; 45° and 90°	Orientation changes tensile and flexural results
Singh and Gupta [10]	Jute/carbon/glass hybrid; orientation	Orientation is a design variable

RESEARCH GAP AND OBJECTIVES

The studies above vary either the filler or the fibre orientation. We did not find one that compares a metallic particulate filler in symmetric and unsymmetric woven E-glass/epoxy laminates made under the same hand lay-up conditions and tested in both tension and bending. A four-laminate study cannot close this gap fully, but it gives a first set of measured numbers for the combination. The objectives were:

- to make four woven E-glass/epoxy laminates (symmetric and unsymmetric, with and without aluminium powder) by hand lay-up;
- to measure their tensile and three-point bending response;
- to separate the effect of stacking symmetry from the effect of the filler;
- to explain why the configurations behave differently; and
- to check the trend with a separate ANSYS analysis of the same configurations.

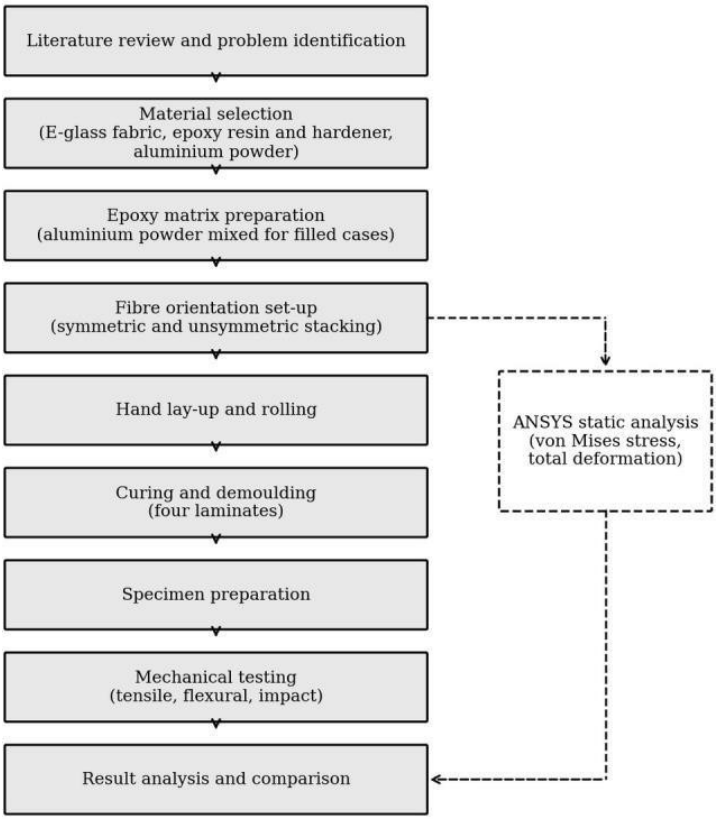


Fig. 1. Methodology flowchart of the work.

MATERIALS AND EXPERIMENTAL METHODOLOGY

1.8 Materials

Reinforcement. The reinforcement was plain-woven E-glass fabric of 350 GSM, that is, one square metre of fabric has a mass of 350 g. In a plain weave each warp yarn passes alternately over and under each weft yarn. Because the fabric is fairly heavy, each ply is relatively thick and fewer plies are needed to reach a given thickness. Each ply was cut to 250 mm × 250 mm. Glass fibre is brittle, so a GFRP laminate loaded along its fibres shows an almost linear stress–strain curve up to failure [1]. The fabric was kept clean and dry, since moisture or dust on the fibres weakens the bond with the resin.

Matrix. The matrix was Araldite LY556, a bisphenol-A based liquid epoxy resin, with HY951 hardener. The resin and hardener were measured as 250 ml and 125 ml (2:1 by volume). Curing is an exothermic reaction between the

epoxide groups of the resin and the amine groups of the hardener. If the hardener is too little or too much, some groups remain unreacted and the cured resin is softer and weaker, so the ratio was followed exactly. The mixed resin has a limited working time (pot life), and a large batch heats itself and cures faster, so the resin was applied soon after mixing.

Filler. Aluminium powder was used in two of the four laminates. A quantity of 15 g was weighed on an analytical balance and stirred slowly into the resin before the resin was applied. The powder was added gradually to avoid trapping air and to reduce clusters, which act as weak points and stress

concentrators. A mask was worn because the powder is an inhalation hazard. Table 2 gives the elastic properties of the three constituents as reported by Hasan et al. [8]; these are literature values and were not measured on our materials.



Fig. 2. Woven E-glass fabric (350 GSM).



Fig. 3. Epoxy resin container.



Fig. 4. Aluminium powder.

Table 2. Constituent properties from the literature [8].

Property	Epoxy	E-glass fibre	Aluminium powder
Tensile strength (MPa)	110	3400	47
Modulus of elasticity (MPa)	4100	72300	70000
Poisson's ratio	0.35	0.2	0.33

1.9 Laminate configurations

Each laminate had 12 plies at 0°, 90°, +45° and −45° measured from a reference direction marked on the mould (Table 3). A woven ply already has yarns at 0° and 90°, so rotating it by 45° puts the yarns at ±45°. The symmetric sequence is a mirror image about the mid-plane. In the unsymmetric sequence only plies 7 and 10 are exchanged (0° and +45°) and the other ten plies are unchanged. Both sequences therefore contain four 0° plies, four

90° plies, two +45° plies and two −45° plies. The amount of fabric at each angle is identical, so any difference between the two stacking types comes from the order of the plies and not from the amount of fabric at each angle.

Table 3. Laminate cases and stacking sequences.

Case	Label	Configuration	Stacking sequence (ply 1 to ply 12)	Al powder
1	L1	Symmetric, no Al	0, 90, 45, −45, 90, 0, 0, 90, −45, 45, 90, 0	No
2	L4	Symmetric, with Al	0, 90, 45, −45, 90, 0, 0, 90, −45, 45, 90, 0	15 g
3	L2	Unsymmetric, no Al	0, 90, 45, −45, 90, 0, 45, 90, −45, 0, 90, 0	No
4	L3	Unsymmetric, with Al	0, 90, 45, −45, 90, 0, 45, 90, −45, 0, 90, 0	15 g

1.10 Tools and equipment

Two flat moulds with a reference direction marked on them, a measuring beaker for resin and hardener, a brush, a roller for consolidating each layer, scissors and a metal scale for marking and cutting the fabric, gloves, an electronic balance for the fabric, an analytical balance for the powder and plastic film for covering the lay-up were used. The beaker measured resin and hardener by volume, the brush spread the resin over each ply, and the roller pressed the resin into the fabric and pushed out air. Grease on the mould worked as the release agent, forming a thin film between the mould and the epoxy so that the cured laminate did not stick.



Fig. 5. Moulds used for the lay-up.



Fig. 6. Measuring beaker used for resin and hardener.



Fig. 7. Roller used for consolidating each layer.

1.11 Fabrication by hand lay-up

Cutting and positioning the plies. The fabric was measured and marked for a ply size of 250 mm × 250 mm, cut by hand, and the plies were collected for lay-up (Fig. 8, Fig. 9). A reference fibre direction was marked on the mould. Each ply was rotated to its angle (0°, 90°, +45° or −45°) with respect to this reference and the chosen stacking sequence was kept during the layer-by-layer lay-up (Fig. 10, Fig. 11).

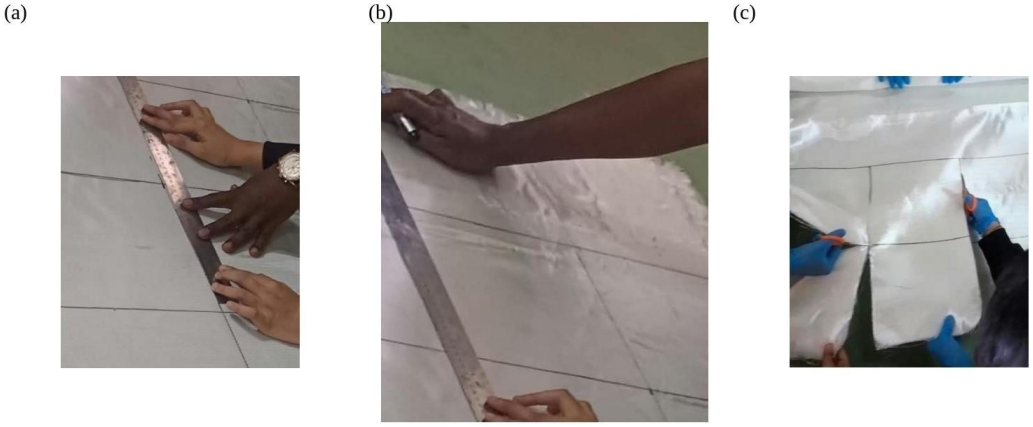


Fig. 8. Measuring, marking and cutting of the woven fabric: (a) measuring; (b) marking; (c) cutting.



Fig. 9. Prepared plies (250 mm × 250 mm).

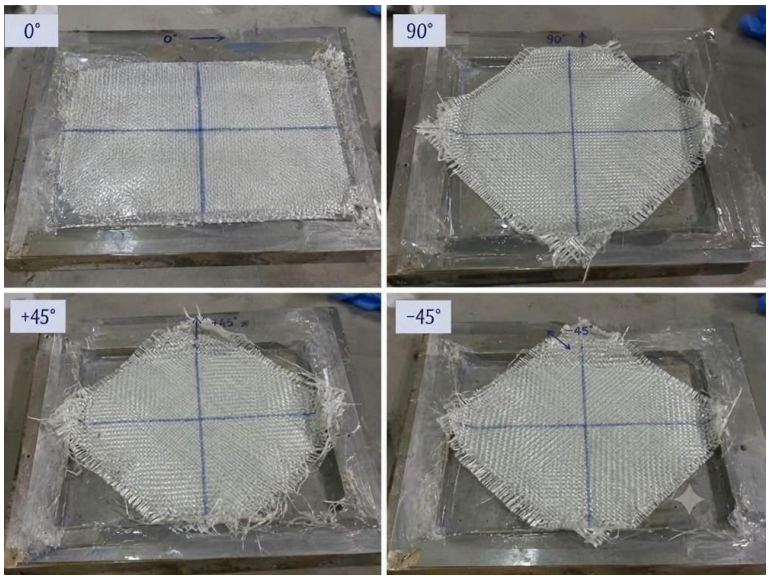


Fig. 10. Woven plies positioned on the mould at 0°, 90°, +45° and −45°.

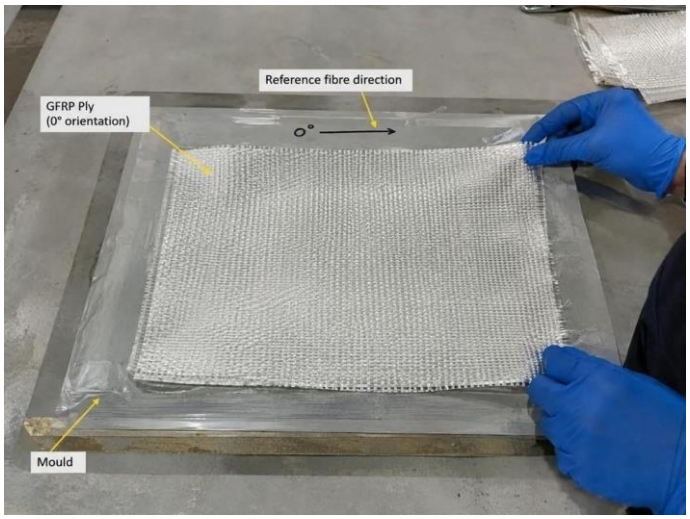


Fig. 11. First ply (0° orientation) placed on the mould with the reference direction marked.

Weighing and mould preparation. The fabric and the aluminium powder were weighed before fabrication (Fig. 12). The mould surface was cleaned and grease was applied as the release agent (Fig. 13).



Fig. 12. Weighing: (a) fabric on the balance; (b) aluminium powder on the analytical balance.



Fig. 13. Application of the release agent on the mould.

Matrix preparation, resin application and rolling. The resin and hardener were measured in a beaker (250 ml and 125 ml) and mixed. For the filled laminates, 15 g of aluminium powder was added to the resin and stirred before use (Fig. 14). Resin was brushed over the fabric so that the fibres were wetted, the next ply was positioned at its angle, and the process was repeated until all 12 plies were laid. A roller was passed over each layer to improve consolidation and reduce trapped air (Fig. 15).



Fig. 14. Preparation of the epoxy matrix.

(a) (b)



Fig. 15. Resin application and rolling: (a) resin applied with a brush; (b) rolling of the wetted laminate.

Curing and demoulding. The completed lay-up was covered with plastic film and left to cure for two days. The cured laminates were then removed from the mould and checked visually (Fig. 16). Four laminates were made: L1 (symmetric, no aluminium), L2 (unsymmetric, no aluminium), L3 (unsymmetric, with aluminium) and L4 (symmetric, with aluminium). The laminates with aluminium powder are visibly greyer than those without it (Fig. 17). The final thickness and fibre volume fraction of the plates were not recorded.

(a) (b)



Fig. 16. Curing and demoulding: (a) lay-up under cover during curing; (b) mould plates after demoulding.

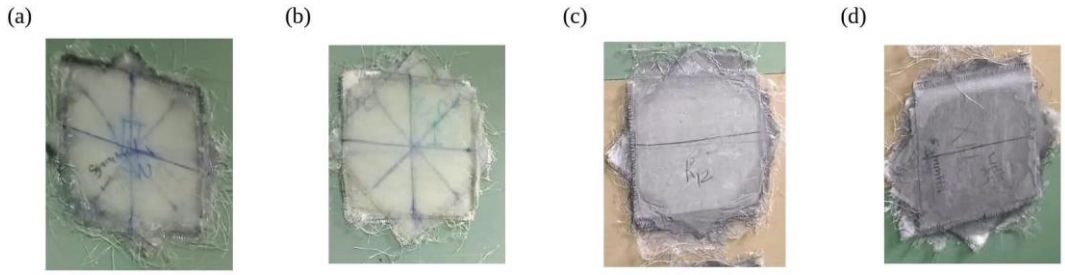


Fig. 17. The four fabricated laminates: (a) L1, symmetric, no Al; (b) L2, unsymmetric, no Al; (c) L3, unsymmetric, with Al; (d) L4, symmetric, with Al.

1.12 Tensile test

Tensile tests were done on 16 October 2026 on a TUF-C-1000 universal testing machine at Nitte Meenakshi Institute of Technology, Yelahanka, Bengaluru. One flat strip of 250 mm × 25 mm × 5 mm (cross-section 125 mmZ) cut from each laminate was gripped at both ends and pulled to failure with no pre-load and an initial gauge length of 100 mm. The machine recorded load against crosshead travel (CHT) and marked the yield, peak and break points on the curve. The specimen axis was aligned with the reference fibre direction marked during lay-up, so that all laminates were tested in the same direction. Flat strips were used instead of the dog-bone shape of ASTM D638 [12], so the strengths are meant for comparing the four laminates with each other and not as standard material values.

The tensile strength is the peak load divided by the original cross-section area:

$$\sigma = P / A \qquad (1)$$

where σ is the tensile strength (MPa), P the peak load (N) and A the cross-section area (mmZ). For Case 1, σ = 15 150 N / 125 mmZ = 121.2 MPa. The yield stress was calculated in the same way from the load at the yield point marked by the machine.

1.13 Three-point bending test

Three-point bending tests were done on 28 October 2026 on a universal testing machine with data-acquisition software, using one specimen per laminate (width 25 mm, support span 100 mm, test speed 20 mm/min). The specimen is supported at two points and loaded at mid-span. The software reports the stress at peak in kN/mmZ, and the loads shown on the screen are rounded to whole kN, so the peak load was recovered from the recorded stress and the area used by the software. The peak loads were only 22.65 N to 26.55 N, which is close to the load resolution of the machine. Absolute flexural strength is therefore not reported. The bending strength was calculated from the beam equation of ASTM D790 [13]

$$\sigma_b = 3PL / (2bdZ) \qquad (2)$$

with P the peak load, L the span, b the width and d the thickness, and it is given relative to Case 1. For specimens of equal size the ratios between laminates do not depend on the thickness value used, so the relative values are reliable even where the absolute values are not.

1.14 ANSYS model

A linear static analysis of the four configurations was run in ANSYS Mechanical APDL (2026 R1). The model is a long rectangular strip of 12 layers (5 mm in total, about 0.417 mm per layer), meshed with a regular grid of SHELL181 elements. One end is fixed and an axial load of 10 kN is applied at the other end, identical for all four cases, so that stress and deformation can be compared directly. The aluminium filler was entered as 5 percent, which is not the same as the 15 g used in the fabricated laminates. The nominal stress under 10 kN on a 125 mmZ section is 80 MPa. The von Mises stress is used only to compare stress patterns and not to predict failure, because the laminate is anisotropic. The 10 kN load is below the yield loads of the tensile curves (10.40 to 12.40 kN), so a linear analysis is a fair working-load model, although the strip is idealised and has no grips, voids or imperfect fibre–matrix bond.

RESULTS AND DISCUSSION

1.15 Tensile results (experimental)

All four strips showed a nearly linear load–travel curve up to the peak and then a sudden drop, which is the brittle failure expected from a woven glass/epoxy laminate. The yield point marked by the machine fell at about 80 % of the peak load for every laminate. The curves of the four laminates are given in Fig. 18 to Fig. 21.

Case 1, symmetric without aluminium. The load rose almost linearly to a peak of 15.15 kN at 10.44 mm travel, with yield at 12.10 kN (yield stress 96.8 MPa). The tensile strength was 121.2 MPa.

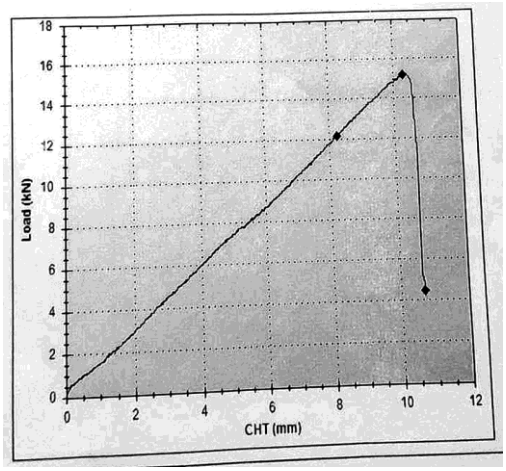


Fig. 18. Tensile load versus crosshead travel, Case 1 (symmetric, no Al).

Case 2, symmetric with aluminium. The peak load was 15.50 kN, the highest of the four, reached at the smallest travel (8.79 mm). Yield was at 12.40 kN (99.2 MPa) and the tensile strength was 124.0 MPa.

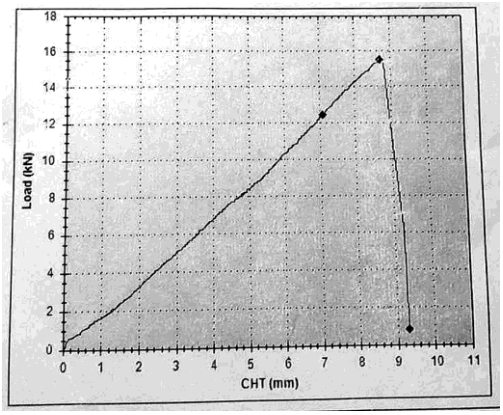


Fig. 19. Tensile load versus crosshead travel, Case 2 (symmetric, with Al).

Case 3, unsymmetric without aluminium. The peak load was 14.00 kN at 11.11 mm, lower than in the symmetric laminates and reached at a larger travel. Yield was at 11.15 kN (89.2 MPa) and the tensile strength was 112.0 MPa.

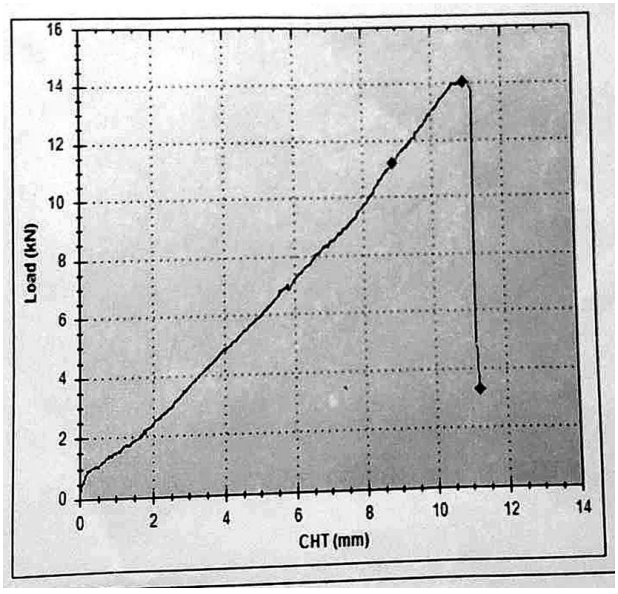


Fig. 20. Tensile load versus crosshead travel, Case 3 (unsymmetric, no Al).

Case 4, unsymmetric with aluminium. The peak load of 13.05 kN was the lowest of the four, and the travel at peak (11.32 mm) was the longest. Yield was at 10.40 kN (83.2 MPa) and the tensile strength was 104.4 MPa.

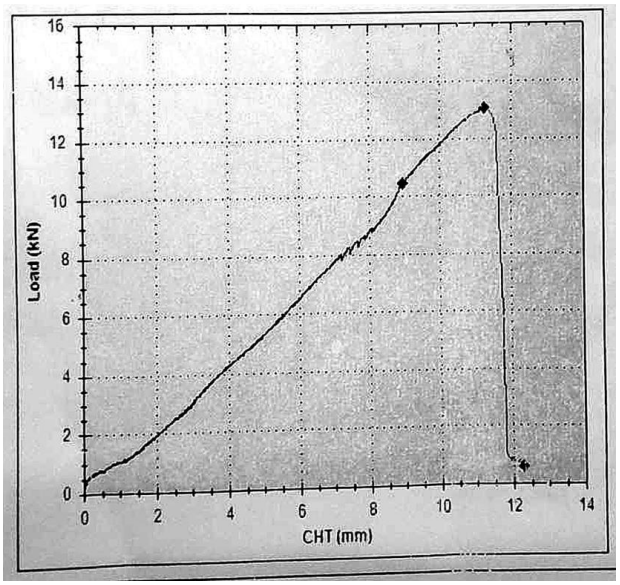


Fig. 21. Tensile load versus crosshead travel, Case 4 (unsymmetric, with Al).

Table 4. Tensile test results (one specimen per laminate; 250 × 25 × 5 mm strips, 100 mm gauge length).

Case	Load at yield (kN)	Yield stress (MPa)	Peak load (kN)	Tensile strength (MPa)	Change in strength vs Case 1
1 Symmetric, no Al	12.10	96.8	15.15	121.2	—
2 Symmetric, Al	12.40	99.2	15.50	124.0	+2.3 %
3 Unsymmetric, no Al	11.15	89.2	14.00	112.0	−7.6 %
4 Unsymmetric, Al	10.40	83.2	13.05	104.4	−13.9 %

The order of tensile strength is Case 2 > Case 1 > Case 3 > Case 4. The 2.3 % gap between Cases 1 and 2 is within the scatter expected from a single hand lay-up specimen, so the two symmetric laminates are practically equal. The clear result is that both symmetric laminates were stronger than both unsymmetric ones: by 8.2 % without aluminium (Case 1 against Case 3) and by 18.8 % with aluminium (Case 2 against Case 4).

1.16 Bending results (experimental)

The bending curves rose almost linearly to a peak at 8.6 to 9.8 mm displacement and then fell in steps as the plies failed one after another (Fig. 22 to Fig. 25). The load axis of the software plot is rounded by the display, so the curves are shown for their shape. Case 2 showed the longest tail after the peak, and its test ended at 32.00 % of the span, against 18.86 % to 22.18 % for the others.

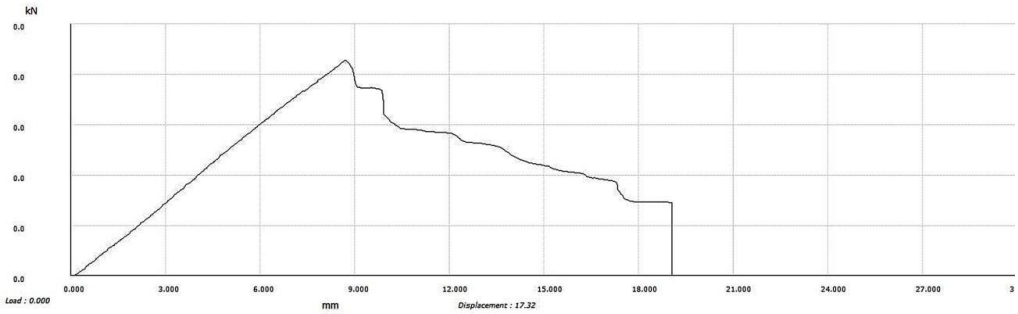


Fig. 22. Bending load versus displacement, Case 1 (symmetric, no Al); horizontal axis in mm.

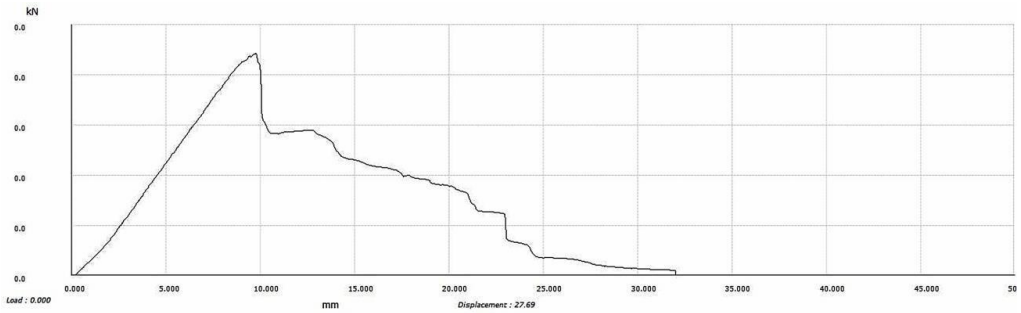


Fig. 23. Bending load versus displacement, Case 2 (symmetric, with Al); horizontal axis in mm.

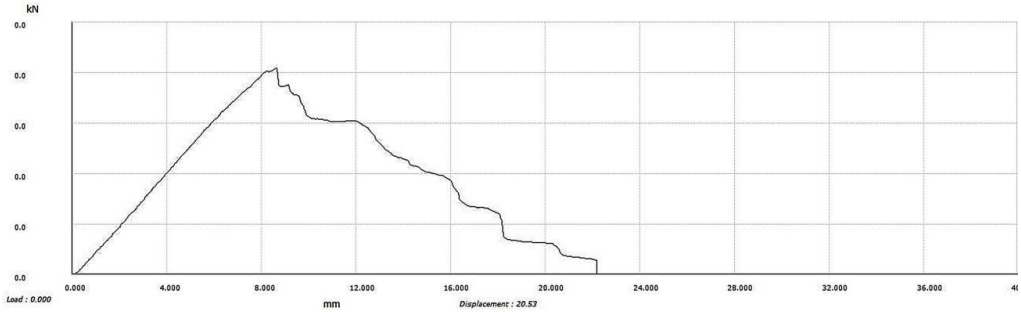


Fig. 24. Bending load versus displacement, Case 3 (unsymmetric, no Al); horizontal axis in mm.

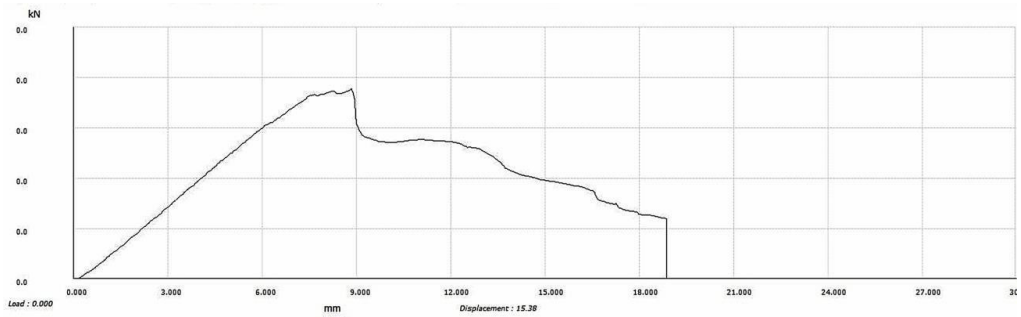


Fig. 25. Bending load versus displacement, Case 4 (unsymmetric, with Al); horizontal axis in mm.

Table 5. Bending test results relative to Case 1 (one specimen per laminate).

Case	Displacement at peak (mm)	Bending strength relative to Case 1	Change vs Case 1
1 Symmetric, no Al	8.71	100 %	—
2 Symmetric, Al	9.76	103.5 %	+3.5 %
3 Unsymmetric, no Al	8.64	95.9 %	−4.1 %
4 Unsymmetric, Al	8.82	88.3 %	−11.7 %

The bending strength order (Case 2 > 1 > 3 > 4) is the same as in tension. The symmetric laminates were stronger than the unsymmetric ones by 4.3 % without and 17.2 % with aluminium. Case 2 was only 3.5 % above Case 1, which is within the scatter expected from a single specimen. In bending, the lower strength of the unsymmetric laminates is again largest when aluminium is present (−11.7 % for Case 4 against Case 1).

1.17 ANSYS results (numerical)

The results in this section come from the ANSYS model of Section 4.7 and are numerical, not experimental. Fig. 26 to Fig. 29 show the von Mises stress and Fig. 30 to Fig. 33 the total deformation of each case. In every stress plot most of the strip lies in one narrow colour band close to the nominal 80 MPa, and the maximum appears only at the loaded end, at the corners of the strip. It is a local effect of the way the load is applied and the end is held, and not the stress in the body of the strip.

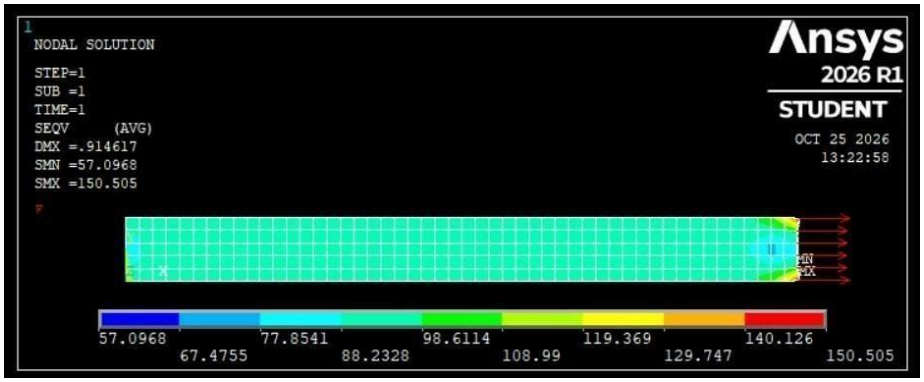


Fig. 26. ANSYS von Mises stress, Case 1: maximum 150.505 MPa.

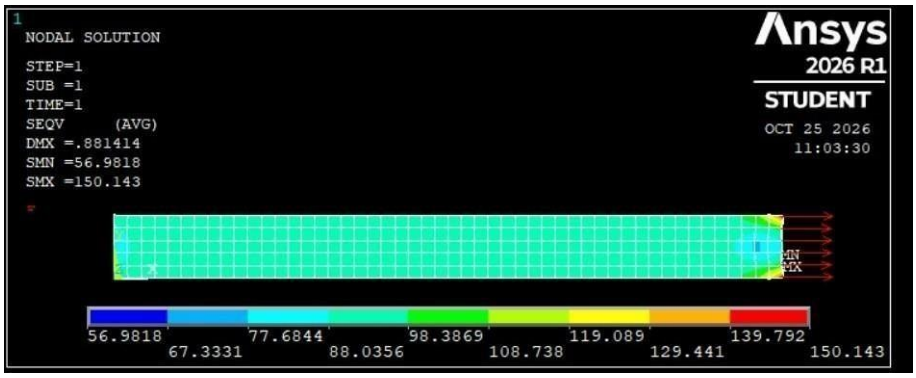


Fig. 27. ANSYS von Mises stress, Case 2: maximum 150.143 MPa.

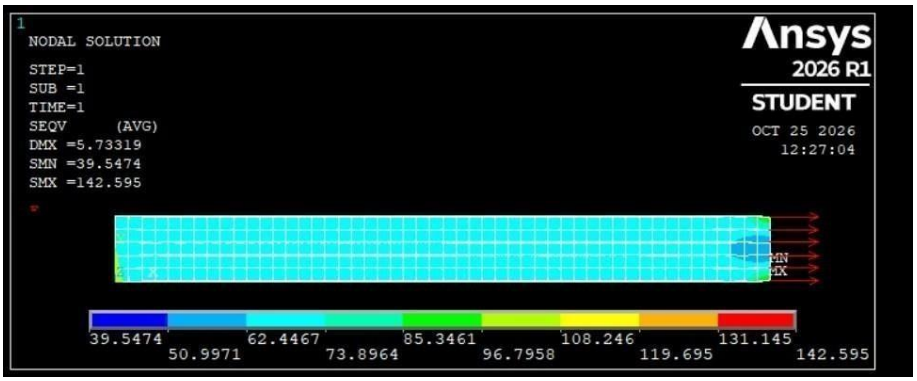


Fig. 28. ANSYS von Mises stress, Case 3: maximum 142.595 MPa.

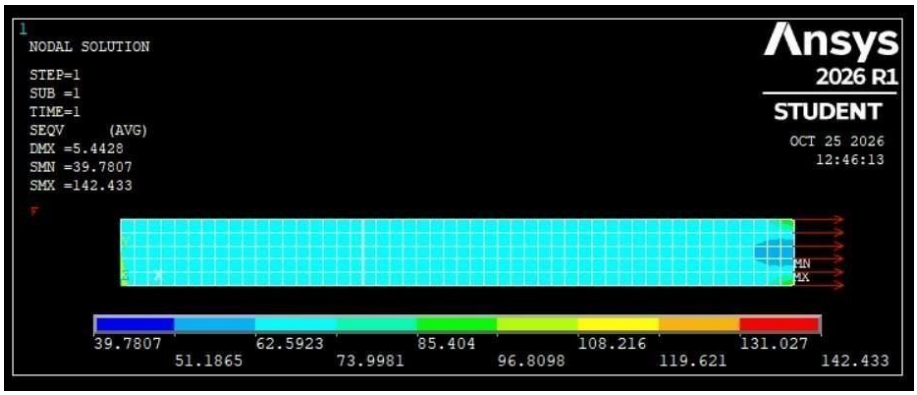


Fig. 29. ANSYS von Mises stress, Case 4: maximum 142.433 MPa.

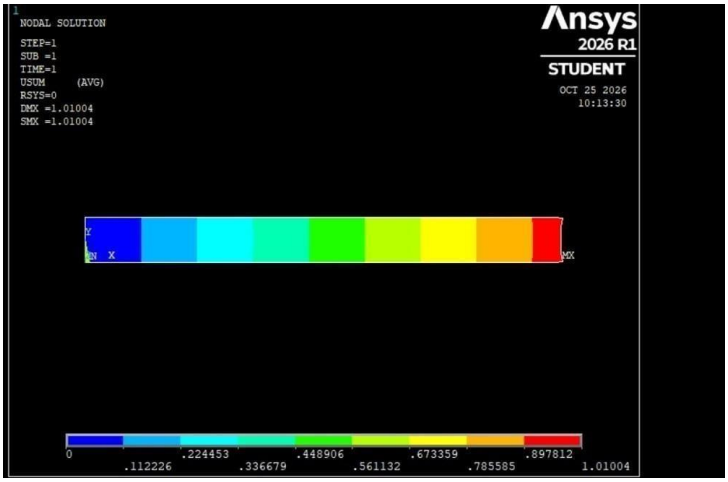


Fig. 30. ANSYS total deformation, Case 1: maximum 1.01004 mm.

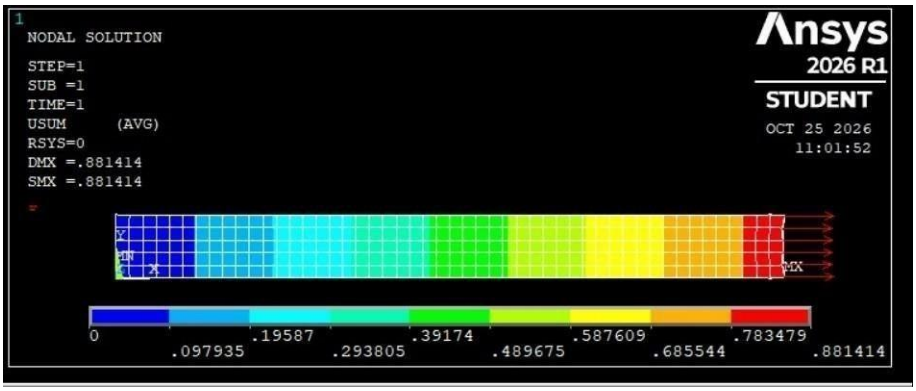


Fig. 31. ANSYS total deformation, Case 2: maximum 0.881414 mm.

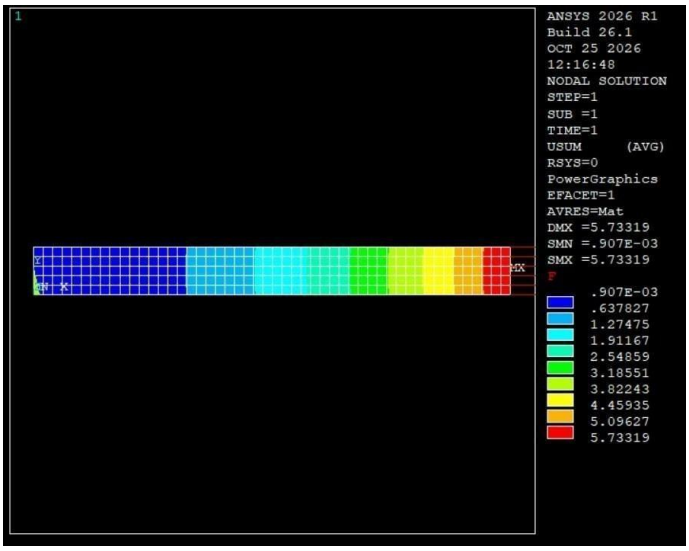


Fig. 32. ANSYS total deformation, Case 3: maximum 5.73319 mm.

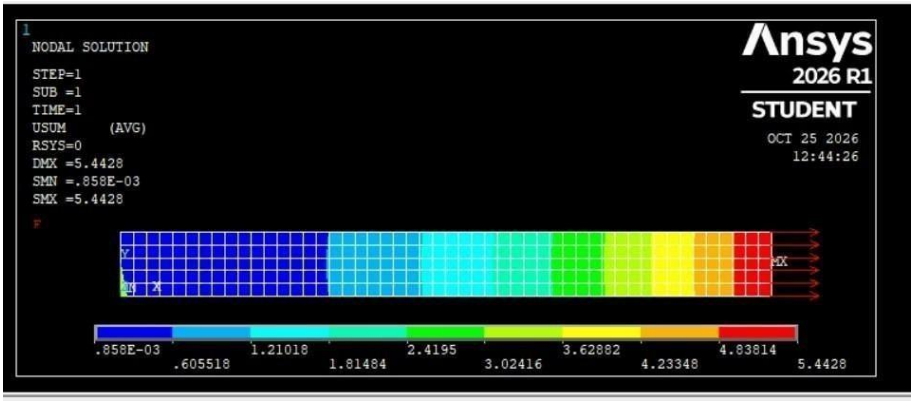


Fig. 33. ANSYS total deformation, Case 4: maximum 5.4428 mm.

Table 6. ANSYS results under a 10 kN axial load (numerical).

Case	Max. total deformation (mm)	Max. von Mises stress (MPa)
1 Symmetric, no Al	1.01004	150.505
2 Symmetric, Al	0.881414	150.143
3 Unsymmetric, no Al	5.73319	142.595
4 Unsymmetric, Al	5.4428	142.433

The maximum stress is almost the same within each stacking type, so the filler has a negligible effect on it in this model. The symmetric laminates deformed less than the unsymmetric ones, and the filled laminate deformed less than the unfilled one in both pairs (−12.7 % for the symmetric pair and −5.1 % for the unsymmetric pair). This agrees with aluminium being stiffer than epoxy, but the change from the filler is small next to the effect of the stacking. The model has no voids or grip effects and uses 5 percent filler, so it is used for direction only and not for absolute values.

1.18 Why the laminates behave differently

Symmetric versus unsymmetric. In classical laminate theory the in-plane stiffness depends on the ply angles and thicknesses, not on their order [2,3]. Our two sequences have the same plies at each angle (Section 4.2), so their ideal in-plane stiffness is the same. What changes is the bending–extension coupling, and the residual curing stress, of the unsymmetric laminate. A likely reading is that the unsymmetric strips bent slightly while being pulled, and so failed at a lower load; the same coupling would also reduce their resistance in bending. We did not measure

curvature, so this is the probable explanation and not a proven one. Differences in resin content and voids between plates, which hand lay-up cannot avoid, may also contribute. The ANSYS model points the same way, but its difference between the two stackings is much larger than in the tests, so it is used for direction only.

Aluminium powder. The filler did not act the same way in the two pairs: it raised the tensile strength by 2.3 % in the symmetric pair and lowered it by 6.8 % in the unsymmetric pair, with the same pattern in bending (+3.5 % and
−7.9 %). Aluminium is stiffer than epoxy, which may help the matrix, but it also makes the resin thicker, which can reduce wetting of the fabric and leave voids or clusters of powder. Which of these effects dominated could not be checked, because fracture surfaces were not examined. The small gain in the symmetric pair is within specimen scatter, so it should not be taken as a real benefit.

COMPARATIVE ANALYSIS

Table 7 collects the percentage effect of stacking symmetry and of the filler on the two experimental strengths, and Fig. 34 shows the strengths of each laminate relative to Case 1.

Table 7. Percentage effect of stacking symmetry and aluminium powder (experimental, one specimen per laminate).

Comparison	Tensile strength	Bending strength
Symmetric vs unsymmetric, no Al (Case 1 vs 3)	+8.2 %	+4.3 %
Symmetric vs unsymmetric, with Al (Case 2 vs 4)	+18.8 %	+17.2 %
Adding Al, symmetric (Case 2 vs 1)	+2.3 %	+3.5 %
Adding Al, unsymmetric (Case 4 vs 3)	−6.8 %	−7.9 %

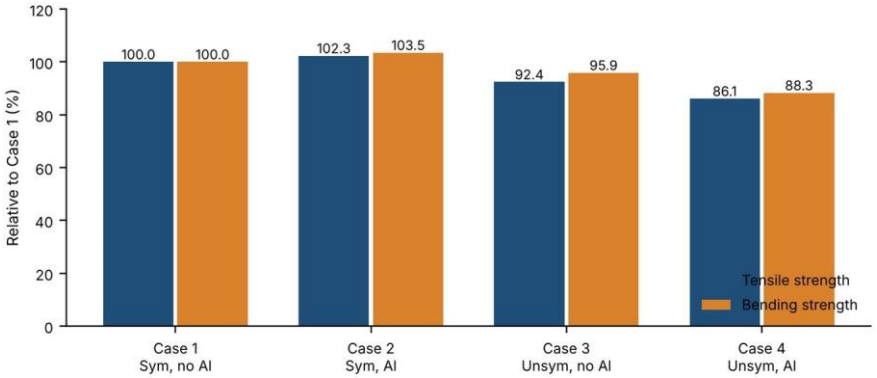


Fig. 34. Tensile and bending strength of each laminate relative to Case 1 (experimental, one specimen each).

Table 8. Rank of each laminate by strength.

Property (1 = highest)	Case 1 Sym, no Al	Case 2 Sym, Al	Case 3 Unsym, no Al	Case 4 Unsym, Al
Tensile strength	2	1	3	4
Bending strength	2	1	3	4

Stacking symmetry has the larger and more consistent effect. Both symmetric laminates were stronger than both unsymmetric ones in tension and in bending, and the ANSYS model points the same way. The loss from unsymmetry was therefore measurable even though the two sequences differ by only two exchanged plies. It is largest when aluminium is present (18.8 % in tension and 17.2 % in bending), partly because Case 4 was the weakest laminate in both tests.

Aluminium powder did not give a consistent benefit. The gains in the symmetric pair (2.3 % in tension, 3.5 % in bending) are too small to separate from specimen scatter, while the losses in the unsymmetric pair (6.8 % and 7.9

%) are larger. The only effect of the filler that stands out in these tests is therefore the negative one in the unsymmetric laminate, and even that rests on one specimen per laminate.

Practical meaning. On these results the symmetric laminates (Cases 1 and 2) are the better choice for lightly loaded secondary structures such as fairings and covers [1], and the unsymmetric laminates are the weaker choice unless the coupling is wanted on purpose. The aluminium powder used here does not justify its extra handling for strength reasons alone; any use of it would have to rest on properties that were not measured, such as thermal conductivity or wear resistance. This study does not give design allowables, which need many specimens per configuration and a building-block test programme as described in FAA AC 20-107B [14].

Limitations. Only one specimen was tested per laminate, so no scatter can be given. Tensile strips were flat and not standard dog-bones. Plate thickness and fibre volume fraction were not recorded. The ANSYS filler content (5 percent) differs from the plates (15 g), and the mechanisms proposed in Section 5.4 were not checked by microscopy.

CONCLUSION

Four woven E-glass/epoxy laminates (symmetric and unsymmetric, with and without 15 g of aluminium powder) were made by hand lay-up and compared in tension, in bending and in a separate ANSYS analysis. Each experimental value comes from one specimen, so the findings are trends. The conclusions supported by the measurements are:

- Tensile strength was 124.0, 121.2, 112.0 and 104.4 MPa for the symmetric filled, symmetric unfilled, unsymmetric unfilled and unsymmetric filled laminates. Bending strength followed the same order.
- Symmetric stacking gave higher strength than unsymmetric stacking: +8.2 % and +18.8 % in tension and +4.3

  % and +17.2 % in bending, although the two sequences differ only in the position of two plies.
- Aluminium powder did not give a consistent improvement. It changed tensile strength by +2.3 % in the symmetric pair and −6.8 % in the unsymmetric pair, and bending strength by +3.5 % and −7.9 %.
- The separate ANSYS model agrees with the tests that symmetric stacking is the better arrangement. It is a trend check under one working load and does not predict strength.

Scope for future work

- Test several standard specimens per laminate so that averages and scatter are available.
- Add impact testing to complete the comparison with tension and bending.

- Vary the aluminium content and particle size (micro and nano) to find the amount that gives the best balance of strength and toughness.
- Compare other stacking sequences, such as angle-ply and cross-ply laminates.
- Use vacuum bagging or infusion instead of hand lay-up to reduce voids and raise the fibre volume fraction.
- Examine fracture surfaces by scanning electron microscopy, and measure the curvature of unsymmetric laminates after curing.
- Refine the ANSYS model with ply-level failure criteria and a filler content matching the plates.

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