Metal Thickness, Fiber Volume Fraction Effect on the Tensile Properties, Debonding of Hybrid Laminates

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ABSTRACT: Hybrid aluminum glass fiber laminates consist of glass fiber reinforced plastic (GFRP) bonded with thin aluminum sheets on either side. Laminates with different aluminum thickness and fiber volume fractions were fabricated by hand layup method and were tested under tensile loading. The variations in the elastic modulus, yield strength, and ultimate strength as well as the extent of delamination were studied. Rule of mixtures predictions of laminate properties under tensile loading compared well with the experimental results. Delamination was found to depend upon the thickness of aluminum alloy sheet, among other factors. Scanning electron microscopic pictures on the fractured hybrid specimen showed that the GFRP failure was due to fiber fracture, fiber pullout, and fiber matrix debonding. On an overall basis, the hybrid laminate showed a significant improvement in the mechanical properties when compared with the GFRP or monolithic aluminum. Though an increase in fiber volume fraction increases the elastic modulus, it does not have any notable effect on the failure mechanism or debonding of the hybrid aluminum glass fiber laminate.

KEY WORDS: hybrid aluminum glass fiber laminate, rule of mixtures, tensile properties.

INTRODUCTION

WHEN TWO DISSIMILAR materials like a metal and a fiber-reinforced plastic (FRP) are bonded, their good material properties are combined. However, the moderate to poor properties are also combined [1]. The good characteristics of metals such as ductility,

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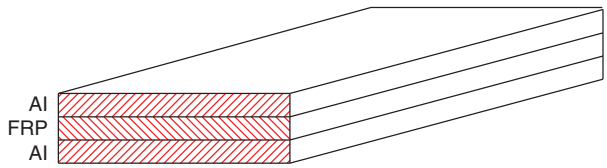

Figure 1. *Hybrid laminate.*

specific stiffness, impact, and damage tolerances, together with the benefits of fiber composite materials such as high specific strength, good corrosion, and fatigue resistances are obtained. These hybrid laminates are used to substitute monolithic metal, resulting in weight savings without much compromise to the strength-to-weight ratio. In particular, these materials find application in tension-dominated structural components and where a small saving in weight could lead to a large saving in fuel cost, as in aerospace and automobile structures, in the long run [2]. These materials can be used where a glossy fine metallic surface finish is required as in automobiles.

The hybrid aluminum glass fiber reinforced plastic (GFRP) laminate consists of thin aluminum alloy sheets bonded to either side of GFRP layer as shown in Figure 1. There may be any number of aluminum layers and FRP layers but the ratio between the number of aluminum layers and FRP layers should be $(n+1)/n$, where n is the number of FRP layers [3]. This implies that the aluminum layers will always be the outermost layer. There are many parameters involved in controlling the mechanical properties of such a hybrid system. These are

(1) Thickness of metal layers
(2) Thickness of FRP layers
(3) Fiber volume fraction in the FRP
(4) Type of matrix and fiber material in the FRP layers
(5) Type of metal in the metal layers
(6) Stacking sequence, fiber orientation in the FRP layers
(7) Type of adhesives used for bonding the metal and FRP layer

While the development of current hybrid metal fiber laminate has been primarily led by changing the type of fiber resin matrix, like aramid fiber, glass fiber and carbon fiber in thermoset [4,5], or thermoplastic resins, it is interesting to explore the influence of other parameters on the mechanical properties.

In this research, an attempt has been made to change the metal thickness and the fiber volume fraction in the FRP of the hybrid laminate and study about their influence over the tensile properties and the extent of debonding of the laminate.

EXPERIMENTAL

Materials

The materials used in the fabrication of the test specimen are:

(1) Aluminum alloy sheets – AA 1050 H 14
(2) E-glass fibers reinforced in epoxy resin (LY 556) matrix
(3) Epoxy resin as adhesive

The properties of these constituent materials are given in Table 1.

Table 1. Material properties.

S. No.	Material	Elastic modulus (GPa)	Yield strength (MPa)	Ultimate strength (MPa)	Poisson's ratio	Failure strain (μm)	Specific weight (Kg/m^3)
1	Aluminum	68	120	145	0.33	25160	2700
2	E-glass fiber	72	–	–	0.20	–	2540
3	Epoxy	3.5	–	–	0.22	–	1100
4	GFRP (Exp)	19.8	–	380	0.208	19800	1440
5	HL (Exp)	41.11	71.6	256	0.266	22000	2093

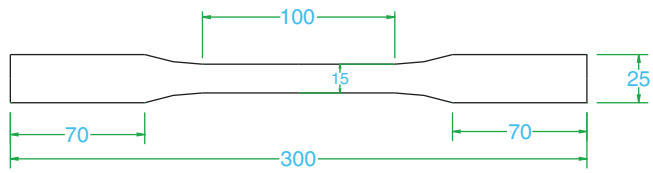

Figure 2. *Geometry of hybrid laminate test specimen.*

Specimen Geometry

The specimen is made to a dogbone shape as shown in Figure 2. As there is no standard specification for tensile testing of such hybrid systems, the dogbone profile used to test FRP specimens has been adopted here [6,7]. The thickness of the aluminum sheets bonded to either side of the FRP layer are given in Table 2.

The metal thickness fraction is defined as the ratio between the aluminum thickness and the total thickness of the hybrid laminate. The various fiber volume fractions used in the GFRP are: 24%, 30%, and 35%.

Specimen Fabrication

Commercially available aluminum alloy sheet of grade AA 1050 H 14, supplied by HINDALCO, was uniformly roughened on one side by scratching the surface using very fine emery paper. This roughening helps to get a good bonding of the epoxy resin with aluminum alloy sheet. An acrylic mold, as per the specimen shape, was made. The aluminum alloy sheet was cut in the rolling direction, as per the specimen shape, using a fine hacksaw in order to avoid any burrs on the edges. The surfaces of the aluminum were wiped and cleaned using acetone to remove any dust particles as well as oxide scale. Chopped strand mats made of E-glass fiber were cut to the specimen shape. Epoxy resin LY 556 and hardener Aradur HY 951 supplied by HUNTSMAN were mixed in the ratio 100 parts to 10 parts by weight, respectively. The outer surfaces of the aluminum sheets and the inner surface of the mold cavity were coated with wax. An aluminum sheet was placed inside the mold with the roughened surface facing up. A coating of the resin-hardener mixture was applied over the roughened aluminum surface. The CSM was placed over the above coating. Unidirectional fibers were then placed under tension over the CSM. Few random-oriented fibers were also placed over the UD E-glass fibers. The UD fibers and the random-oriented fibers were wetted with resin-hardener mixture. A CSM layer was again placed and wetted with the resin-hardener mixture.

Table 2. Thickness of aluminum and FRP layers.

S. No.	MTF	Aluminum (mm)	FRP (mm)	Total thickness (mm)
1	0.4516	0.7 + 0.7	1.7	3.1
2	0.4137	0.6 + 0.6	1.7	2.9
3	0.3703	0.5 + 0.5	1.7	2.7
4	0.3200	0.4 + 0.4	1.7	2.5

The outer aluminum sheet was then placed over this CSM. The mold cavity was closed by a wax-coated acrylic sheet. Weights were placed over the sheet in such a way that a uniform pressure was obtained. The set up was left for curing for 6 h at room temperature.

Any excess resin oozed out. The hybrid laminate was taken out of the mold and epoxy paste sticking on the sides was cleaned. End tabs were made by winding glass fiber rovings impregnated with epoxy mixture paste over the tab portion of the specimen.

Emery paper was placed over the above rovings in order to ensure good gripping during tensile testing.

Specimens of different fiber volume fractions were made by varying the volume percentage of fibers. Specimens of plain GFRP to the required thickness were fabricated as per the same procedure outlined above, but without the aluminum sheets.

Plain aluminum specimens of thickness 2 mm were cut and tensile tested according to ASTM E-8-2002 at room temperature.

Specimen Testing

All the specimens were tested in a Universal tensile testing machine (SIMADZU make) with a recommended crosshead speed of 1 mm/min at room temperature. Electrical resistance strain gages were bonded on the specimen surface in the longitudinal and transverse directions within a gage length of 50 mm and the linear and lateral strains were measured using an electronic strain meter. Due care was taken to align the specimen without any eccentricity as well as no slipping of the specimen between the gripping jaws.

RESULTS AND DISCUSSIONS

Effect of Metal Thickness and Fiber Volume Fraction on the Elastic Modulus of the Hybrid Laminate

Theoretical prediction based on ROM [8]:

$$E_{\mathrm{hl}} = (\mathrm{MTF} * E_{A1}) + (1 - \mathrm{MTF}) * E_{\mathrm{frp}} \tag{1}$$

The elastic modulus of the aluminum alloy and that of GFRP (at 24% fiber volume fraction) is obtained experimentally and not by applying ROM to their constituent

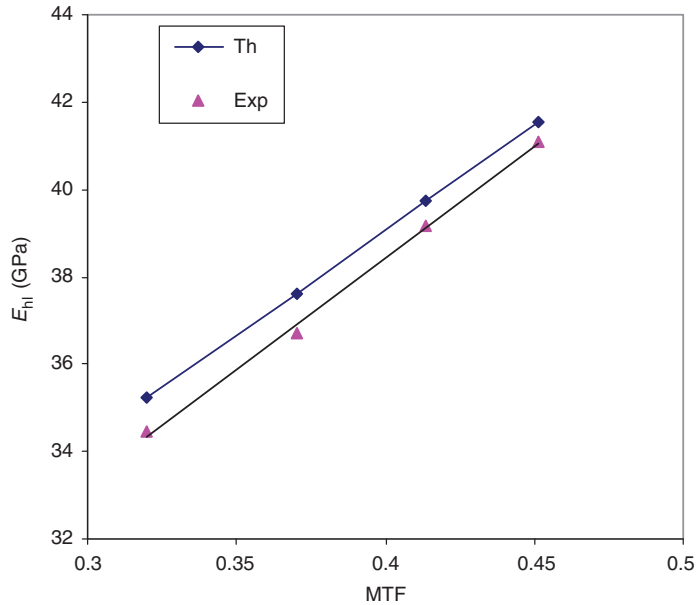

Figure 3. *Metal thickness fraction vs elastic modulus.*

properties i.e., glass fibers and epoxy matrix. The experimental and theoretical values of elastic modulus of the hybrid laminate for various MTF are plotted and shown in Figure 3.

EFFECT OF METAL THICKNESS FRACTION

(1) It is noted that an increase in the metal thickness fraction increases the elastic modulus of the hybrid aluminum–GFRP laminate. This is due to the fact that aluminum behaves as an elastic plastic material and the GFRP is linear and brittle up to the point of failure. Hence a higher metal volume tends to increase the elastic behavior/modulus of the hybrid material.

(2) It was also observed that when the metal thickness is kept at 0.7 mm, the FRP fails first followed by fracture of aluminum. After FRP failure, the aluminum layers starts taking up the entire load with practically no delamination under tensile loading. The sudden release of strain energy at the time of GFRP failure does not give rise to delamination indicating a good bonding has been achieved. If the metal thickness is kept below 0.7 mm, the aluminum breaks first and immediately followed by GFRP failure. However, in this case a considerable amount of delamination is found. The reason for this behavior could be that a lower metal volume fraction results in a lower yield point and hence the early creation of a plastic zone in the hybrid structure. Within the plastic zone the metal experiences a higher stress and undergoes a larger deformation than the elastic fiber layer. This difference causes delamination, especially when the maximum shear strain of the epoxy interface is exceeded.

(3) The predicted value and the experimental value differ by 2%, with the experimental value on the lower side.

Table 3. Elastic modulus of hybrid laminates for various fiber volume fractions.

MTF	FBV (%)	E_{Al}	E_{frp}	E_{hl} (Th)	E_{hl} (Exp)	E_{frp}/E_{Al}	E_{hl}/E_{Al} (Th)	E_{hl}/E_{Al} (Exp)
0.4516	24	68	19.8	41.56	41.11	0.2912	0.6111	0.6045
0.4516	30	68	23.82	43.76	43.1	0.3503	0.6435	0.6338
0.4516	35	68	27.31	45.67	44.8	0.4016	0.6716	0.6588
0.3703	24	68	19.8	37.63	36.72	0.2912	0.5534	0.5400
0.3703	30	68	23.82	40.16	39.43	0.3503	0.5906	0.5798
0.3703	35	68	27.31	42.36	41.34	0.4016	0.6229	0.6079

EFFECT OF FIBER VOLUME FRACTION

(1) The elastic modulus of hybrid laminates for various fiber volume fractions are given in Table 3. It is observed that for a given MTF, an increase in fiber volume fraction in the FRP tends to increase the elastic modulus of the hybrid laminate. This is due to the fact that as the fiber volume fraction increases, the elastic modulus of FRP increases [9]. Hence a higher contribution of strength from the FRP side increases the elastic modulus as well as stiffness of the hybrid laminate. To get a fair view, both the E_{hl} and E_{frp} are normalized with respect to E_{Al}.

(2) It is also observed, that as the MTF decreases, there is a decrease in the elastic modulus of the hybrid laminate. However, if we reduce the MTF and increase the fiber volume fraction we find that the elastic modulus of the hybrid laminate is not significantly affected. Hence if we desire to reduce the total thickness of the hybrid structure, we can reduce the thickness of the aluminum layer up to a level where no delamination occurs and yet retain the elastic modulus by increasing the fiber volume fraction.

Effect of Metal Thickness and Fiber Volume Fraction on the Tensile Yield Stress of the Hybrid Laminate

Theoretical prediction based on ROM:

$$\sigma_{y\,hl} = \mathrm{MTF} * \sigma_{y\,A1} + (1 - \mathrm{MTF})\sigma_{y\,frp}, \tag{2}$$

$$\varepsilon_{hl} = \varepsilon_{A1} = \varepsilon_{frp}, \tag{3}$$

$$\sigma_{y\,frp}/E_{frp} = \sigma_{y\,A1}/E_{Al}, \tag{4}$$

$$\sigma_{y\,frp} = \sigma_{y\,A1} * E_{frp}/E_{Al}. \tag{5}$$

Substituting for $\sigma_{y\ frp}$ in Equation (2):

$$\sigma_{y\,hl} = [(\mathrm{MTF}+(1 - \mathrm{MTF})E_{frp}/E_{Al})]\sigma_{y\,Al}. \tag{6}$$

The yield stress of hybrid laminate is found experimentally by identifying the stress at the knee point of the bilinear stress strain curve (Figure 4).

EFFECT OF METAL THICKNESS FRACTION

(1) The tensile yield strength of hybrid laminate for various metal thickness fractions are plotted and shown in Figure 5. It is observed that as the MTF increases, the yield stress

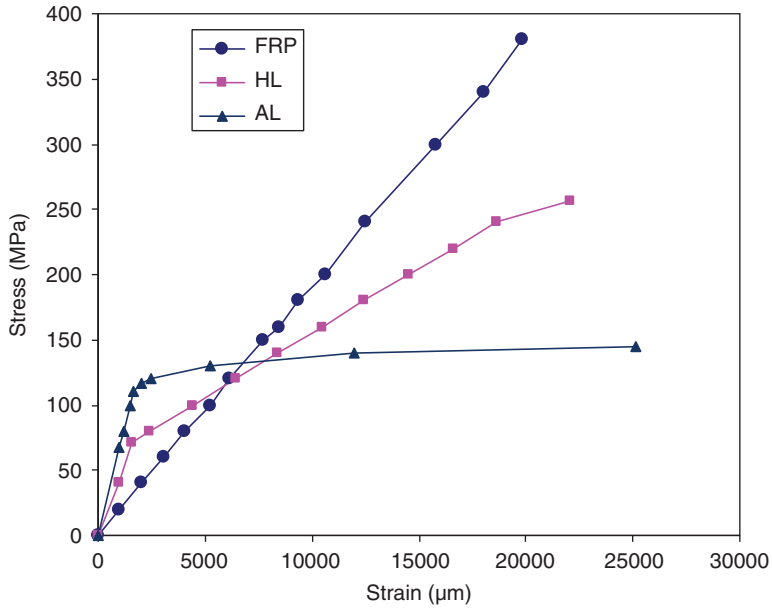

Figure 4. *Stress–Strain diagram.*

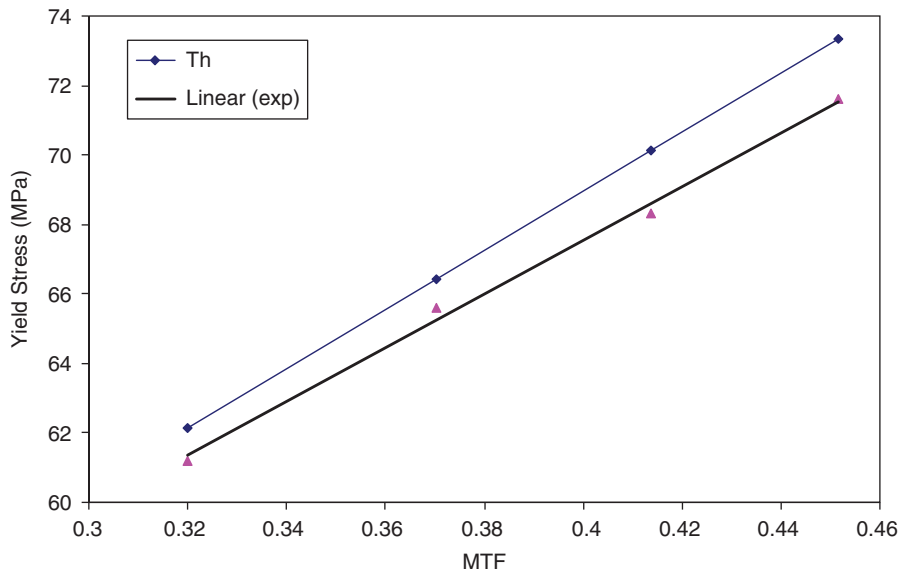

Figure 5. *Metal thickness fraction vs yield stress.*

of the hybrid laminate increases. This is again due to the fact that a higher metal volume in the hybrid laminate increases the elastic modulus and subsequently the yield point, as yielding is evident only because of the metal layer showing yielding.

(2) The difference between the theoretical and experimental value is about 2%.

Table 4. Tensile yield strength of hybrid laminates for various fiber volume fractions.

MTF	FBV (%)	E_{frp}	$\sigma_{y\,Al}$	$\sigma_{y\,hl}$ (Th)	$\sigma_{y\,hl}$ (Exp)	E_{frp}/E_{Al}	$\sigma_{y\,hl}/\sigma_{y\,Al}$(Th)	$\sigma_{y\,hl}/\sigma_{y\,Al}$ (Exp)
0.4516	24	19.8	120	73.35	71.6	0.2911	0.6112	0.5966
0.4516	30	23.82	120	77.24	75.31	0.3503	0.6437	0.6275
0.4516	35	27.31	120	80.61	78.83	0.4016	0.6718	0.6569
0.3703	24	19.8	120	66.41	65.6	0.2911	0.5534	0.5466
0.3703	30	23.82	120	70.32	69.33	0.3503	0.586	0.5777
0.3703	35	27.31	120	74.76	73.48	0.4016	0.623	0.6123

EFFECT OF FIBER VOLUME FRACTION

(1) The tensile yield strength of hybrid laminate for various fiber volume fractions are given in Table 4. The yield stress of hybrid laminate and the elastic modulus of FRP are normalized with respect to yield stress and elastic modulus of aluminum respectively. It is observed that for a given MTF, an increase in fiber volume fraction increases the yield stress of the hybrid structure. This is because of higher elastic modulus of the GFRP obtained due to the increase in fiber volume fraction. This higher elastic modulus in the GFRP layer increases the net stress level in the hybrid layer and hence the yield stress.
(2) It was earlier noted that a decrease in MTF decreases the yield stress of the fiber metal laminate for a given fiber volume fraction. However, if we increase the fiber volume fraction, we could get a higher yield stress in the hybrid structure even though the MTF is lower.

Effect of Metal Thickness and Fiber Volume Fraction on the Ultimate Stress of the Hybrid Laminate

Theoretical prediction based on ROM:

$$\sigma_{u\,hl} = \mathrm{MTF} * \sigma_{u\,Al} + (1 - \mathrm{MTF})\sigma_{u\,frp}. \tag{7}$$

EFFECT OF METAL THICKNESS FRACTION

(1) The ultimate strength of the hybrid laminate with respect to various MTF are plotted and shown in Figure 6. The ultimate strength of the hybrid laminate increases with a decrease in MTF. This is due to the fact that the FRP ultimate stress plays a predominant role in contributing to the ultimate stress of the hybrid metal composite system.
(2) There is 8% difference between the theoretical and experimental values, with the experimental values on the lower side. This is because, in the theoretical calculation it is presumed that failure of the aluminum and the FRP layer occurs simultaneously, whereas in the actual case it is not so.

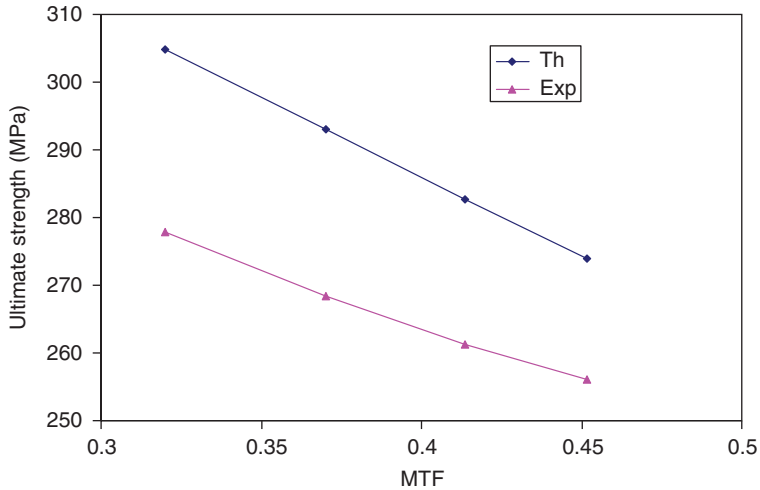

Figure 6. *Metal thickness fraction vs ultimate strength.*

Table 5. Ultimate strength of hybrid laminates for various fiber volume fractions.

MTF	FBV (%)	$\sigma_{u\,hl}$ (Th)	$\sigma_{u\,hl}$ (Exp)	$\sigma_{u\,frp}$ Exp)	$\sigma_{u\,Al}$	$\sigma_{u\,frp}/\sigma_{u\,Al}$	$\sigma_{u\,hl}/\sigma_{u\,Al}$ (Th)	$\sigma_{u\,hl}/\sigma_{u\,Al}$ (Exp)
0.4516	24	273.86	256.0	380	145	2.62	1.88	1.76
0.4516	30	321.03	297.9	466	145	3.21	2.21	2.05
0.4516	35	357.17	326.8	532	145	3.66	2.46	2.25
0.3703	24	293.05	268.4	380	145	2.62	2.02	1.85
0.3703	30	347.28	320.8	466	145	3.21	2.39	2.21
0.3703	35	388.21	354.2	532	145	3.66	2.68	2.44

EFFECT OF FIBER VOLUME FRACTION

The tensile ultimate strength of hybrid laminate for various fiber volume fractions are given in Table 5. It is observed that for a given MTF, an increase in fiber volume fraction increases the ultimate tensile strength of the hybrid structure. An increase in fiber volume fraction actually increases the ultimate strength of FRP. This in turn contributes to the increased ultimate stress of the hybrid laminate. For a fair comparison, the ultimate stress of the hybrid laminate and the ultimate stress of the FRP are normalized with respect to the ultimate strength of aluminum.

SPECIFIC STIFFNESS AND SPECIFIC STRENGTH

Figures 7 and 8 show the comparison of specific stiffness and specific strength between monolithic aluminum, GFRP, and the hybrid laminate. It is found that the specific

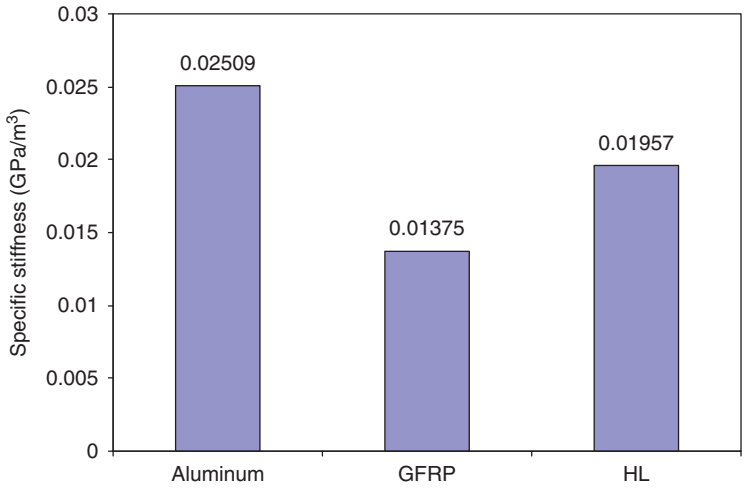

Figure 7. *Comparison of specific stiffness.*

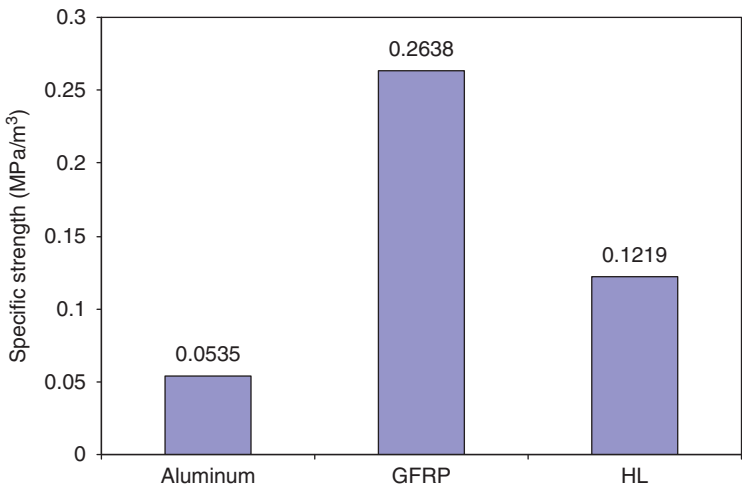

Figure 8. *Comparison of specific strength.*

stiffness and the specific strength of the hybrid laminate showed an improvement over the composite and monolithic aluminum, respectively.

SCANNING ELECTRON MICROSCOPIC STUDY

A scanning electron microscopic (SEM) study on the fractured surface of the specimen showed that the failure of GFRP was due to fiber pullout, fiber fracture, and matrix debonding (Figure 9). Formation of necking prior to aluminum layer fracture (typical for ductile metal) was also visibly seen on the aluminum surface, irrespective of the aluminum thickness (Figure 10).

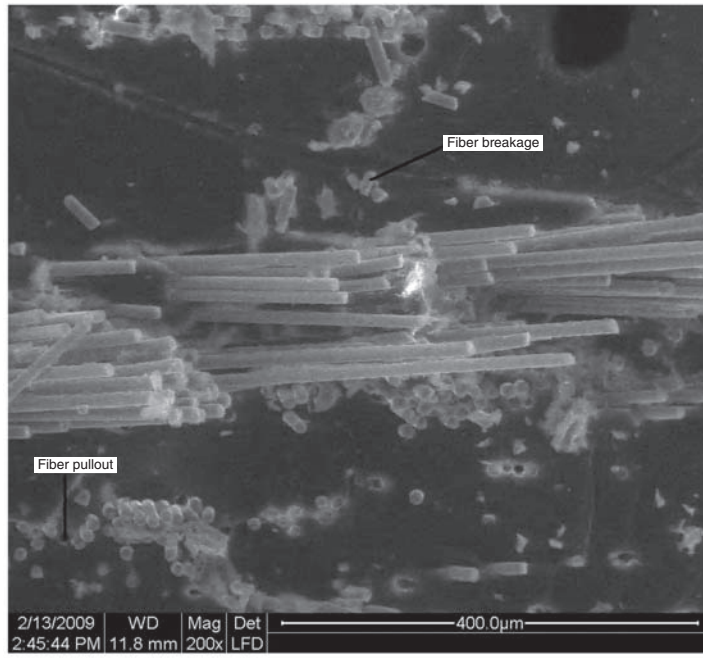

Figure 9. *SEM micrograph of fractured specimen showing fiber pullout and fiber breakage.*

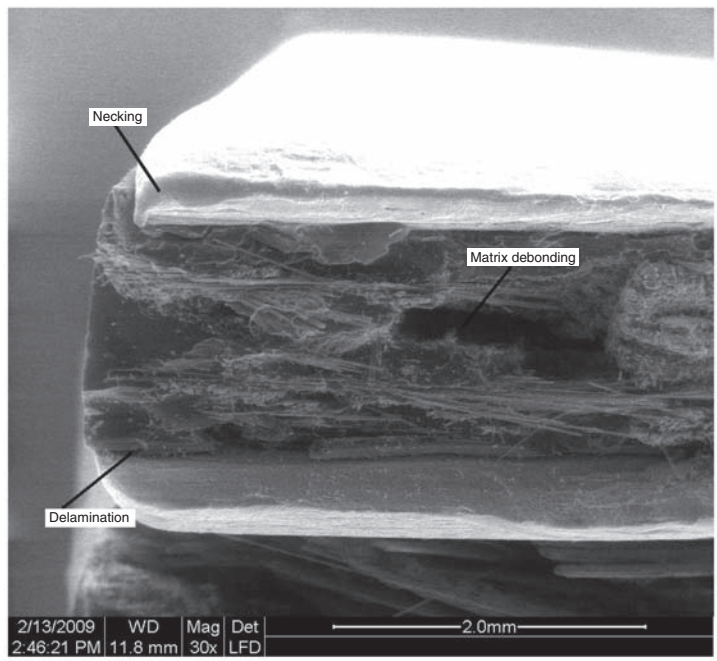

Figure 10. *SEM micrograph of fractured specimen showing necking, delamination, and matrix debonding.*

CONCLUSION

The tensile properties of hybrid aluminum glass fiber laminate were evaluated for different metal thickness fractions and fiber volume fractions. Theoretical predictions of the tensile properties based on ROM compared well with the experimental results. It is found that the metal thickness is a factor in controlling the delamination between aluminum and composite layers. Delamination was prevalent when the metal thickness was reduced. The elastic modulus and the yield strength increased with an increase in metal thickness fraction, but the ultimate strength was found to decrease. An increase in the fiber volume fraction increases the elastic modulus, yield stress as well as the ultimate strength of the hybrid laminate. The specific strength and the specific stiffness of the hybrid laminate showed an improvement over the aluminum and the composite respectively. Hence, such hybrid laminates could be used as a substitute for monolithic metal and especially in areas where weight savings is very important. However, a careful consideration of metal thickness and fiber volume fraction should be made while designing such hybrid structural material, among other parameters.

ABBREVIATIONS

GFRP = Glass fiber reinforced plastic
HL = Hybrid aluminum glass fiber laminate
MTF = metal thickness fraction
SEM = Scanning electron microscopy
Th = Theoretical
Exp = Experimental
FBV = Fiber volume fraction
FEA = Finite element analysis
UD = Unidirectional
CSM = Chopped strand mat

NOMENCLATURE

E_{hl} = Elastic modulus of hybrid laminate
E_{Al} = Elastic modulus of aluminum
E_{frp} = Elastic modulus of FRP
$\sigma_{y\ hl}$ = Yield stress of hybrid laminate
$\sigma_{y\ Al}$ = Yield stress of aluminum
$\sigma_{y\ frp}$ = Yield stress of FRP
$\sigma_{u\ hl}$ = Ultimate stress of hybrid laminate
$\sigma_{u\ Al}$ = Ultimate stress of aluminum
$\sigma_{u\ frp}$ = Ultimate stress of FRP
ε_{Al} = Strain in aluminum
ε_{frp} = Strain in FRP
ε_{hl} = Strain in hybrid laminate

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