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Investigation on Static and Dynamic Mechanical Properties of Epoxy Based Woven Fabric Glass/Carbon Hybrid Composite Laminates

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Abstract

Balanced mechanical properties within the fabric plane and excellent formability have rendered the woven glass fabric composite laminates popular in aircraft, automobile, marine and civil structures. In practice, while preferring glass woven fabric layers in fabrication, to achieve the required design strength, the nominal size of the component was increased. This increased the total weight of the component. In the present work, glass laminate is strengthened and stiffened by interplying high modulus carbon fabric layers for attaining better specific properties. Two symmetrical four layered glass/carbon hybrid laminates and two dedicated four layered glass or carbon laminates were fabricated separately using the hand lay up and compression moulding techniques. The static mechanical properties like tensile strength, flexural strength and impact strength and dynamic mechanical properties such as storage modulus, loss modulus and loss factor of these laminates were experimentally evaluated as per ASTM standards and reported. The influence of stacking sequence of composite laminates on static and dynamic mechanical properties was discussed in detail. The modulus curves of dedicated and hybrid composite laminates in a Cole-Cole plot show an imperfect semi-circular curve indicating the heterogeneity of the laminates and relatively good fibre/matrix bonding. A conclusion as to the superiority of one of the hybrid constructions for structural applications could also be reached.

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1. Introduction

Advantages like excellent integrity, conformability and balanced properties within the fabric plane, made woven fabric composites more popular in structural applications such as automobile, aircraft, marine and civil structures. However in practice while preferring glass woven fabric layers, more numbers of layers are required to achieve the required design strength. This results in the increased nominal size which in turn increases the weight of the component/structure. In the present work an attempt is made to improve the specific strength and modulus of glass fabric laminate without much increase in thickness of the laminate by inter-plying high modulus carbon fabrics in fabrication.

Epoxy based woven fabric composites are viscoelastic in nature which exhibit a combination of both elastic and viscous behaviour [1]. Hence complex modulus notation (E^*) is used to define the viscoelastic material as shown in Eqn. (1).

$$E^* = E' + E'' = E'[1 + i(\tan\delta)] \quad (1)$$

where E' = the elastic storage modulus, a measure of stored energy,
 E'' = the loss modulus, a measure of dissipation of energy as heat,
 $\tan\delta$ = the loss factor or damping factor

Therefore characterization of composite material should include both static mechanical properties like tensile, flexural strength, etc. and the dynamic mechanical properties such as storage modulus, loss modulus and loss factor.

Numerous works have been carried out in the past on the static and dynamic mechanical properties of composite materials made of glass fibres and these works have mainly focused on unidirectional and angle ply laminate. But the number of studies dealing with mechanical properties of woven fabric hybrid composite laminates is very minimal. Bunsell and Harris studied the tensile behaviour of bonded and unbonded glass/carbon hybrid composite laminates [2]. Kretsis reviewed the effect of stacking sequence on tensile, compressive, flexural and shear properties of glass/carbon hybrid laminates with unidirectional plies [3]. Saka et al studied the tensile behaviour of epoxy based unidirectional glass/carbon hybrid composites [4]. Kedar S Pandya et al studied the hybrid effect on tensile and compressive strength of hybrid composites of 8H satin weave T300 carbon fabric and plain weave E-glass fabric with epoxy resin [5].

Hameed et al studied the morphology, dynamic mechanical and thermal characteristics of modified epoxy resin/glass fibre composites [6]. Siha et al investigated the dynamic mechanical properties of unidirectional glass fibre-PMMA composite laminates [7,8]. Ghosh et al Dynamic Mechanical analysis of FRP composites based on different fibre reinforcements and epoxy resin as the matrix material [9]. Jacob et al [10,11], Jawad et al [12], Manikandan Nair et al [13] worked on evaluation of dynamic mechanical properties of natural fibre reinforced polymer composites.

In the present study, the static and dynamic mechanical properties of hybrid composites made of plain weave E-glass fabric and T300 carbon fabric embedded in epoxy resin has been investigated. The influences of stacking sequence of glass and carbon fabric layers on these mechanical properties are discussed.

2. Fabrication of Composite laminates





E-Glass fabric and T300 carbon fabric of areal density 600 gsm were used as reinforcement. Epoxy resin LY556 premixed and homogenized with hardener HY951 in the ratio of 9:1 by volume was used as matrix. For the present investigation, four different layer sequences were considered as shown in Fig.1. Dedicated four layered glass laminate (4G), dedicated four layered carbon laminate (4C) and hybrids of glass/carbon for the same four layer arrangements were fabricated. In fabricating hybrid composites, glass laminate was modified by the following sequence. The two of the carbon layers were plied as core (H1) and in the other type hybrid, the two of carbon layers were plied as envelope (H2).



Fig.1. Image showing the four different samples fabricated by Hand Layup technique

All four types of composite laminates considered for investigation were fabricated by hand layup technique. A uniform fibre weight fraction of $W_f = 0.6$ was controlled for all four types of laminates in fabrication. This approximates to a overall fibre volume fraction of $V_f = 0.4$, considering the fibre density as 2.52 g/cc and the matrix density as 1.2 g/cc. To ensure a uniform thickness for all laminates, an aluminium dam of size of $300 \times 300 \times 3 \text{ mm}^3$ was used between the match plates. The casting was cured at room temperature for 24 hours in compression moulding machine with nominal pressure of 2.5 MPa. After curing, the laminates were cut into ASTM standard size specimen for mechanical testing. All the test specimens were finished by abrading the edges on a fine emery paper to improve the surface finish. Table 1 shows the weight fraction measured by resin burn out test [14] and average thickness of laminates measured for the four different layer arrangements considered.

Table 1. Measured Volume fraction and Average thickness of four types of composite laminates

Specimen	Layer Sequence	Measured Weight Fraction (W_f)	Average thickness (t) [mm]
4G		0.612	2.02
4C		0.619	2.49
H1		0.617	2.38
H2		0.618	2.38

3. Experimental Evaluation of Mechanical Properties

Tensile test specimens were cut according to ASTM D3039 standard [15]. The size of the specimen is $250 \times 25 \times t \text{ mm}^3$. Tensile tests were conducted on servo hydraulic universal testing machine INSTRON 3382 with the cross head speed of 5 mm/min at room temperature. Flexural test was performed as per ASTM D790 for all samples with a recommended span to depth ratio of 16:1 [16]. The size of the specimen is $127 \times 12.5 \times t \text{ mm}^3$. The flexural test was conducted on the same machine with feed rate of 1.2 mm/min. The impact test was carried out using an Izod

Impact tester TINUS OLSEN-104 according to ASTM D256 standard [17]. The specimen size is $63 \times 12.5 \times t$ mm³ with U notch cut against the thickness. Five specimens were tested for each type of laminate in all testing method and average value was calculated.

DMA tests were performed as per ASTM D4065 in the universal instrument of model TA Q800 with isochronal conditions at 1 Hz, and the temperatures were varied between 30°C and 140°C at rate of 5°C/min [18]. The samples were thin rectangular strips with dimension of $63 \times 13 \times t$ mm³. The specimens were excited by sinusoidally varying forced vibration with amplitude of 15µm and then the input and corresponding response were measured simultaneously. The out of phase response with input represents the viscoelastic behaviour of the material.

4. Results and Discussion

4.1 Static Mechanical Properties

The stress-strain curves of the woven fabric composites with four different layer sequences are shown in Fig.2. The maximum stress is found for dedicated carbon laminate arrangement, 4C. There is considerable tensile strength variation between dedicated 4G glass beam and dedicated 4C carbon beam as expected [2,3]. This is due to high resistance offered by high modulus carbon fibre against tensile loading. There is variation in tensile modulus in hybrid laminates as shown in Table 2. Though the four layers of hybrid laminate are equally loaded, the variation in strain between glass and carbon layers caused the marginal difference in tensile strength. Kedar et al [5] also confirmed that the hybrid laminate with glass layer in the exterior and carbon layer as interior gives higher ultimate tensile strength.

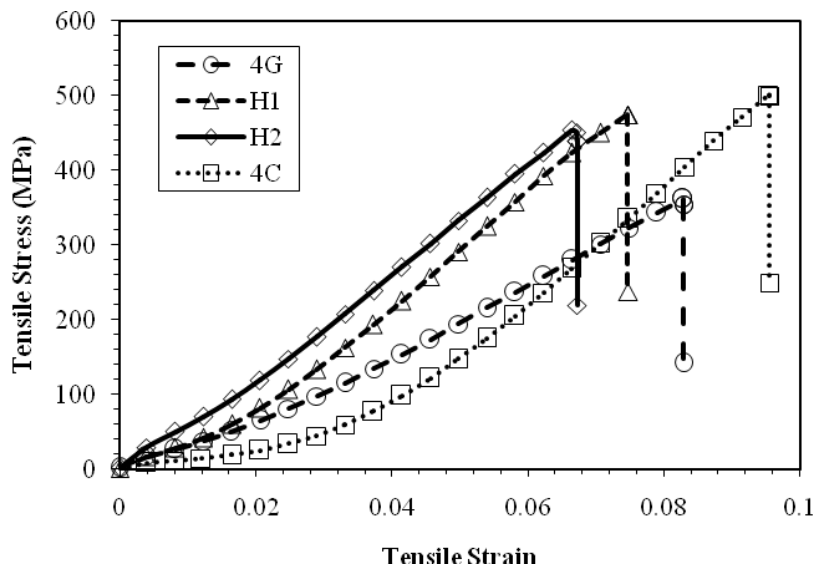


Fig.2. Stress-strain curves of woven fabric composites with different layer arrangements obtained from tensile test

Table 2. Average Static Mechanical Properties of dedicated and hybrid composite laminates

Specimen	Tensile Strength [MPa]	Flexural Strength [MPa]	Impact Strength [kJ/m ²]
4G	365.79	378.40	147.14
4C	462.08	573.27	100.20
H1	413.62	491.21	143.58
H2	403.41	507.24	103.75

Fig.3 shows the flexural load-deflection curves of the composites with four different layering sequences. Flexural strength of composite laminate is majorly controlled by the strength of outer layer which is in direct contact to bending load [1]. There is a considerable flexural strength variation between dedicated 4G glass laminate and dedicated 4C carbon laminate [2,3]. Among hybrid samples, H2 arrangement has shown marginal increase in flexural strength than H1 arrangement as shown in Table 2. This is because the laminate with high modulus carbon fibre plied as envelope offers more resistance to flexural loading than low modulus glass fibre plied as envelope. The difference in the flexural strength among hybrid laminates confirms that the stacking sequence controls the flexural property.

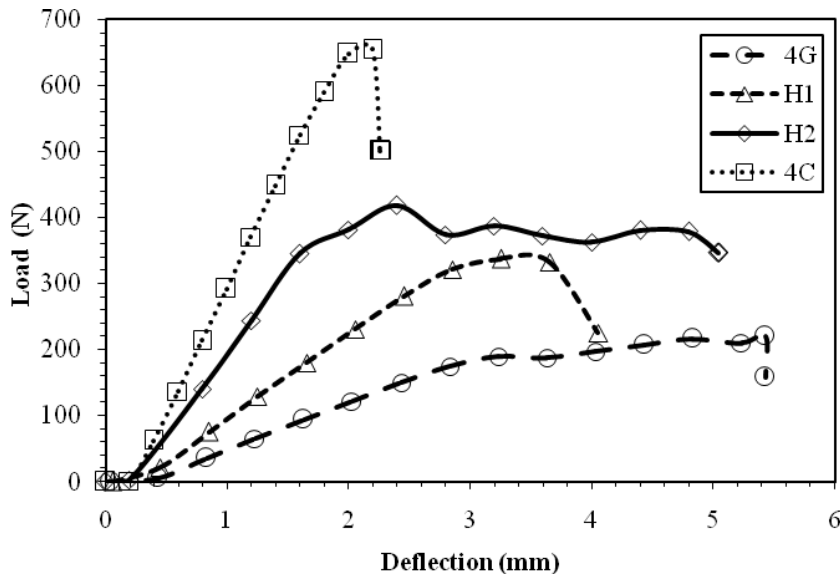


Fig.3. Load-deflection plots of woven fabric composite laminates with four different layer arrangements obtained from flexural test

The interlacing of yarns present in woven fabric offers higher stiffness against impact load and thus woven fabric composites have higher impact strength than nonwoven counterparts. The major damage mechanism in fibre composites is mainly matrix cracking, fiber fracture, and delamination [1]. For woven fabric composite during low velocity impact loading, the predominant damage mechanism is found as delamination. In case of layered composite during impact loading, more amount of energy is consumed for delamination of the layers and fibre bundle cracks [4]. Table 2 gives the effect of different layer sequences on impact strength of the composites. Impact strength of laminates with low modulus glass fibres are higher than that of laminates made of high modulus carbon fibres. Among hybrids, laminate with H1 arrangement has higher value than H2 arrangement.

This variation in impact strength is caused because the alternate layers made of different fabrics affect the crack propagation during impact loading.

4.2 Dynamic Mechanical Properties

The factors governing the dynamic mechanical characteristics of composite materials are matrix type, fibre loading, fibre length, fibre dispersion and fibre matrix adhesion [13]. The effect of temperature on the storage modulus of the dedicated and hybrid composite laminates is shown in Fig.4. Table 3 shows the E'_{max} values of dedicated and hybrid composite laminates. The storage modulus E' values increased with the increase of carbon fibre content in the composites. High modulus carbon fibre of dedicated carbon laminate caused the large storage modulus than dedicated glass laminate. It is imperative to note that the storage modulus of hybrid laminate H2 is higher than other laminates including dedicated carbon laminate. This shows that hybrid layer arrangement with carbon fibre as envelope, H2, has very high storage modulus than the other hybrid arrangement, H1. This is referred to as synergy and positive hybrid effect. Flexural strength values of dedicated and hybrid composite laminates shown in Table 2 also support this attribute. There is significant fall in the storage modulus between the temperatures 80°C and 100°C. Increasing the temperature beyond the glass transition temperature T_g causes the change in state of composite laminates from solid to rubbery. In this rubbery region, the storage modulus values of all laminates become very less since the resin matrix loses its stability.

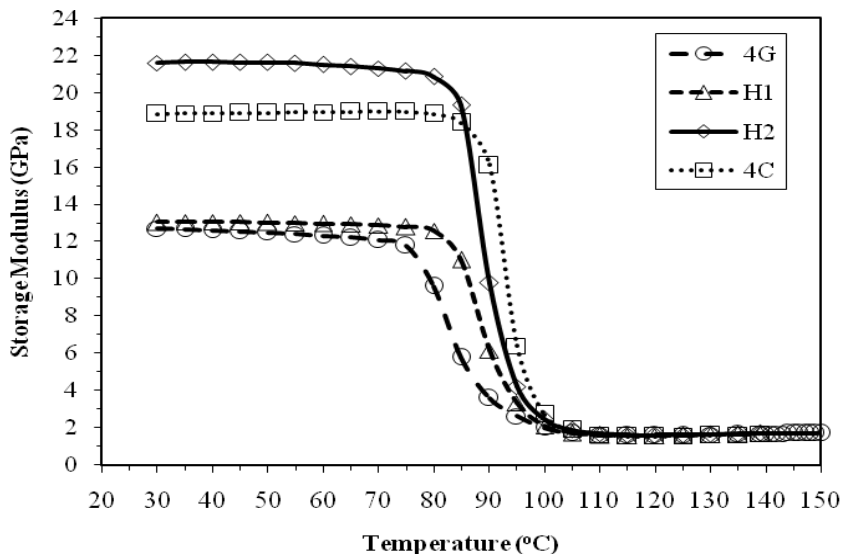


Fig.4. Variation of Storage Modulus of dedicated and hybrid laminates with temperature

Loss modulus (E'') is the measure of dissipated heat energy per cycle in a viscoelastic material under dynamic condition. Fig.5 shows the variation of loss modulus of the dedicated and hybrid composite laminates with temperature. The glass transition temperature T_g of the resin is measured from the peak of the loss modulus curve as per ASTM D4065 [18] and the corresponding values are shown in Table 3. The maximum loss modulus for composite laminate occurs at glass transition temperature T_g of the system. The transition peak occurs at 85°C for the dedicated glass laminate. In the hybrid laminate the transition peak shifted to 90°C and in the dedicated carbon laminate, it is 95°C. The increase in T_g is due to the immobilization of the polymer molecules near the surface of the carbon fibre [7-9]. Thus the incorporation of carbon fibre shifted the transition peak to higher temperature and

increases the E'' value of corresponding T_g considerably (6% and 89% for hybrid H1 and H2 arrangements respectively). In earlier research, Jawad et al also reports that reinforcing fibre play an important role on T_g [12]. Fig.5 shows that loss modulus of hybrid laminate H2 is much higher than the other laminate H1 and raises to a larger extent than dedicated glass laminate, 4G. Increased energy absorption due to the layering sequence, CGGC, caused the large increase (89%) in loss modulus peak in hybrid H2.

The magnitude of the loss factor ($\tan\delta$), which is the ratio of the loss modulus to the storage modulus (E''/E'), gives balance between the elastic and viscous phase in a polymeric material [6]. Fig.6 shows the variation of loss factor ($\tan\delta$) of the dedicated and hybrid composite laminates as a function of temperature. It is observed from the plot that the loss factor increases with increase in temperature; it reaches maximum level in transition region and then starts decreasing in rubbery region

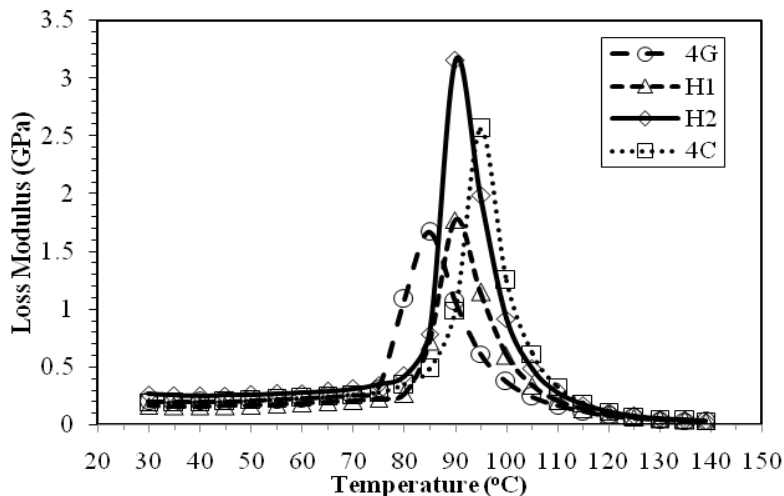


Fig.5. Variation of Loss Modulus of dedicated and hybrid laminates with temperature

Below glass transition temperature T_g , the chain segments present in the resin are in frozen state causes low $\tan\delta$ values in all laminates. In the transition region resin molecules attain high mobility which causes high $\tan\delta$ values [10-11]. The $\tan\delta$ value is high for hybrid laminate, H2, than dedicated carbon and dedicated glass laminate. Among hybrids, transition peak values, T_g are same as 95°C however the $\tan\delta$ value at the T_g is 17% higher for H2 arrangement than H1 arrangement. Thus it is shown that hybridization of carbon fibre with glass fibre improves the damping performance of the composite laminate. The peak height values of $\tan\delta$ curves are given in Table 3. Dedicated glass laminate, 4G, shows lowest $\tan\delta$ peak value and highest peak value is for hybrid laminate H2. Thus it is shown that the hybrid arrangement H2 has good damping due to the two inner glass/epoxy layers. Earlier Finegan and Gibson also reported that the damping performance of composite laminate can be improved by the hybridization approach [19]. It is also noted from Table 3 that the T_g value of composite laminate indicated by the $\tan\delta$ peak was higher than that indicated from the corresponding E'' peak as the T_g cannot be precisely measured with a knowledge of loss factor only as it is also a function of storage modulus.

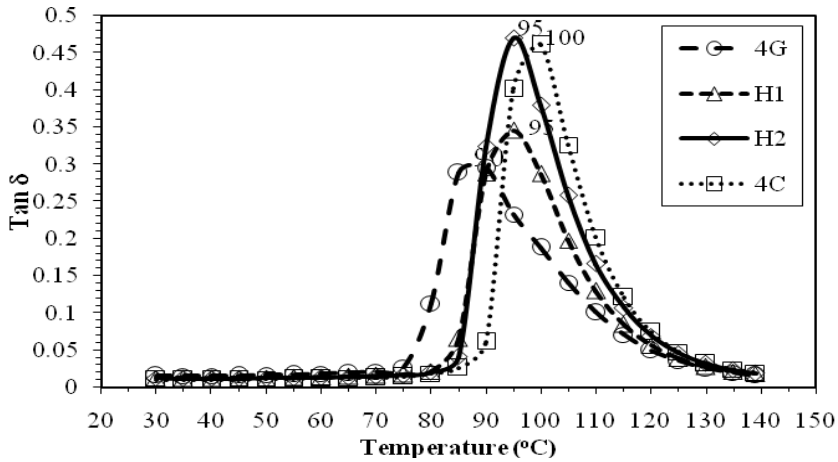


Figure 6: Variation of Loss factor of dedicated and hybrid laminates with temperature.

Table 3. E'_{max} , E''_{max} , Peak height of $Tan\delta$ curve, T_g at $Tan\delta_{max}$ and T_g at E''_{max} of dedicated and hybrid composite laminates

Specimen	Storage Modulus (E'_{max}) [GPa]	Loss Modulus (E''_{max}) [GPa]	Peak Height of $Tan\delta$ curve	T_g from $Tan\delta_{max}$ [°C]	T_g from E''_{max} [°C]
4G	12.684	1.665	0.3235	90	85
4C	18.849	1.250	0.4609	100	95
H1	13.033	1.771	0.4016	95	90
H2	21.601	3.150	0.4696	95	90

Fig.7 shows the Cole-Cole plots of dedicated and hybrid composite laminates. Cole-Cole plot, where the loss modulus (E'') values are plotted against storage modulus (E'), is used to measure viscoelastic properties of fibre

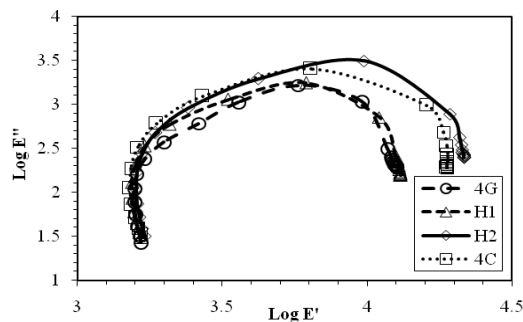


Fig.7: Cole-Cole plots of dedicated and hybrid composite laminates

reinforced polymer composite materials. The Cole-Cole plot for pure polymeric material is a perfect semi-circle diagram [20]. In the present investigation, the curves of dedicated and hybrid composite laminates in Cole-Cole plot show an imperfect semi-circular curve indicating the heterogeneity of the laminates with a good matrix and fibre bonding. The present investigation clearly reveals that the hybrid laminate with H2 arrangement has better tensile

and flexural strength values than the other hybrid arrangement, H1. Impact strength of hybrid laminate H2 is merely closer to that of H1 arrangement. Dynamic Mechanical Analysis test results show that H2 hybrid laminate has higher storage modulus, loss modulus and loss factor than the H1 arrangement. Therefore it is confirmed that H2 hybrid arrangement, arrived at by replacing the outer layers of a 4G laminate by carbon fibres, performs better than a 4G and is closer to a dedicated carbon 4C laminate. It is seen that with the carbon fibres as the outer layers as in H2, the damping is restricted to the inner glass fibre layers due to the elastic waves generated in the outer carbon layers going through a severe damping in the inner glass layers. It appears that the surface Raleigh waves are more consistent in a carbon layer than a surface glass layer. As the surface layers normally experience Raleigh, transverse and other modes of elastic stress waves as compared to the inner layers, it is wiser to have low damping carbon layers at the surface and high damping layers like glass or a natural fibres as the inner layers. Thus the H2 arrangement could be the better alternative for a dedicated glass laminate in structural applications where high strength to weight ratio is critical.

5. Conclusions

Static and dynamic mechanical characterization of woven fabric plain weave glass/carbon inter-ply hybrid composite laminates was carried out experimentally. The effect of stacking sequence on mechanical properties was investigated for four layer composite laminates. Dedicated carbon laminate has higher mechanical strengths than dedicated glass laminate except for impact strength. The variation in tensile strength and impact strength among hybrid laminates is minimal and H2 hybrid arrangement has higher flexural strength than H1 hybrid laminate. Storage modulus, loss modulus and loss factor of hybrid laminate H2 is greater than H1 hybrid laminate and dedicated carbon laminate. The glass transition temperature, T_g of H2 laminate was shifted through 5° C from dedicated glass laminate which facilitates the higher operating temperature. Hybrid laminate with carbon fibre as enveloping layer, H2, performs better than other hybrid arrangement, H1 and proves to be good alternative for glass laminate.

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