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Synthesis and Mechanical Characterization of Woven Banana and Glass Fiber Reinforced Epoxy Composites

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Abstract—Use of eco-friendly composites gain attraction due to its light weight and moderate strength in the recent years. Woven fabrics are attractive as reinforcement since they provide excellent integrity and conformability for advanced structural composite applications. In this work, woven banana and glass fibre (WRM) fabrics were arranged in different stacking sequences to prepare the composite. The effect of this layering arrangement, woven architecture and influence of glass fibre hybridization on the mechanical properties such as tensile strength, modulus, bending characteristics, impact energy absorption etc. are investigated. The inter-laminar shear strength and fracture toughness study of the fabricated composites arealso focused. Three types of hybrid laminates are fabricated by using hand lay-up method. By introducing weaving architecture to form the fibre laminates, around 50 % of the improvement in tensile strength and a considerable difference in impact strength was obtained. The layer sequence has greater effect on flexural and inter-laminar shear properties than tensile properties. An overall comparison between the properties of all the laminates revealed that the hybrid laminate with glass plies as skin layers gives the optimum combination with a good balance between the properties and cost. The fracture toughness and inter-laminar shear strength of the hybrid composites were even higher than those of glass fibre reinforced composites due to the excellent hybrid performance of the hybrid interface.

Keywords- Composites, Fracture Toughness, ILSS, Mechanical Testing, Natural fibres, Woven Banana fibres, Woven Roving Mat

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1 Introduction

Advanced composite materials are of great importance to designers to produce efficient lightweight structures due to their high stiffness to weight and strength to weight properties. In the fast developing world, the concern for the environmental pollution and the prevention of non-renewable and no biodegradable resources has attracted researchers seeking to develop new eco-friendly materials and products based on sustainability principles. The natural fibres are renewable, non-abrasive, bio-degradable, possess a good calorific value, exhibit excellent mechanical properties and can be incinerated for energy recovery have low density and are inexpensive. This good environmental friendly feature makes the materials very popular in engineering markets such as the automotive and construction industry. Their low-density values allow producing composites that combine good mechanical properties with a low specific mass. The tensile load carrying capacity of the natural fibre reinforced composites are found to be increasing with the fibre content up to an optimum level and then start declining [1].

Now a days' conventional material for the medium load applications are replaced by the composite materials. Banana empty fruit bunch fibre is better in tensile strength than the neat polyester resin and it can be used in industrial applications such as partition panels and packaging [2].The replacements of the conventional material for curved pipes are succeeded by natural (hemp) and glass fibre together with 20% cost reduction and 23% weight reduction [3].

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As single natural fibre composites are not having sufficient strength to replace the conventional materials, the hybrid combinations of natural fibres are preferred.

The mechanical and thermal properties of the jute fibre reinforced epoxy composite are found to be increased with the addition of banana fibre up to 50% by weight [4]. With the combination of banana and sisal fibre, fibre length and weight percentage are the major factors in deciding the mechanical properties and in another study, banana and sisal fibre with 50:50 weight percentage showed maximum tensile strength along with 40% weight fraction of total fibre content [5].

Due to low density, high tensile strength, high tensile modulus, and low elongation at break of banana fibres, composites based on these fibres have very good potential use in the various sectors like construction, automotive, machinery, etc.[6]. The polymer banana reinforced natural composites is the best natural composites among the various combination. It can be used for manufacturing of automotive seat shells among the other natural fibre combinations [7].

The fracture toughness and Viscoelastic properties of banana/sisal fibre hybrid polymer composites were carried out with special reference to the effect of fibre loading, frequency and temperature. The fracture toughness and energy release rate are found maximum at 30 wt. % of hybrid composite. This is due to the strong adhesion between fibre and matrix at 30 wt. % fibre loading [8].

The woven fabric composite materials have better out-of-plane stiffness, strength and toughness properties than laminate composites [9]. The selection of weave design is important as it has a greatly influence on the tensile properties of the dry fabric and composite. A weave design with low crimp percentage will increase the tensile strength of dry fabric by fully utilizing the fibre strength [10].

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It is observed that the layering pattern has significant effect on the tensile, flexural and impact properties of the composite [11]. The tensile strength on the pseudo-stem banana woven fabric reinforced epoxy composite is increased by 90% compared to virgin epoxy. The flexural strength increased when banana woven fabric was used with epoxy material. The banana fibre composite exhibits a ductile appearance with minimum plastic deformation [12]. Studies by R. Yahya et al. revealed that hybrid composite (Kenaf - Kevlar) with Kevlar as skin layers improves the tensile and flexural strength. In impact, hybrid composite with Kenaf as skin layers has higher impact properties compared with Kevlar as skin layers [13].

The incorporation of the glass fibres with the natural one notably enhanced the mechanical properties of the composites. Incorporation of glass fibre up to 20% by mass with the bamboo fibre improved the tensile and flexural modulus by 12.5% and 10% respectively [14]. Addition of glass fibre as extreme plies in the jute fabrics considerably improved the flexural and inter-laminar shear properties [15]. In another study, unidirectional glass and flax fibre composites showed superior inter-laminar shear strength than the glass fibres and tensile properties can be enhanced with the addition of glass fibres [16]. Glass fibre reinforced polymer composites can be replaced with the hybrid combination of sisal–jute with glass ply [17]. The banana-glass fibre hybrid composites have more tensile strength than other composites can withstand the tensile strength of 39.5 MPa followed by the hemp-glass fibre reinforced composites which holds the value of 37.5MPa. It is suggested that these banana-hemp-glass fibres reinforced hybrid epoxy composites can be used as an alternate material for synthetic fibre reinforced composite materials [18]. Banana fibre reinforced glass composites having highest ultimate tensile strength and impact strength compared to other specimens [19]. 50% Banana fibre with 50% epoxy resin composite materials can withstand the higher loads compared to other combinations [20]. Effect of glass fibre hybridization on randomly oriented natural fibres is studied. Stacking sequence of banana and sisal fibres improves the strength properties [21]. The above reviews obviously shows that there are not enough work done on the impact of stacking sequence, woven architecture and addition of glass fibres with two or more natural fibres. In this work, woven banana and glass fibre (WRM) fabrics were arranged in different stacking sequences to prepare composite. The effect of this layering arrangement, woven architecture and influence of glass fibre hybridization on the mechanical properties are investigated. The inter-laminar shear strength and fracture toughness study of the fabricated composites are also focused.

2 METHODOLOGY

2.1 Materials

Banana fibers were procured from Fibre Design cum Development centre, Khadhi and village industries commission, Kerala, India and weaved manually. Each woven fabric bundle must consist of 200-250 yarns and the thickness of each layer is 1.2 mm. The fabricated laminates were made with woven roving (WRM) glass fibre mat as one of the reinforcement in the epoxy matrix. The warp yarns run in the direction of fabric (length wise) and fill/weft yarns generally run crosswise. The advantage of using epoxy resin is that, there will not be any volatile by-products during curing and it gives 100% solid content on curing. The physical properties of glass fibre and banana fibres are shown in Table 1.

TABLE 1
PHYSICAL & MECHANICAL PROPERTIES OF BANANA AND GLASSFIBRE

Properties	Density (kg/m^3)	Flexural Modulus (GPa)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at break (%)	Cellulose (%)	Lignin (%)	Moisture Content (%)
Banana fibre	135 0	4	56	3.5	2.6	62	5	11

Properties	Specific Gravity	Modulus (GPa)	Strength (MPa)	Percentage Tensile Elongation	Coefficient of thermal expansion (μm/m/℃)
E-Glass	2.60	72	3450	4.8	5.0

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2.2 Synthesis of Composites

The composite laminates for this work were fabricated by hand lay-up process. Hand lay-up is the simplest and low cost manufacturing method suitable for academic purposes/low volume production. Initially the banana fibres are dried under the hot sun to remove the moisture for more than 24 hours. In order to orientate the fibre in the composite material, the dried banana fibres are to be woven. The method for weaving the banana fibre for making a specimen is well detailed by Jones [22]. The woven fibre mats of uniform thickness were prepared from banana fibres of particular length. Three different kinds of laminates were prepared with stacking sequences B/B/B (Laminate 1), G/B/B/G (Laminate 2) and G/B/G/B/G (Laminate 3).

A stoichiometric amount of curing agent (hardener) was added to the epoxy resin mixture and stirred for making woven banana and glass fibre reinforced composite panels of 270 × 200 × t mm size by hand lay-up process. The mixing ratio of epoxy to hardener was 10:1 by weight. The hand lay-up process needs to be completed within the gel time of the epoxy which is around 30 minutes. After the hand lay-up process, the laminates with different stacking sequences were allowed to cure at room temperature for 24 hours. A thin Mylar film was inserted as crack initiator for the Mode I fracture samples. The post cured laminates with different thickness are then cut to test specimens as per respective ASTM standards for mechanical characterization.

2.3 Mechanical Characterization of Composites

2.3.1 Tensile Test

The ability of the material to stretch without breaking is termed as tensile strength. The tensile strength of the laminate was measured by the ASTM standard, ASTM: D3039. The spec-

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imen should ensure that the breakage should occur in the expected region and its necessity depends on the localization of the breakage. The tensile test was done on KALPAK UTM (Model no. KIC-2-1000-C with a maximum load capacity of 100 kN). The samples were tested at a loading rate of 2 mm/min. Specimen which was cut from the three different types of laminates were subjected to tensile test for five samples per laminate to get an average value. The extensometer used here has the gauge length of 25 mm.

2.3.2 Flexural Test

A flexural test imposes tensile stress on the convex side and compressive stress on the concave side of the specimen which causes a shear stress along the centre line. It measured the force required to bend the beam. The flexural test was performed on the KALPAK UTM (Model no. KIC-2-1000-C with a capacity of 10 kN). The geometrical dimension of the nominal specimen was made according to the standard ASTM: D790. The load was applied at a rate of 2 mm/min till the specimen fractures and breaks. The maximum load at failure was used to calculate the flexural stress. The span to depth ratio of 16:1 is selected as per ASTM D 790. The effect of interlaminar failure can be minimized by increasing the span to depth ratio until the failure mode changes from ILSS to flexure failure at outer fibres. The flexural strength, flexural strain and modulus of elasticity in bending are obtained by using the expressions from ASTM D790.

2.3.3 Impact Test

The capability of the material to withstand suddenly applied load is its impact strength. The impact strength of the laminates was tested by Izod impact test rig. This test measured the kinetic energy needed to initiate the fracture and to continue until the breakage of specimen. The matrix fracture, fibre matrix debonding and fibre pull out are important failure modes observed in the fibre composites due to impact loading. The standard dimension for the Izod test is ASTM D 256.

2.3.4 Interlaminar shear strength (ILSS) – Short Beam Test

The test is conducted to determine the bond strength between the layers. Varieties of failure modes can occur in the case of composites as the nature of internal stresses are complex due to the nature of constituent materials. Hence it is not possible to relate the short beam strength to any one material property. However failures are dominated by the resin and interlaminar properties and it is very much related to the matrix dominated toughness property. Three point bending test with a low ratio of width to span (1:3) is used for ILSS test. The interlaminar shear strength (Short beam strength) is obtained by using the expression as per ASTM D256.

2.3.5 Mode-I Interlaminar Fracture Toughness (GIC)

Double cantilever beam (DCB) method was used for find out the Mode-I interlaminar fracture toughness (GIC). This was carried out in the Mode-I crack opening set up in UTM on DCB specimens as shown in Fig.1. The modified beam theory expression was used for calculating strain energy release rate of DCB as:

$$G_{IC} = \frac{3P\delta}{2b(a+|\Delta|)} \qquad (kJ/mm^2)$$

Where Δ is the effective delamination extension which is the correction factor for rotation of DCB arms in the delamination front. The value of Δ is determined experimentally by generating a least square plot of the cube root of compliance, C1/3, as a function of delamination length. The compliance C is the ratio of the load point displacement to the applied load, δ/P. A thin non-adhesive Mylar film was inserted to form the initiation site for the delamination with an initial delamination length (ao) of 50 mm and the same is shown in Fig.1.

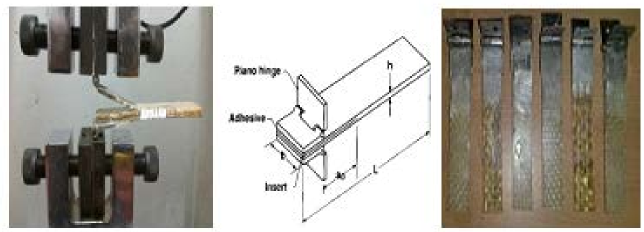


Fig.1 Mode-I specimens with piano hinges

3. Results and Discussion

3.1 Tensile Properties

The in-plane tension test is conducted to determine the ultimate uniaxial tensile strength and tensile modulus for the fabricated composites. The average tensile properties, determined from five tests on each material, are shown in Table 2. The strain measurements were taken by extensometers clipped on the specimens. The tensile stress-strain curves for linear elastic portion are shown in Fig.2.

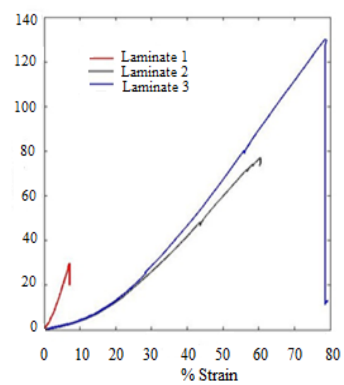


Fig.2 Tensile Test Results-(Experimental)

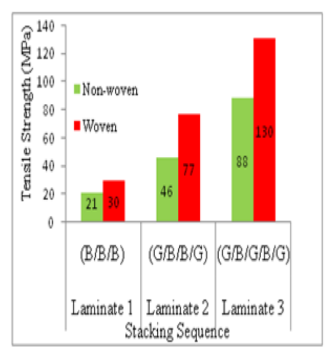


Fig.3 Plot to show the variation of Tensile Strength

Two unique positions exist in a woven fabric composite. One is the interstitial position, which is surrounded by four different yarns and the other is undulated position, which is defined as intersection point of warp and fill yarns. Compared to other regions, these positions become resin rich regions in the fibre-reinforced polymer composite. Fig.4 gives the sketch of typical plane weave fabric showing the interstitial region and the undulated region.

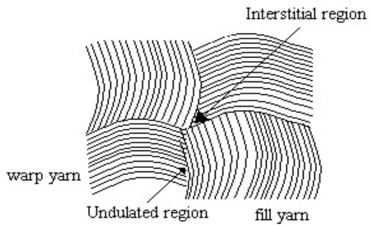


Fig.4 Schematic representation of a typical plain weave fabric

Experimental results show that the tensile strength of the woven banana composite (laminate 1) is 30 MPa which is higher compared to non-woven composites [21]. The weaving of the fibre provides an interlocking that increases strength more than that could be achieved by fibre matrix adhesion. Failure of the composite will require fibre breakage, since fibre pull out is not possible in tightly woven fibres.

By introducing two layers of woven banana mat in between the glass fibres (WRM), ie, Laminate 2, the strength is found increased to 77 MPa. The strength can't be improved by adding more layers of woven banana mat [19]. Increase in the number of layers leads to more interstitial positions and more resin rich regions. These resin rich regions are the points where crack initiation occurs. These cracks propagate through the resin rich regions. This ultimately leads to crack initiation followed by delamination in the composites. Moreover, this observation supports the fact that the composite failure is determined by crack initiation in the matrix rich region of the composite, namely the interstitial and the undulated regions.

By introducing a glass fibre mat (WRM) as in laminate 3, strength increment of 78% is obtained compared to laminate 2. That means, laminate 3 produces an ultimate tensile strength of 130 MPa, which is better compared to other laminates and non-woven architectures. The resulting stacking sequence provides better tensile properties. All the work [18]-[19] indicates that high strength fibre as skin improves the mechanical properties of the sandwich composite which is also evident here. The high strength and modulus woven glass fibre provided at the top and bottom layer withstand the applied load whereas core (banana) absorb and distribute the loads uniformly. For comparison against non-woven architecture with same stacking sequence, the experimental results are taken from [21]. The variation of tensile strength against woven architecture and stacking sequences are shown in Fig.3.

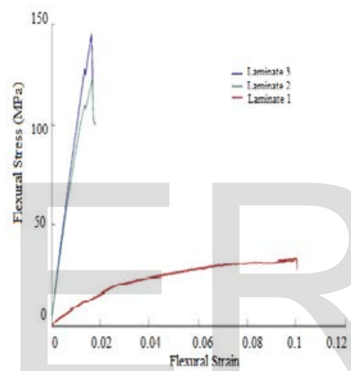
3.2 Flexural Properties

Table 2. Mechanical Properties of Composites

Laminate	Tensile Strength (MPa)	Tensile Modulus (GPa)	Flexural Strength (MPa)	Flexural Modulus (GPa)	Impact Energy (J)	Short Beam Strength (MPa)
Laminate 1	30	1.10	33	0.78	4	27.76
Laminate 2	77	4.95	122	6.34	12.5	30.34
Laminate 3	130	5.17	145	11.03	14	44.69

Fig.5 shows the variation of flexural properties of various composites tested. Similar trend, as seen in tensile properties, is observed in flexural properties also. Sandwich composite of laminate 3 exhibits higher flexural strength and modulus. The values are 145 MPa and 11.03 GPa respectively. This shows that addition of glass fibre (WRM) as skin layer increases the strength and stiffness of banana fibre composite. The basic bending theory proposes that under bending load, top layer is subjected to compression, bottom layer is subjected to tension and middle layer is subjected to shear.

From this basic theory, it is understood that the main load carrying member is skin in the sandwich composite and hence skin layers should be made of high strength fibres to withstand high load. It is thus established that the composite made of Glass/Banana/ Banana/ Glass (laminate 2) exhibit higher flexural strength and modulus than laminate 1. Improvement of flexural strength and flexural modulus are observed and is shown in Table 2.



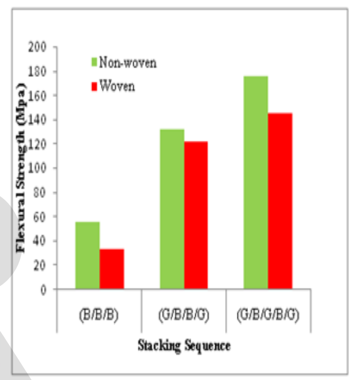


Fig.5 Flexural stress-strain curves of different laminate

Fig.6 Plot to show the variation of Flexural Strength

The flexural stress is a function of strain, which is found to be the highest for composites made of 5 layers of the fabric (laminate 3). In woven fabric composites, the interlacing of the fibres leads to deformation of the fibres in a predictable and reversible manner. The value of the flexural modulus increases with number of layers. When the numbers of layers are increased, delamination between the layers becomes the predominant mechanism of failure. The flexural modulus value for the four layer laminate is 6.34 GPa and for the five layer laminates 11.03 GPa. The glass hybrid laminate is better than pure natural laminate and the properties seem to be increasing with the addition of the glass fibres while the addition beyond a particular limit affects its strength adversely. It also confirms that even though hybridization improves the properties of the composite, the layering sequence has much more effect on the flexural properties of the composite. Woven architecture has comparatively lesser influence on the flexural properties because of the presence of point loading and bending mode of failure of the composite. This can be justified from the fact that the flexural strength and stiffness are controlled by extreme layers of reinforcement and number of layers. The variation of flexural strength against woven and non-woven architecture [21] with different stacking sequences is shown in Fig.6.

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3.3 Impact Properties

Composites made of woven fabric composites have high impact strength compared to composites made of non-woven fibres. Impact energy is a blend of three forms of energy - stored energy, absorbed energy and dissipated energy. The interlacing of yarns, in the case of woven fabrics, provides higher out-of-plane stiffness and can take up the loads due to load path eccentricities.

The impact strength of the composites increases with increase in the fibre weight fraction. When the fibre weight fraction is increased, more energy is needed to break the coupling between the interlaced fibre bundles. Moreover, in the case of banana fibre, fibrillation also takes place with impact damage and increase in fibre content requires more energy for fibrillation. The number of layers as well as the layering pattern affects the impact strength. The maximum value of impact strength is obtained for composites with five layers (laminate 3) of fabric. The ultimate mode of failure in woven fabric composite is found to be delamination. All the delamination mechanisms originate primarily from matrix cracks. This delamination propagates an interface between reinforcements or between different layers.

Table 2 gives the values of the impact strength in the case of composites with different layering patterns. In the five layer arrangement, maximum energy dissipation occurs because the impact energy will be dissipated by the delamination between the layers as well as for intra-bundle cracks. Experimental results show that the laminate 2 has highest gain in impact strength (23%) than non-woven composites and other laminates considered for the analysis. The higher impact strength of WRM as skin in banana composite has better impact strength as glass fibre absorb more energy than banana fibre.

By increasing the number of layers of woven banana mat in between the glass fibre skin layers, the strength can be increased to higher values.

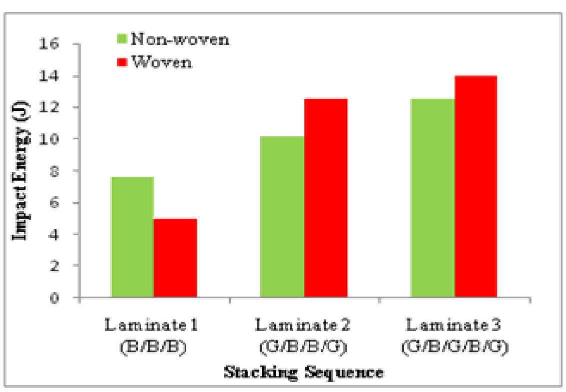
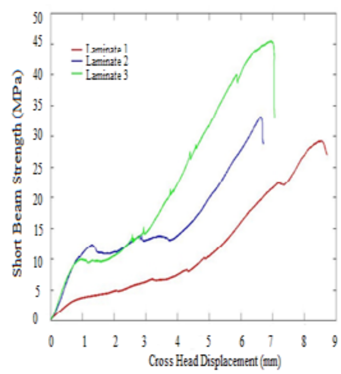


Fig.7 Plot to show the variation of Impact Energy

As the number of layers offibres increases as in laminate 3, impact strength improves by 12% compared to laminate 2. The variation of impact energy against woven and non-woven architecture [21] with different stacking sequences is shown in Fig.7.

3.4 Interlaminar shear strength (ILSS) – Short Beam Test

The short beam interlaminar shear strength (ILSS) was determined with specimens of width twice the thickness and length six times the thickness machined from the fabricated planar woven composite laminates as per ASTM D 2344-06. The three point bending test was carried out on a KALPAK UTM with a constant cross head speed of 2 mm/min and the test results are shown in the Table 2. Fig.8 shows the plot between short beam shear strength and cross head displacement for different laminates.



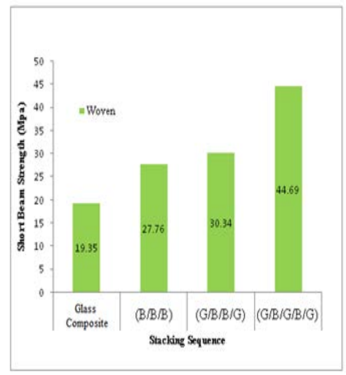


Fig.8 Short beam strength vs Cross-head displacement

Fig.9 Plot to show the variation of Short beam strength

During interlaminar shear tests, all specimens failed by delamination. Experimental results show that the short beam shear strength for woven banana composites (27.76 MPa) were higher than those of glass fibre reinforced composites (19.35 MPa). By constraining the delamination providing roughened woven banana fibres in between the glass fibre, shear strength is improved. By introducing a glass fibre mat like in laminate 3 gives higher strength (44.69 MPa) compared to laminate 2 and laminate 1. The interlaminar shear strength of the hybrid composites was even higher than those of glass fibre reinforced composites due to the excellent hybrid performance of the hybrid interface. It is observed that the short beam strength improves by 131 % when glass fibres (WRM) were replaced with woven banana fibre. These macro-scale results have been correlated with the woven banana mat structure, rough surface of banana fibre and fibre bonding between banana fibre layers and glass fibre layers.

Improvements on interlaminar shear strength by hybridizing banana and glass fibres significantly depended on the fibre bonding between glass fibres and banana fibres which was mainly caused by the woven banana mat structure and rough surface of banana fibre mat compared to their glass counterparts, as shown in Fig.8 and Fig.9.

3.5 Mode-I Interlaminar Fracture Toughness(GIC)

The double cantilever beam (DCB) testing was carried out according to the ASTM D5528 standard with specimen size of $125 \times 25 \times t$ mm with an initial crack length (a0) of 50 mm. The

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pre-crack was done by inserting a non-adhesive thin Mylar sheet during the laminate fabrication and steel hinges were attached to the specimen to ensure that the specimen is always vertically loaded. The end of the DCB specimen was opened with a cross head speed set at 2 mm/min. Load-crack opening displacement curves for laminate 4, laminate 5 & laminate 6 are shown in Fig.10.

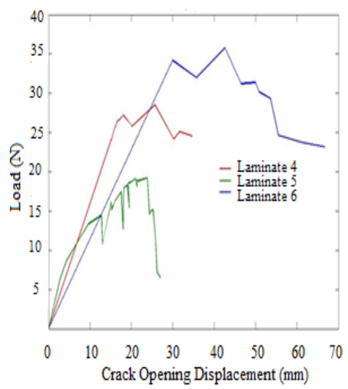

Fig.10 Load-COD curves for different laminates

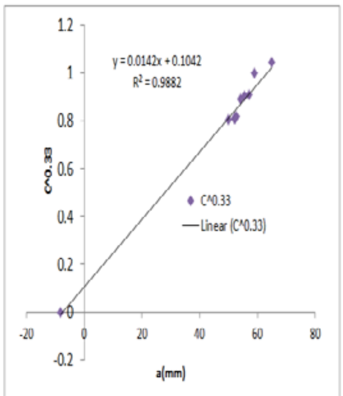

Fig.11 Plot for determination of effective delamination Extension(Δ)

Table 3.Mode-I fracture toughness values (GIC) obtained for different laminates.

	Stacking Sequence		
Properties	Laminate4 (Glass Composite)	Laminate5 (G/B/B/G)	Laminat6 (G/G/B/B)
G_{IC} (kJ/m2)	0.56	0.41	1.25
Gain in G_{IC}	-	26.78%	123%

The testing was done by 10 kN capacity computer controlled KALPAK UTM with DCB set up. The steady state delamination fracture toughness values (GIC) obtained for different combination of laminates is given in Table 3. The Mode-I inter-laminar fracture toughness was calculated based on the modified beam theory (MBT). The beam theory expression for strain energy release rate of a perfectly built in (clamped at the delamination front) DCB will overestimate the GIC in the present case, as the beam in the present study is not perfectly built-in, as rotation may occur at the delamination front. Hence in the MBT, correction delamination length (Δ) is found as shown in Fig.11, where C is the ratio of deflection to load, and added to the crack length. It is found that fracture toughness of laminate 6 is better than other samples due to strong adhesion between fibre and polymer matrix and minimum possibility of providing voids in the composite. This shows that the interlaminar adhesion between glass and banana fibre mat provides better bonding and thus results the higher interlaminar fracture toughness compared to glass fibre laminates.

Thus, the torn out glass fibres and rough surface of banana mat played as the major bonding between the banana fibre layer and glass fibre layer, which led to the increased interlaminar fracture toughness. The G_{IC} value of hybrid combination of glass and woven banana mat, that is laminate 6, shows an improvement of 123% compared to glass fibre composites. The hybrid combination of flax fibre and glass fibre results in aG_{IC}value of 0.56 kJ/m² [16]. That means the fracture toughness between glass and woven banana mat is better compared to hybrid combination of flax and glass fibre. This happens due to the woven architecture of the reinforcing fibres, rough surface of the banana fibres and better bonding between glass and banana mat.

4 Conclusions

Effect of stacking sequence, influence of glass fibre hybridization and woven architecture on mechanical and interlaminar properties of woven banana-glass fibre reinforced epoxy composites, have been experimentally evaluated. From the results of this study, the following conclusions are drawn.

- ❖ The maximum tensile strength and flexural strength of 130 MPa& 145 MPa is observed for banana hybrid combination with three layers of glass fibre (laminate 3). The interlocking effect of the woven architecture enhances the tensile strength and tensile modulus.
- ❖ Better impact energy of 14 J is obtained in the banana fibre laminate with three alternate layers of glass fibre (laminate 3). The number of layers, woven architecture and the stacking sequence are the major factors which affect the impact strength.
- ❖ The interlaminar shear strength and the interlaminar fracture toughness of banana/glass fibre reinforced hybrid composites were higher than those of GFRP. The woven banana mat structure and the rough surface of banana fibres led to remarkable fibre bonding between banana fibres and glass fibres, thus improved the interlaminar properties of hybrid laminates.
- ❖ It is observed that the short beam strength improves by 131 % when glass fibres (WRM) were replaced with woven banana fibre.
- ❖ The strain energy release rate of composite seems to increase with strong adhesion between fibre and polymer matrix which also gives less possibility of voids in the composite.

From the observations, the hybrid composite laminates are showing moderate performance than the glass fibre composites. Hence it is suitable for the medium load applications such as welding helmet, chair, table, roof, and automobile body panels.

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