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Article

Development of Improved Flexural and Impact Performance of Kevlar/Carbon/Glass Fibers Reinforced Polymer Hybrid Composites

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Abstract: The present investigation focuses on developing cost-effective Carbon/Glass/Kevlar fiber-reinforced polymer hybrid composite laminates for achieving its synergistic effect on flexural and impact performance. It investigates the effect of stacking sequence induced by the use of different fiber types (Kevlar = K, glass = G, and carbon = C) on the flexural and impact performance of the composites. Five hybrid composites (labelled as A = $[G_2K_3G_2]$, B = $[KG_2CG_2K]$, C = [CKGCGKC], D = [CGKCKGC], E = $[CK_2CK_2C]$) and three plain (i.e., non-hybrid) composites (F = $[K]_7$, G = $[G]_7$, H = $[C]_7$) have been fabricated through manual pre-preg lay-up manufacturing techniques. The flexural strength and modulus, hardness, and Izod impact strength have been evaluated for the fabricated composites and compared. The results showed that the D-type hybrid composite achieves the maximum positive hybrid effect as compared to other hybrid composites, possesses a hardness of 59 BHN, a flexural strength of 380 MPa, and modulus of 36 GPa, and impact strength of 80 KJ/m^2. The fracture surfaces of the hybrid composite specimen have been analysed using scanning electron microscopy, and compared against the properties achieved for enabling correlations. Furthermore, the cost-efficiency of the hybridization in terms of flexural strength/cost, modulus/cost, and impact strength/cost ratio were evaluated for potential engineering and design applications.

Keywords: carbon/glass/kevlar hybrid composites; flexural; Izod impact; FRP laminates; stacking sequence

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1. Introduction

Industries such as railway, automotive, aerospace, space, and windmill require lightweight materials, which are satisfied by fiber-reinforced polymer composites due to their high strength-to-weight ratio, good fatigue life, and corrosion resistance compared to traditional engineering metallic materials. Carbon fiber-reinforced polymer composites possesses high strength to weight ratio. It satisfies the requirement in structural engineering components in ships, aircraft, and sports where other engineering materials cannot be replaced [1,2]. However, due to high material and manufacturing costs, it restricts essentially for common engineering materials in automotive and railway applications. Nevertheless, the carbon fibers are inherently brittle, and a minor impact load can cause severe damage to the structure of the composites [3–5]. Different researchers have adopted various strategies to overcome the weakness of carbon fiber in structural applications. One of the methods is toughening the thermosetting matrix by mixing different organic (carbon nanotubes) and inorganic nanofillers (Al_2O_3, SiO_2, and TiO_2) [6]. The other method is to do hybridization with ductile fibers such as woven glass fibers [7]. Woven Kevlar fibers can also improve the fracture toughness of the hybrid composites [8]. Therefore, the hybridization of ductile fibers with high-strength carbon fibers may achieve the desired mechanical properties for different engineering applications at a lower cost [9–12]. Carbon and Kevlar fibers are costly, which would be a significant barrier to their hybridization. Therefore, there is a need for glass fibers hybridizations with them. As a result, hybrid material will give high strength and stiffness, better fracture and impact resistance, and lower the weight and cost of the composite [13–15]. The hybridization lowers the cost of hybrid composite, has optimum mechanical properties, and enables its exponential rise in demand and implementation. The need for such material grows rapidly, particularly in space and aviation, vehicles, military, marine, medical equipment, and other industrial applications [16,17]. The hybrid structural configuration can be divided into three types, i.e., layer-by-layer, fiber-by-fiber, and yarn-by-yarn [18]. However, the layer-by-layer method is sustainable due to the easy manufacturing process and lower cost of developing hybrid composites. The characteristic of materials, working parameters, and stacking order of interlayer fibers of hybrid composites affects the mechanical properties [19]. Several research studies have previously been investigated, and there is significant information that necessitates well-thought-out analysis and organized research in hybrid polymer matrix composites. Randjbaran et al. [20] revealed that the first layer should be stacked with glass fiber and is preferable to Kevlar fiber. As the glass fiber impact, energy absorption is higher than Kevlar fiber. Vinay et al. [21] found that glass–carbon and carbon–Kevlar hybrid composites have excellent hardness and flexural properties because of their good adhesive bonding. Khan et al. [22] found a positive hybrid effect of glass–carbon hybrid composites. Flexural and impact properties depend on the stacking order of fiber layers in hybrid composite laminates. Stacking the stiffer carbon fiber in the middle layers of the composite, strength is found to be highest. By increasing the number of high-performance fibers, mechanical properties are improved. It has been suggested that the fatigue and mechanical characteristics of the glass–carbon hybrid composite can be used to build structural components [10,23–26]. Cihan et al. [27] reported that both pure flax composites and flax hybrid composites exhibit excellent mechanical properties compared to E-glass fiber-reinforced polymer composites. Kenaf-glass–epoxy hybrid composites possess superior mechanical properties as compared to flax-glass–epoxy hybrid composites [28]. Effect of kenaf and flax natural fiber reinforcement in glass and carbon fiber on flexural and wear properties was studied by Subhrajyoti Saroj and Ramesh Kumar Nayak [29]. They found that $C_2F_3C_2$ and $G_2K_3G_2$ shows maximum hybridization effect to improve the mechanical and wear properties of the hybrid composites. The above literature study shows that glass and Kevlar fiber have high strain to failure compared to carbon fiber. On the other hand, carbon fiber has better strength and modulus than the previous one. The hybridization of glass–carbon–Kevlar is necessary to study the enhanced strength, modulus, and impact properties. The sensitivity of the stacking sequence of carbon, glass, and Kevlar fiber on flexural and impact response has not been adequately discussed, along with its cost-efficiency. Therefore, in the present investigation, the effect of the stacking sequence of glass–carbon–Kevlar fiber on hardness, flexural strength, modulus, and impact strength and its cost efficiency is evaluated and compared. Furthermore, scanning electron microscopy (SEM) is used to understand the mode of failure and straightening mechanism of the hybrid composites.

2. Materials and Methods

2.1. Materials

The glass, carbon, and Kevlar fibers are bidirectional twill woven roving in nature. The surface density of glass, carbon, and Kevlar are 360 gsm, 200 gsm, and 200 gsm, respectively. The carbon, Kevlar, and glass fiber are procured from Soller composites and Owens Corning, India. The matrix is epoxy polymer, and it is a Diglycidyl ether of Bisphenol A type, and the hardener is Triethylene of tetra-amine. The ratio of epoxy to hardener is 10:1 as per the manufacturer's specification. The commercial name of the epoxy polymer is Lapox L-12, and the hardener is K-6. The epoxy and hardener were procured from Atul Industries, India. These materials are used for the fabrication of hybrid composites.

2.2. Sample Preparation

The plain and hybrid composites plates contain seven layers. The fiber sequence in hybrid composites is designed so that high-strength carbon or Kevlar fiber is at the center of the hybrid composite laminates to sustain the maximum flexural load. The composite laminates are fabricated by a manual pre-preg hand lay-up process. The silicon spray is applied to the releasing sheet and it helps to remove the laminated plates easily. The weight proportion of epoxy to total fiber is 50:50. During the fabrication process, a mild steel roller with weighting 2.5 kg is used to remove air bubbles and voids entrapped during the fabrication process. It also enables the uniform distribution of epoxy polymer matrix in each layer. Figure 1 shows the stacking configurations of hybrid composites (A = [$G_2K_3G_2$], B = [KG_2CG_2K], C = [CKGCGKC], D = [CGKCKGC], E = [CK_2CK_2C]) and three plain composites (Kevlar = F = $[K]_7$, glass = G = $[G]_7$, carbon = H = $[C]_7$). The carbon fiber is kept at the center and outer of the hybrid composites to withstand maximum load and improve the maximum strength. The Kevlar and glass fiber are kept neighbor of carbon fiber of the composites to absorb maximum energy and improve the impact strength. The thickness of plain glass, carbon, and Kevlar fiber-reinforced polymer composites are around 3 mm, 2.1 mm, and 2.5 mm. However, the hybrid composite thickness is varied from 2.3 to 2.6 mm. The plain and hybrid composite laminates are cut as per ASTM specifications. The composite laminates are cured at room temperature for 24 h. The specimens are post-cured for 6 h at 140 °C and cooled very slowly (Furnace cooling). The theoretical density of the composites is calculated as per Equation (1).

$$\rho_{ct} = \frac{1}{\frac{w_c}{\rho_c} + \frac{w_k}{\rho_k} + \frac{w_g}{\rho_g} + \frac{w_m}{\rho_m}} \tag{1}$$

where w, c, k, g, m, and ρ stands for weight fraction of the fiber/matrix, carbon, Kevlar, glass, polymer matrix, and density of the materials, respectively. The experimental density is measured using density measurement kid and as per the Archimedes principle. The gas bubbles are entrapped in the composites in the form of voids and determined as per Equation (2).

$$Void\ (\%) = \frac{\rho_{c\ t} - \rho_{c\ exp}}{\rho_{c\ t}} \times 100 \tag{2}$$

where "t" stands for theoretical and "exp" stands for experimental values of density of the composites. The void content in plan and hybrid composites is evaluated using Equations (1) and (2) and reported in Table 1. The void present in composites varies from 0.75 to 2.84%. This is because, in manual pre-preg hand layup techniques, entrapment of voids is unavoidable.

Table 1. Plain and hybrid composites name and their coded name, density, and void content.

Composite Type	**$G_2K_3G_2$**	**KG_2CG_2K**	**CKGCGKC**	**CGKCKGC**	**CK_2CK_2C**	**K_7**	**G_7**	**C_7**
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Theoretical Density ($\rho_{c\ t}$)	1.4340	1.4460	1.3917	1.39	1.2958	1.2584	1.5315	1.3509
Experimental Density ($\rho_{c\ exp}$)	1.4231	1.4214	1.3612	1.3521	1.2622	1.2231	1.4912	1.3221
Void Content (%)	0.7581	1.7041	2.1903	2.8446	2.5933	2.8025	2.6309	2.1303

Liu et al. [30] suggested that both the strength and modulus decrease with increasing porosity. A higher void sensitivity for ILSS, flexural strength and flexural modulus are obtained, and tensile strength decreases relatively slowly, while the tensile modulus is insensitive to the void content. The size of the voids also reduces the strength of the composites [31]. Furthermore, the void helps to absorb more moisture and followed by degradation of its mechanical properties. The void content in the composites may not be uniform throughout the composite laminates. Therefore, the physical and mechanical properties of the composites will vary in the same composites. Hence, the average values of hardness, strength, and impact resistance with standard deviation are reported in article.

Figure 1. Schematic diagram of stacking sequence of plain and hybrid composites.

2.3. Hardness Testing

The hardness of plain and hybrid composite materials is determined as per ASTM D2583 standard using a portable Barcol hardness tester. It is a method for measuring the hardness of rigid plastics, both reinforced and non-reinforced. In the Barcol hardness tester, the tip of the impresser is pressed against the material to be tested, and the material's hardness determines how deep the tip indents, which is transferred through a tension spring and lever that can be read on a dial. Five samples of each type of composite are used to determine the Barcol Hardness Number (BHN), and the average values are reported.

2.4. Flexural Strength and Modulus

The interface of the fiber-reinforced polymer composites is the heart of the composites. The flexural test is conducted to understand the load transfer behavior of the matrix to different fibers. The results presented in the current paper form a comparative analysis in terms of as-received mechanical response. The specimens have been carefully stored and tested immediately post manufacturing to ensure minimal moisture absorption has been received by the specimens. The hygrothermal and moisture absorption effects will be accounted for in a separate study. In that sense, the ultimate study presented in our article addresses the immediate and initial crashworthiness response of the specimen. A future study would determine the continued crashworthiness via accounting for controlled moisture absorption. The test is carried out on a universal testing machine with a three-point bending system. The test used rectangular specimens with dimensions 70 mm × 12.7 mm × thickness (mm). The span to thickness ratio is varied from 20 to 30 due to different thicknesses of the composite laminates, and crosshead speed is kept fixed, i.e., 5 mm/min. Three specimens of each type of composites are tested and the average values are taken into account for the analysis. Equations (3)–(5) are used to determine the flexural strength (σ_F), modulus (E_F), and strain to failure (ε_F) of the composites. The flexural properties are determined as per the ASTM D790 standard.

$$\sigma_F = \frac{3P_{max}L}{2wt^2} \tag{3}$$

$$E_F = \frac{mL^3}{4wt^3} \tag{4}$$

$$\varepsilon_F = \frac{6\delta t}{L^2} \tag{5}$$

where L is the support span length, w is the width of the specimen, t is the thickness of the samples, P_{max} is the maximum flexural load before failure, m is the slope of initial segment load versus displacement curve and δ is mid-span deflection.

2.5. Impact Strength

Impact resistance of composite is defined as the ability of the composites to resist fracture under impact loads. Izod impact test measuring machine is used to determine the impact strength of the composites as per ASTM D256 standard. The specimen has a V notch, and the dimension of the notch is as per the ASTM standard. The sample is placed vertically with a pendulum striking at the tip position, and the impact strength is determined. The requisite specimens are rectangular, having dimensions of 64 mm × 12.7 mm × thickness (mm). Three specimens of each type are tested, and impact strength (KJ/m^2) is calculated by dividing the recorded absorbed impact energy by the cross-section area of the sample. The average values are taken into account for the analysis. Figure 2 shows the schematic diagram of the Izod impact test. The load is applied in front of the notch created in the samples.

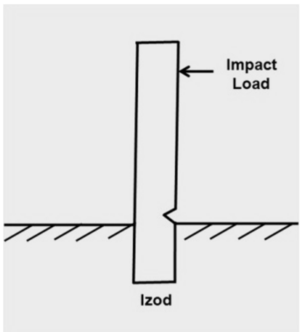

Figure 2. Schematic diagram of Izod Impact test.

3. Results and Discussion

3.1. Hardness

The hardness of the composites is measured using a Barcol hardness tester. The hardness of different composites is shown in Figure 3. The results showed that specimen D ([CGKCKGC]) has the highest hardness value of 59 BHN among the hybrid composites, which is 27% more than that of plain Kevlar fiber-reinforced polymer composite (F). The stiffer carbon fiber on the outer layer of composite followed by glass and Kevlar fiber resist the indentation as compared to Kevlar followed by glass fiber in C ([CKGCGKC]) type hybrid composites.

It is worth mentioning that fiber sequence makes the difference in hardness properties of the hybrid composites, although the same number of glass, carbon, and Kevlar fiber is present in the two-hybrid composites (C&D). Nayak et al. [16] have also reported similar findings that outer carbon layers improve the hardness of the composite due to the high modulus of carbon fiber compared to glass fiber. It is also observed that all hybrid composites' hardness varies between plain Kevlar and carbon fiber-reinforced polymer composites, which is as expected.

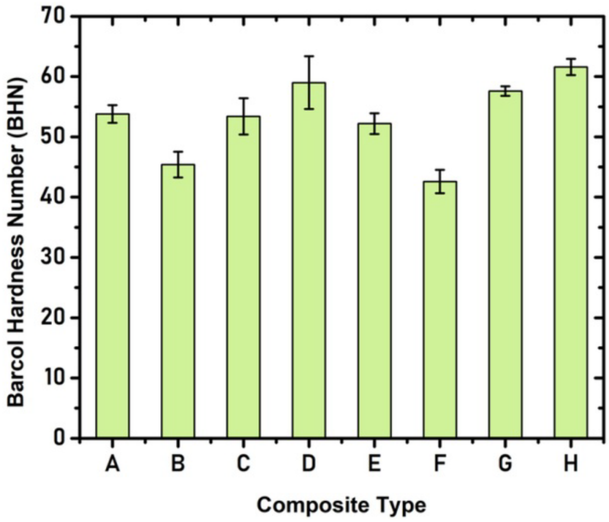

Figure 3. Barcol Hardness of different composites.

3.2. Comparison of Flexural Strength and Modulus

In the current investigation, the strong carbon fiber is hybridized with high ductility glass and Kevlar fiber to tailor the mechanical properties and have some economic advantages. The flexural strength is evaluated through a three-point bending test. The flexural strength versus stain of plain and hybrid composites is shown in Figure 4a. It is observed that plain carbon fiber-reinforced polymer composite has maximum flexural strength, plain Kevlar-reinforced polymer composite has a maximum strain, and plain glass fiber-reinforced polymer composites have the intermediate value of strength and ductility. This is because the carbon fiber possesses high strength and modulus and glass and Kevlar fiber possess high strain to failure. The hybrid composite B (KG_2CG_2K) has the maximum strain before fracture compared to other hybrid composites due to a higher number of high strain fibers present in it.

Figure 4b,c show flexural strength and modulus versus composite type. It is observed that the hybrid composite of type D (CGKCKGC) possesses the maximum strength and modulus among all hybrid composites. D's flexural strength and modulus have improved by 36% and 176%, respectively, compared to plain Kevlar fiber-reinforced polymer composites. Compared with plain glass fiber-reinforced polymer composites, the flexural strength and modulus have improved by 20% and 56%, respectively. It is observed that, although the number of Kevlar, glass, and carbon fiber is the same in hybrid composite C and D, the flexural strength is remarkably different between them and indicates how the stacking sequence is sensitive to the flexural strength and modulus of a hybrid composite. The hybrid composite D ([CGKCKGC]) contains alternate carbon, glass, and Kevlar fiber layers. Glass and Kevlar fiber layers have high strain capacity and help bridge the crack developed by low strain capacity of carbon fibers and avoid the brittle failure of hybrid composites. Dipak Jesthi and R. K. Nayak [11] developed hybrid composites using glass and carbon fiber-reinforced polymer composites. They found that $[GCG_2C]_S$ type has the highest flexural strength and modulus i.e., 462 MPa and 27.8 GPa respectively. The higher flexural strength is due to higher number of carbon fibers present in it as compared to the D type hybrid composites. However, the flexural modulus of D type hybrid composite is 36.52 GPa which is more than $[GCG_2C]_S$ type hybrid composites. Gurunathan et al. [32] reported that biocomposites have good potential to be used in automobile and building industries due to its high specific strength and modulus. However, these composites have high tendency to absorb moisture and leading to reduction on mechanical properties in water and high humidity environment.

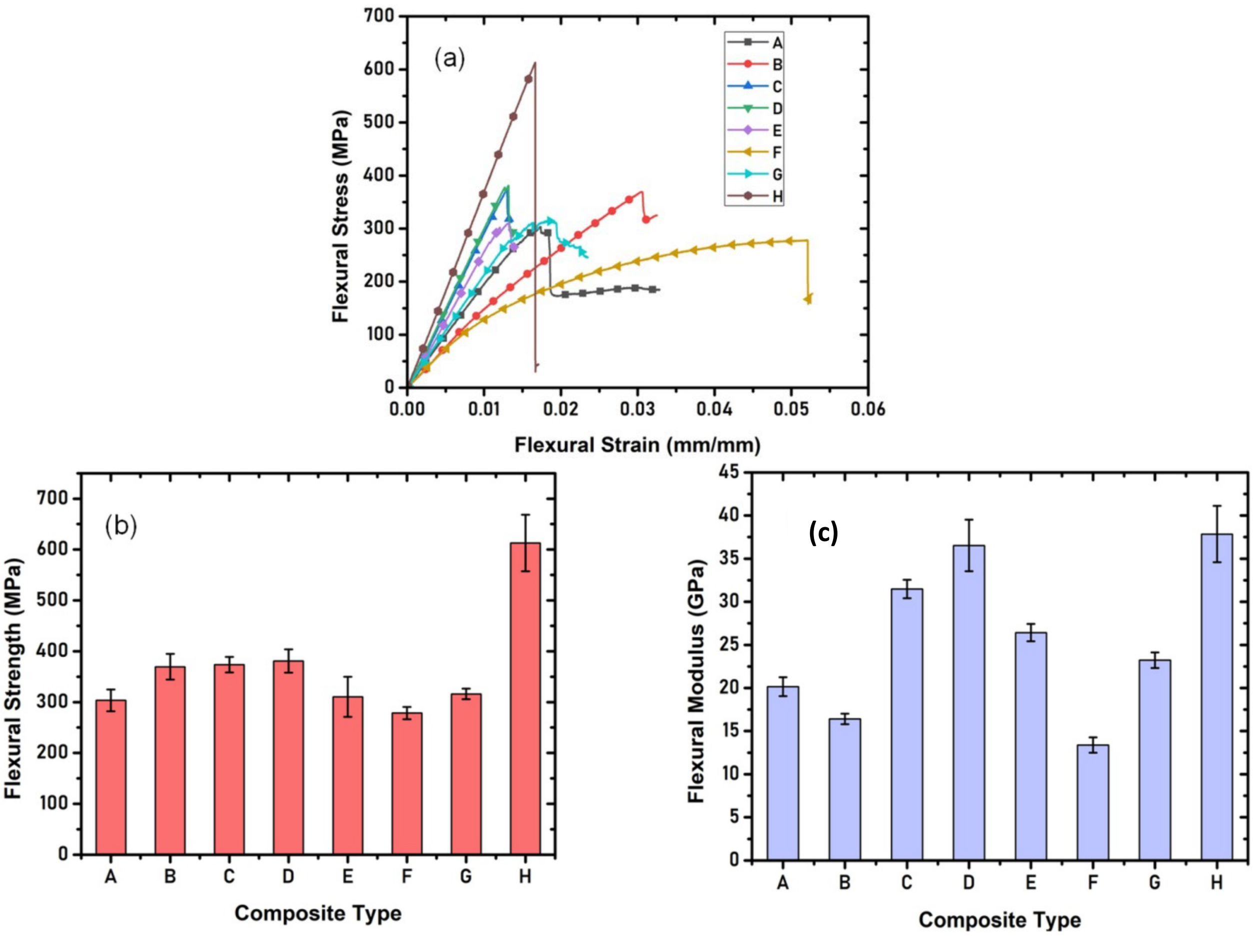

Figure 4. (**a**) Flexural strength versus strain, (**b**) Flexural strength, and (**c**) Flexural modulus versus composite type.

Figure 5 shows the schematic diagram of the expected failure mechanism of hybrid composites during a three-point bending load. It is expected that the glass and Kevlar fiber will fail first than carbon fiber due to low load-bearing capacity. In hybrid composites, C and D, due to the presence of carbon fiber at the center and the top layer of the composites, show maximum flexural strength compared to other hybrid composites which are observed experimentally. The strength of glass fiber is more than Kevlar fiber. Therefore, it is expected that the Kevlar fiber fails earlier than glass fiber in hybrid composites. In hybrid composite D, Kevlar fiber is near to the central carbon fiber and fails first as compared to glass fiber. But due to the high strength of glass and carbon fibers surrounding Kevlar fiber, it requires more load for failure and this may be one of the reasons to have the highest flexural strength and modulus of hybrid D, although the number of fiber layers in C and D are same. G. Kretsis [25] has revealed that flexural properties of hybrid composites were not only influenced by their composition but also by the stacking sequence of the hybrid composite. Dipak Jesthi and R. K. Nayak [11] also found that the stacking sequence of glass/carbon fiber is sensitive to the mechanical properties.

Specific strength and modulus data are required during designing any engineering component. The flexural strength and modulus divided by their density are known as the specific strength and modulus of the composite, respectively. This data helps to design lightweight and high-strength engineering components. The specific flexural strength and modulus of plain and hybrid composites are reported in Table 2.

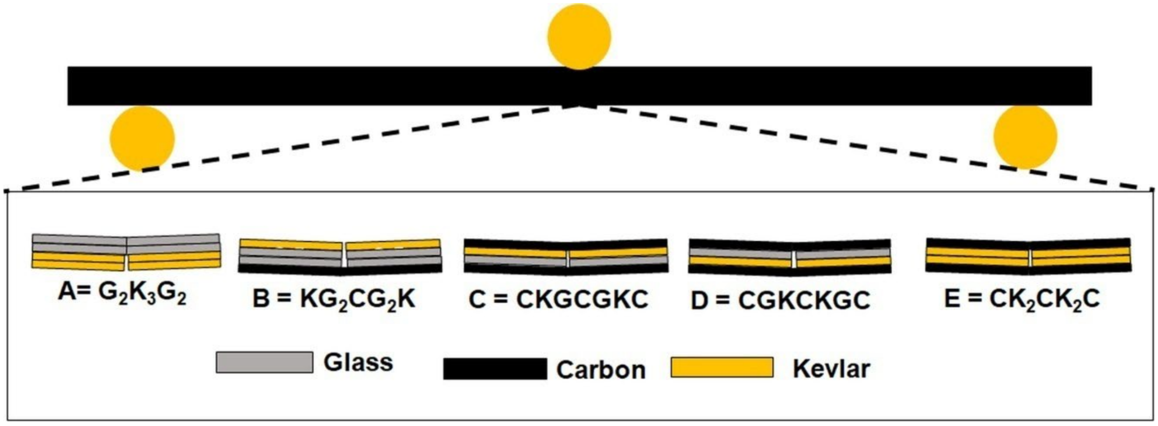

Figure 5. Schematic diagram of failed hybrid composites under three-point bending load.

Table 2. Specific flexural strength and modulus of composites.

Composite Type	Flexural Strength (MPa)	Flexural Modulus (GPa)	Density of Composites (g/cm^3)	Specific Strength of Composites (10^3 m^2/s^2)	Specific Modulus of Composites (10^6 m^2/s^2)	Carbon Fiber %
A	303.45	20.16	1.40	0.22	14.40	0
B	369.50	16.42	1.41	0.26	11.65	14
C	373.51	31.47	1.36	0.27	23.14	43
D	380.96	36.52	1.35	0.28	27.05	43
E	310.34	26.42	1.26	0.25	20.97	43
F	278.40	13.38	1.22	0.23	10.97	0
G	316.13	23.22	1.49	0.21	15.58	0
H	613.01	37.85	1.32	0.46	28.67	100

It is observed that the hybrid composites of type D have 43% of carbon fibers and show similar specific flexural modulus of plain carbon fiber composites (100% Carbon fiber). On the other hand, the specific flexural strength of D-type hybrid composites shows maximum compared to other plain and hybrid composites except plain carbon fiber-reinforced polymer composites. This is due to lower density of hybrid composites and three threelayers of high strength carbon fiber present in it. The low density of the hybrid composites is due to majority of fibers are carbon and Kevlar, whose density is lower than glass fiber. In this hybrid composite, the load transfer is better from surface to the centre as compared to type C hybrid composites. This is because the load transfers from the surface carbon fiber to glass fiber followed by Kevlar fiber in D type hybrid composites and in C type hybrid composites the load transfers from the surface carbon fiber to Kevlar fiber followed by glass fiber to the centre high strength carbon fiber. The improvement of specific flexural strength and modulus of type D hybrid composite creates an opportunity to be used in structural components for possible engineering applications.

3.3. Izod Impact Strength

Composite materials having high toughness are desirable in structural applications to avoid catastrophic failure. It is known that carbon fibers are more brittle than Kevlar and glass fiber. Therefore, to improve the impact strength of the composites, glass–carbon–Kevlar fibers are hybridized with different stacking sequences. Figure 6 shows the Izod impact strength versus composite type. It is observed that the carbon fiber has the lowest impact strength, and the hybrid A has the maximum impact strength. The hybrid composite A has a synergistic effect of glass and Kevlar fiber, by which the Izod impact strength has been improved and exceeds the maximum impact strength of Kevlar fiber.

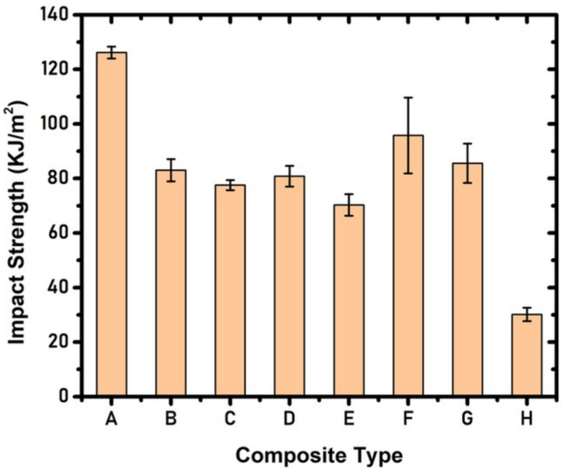

Figure 6. Izod impact strength of different composites.

This positive hybrid effect is more than the maximum impact strength value of the Kevlar fiber. This is because both high strains to failure fibers resist the crack growth of the composites and have a synergistic effect. The result shows Izod impact strength is sensitive to the fiber stacking sequence of the hybrid composites (C&D). Naik et al. [26] have reported that the stacking order of hybrid composites influences impact strength. The hybrid composite D improved its impact strength by 166% compared to plain carbon fiber-reinforced polymer composites.

Figure 7 shows the Izod impact specimen deformation after the impact test. The hybrid composites A, B, C, and D fail with deformation. However, the plain carbon composite (H) fails catastrophically and shows the least deformation (brittle). The plain and hybrid composite having Kevlar and glass fiber undergoes high strain to failure. It is because Kevlar and glass fiber has higher strain capacity, absorbing more energy than carbon fiber before failure. Interestingly, the Kevlar fiber-reinforced polymer composite did not fail. The hybrid composites fail with substantial deformation compared to plain carbon fiber-reinforced polymer composites. Therefore, it is expected that the hybrid composite will not fail catastrophically in service and better reliability compared to plain carbon fiber-reinforced polymer composites in engineering applications.

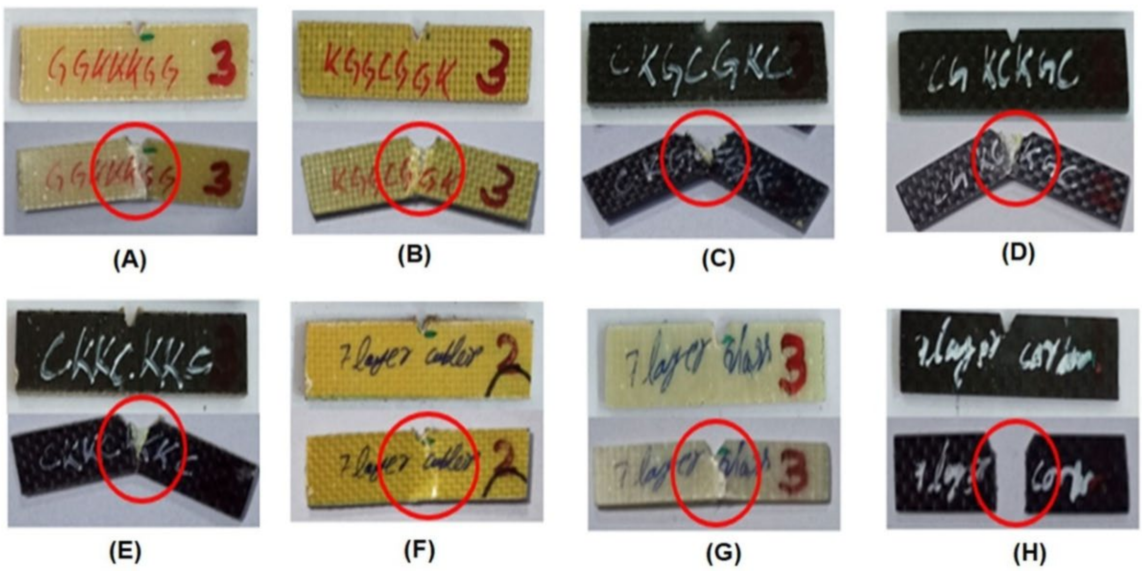

Figure 7. Izod impacted composite tested samples of composite type A, B, C, D, E, F, G and H.

3.4. Fractographic Analysis

Figure 8a–c show the fracture surface of plain Kevlar, glass, and carbon fiber-reinforced polymer composites, respectively. It is observed that the Kevlar fibers are highly strained and delaminated from the polymer matrix. Fibrillation in Kevlar fibers means the breakage of Kevlar fiber bundles into smaller fibers, and this phenomenon increases the energy absorption of the composites. The glass fiber shows a good interface bond and matrix drainage during failure. Matrix toughening and a good interface bond between matrix and carbon fiber are observed in carbon fiber-reinforced polymer composites.

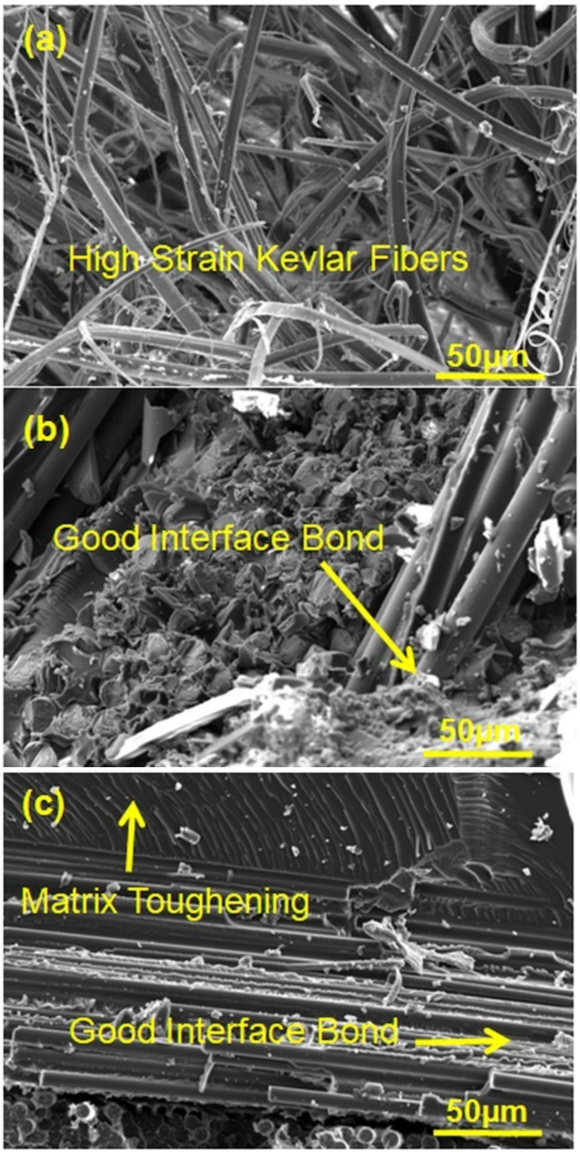

Figure 8. SEM images of the fractured surface of plain (**a**) F, (**b**) G, and (**c**) H.

The good interface bond and matrix toughening enable better strength and modulus of the composites. The carbon fibers are broken in a brittle manner as compared to glass and Kevlar fiber. Figure 9 shows the fracture surface of D-type hybrid composites, where the maximum hybridization effect is observed. The fracture surface indicates better adhesion, matrix toughening, and broken fibers are the different failure mechanisms for the improvement of the overall strength and modulus of the hybrid composites. The matrix phase of the glass fiber is substantially cracked and scattered as resin debris in the composite, which causes matrix fragmentation in the specimen. The epoxy matrix fragments can be seen on the fiber's surface, indicating good matrix adherence.

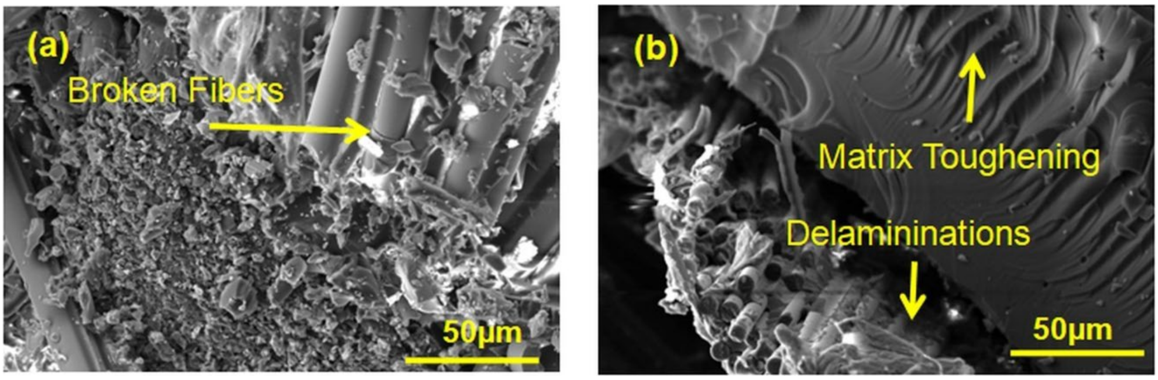

Figure 9. SEM images of the fractured surface of the hybrid composites D (**a**) fiber broken (**b**) matrix toughening and delamination.

3.5. Cost Analysis

The increasing order of cost of woven fabric fiber is that of glass, Kevlar, and carbon. Each type of fiber has its advantages and limitations. For example, carbon fiber is costly and has high strength and modulus but low impact strength and brittle fracture. On the other hand, glass and Kevlar fiber have low strength, high impact strength, and ductile failure compared to carbon fiber-reinforced polymer composites. Therefore, fiber hybridization is made to tailor the mechanical properties and avoid catastrophic failure. Table 3 shows the relative individual cost of composites and normalized with carbon fiber-reinforced polymer composites. The plain carbon fiber-reinforced polymer composites are 10 and 7 times more than glass and Kevlar fiber-reinforced polymer composites, respectively [33]. The cost of hybrid composites C and D is around 35% less than plain carbon fiber-reinforced polymer composites.

Table 3. Cost comparison between plain and hybrid composites and normalized with carbon fiber-reinforced polymer composites.

Composite Type	Stacking Sequence	CFRP Cost ($)	GFRP Cost ($)	KFRP Cost ($)	Total Cost ($)
A	[$G_2K_3G_2$]	0.00%	5.71%	30.00%	35.71%
B	[KG_2CG_2K]	14.28%	5.71%	20.00%	39.99%
C	[CKGCGKC]	42.85%	2.84%	20.00%	65.69%
D	[CGKCKGC]	42.85%	2.84%	20.00%	65.69%
E	[CK_2CK_2C]	42.85%	0.00%	40.00%	82.85%
F	[K]$_7$	0.00%	0.00%	70%	70.00%
G	[G]$_7$	0.00%	10.00%	0.00%	10.00%
H	[C]$_7$	100%	0.00%	0.00%	100.00%

The engineering properties such as flexural strength and modulus/cost and impact strength/cost of plain and hybrid composites are calculated to understand the cost and performance of composites for engineering application in practice. The comparison of flexural strength and modulus/cost and impact strength/cost of composites are reported in Table 4. It is observed that the plain carbon fiber composites have higher performance and plain glass fiber-reinforced polymer composites have better cost efficiency (Strength/cost, Modulus/coat, and Impact strength/cost). It is observed that replacing a few carbon fibers with glass and Kevlar fiber combinedly improves the cost efficiency and performance.

Table 4. Comparison of flexural strength and modulus/cost and impact strength/cost of composites.

Composite Type	Stacking Sequence	Flexural Strength	Flexural Strength (MPa)/ Cost Ratio	Flexural Modulus (GPa)	Flexural Modulus (GPa)/ Cost Ratio	Impact Strength (KJ/m^2)	Impact Strength (KJ/m^2)/Cost Ratio
A	[$G_2K_3G_2$]	303	849	20	56	126	353
B	[KG_2CG_2K]	369	923	16	40	83	208
C	[CKGCGKC]	373	568	31	47	77	117
D	[CGKCKGC]	380	578	36	55	80	122
E	[CK_2CK_2C]	310	374	26	31	70	84
F	[K]$_7$	278	397	13	19	95	136
G	[G]$_7$	316	3160	23	230	85	850
H	[C]$_7$	613	613	37	37	30	30

The hybrid C and D have the same number of glasses, carbon, and Kevlar fiber. Due to different stacking sequences between them, the hybrid D-type composites possess better cost efficiency (Strength/cost, modulus/cost, and impact strength/cost) compared to type C type hybrid composites. In engineering practice, the design engineer considers the performance first and then the cost. However, suppose the cost efficiency data of the composites is available. In that case, it will be more accessible to the design engineer to select the suitable materials at lower cost at the design stage itself. The hybrid composite has better cost-efficiency. Type D hybrid composite is suitable for intermediate structural components such as commercial, automotive bodies, bumpers, and other parts that satisfy the strength/cost ratio values.

4. Conclusions

The plain and hybrid composites of glass, Kevlar, and carbon fiber-reinforced polymer composites are developed through manual pre-preg lay-up technique. The synergistic effect of different fiber combinations on flexural strength, modulus, and impact strength are evaluated. The following conclusions may be drawn.

Plain Carbon fiber-reinforced polymer composite has the highest hardness, i.e., 61.6 BHN, which is 30.8% more than Kevlar fiber-reinforced polymer composites.

Hybrid composite of type D ([CGKCKGC]) showed highest flexural strength and modulus of 380.96 MPa and 36.52 GPa, respectively, and it is due to the stiffer carbon fiber on the outer and middle layer of the composite.

Hybrid composite of type A ([$G_2K_3G_2$]) showed maximum impact strength, i.e., 126 KJ/m^2, because of the synergistic effect of both glass and Kevlar fiber present in it.

The plain glass, Kevlar, and hybrid fiber-reinforced polymer composite showed ductile deformation failure as it has high strain capacity, and the plain carbon fiber composite showed brittle failure due to low strain capacity.

Compared to all other hybrid composites, the type D ([CGKCKGC]) hybrid composite showed significantly superior mechanical properties and high cost-efficiency.

From SEM analysis, it is observed that the strengthening mechanism of the composites is attributed to fiber breakage, good interface bond, and matrix toughening.

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