

Article



Mechanical Characteristics and Adhesion of Glass-Kevlar Hybrid Composites by Applying Different Ratios of Epoxy in Lamination

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Abstract: Hybrid composites have great potential for specific strength and specific stiffness, effective in aerospace industries, submarines, and light-weight automotives. The mechanical strength and adhesiveness of hybrid laminates can be enhanced by effective use of matrix materials in different ratios of epoxy resin and epoxy hardener. Gentle use of resin and hardener in the fabrication of hybrid composites can alter tensile modulus, the bonding strength between matrix and fabric. Spectacular progress has been achieved by the selection of appropriate amounts of resin and hardener in the hybridization of composite laminate. Hybridization was made by Kevlar inorganic/organic fabrics and glass fabrics stacked with epoxy matrix material. To achieve the combination of mechanical properties and bonding strength, transparent epoxy resin and hardener of commercial grades mixed in various ratios are incorporated as matrix material to fabricate laminate. Three different sheets, named A (3:2), B (4:1), and C (2:3), were embedded by the hand layup method to prepare a hybrid composite. Experimental tests, according to ASTM 3039, were performed to determine the tensile mechanical properties. Peel tests, according to ASTM 6862-11, were performed to investigate the interlaminar strength between Kevlar and glass layers. Shore A and Shore C hardness durometers were used to find out the hardness of the specimens at different spots using the ASTM D-2240 standard. Finally, physical testing, such as density and then water absorption, was carried out using the ASTM D-570 standard to check the swelling ratio of the different specimens. The results obtained highlight that the specimen of the glass/Kevlar hybrid embedded in the ratio 3:2 in lamination has the best mechanical properties (tensile strength and hardness) and the lowest swelling ratio, while the material system in the ratio 4:1 shows the best interlaminar properties and adhesion capabilities.

Keywords: glass/Kevlar; hybrid composites; hand layup; epoxy; hardener; tensile; hardness shore D; water absorption; density; peel; ratio

1. Introduction

Composites have distinct phases, made by dissimilar fibers and matrix materials. Reinforcement fibers or stacking sheets are employed in matrix materials for making composite structures at the macroscopic level. Matrix materials have a continuous phase and are used as adhesives, and fibers have a discontinuous phase in metal matrix composites (MMCs), ceramic



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/). matrix composites (CMCs), and polymer matrix composites (PMCs) [1]. Reinforcing synthetic fibers, such as Kevlar fibers, carbon fibers, and glass fibers, and natural fibers, such as jute, sisal, hemp, etc., serve as a dispersed phase in composite materials [2]. In aeronautical applications, light-weight, high-strength organic/inorganic stacked laminated hybrid composites are ideal candidates [3]. The organic fiber Kevlar is five times better than steel due to its specific weight ratio. Kevlar has improved interfacial fracture toughness and degree of symmetry in its internal structure [4]. High-strength aramid fiber is employed as core material in hybrid laminate to prepare light-weight, high-strength bulletproof vests and helmets [5]. In the last few decades, researchers have focused on enhancing the performance of composite materials by mixing synthetic and natural fibers to prepare hybridized structures [6]. E-glass fibers have better ultimate tensile strength and are placed in the outside layer in lamination to produce a flaw-free structure [7]. There is no significant difference in the density if layup placement changes in hybridization [8]. Aramid (Kevlar), a synthetic fiber, was developed in 1965 by two research scientists, Stephanie Kwolek and Herbert Blades. Kevlar belongs to the aromatic polyamide family and consists of extended chains of synthetic polyamide [9]. Aramid fibers have incredible ultimate tensile strength, achieved by intermolecular hydrogen bonds and the aromatic stacking interface of aromatic groups in the neighboring strands [10]. The interatomic bonding is considerably stronger than the van der Waals intermolecular connection in other manmade polymers [11]. Kevlar (aramid) is based on comparatively stiff molecules, which formulate the planar sheet-like arrangement, comparable to silk protein. The intermolecular relation among the molecular strands of Kevlar significantly enhances mechanical strength characteristics and provides superior heat and flame resistivity [12]. Kevlar, which is by now renowned as an elevated-performance fiber, has a remarkable strength-to-weight ratio and improved toughness [13]. As far as cost competitiveness is concerned, glass fiber is cheap and easily available in the market, whereas Kevlar fiber is considerably expensive [14]. To achieve a balance between the cost competitiveness and the strength-to-weight ratio of laminate, hybrid composites are fabricated by stacking E-glass/Kevlar fibers [15]. The amount of water absorption in laminate reduces the mechanical strength of the hybrid composite by weakening the fibers' strength [16,17]. Glass fibers are placed at the interface and Kevlar fibers are used in the core to make a sandwich structure [18]. Glass-fiber-reinforced polymers are used to make printed wire boards for electronic appliances [19]. The mechanical behavior of fiber-reinforced polymers was investigated by understanding ultimate tensile strength, stiffness, and fibermatrix bond strength [20]. Kevlar fibers are used as core in the lamination sequence to suppress the fracture toughness of the hybrid composite [21]. The ratios of epoxy resin to hardener and the volume fraction are effective tools in the fabrication of composite materials [22]. Kevlar fibers reinforced with glass fibers have incredible capacity to produce less dense materials with superior strength, which attain high break and bear resistance characteristics [23]. Epoxy resin and epoxy hardener have good bonding strength and are positioned within layers of fibers to produce rigid and environment-resistant materials [24]. However, the mechanical properties of composite materials strongly depend on the adhesive material as well as the different ratios in which resin and hardener are mixed together to form a matrix phase [25]. The proper use of adhesive materials can supplement the mechanical properties, reduce component weight, increase durability, provide better design latitude, handle high levels of stress, and increase the strength of composites [26]. The performance of the continuous phase is related with the ratio of resin to hardener in the discontinuous phase in hybridization [27]. The interfacial bond strength of the glass/Kevlar hybrid composite is investigated by conducting a peeling test of the hybrid composite laminate [28]. In advanced technologies, materials are required with a combination of properties, such as strength, stiffness, impact, water absorption, and strengthto-weight ratio. Glass/Kevlar hybrid composites have an unusual combination of properties, which cannot be met by other conventional materials [29]. The strength of a composite depends not only on the assets of the matrix but also on how well it sticks to the particles and fibers of the dispersed phase [30]. It is vital that adhesive bonding forces between fiber and matrix be high to minimize fiber pull-out [31]. Sufficient bonding is essential to take advantage of the stress transfer from the weak matrix to the durable fibers.

2. Experimental Work

2.1. Preparation of Specimens

In E-glass fabrics with Kevlar 49, each layer has a thickness of 0.5 mm stacked with epoxy resin and a hardener of commercial grade as adhesive medium for the fabrication of hybrid composites. E-glass fabrics were placed at the top and the bottom, whereas the central layer was of Kevlar 49. In this study, laminates of hybrid composites (A, B, and C) were fabricated (Figure 1) with dissimilar amounts of epoxy resin and hardener using the hand layup method given in Table 1. Materials properties of E-glass, Kevlar, and epoxy given in Table 2.



Figure 1. Specimens fabricated using different resin ratios (A = 3:2, B = 4:1, C = 2:3) respectively.

Layer Formation	Layers	Glass Fibers	Kevlar 49	Ratio of Epoxy Resin	Ratio of Hardener
Α	03	02	01	3	2
В	03	02	01	4	1
С	03	02	01	2	3

Table 1. Layup placement of glass fibers and Kevlar 49 by applying different ratios of resin and hardener.

Material	Fiber Strength	Laminate Strength	Density of Laminate (g/cc)	Strength-to- Weight Ratio
E-glass	3450	1500	2.66	564
Kevlar	2757	1430	1.44	993
Ероху	N/A	12–40	1–1.15	28

Table 2. Materials properties of E-glass, Kevlar, and epoxy.

2.2. Tensile Test

During a tension test, standard specimens are placed on the grip of a tensile testing machine (Cometech, Taichung, Taiwan) (Figure 2) so that the specimens undergo tension before fracture. In usual practice, the gauge length of the standard sample increases and the cross-section area reduces during operation. The stress-strain diagram results and the data are analyzed. The standard specimen of ASTM D-3039 was used to conduct the test for a hybrid laminate [32]. Three specimens (24 mm wide and 150 mm long) were subjected to the grip of a 5 kN universal tensile testing machine. The strain rate (s⁻¹) was set to conduct the tensile test for each laminate. The laminate with the same dimensions as those of the glass/Kevlar hybrid with different ratios of epoxy resin and hardener—A (3:2), B (4:1), and C (2:3)—was examined at room temperature. The results and statistical analysis of specimens A, B, and C were tabulated, and the peak stress and peak load of each specimen were investigated considering the stress (N/mm²) and the strain (%).



Figure 2. A 5 kN universal tensile testing machine.

2.3. Peel Test

The peel adhesion test is used to determine the force required to debond two components joined by a strong adhesive. The test result, also known as bond strength, is generally represented as N (force to debond)/24 mm depending on specimen width. There are various types of peel tests. Examples include the 90° peel test, 180° peel test, single lap joint shear test, and T peel test. In this work, 90° peel tests were performed with two different test setups named type I and type II.

2.3.1. Sample Preparation

Three specimens, each being 24 mm wide and 150 mm long, was used to perform 90° peel tests, according to the ASTM D-6862-11 standard [33]. The samples were directly cut from the prepared sheets (27 cm \times 9 cm), in which one of the two glued components was flexible enough to be bent 90° without breaking.

2.3.2. Type I: When Glass Fiber Is Clamped on Both Upper and Lower Jaws of the UTM for Debonding

One layer of glass fiber is clamped on the upper, movable jaw and another layer of glass fiber is fixed on the lower, fixed jaw of the universal tensile testing machine. The force is set at zero and then, on pushing the start button, the specimen from one end starts debonding, either mechanically or chemically, until the movable layer of glass fiber is completely peeled apart or destroyed.

2.3.3. Type II: When Glass Fiber Is Clamped on the Upper Jaw and Kevlar Is Clamped on the Lower Jaw of the UTM for Debonding

An attempt is made to prevent the glass fiber from breaking during peeling. Kevlar fiber is clamped on the lower, fixed jaw and glass fiber is clamped on the upper, movable jaw to peel apart to check the adhesion between glass fiber and Kevlar by peeling them apart completely.

3. Hardness Test

Hardness is resistance to indentation or penetration. Shore A and Shore C durometers are used as portable hardness testers to find the hardness of three specimens. The shore durometer is a device for measuring the hardness of polymers, polymer matrix composites, and elastomers. Higher numbers on the scale indicate a greater resistance to indentation and, thus, harder materials.

The hardness test is carried out as per the ASTM D2240 standard [34] using Shore A and Shore C durometers shown in Figure 3. An indentation is formed by a given force on a standardized indentation head. This test method is widely used for composite and



polymer testing. As per ASTM standards, three samples are prepared with different resin



and hardener ratios with the dimensions 24 mm \times 24 mm.

The hardness test was carried out using two types of durometers, Shore A and Shore C. A load was applied, and the readings on the dial were noted down. The indentation was measured from different spots, and mean average values were calculated.

4. Density Test

A physical balance was used to evaluate the density of the hybrid composites. As per ASTM standards, three specimens were made. The specimens were placed onto the physical balance and the readings were obtained from the screen. The density was measured by putting the values in the formula Density $=\frac{Mass}{Volume}$. The dimensions of the specimen used for the density test were 24 mm \times 24 mm \times 0.2 mm.

5. Water Absorption Test

Water absorption is the amount of water uptake by a material under specific conditions. A physical balance was used to measure the amount of water absorbed by the specimens. As per the ASTM D-570 standard [35], three specimens were fabricated for water absorption, as shown in Figure 4. The samples were first weighed in dry condition and then put into distilled water at 31 °C for 24 h. The samples were then weighed again.



Figure 4. Specimens for the water absorption test using the ASTM D-570 standard.

Measurements

Water absorption is calculated as an increase in the weight percentage of specimens. Swelling ratio % = $\frac{\text{Wet laminate area} - \text{Dry laminate area}}{\text{Dry laminate area}} \times 100$ [36] Standard specimens are the same as in the density test (24 mm \times 24 mm \times 0.2 mm).

6. Results and Discussion

6.1. Tensile Test

A tensile test was carried out using the ASTM standard D-3039 [37] to analyze the mechanical behavior and strength of specimens under tension. The results are shown in the graphs below (Figure 5).



Figure 5. Tensile test results of each configuration: (A–C).

According to the graphs of the tensile test, specimen A, with 60% resin and 40% hardener, has the maximum value of stress, 1880 MPa, as shown in the graphs in Figure 5. There is a little fluctuation at stress 635 MPa in the graph of specimen B due to the prior breaking of glass fiber than Kevlar. As far as specimen C is concerned, it has the lowest value of tensile stress due to very poor adhesion between glass fiber and Kevlar with 40% epoxy resin and 60% hardener.

6.2. Peel Test

As the peel test is performed in two ways, in both conditions, the laminate of same dimensions as those of glass/Kevlar with different ratios of epoxy resin and epoxy hardener (A (3:2), B (4:1), and C (2:3)) was examined at room temperature.

Type I: When Glass Fiber is Clamped on Both Upper and Lower Jaws for Debonding.

Both the upper and lower layers of glass fabric are peeled off from Kevlar fabric, and a graph is plotted against the force required to debond/24 mm and the strain to examine the adhesiveness between glassy fiber (GF) and Kevlar.

The results of the peel test are shown in Figure 6 in the form of the force required to debond different specimens.

According to this figure, it is clear that specimen B (with 80% resin and 20% hardener) uses maximum force in debonding the laminate layers compared to other specimens with codes A and C. This force is expressed as 16.5 N/24 mm. Comparison values of the peel test shown in Figure 7.

Type II: When Glass Fabric is Clamped on the Upper Jaw and Kevlar is Clamped on the Lower Jaw for Debonding.

Kevlar fabric is clamped on the lower, fixed jaw and glass fabric is clamped on the upper, movable jaw to check the adhesion between the glass fabric and Kevlar by peeling them apart completely. Peel test examination of type II shown in Figure 8.

This is a special segment of the peel test, when glass fiber is clamped on the upper jaw and Kevlar is clamped on the lower jaw for debonding, in which an attempt is made to enhance the debonding force. The specimen with code B shows the maximum debonding force (38 N/24 mm) in this case also, as shown in the comparison graph in Figure 9.



Figure 6. Peel test analysis of type I specimens (A–C).



Figure 7. Comparison values of the peel test of type I specimens (A–C).



Figure 8. Peel test examination of type II specimens (A–C).





6.3. Hardness Test

A portable hardness tester was used to perform the hardness test according to the ASTM A 1038-17 standard [38]. Three samples with size 24 mm \times 24 mm were prepared with different epoxy resin and epoxy hardener ratios (A = 3:2, B = 4:1, and C = 2:3). A load was applied, and the readings on the dial were noted down.

Shore A Hardness Test (Table 3):

Tab	le 3	. Shore	Αŀ	hard	ness	of	three	dif	fferer	nt s	peciment	3.
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Readings		Α			В			С	
	A1	A2	A3	B 1	B2	B 3	C1	C2	C3
1.	95	93	96	91	94	94	80	85	80
2.	96	95	97	93	92	85	85	86	84
3.	95	91	96	91	95	88	86	84	81
Mean of indentation Mean hardness	95.33	93 94.887	96.33	91.66	93.67 91.443	89	83.67	85 83.44	81.67

Shore C Hardness Test (Table 4):

Table 4. Data analysis of Shore C hardness of three distinct configurations.

Readings		Α		В				С		
iteauiigo	A1	A2	A3	B 1	B2	B 3	C1	C2	C3	
1.	82	78	85	72	76	75	68	74	65	
2.	83	81	86	75	70	78	78	75	68	
3.	78	79	86	70	84	77	75	78	66	
Mean of indentation Mean hardness	81	79.33 82	85.67	72.33	76.67 75.23	76.67	73.67	75.67 71.89	66.33	

Tables 3 and 4 report that there is a small variation in harness by applying dissimilar ratios in lamination. It is evident that hardness does not rely on the ratio of matrix material in hybridization [1].

6.4. Density Test

According to the results of the density test, specimen A has the best value of density compared to specimens B and C, as described in Table 5.

Specimen	Weight (g)	Density (g/cm ³)	Mean (g/cm ³)
А	0.98	1.0	0.96
В	0.91	0.88	0.86
С	0.85	0.72	0.82

Table 5. Measured density of specimens A, B, and C at difference resin ratios.

6.5. Water Absorption Test

Results of water absorption for specimens A, B, and C by applying different ratios of matrix in lamination given in Table 6.

Table 6. Results of water absorption for specimens A, B, and C by applying different ratios of matrix in lamination.

Specimen	W1 (g)	W2 (g)	Mean W1	Mean W2	Swelling Ratio %
А	0.98	1.0	0.96	1.18	1.23
В	0.91	0.95	0.86	1.20	1.08
С	0.85	0.78	0.82	1.32	1.46

The water absorption ratio is calculated as an increase in the weight percentage of specimens A, B, and C by using the formula Swelling ratio $\% = \frac{\text{Wet laminate} - \text{Dry laminate}}{\text{Dry laminate}} \times 100$. By analyzing Table 5, it is observed that specimen A absorbs the minimal amount of water and, thus, has the minimum swelling ratio compared to specimens B and C. From the research findings, it is evident that specimen A has superior strength performance than samples B and C. The minimal swelling ratio is best suited for mechanical properties of hybrid composite materials.

7. Conclusions

Efforts were made to enhance the interlaminar adhesion of glass/Kevlar hybrid composites by using dissimilar proportions of epoxy resin and hardener. In this regard, mechanical and physical testing of hybrid composites was performed. Experimental verification shows that the resin and hardener ratio has a profound influence on both the mechanical and physical properties of hybrid composites. The laminate with 60% resin and 40% hardener has superior mechanical properties, such as tensile strength hardness and minimum swelling ratio, compared with 40% resin and 60% hardener in a matrix, whereas specimens made of 80% epoxy resin and 20% hardener have better bonding strength among the layers compared to other specimens. The specimens in which the ratio of hardener is suppressed rather than that of resin have mechanical properties such as adhesion and deduce.

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