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Synergistic Effect of Hybrid Nanofillers on Flexural and Impact Behaviour of Glass/Carbon Reinforced Epoxy Hybrid Composites

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Abstract

Addressing the issues of epoxy's brittleness and limited stiffness/toughness in long-term applications such as marine, aerospace, and other energy sectors, the novel approach involves the synergistic effects of integrating two nanofillers into an epoxy matrix. Therefore, the study aims to explore the synergistic effects of MWCNTs and HNTs hybrid nanofillers on the flexural, impact, and hardness characteristics of glass/carbon/epoxy-based composites. Three hybrid composites were formulated with equal-weight proportions of two nanofillers. The compositions included: no fillers, 0.5 wt. % of MWCNT + 0.5 wt. % of HNT, and 1 wt. % of MWCNT + 1 wt. % of HNT, respectively. Examining flexural strength, Izod impact strength, and hardness, the composites indicate that the combination of 1 wt. % MWCNT and 1 wt. % HNT achieves the most pronounced positive hybrid effect, displaying substantial enhancements in flexural strength (684 MPa), impact strength (156.86 KJ/m^2), and hardness (54.73 BHN) compared to others. This research underscores the importance of synergistic nanofiller interactions in optimizing glass/carbon fiber hybrid composites for applications in diverse industries.The FESEM images revealed the enhanced fiber-matrix strength, matrix toughness, and resin-fiber adhesion due to a hybrid combination of nanofillers in composite, enhancing the impact properties of the composite via MWCNT pullout/bridging and HNT crack deflection.

Keywords: Hybrid glass/carbon fibers reinforced polymer; Multiwall carbon nanotubes (MWCNTs); Halloysite nanotubes (HNTs); Flexural properties; Impact properties; Morphological Characteristics.

1. Introduction

Hybrid fiber-reinforced composites, uniting glass and carbon fibers in polymers, bolster strength and durability[1], yielding weight reduction and cost savings across aerospace, marine, and other sectors. This results in diminished fuel consumption, driving increased demand for this innovative technology[2]–[4].Ensuring the robustness of applications such as wind turbines, ship hulls, and airframes in various environmental conditions remains a significant challenge. Additionally, addressing their vulnerability to impact and bending events represents an ongoing issue that has yet to be resolved.Research has extensively explored the impact and bending properties of glass/carbon (G/C) fiber hybrid composites[5]–[7]. Carbon fibers offer greater strength and stiffness with low density but lack damage tolerance due to brittleness. In contrast, glass fibers are cost-effective with lower mechanical properties but superior impact resistance.A studies by Zhang et al.[2] found that outer-layer carbon reinforcement in glass/carbon (G/C) fiber hybrid composites improves flexural properties, while Dong et al.[8] optimized flexuralstrength with glass on top surface and carbon at below inglass/carbon (G/C) fiber hybrid composites. Jesthi and Nayak[9]improved marine hybrid composites with [GCGGC]s stacking, enhancing flexural and impact properties. Another study of Jesthi and Nayak[10], [GGGCC]s showed better flexural and impact extension but [CCGGG]s had higher toughness and strength. Investigation into G/C hybrid composites for structural applications like automobiles and construction reveals enhanced toughness, impact resistance, and energy absorption. Hybridcomposite performance hinges on various factors, including thickness, fabric structure, matrix toughness, stacking sequence, and fiber-matrix hybridization. Despite glass and carbon fibers hybrid composites displaying impressive impact and flexural properties, their lateral and interlayer characteristics are deficient, making them prone to fracture under out-of-plane loads. Researchers seek improvement through interlayer reinforcement, considering factors like reinforcement type, arrangement, volume fraction, polymer type, and fillers. Nanofillers introduced through nanotechnology present an affordable and safe solution[11], optimizing mechanical properties, particularly bending and toughness. Ongoing research concentrates on developing polymer composites with diverse fillers for stronger, safer, and cost-effective structures.

In recent years, research has concentrated on augmenting epoxy properties by integrating nanofillers, with carbon nanotubes and halloysite nanotubes showing promise. Carbon nanotubes, particularly prized among nanofillers, effectively address brittleness and cracks in epoxy resin, commonly used as a matrix in fiber polymer composites. Valued for strong adhesion, customizable properties, high modulus, elevated temperature resistance, and low creep, even low levels of CNT incorporation enhance mechanical properties[12]–[14], bolstering toughening mechanisms[15] in fiber-reinforced polymer composite interfaces. M.D. Kiran et al.[16] observed about 40% enhancement in impact strength with 0.75% MWCNT in carbon epoxy composites. In an experimental investigation, Rathore et al.[17]improved glass fiber-reinforced epoxy composites with 0.1% MWCNTs, achieving an 11.5% boost in flexural strength and a 32.8% increase in flexural modulus. Naturally occurring halloysite nanotubes (HNTs), resembling MWCNTs, prove a cost-effective and promising particle filler. A recent research of, M. D. Kiran et al.[18]showed enhanced flexural strength and modulus in carbon fabric-reinforced epoxy composites at low wt.% of HNTs. Deng et al.[19] observed significant mechanical improvements in epoxy with 10 wt.% HNTs, attaining an 11.5% elevation in flexural strength and a 32.8% rise in flexural modulus. Y. Ye et al.[20]enhanced impact strength in epoxy based carbon composites by 25% with 2 wt.% HNTs, also improving storage modulus and glass transition temperature. Studies by Md. Shahneel Sahrudin et al.[21] introducing HNTs and MWCNTs to epoxy at various levels, 0.2 wt.% HNTs yielded superior flexural modulus and strength, surpassing lower-concentration CNT-epoxy composites.Similarly, Fang Liu et al.[22] improved carbon fiber/epoxy composites using halloysite nanotubes, enhancing compressive and flexural characteristics.In a review by T.S. Gaaz et al. [23], the notable enhancement in flexural strength attributed to the high aspect ratios of HNTs was underscored, indicating promising improvements. Furthermore, the most substantial increase in tensile strength was observed with the addition of 7% HNTs.

The previous literature study reflects that in order to optimize composite strength, filler reinforcement is typically kept at 1 wt.% or lower to prevent dispersion challenges and stress concentrations[24]. Enhanced properties result from improved nanofiller-matrix interactions, driven by their high surface-to-volume ratio. Researchers explore blending multiple fillers to strengthen polymer matrices and create superior composites, with simultaneous use of two nanofillers showing promise for hybrid materials and potential synergistic effects, expanding the range of novel structural composites.Mohd Shahneel Sahrudin et al.[25]demonstrated synergistic effects of low-weight nanofillers (HNTs + CNTs) in epoxy, increasing flexural strength (up to 46%), and modulus (up to 17%). Similarly, Ling Jiang et al.[26]showed improved strength and toughness in polyurethane composites with silane-treated-HNT/acid-treated-MWCNT hybrid nanofillers. There is a scarcity of research in the existing literature concerning the synergistic effects of introducing hybrid nanofillers, specifically MWCNT and HNT, into fiber-reinforced hybrid composites.

In spite of the available research, the interaction between structural rearrangement in hybrid fibers and the synergistic effects of (MWCNT+ HNT) hybrid nanofillers approaches on the bending and impact strength performance of fiber-reinforced compositeshas been inadequately explored in the literature. Many researchers have separately applied these approaches, making it crucial to investigate their combined influence for a comprehensive understanding of their effect on flexural and impact properties. In the current investigation, the fabrication of symmetrical composite with plain glass fiber $[G_5]_S$, carbon fiber

$[C_5]_S$, and hybrid composites having interply rearrangement $[G_3C_2]_S$ with and without nanofillers were done by using compression moulding techniques. The symmetrical hybrid composites were configured with carbon fibers on the inner side and external glass fibers on the outer side. The primary focus was on developinga superior and reliable hybrid composite suitable for various long-term applications. Therefore, the study aims to explore the synergistic influence of MWCNTs and HNTs hybrid nanofillers on the flexural, impact, and hardness characteristics of glass/carbon/epoxy-based composites

2. ExperimentalWork

2.1. Materials

In the present investigation, the bi-directional woven fabric E-glass fiber of 400 gsm were supplied by Valmiera Glass UK Ltd, and the bi-directional carbon fabric of 200 gsm, 3 k plain waving were supplied by Marktech Composites Pvt. Ltd, Bangalore, India, as shown in Figure 1 (a), and (b) respectively. The hybrid composite consists of a 72:28 weight ratio of glass to carbon fibers, with both the plain glass/carbon fiber composites and hybrid composites comprising ten fiber layers. The overall weight ratio between reinforcement fibers and epoxy polymer is 55:45. LY-556 epoxy polymer and W152 LR hardener, obtained from CF Composites, Mumbai, India, are mixed in a 100:30 ratio. The properties of the reinforcement and matrix materials are detailed in Table 1

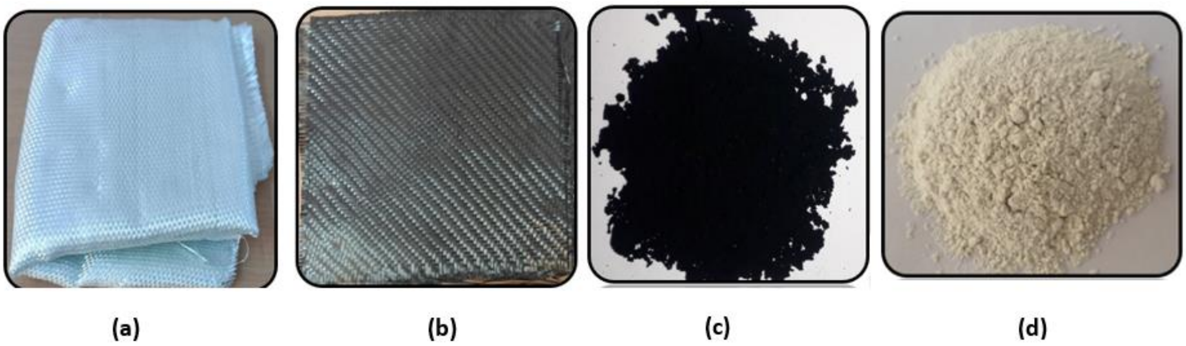


Figure 1: (a) E-glass fiber, (b) Carbon fiber, (c) MWCNT, and (d) HNT used in this study

2.1.1 Nanofillers.

The use of MWCNTs and HNTs as secondary reinforcements are illustrated inFigure 1 (c), and (d) respectively. The MWCNTs, synthesized through chemical vapor deposition by AD-NANO Technologies Pvt. Ltd, Shivamogga, India, were employed.These MWCNTs have an outer diameter of 10 to 30 nm, inner diameter of 5 to 10 nm, density of 2.1 g/cm^3, surface area of 110 to 350 m^2/g, and a length exceeding 10 µm with 99% purity. Halloysite nanotubes (HNT), obtained from Sigma Aldrich Company, Bengaluru, India, have diameters of 30 to 70 nm, lengths of 1–3 µm, a tube-like structure, density of 2.53 g/cm^3, and surface area of 64 m^2/g, making them suitable for reinforcing epoxy matrix composites due to their elevated aspect ratio and minimal percolation characteristics. The FESEM images ofMWCNTs andHNTs are shown in Figure 2 (a), and (b) respectively.

Properties/Grade	Carbon Fiber	E-glass Fiber	Epoxy
Density (g/cm^3)	1.76	2.54	1.32
Tensile strength (MPa)	4900	3100-3800	83-93
Tensile modulus (GPa)	230	65.5-73.8	3.42
Elongation at break (%)	2.1	4.0	-

Table 1. Physical and mechanical properties of carbon fiber, E-glass fiber, epoxyresin

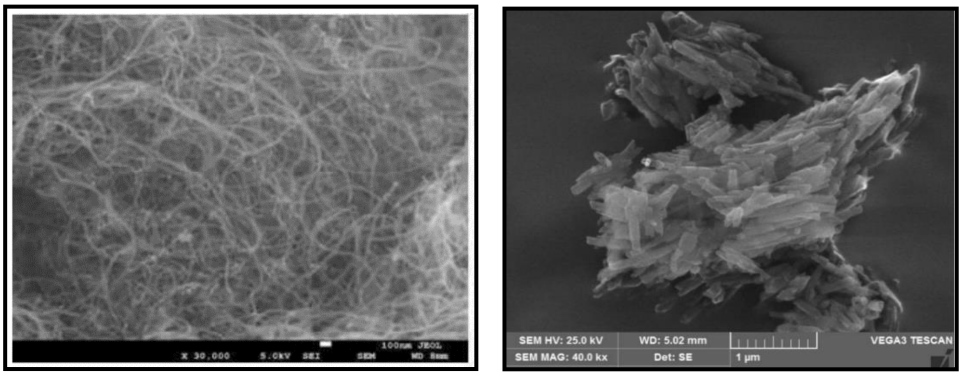
2.2. Methods

2.2.1 Preparation of MWCNT/HNT modified epoxy

Achieving uniform dispersion of nanofillers in high-density epoxy is challenging due to increased viscosity. To address this, nanofiller powders (MWCNTs and HNTs) were dried, combined in equal weights such as 1 wt.% (0.5 wt. % MWCNT + 0.5 wt. % HNT), and 2 wt.% (1 wt. % MWCNT + 1 wt. % HNT), mechanically stirred, magnetically stirred, and sonicated. The modified epoxy resin was preheated, further sonicated to break agglomerates, cooled, and gradually mixed with hardener. Vacuum degassing was employed to prevent bubble formation during the entire process, ensuring even nanofiller distribution.

2.2.2. Preparation of glass/carbon modified epoxy-based laminates

The glass/carbon fiber epoxy laminates were made via compression molding. A release agent was applied to the mould, and epoxy was spread on one side of the fiber mat, layered with another mat, and compressed. Six layers of glass and four layers of carbon were used in hybrid composites, while plain composites had ten layers of either glass or carbon. The stacking sequence of fabricated composite laminates.The Figure 3 illustrates five symmetrical composites: (G-E) for the plain glass fiber epoxy composite, (C-E) for carbon fiber epoxy composite (C-E), (GC-E)$N_0$for unmodified glass fiber/carbon fiber epoxy composite with 0 wt.% of (0 wt.% MWCNT + 0 wt.% HNT) nanofillers, (GC-E)$N_1$for modified glass fiber/carbon fiber epoxy composite with 1 wt.% of (0.5 wt.% MWCNT + 0.5 wt.% HNT) nanofillers, and (GC-E)N_2 modified glass fiber/carbon fiber epoxy composite with 2 wt.% of (1 wt.% MWCNT + 1 wt.% HNT) nanofillers. The composite laminates obtained were cut to the necessary dimensions in accordance with ASTM standards, utilizing a water jet cutting machine.



(a) (b)

Figure 2: FESEM images of (a) MWCNTs and (b) HNTs

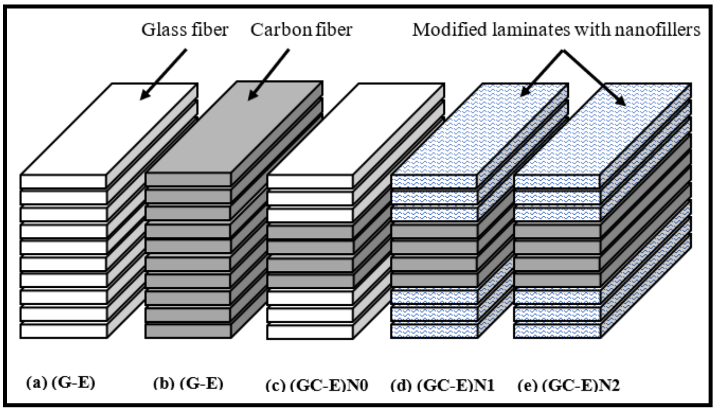


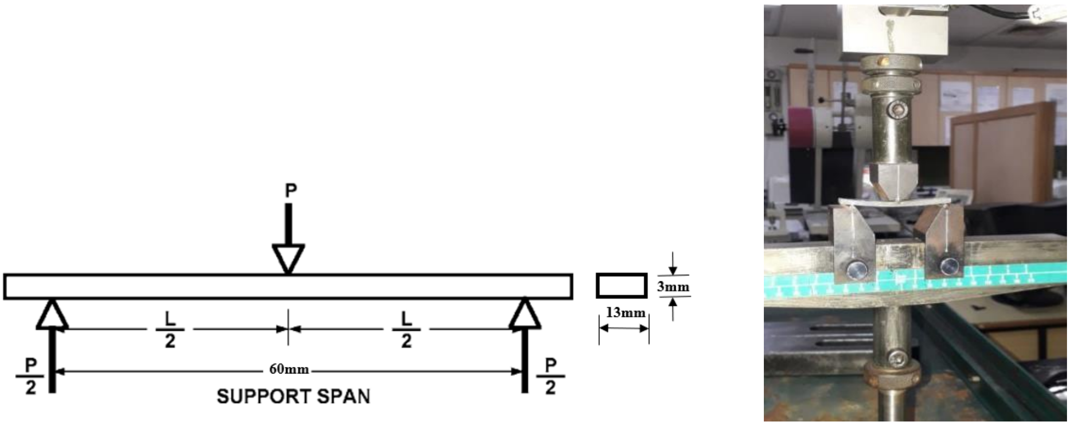
Figure 3: Stacking sequence of composite laminates

2.3. Characterization of Composite

To explore the synergistic effect of hybrid nanofillers, MWCNTs, and HNTs on the flexural, impact, and hardness properties of glass/carbon/epoxy-based composite laminates, the study adhered to ASTM standards, and the findings are elaborated in the subsequent sections.

2.3.1. Flexural Testing

All five composite types underwent ASTM D7264 flexural testing with 70mm x 13mm x 3mm specimens and 60mm support spans, as shown in Figure 4 (a), and (b) respectively. The Universal Testing Machine (TINIUS OLSEN H25KT) conducted flexural tests with a 60mm span, 2mm/min crosshead speed. Three specimens per composite were tested, and the average result was recorded.



(a) (b)

Figure 4: (a) Loading diagram of three-point bending test arrangement and (b) Flexural test specimens during the test

2.3.2Impact Testing

The Izod test was employed to assess the impact strength of the composites. In this test, a vertical orientation is adopted, and a hammer (pendulum) strikes the upper tip of the specimen, as illustrated in Figure 5. Test specimens, measuring 65 mm x 12.7 mm x 3 mm dimensions, were prepared according to ASTM D256 standards.

Figure 5: Impact test specimens during the test

2.3.3 Hardness Testing

The hardness of five distinct composite types was evaluated with a portable Barcol hardness tester, following the ASTM D2583 standard. This approach is commonly employed to evaluate the hardness of both unreinforced and reinforced rigidplastics.The resulting Barcol Hardness Numbers (BHN) were calculated for each composite, and average values were recorded. Barcol hardness test is inexpensive, portable, and highly user- friendly.

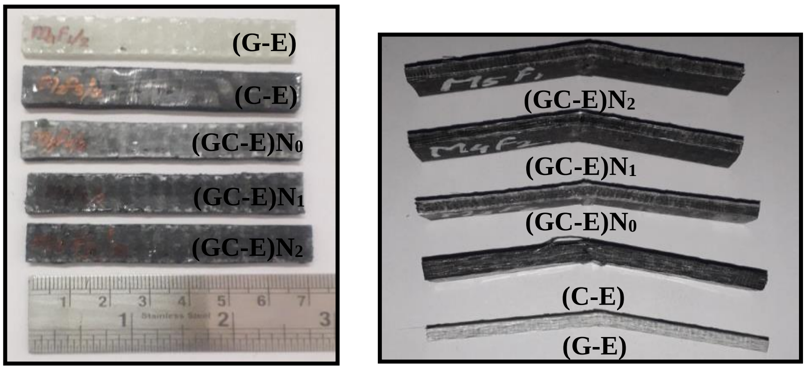
2.3.4 Morphological Studies

The structures of specimens that experienced impact failure were examined using Field Emission Scanning Electron Microscopy (FESEM) with a Nova Nano SEM 450. Furthermore, it was utilized to assess the dispersion of MWCNT and HNT nanofillers in the matrix, aimed at comprehending the failure mechanisms.

3. Results and discussion

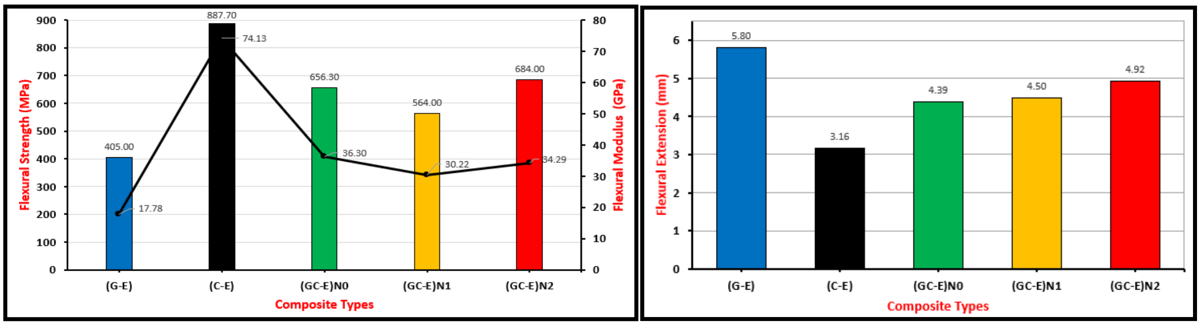
3.1 Flexural testing result

The condition of the specimens before andafter the flexural test is depicted in Figure 6. The provided data in Figure 7 (a) and (b) presents the results of 3-point bending flexural tests conducted on a range of composite specimens. These specimens include pure glass fiber epoxy (G-E), pure carbon fiber epoxy (C-E), and hybrid glass fiber/carbon fiber epoxy (GC-E) composites, both with and without the inclusion of nanofillers. The Figure 7also include the average values for flexural strength, flexural modulus, and flexural extension for each of these composite types.The results of the flexural tests revealed notable variations among the composite specimens. The (G-E) composite specimens displayed the lowest flexural strength at 405 MPa and the lowest flexural modulus at 17.78 GPa. In contrast, the (C-E) composite specimens exhibited the highest flexural strength at 887.70 MPa and the highest flexural modulus at 74.13 GPa. Interestingly, the (G-E) composites demonstrated the greatest displacements before reaching failure compared to all other specimens.It was observed that a significant enhancement in flexural strength occurred when transitioning from (G-E) specimens, with a strength of 405 MPa, to (GC-E)N_0 hybrid specimens, with a strength of 656.30 MPa. This marked an improvement of nearly 62%, as depicted in Figure 7 (a). Similarly, the flexural modulus of (GC-E)N_0 hybrid specimens increased to 36.30 GPa from 17.78 GPa, a remarkable boost of 103.93% when compared to the plain (G-E) composites.The improved flexural characteristics of the (GC-E)N_0 hybrid composites were attained by a deliberate arrangement that positioned the glass fiber layers in the outer section, where greater ductility is present. This strategy resulted in a similar observation as reported for the interply rearrangement of glass fiber and carbon fiber layers in hybrid composites[9], [27].



(a) (b)

Figure 6:Flexural test specimens (a) before and (b) after the test



(a) (b)

Figure 7: (a) Flexural strength and flexural modulus of different composites and

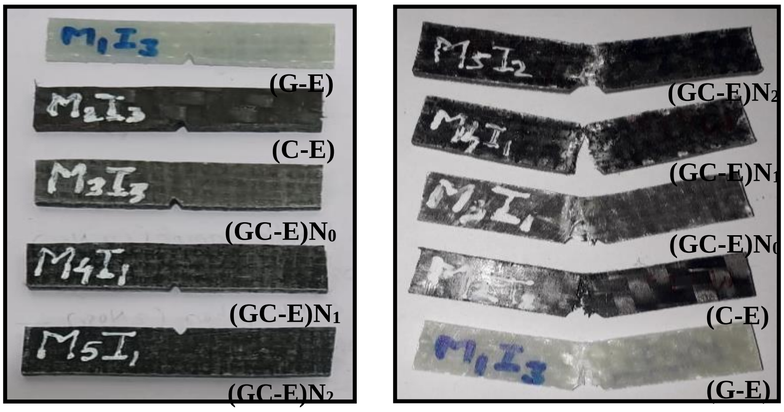
(b) Flexural extension of different composites

As depicted in Figure 7 (a), the incorporation of nanofillers in composite materials plays a crucial role. When 1 wt. % MWCNTs and 1 wt. % HNTs were added, the flexural strength of (GC-E)N$_2$ composites exhibited a notable increase of approximately 4.22% when compared to unmodified (GC-E)N$_0$ hybrid specimens. Furthermore, the flexural modulus of (GC-E)N$_2$ improved by 13.58% in comparison to (GC-E)N$_1$ hybrid specimens.Conversely, when 0.5 wt. % MWCNTs and 0.5 wt. % HNTs were introduced into (GC-E)N$_1$ composites, there was a 14% reduction in flexural strength compared to the unmodified (GC-E)N$_0$ hybrid specimens. However, a positive trend emerged in the form of a 2.27% increase in flexural extension when compared to the flexural strain of the unmodified (GC-E)N$_0$ hybrid composite specimens. This improvement in flexural extension was consistent across all the modified and unmodified hybrid composites, as illustrated in Figure 7 (b). These findings underscore the significance of nanofillers in epoxy composites, demonstrating their capacity to influence both strength and ductility characteristics.

3.2 Impact testing result

The condition of the specimens before andafter the impact test is depicted in Figure 8. The provided data in Figure 9 presents the results of Izod impact tests conducted on a range of composite specimensby creating a notch at the middle. These specimens include pure glass fiber epoxy (G-E), pure carbon fiber epoxy (C-E), and hybrid glass fiber/carbon fiber epoxy (GC-E) composites, both with and without the inclusion of nanofillers. The absorption of energy value at the notch is measured and recorded. The results of the impact tests revealed notable variations among the composite specimens. The plain (C-E) composite specimens displayed the lowest impact strength at 58.82 KJ/m^2 and the highestimpact value at 239.65KJ/m^2 of plain (G-E) composite because of carbon fiber are more brittleness in nature.The impact strength of the hybrid composite (GC-E)N$_0$, featuring an interply sequence of glass and carbon fibers, exhibits a notable improvement of 118.54% compared to the plain (C-E) composite.Similar observations were in agreement with investigation by Jesthiand Nayak [9].

Further, it was observed that there was a progressive improvement in impact strength of (GC-E)N$_0$,(GC-E)N$_1$,and (GC-E)N$_2$ hybrid composites.With the addition of 0.5 wt. % MWCNTs and 0.5 wt. % HNTs into (GC-E)N$_1$composites exhibited a enhancementin impact strength by5.14 % when compared to unmodified (GC-E)N$_0$ hybrid specimens. Similarly, after increasing the nanofiller loading content such as 1 wt. % MWCNTs and 1 wt. % HNTs into (GC-E)N$_2$ composites resulted significantly improvement in impact strength by 22.10 % compared to the unmodified (GC-E)N$_0$ hybrid specimens.In hybrid composite interply sequence of G/C fibers and synergistic effect of hybrid nanofillers MWCNTs/HNTs played a crucial role in augmenting the material's impact strength, contributing to an overall enhancement in the composite's toughness



(a) (b)

Figure 8: Impact test specimens (a) before and (b) after the test

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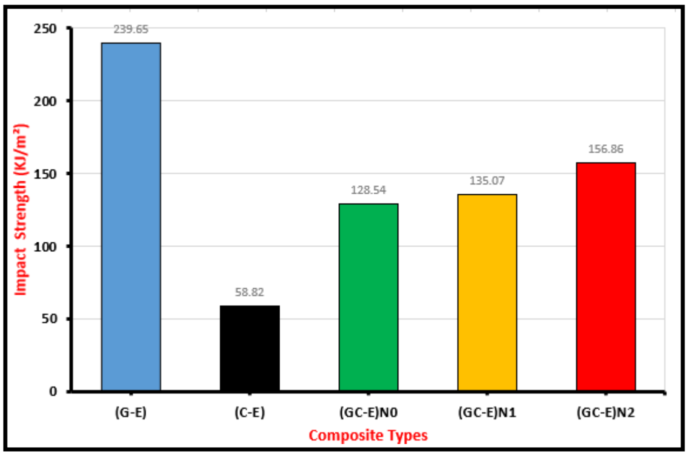


Figure 9: Impact strength of different composites

3.3 Hardness testing result

The composite material's indentation hardness was evaluated using a Barcol hardness tester, following the ASTM D2583 standard.The hardness levels of various composites are depicted in Figure 10, including glass fiber epoxy (G-E), carbon fiber epoxy (C-E), and glass fiber/carbon hybrid composites with and without the incorporation of nanofillers. Notably, the carbon fiber epoxy composite (C-E) exhibited the highest hardness, while the glass fiber epoxy composites (G-E) displayed the lowest values.Nevertheless, there is an interesting observation when considering the synergistic effect of two nanofillers in (G-E)N_1 and (G-E)N_2 composites. These combinations led to an improvement in hardness values by 3.45% and 6.69%, respectively, when compared to the (G-E)N_0 composite.This indicates that both the modified hybrid composites exhibit a higher level of hardness in comparison to the glass fiber epoxy (G-E).The enhanced hardness value can be attributed to the well-established interfacial interactions of both the nanofillers HNTs and MWCNTs.

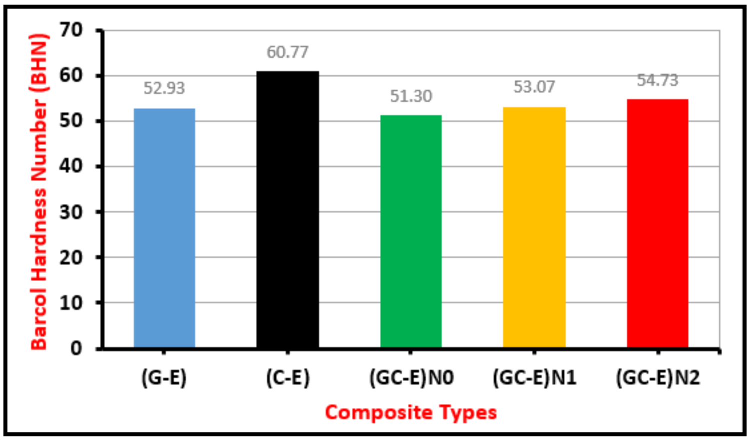
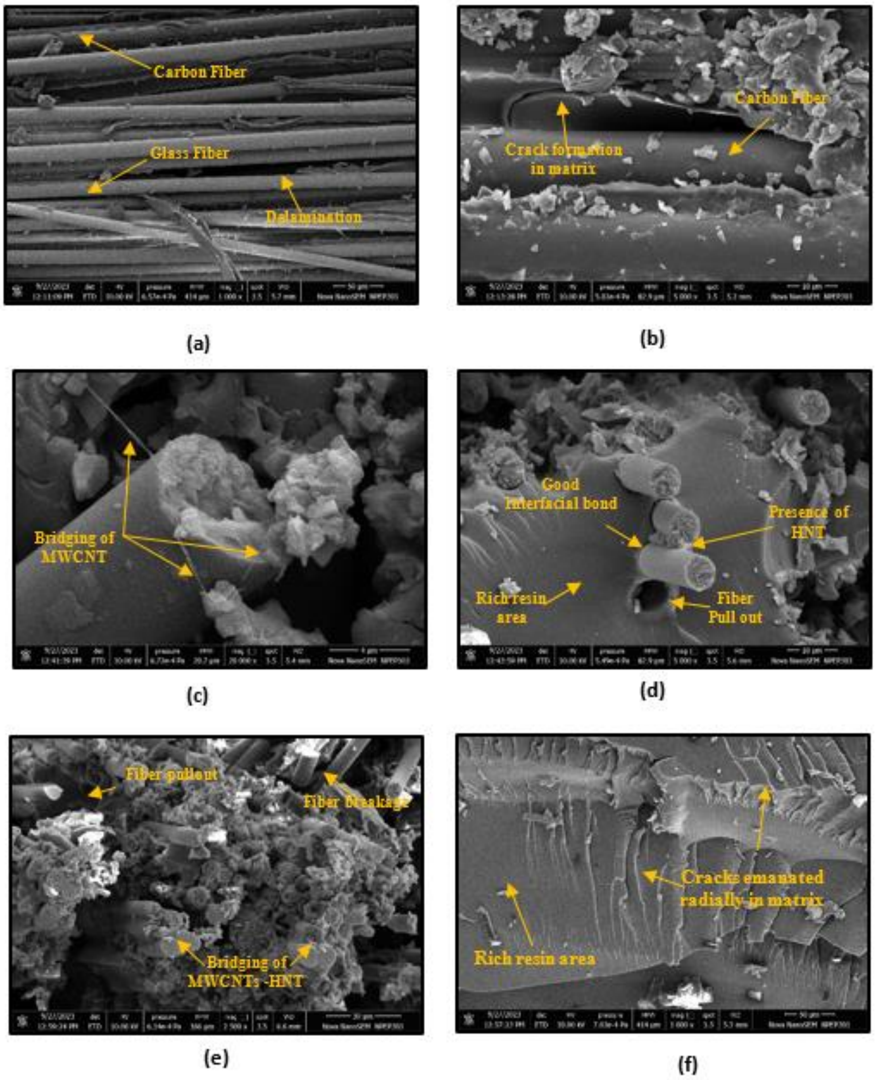


Figure 10: Comparison of Hardness of thedifferent composites

3.4Morphological result

The field emission scanning electron microscope images of fabricated compositelaminates under animpact behaviour gives the general information about the fracture surfaces of hybrid composites. From FESEM analyses from research, excellent dispersion of nanofillers (MWCNTs and HNTs) with no sign of agglomeration was noted in the both the modified hybrid composites specimens that is (GC-E)N_1 and (GC-E)N_2.Figure 11 (a), and (b) confirm the presence of both glass fiber and carbon fiber in the hybrid composites (GC-E)N_0, showcasing strong fiber-matrix adhesion.The failure mechanism is readily noticeable through the development of cracks in the epoxy matrix, splitting anddelamination of fibers, which reduces the interfacial bond with the polymer matrix. However, introducing the synergistic effect of nanofillers at loadingcontent of 0.5 wt.% and 1 wt.% each reinforces the matrix and establishes a robust bond between the matrix and the (GC) hybrid fibers, which results in theoverall fiber-matrix adhesion was greatly improved in the modified nanofillers hybrid specimens compared to the unmodified hybrid composite. Figure 11 (c), and (d) shows FESEM images of the (GC-E)N_1 composite, indicating theconfirmation of the presence of MWCNT and HNT nanofillers within the polymer matrix.Additionally, it demonstrates the bridging effect of MWCNTs at the polymer matrix-fiber interface, enhancing interfacial strength and resistance to debonding. However, The FESEM images of (GC-E)N_2 composite in the Figure 11 (e), and (f) also showcases the crack-bridging and crack-deflection effects of MWCNT and HNT nanofillers, offering insights into the toughening mechanism.MWCNT fillers exhibit strong adhesion to the fibers, enhancing fiber-matrix bonding. Furthermore, HNT fillers in the epoxy resin play a role in managing micro-crack development within the matrix by forming bridges with nanotubes. The resin rich region was indicating the effective dispersion of nanofillers (MWCNT and HNT) within the epoxy, fostering strong interfacial bonding between the fiber and matrix. The commonly observed failure modes were fiber pull-out, fiber breakage and matrix damage under the impact behaviour..



(a) (b) (c) (d) (e) (f)

Figure 11: FESEM images (a)-(b) for (GC-E)N_0 ,(c)-(d) for (GC-E)N_1 and, (e)-(f) for (GC-E)N_2 at fracture surface of impact test specimen

4. Conclusions

In the current study, theprimary focus was on investigating the synergistic effects of multi-walled carbon nanotube and halloysite nanotube (MWCNT + HNT) hybrid nanofillers on epoxy-based glass/carbon composites. Epoxy resin modification with these nanofillers at low loading content showed enhanced flexural,impact, and indentation behavior in the hybrid composite laminate.The observation from the fracture surfaces of the specimen validates the reinforcement mechanisms of the nanofillers.In summary, specific conclusions can be drawn:

- The incorporation of 1 wt.% MWCNTs + 1 wt.% HNTs in the (GC-E)N_2 composite enhances flexural strength by 4.22% compared to the unmodified (GC-E)N_0. Additionally, (GC-E)N_2 exhibits a 13.58% improvement in flexural modulus over (GC-E)N_1, which, with 0.5 wt.% MWCNTs and 0.5 wt.% HNTs, undergoes a 14% decrease in flexural strength but a 2.27% increase in flexural strain compared to unmodified (GC-E)N_0.
- The enhancement in the flexural extension was observed in hybrid composites (GC-E)N_1 and (GC-E)N_2 as compared to (GC-E)N_0.
- The hybrid composite (GC-E)N_0, featuring the stacking sequence $[G_3C_2]_S$, demonstrated outstanding impact characteristics with an impressive strength of 128.54 KJ/m^2. These values align with the impact strengths observed in (G-E) and (C-E) composites
- The impact strength of the (GC-E)N_0 hybrid composite benefited from both MWCNTs and HNTs. Particularly, the introduction of 1 wt.% each of MWCNTs and HNTs in the (GC-E)N_2 composite resulted in a significant 22.10% boost in impact strength compared to the unmodified (GC-E)N_0 specimen.
- The Barcol hardness test, assessing material indentation hardness, indicates increased hardness values with higher MWCNTs and HNTs dispersion. Modified hybrid composites (GC-E)N_1 and (GC-E)N_2 exhibit Barcol Hardness Number enhancements of 3.45% and 6.69%, respectively, compared to (GC-E)N_0.
- The FESEM analysis indicates that the composites derive reinforcement from the bridging effect of MWCNT with the epoxy matrix, leading to enhanced interface bonding and toughening of the epoxy matrix.The enhanced properties of the composite result from several key factors: the synergistic interaction between the two types of nanofillers (MWCNTs and HNTs), well-distributed particles, enhanced bonding with the epoxy matrix, and the interply rearrangement of glass fiber and carbon fibers between the plies. Combining treated MWCNTs and HNTs as reinforcement materials represents a promising strategy for developing novel materials with enhanced performance.
- A future research focus could involve an in-depth exploration of the performance of this hybrid nanocomposite under adverse conditions and various load levels. This novel concept, featuring advanced hybrid composite materials, holds great promise.

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Conflicts of Interest:
The authors declare that there is no conflict of interest.

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