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Investigation of the mechanical properties of nanocomposites with multi-wall carbon nanotube reinforcement and carbon fiber/epoxy

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ABSTRACT

In this study, the focus is on exploring the remarkable world of aircraft structures with the aim of creating a material that pushes boundaries and garners global attention. The successful formulation of a composite material is investigated by skillfully manipulating weight and quantity ratios. To achieve the desired outcome, different weight ratios of multi-walled carbon nanotubes (MWNTs), specifically 8g and 16g, are combined. Furthermore, these MWNTs are proportionately mixed with epoxy in volumes of 200ml, 400ml, 600ml, and 800ml, following a valence equation that correlates the gram ratio of MWNTs with epoxy. For the purpose of ensuring homogeneity and facilitating optimal component blending, an electric convector with a magnetic core is employed to generate vortices, aiding in the thorough mixing of the constituents. Subsequently, the mixture is hardened after proper placement. Prior to casting, the introduction of the hardener, whether in its liquid state or by incorporating reinforcement layers of carbon nanofibers (ranging from 0 to 16 layers), enhances and fortifies the desired properties of the material. The ingenuity of this approach is showcased by the exceptional results obtained from the evaluation of tensile stress and impact. Through rigorous testing and meticulous analysis, the findings validate the theoretical foundation upon which this endeavor is built, underscoring the success of this innovative concept.

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1. Introduction

Enhancing hardness and durability by means of reinforcement belongs to one of the predominant challenges in polymer science. One of the primary concerns in the field of polymers revolves around their inherent low hardness and durability. To overcome this limitation, the incorporation of reinforced particles or fibers has emerged as a common strategy. In the case of epoxy resin, improving its mechanical properties while mitigating the weight and issues associated with various metals has been a key objective since its inception. Epoxy resin exhibits weaknesses in mechanical, chemical, and thermal properties, which necessitates further enhancements.

By introducing the appropriate curing agent, epoxy resin undergoes a reaction that forms interconnected, thermoplastic, three-dimensional (3D) structures. This results in improved coefficients, fracture strength, and bonding strength. However, an excessive cross-linking ratio can lead to reduced flexibility and low breaking strength, thereby limiting the application of epoxy compounds in mechanical components (Basara et al. 2005), (Domun et al. 2015) and (Vietri et al. (2014). Consequently, various forms of reinforcement, such as emerging nanocomposites in the form of fibers or powders, have been developed to bolster the mechanical properties of epoxy compounds. Mirsalehi et al. (2021) fabricated epoxy hybrid nanocomposites reinforced with carbon fibers (CFs) using filament winding. They enhanced the transverse mechanical properties by incorporating 0.5 and 1.0 Wt.% multi-walled carbon nanotubes (MWCNTs) into the epoxy/CF composites. The study demonstrated that the addition of 1.0 Wt.% MWCNTs improved tensile strength and elongation at break by 53% and 50%, respectively, in comparison to epoxy/CF laminate composites, while also increasing flexural strength, secant modulus, and elongation by 15%, 7%, and 9%, respectively. SEM analysis suggested that MWCNT bridging played a role in enhancing these properties. In the study by Montazeri et al. (2010), they used untreated and acid-treated multi-walled carbon nanotubes (MWNTs) to create MWNT/epoxy composites through sonication. The research aimed to investigate how adding MWNTs and modifying their surfaces affected mechanical properties. They utilized a modified Halpin-Tsai equation, incorporating orientation and an exponential shape factor, and found a strong correlation between the predicted and experimentally obtained the Young's modulus and tensile strength values. Additionally, the fracture surfaces of MWNT/epoxy composites were analyzed using scanning electron microscopy (SEM). This study provided insights into the impact of MWNT addition and surface treatment on composite mechanical properties.

In the study by Yang et al. (2018), the use of multiwalled carbon nanotubes (MWCNTs) as a mechanical reinforcement in epoxy polymer was explored. The research revealed that adding varying concentrations of MWCNTs led to increased flow stress and fracture strain in the composite materials. Furthermore, the presence of MWCNTs was observed to initiate crystallization within the epoxy, a phenomenon believed to enhance the strength of the composite. The study also utilized scanning electron microscopy (SEM) to analyze the fracture surfaces of the MWCNT-reinforced composite, providing valuable insights into the reinforcement mechanisms.

The research work by Kinloch et al. (2014) focused on enhancing the fracture toughness and cyclic-fatigue resistance of epoxy-polymer blends. The study investigated the effects of incorporating various toughening agents into epoxy resins and examines their impact on the mechanical properties of the resulting blends. Through their findings, the researchers demonstrated strategies to improve the overall performance and durability of epoxy-based materials in demanding applications. Cha et al. (2019) compared the mechanical properties of epoxy nanocomposites reinforced with functionalized carbon nanotubes and graphene nanoplatelets. The study aimed to evaluate the effects of different nanofillers on the strength and stiffness of the epoxy matrix. This investigation also provided a comparative analysis of the reinforcement efficiency and potential applications of functionalized carbon nanotubes and graphene nanoplatelets in epoxy nanocomposites.

Martone et al. (2010) examined the reinforcement efficiency of multi-walled carbon nanotube/epoxy nanocomposites. The researchers analyzed the mechanical properties of the nanocomposites and discussed the interactions between carbon nanotubes and the epoxy matrix, contributing to the understanding of their reinforcement mechanisms. Gao et al. (2020) investigated the effect of multi-walled carbon nanotube diameter on the mechanical properties and microstructure of cement-based materials. The study explored the relationship between nanotube diameter and the performance of cement composites, providing insights for optimizing their mechanical properties. Shokrieh et al. (2013), Tarfaoui et al. (2016) and Dong et al. (2017) studied the mechanical properties of multi-walled carbon nanotube/polyester nanocomposites and investigated the effects of carbon nanotube reinforcement on the mechanical behavior of polyester composites, offering insights into the potential applications of these nanocomposites. Srivastava et al. (2019) studied the flexural strength enhancement in carbon fiber-epoxy composites through graphene nano-platelets coating on fibers. The study explored the effects of graphene nano-platelets on the interfacial properties and mechanical behavior of the composites, providing insights into strengthening strategies. Deng et al. (2015) and Guo et al. (2016) investigated the influence of graphene oxide coatings on carbon fiber by ultrasonically assisted electrophoretic deposition on the composite interfacial property. The study explored the impact of graphene oxide coatings on the interfacial properties and performance of the composites, contributing to the understanding of their structure-property relationships.

Kazemi et al. (2023) employed Abaqus software to simulate cylindrical sandwich panels featuring aluminum foam cores and aluminum face-sheets, subjected to explosive loads. By varying foam core densities while maintaining mass and thickness, the study revealed that optimized laminated cores reduced displacement by 59.8% compared to models with equal mass and core thickness. Furthermore, the investigation demonstrated that by increasing the face-sheet thickness and curvature, the blast resistance enhanced, thus providing insights for designing energy-absorbing panels in fields like structural engineering and defense. Prince et al. (2022) focused on aluminum metal matrix composites, vital in aerospace, defense, and automotive industries. Al 8011 alloy with TiC reinforcement was investigated using stir casting. Wear resistance was evaluated using a pin-on-disc tester, revealing improved performance compared to the matrix metal. Microstructural analysis highlighted TiC distribution, while Izod impact testing showcased enhanced properties for Al 8011 with 7% TiC content. Amrit et al. (2022) examined how design factors like subtended angle, aspect ratio, and stiffener orientation affect the first five modal frequencies of thin steel plates used in construction, aerospace, and marine industries. Employing the finite element method and statistic analysis, the study determines that a specific combination – a thin plate with 80° subtended angle, 1.75:1 aspect ratio, and crossed stiffener orientation – optimizes the first five natural frequencies, emphasizing stiffener type as the dominant factor. This research provided important information for enhancing the stiffness of these plates in various applications. Saadatyar et al. (2021) investigated the enhancement of mechanical properties in unidirectional carbon fiber-reinforced epoxy (UCFRE) by incorporating multiwall carbon nanotubes (MWCNTs) in varying amounts. The addition of 0.1 phr of MWCNTs increased transverse tensile strength, modulus, and strain-at-break by 28.5%, 25%, and 14% respectively, while 0.3 phr of MWCNTs improved fracture toughness, interlaminar shear strength, and lap shear strength by 39%, 8%, and 5%, respectively. These improvements were attributed to the improved fiber-matrix adhesion, interlocking, and toughening effects facilitated by the presence of MWCNTs.

To explore the enhancement of polymer arrays, we investigate the incorporation of nanoparticles into epoxy matrices. Several techniques exist for nanoparticle integration, including mechanical stirring utilizing a gradient heater. Additionally, the effect of different weight ratios (0.05, 0.1, and 0.5 wt.%) of nanoparticles within the matrix is to be examined. Furthermore, the experiment covers a range of nanoparticle diameters, carefully controlling the gravimetric mixing of each component. Notably, the inclusion of a carbon fiber mat proves advantageous in improving mechanical properties, particularly in terms of durability, hardness, tensile strength, and impact resistance. The objective of our work is to analyze the influence of the weight fraction of multi-walled nanocarbon powder in combination with carbon fiber reinforcement on the mechanical characteristics of epoxy composites. Tensile and impact tests are conducted by pouring the homogenously mixed mold at a specific temperature ratio of 4:1 by weight. The mixture is poured gradually and cautiously into the mold to ensure the absence of voids until it is completely filled. Following this, the composite is allowed to harden for approximately 16 hours at ambient temperature (25°C).

2. Test configuration

The experimental section describes the materials utilized in the fabrication of test samples, including the matrix and reinforcement components. Epoxy resin was chosen as the matrix material, while powder (multi-wall carbon nanotubes) and carbon fiber mats were employed as the reinforcement materials.

The epoxy resin, when combined with a hardener at a density of approximately 2.1 g/cm^3, forms thermoplastic solids. The mixing ratio used was 1:2 based on weight. To facilitate the hardening process, a resting period of 30 minutes at around 25°C was implemented. The weight ratios varied based on the number of carbon fiber mat layers placed in the casting mold.

For the sample dimensions, a size of 25×25 cm^2 was adopted, with a thickness of 1 cm. Each specific test (tensile, impact, bending) necessitated the creation of a dedicated mold, adhering to predetermined dimensions. CNC machining technology was employed to fabricate these molds. The process involved placing a square component inside the mold, surrounded by glass and secured using glass paste. Wax was applied to the glass surfaces to prevent material adhesion, and meticulous adjustments were made to ensure the sample's precise shape. The surfaces were then smoothed and refined.

In the case of bending tests, the multi-wall carbon nanotube powder was mixed with epoxy resin according to the prescribed weight fraction. Additionally, the carbon fiber mat was blended with the epoxy resin to achieve the desired weight ratio. Acetone, in combination with a heated magnetic stirring plate, was used to facilitate the thorough mixing process. The resulting mixture was then poured into the mold, ensuring a slow and meticulous pouring technique to avoid the formation of cavities. Subsequently, the filled mold was left undisturbed for approximately 16 hours at room temperature (25°C) to allow for complete hardening.

Figure 1 illustrates the process, showcasing the mixing of epoxy resin and multi-wall carbon nanotubes using a magnetic stirring technique on a hot plate. The homogeneous mixing was maintained for one hour, adhering to the weight ratio of 1:2.

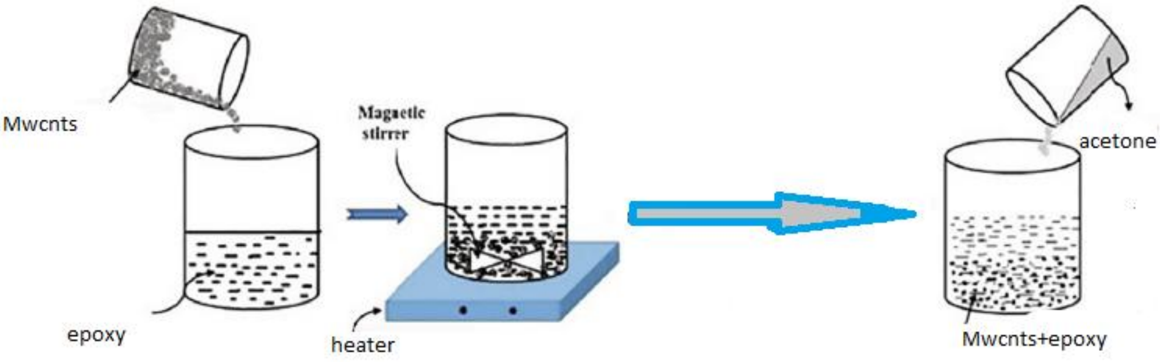

Figure 1. Technical mixtures (mwcnts)/Epoxy

3. Result

3.1 Tensile Testing and Analysis of Reinforced Epoxy Samples

To conduct the tensile tests, samples were prepared according to ASTM D3039 standards. These samples consisted of reinforced epoxy with a combination of carbon nanotubes and carbon fiber mats. The weight fraction of multi-walled carbon nanotubes was maintained at 2%, while the carbon fiber layers varied (16, 8, 4, 0). Figure 2 depicts the dimensions in [mm] of the specimen used for the tensile test.

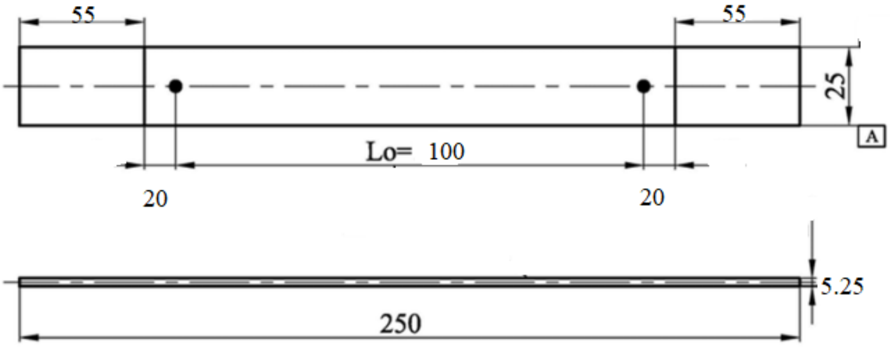

Figure 2. Standard dimensions of tensile test specimen (all dimensions in millimeter)

Molds were utilized to fabricate the tensile test samples. After the hardening process, each sample underwent cutting using a CNC machine, resulting in standard dimensions of width 25 mm, length 250 mm, and varying thicknesses (5.25, 3, 6, 7.25 mm), depending on the number of carbon fiber layers applied.

The charts given in Figures 3-6 express the load-curve deformation projected based on the number of carbon fiber layers (0, 4, 8, 16). One may notice certain points in these curves, which represent force values of interest and they will be explained in what follows. Pont P1 represents the initial force that affects the sample more than the corresponding deformation initiation. The force P2 follows P1 and has the least impact onto the sample at the beginning of deformation. It signifies the lower end of the the spectrum. Finally, Pm denotes the maximum force the sample can withstand, and upon which a fracture occurs. Finally, Pp denotes the force at the upper limit of elongation.

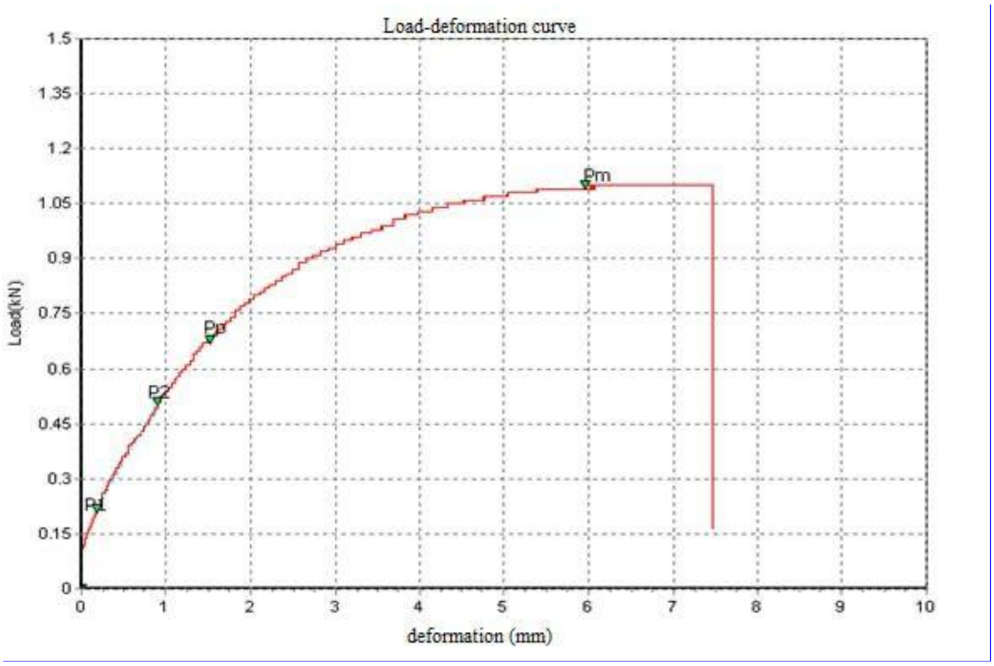

Figure 3. Load-curve deformation for zero layers of carbon fiber

The tensile operations were performed on each sample to obtain crucial data regarding their mechanical behavior. The results were used to calculate the respective stresses, and load-deformation curves were plotted to represent the behavior of the samples under different applied loads. The analysis focused on correlating the number of carbon fiber layers and their application mechanism with the observed stress-strain characteristics.

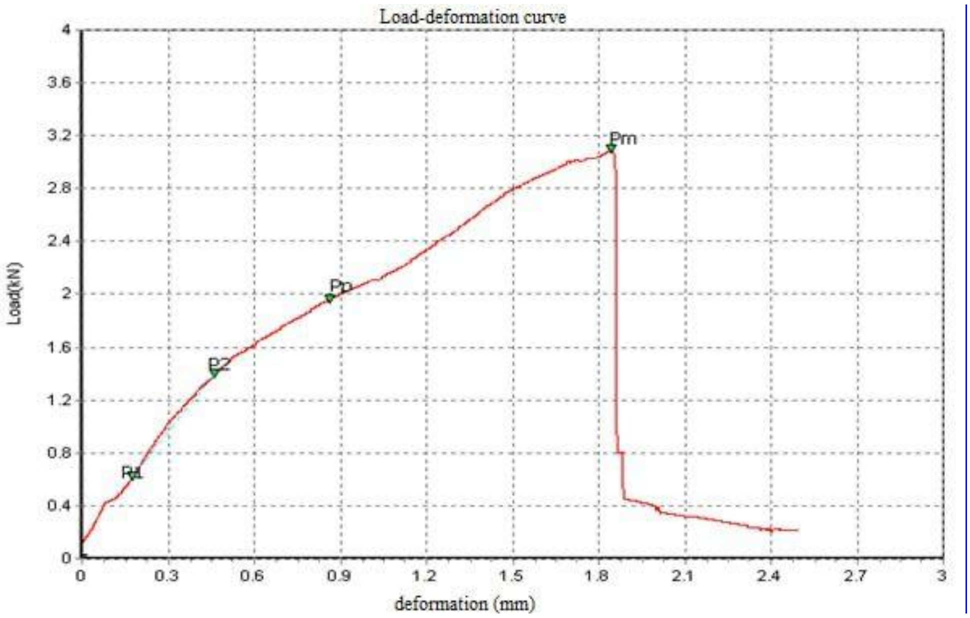

Figure 4. Load-deformation curve for four carbon fiber layers

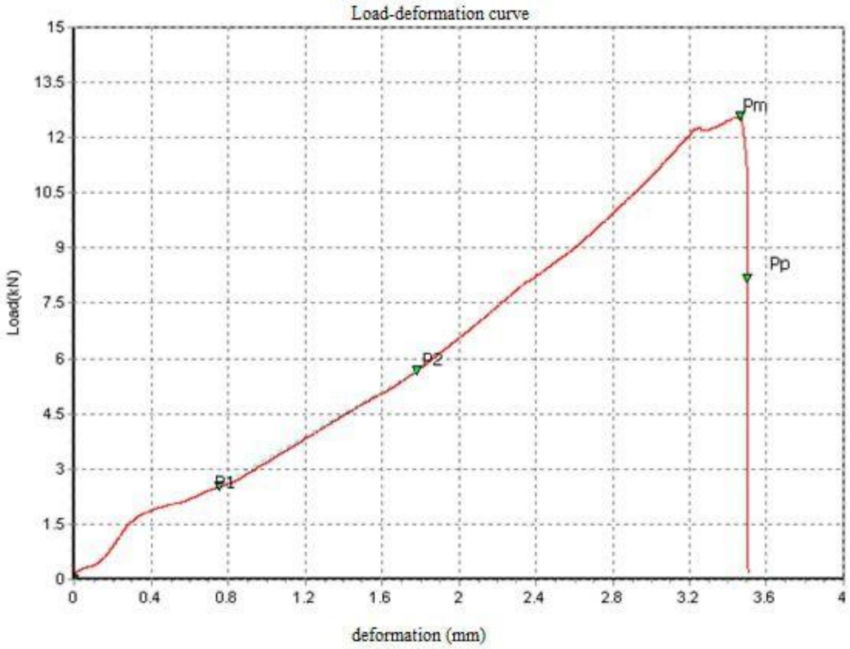

Figure 5. Load-deformation curve for eight carbon fiber layers

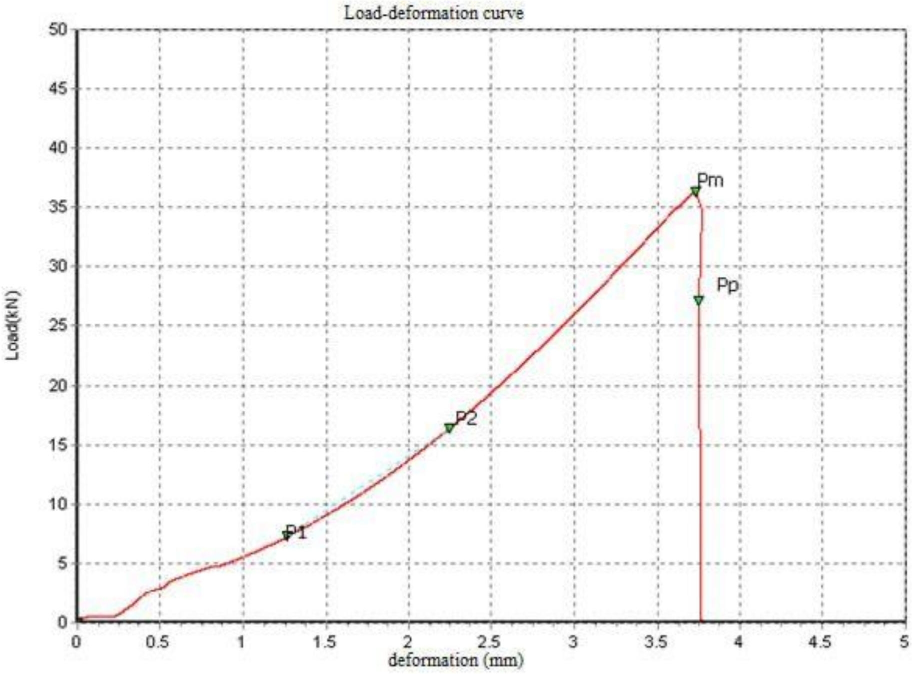

Figure 6. Load-deformation curve for sixteen carbon fiber layers

The results of this comprehensive experiment are not only given in the above charts illustrating the load-deformation relationships, but they are also summarized in Table 1, which in addition includes the calculated stresses. These findings shed light on the influence of the number of carbon fiber layers and their arrangement on the overall mechanical performance of the reinforced epoxy samples. In this table, A represent the cross-sectional area. The stress $\sigma 1$ indicates the stress at the yield point, where material starts to deform plastically, and it is used to determine the maximum allowable loads in mechanical components, representing the limit for avoiding permanent deformation, while $\sigma 2$ represents the maximum stress the material can endure under tension before breaking. The ultimate tensile strength, found at the highest point of the stress-strain curve, is denoted by σm.

Table 1. The tensile test results for the varing number of carbon fiber layers

Number of layers	Cross sectional area A [mm²]	Force P [kN]	Yield stress σ [MPa]	Force P1 [kN]	Yield stress $\sigma1$ [MPa]	Ultimate force Pm [kN]	Ultimate stress σm [MPa]	Young's Modulus [GPa]
0	75	0.91	12.13	0.83	11.06	1.31	17.46	0.713
4	150	1.93	12.88	1.73	12.56	3.1	20.66	1.84
8	131.2	8.16	62	8.16	62	12.58	96	2.384
16	193.75	30.66	158.24	30.66	158.24	43.02	222.038	5.274

3.2. Exploring Impact Resistance: Evaluating the Effect of Carbon Fiber Layers

Impact force is a crucial parameter that measures a material's ability to withstand sudden and intense forces. In this study, a crash test following ASTM E23 standards was conducted to assess the impact strength of the samples.

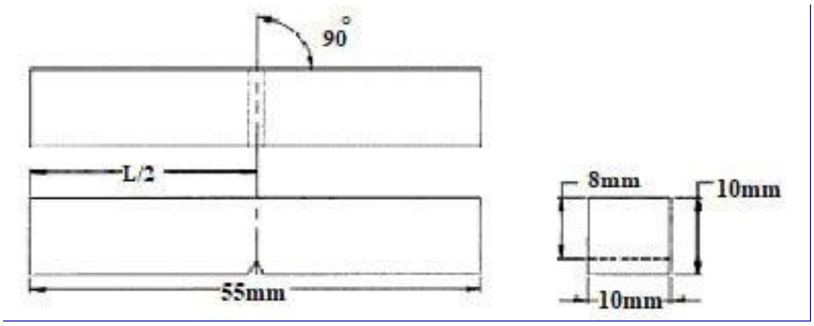

Figure 7. Cross-sectional views of specimen as per ASTM E23 standards for impact test

The determination of impact strength in this study was based on predefined criteria. Notably, and as expected, an increase in the number of carbon fiber layers (0, 4, 8, 16) led to a progressive enhancement in the compound's resistance to impact forces. The dimensions of the samples employed in this assessment, as depicted in Figure 7, measure 55 mm in length, 10 mm in width, and vary in the thickness due to differences in the number of carbon fiber layers applied (3, 5.25, 6, 7.25 mm). To create a crack within the standard shape, a piece was cut at an 8mm thickness angle of 90 degrees, resulting in the crack depicted as seen in the figure.

Figure 8 provides a visual representation of the observed increase in resistance as the number of carbon fiber layers is increased. This diagram underscores the substantial influence of carbon fiber layers on the overall impact resistance of the compound, thereby illustrating improved performance with an increasing number of layers, which was expected.

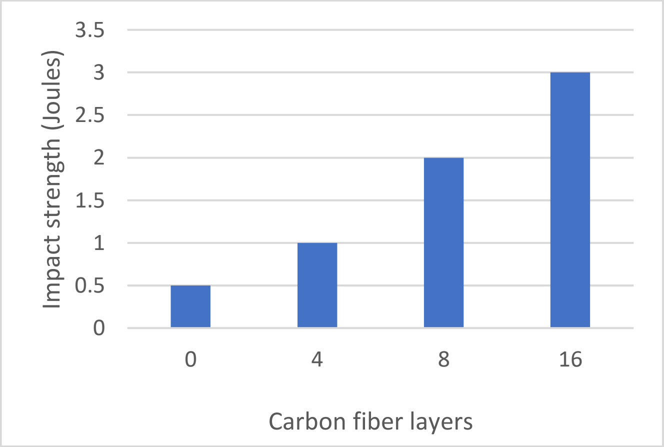

Figure 8. Variation of impact strength with the change in the number of carbon fiber layers

4. Conclusion

In conclusion, this study has shed light on the promising advancements in composite materials by examining the integration of multi-walled carbon nanotubes and carbon fiber layers within an epoxy matrix. The investigation revealed several key findings that have implications for various industries, particularly in the development of aircraft structures and high-stress mechanical components.

First and foremost, the research confirmed the efficiency of multi-walled carbon nanotubes as a remarkable enhancer of mechanical properties. These nanotubes exhibit superior tensile strength, rigidity, and engineering characteristics while remaining cost-effective and lightweight, making them highly desirable for applications requiring exceptional performance.

The study's exploration of different proportions of multi-walled nanotubes within the epoxy matrix, in conjunction with varying numbers of carbon fiber layers, has highlighted the potential for significant improvements in mechanical properties. The observed increase in strength, deformation resistance, and modulus of elasticity underscore the importance of carefully tuning composite formulations to achieve desired outcomes.

Furthermore, the incorporation of interwoven carbon fibers to reinforce the epoxy and nanotube components has proven to be an effective strategy, further enhancing mechanical properties and providing a holistic approach to composite material development.

Overall, the outcomes of this research have far-reaching implications. They not only contribute to the advancement of composite materials but also offer practical solutions for industries where high strength, durability, and cost-efficiency are paramount. The findings presented here represent a significant step forward in the quest for innovative and high-performance materials, promising to reshape the landscape of engineering applications and aerospace technology.

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