

ENHANCING INTERLAMINAR SHEAR STRENGTH (ILSS) OF WOVEN FABRIC HYBRID POLYMERIC NANOCOMPOSITES BY INCORPORATING MULTI WALLED CARBON NANOTUBES

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Abstract

In this work, multi walled carbon nanotubes (MWCNTs) with weight percentage of 0.1% and 0.2% were incorporated in the epoxy polymer resin to form epoxy nanocomposites. The investigation of the effect of MWCNTs on the mechanical behavior of epoxy nanocomposite was carried out. The hybrid composite containing Glass/Carbon/Basalt fibers with MWCNT modified epoxy nanocomposite were fabricated using vacuum assisted resin transfer molding method (VARTM) and tested for its interlaminar shear strength according to ASTM standards. Scanning Electron Microscopy (SEM) technique was used to evaluate the dispersion of MWCNTs in polymer epoxy. Moreover, effect of fiber orientation on the interlaminar shear strength of the hybrid nanocomposites was investigated. The addition of 0.1 wt% of MWCNTs enhanced the interlaminar shear or short beam strength by 10% and by 5% with 0.2 wt% of MWCNTs. The aim of this research work is to find the effect of MWCNTs on mechanical properties of modified epoxy nanocomposites laminates, exclusively for airplane and automobile structural applications.

Keywords: Interlaminar shear strength; MWCNTs; Epoxy; VARTM method

Introduction

Multi-walled carbon nanotubes (MWCNTs) have attracted attention from composite industry due to outstanding mechanical and electrical properties, their high aspect ratio. MWCNTs also play important role in improving adhesion at fiber matrix interface. The improved mechanical properties of fiber reinforced nanocomposites depend on uniform dispersion of MWCNTs in thermoset resin. Among the available dispersion techniques, the combination of sonication and direct mixing

showed the lowest density of MWCNT aggregates. The surface treated nanofillers have shown uniform dispersion in resin compared to untreated MWCNTs. Mingming Yu *et al.* (2024) investigated that carbon fibers coated with sizing agent containing grapheme oxides, hydroxylated CNT and fullerenols results in improving interfacial bonding strength of the composite material due to the interfacial compatibility between carbon fiber and matrix. Sulaiman *et al.* (2024) analysed the

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effect of MWCNTs on tensile, and flexural performance of plain and woven hybrid composite and concluded that incorporation of MWCNTs in epoxy resins results in improvement in mechanical and impact resistance performance of hybrid composites made from carbon and Kevlar fibers. Yuksel *et al.* (2024) concluded that proper dispersion of nanoparticles in epoxy resin is governing factor in enhancement of mechanical properties. From SEM images it is observed that properly dispersed MWCNTs and graphene results in improvement of mechanical performance. Srinivasa Perumal *et al.* (2024) observed that addition of rutile in epoxy resin showed enhancement in mechanical properties of glass fiber composite. Shinde *et al.* (2014a) used plain weave fabrics of glass, carbon, basalt and diglicidyl ether of bisphenol F epoxy resin (DGEF) to manufacture the modified epoxy nanocomposite laminates. Uthale and Shinde (2021) and Sridhar and Varadarajan (2016) studied the effect of orientation of fiber on the mechanical properties of modified epoxy hybrid nanocomposite laminates. The deterioration of mechanical properties with increasing angle of fiber orientation has been observed. The 0° fiber orientation has shown significant improvement in strength and modulus properties as compared to 30°, 45° and 60° orientations. Shukla and Sharma (2019) investigated the effect of CNT and graphene on the mechanical behavior of nanocomposites. The results showed that simultaneous addition of graphene and CNTs to epoxy resin significantly improved mechanical properties compared to adding only nanofillers to epoxy resin due to formation of strong bond. Scanning electron microscopy (SEM) has been used to observe morphological characteristics of composites. Uthale *et al.* (2024) carried out FE analysis for analyzing failure modes as it is experimentally difficult to observe the internal damage in various loading condition.

In spite of these advancements, challenges still exist in achieving strong interfacial bonding, uniform dispersion, and multi-phase synergy in hybrid nanocomposites. Many researchers have largely focused MWCNT's effect on mechanical properties of carbon fiber reinforced composites but no one has studied in detail the effect of MWCNT on interlaminar shear strength of hybrid (carbon + basalt + glass fiber) polymeric nanocomposites.

The novelty of the research work lies in the addition of MWCNTs into an epoxy polymer matrix through a controlled sonication process aiming at uniform dispersion and improved fiber matrix bond in a hybrid polymeric nanocomposite. This work not only addresses common dispersion challenges

but also introduces multifunctional benefits, including improved mechanical integrity. The study systematically evaluates the effect of MWCNT and fiber orientation on interlaminar shear performance, supported by morphological characterization through scanning electron microscopy (SEM).

Thus, this study gives a comprehensive insight into the effect of combining MWCNTs on behaviour of woven fabric hybrid polymeric nanocomposites, covering the way for developing materials for aerospace, automotive, and defence applications.

Multi-walled carbon nanotubes (MWCNTs) have attracted attention from composite industry due to outstanding mechanical and electrical properties, their high aspect ratio. MWCNTs also play important role in improving adhesion at fiber matrix interface. The improved mechanical properties of fiber reinforced nanocomposites depend on uniform dispersion of MWCNTs in thermoset resin. Among the available dispersion techniques, the combination of sonication and direct mixing showed the lowest density of MWCNT aggregates. The surface treated nanofillers have shown uniform dispersion in resin compared to untreated MWCNTs. Mingming Yu *et al.* (2024) investigated that carbon fibers coated with sizing agent containing graphene oxides, hydroxylated CNT and fullerenols results in improving interfacial bonding strength of the composite material due to the interfacial compatibility between carbon fiber and matrix. Sulaiman *et al.* (2024) analysed the effect of MWCNTs on tensile, and flexural performance of plain and woven hybrid composite and concluded that incorporation of MWCNTs in epoxy resins results in improvement in mechanical and impact resistance performance of hybrid composites made from carbon and Kevlar fibers. Yuksel *et al.* (2024) concluded that proper dispersion of nanoparticles in epoxy resin is governing factor in enhancement of mechanical properties. From SEM images it is observed that properly dispersed MWCNTs and graphene results in improvement of mechanical performance. Srinivasa Perumal *et al.* (2024) observed that addition of rutile in epoxy resin showed enhancement in mechanical properties of glass fiber composite. Shinde *et al.* (2014b) used plain weave fabrics of glass, carbon, basalt and diglicidyl ether of bisphenol F epoxy resin (DGEF) to manufacture the modified epoxy nanocomposite laminates. Shinde *et al.* (2021) and Sridhar and Varadarajan (2016) studied the effect of orientation of fiber on the mechanical properties of modified epoxy hybrid nanocomposite laminates. The deterioration of mechanical properties with increasing angle of fiber orientation has been

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Materials and Methods

Materials

The diglycidyl ether of bisphenol F epoxy resin with 4500 to 6500 mPa.s viscosity and density of 1.15 to 1.18 g/cm³ was mixed with diethyl

toluene diamine hardener in an epoxy resin to hardener ratio of 74:26 parts by weight. Hardener had a specific gravity of 1.18 to 1.20 gm/cc and a viscosity of 2950 to 4050 mPa.s. The matrix material was supplied by Fine Finish Organics Ltd, Raigad, India, while the plain woven fabrics made with carbon, glass and basalt as a reinforcing materials were provided by CF Composites Delhi, India. The fiber properties are listed in Table 1.

The nanomaterial was purchased from Nano Research Lab, Jharkhand, India and used (MWCNT: Purity 97%, outer diameter 20-30 nm, length 15-20 μ m, specific surface area of 330 m²/g and bulk density of 0.15-0.25 g/cm³). Transmission electron microscope (TEM) images of multi-walled carbon nanotubes at the scale of 5nm, 20nm, 100nm are shown in Figure 1. Characterization of MWCNTs was carried out at IIT Bombay.

Preparation of Neat Epoxy

Neat epoxy samples were fabricated with epoxy resin to hardener ratio of 74:26 parts by weight. One sided mold of size 350mm $\times$ 350mm was formed on toughened glass. Matrix material was kept in furnace at 65°C for 30 minutes for pre-curing reaction and degasification. Mixture of epoxy resin and hardener was poured on glass surface and followed curing cycle.

The curing cycle used for all samples is shown in Figure 2. The samples were cured in the furnace at 120-125°C for 7h. Shinde *et al.* (2021) studied different synthesis, characterization, testing, modeling, and simulation techniques for polymer nanocomposites.

Table 1. Mechanical properties of Reinforcing Fibers

Reinforcing Element (Fiber)	Density, Kg/m ³	Tensile Strength, MPa	Young's Modulus, GPa
Carbon	1850	4000-4200	240-260
Glass	2550	3000-3200	72-75
Basalt	2650	3400-3500	85-90

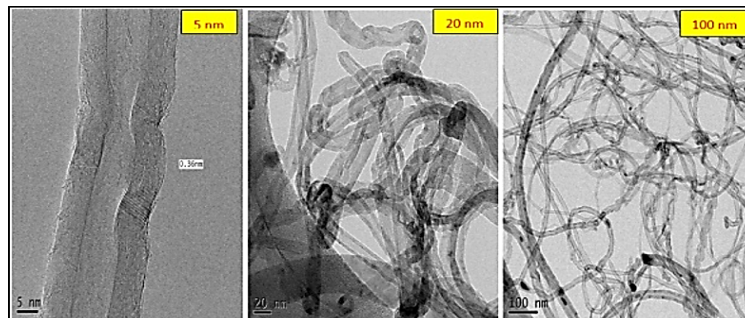


Figure 1. Transmission Electron Microscopy (TEM) images of MWCNTs at different scales: (a) 5 nm, (b) 20 nm, and (c) 100 nm. Characterized at IIT Bombay

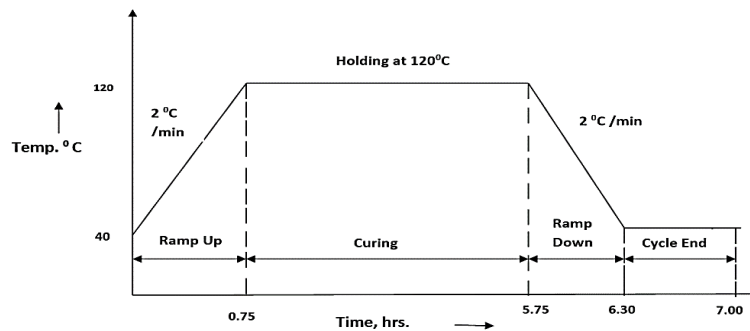


Figure 2. Curing cycle used for neat epoxy and MWCNT-modified epoxy nanocomposites

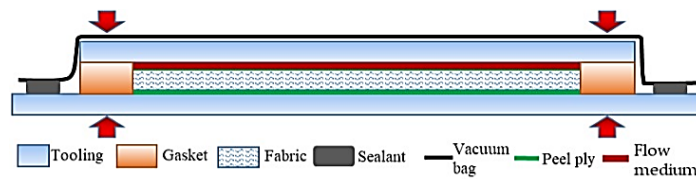


Figure 3. Schematic illustration of the Vacuum Assisted Resin Transfer Molding (VARTM) process. Fielding *et al.* (2004)

Dispersion technique for the MWCNTs in the epoxy and Preparation of MWCNT Modified Epoxy Nanocomposite

MWCNTs were preheated in a muffle furnace at 100°C for 2 hours to remove moisture. Based on weight percentage, (315g epoxy resin was taken to achieve sheet thickness of 4mm) MWCNTs with 0.1 wt.% (0.315g) and 0.2 wt.% (0.630g) were added in epoxy resin to make epoxy nanocomposite. Initially magnetic stirrer was used to get homogeneous mixture and magnetic bead was set at 500 rpm for 60 minutes at 45°C, then mixture was kept in Ultra autosonic probe sonicator of capacity 20kHz, 1200W for 90 minutes to achieve uniform dispersion of MWCNTs in resin. The sonication duration of sonication treatment corresponds to literature. After completion of sonication process, 110.67 g and 221.35g of hardener was added to mixture for 0.1 wt.% and 0.2 wt.% respectively. After keeping the mixture of epoxy resin and hardener in furnace for 20 minutes at 65°C for precuring reaction and degasification, poured on glass surface and followed same curing cycle as used for neat epoxy.

Preparation of Hybrid (Carbon/Glass/Basalt Reinforced) MWCNT Modified Epoxy Nanocomposites Laminates

VARTM method was used to obtain nanocomposite laminates. Figure 3 shows schematic of VARTM process.

In VARTM process, single-sided mold was used, and initially a release agent was used on glass surface to allow easy removal of the composite laminate from the surface after curing. Fabrics were cut into squares 305 mm × 305 mm. A total of 18 layers of plies were used to achieve an average thickness of 4 mm. Layers of fabrics were kept on glass as per stacking sequence of C/B/G/C/B/G/C/B/G/C/B/G/C/B/G/C. A sheet of vacuum bag was placed on top and then applied sealant tape around it. A vacuum pump was used to introduce the resin into the mold through port. Figure 4(a) and (b) shows schematic of VARTM set up schematic and process trial respectively.

Shinde *et al.* (2021) studied the composite manufacturing methods and concluded that the use of VARTM method could achieve a fiber volume ratio up to 70% with subsequent mechanical properties.

Fabrication process flowchart is shown in Figure 5.

Characterization Tests

Tensile test and flexural test specimens of neat epoxy and MWCNT modified nanocomposite were carried out according to ASTM D638 standard and ISO 178 standards respectively. Figure 6(a) and Figure 6(b) shows standard dimensions of tensile and flexural test specimen respectively.

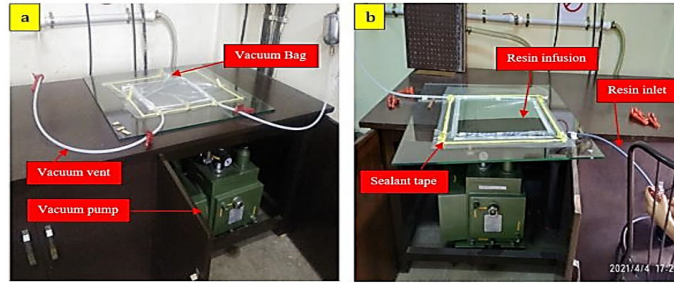


Figure 4. VARTM fabrication: (a) VARTM setup; (b) Trial process image

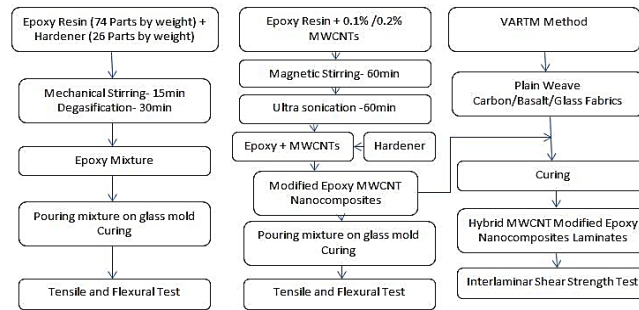


Figure 5. Flowchart of the fabrication process of MWCNT-modified epoxy nanocomposite laminates

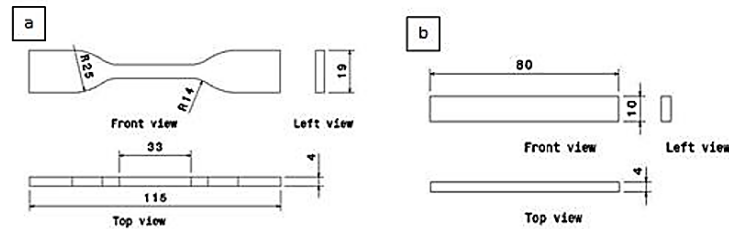


Figure 6. Standard specimen dimensions: (a) ASTM D638 tensile test; (b) ISO 178 flexural test

Interlaminar shear strength test of Hybrid (Carbon/Glass/Basalt Reinforced) MWCNT modified epoxy nanocomposites Laminates was carried out according to ASTM D2344 standards. The figure 7 depicts standard size of interlaminar shear strength specimen.

Shimadzu AGS-X make universal testing machine (UTM) with 100 KN capacity was used for the tests. The five tensile and five flexural test specimens of each category as neat epoxy, epoxy with 0.1% and 0.2% MWCNTs were tested, while five ILSS test specimens of each category as hybrid composite, hybrid with 0.1% and 0.2%MWCNTs were tested. Mean of five samples is considered for analysis. Specimens were subjected to strain rate of 2 mm/min.

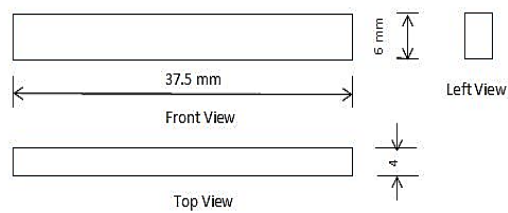


Figure 7. ASTM D2344 standard specimen for interlaminar shear strength (ILSS) testing

SEM images of MWCNT modified epoxy nanocomposite were taken to observe the distribution of MWCNTs in epoxy resin and to observe agglomeration of MWCNTs. Moreover,

fracture surface images of hybrid (carbon/glass/basalt reinforced) nanocomposites laminates were obtained.

Result and Discussions

Mechanical Properties of Neat Epoxy and MWCNT Modified Epoxy Nanocomposites

Figure 8 presents failure modes of the neat epoxy and modified nanocomposite specimens after tensile testing. As expected, failure was observed near neck section of specimen.

The effect of presence of MWCNTs in epoxy on tensile strength and elastic modulus is presented in figure 9(a) and figure 9(b) respectively. The tensile strength of neat epoxy was measured as 65MPa. The nanocomposite that has MWCNTs of 0.1 wt.% showed better performance with 75MPa. However, nanocomposite that has MWCNTs of 0.2% has shown 7.69% decrease in tensile strength compared to neat epoxy. Mirzamohammadi *et al.*

(2022) also reported comparable results for hybrid composites.

Tensile test results revealed that incorporation of 0.1% MWCNTs in epoxy showed better performance with 9.47% increase in elastic modulus, while addition of 0.2% MWCNTs in epoxy results in 4.21% decrease in elastic modulus compared to that of neat epoxy. Decrease in tensile strength and elastic modulus with 0.2% MWCNTs in epoxy was due to agglomeration of MWCNTs.

Figure 10 presents neat epoxy, epoxy with 0.1% and 0.2% MWCNT specimens after flexural test Figure 11 depicts the effect of addition of MWCNTs in resin on flexural properties of neat epoxy and MWCNT modified epoxy nanocomposites. The stress-strain graph of epoxy with 0.1% MWCNTs shows better strength in comparison with neat epoxy. However, epoxy with 0.2% MWCNTs shown less strength and limited strain at failure. The presence of 0.1% MWCNTs in epoxy enhanced flexural strength by 11.43% compared to neat epoxy, while presence of 0.2%



Figure 8. Specimens after tensile testing: (a) Neat epoxy; (b) 0.1% MWCNTs; (c) 0.2% MWCNTs

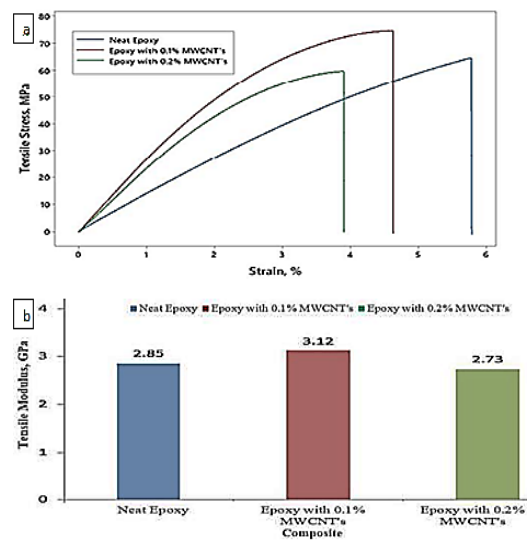


Figure 9. Tensile performance of neat and MWCNT-modified epoxy nanocomposites: (a) Tensile strength; (b) Elastic modulus

MWCNTs in epoxy decreased the flexural strength by 15.47%. The flexural test revealed that addition of 0.1% MWCNTs in epoxy showed best performance with 11.55% increase in flexural modulus, while incorporation of 0.2% MWCNTs in epoxy showed 2.95% decrease in flexural modulus compared to the modulus of neat epoxy. Decrease in flexural properties was due to brittleness of epoxy with 0.2% MWCNTs with more agglomeration of MWCNTs.

Mechanical Characteristics of Hybrid (Carbon/Basalt/Glass Reinforced) MWCNT Modified Epoxy Nanocomposites Laminates

In this study, 0° and 45° fiber orientations were selected to represent two critical conditions: fiber-

aligned and off-axis configurations. Laminates with 0° and 90° fiber orientation consistently exhibited superior mechanical performance due to optimal alignment of fibers with the loading axis. These orientations capture the maximum variation in interlaminar shear behavior, particularly delamination tendencies. Prior studies have shown that intermediate orientations such as 30° and 60° exhibit mechanical responses that fall between these two extremes, and their inclusion offers limited additional insight into interlaminar failure mechanisms. Therefore, the focus was maintained on 0° and 45° orientations to ensure clarity, resource efficiency, and targeted analysis of ILSS characteristics.



Figure 10. Specimens after flexural testing: (a) Neat epoxy; (b) 0.1% MWCNTs; (c) 0.2% MWCNTs

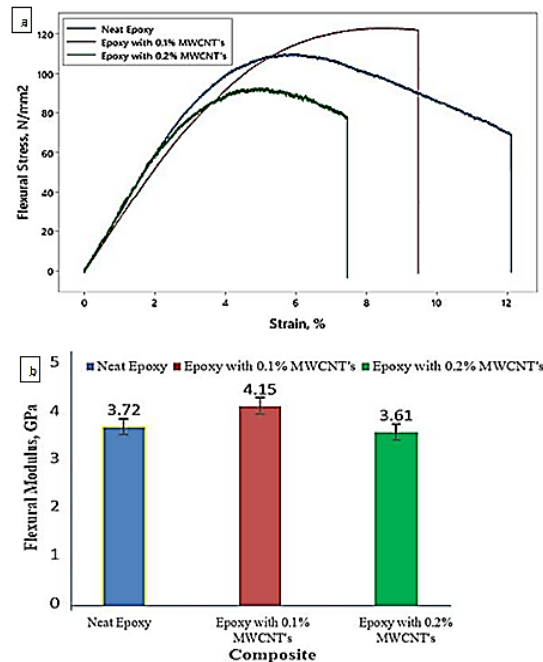


Figure 11. Flexural performance of neat and MWCNT-modified epoxy nanocomposites: (a) Flexural strength; (b) Flexural modulus

Figure 12(a) presents interlaminar shear strength test specimens of hybrid MWCNT modified epoxy nanocomposite laminates for 0.1% MWCNTs before testing. Failure of specimen in the perpendicular direction to loading and direction to through thickness is presented in figure 12(b).

The interlaminar shear strength test specimens of hybrid MWCNT modified epoxy nanocomposite laminates with 0.2% MWCNTs for 0° fiber orientation before testing and after failure are presented in figure 13.

The interlaminar shear strength test specimens of hybrid MWCNT modified epoxy nanocomposite laminates with different percentage of MWCNTs for

45° orientation before testing and after failure are shown in figure 14 and 15 respectively.

The delamination was observed in case of hybrid and hybrid MWCNT modified epoxy nanocomposite laminates, which is clearly visible in through thickness direction of specimens.

Figure 16(a) depicts stress vs. strain graph for 0° fiber orientations for hybrid and modified hybrid nanocomposite laminates to determine short beam strength. The modified hybrid nanocomposite laminates with 0.1 weight % of MWCNTs has shown maximum stress compared to other two combinations.

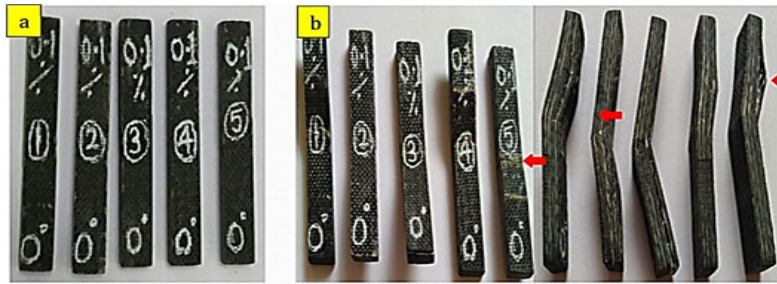


Figure 12. ILSS specimens with 0.1% MWCNTs (0° orientation): (a) Before testing; (b) After testing

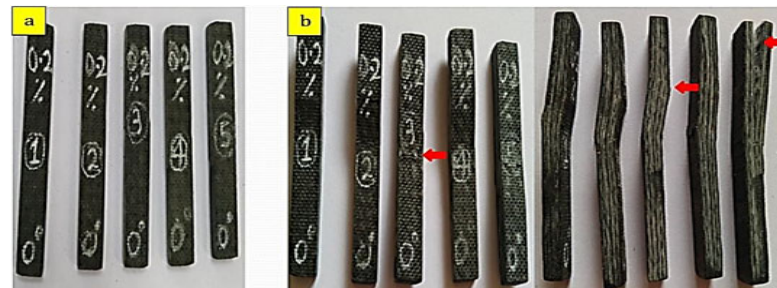


Figure 13. ILSS specimens with 0.2% MWCNTs (0° orientation): (a) Before testing; (b) After testing

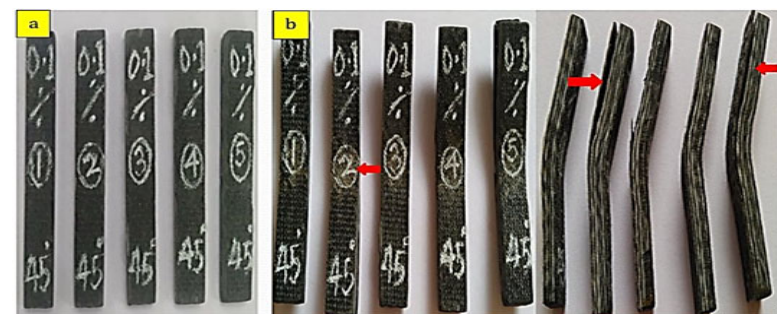


Figure 14. ILSS specimens with 0.1% MWCNTs (45° orientation): (a) Before testing; (b) After testing

Figure 16(b) shows interlaminar shear strength of hybrid and modified hybrid nanocomposites for 0° fiber fill directions. The modified hybrid nanocomposite laminates with 0.1 weight % of MWCNTs has shown higher interlaminar shear strength (32.27 N/mm^2) compared to other two combinations.

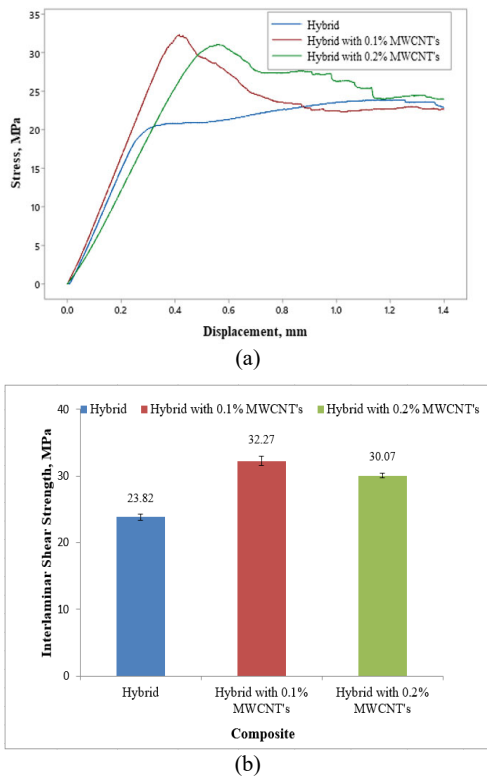


Figure 16. ILSS test results (0° fiber orientation): (a) Stress-strain curves; (b) Interlaminar shear strength

Figure 17(a) shows the stress vs strain curve (45° fiber orientation) used to determine interlaminar shear strength. Figure 17(b) gives delamination resistance values of hybrid, and hybrid modified nanocomposite for 45° fiber direction.

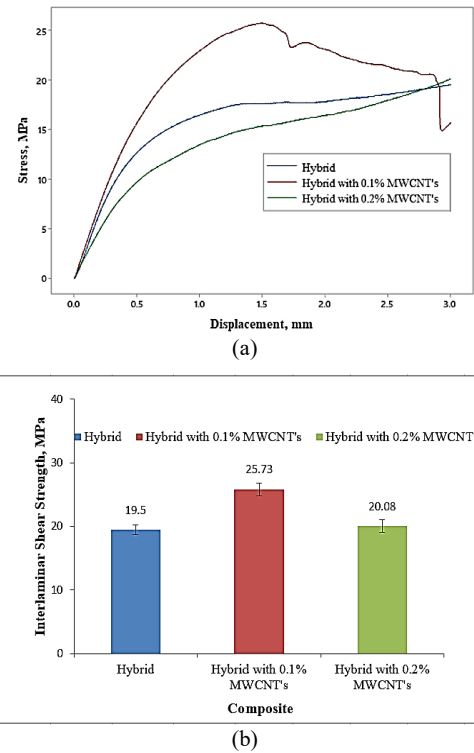


Figure 17. ILSS test results (45° fiber orientation): (a) Stress-strain curves; (b) Interlaminar shear strength

The interlaminar shear properties of hybrid and hybrid MWCNT modified epoxy nanocomposite laminates observed through experimentation are given in Table 2.

The addition of 0.1wt% of MWCNTs in neat epoxy to develop hybrid composite results in improvement in interlaminar shear strength by 26.18% and 24.21% for 0° and 45° fiber direction respectively in comparison with hybrid composite, while addition of 0.2 wt % MWCNTs in hybrid composite showed the improvement in short beam strength by 20.82% and 2.88% for 0° and 45° fiber direction respectively in comparison with hybrid composite.

Table 2. Interlaminar shear strength of hybrid and hybrid MWCNT modified epoxy nanocomposite laminates

Composite Type	Mean Interlaminar Shear Strength, MPa (0° fiber orientation)	Mean Interlaminar Shear Strength, MPa (45° fiber orientation)	% Decrease in strength at 45° fiber orientation
Hybrid	23.82 (1.85)*	19.50 (1.34)	18.13
Hybrid + 0.1% MWCNTs	32.27 (1.46)	25.73 (1.25)	20.26
Hybrid +0.2% MWCNTs	30.07 (1.52)	20.08 (0.98)	33.22

Morphological Assessment

The scanning electron microscopic images of neat epoxy and MWCNT (0.1wt.% and 0.2 wt.%) modified epoxy nanocomposites are depicted in figures 18 and 19 respectively. From SEM analysis, it is observed that surface defects in neat epoxy may lead to fracture results in poor structure durability.

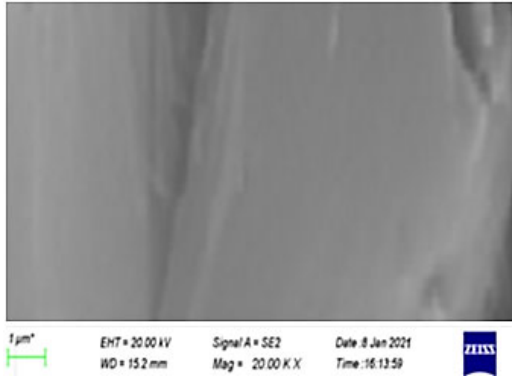


Figure 18. SEM micrograph of fracture surface of neat epoxy resin, showing surface defects and voids

Figure 19(a) shows the microscopic image of specimen at failed surface resulted in the proper dispersion of nanoparticles, while figure 19(b) indicates MWCNTs are not properly dispersed but agglomerated in epoxy resin. Nanocomposites with 0.2 weight % MWCNTs, has shown more agglomeration compared to 0.1 weight % MWCNTs. Nanoparticle-matrix adhesion, homogeneity, nanoparticle orientation, weight % of nanotubes and aspect ratio plays important role in uniform distribution of MWCNTs in resin.

Kumar *et al.* (2019) also noticed same results and concluded that, addition of 0.2 weight % nanoparticles result in deterioration of properties attributed to agglomeration-induced stress concentrations, a trend also observed in polymer nanocomposites beyond the percolation threshold. Patil *et al.* (2018) concluded that, increase in weight percent of nanoparticles results in heterogeneous composition due to greater amount of clustering with larger lump size.

Agglomeration of MWCNTs reduces the available surface area for stress transfer and introduces microstructural discontinuities, acting as crack initiation sites. This effect is more prominent

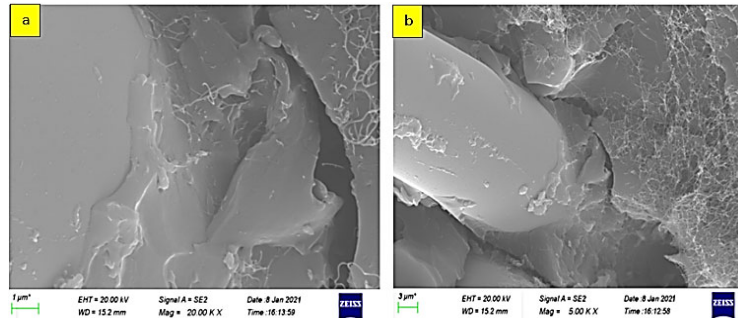


Figure 19. SEM images of MWCNT-modified epoxy nanocomposites: (a) 0.1% MWCNTs (uniform dispersion); (b) 0.2% MWCNTs (agglomeration visible)

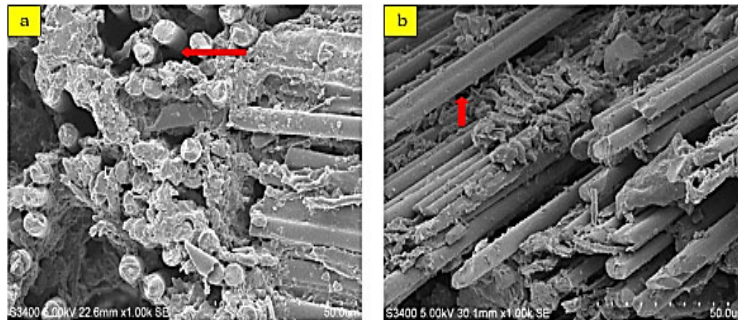


Figure 20. SEM images of fractured ILSS specimens for hybrid laminates: (a) 0.1% MWCNTs (good fiber-matrix bonding); (b) 0.2% MWCNTs (visible debonding)

beyond the percolation threshold. Alternative methods like surface functionalization (e.g., carboxylation) or solvent-assisted dispersion could mitigate this effect. Netravali and Mittal (2011) noticed that, surface treatment approaches cause changes in surface energy, wettability, roughness, and interfacial interactions leading to enhancement of the fibre-matrix adhesion.

Figure 20(a) and Figure 20(b) presents SEM images of flexural specimen of hybrid nanocomposites with 0.1% and 0.2% MWCNTs respectively for 0° fiber orientation. The arrows indicate the fiber matrix debonding. The SEM image shown in Figure 20(b) illustrates comparatively weak bonding at fiber matrix interface.

Conclusions

This work revealed that incorporation of 0.1 weight % MWCNTs in epoxy are highly effective on mechanical properties of modified epoxy nanocomposites. Addition of 0.1 wt.% of MWCNTs in epoxy has shown more than 10% increase in tensile and flexural strength compared to neat epoxy. While, addition of 0.2 wt.% of MWCNTs in epoxy results in decrease in mechanical properties compared to neat epoxy due to increased brittleness of epoxy and agglomeration of MWCNTs. The interlaminar shear strength of Hybrid (Carbon/Glass/Basalt Reinforced) MWCNT modified epoxy nanocomposites laminates with incorporation of 0.1 wt.%, was increased by 26.18%. Modified nanocomposites laminates with 0° fiber orientation have shown good performance in comparison with 45° fiber orientation in all aspects. However, the composites with 45° fiber orientation gave the maximum strain before the shear failure because fibers at $\pm 45^\circ$ attempted to position in 0° and 90° direction, under the loading. Based on the findings of the work, it can be suggested that the modified epoxy nanocomposites with 0.1 wt.% MWCNTs have good potential in interlaminar shear strength that can be used in aerospace and automobile industries to avoid delamination. There is further scope in improvement in mechanical properties by avoiding agglomeration of MWCNTs through proper dispersion techniques.

Future work may explore surface-functionalized MWCNTs, alternate dispersion media, or gradient fiber orientations for further performance optimization in aerospace-grade laminates.

References

- Fielding, J. C., Chen, C., and Borges, J. (2004). Vacuum infusion process for nanomodified aerospace epoxy resins. In Proceedings of the SAMPE Symposium and Exhibition.
- Mirzamohammadi, S., Eslami-Farsani, R., and Ebrahimnezhad-Khaljiri, H. (2022). The experimental assessment of carbon nanotubes incorporation on the tensile and impact properties of fiber metal laminate fabricated by jute/basalt fabrics-aluminum layers as hybrid structures. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 237(8), 1877-1886. <https://doi.org/10.1177/09544062221134223>
- Netravali, A. N., and Mittal, K. L. (2011). Fiber surface treatment: Relevance to interfacial characteristics. In Wiley encyclopedia of composites (pp. 1-19). <https://doi.org/10.1002/9781118097298.wecoc206>
- Patil, A., Patel, A., and Sharma, P. K. (2018). Effect of carbon nanotube on mechanical properties of hybrid polymer matrix nanocomposites at different weight percentages. Materials Today: Proceedings, 5(2), 6401-6405. <https://doi.org/10.1016/j.matpr.2017.12.251>
- Shinde, D. K., and Kelkar, A. D. (2014). Effect of TEOS electrospun nanofiber modified resin on interlaminar shear strength of glass fiber/epoxy composite. World Academy of Science, Engineering and Technology, International Journal of Materials and Metallurgical Engineering, 8, 54-60.
- Shinde, D. K., Emmanwori, L., and Kelkar, A. D. (2014). Comparison of mechanical properties of EPON 862/W with and without TEOS electrospun nanofibers in nanocomposite. In Proceedings of the SAMPE Seattle Conference (pp. 16-20).
- Shukla, M. K., and Sharma, K. (2019). Effect of carbon nanofillers on the mechanical and interfacial properties of epoxy-based nanocomposites: A review. Polymer Science, Series A, 61(4), 439-460. <https://doi.org/10.1134/S0965545X19040096>
- Sridhar, D., and Varadarajan, Y. (2016). Significance of the type of reinforcement on the mechanical behavior of polymeric composites. American Journal of Materials Science, 6, 1-5. <https://doi.org/10.5923/c.materials.201601.01>
- Srinivasa Perumal, K. P., Selvarajan, L., Mathan Kumar, P., and Shriguppikar, S. (2025). Enhancing mechanical and morphological properties of glass fiber reinforced epoxy polymer composites through rutile nanoparticle incorporation. Progress in Additive Manufacturing, 10(1), 831-848. <https://doi.org/10.1007/s40964-024-00675-0>
- Sulaiman, B. H., Abdo, A. R., Erklig, A., Bozkurt, Ö. Y., and Bulut, M. (2024). Effectiveness of multi-walled carbon nanotubes on the improvement of tensile, flexural, and low-velocity impact properties of hybrid Kevlar/carbon fiber reinforced epoxy-based composites. Polymer Composites, 45(8), 7647-7660. <https://doi.org/10.1002/pc.28294>
- Uthale, S., and Shinde, D. K. (2021). Comparison of mechanical properties of hybrid woven fabric reinforced epoxy composites fabricated using glass, carbon, and basalt fibers. In Proceedings of SAMPE neXus 2021.
- Uthale, S., Shinde, D. K., Shahapure, N., Kulkarni, S., and Nikam, M. (2024). Effect of MWCNTs on mechanical properties of woven fabric hybrid polymeric nanocomposites and finite element analysis of nanocomposite. International Journal on Interactive Design and Manufacturing (IJIDeM), 18(10), 7477-7494. <https://doi.org/10.1007/s12008-023-01225-8>

- Yu, M., Ding, J., Xiao, R., Xie, W., Shan, C., Liu, Z., and Sun, J. (2024). Effects of carbon nanomaterials on the interfacial properties of carbon fiber reinforced epoxy resin composite. *Polymer Composites*, 45(16), 15201-15210. <https://doi.org/10.1002/pc.28830>
- Yuksel, E., Eksik, O., Haykiri-Acma, H., and Yaman, S. (2024). Mechanical properties of a carbon fiber reinforced epoxy resin composite improved by integrating multi-walled carbon nanotubes and graphene nanoplatelets. *Journal of Composite Materials*, 58(7), 911-921. <https://doi.org/10.1177/00219983241230740>