Flexural and shear properties of CFRP laminates reinforced with functionalized multiwalled CNTs

Getahun Tefera, Glen Bright and Sarp Adali

 Discipline of Mechanical Engineering, University of KwaZulu-Natal, Durban, South Africa

ABSTRACT
This study focuses on mechanical characterization of carbon fiber reinforced polymer (CFRP) laminates reinforced with non-treated and treated multiwalled carbon nanotubes (CNTs) using nitric acid. The CNTs were treated using nitric acid to obtain carboxylic functional group. The epoxy resins are mixed with 0.3%wt of multiwalled CNTs at a constant mixing speed of 2000 rpm and mixing times varied from 24 to 96 h. Laminates reinforced with treated multiwalled CNTs show an increase in the flexural strength by 17.4 and 15.3% at mixing times of 24 and 96 h as compared to control laminates. The test results indicated that laminates reinforced with treated multiwalled CNTs have improved interlaminar shear failure stress which is 14 and 7% higher at mixing times of 24 and 96 h as compared to control specimen. Improvement in behavior was achieved for functionalized CNTs based laminates which prevents agglomeration. Longer mixing time (96 h) is not beneficial for enhancing the mechanical properties due to the break-up of small aggregates by overcoming the effect of van der Waals forces.

GRAPHICAL ABSTRACT

ARTICLE HISTORY
Received 10 June 2021
Accepted 23 July 2021

KEYWORDS
Carbon nanotubes; nanocomposites; mechanical properties; fracture properties; short beam shear; three-point bending; carbon fiber; FTIR

Introduction
Carbon fiber reinforced polymer (CFRP) composites have been extensively used as structural materials for aircraft, automotive, aeronautical and space engineering components and for wind turbine blades. Application of CFRP in these industries reduces the weight of components, thereby leading to energy savings [1]. To broaden the use of CFRP composites in many engineering applications, it is important to improve the mechanical properties of the binder material. Polymers have excellent dimensional stability, good adhesion, compatibility with most fibers, wear resistance and low cost. However, these materials have inherent brittleness and poor mechanical properties which limits their wider use. Recently, researchers have carbon nanotubes (CNTs) to reinforce polymer matrix to improve its mechanical properties [2]. Both experimental and theoretical studies indicated that CNTs have exceptional stiffness of up to 1 TPa and strength of order 100 GPa. This made CNTs an ideal reinforcing material to improve not only the mechanical properties but also thermal, magnetic and...
electrical properties of composites [3–5]. Fawad Tariq et al. [6] developed a composite material by combing carbon fabric and MWCNTs in epoxy matrix. Tensile and flexural strength were conducted to determine the effect of MWCNTs on mechanical behavior of CFRP material. Improvement in tensile and flexural strength was attributed to the micro-crack bridging effect of MWCNTs. Because of its excellent properties, CNTs can be used as ideal reinforcing agents for composite structures [7–10].

Since the discovery of CNTs in 1991 by Iijima, the material has received considerable attention for use in several applications such as superconductors, nanoelectronics, nanowires, electrochemical capacitors and nanocomposite structures [11, 12]. The properties that can be improved with the addition of CNTs include tensile modulus, tensile strength, flexural strength, interlaminar shear strength (ILSS), toughness, damping behavior and glass transition temperature [13, 14]. Achieving good dispersion and aligning of CNTs in a polymer matrix are critical concerns as well as a challenging task due to strong attractive forces leading to agglomeration and aggregation in the form of bundles [15]. These issues are main obstacles for developing high-performance polymer/CNT composites by improving the load transfer capacity of polymer/CNT interface.

Improvement in mechanical, electrical and thermal properties on composite structures has been shown by growing of CNT onto carbon fiber (CF) surface. Particularly, the interfacial adhesion between the CF and the matrix will be improved due to the presence of CNT [16]. Chemical vapor deposition (CVD) is one of the techniques used in the production of hybrid CF-CNT, which had involved the in-situ growth of the CNT on the CF surface. In this method, the CF surface used as a substrate exposed to a volatile precursor material, which react and decomposes on CF surface to form the desired CNT deposit. However, CF substrate may be contaminated by the catalysts transition metals for growth of the CNT during in-situ growth [17]. Electrospray deposition (ESD) method is used to produce uniform dispersion of non-agglomerating nano or micro-droplets, which are suitable for producing micrometer-thin or thinner layers of spray and uniform coatings into the fibers, which improved interfacial bonding in composite structures [18]. Functionalization of CNTs has been considered as a better technique to prevent agglomeration and to achieve better interfacial characteristics between CNTs and the polymer matrix. During covalent functionalization, CNTs are oxidized using acids in order to obtain hydroxyl or carboxylic groups to the end caps to form direct chemical bonding between nanotubes [19]. Chemical functionalization of CNTs is an effective way to prevent nanotubes from aggregation. This approach supports a better dispersion and stabilizes the CNTs within the polymer matrix [20, 21]. Hu et al. [22] studied the effect of curing process and mixing time on electrical properties for a mixture of polymer matrix and multiwalled CNTs. They identified the curing temperature and mixing conditions as key factors for the formation of a conducting network.

Jaemin Cha et al. [23] investigated the changes in mechanical properties of CNT/epoxy nanocomposites through functionalization of CNTs. The results indicated improvements in tensile strength, stiffness and fracture toughness with the addition of 2 wt% of functionalized CNTs. In addition, the behavior of crack propagation was studied as shown an improvement in fracture toughness.

Researchers have been using mechanical adhesion/compatibility methods to disperse the CNTs in a polymer matrix. For example, Kim et al. [24] used high-energy mechanical sonication to disperse CNTs in a polymer matrix to fabricate and characterize the behavior of CFRP epoxy composites. Sonication time has been observed as affecting the mechanical, electrical and thermal properties of the nanocomposites. Optimized sonication time maximized the CNTs dispersion, stabilization and damage minimization [25].

In another study, Gojny et al. [26] investigated the importance of surface functionalization on the mechanical performance of epoxy nanocomposites for different CNTs and noted that functionalized nanocomposites had improved strength, stiffness and fracture toughness. A sufficient stress transfer from polymer matrix to the CNTs is essential to achieve the potential of CNTs as reinforcement. The interfacial bonding between CNT and polymer matrix can be enhanced by functionalizing the CNT surface.

Almuhammadi et al. [27] worked on enhancing the delamination resistance of unidirectional CF composite laminates using functionalized MWCNTs. It was noted that the introduction of functionalized MWCNTs affected the interlaminar fracture toughness of the laminates. To improve the fracture toughness of quasi-isotropic CFRP composite laminates, Kostopoulos et al. [28] used modified MWCNTs and subjected the laminates to low-velocity impact using a drop tower. The results indicated that the inclusion of MWCNTs into the polymer matrix improved the fracture toughness under Mode I and Mode II loadings. Moreover, incorporation of MWCNTs, graphene oxide and CF into the epoxy enhanced the Modes I and II interlaminar fracture toughness [29, 30]. Double
cantilever beam (DCB) and End notched flexure (ENF) tests were conducted. The experimental results showed improvement of the interlaminar fracture toughness of the laminates.

Guo et al. [31] studied the electrical conductivity of laminated composites used in aircraft industries. They prepared butyl glycidyl ether (BGE) and MWCNTs, and then dispersed it in an epoxy resin. The mixture of MWCNT-BGE/epoxy was transferred into the interlayer of CF/epoxy composite laminates using spray techniques. The electrical conductivity of the through-thickness has improved by 283%. Additionally, authors recommended that this method of laminate preparation is important for improving the ILSS. These results indicated that functionalization of CNTs, mixing speed, curing temperature and mixing rate of polymer matrix containing multiwalled nanotubes need further research to investigate their effect on the mechanical properties of the nanocomposites and also to optimize these properties.

In this study, the improvements in short beam shear (SBS) and flexural properties of multiwalled CNTs/CF/epoxy laminates are studied experimentally as a function of constant mixing speed and variable mixing time. An epoxy resin is reinforced with modified and non-modified MWCNTs using overhead stirrer at 2000 rpm for 24 and 96 h in steps of 24 h. All laminates contain 0.3 wt% of MWCNTs with respect to the epoxy resin. ILSS, flexural strength, flexural modulus, failure strain and fracture behavior of the laminates are examined using three-point bending tests, short beam tests and scanning electron microscope (SEM). Dispersion states of MWCNTs in the polymer matrix are morphologically characterized by the Fourier transform infrared (FTIR) and transmission electron microscopy (TEM).

**Experimental**

**Materials**

The commercial unidirectional CF (Toray-300), prime 27 LV, epoxy resin and prime 27 LV slow hardener were purchased from AMT composites, South Africa (SA). The physical and mechanical properties of the materials are shown in Table 1. Commercially available multiwall CNTs (outer diameter: 10–20 nm, length: 3–8 μm, 99% purity) were purchased from Capital Lab Supplies, Cape Town, SA. Dimethylformamide (DMF) was purchased from United Scientific, Cape Town, SA. The effect of non-modified (untreated) and modified (treated) MWCNTs on the properties of CFRP composites is the subject of this work. The production process of acid-modified multiwall CNTs is described next. Five grams of multiwall CNTs were refluxed at 100 °C for 7 h in HNO3 (200 mL, 55% concentration). After cooling to the ambient temperature, the carboxylic functionalized (MWCNTs-COOH) was washed several times using distilled water until neutralization and dried in an oven at 80 °C for 12 h before use. Centrifugation at 3000 rpm for 5 min was applied for solid-liquid separation. The refluxing process is presented in Figure 1(a). Silicon oil bath was used during the refluxing process to maintain a proper heat transfer. Subsequently, the modified and non-modified MWCNTs were dispersed in 30 mL DMF and 100 mL acetone solution in a flask for 120 min and finally, the MWCNT solution was centrifuged at 2000 rpm for 5 min.

FTIR spectroscopy is the best technique to characterize the functionalities present in the structure of MWCNTs and epoxy resin. Treated and untreated MWCNTs were mixed with epoxy resin at 2000 rpm for 24, 48, 72 and 96 h to examine the chemical structures with FTIR spectrum.

**Dispersion procedures of MWCNT and preparation of laminates**

Dispersion agents were used for dispersion of non-treated and treated multiwall CNTs in the epoxy as shown in Figure 2. Treated (MWCNTs-COOH) and non-treated (MWCNTs) were prepared and drawn into a beaker to mixed with the epoxy. The epoxy was heated at 60 °C for 30 min to reduce viscosity before adding the multiwall CNTs. The non-modified MWCNTs and epoxy subjected to overhead stirrer with the rotational speed of 2000 rpm for 24, 48, 72 and 96 h. Similarly, the modified MWCNTs and epoxy were subjected to overhead stirrer at a rotational speed of 2000 rpm for 24, 48, 72 and 96 h. Later, the dispersed material was degassed for about 30 min to remove the entrapped air from the inside of the mixtures. The hardener and the epoxy were mixed using an overhead stirrer with a rotational speed of 500 rpm for about 15 min, then degassed for 10 min.

CFRP laminates were prepared using resin transfer molding (RTM) method. Fourteen layers of unidirectional carbon fabric were laid up in the unidirectional orientation considering testing standards. The epoxy material to hardener ratio was 10:2.8. The MWCNTs/epoxy mixtures were infused

| Table 1. Physical and mechanical properties of unidirectional carbon fiber and epoxy resin [32]. |
|:---:|:---:|:---:|:---:|:---:|
| Materials | Young's Modulus (GPa) | Tensile strength (MPa) | Density (kg/m³) | Poisson’s ratio |
| T-300 carbon | 230 | 3530 | 1760 | 0.30 |
| Epoxy | 3.3 | 69.9 | 1100 | 0.36 |

NanoComposites
into the CFs in vacuum during RTM process. After the MWCNTs/epoxy infusion, CFRP laminates were cured on a glass table at 25°C for 24 h, and then demoulded and post cured in an oven for 16 h at 65°C. Five laminates for each test were cut using a CNC machine with a tolerance of 0.02 mm. Laminates were cleaned and the flash was removed with sandpaper prior to testing. All of the specimens were measured, inspected for defects and placed into the test laboratory for acclimatization to testing conditions. The fiber volume fraction and thickness of the laminates considered for SBS and flexural test were 55% and 4.5 mm, respectively.

**Characterization**

SEM and FTIR analyses were conducted to study the fracture behavior and microstructure of laminates. For SEM images, all specimens were coated three times with gold sputter. TEM was used to examine the dispersion quality and distribution of treated and untreated MWCNTs in the epoxy. The
ILSS, flexural strength \((\sigma_f)\), flexural modulus \((E_f)\) and strain at failure \((\varepsilon_f)\) values were measured using a Lloyd LR test machine based on ASTM D 2344 and ASTM D7264/D7264M-07 standards [33, 34]. At least five samples were tested for SBS and flexural tests at a constant crosshead speed of 1 mm/min. The setups to characterize the laminates are shown in Figure 3. In the SBS test, the ILSS was determined based on classical (Bernoulli–Euler) beam theory. The maximum ILSS for rectangular laminate occurs at the mid-thickness and calculated to be

\[
\text{ILSS} = \frac{3P_{\text{max}}}{4bh}
\]  

(1)

where \(P_{\text{max}}\) is the maximum load and \(b\) and \(h\) are the width and thickness of the laminates. The span-to-depth ratio for the SBS test for the samples of \(L/h = 4\) was considered. The average span, width and thickness of the samples were around 18, 9.4 and 4.5 mm.

The flexural strength and strain at failure on the composite laminates can be estimated by

\[
\sigma_f = \frac{3P_{\text{max}}L}{2bh^2}
\]  

(2)

\[
\varepsilon_f = \frac{6Dh}{L^2}
\]  

(3)

where \(D\) is the deflection of the laminates. We selected a span to thickness ratio for the laminates of \(L/h = 32\). The span, width and thickness of the flexural specimens were around 145, 13 and 4.5 mm, respectively. The stiffness of the laminates was estimated from \(\sigma_f\) and \(\varepsilon_f\) values, respectively.

Results and discussion

Characteristics of treated and non-treated MWCNTs

Figure 4 shows the FTIR spectrum of non-treated MWCNTs/epoxy at different mixing times. In the case of non-treated MWCNTs, sharp peaks and weak signal at 3459 cm\(^{-1}\) corresponded to \(O-H\) stretching bands. Further, the peaks at 2971 and 2868 cm\(^{-1}\) contributed to the presence of \(C-H\) stretching vibrations. In this case, broader signals appeared. The peaks at 2134 cm\(^{-1}\) linked to the \(C=C\) stretching bands. The spectrum of non-treated MWCNTs/epoxy shows the highest intensity and sharp peaks at about 1739 cm\(^{-1}\), corresponding to \(C=O\) stretching vibration. The peaks at 1604 cm\(^{-1}\) correspond to \(C=C\) stretching bands. In all cases, the absorption bands within each functional group slightly varied as a function of the mixing times as shown in Figures 4 and 5. This indicated that mixing time might affect conducting network between each atom and may lead to more stretching [35].

The treated surface of the MWCNTs-COOH mixed with the epoxy resin was examined with FTIR spectra as shown in Figure 5. The band at 3457 cm\(^{-1}\) is related to stretching vibration of \(O-H\) groups. As can be seen from treated FTIR spectra, the stretching vibrations of \(C-H\) group appear between 2927 and 2867 cm\(^{-1}\). Sharp signal and medium intensity at 1606 cm\(^{-1}\) linked to \(C=C\) stretching vibration. The FTIR observations on treated MWCNTs confirm that the shape and signal intensity could be linked to bonding of MWCNTs-COOH with the epoxy resin. Functionalization of MWCNTs improved the bonding with functional groups and this may contribute to better behavior and interfacial strength.
Behavior of MWCNTs with respect to dispersibility in epoxy resin

Dispersing of nanotubes in a polymeric matrix is a challenging process. In order to homogeneously disperse the treated and non-treated MWCNTs in the epoxy, high sonication and stirring times, including a large energy input, are needed to reduce the van der Waals forces of attraction between the nanotubes [26]. High energy due to sonication may cause reduction in the effective length and may also cause damage to the nanotube structures. In this study, we use the same sonication methods for treated and non-treated multiwall CNTs, but different stirring times to disperse epoxy evenly. TEM is used to characterize the distribution of treated and non-treated multiwall CNTs within the matrix. TEM images of non-treated MWCNT/epoxy are shown in Figure 6(a–d). As it can be seen from Figure 6(a–c), MWCNTs in epoxy have a low dispersibility. The figures indicate a high level of agglomeration of multiwall CNTs. This may have occurred due to strong forces of attraction between MWCNTs. The dispersion of multiwall CNTs is observed to be slightly better in Figure 6(d). This may be due to the higher stirring time.

TEM images of the treated MWCNTs/epoxy are shown in Figure 7(a–d). Functionalization of MWCNTs leads to an improved mixing with the matrix. As shown in Figure 7, better dispersion is obtained on treated MWCNTs/epoxy as a function of the stirring times. This may be due to better bonding of MWCNTs-COOH/epoxy which leads to better-conducting networks. The levels of dispersion using sonication and using overhead stirring methods varied the dispersibility of treated multiwall CNTs as a function of the mixing rate. As shown in the TEM images (Figure 7), the dispersion and nanotube damage (Figure 7(d)) increased as the mixing time increased.
Short beam shear (SBS) test

The variation of apparent ILSS for CFRP, untreated MWCNTs-CFRP and treated MWCNTs-CFRP laminates at different stirring times is shown in Figure 8 and Table 2. The ILSS of the control laminate is 58.7 MPa. Addition of MWCNTs to epoxy improves the matrix-dominated behavior of the material. For the case of untreated MWCNTs-CFRP, the ILSS remains the same at 61.9 MPa with stirring times of 24 and 96 h. However, the ILSS of treated MWCNTs-CFRP increases to 66.7 and 62.8 MPa at the specified stirring times. The maximum increase in ILSS was obtained for treated MWCNTs-CFRP laminates as compared to the other cases. The change of ILSS with CFRP laminates was about 14 and 7%. The ILSS of treated MWCNTs-CFRP show increases of 8 and 2% as compared to untreated MWCNTs-CFRP laminates at stirring times of 24 and 96 h. As indicated by the experimental results, incorporation of MWCNTs into the epoxy matrix improved the ILSS of the laminates. However, the ILSS of the laminates decreased with stirring time. This may be due to nanotube damage and loss of nanotube network formation. In this study, the optimal stirring time is specified as 24 h.

Three-point bending test

For a span-to-depth ratio of $L/h = 32$, the stress-strain plots of control CFRP, untreated MWCNTs-
CFRP and treated MWCNTs-CFRP laminates are shown in Figure 9. The effect of the incorporation of MWCNTs on flexural properties of unidirectional CFRP laminates can be observed in Table 2. CFs have high strength and stiffness but low strain properties as compared to glass fibers [36]. After the incorporation of MWCNTs into the epoxy matrix, the strain properties of MWCNTs-CFRP laminates improve by about 21.6% compared to control CFRP laminates. Thus, reinforcing by multiwalled

Figure 7. TEM images of treated MWCNTs at stirring times of 24 h (a), 48 h (b), 78 h (c) and 96 h (d).

Figure 8. ILSS with deflection of CE, non-treated MWCNTs-CE and treated MWCNTs-CE laminates at different stirring time.
nanotubes provides another way of improving the failure strain of CFRP polymers.

The flexural strength and modulus properties of control CE, non-treated and treated MWCNTs laminates at different stirring times are shown in Figure 10. The flexural strength and modulus of the control CFRP laminates are 807.8 MPa and 109.2 GPa. In the case of untreated MWCNTs-CFRP, the flexural strengths remain the same at around 839 MPa. While the flexural stiffnesses are reduced to 93.1 and 98.8 GPa at stirring times of 24 and 96 h. The flexural strengths of treated MWCNTs-CFRP laminate are about 948 and 931 MPa at the specified stirring times. However, the stiffnesses of the laminates are reduced to 105.3 and 108.3 GPa. The highest increase in flexural strength was obtained for treated MWCNTs-CFRP laminates as compared to other laminates. Comparing control CFRP to non-treated MWCNTs-CFRP laminates, the flexural strength decreased by 3.7 and 3.9% at stirring times of 24 and 96 h. In the case of treated MWCNTs laminates, the flexural strength increased by 17.4 and 15.3% as compared to control CE laminates.

The incorporation of MWCNTs in glass fiber/epoxy matrix improved the strength and the failure strain of composite laminates as noted in [37]. These results validate the strength and the failure strain behavior of laminates after the incorporation of MWCNTs. The flexural moduli of untreated

| Sample       | ILSS (MPa) | Flexural strength (MPa) | Strain (%) | Flexural modulus (GPa) |
|--------------|------------|-------------------------|------------|------------------------|
| Control      | 58.7       | 807.8                   | 0.74       | 109.2                  |
| Treated (24 h) | 66.7     | 948.0                   | 0.90       | 105.3                  |
| Untreated (24 h) | 61.9    | 839.9                   | 0.85       | 98.8                   |
| Untreated (96 h) | 61.9    | 839.9                   | 0.85       | 98.8                   |
| Treated (96 h) | 62.8     | 931.0                   | 0.86       | 108.3                  |

Figure 9. Stress versus strain curves from bend test.

Figure 10. Average flexural strength and modulus of control CE, non-treated and treated MWCNTs composite laminates.
MWCNTs-CFRP are reduced by 17.3 and 10.5% as compared to control CFRP laminates at the specified stirring times. For the case of treated MWCNTs-CFRP laminates, the flexural modulus is slightly reduced by 3.6 and 0.8% as compared to control CFRP laminates. As observed in this study, the mechanical properties of treated and untreated laminates vary depending on the stirring times. All results indicate improved mechanical behavior at a stirring time of 24 h rather than 96 h. These results indicate that MWCNTs can be damaged and are better dispersed as the stirring time increases. Stirring time of MWCNTs at 24 h is the preferred time to enhance the behavior of nanocomposite material.

**Fracture behavior of the laminates**

Common failure modes for FRP laminates under flexural loading include compressive and tensile failures, and delamination. The compressive failure is common and dominant failure mode for FRP composites [38]. On the other hand, delamination failure is the dominant mode in the case of SBS tests. Addition of MWCNTs to the epoxy can contribute to improved material properties and increase the toughening and strengthening at nanoscale which can affect the failure modes.

Next, after conducting three-point bending and SBS tests, failure modes of control and treated MWCNTs-CFRP laminates are studied using SEM images. SEM images of control and treated MWCNTs-CFRP laminates after failure under SBS test are shown in Figure 11. From Figure 11(a), it can be seen that longitudinal delamination between fibers and rupture of epoxy matrix occurs in the case of the control laminate. In the case of treated MWCNT-CFRP laminate (Figure 11(b)), voids with discontinuous cracks are observed. Discontinuous cracks may have happened due to the incorporation of treated MWCNTs in the epoxy matrix which can lead to changes in ILSS properties between the layers.

SEM images of control and treated MWCNTs-CFRP laminates after failure under three-point bending test are shown in Figure 12. The cross-sectional image of the fracture surface in Figure 12(a) shows that a straight crack propagation can be observed in the case of the control laminate. Intermittent voids and cracks were detected in the case of treated MWCNTs-CFRP laminates (Figure 12(b)). This may have happened due to the improvement in the bonding strength between the fibers and the epoxy matrix as a result of addition of MWCNTs to the epoxy matrix.

**Conclusions**

Properties of CNT-based composites are important in many fields of engineering. This work presents a study on flexural and shear properties of untreated and treated MWCNTs-CFRP with a control CFRP composite laminates. The mechanical properties are studied using three-point bending and SBS tests with the flexural strength, modulus and strain of the test specimens compared to assess the effect of MWCNT reinforcement. The test specimens were prepared with the incorporation of CFs into a multiwall CNTs reinforced epoxy matrix. The epoxy resin was modified with 0.3% wt of multiwalled CNTs at a mixing speed of 2000 rpm and at mixing times of 24, 48, 72 and 96 h. MWCNT/epoxy was infused into unidirectional carbon fabric using RTM process. Based on the test results of the nanotube enhanced laminates and control CFRP laminates,
the following observations and conclusions can be drawn:

1. Higher flexural strength is obtained for laminates reinforced with treated MWCNTs with an increase of 17.4 and 15.3% at stirring times of 24 and 96 h as compared to the control. The lower flexural strength corresponding to the stirring time of 96 h might be due to reduced nanotube network formation.

2. The incorporation of MWCNTs improves the failure strain, but slightly lowers the stiffness of the laminates due to the inverse relation with strain. In the case of laminates reinforced with treated MWCNTs-CFRP, the flexural modulus is reduced by 3.6 and 0.8% as compared to control corresponding to the stirring times of 24 and 96 h.

3. Higher ILSS was obtained for laminates reinforced with treated MWCNTs-CFRP as compared to the other cases. The change in ILSS as compared to the control was observed to be an increase of 13.7 and 7% corresponding to the stirring times of 24 and 96 h.

4. Addition of MWCNTs to the epoxy matrix can contribute toward the toughening and strengthening at nanoscale resulting at interrupted cracks and voids.

5. All results indicate an optimal behavior at a stirring time of 24 h as compared to 96 h. MWCNTs can be damaged as the stirring times increase. In this study, a stirring time of 24 h is the preferred time to optimize the behavior of nanocomposite laminates.

Disclosure statement
The authors declare that they have no conflict of interest.

Notes on contributors
Getahun Tefera (PhD):
Postdoctoral fellow: Discipline of Mechanical Engineering, University of KwaZulu-Natal, Durban, South Africa.
Research interest: Research on composite wind turbine blade structural design and optimization of structures using nanocomposite.
Contribution of the Author for this paper: experimental setups, experimental work, writing the draft manuscript.

Glen Bright (Professor):
Dean and senior lecturer: Discipline of Mechanical Engineering, University of KwaZulu-Natal, Durban, South Africa.
Research interest: Mechatronics, Robotics, Advanced Manufacturing Systems and composite and nanocomposite research areas.
Contribution of the Author for this paper: writing the draft manuscript, guiding the experimental setups and editing the paper.

Sarp Adali (Professor):
Senior lecturer: Discipline of Mechanical Engineering, University of KwaZulu-Natal, Durban, South Africa.
Research interest: working on the design of composite structures, theoretical and computational design of structural materials and experimental characterization of nanocomposites applicable for different structures.
Contribution of the Author for this paper: writing the draft manuscript, guiding and supporting the experimental setups and editing the paper.

References
1. Arai M, Matsushita K, Hirota S. Criterion for interlaminar strength of CFRP laminates toughened with...
15. Zakaria MR, Akil HM, Omar MF, et al. Enhancement of mechanical and thermal properties of carbon fiber epoxy composite laminates reinforced with carbon nanotubes interlayer using electrospray deposition. Compos C Open Access. 2020;3:100075.

16. Cha J, Jin S, Shim JH, et al. Functionalization of carbon nanotubes for fabrication of CNT/epoxy nanocomposites. Mater Des. 2016;95:1–8.

17. Singh BP, Singh D, Mathur RB, et al. Influence of surface modified MWCNTs on the mechanical, electrical and thermal properties of polyyimide nanocomposites. Nanoscale Res Lett. 2008;3(11):444–453.

18. Dittrich B, Wartig K-A, Mühlaupt R, et al. Flame-Retardancy properties of intumescent ammonium poly(phosphate) and mineral filler magnesium hydroxide in combination with graphene. Polymers. 2014;6(11):2875–2895.

19. Hu N, Masuda Z, Yamamoto G, et al. Effect of fabrication process on electrical properties of polymer/multiwall carbon nanotube nanocomposites. Compos A Appl Sci Manuf. 2008;39(5):893–903.

20. Cha J, Jun GH, Park JK, et al. Improvement of modulus, strength and fracture toughness of CNT/epoxy nanocomposites through the functionalization of carbon nanotubes. Compos B Eng. 2017;129:169–179.

21. Kim M, Bin Park Y, Okoli OI, et al. Processing, characterization, and modeling of carbon nanotube-reinforced multiscale composites. Compos Sci Technol. 2009;69(3–4):335–342.

22. Song YS, Youn JR. Influence of dispersion states of carbon nanotubes on physical properties of epoxy nanocomposites. Carbon. 2005;43(7):1378–1385.

23. Gojny FH, Wichmann MHG, Fiedler B, et al. Influence of different carbon nanotubes on the mechanical properties of epoxy matrix composites - A comparative study. Compos Sci Technol. 2005;65(15–16):2300–2313.

24. Almuhammadi K, Alfano M, Yang Y, et al. Analysis of interlaminar fracture toughness and damage mechanisms in composite laminates reinforced with sprayed multiwalled carbon nanotubes. Mater Des. 2014;53:921–927.

25. Kostopoulos V, Baltopoulos A, Karapappas P, et al. Impact and after-impact properties of carbon fibre reinforced composites enhanced with multiwalled carbon nanotubes. Compos Sci Technol. 2010;70(4):553–563.

26. Rodríguez-González JA, Rubio-González C, Jiménez-Mora M, et al. Influence of the hybrid combination of multiwalled carbon nanotubes and graphene oxide on interlaminar mechanical properties of carbon fiber/epoxy laminates. Appl Compos Mater. 2018;25(5):1115–1131.

27. Lyashenko-Miller T, Fitoussi J, Marom G. The loading rate effect on mode II fracture toughness of composites interleaved with CNT. Nanocomposites. 2016;2(1):1–7.

28. Guo J, Zhang Q, Gao L, et al. Significantly improved electrical and interlaminar mechanical properties of carbon fiber laminated composites by using special carbon nanotube pre-dispersion mixture. Compos A Appl Sci Manuf. 2017;95:294–303.

29. Aklilu G, Adali S, Bright G. Experimental characterization of hybrid and non-hybrid polymer composites at elevated temperatures. Int J Eng Res Africa. 2018;36:37–52.
33. Standard testing manual: ASTM D2344/D2344M. Standard test method for Short-Beam strength of polymer matrix composite materials and their laminates. ASTM Stand. 2003. p. 136–140.

34. Standard testing manual: ASTM D7264/D7264M-07. Standard test method for flexural properties of polymer matrix composite materials. ASTM Stand. 2007. p. 1–11.

35. Martin CA, Sandler JKW, Shaffer MSP, et al. Formation of percolating networks in multi-wall carbon nanotube–epoxy composites. Compos Sci Technol. 2004;64(15):2309–2316.

36. Khatri SC, Koczak MJ. Thick-section AS4-graphite/E-glass/PPS hybrid composites: part I. tensile behavior. Compos Sci Technol. 1996;56(2):181–192.

37. Rathore DK, Prusty RK, Kumar DS, et al. Mechanical performance of CNT-filled glass fiber/epoxy composite in-situ elevated temperature environments emphasizing the role of CNT content. Compos A Appl Sci Manuf. 2016;84:364–376.

38. Dong C, Davies IJ. Effect of stacking sequence on the flexural properties of carbon and glass fibre-reinforced hybrid composites. Adv Compos Hybrid Mater. 2018;1(3):530–540.