Fabrication and characterization of epoxy modified with 0.5% MWCNTs

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Abstract
In the present work, tensile, shear and impact properties of epoxy modified with multi-walled carbon nanotubes (MWCNTs) are measured experimentally in accordance with ASTM standards.The MWCNTs were dispersed into the epoxy resin using ultrasonic processor. To avoid damaging the nanotubes, the sonication process was performed at low-amplitude (225W) in a short duration of 30 min. The mixture was evacuated to remove air bubbles before further mixing with hardener. Results from the experimental study showed that incorporation of the MWCNTs into the epoxy resin improves the tensile strength and modulus of the MWCNT-nanocomposite by 11% and 68.7%, respectively, compared with those of the neat epoxy. The shear strength and in-plane shear modulus of the MWCNT-nanocomposite were improved by 22.2% and 29%, respectively. The drop weight impact performance of the MWCNT-nanocomposite showed an improvement in the maximum contact force and the absorbed energy of the MWCNT-nanocomposite by 9.5% and 11.4%, respectively.

I. INTRODUCTION

One of the important limiting factors for the use of multi-walled carbon nanotubes (MWCNTs) in modifying the epoxy resin is their agglomeration and poor distribution/dispersion especially at high concentrations. The van der Waals attractive interactions owing to high aspect ratio of MWCNTs leads to agglomeration in the form of bundles or ropes[1] with highly entangled network structures, which are very difficult to disperse. Hence, in the present study, the sonication parameters were carefully selected to minimize the agglomeration of MWCNTs in the epoxy resin. Moderate loading percentage of MWCNTs can result in good dispersion as well as lower agglomeration. Accordingly, based on the extensive literature survey, a 0.5 wt% MWCNTs was selected that showed improvements in the mechanical properties for different epoxy systems by many researchers[2-11].

Sonication parameters can play a vital role in the dispersion of nanomaterials in polymer resin. The most important parameters include viscosity of the polymer resin, type of nanomaterials, temperature control, cooling medium (air, water, water/ice), beaker material and dimensions, immersion depth of the sonicator probe, sonicator probe diameter, sonication mode (pulse or continuous) sonication power and amplitude, sonication time and sonication energy densities (W•s/ml)[7]. Sonication of carbon nanotubes (CNTs) can lead to defects

on the walls and the ends of the CNTs and even cutting the nanotubes[12-14]. To avoid damaging of carbon nanotubes (CNTs), the sonication time should be in the range of 20 to 30 min as recommended by Hu *et al.*[12]. Therefore, in this study the sonication process was performed at low-amplitude (225W) in a short duration of 30 min.

Jen and Wang[2] reported that the static strength was slightly decreased due to agglomeration of the CNTs when the CNT exceeds 0.5wt%. Mactabi *et al.*[3] reported that the 0.5wt% MWCNTs has the highest improvement in the average shear strength of the single lap joint compared with neat and 1.0wt% MWCNTs. Khashaba *et al.*[7] found that the nanocomposite with 0.5wt% of MWCNTs has the maximum tensile properties compared with that have weight percentages of 0.25wt%, 0.75wt% and 1.00wt% MWCNTs. The good dispersion of 0.5wt% MWCNTs in epoxy adhesive was result in high improvements in the mechanical properties of scarf adhesive joint in carbon fiber composites, as reported by Khashaba *et al.*[8,11].

The well-dispersed nanofillers in epoxy resin can act as a physical cross-links for the molecular chains[15,16] that leads to an improvement in the interfacial properties. For the CNT-nanocomposites, it is expected that part of the applied load can be transferred from the weak matrix to the nanofillers with higher mechanical properties (predicted tensile strengths of 100 GPa and elastic modulus of up to 1 TPa[17]), and thus improving the mechanical properties

of the nanocomposites. The very low volume (or weight) fractions of the CNTs (for reducing the agglomeration effects) as well as their short-length are the limiting factors for the achievable structural components with high mechanical properties.

The increased stiffness of the modified epoxy with MWCNTs has different effects on the other mechanical properties such as absorbed energy. Therefore, any selection of material characteristics for optimal impact energy should consider the other mechanical properties. Accordingly, the main objective in the present study is to investigate the effects of MWCNTs infusion into epoxy resin on the tensile, shear and impact properties, grouped in one article. The MWCNTs was dispersed using sonication technique. The sonication parameters were carefully selected to minimize the agglomeration as well as the damage of MWCNTs. A series of ASTM

tests was performed to characterize the tensile, in-plane shear and impact properties of the fabricated MWCNT-nanocomposites and the results were compared with those of the neat epoxy.

2. Experimental Work

2.1. Materials

The used epoxy consists of two parts, which are: epoxy part-A (Araldite PY 1092–1) and epoxy part-B (Hardener HY 1092). The weight mixing ratio is 100:45 respectively. The epoxy system was developed by Huntsman Advanced Materials, Americas for manufacturing FRP composites for structural engineering. The MWCNTswere manufactured by Timesnano, Chengdu Organic Chemicals using Chemical Vapor Deposition technique. The physical properties of the epoxy resin as well as MWCNTs are shown in Table 1.

Table 1: Typical properties of the constituent materials of the MWCNT-nanocomposite

Materials	Properties
Epoxy resin	• Viscosity of PY 1092–1/ HY 1092 epoxy system is 300 mPa. sat 25ºC • Density of epoxy system is 1.1034 g/cm³.
Non-functionalized Multi-Walled Carbon Nanotubes (MWCNTs)	• Length ≈30 μm • Inner diameter 2-5 nm • Outer diameter < 8 nm • Density = 2.1 g/cm³ • Purity > 95 wt%

2.2. Preparation of Neat Epoxy Panels

Glass mold with dimensions of 350 mm x 350 mm was used to fabricate the neat epoxy panels. Four glass strips with dimensions of 6 mm thickness, 10 mm width and 340 mm length were bonded by silicon rubber on the four edges of the glass plate to prevent sealing the epoxy from the mold. The glass mold was treated by liquid wax to prevent sticking the epoxy panel with glass mold. The wax was dry up within 4-5 minutes. To obtain epoxy panel with constant thickness, the mold was adjusted horizontally using three leveling water balances as shown in Fig. 1a.

Epoxy part B was added gradually to epoxy part A and manually stirred for 10 min[18]. The epoxy was poured into waxed glass mold box, which positioned in a horizontal plane using three leveling water balances as shown in Fig. 1a. The high surface area of the mold and low viscosity of the epoxy allow trapped air voids to escape from mold. Then, the mold was cured at room temperature for 21 days. The four glass strips that were bonded on the mold edges are removed by shearing the silicon layer by sharp cutter. Now, it is easy to remove the epoxy panel from the glass mold as shown in Fig. 1b. The thickness of the fabricated neat epoxy panels was ≈4.25 mm.
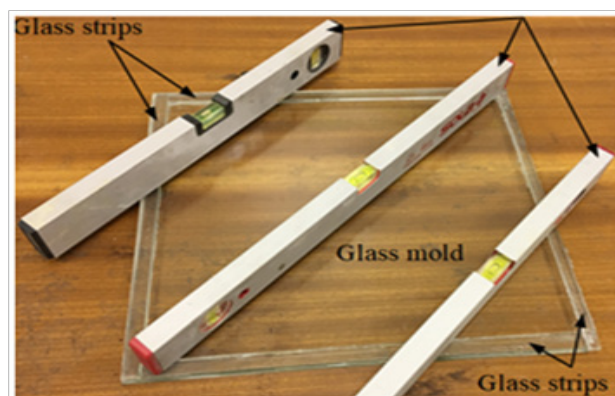

Fig. 1: Fabrication of neat epoxy panel: (a) Glass mold treated by liquid wax, and (b) The fabricated panel

2.3. Fabrication of MWCNT-Nanocomposite

2.3.1. Determination the mass of MWCNTs and epoxy

Because MWCNTs have large aspect ratio (length/diameter), they tend to aggregate and form bundles or ropes, usually with highly entangled network structure, which significantly limits their dispersion in the epoxy resin. Agglomerations of MWCNTs reduce the interfacial area in the nanocomposites, and hence reduce the opportunity to take the advantage of the unique properties of the MWCNTs[19]. Based on the extensive literature survey, a 0.5wt% MWCNTs was selected, which showed improvements in the mechanical properties for different epoxy systems by many researchers[2-11]. The mass of the MWCNTs was estimated based on the total mass of PY 1092–1/HY 1092 epoxy system using digital balance with sensitivity of 0.0001 g.

2.3.2. Manual stirring

The 0.5wt% MWCNTs (2.76 g) is mixed manually in 552 g (500 cm^3) epoxy part-A by adding them little by little during the manual stirring of the epoxy. The manual stirring of MWCNT/epoxy mixture is continued up to 5 min before the sonication process to avoid the agglomeration.

2.3.3. Sonication of MWCNTs/Epoxy Mixture

The MWCNTs were dispersed in epoxy part-A (PY 1092–1) using Ultrasonic Processor (model Cole–Parmer 750W). The dispersion of MWCNTs is more difficult in a viscous medium, due to the sharp increase of the polymer viscosity with increasing the nanofiller loading percentage[20]. Accordingly, the following sonication parameters were carefully selected from the literature review:

• The MWCNTs-epoxy mixture is powered into aluminum beaker of 80 mm diameter. The generated heat during the sonication process was dissipated through the high thermal conductivities aluminum beaker, which subjected to water-cooling bath. The small diameter of the aluminum beaker maximizes the contact surface area of the mixture with the beaker wall as well as with sonicator probe, which increases the dissipation of the heat and improves the dispersion of the MWCNTs in the epoxy resin.

• The Cole–Parmer Ultrasonic Processor was supplied with two sonicator probe of 12.5 mm and 25 mm diameter. The sonicator probe with larger diameter was selected to provide energy released over a greater area[20, 21]. It was positioned at the center of the beaker and immersed to a depth of 50 mm (keeping a gap of 20 mm with the beaker bottom). Large probe immersion depth increases the mixture surface area that was exposed to the acoustic waves and thus improves the dispersion of the MWCNTs in the epoxy resin.

• The sonication temperature of the mixture was kept less than or equal to 50⁰C via the temperature probe, which is clamped at a distance of 1 cm away from the sonicator probe. The sonication process stops and restarts automatically for temperatures higher and lower than 50⁰C, respectively.

• The sonication amplitude (input power into the mixture) is an important parameter in dispersion of MWCNTs into the epoxy resin. The increased viscosity of the epoxy owing to infusion of MWCNTs can dampen the cavitation process. The literature on the sonication parameters of CNTs showed that the sonication process can damage nanotubes by causing defects on their ends, walls and even cutting the tubes as reported by Hu *et al.*[12]. They recommended that the sonication time should be much shorter. Therefore, to avoid damaging of MWCNTs, a 30% sonication amplitude (=30x750/100 = 225 W) was implemented for 30 min to disperse them into the epoxy resin. Thus, the estimated energy densities during the sonication of MWCNTs mixture was 810 W•s/ml.

• The sonication of MWCNT/epoxy mixture was performed in pulsed mode with 15 s on and 30 s off to delay the rate of temperature increase and thus provide a better temperature control compared with continuous mode process.

2.3.4. Removing Bubbles from the MWCNT-Epoxy Mixture using Drying Vacuum Oven

The developed cavitation bubbles during the sonication processes are cyclically growing until they attain a critical diameter that induces implosive collapse[20,22] accompanied with splitting up the agglomerated nanofillers. The shock waves from the implosive collapse of the bubbles. The micro-streaming generated by cavitation oscillations leads to dispersion effects. Thus, the sonication process greatly contributes to the removal of air bubbles for the mixture.

To complete removing of the trapped bubbles, the sonicated mixture is placed in vacuum drying oven Model DZF-6050 at 133 Pa. The increased viscosity of nanophased epoxy (especially with high nanofiller loading percentage) prevents the bubbles from escape even under vacuum conditions. Therefore, it is essential to apply heating to the nanophased epoxy during evacuation processes. For this purpose, vacuum drying oven was used as following:

• The nanophased epoxy (500 cm^3) was kept in a wide glass beaker with 5000 cm^3. Therefore, the height of the epoxy in this baker is less than 1/10 its total height (of 500 cm^3 beaker). This will maximize the mixture surface area, and accordingly allow the bubbles to escape freely.

• The wide container is then placed into an oven that has been pre-heated to 40⁰C for approximately thirty minutes [23].

• The bubbles can be easily observed visually accumulated on the surface of the nanophased epoxy. Most of the bubbles are not collapsed owing to their high surface tension.

Applying vacuum of 133 Pa for 30 min can easily remove all the observed bubbles on the surface and that inside the mixture.

2.3.5. Mixing the MWCNT/epoxy-A with Epoxy Part-B and pouring into waxed mold

Before adding epoxy part-B to MWCNT, epoxy-Ait

should be cooled at the room temperature. This because raising the evacuation temperature of epoxy to 40°C can act as a catalyst and speed up the cure. The mixture (MWCNT/epoxy-A) is manually stirred using wooden strip and the hardener (epoxy part-B) is added drop by drop, while the stirring is continued up to about 5 min[18]. The MWCNT-nanocomposite panels with thickness of ≈4.6 mm are prepared by pouring the nanophased epoxy into glass mold (350 mm x 350 mm) that treated by liquid wax.

2.3.6. Cutting the test specimens

The test specimens were cut according to the ASTMs dimensions using CNC abrasive water jet machine. The main advantage of the abrasive water jet cutting process is the eliminating of generated temperature that accompanied with conventional cutting operations. The generated temperature can soften and/or burn the matrix that re-solidified after cooling. Re-solidifying of the cut zone in the polymer specimens is always accompanied with high stress concentration, which can leads to premature failure under mechanical loads of the testing machines.

2.4. Mechanical testing
2.4.1. Tension tests

The tensile properties of the NE and the MWCNT-nanocomposite were determined according to ASTM D 638. The test specimens were cut to the dimensions shown in Fig. 2, ASTM D 638. Images of the machined NE and MWCNT-nanocomposite tensile specimens were illustrated in Fig. 3. The tensile tests were performed on servohydraulic universal testing machine (Instron 8872, 10 kN) at ambient laboratory environment. The capacity of the selected testing machine is very suitable for testing neat epoxy as well as MWCNT-nanocomposite. The longitudinal strain was recorded during the tensile test using Extensometer (Instron 2620-601) with gauge length of 50 mm, as shown in Fig. 4. At least, four test specimens were tested, for each material type, at constant cross–head speed of 1.0 mm/min. The ultimate tensile strength (σ) was calculated by dividing the ultimate tensile load P_{ult} by the cross-section area (A) ; while, true modulus (E_T) was estimated from the slope of the initial linear region of the stress-strain curve.
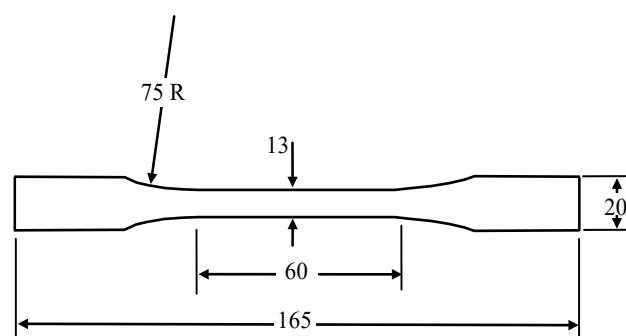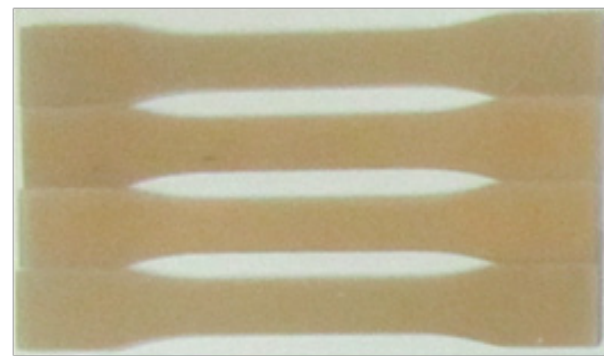

(a) Neat epoxy (NE)

(b) MWCNT-nanocomposite

Fig. 3: Tensile specimens: (a) Neat epoxy, and (b) MWCNT-nanocomposite

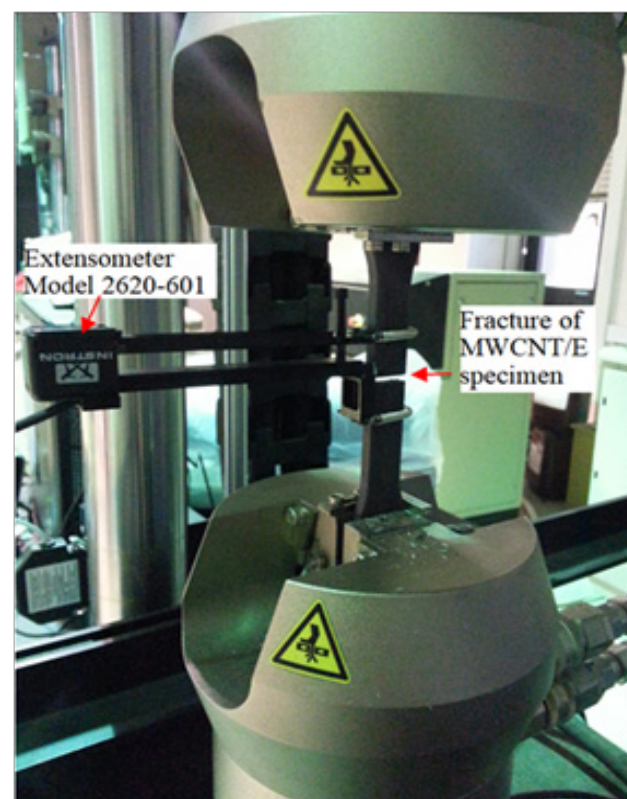**Fig. 2:** Dimensions of tensile specimens, ASTM D 638

Fig. 4: Experimental setup for tension tests

2.4.2. In-Plane shear tests

In-plane shear tests were carried out on neat epoxy and MWCNT-nanocomposite using double V-notch specimens, and Iosipescu shear test fixture according to ASTM D5379 as shown in Figs. 5 and 6. The dimensions of the test specimen are indicated in Fig. 5a. At least five double V-notches specimens were cut for both NE and MWCNT-nanocomposite. For each material type, four specimens were instrumented with $\pm 45^\circ$ strain gauges to measure the shear strain (γ_{xy}), and thus shear modulus (G_{xy}), Fig. 5b. The strains were acquired via 4-channels Data Acquisition (Model 9237 NI), which were connected to a computer. The test specimens were loaded in shear via the Iosipescu shear test fixture using a universal testing machine (model Instron Model 8872) according to ASTM D5379, see Fig. 7.

(a)

(b)
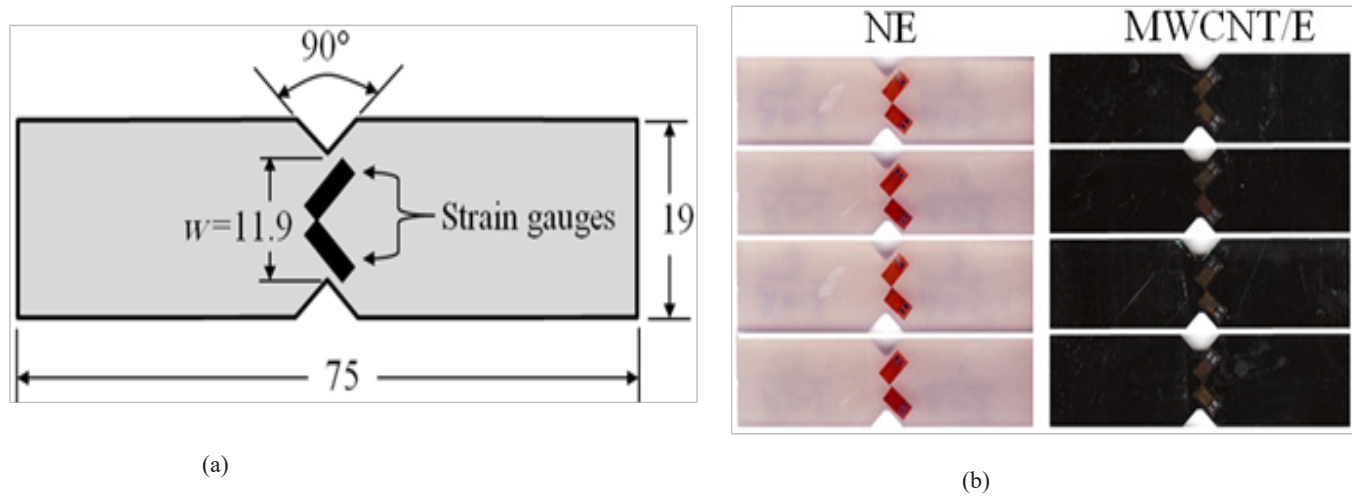
Fig. 5: Shear test specimens: (a) Dimensions, and (b) images of the double V-notches specimens
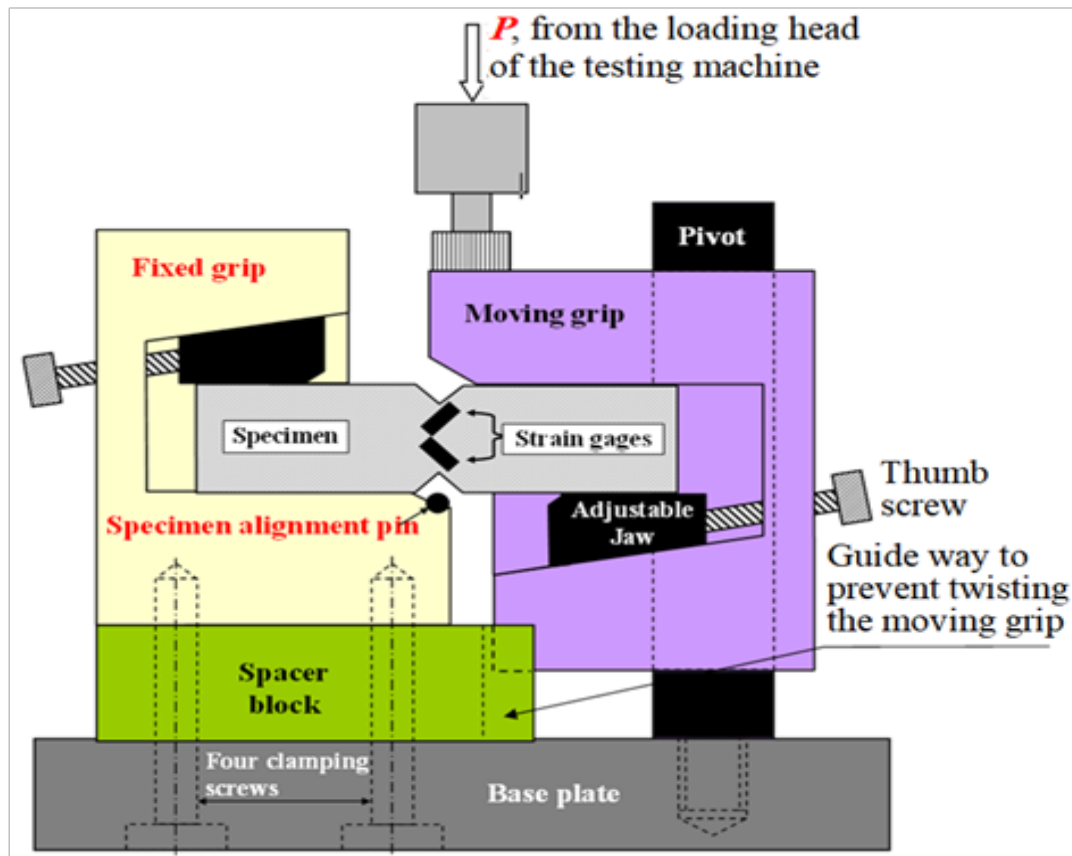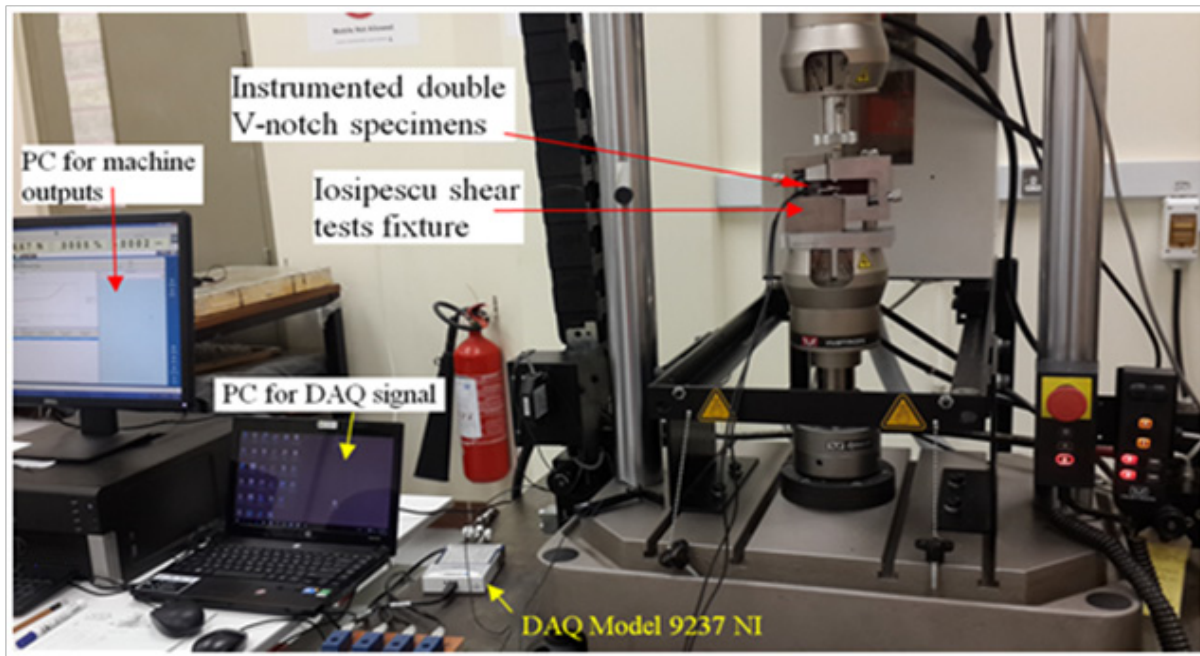

Fig. 6: Iosipescu shear tests fixture

Fig. 7: Instron testing machine Model 8872 with in-plane shear test setup

The principle of the Iosipescu shear test is to apply a displacement, with a constant rate of 1 mm/min, on the double V-notch specimen via the movable grip, which results in constant shear force and pure shear stress (zero bending moment)[24,25] at the central region of the specimen. The in-plane shear strength (γ_{xy}) was calculated from the following equation:

$$\tau_{xy} = \frac{P}{A} \qquad (1)$$

where P is the ultimate load, and A is the cross-sectional area between the roots of the two V-notches.

The in-plane shear modulus (G_{xy}) was estimated from the slope of the initial linear region of shear stress vs shear strain curves $(\Delta\tau_{xy}/\Delta\gamma_{xy})$ as:

$$G_{xy} = \frac{\Delta\tau_{xy}}{\Delta\gamma_{xy}} \qquad (2)$$

Where γ_{xy} the in-plane shear strain, which was estimatedas follows[25]:

$$\gamma_{xy} = \varepsilon_{-45} - \varepsilon_{+45} \qquad (3)$$

Where ε_{-45} and ε_{+45} are the measured strains of the -45° and +45° strain gauges, respectively.

2.4.3. Impact Tests

Drop mass impact tests were performed in accordance with ASTM D 7136 using instrumented falling weight impact tester (model CEAST 9340) as shown in Fig. 8a. Three specimens were cut for both NE and MWCNT-nanocomposites to dimensions of 101.6 x 152.4 ± 0.1 mm, ASTM D 7136. The specimen was fixed inside thermal conditioning chamber on a steel plate with rectangular window of 75 x 125 mm using four clamps, Fig. 8b. All the impact tests were performed at impact energy of 20 J and total mass (m_T) of 12.632 kg, which equal the sum of tup holder mass of 2.5 kg, tup mass of 0.632 kg, and the additional mass of 9.5 kg. From Eq. (4), the software of the testing machine estimates the impactor height (H = 0.161 m) and the initial impact velocity (v = 1.779 m/s) using Eq. (5), with acceleration due to gravity of 9.81 m/S².

$$H = \frac{E}{m_T g} \qquad (4)$$
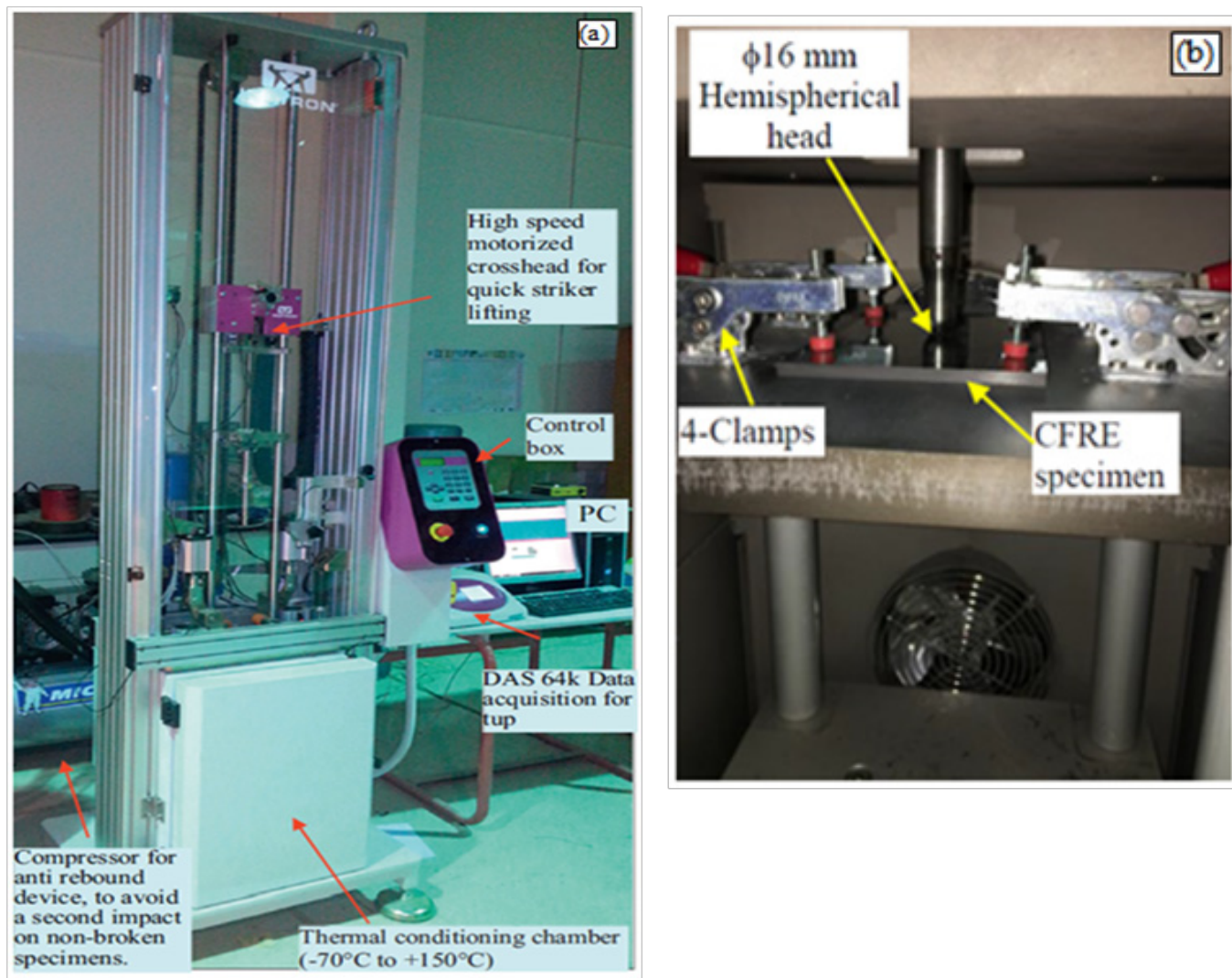
$$v = \sqrt{2gH} \qquad (5)$$

Fig. 8: Impact test machine (a) falling weight impact tester, and (b) thermal conditioning chamber showing specimen fixtures.

The results of the CEAST 9340 falling weight impact tester can be obtained directly on the PC monitor as well as saved in XLS sheet to establish the following relationships: force-time/displacement relationships, energy-time/displacement relationships and peak points.

3. Results and discussions
3.1. Tension Test Results

Fig. 9 a and b shows the tensile stress-strain curves of neat epoxy (NE) and MWCNT-nanocomposite, respectively. The stress-strain curves typically behave almost linearly, followed by nonlinear plastic behavior. The true Young's modulus of NE and MWCNT-nanocomposite were estimated from the slope of the initial linear region of the stress-strain curves. Fig. 10 shows images of some fractured specimens, which indicates that the failure occurred in the gauge length typically, as

specified by the ASTM D 638.

Figs. 11 and 12 show comparison between the average tensile strength and modulus of both NE and MWCNT-nanocomposite, respectively. The results in Fig. 11 showed that the improvement percentage in the tensile strength of the MWCNT-nanocomposite is 11% compared with neat epoxy (NE). The results in Fig. 12 showed that the improvement percentage in the true tensile modulus of the MWCNT-nanocomposite is 68.7% compared with neat epoxy (NE). The well dispersed MWCNTs in epoxy resin act as physical cross–links for the epoxy molecular chains[15,16] that leads to an improvement in the interfacial bonding between them. Hence, the applied mechanical loads can be effectively transferred from the weak matrix to the high strength (100 GPa) and high modulus (1 TPa) CNTs[17], which played an important role in improving the tensile properties (strength and modulus) of the nanocomposite.
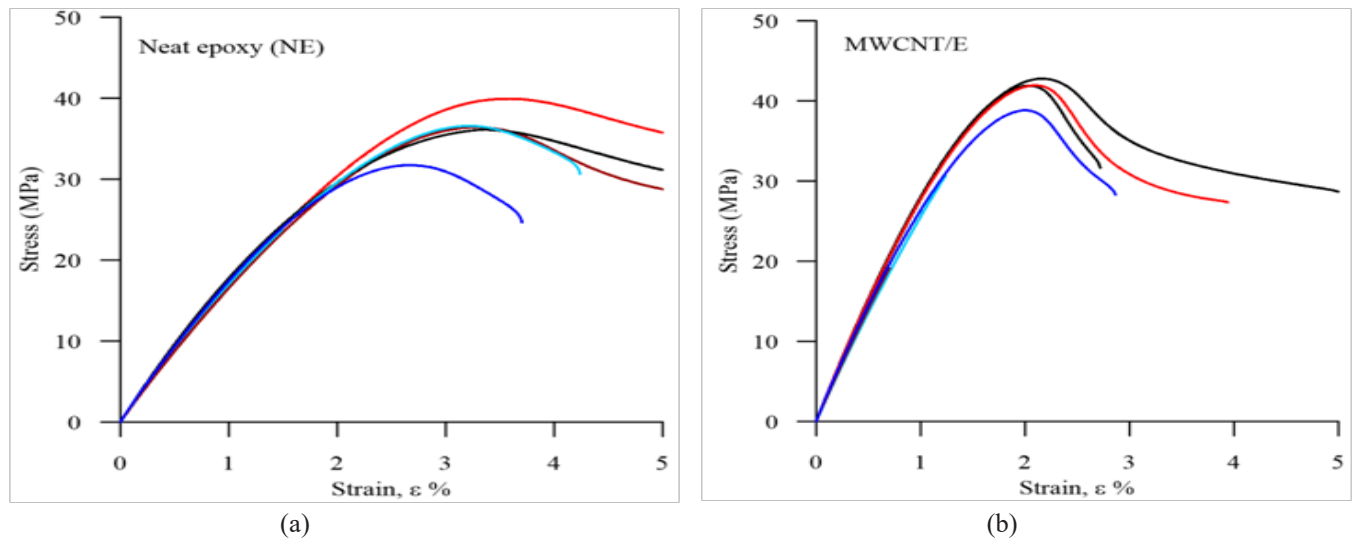
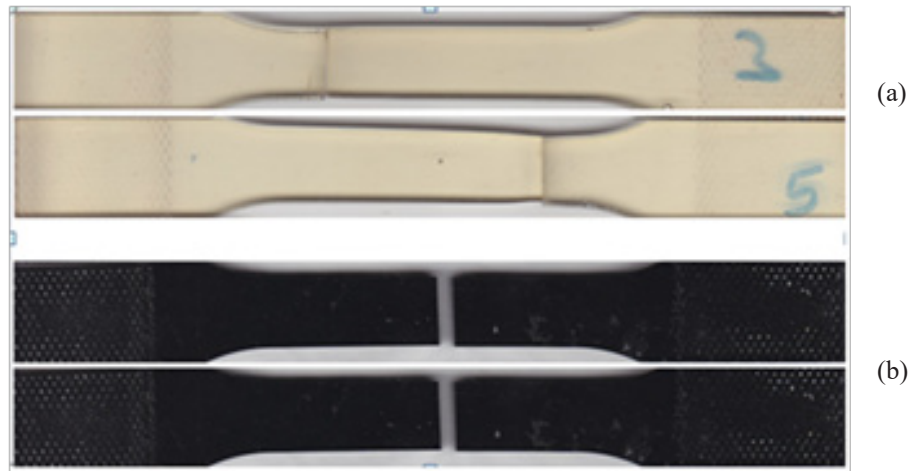**Fig. 9:** Stress-strain curves of: (a) neat epoxy, and (b)MWCNT-nanocomposite.

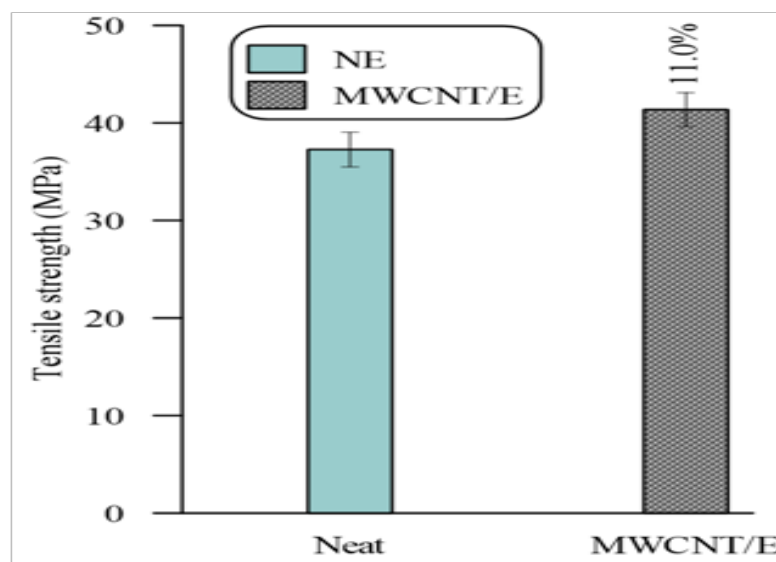**Fig. 10:** The fractured specimens in tension test for: (a) NE, and (b) MWCNT-nanocomposite.

Fig. 11: Tensile strength of NE and MWCNT-nanocomposites and the improvement percentage.
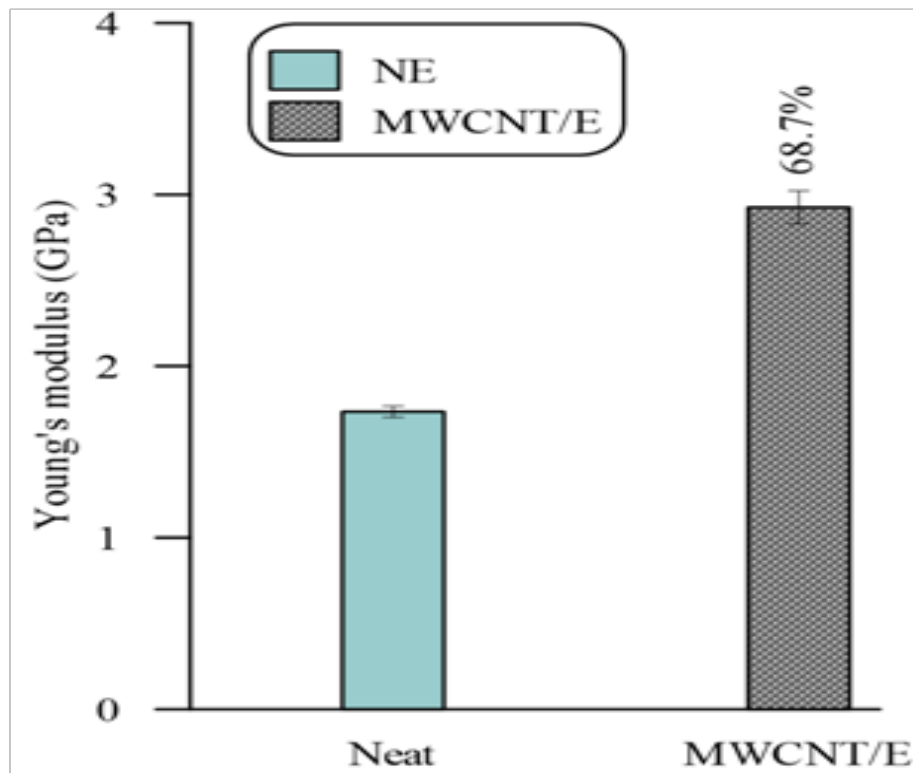
Fig. 12: Young's modulus of NE and MWCNT-nanocomposites and the improvement percentage.

3.2. In-Plane Shear Test Results

Shear load versus displacement relationships of neat epoxy and MWCNT-nanocomposite are illustrated in Fig. 13a and (b), respectively. The load-displacement curves in these figures typically behave almost linearly, followed by nonlinear behavior and plastic deformation at the ultimate load. The load is then decreased due to crack from the tip of the V-notch toward the specimen center, as shown in Fig. 14.
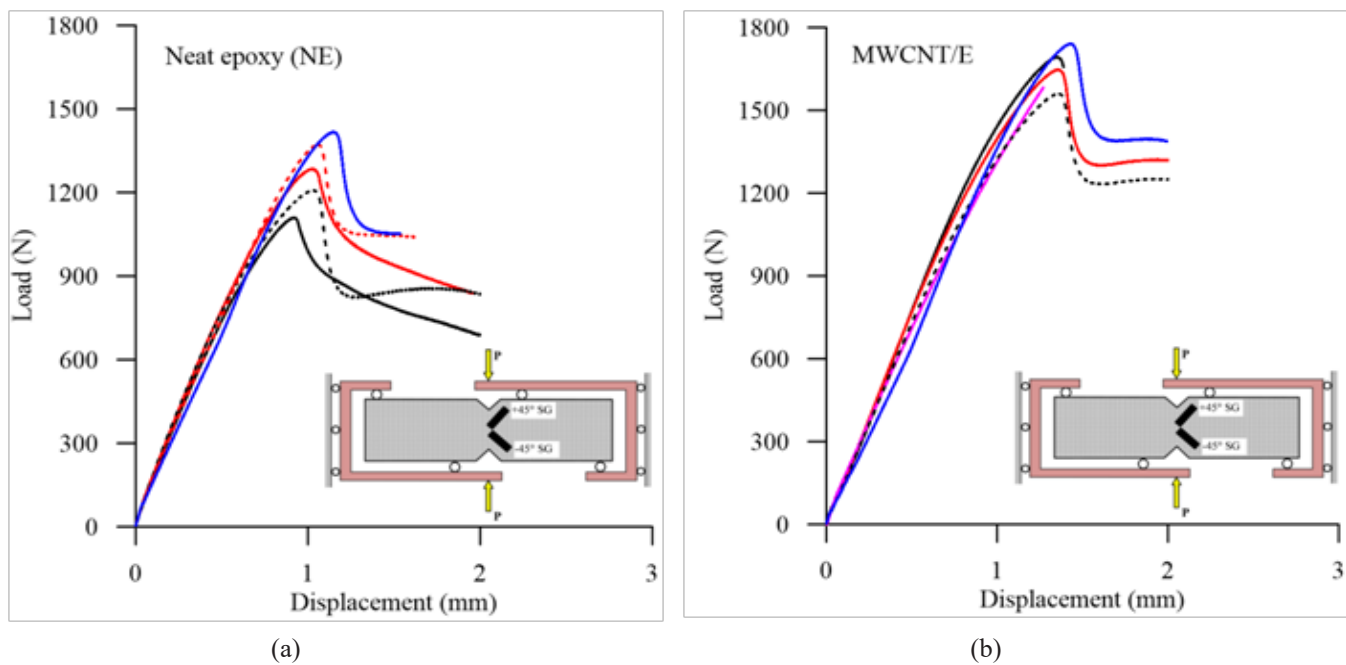

Fig. 13: Load-displacement curves of: (a) neat epoxy, and (b)MWCNT-nanocomposite.

(a)

(b)

Fig. 14: Fractured specimens in shear test for : (a) NE, and (b) MWCNT-

The shear strengths of NE and MWCNT-nanocomposite were calculated by dividing the ultimate loads by the actual cross-section area of the test specimens (distance between the two V-notches multiplied by thickness). The average values of the five tests are presented in bar chart as shown in Fig. 15. The results in this figure showed that the improvement percentage in the shear strength of the MWCNT-nanocomposite is 22.2% compared with NE.

The shear strains (γ_{xy}) of neat epoxy and MWCNT-nanocomposite were measured by strain gauges, which were bonded at 45^{0} at the center of the test specimen. Fig. 16a and b shows strains of ±45° SGs versus shear stress of neat epoxy and MWCNT-nanocomposite, respectively.

Fig. 17a and b shows shear stress-shear strain relationships of neat epoxy and MWCNT-nanocomposite, respectively. The in-plane shear moduli (G_{xy}) of NE and MWCNT-nanocomposite were estimated from the slope of the initial linear region of shear stress vs shear strain curves of Fig. 17.

The average values shear modulus of the five tests are presented in bar chart as shown in Fig. 18. The results in this figure showed that the improvement percentage in the shear modulus of the CNTs/E nanocomposite is 29% compared with neat epoxy (NE). The improvement of the shear properties (strength and modulus) of MWCNT-nanocomposite was attributed to the bridging effect of the MWCNTs, which arresting or retarding crack propagation between the two V-notches of the test specimen.
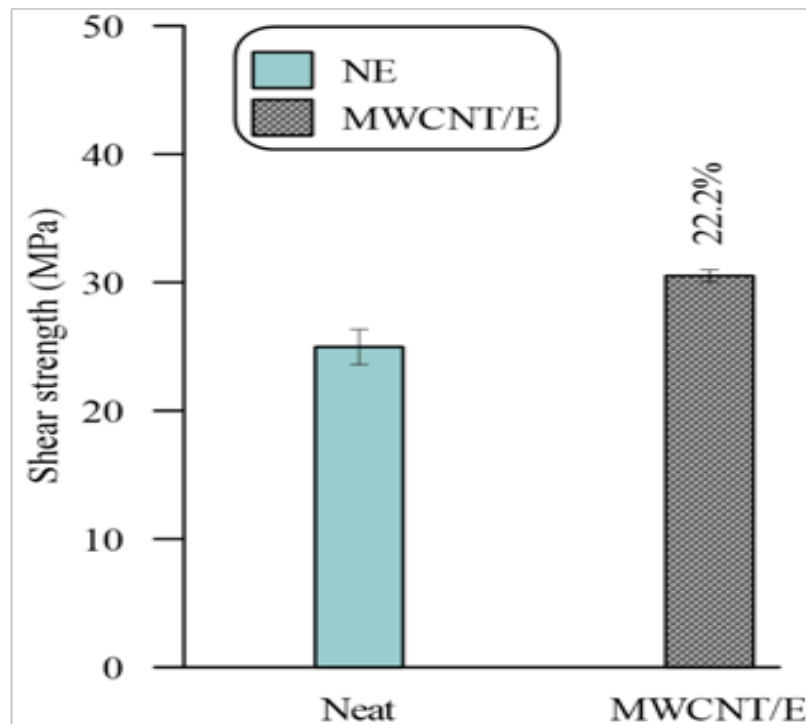

Fig. 15: Shear strength of NE and MWCNT-nanocomposite and the improvement percentage.
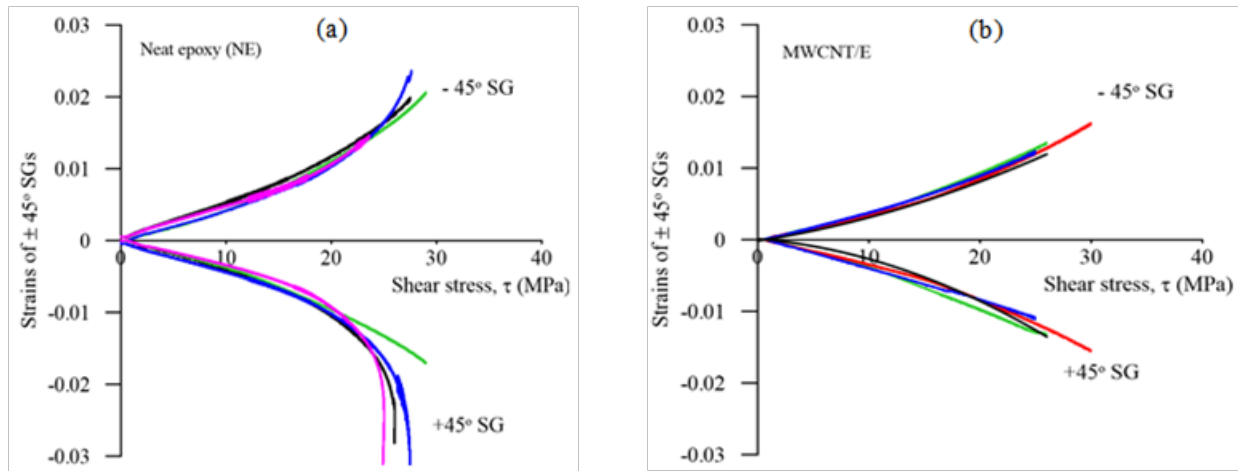
Fig. 16: Strains of ±45º SGs versus shear stress of: (a) NE, and (b) MWCNT-nanocomposite nanocomposite.
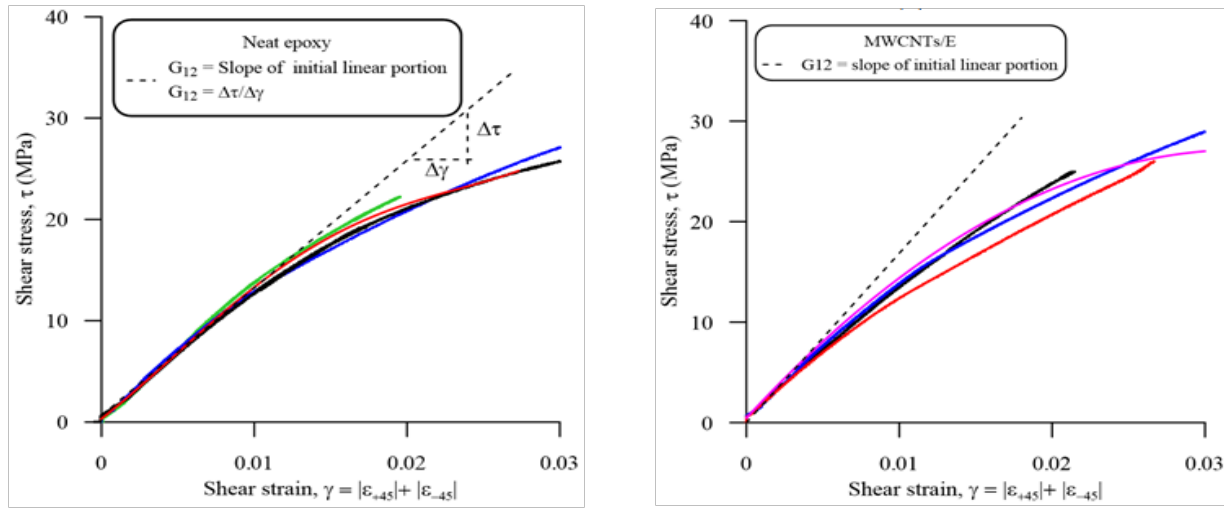

Fig. 17: Shear stress-shear strain relationship of: (a) NE, and (b) MWCNT-nanocomposite.
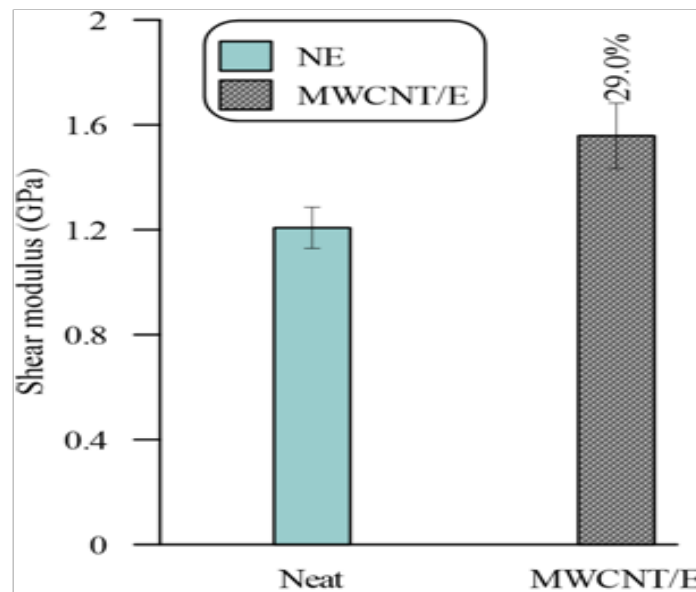

Fig. 18: Shear modulus of NE and MWCNT-nanocomposites and the improvement percentage.

3.3. Impact Test Results

Fig. 19 shows contact force vs displacement and energy vs displacement relationships of NE and MWCNT-nanocompositein drop-weight impact tests under impact energy of 20J. The first stage of force vs. impactor displacement (specimen deflection) curves of the NE and MWCNT-nanocomposite showed that the force was linearly increased, as the specimen deflection increases, up to a critical threshold force $F_{threshold}$ that is related to damage initiation[26]. The initial linear region of the force-displacement curves of Fig. 19 was due to the elastic bending of the specimens. The bending elastic stiffness can be calculated from the slope of the initial linear portion of the force-displacement curves of Fig. 19. The results in Fig. 19 showed that the MWCNT-nanocomposite has higher stiffness compared with NE. This result agrees well with the increase of the tensile and shear moduli of the MWCNT-nanocomposite relative to NE as shown in Figs. 12 and 18, respectively. The drop in the force-displacement curves after the initial damage (at $F_{threshold}$) is followed by further increases in the force up to the maximum force (F_{peak}) with slope lower than the initial linear portion. The peak force is followed by a sudden drop due to the catastrophic fracture of the specimen accompanied with impactor perforation/penetration of the specimen.
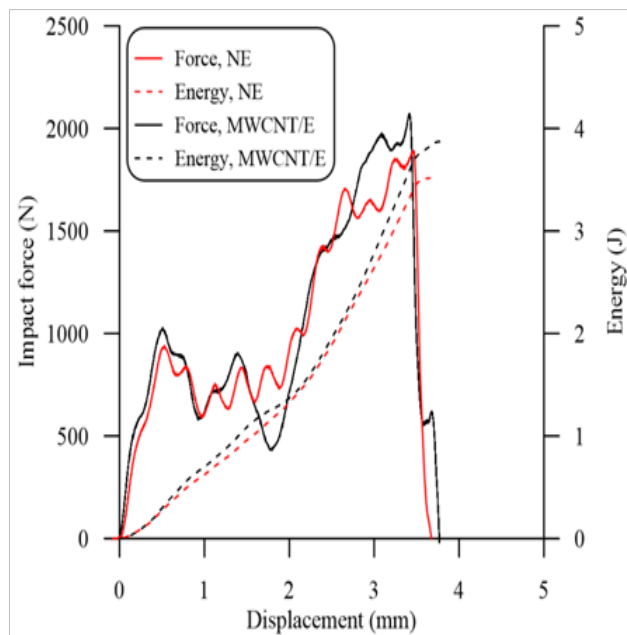

Fig. 19: Force and energy versus displacement in impact tests of NE and MWCNT-E nanocomposite.

Figs. 20 and 21show the average values of the maximum contact force and energy at failure of NE and MWCNT-nanocomposite, respectively. The results in Figs. 20 and 21 showed that incorporation of MWCNTs into the epoxy improve the maximum contact force and energy at failure of the MWCNT-nanocomposite by 9.5% and 11.4%, respectively. These improvements are

in the range of the improvement in the tensile strength of MWCNT-nanocomposite(11%). The improvement in the maximum contact force of the MWCNT-nanocomposite was attributed to the improvement in the tensile strength, whereas the improvement in the absorbed energy was due to the energy consumed in pull-out the MWCNTs.
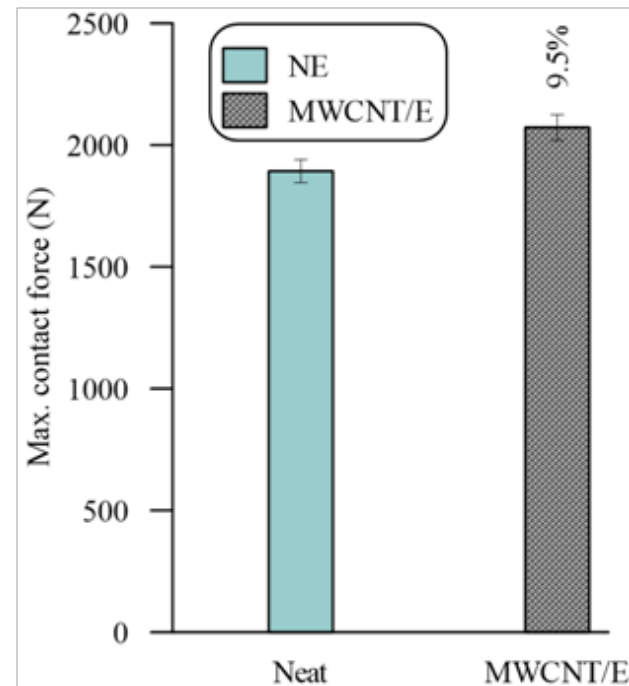

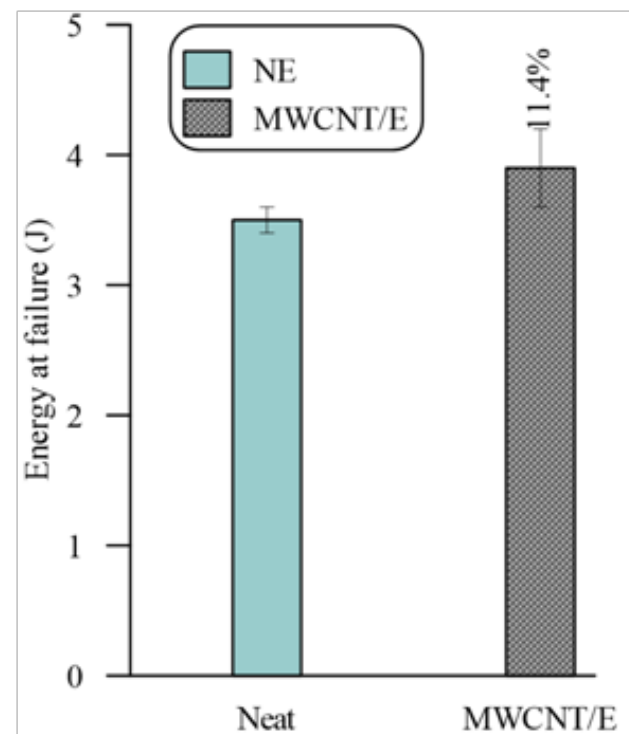**Fig. 20:** Max. contact force of NE and MWCNT-nanocomposites and the improvement percentage.

Fig. 21: Energy at failure of NE and MWCNT-nanocomposites and the improvement percentage.

4. CONCLUSIONS

In this work, the effects of MWCNTs infusion into epoxy resin on the tensile, shear and impact properties were measured experimentally in accordance with ASTM standards. Experimental results of the modified epoxy with MWCNTs are compared with the neat epoxy (NE). Some of the important concluding remarks are summarized as follows:

• The fractures of the tensile test specimens are in the gauge lengths (away from the grips of the testing machine), which satisfy the condition of the ASTM D 638. The well dispersed MWCNTs in epoxy resin act as physical cross–links for the epoxy molecular chains and accordingly, the tensile strength and modulus of the nanocomposite were improved by 11% and 68.7%, respectively, compared to the neat epoxy.

• Incorporation of the MWCNTs into the epoxy resin improved the shear strength and modulus of the MWCNT-nanocomposite by 22.2% and 29%, respectively, compared with the neat epoxy. The improvement of the shear properties (strength and modulus) of MWCNT-nanocomposite was attributed to the bridging effect of the MWCNTs, which arresting or retarding crack propagation between the two V-notches of the test specimen.

• The force vs. specimen deflection (impactor displacement) relationships of the drop weight impact of the MWCNT-nanocomposite showed higher bending elastic stiffness compared with NE. This result agrees well with the increase of the tensile and shear moduli of the MWCNT-nanocomposite relative to NE. The improvement percentages in the maximum contact force and absorbed energy of the MWCNT-nanocomposite are 9.5% and 11.4%, respectively. The improvement in the maximum contact force of the MWCNT-nanocomposite was attributed to the improvement in the tensile strength (11%), whereas the improvement in the absorbed energy was due to the energy consumed in pull-out the MWCNTs from the epoxy matrix.

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