

Reinforcing Effect of Surface-Modified Multiwalled Carbon Nanotubes on Flexural Response of E-Glass/ Epoxy Isogrid-Stiffened Composite Panels

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Abstract

The lack of scientific information about the utilization of nanoparticles on grid-stiffened composite (GSC) fabrication was the driving force for the selection of this study. In the present work, GSC panels reinforced with various amounts of surface modified multi-walled carbon nanotubes (MWCNTs) (0–0.5 wt% at a step of 0.1 wt%) have been investigated in terms of their capability to improve the mechanical properties under three-point flexural condition. Out of these specimens, the maximum value of improvement in the flexural stiffness, load bearing capacity, and specific energy absorption was related to the specimen with 0.4 wt% MWCNTs. It would be worth mentioning that in these structures, a considerable energy absorption was observed after the primary failure related to the load peak. The field-emission scanning electron microscopy observations of the fracture surfaces of the nanocomposites clearly indicated that the enhancement in the flexural properties was due to the improvement in the interfacial adhesion between the E-glass fibers and MWCNTs-enhanced epoxy matrix.

1. Introduction

Grid-stiffened composite (GSC) structures are increasingly used in many structural applications replacing metallic materials owing to their combination of high specific strength

and stiffness, high impact resistance, high efficiency under compressive loading condition, superior load bearing capacity, and excellent energy absorption capability [1–4]. Aerospace and aircraft industries are the two largest consumers of these structures [5]. Payload attach fitting (adapter), aircraft fuselage, airplane wings, and solar array substrates are some applications of these structures in aerospace and aircraft industries [6–8]. GSC structures are characterized by a network of helical or axial ribs which are supported by a shell component, namely “skin.” In these structures, the ribs are accounted as the main load bearing members. Also, the unidirectional nature of the ribs is very efficient because it leads to mass efficiency and very high reliability in these structures [3, 9, 10]. The different design parameters such as rib cross-section, rib angle, and skin thickness have a significant impact on the final properties of GSC structures [11–13]. Several studies in this case have been conducted in the past. In a research work which had done by Gan et al. [11], energy absorption in E-glass/polypropylene isogrid-stiffened composite panels under quasi-static transverse loading was evaluated both experimentally and analytically. Their observations showed that the energy absorption to failure for loading on the rib side was greater than that for loading on the skin side. However, the peak load was more for skin-side loading compared to rib-side loading. Parametric optimization of geometry of E-glass/ polypropylene isogrid-stiffened composite panels for obtaining the maximum energy absorption under transverse quasi-static and dynamic impact loading has been investigated by Jadhav and Mantena [12]. In this study, rib width and thickness, center-to-center distance between rib joints and skin thickness were optimized. In another research [13], the authors investigated impact response of the E-glass/polypropylene isogrid-stiffened composite panels. The results indicated that the energy adsorption under dynamic impact loading was more than that for quasi-static loading.

To the best of our knowledge, few studies have been reported in the open literature that investigated the mechanical properties of CGS structures from the viewpoint of material modification [14, 15]. According to previous works, it is expected that modification of fibrous composites by adding the nano-fillers will cause positive effects on their mechanical properties [16–18]. Such type of composites containing mixtures of microscale fibers and nanoscale fillers in a polymeric matrix is called multiscale composites [19]. The introduction of nanofillers with micro-fiber reinforcement in a polymeric matrix can be obtained by dispersing the nanofillers in the matrix [20] or reinforcing of fibers through growing of nanofillers on their surfaces [21]. Shokrieh et al. [22] evaluated the influence of adding multi-walled carbon nanotubes (MWCNTs) at various contents on the tensile and flexural behaviors of chopped strand mat/polyester composites and reported that adding only 0.05 wt% MWCNTs increased the flexural strength of the multiscale composite by 45% while the tensile strength was not changed significantly. Gojny et al. [23] reported an increase of 19% in interlaminar shear strength (ILSS) of glass fiber/epoxy composites (GFECs) with 0.3 wt% of amino-functionalized double-wall CNTs addition. In Ref. 24, it was shown that CNT/epoxy nanocomposite matrix improved interfacial load transfer from the matrix to carbon fibers, compared to the epoxy one. Rao et al. [25] reported that the addition of 0.5 wt% CNTs was effective for maximum mechanical properties of the resin and 1 wt% CNTs for the mechanical properties of the CNT-carbon fiber reinforced polymers (CNT-CFRPs). Zhou et al. [26] found that the highest enhancement in the strength and fracture toughness of carbon/epoxy composites was obtained for 0.3 wt% CNT addition. In the work by Sanchez et al. [27] the highest flexural strength of carbon fiber/epoxy composites was achieved via addition of 0.1 wt% of CNTs. As asserted by Qiu et al. [28] the tensile strength and Young's modulus of GFECs enhanced by 14% and 20%, respectively, through the addition of 1 wt% CNTs into the matrix.

The main aim of the present research is to demonstrate that an epoxy-MWCNTs nanocomposite can be used as a modified matrix of fibrous isogrid composite structures with greatly improved mechanical properties. In this work, E-glass reinforced epoxy nanocomposites with various MWCNTs wt% were fabricated and the effects of MWCNTs addition on three-point flexural properties of the produced specimens were investigated.

2. Experimental

2.1. Materials

ML-506 epoxy resin based on epoxy bisphenol F with hardener HA-11, both supplied by Mokarrar Engineering Materials Co., Iran, was used as matrix material. The resin–hardener ratio was 100:15 by weight, as recommended by the manufacturer. This resin system was selected due to its low viscosity and long gel time (60 min) at 25°C. A summary of the some specifications of ML-506 epoxy resin, reported by manufacturer, is listed in Table 1.

Table 1. Some properties of ML-506 epoxy resin used in this study.

Characteristic (unit)	Quantity
Density in combination with HA-11 hardener (g/cm ³)	1.1
Viscosity in combination with hardener (centipoise)	1,450 (at 25°C)
Tensile modulus (GPa)	2.79
Compressive modulus (GPa)	2.6
Flexural modulus (GPa)	3.65
Ultimate tensile strength (MPa)	76.1
Compressive strength (MPa)	97.4
Flexural strength (MPa)	96.0

Unidirectional E-glass fibers with a density of 2.58 g/cm³, average diameter of 12 μm, tensile modulus of 72 GPa, and tensile strength of 0.432 N/tex, supplied by LINTEX International Co., Ltd, China, were used as the reinforcement component. Two dimensional plain weave E-glass fibers with surface density of 400 g/m² were also employed to fabricate the grid composite panels.

The filler was COOH-MWCNT, provided by Cheap Tubes Inc., USA. The MWCNTs had a specific surface area of 233 m²/g, with a COOH content of 2 wt%. The average aspect ratio of the MWCNTs was ~1330. Figure 1 represents field-emission scanning electron microscopy (FESEM) image of as-received COOH-MWCNTs. In order to functionalize MWCNTs with silane, a silane coupling agent namely “3-GPTM,” from Merck Chemical Co., Germany was utilized. The molecular formula of 3-GPTMS (an epoxy-based silane coupling agent) is C₉H₂₀O₅Si.

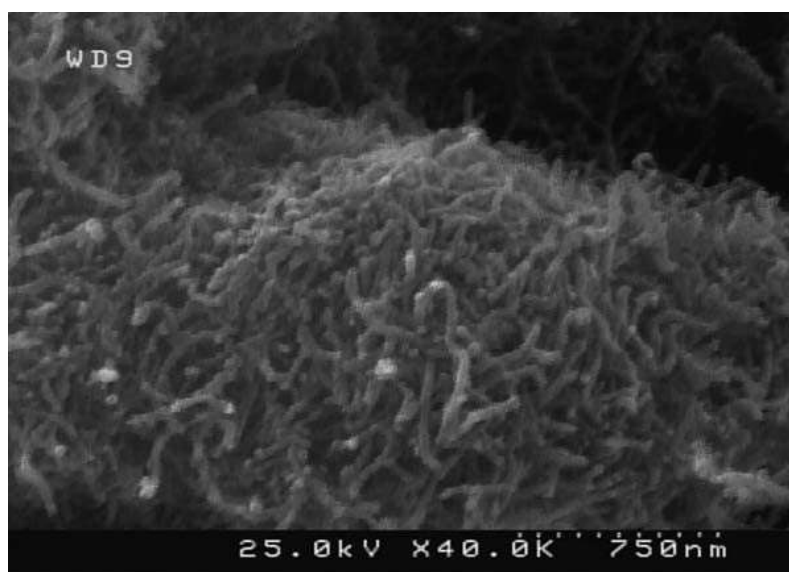


Fig. 1. FESEM image of as-received COOH-MWCNTs.

2.2. Surface Modification of MWCNTs

About 0.5 g of as-received COOH-MWCNTs was dispersed in 100 mL solution of 95 mL ethanol and 5 mL distilled water and then sonicated with a probe sonicator for 10 min. The silane coupling agent, 3-glycidoxypyltrimethoxysilane (3GPTS), was added to the mixture with a concentration of 1:1 with respect to the weight of MWCNTs [29]. The obtained mixture was kept refluxing at 70°C for 12 h. The pH value of the mixture was adjusted to 4–5 by the addition of hydrochloric acid (37% concentrated HCl) [29, 30]. Once the process was finished, the reaction products were separated from the solvent by centrifugation (8 h at 4,000 rpm) and washed with ethanol twice to remove un-reacted silane coupling agent. Finally, the modified particles were dried in a convection oven at 80°C for 5 h. The obtained silanized MWNTs are denoted as 3-GPTS/ MWNTs.

2.3. Mold Fabrication

In this research, composite panels with isogrid lattice patterned reinforcements were fabricated. Silicone molds were used to fabricate the grid specimens. The main reasons of selecting silicone for making molds were its rubbery state and bearing high elastic strain, which facilitates the removal of specimen from the mold. The silicone compound used in this research consisted of RTV-3325 and 6H components which were mixed in 100:4 ratio by weight. The molds were fabricated by pouring liquid silicone mixture over a pre-fabricated polyvinyl chloride (PVC) template (Fig. 2a) and then holding at room temperature for about 6 h to make it to cure. The silicone mold is shown in Fig. 2b.

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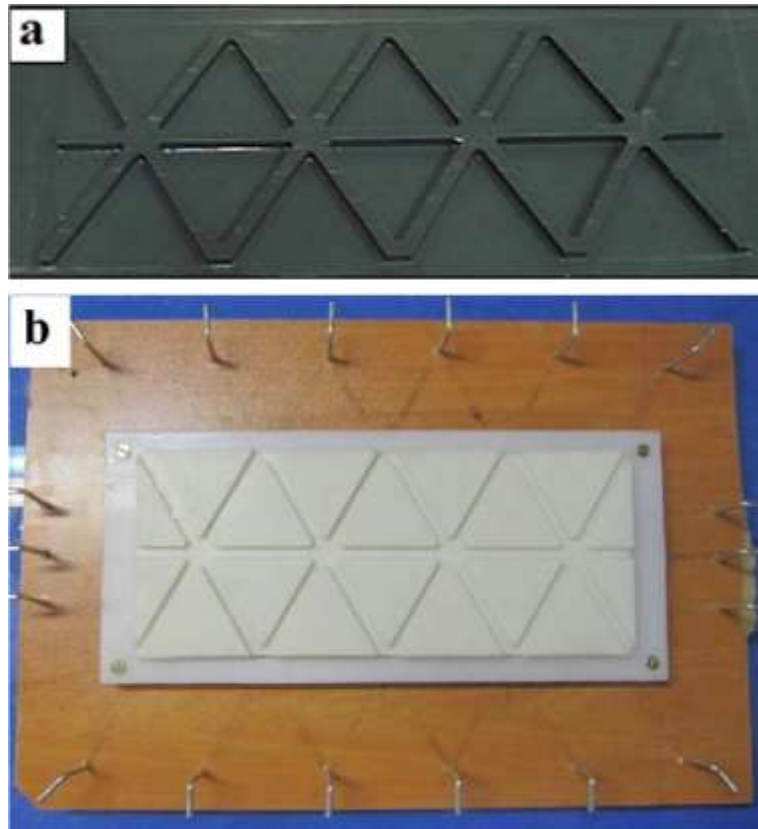


Fig. 2. (a) PVC template and (b) silicone mold.

2.4. Specimen Preparation

In order to fabricate multiscale composite panels, a mixture containing epoxy and MWCNTs is prepared in the first step. To do so, a combination of sonication and high stirring were employed to uniformly disperse MWCNTs in the epoxy matrix. The mixtures were prepared according to the following procedure: the epoxy resin was weighted and diluted in acetone and then the selected amounts of MWCNTs were added to it. After primary mechanical stirring (20 min at 2000 rpm) of MWCNTs and epoxy resin using an overhead mechanical stirrer (SDS-11D, Fintek Co., Korea), the mixture was ultrasonically agitated for 90 min using a probe of 14-mm tip diameter, at 120 W and 30% duty cycle (Ultrasonic Homogenizer 400 W, 24 kHz, FAPAN Co., Ltd., Iran). During the mixing process, a water cooling system was employed to keep the temperature of the mixture at a constant temperature of 45°C. Finally,

the mixture was degassed under vacuum until all excess acetone and air bubbles were completely removed from the mixture. After dispersing the MWCNTs in the epoxy resin, a stoichiometric amount of curing agent (HA-11 hardener) was manually incorporated with the resultant mixture for 5 min. The MWCNT-epoxy mixtures were then used to fabricate the specimens.

The isogrid composite panels were prepared using a manual filament winding method with the aid of a simple designed fixture (see Figs. 3 and 4). Six groups of panels containing various MWCNT loadings (0–0.5 wt% at a step of 0.1 wt%) were produced. First, resin impregnated unidirectional E-glass fiber rovings were placed into grooves of silicone mold layer by layer to form the ribs of grid structures (Figs. 3a and 4a). Afterwards, laying up the skin using four layers of E-glass woven fabrics was conducted (Figs. 3b and 4b). The skin thickness of all the specimens was 1.8 mm. After completing the manufacturing process, the material was kept for 3 h at room temperature for primary curing. In order to conduct the ultimate curing and to achieve the maximum strength, the specimens were tested after 7 days of holding at room temperature. The specimens were characterized by length of 300 mm, width of 125 mm, and thickness of 7.8 mm. The cross-section area of all ribs was a quadrangle with the area $6 \times 6 \text{ mm}^2$. In all cases, the total volume fraction of glass fibers was kept constant at values of 0.44 and 0.48 in ribs and skin parts, respectively. Burn-off test was utilized for this case. Figure 5 depicts the fabricated composite panels.

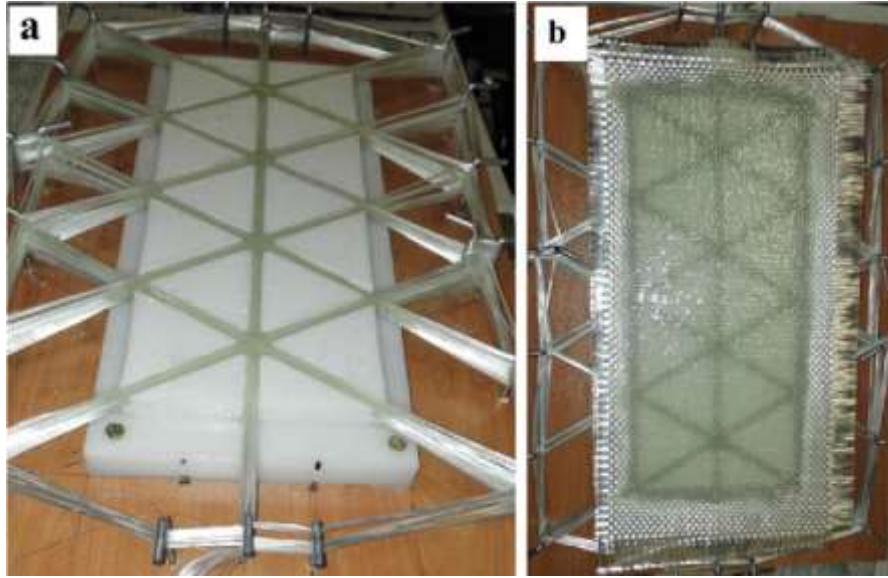


Fig. 3. Fabrication of isogrid E-glass/epoxy composite panel, (a) rib formation and (b) skin lay-up.

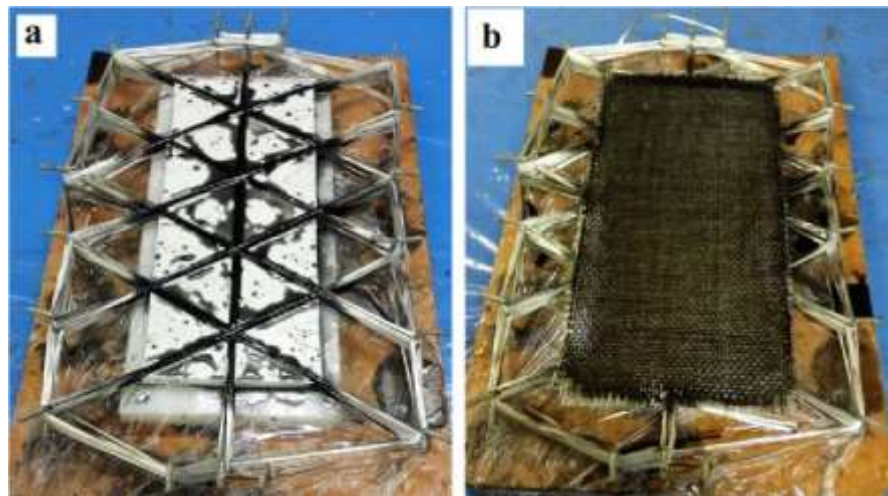


Fig. 4. Fabrication of isogrid E-glass/epoxy composite panel containing MWCNTs, (a) rib formation and (b) skin lay-up.

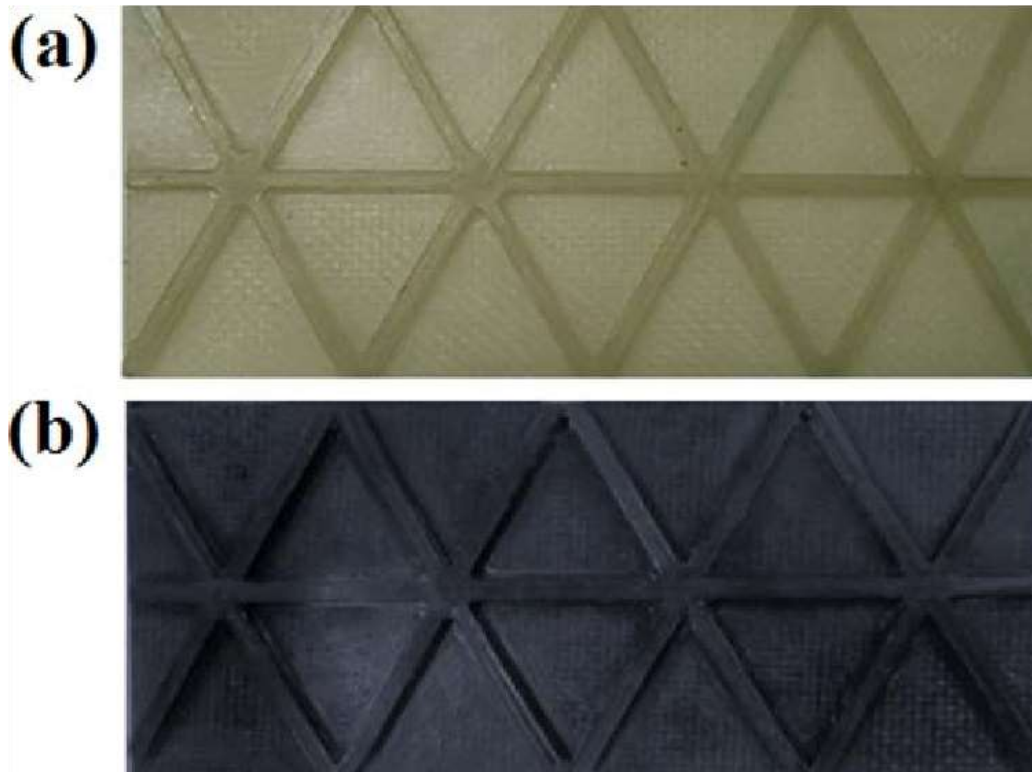


Fig. 5. Fabricated isogrid composite panels (a) without and (b) with MWCNTs addition.

2.5. Three-Point Flexural Test

Flexural test was conducted in accordance with ASTM: D7264-07 by using the universal testing machine, Hounsfield: H25K. The composite panels with dimensions of $300 \times 125 \times 7.8$ mm³ were exposed to the three-point bending configuration of flexural test. The representation of three-point bending setup is shown in Fig. 6. In this configuration, the composite panel rests on two supports and is loaded from skin side using a loading nose midway between the supports. All tests were carried out at room temperature and three specimens of each type were tested. Cross-head speed was set to 5 mm/min and span length kept to 250 mm. In this condition, the span-to-thickness ratio was 32:1. During the loading, the flexural load as a function of axial displacement was recorded for each specimen.

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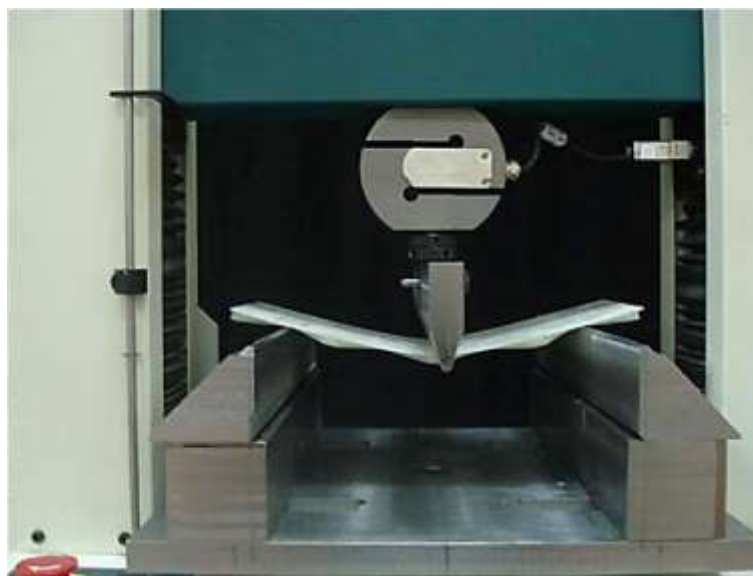


FIG. 6. Experimental setup for three-point flexural test.

2.6. FTIR and FESEM Analyses

The infrared spectra of as-received and silane-modified MWCNTs were recorded using a FTIR spectrometer (FTIR-460 plus, Jasco) to observe the surface functional groups onto the powders. The MWCNTs were mixed with powdery KBr and then pelletized. The specimens were scanned (250 times per measurement) at wavelength range of 400–4,000 cm^{-1} , with a resolution of 4 cm^{-1} . The fracture surface of the specimens was investigated using a FESEM (HITACHI S-4160, 25 kV) to correlate the fracture surface morphology with the obtained mechanical response. Before examination, the fracture surfaces were sputter coated with a thin gold layer for improved conductivity.

3. Results and Discussion

3.1. Characterization of Modified MWCNTs

Fourier transform infrared spectroscopy (FTIR) analysis was conducted to characterize the chemical changes on the surface of MWCNTs due to surface modification by the silane

coupling agent (3-GPTS). Figure 7 shows the FTIR spectra of the as-received COOH/MWCNTs and 3-GPTS/ MWNTs. The two absorption peaks at 1156.6 cm^{-1} and 1716.5 cm^{-1} , related to the C—O and C=O stretching vibrations of carboxylic groups, respectively, can illustrate the presence of the —COOH groups on the surface of the as-received MWNTs (Fig. 7a) [31]. The bands at 3179.5 cm^{-1} and 2519.7 cm^{-1} can be assigned to the stretching vibration of absorbed water and the hydroxyl groups on the surface of MWNTs [32]. The broad absorption peaks at 1412.9 cm^{-1} and 801.5 cm^{-1} are due to the OH bending deformation in —COOH [33]. In addition, the characteristic peaks at 2872.9 cm^{-1} and 1592.7 cm^{-1} are associated with the C—H and C=C groups [34]. On the contrary, for the 3-GPTS-MWCNTs (Fig. 7b), an extra peak corresponding to the Si—O—C bond is observed at around 852.3 cm^{-1} [32]. This observation confirms that 3GPTS has been successfully grafted to the surface of MWCNTs. A schematic illustration of the reaction of 3GPTS silane coupling agent with COOH group of MWCNTs is shown in Fig. 8.

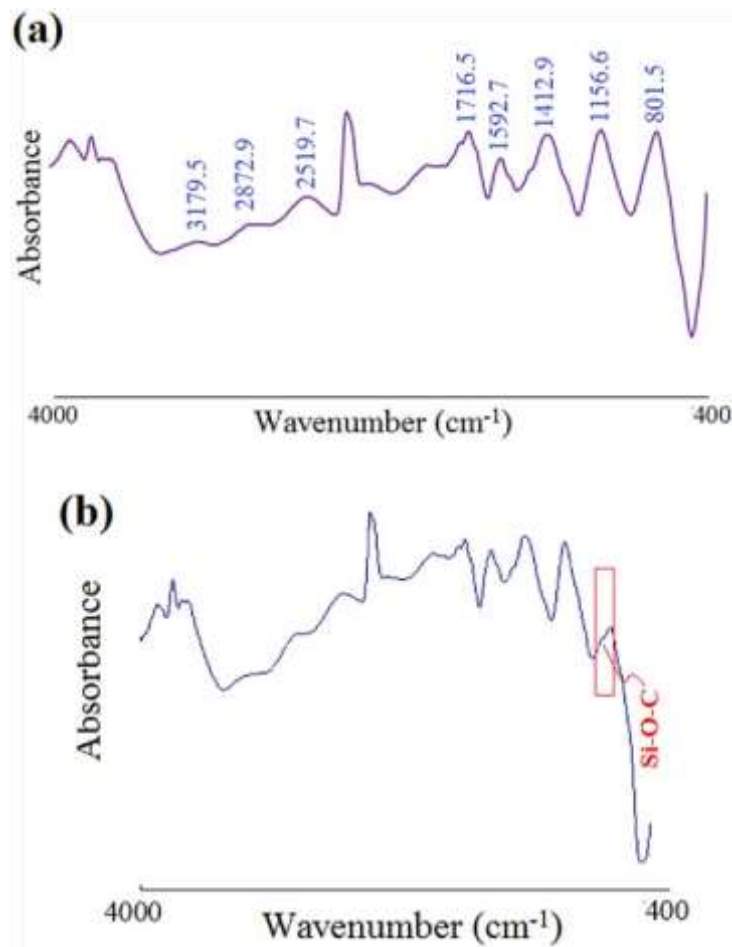


Fig. 7. FTIR spectra of (a) COOH-MWCNTs and (b) 3-GPTS treated MWCNTs.

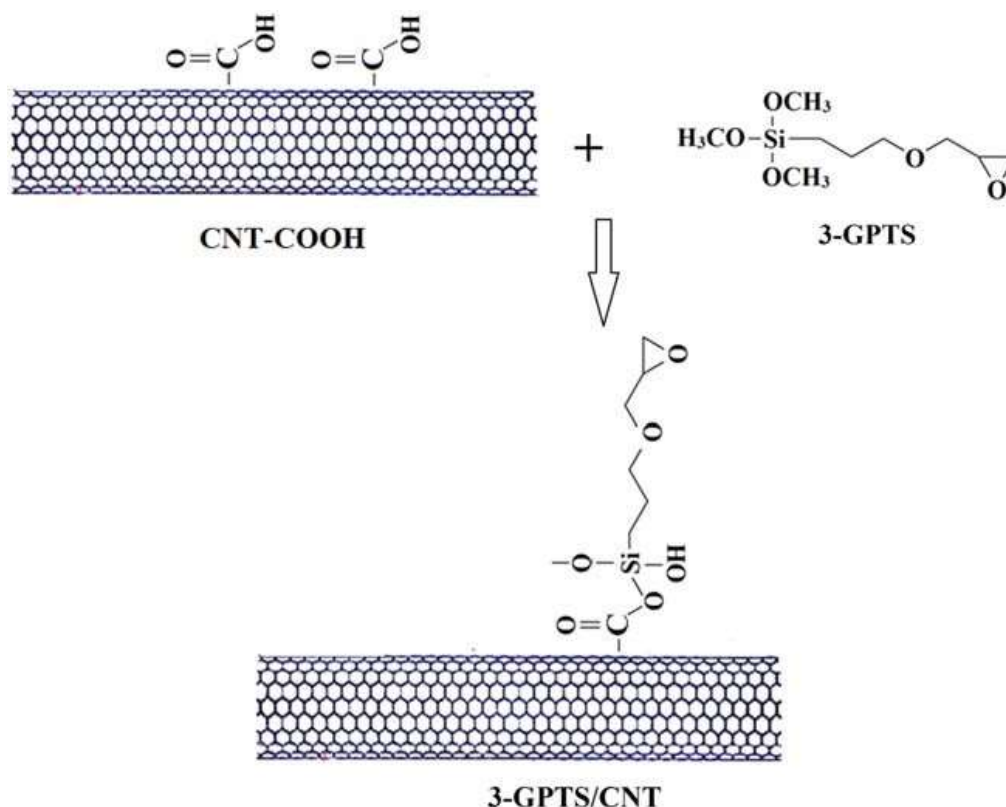


Fig. 8. Schematic illustration of the reaction of 3-GPTS silane coupling agent with COOH groups of MWCNTs.

The chemical formula of 3-GPTS is $\text{RSi}(\text{OCH}_3)_3$. R group ($\text{C}_6\text{H}_{11}\text{O}_2$) is a non-hydrolyzable organic radical that covalently bonds to organic resins. The 3-GPTS coupling agent was exposed to hydrolysis before the surface treatment according to Eq. 1. Reactive silanol groups ($\text{Si}-\text{OH}$) are formed during hydrolysis which can condense with other SiOH groups.



At the end of reaction, the bond between Si atoms and OH groups in 3-GPTMS is replaced by a bond between MWCNT and Si atoms and as a result, a strong covalent linkage is formed between them. When the functionalized MWCNTs are introduced into the epoxy resin, the 3GPTS with an epoxide group will react with the matrix in the presence of amine hardener, forming a network structure.

3.2. Three-Point Flexural Properties

Figure 9 shows the flexural load–displacement curve for the E-glass/epoxy iso-GSC panel. It should be noted that the bending test was performed from the skin side until displacement of 80 mm. From Fig. 9, following an initial linear region, the specimen reached to a peak load, failed at this point with an abrupt drop in load and afterwards absorbed energy. It is interesting that in this structure, a considerable portion of energy absorption is obtainable after the primary failure occurring at the peak load point. Various failure modes observed during the testing of the isogrid panel are depicted in Fig. 10.

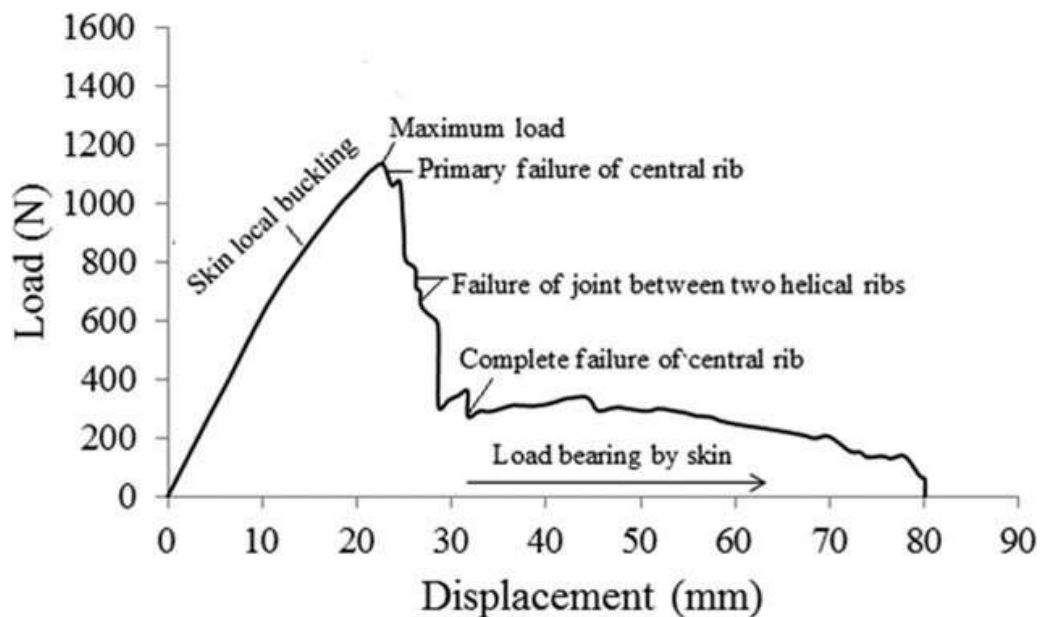


Fig. 9. Load–displacement flexural curve for E-glass/epoxy isogrid composite panel.

Figures 11a–e illustrates the flexural load–displacement curves for the multiscale E-glass/epoxy/MWCNTs isoGSC panels containing various amounts of MWCNTs. A similar trend is observed for all the specimens. The summary of the flexural properties of the specimens extracted from Fig. 11 is illustrated in Table 2. The flexural stiffness of each isogrid composite panel was determined by measuring the slope in the linear region of the corresponding load–

displacement curve. The value of stiffness for the specimen contains 0.5 wt% of 3-GTMS/MWCNTs is 62.6 N/mm, which shows an increase of 29% as compared to the MWCNTs-free specimen. The enhanced stiffness observed for the 0.5 wt% 3-GPTS/MWCNTs loaded specimen is expected because of the higher modulus of the MWCNTs compared with the epoxy matrix. Another reason for observed trend is attributed to the restriction of the polymer chain mobility under loading due to the presence of functionalized MWCNTs in the matrix. However, it is noticeable that the stiffness of the specimen with 0.5 wt% MWCNTs is only 2% higher than that of the specimen with 0.4 wt% MWCNTs addition. This behavior is probably due to the poor interaction of epoxy matrix with MWCNTs at higher nanofiller loading. In this case, some agglomerates can be created (see section “Fracture analysis”).

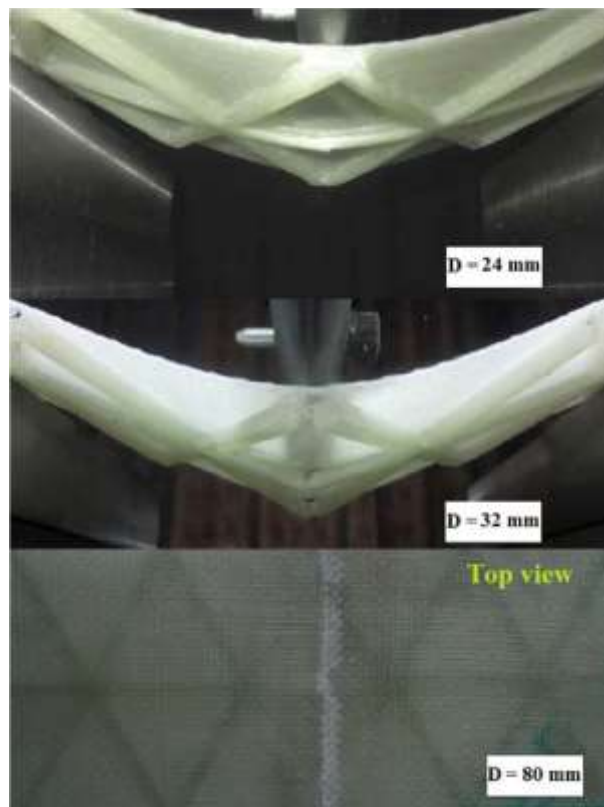


Fig. 10. Various failure modes observed during the flexural testing of E-glass/epoxy isogrid panel.

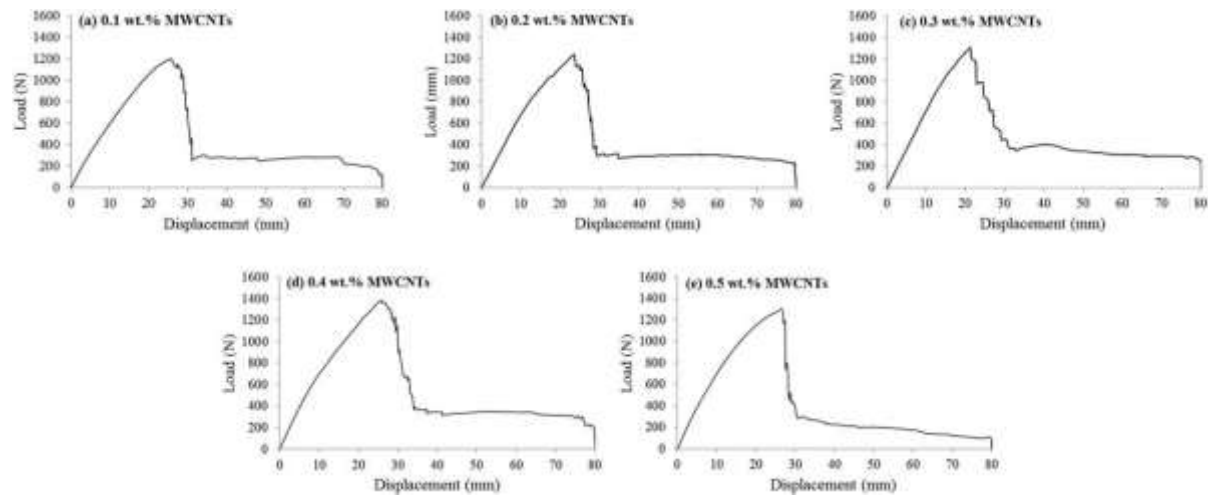


Fig. 11. Load–displacement flexural curves for E-glass/epoxy/MWCNTs isogrid composite panels containing various amounts of MWCNTs.

Table 2. Three-point flexural test results for isogrid composite panels containing various MWCNTs loadings

MWCNT loading (wt%)	Flexural stiffness (N/mm)	Increase in flexural stiffness (%) ^a	Maximum load (N)	Increase in maximum load (%) ^a
0	62.6 (1.9) ^b	—	1131 (32)	—
0.1	67.4 (2.0)	8	1198 (33)	6
0.2	69.2 (2.0)	11	1242 (31)	10
0.3	72.4 (1.9)	16	1307 (32)	16
0.4	79.1 (1.7)	26	1380 (28)	22
0.5	80.7 (2.2)	29	1298 (35)	15

^a With respect to the 0% MWCNT-loaded specimen.

^b Numbers in the brackets are standard deviations.

The maximum load observed on the load–displacement curves was used as a favorable criterion for the comparison of the load-bearing capacity of the specimens. In an isogrid panel, fiber breakage and fiber microbuckling are two damage mechanisms occurring under transverse loading from the skin side. It can be mentioned that under flexural loading, longitudinal rib of isogrid composite panel along with skin sustains the maximum applied load. From the data presented in Table 2, it can be found that the maximum load increases with MWCNTs weight percent up to 0.4 wt%, beyond which it declined. By addition of 0.4 wt% MWCNTs, the maximum load increases about 22%. Such a finding may be due to the two main reasons: First, the fiber–matrix interfacial characteristics should be addressed. It has been well documented that the interfacial characteristics between the matrix and the reinforcement in fibrous composites play a significant role in determining their final performance [35]. When the matrix material is reinforced by MWCNTs, the frictional slippage of fiber–matrix interface against applied load is restricted due to the presence of nanofillers. In fact, MWCNTs act as mechanical interlocking between the E-glass fibers and matrix creating a high friction coefficient. This implies that in case of nanocomposite matrix, the applied load can be effectively transferred from the matrix to the fiber reinforcement. Therefore, the load bearing capacity of nanocomposite specimens is higher than free-MWCNTs one. The second reason is attributed to the increase of the required stress level for fiber breakage and fiber microbuckling when the matrix is reinforced by MWCNTs. In fibrous composites, fibers (especially fiber skin) and fiber–matrix interface are accounted as stress concentration regions [36]. Introduction of MWCNTs to the matrix can effectively reduce the stress concentration onto the fibers during loading. The observed drop in the load bearing capacity of the specimen with 0.5 wt% MWCNT loading can be related to the decreasing of matrix–fiber adhesion resulting in the formation of a discontinuous matrix network and also with higher MWCNT concentration,

defects are formed. In this case, the increasing of the resin viscosity and insufficient dispersion of MWCNTs within the matrix may lead to improper wetting of fibers during the fabrication stage resulting in the formation of a poor fiber/matrix interface [37].

A typical parameter to quantify the energy absorption capability of a structure is specific energy absorption (SEA) [38] which is defined as the ratio of the energy absorbed (area under the load–displacement curve (E_a)) to the mass of failed specimen (m_s). Here, m_s is mass of isogrid panel between supports. The energy absorption characteristics of all tested specimens with various MWCNT loadings are illustrated in Fig. 12. It can be inferred from this graph that the energy absorption follows the same trend as the flexural maximum load because both of them are directly affected by the dispersion quality of MWCNTs in the matrix. At 0.4 wt% MWCNTs, the energy absorption of the fibrous composite panel increases by 31%. In fiber-reinforced composites matrix, cracking and fiber-matrix debonding are two main mechanisms occurring during loading [39]. The elastic modulus of MWCNTs compared to epoxy matrix (E_{CNT}/E_{epoxy}) is high, so stress gradient in the vicinity of fillers can lead to the creation of high stress concentration in these regions and the formation of micro-cracks. MWCNTs act as barriers in the matrix against the crack opening during its growth, through crack bridging mechanism [40]. Therefore, a higher level of energy is needed for crack growth. Also, adding MWCNTs can improve the interface between the fibers and matrix. The increase in the energy absorption of the nanocomposite specimens is therefore due to the modified matrix of the fibrous composite. This suggests that isogrid fibrous composite panels reinforced by MWCNTs have higher capacity to energy absorption compared to that panel without MWCNTs addition. The observed reduction in the energy absorption of the composite with 0.5 wt% MWCNTs in comparison to the composite containing 0.4 wt% MWCNTs is probably due to the formation of some agglomerates at higher MWCNTs loading. These agglomerates act as stress

concentration regions and crack initiation can easily take place from these regions [41]. It is noticeable that although higher sonication power and time can lead to a better MWCNTs dispersion, however, it can break the MWCNTs, declining the reinforcing efficiency of them.

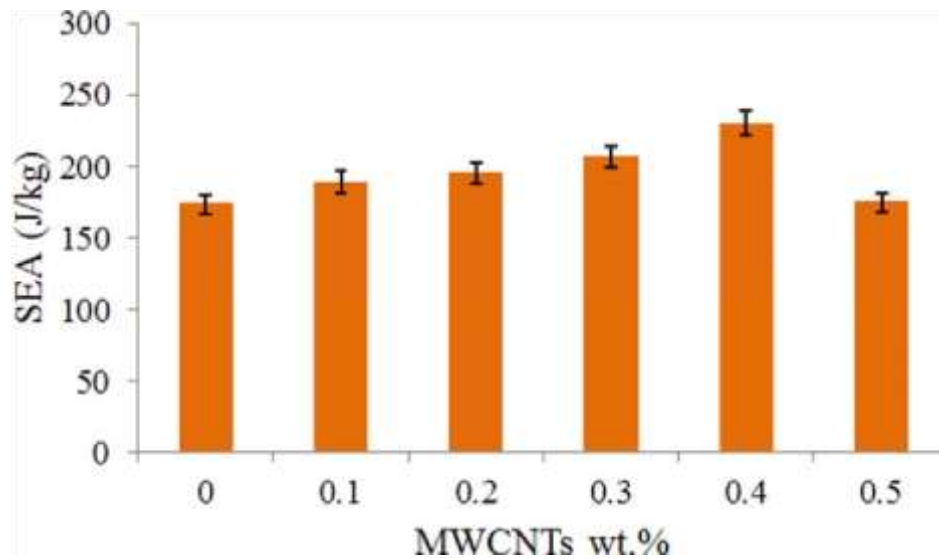


Fig. 12. SEA versus MWCNTs loading for the multiscale isogrid composite panels.

3.3. Fracture Analysis

Figure 13 shows SEM images of the fracture surfaces of longitudinal ribs related to the isogrid composite panels with 0.4 wt% and without MWCNT addition. A remarkable difference between the fracture surfaces of the specimens can be observed. From Fig. 13a, it can be seen that the failure surfaces of the pulled-out fibers are relatively featureless and smooth which is an indicative of poor matrix–fiber interface [42]. SEM micrograph of the 0.4 wt% loaded specimen in Fig. 13b clearly illustrates some remained matrix on the fibers. The visible matrix residues on the fiber surface are unequivocal signs of an effective interfacial adhesion and bonding between fibers and matrix [42]. Therefore, the fibers could receive an efficient stress transfer from the matrix. Figure 14 represents the SEM micrographs of the

matrix fracture surface of the specimens. Compared to the epoxy-matrix composite (Fig. 14a), the fracture surface of the MWCNT/epoxy-matrix one exhibits regular shear steps (as shown in Fig. 14b). This phenomenon is due to the presence of MWCNTs within the matrix, manifesting that the crack propagation was resisted by them. A relatively smooth fracture surface of the epoxy matrix exhibits a typical brittle fracture behavior. For this specimen, shear stress is transmitted slowly from one layer to another and there exists a little difference between the layers. With reference to the Fig. 15a and b, which is taken from the fracture surface of the 0.4 wt% MWCNTs-enhanced matrix at higher magnifications, a very good dispersion of MWCNTs in the matrix and an effective bridging effect are characterized. The MWCNTs which are visible on the fracture surface are either pulled out or broken proposing the bridging toughening mechanism [43]. Fracture surface of the specimen containing 0.5 wt% MWCNTs is depicted in Fig. 16. It represents the presence of some MWCNTs agglomerates in the matrix creating regions of stress concentration that decline the required stress for specimen failure. This implies that the surface modification of MWCNTs alone could not prohibit the agglomeration of MWCNTs at higher loadings.

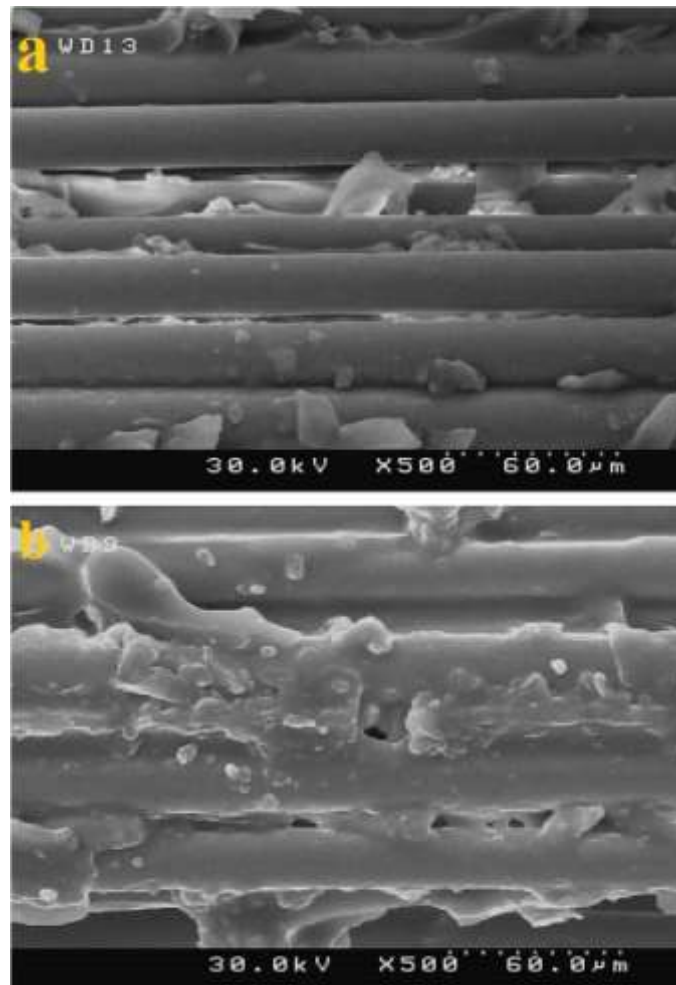


Fig. 13. FESEM images of the fracture surfaces of longitudinal ribs with (a) epoxy matrix and (b) MWCNT-enhanced epoxy matrix.

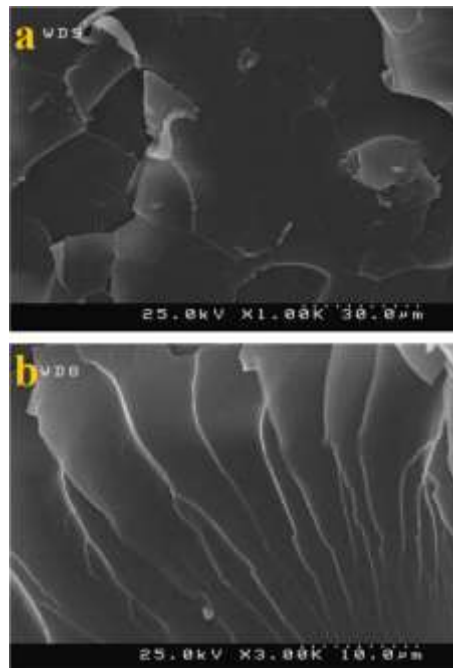


Fig. 14. FESEM images of the matrix fracture surfaces of longitudinal ribs (a) unmodified and (b) modified by MWCNTs.

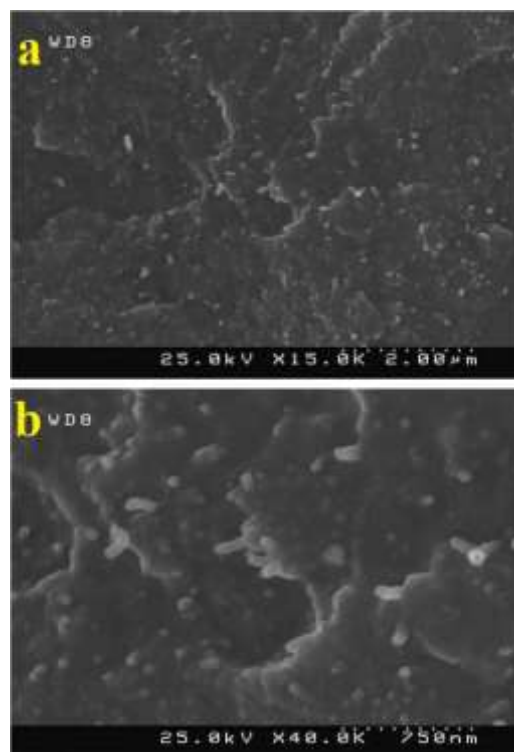


Fig. 15. FESEM images taken from the fracture surface of the epoxy-0.4 wt% MWCNTs matrix at two high magnifications.

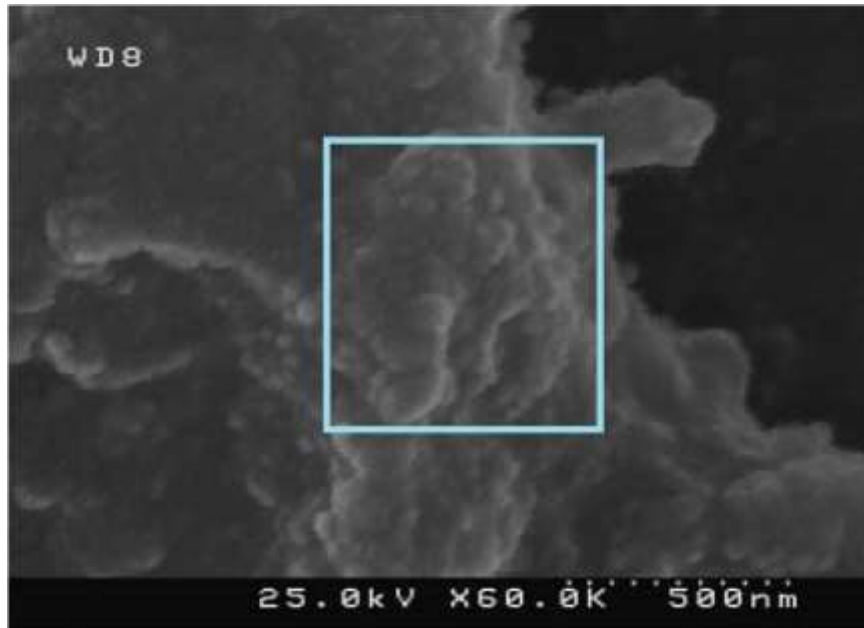


Fig. 16. FESEM image of the fracture surface of a specimen having 0.5 wt% MWCNTs, (agglomerates act as stress concentration regions).

4. Conclusions

On the basis of this work devoted to investigating the effect of surface-modified MWCNTs addition on three-point flexural properties of E-glass/epoxy isogrid composite panels, the following conclusions can be drawn:

1. GSC panels with improved flexural properties could be developed through matrix enhancing using 3-GPTS/ MWCNTs. In these structures, a considerable portion of energy absorption was obtainable after the primary failure occurring at the peak load.
2. FTIR results verified the successful grafting of 3-GPTScoupling agent onto the surface of as-received COOHMWCNTs.
3. The flexural properties of isogrid nanocomposite panels were always higher than that of specimen without adding MWCNTs.

4. The load bearing capacity of the specimens was firstly increased and then declined by increasing the MWCNTs loadings. At 0.4 wt% MWCNTs loading, the highest load bearing capacity was observed. Adding the MWCNTs to the matrix of the composites resulted in continues increasing of their flexural stiffness. However, this effect decreased for the 0.5 wt% MWCNTs incorporation.
5. With the addition of 0.4 wt% MWCNTs, compared to the E-glass/epoxy isogrid composite, the SEA of the specimen was increased by 31%. However, at 0.5 wt% MWCNTs loading, the SEA improvement was limited to 16% due to the agglomeration of MWCNTs.
6. The fracture surface examination of the specimens showed improved interfacial adhesion between the E-glass fibers and MWCNTs-enhanced matrix.
7. Overall this study demonstrates that 3-GPTS/MWCNTs dispersed within the matrix can significantly enhance the three-point flexural properties of fibrous GSC structures.

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