

Investigation on the flexural response of multiscale anisogrid composite panels reinforced with carbon fibers and multi-walled carbon nanotubes

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Abstract

Grid stiffened composite structures have been maturely developed in aircraft and automobile industries due to their excellence properties such as high specific strength, high specific stiffness, excellent energy absorption capability and corrosion resistance. In the current investigation, the effect of multi-walled carbon nanotubes (MWCNTs) addition in various weight percentages (0, 0.1, 0.25 and 0.4) on the flexural response of anisogrid composite panels was evaluated. For fabrication of the composite specimens, hand lay-up method was used where plain weave E-glass fibers and unidirectional carbon fibers impregnated to the epoxy resin that modified with MWCNTs, were used in the skin and rib parts, respectively. Experimental results from three-point bending test showed that with the addition of 0.4 wt.% of MWCNTs, the maximum flexural load, flexural stiffness and energy absorption of AGC panels increased by 24%, 35% and 25%, respectively. Microscopic analyses revealed that the improvement in the flexural properties of anisogrid composite panels with the addition of MWCNTs was due to improvement in the interfacial properties of matrix and fibers.

Keywords: Anisogrid composite panels, Multiscale composites, Multi-walled carbon nanotubes, Flexural response, Microscopic studies

1. Introduction

Nowadays various industries particularly aerospace and aircraft industry require structures with high strength and stiffness combined with low weight.¹ In recent decades, more investigations had been conducted in the field of composite materials which led to the rise of the advanced structures called grid stiffened composite (GSC) structures.² On the other hand, the polymer matrix composite materials because of having high specific strength and stiffness are highly concerned in aerospace industry especially in the construction of GSC structures.³⁻⁵

The main components of the GSC structures are network of the ribs and skin. The ribs are the main load-bearing elements which have a unidirectional structure. Due to the present of separate ribs, cracks cannot easily spread from one rib to adjacent rib, leading to improving the load bearing capacity of the structure. Therefore, they have high damage tolerance.⁶⁻¹⁰ The network of the ribs is supported by skin which has the low and is determined on the basis of structural performance. It should be mentioned that the ribs significantly enhance the load bearing capacity and damage tolerance without much increment in the weight of the structure. The anisogrid lattice concept is characterized by a relatively dense system of intersecting diagonal and transverse ribs forming a regular pattern of hexagonal or triangular cells.¹¹⁻¹⁴ So far, several investigations have been carried out in relation to the mechanical properties of GSC structures under various loading.¹⁵⁻¹⁷ Gan et al.¹⁵ investigated the ability of energy absorption in isogrid composite panels include rib-skin

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system under quasi-static transverse loading. The results showed that during loading, although maximum load from the skin side was more than the rib side but energy absorption was more from the rib side.

Research results of Jadhav and Mantena¹⁶ indicated that the specific energy absorption of isogrid E-glass/polypropylene composites under dynamic impact loading was much greater than the quasi-static transverse loading. Kim¹⁷ studied the response of isogrid carbon fiber/epoxy composites under axial compression. In this investigation, buckling of the ribs was the first failure mode and the skin buckling was secondary failure mode which was occurred after buckling of the ribs.

Development of nanotechnology in the field of composite materials has created promising advances in the production of new materials for structural applications. Carbon nanotubes (CNTs) are formed from carbon sheets with the thickness of one atom and hollow cylindrical shape which have high stiffness, strength, hardness, and remarkable thermal and electrical properties.¹⁸⁻²² Several studies have been conducted in relation to modifying the mechanical properties of fiber reinforced polymer matrix composites through addition of CNTs.²³⁻³⁰ Ulus et al.²³ investigated the effect of MWCNTs addition on the flexural behavior of carbon fiber/ epoxy composites and the experimental results showed that flexural strength and bending stiffness with the addition of 0.3 wt.% of carbon nanotubes increased by 65% and 19.4%, respectively.

Garg et al.²⁴ investigated the effect of MWCNTs addition on the flexural behavior of glass fiber/epoxy composites and the obtained results showed that with the addition of 0.1 wt.% of carbon nanotubes, the flexural strength of glass fiber reinforced composites showed an improvement of 74%, as compared to the control sample. Hossain et al.²⁵ reported that

with the addition of 0.3 wt.% of MWCNTs, flexural strength and modulus increased by 27% and 14%, respectively. Rahman et al.²⁶ Showed that the flexural strength and flexural modulus of glass fiber/epoxy composite enhanced by 38% and 22%, respectively, through addition of 0.3 wt.% MWCNTs that functionalized with amine group. Kim et al.²⁷ found that with the addition of silane functionalized MWCNTs, the flexural strength and flexural modulus of basalt fiber/epoxy composites were increased by 34% and 54%, respectively.

Lee et al.²⁸ investigated the tensile properties of carbon fiber/epoxy composites containing unmodified and silane-modified MWCNTs at 1 wt.%. The results showed that tensile strength of composites containing silane-modification MWCNTs was 15.8% higher than composites containing unmodified MWCNTs. Khosravi and Eslami-Farsani²⁹ found that with the addition of 0.4 wt.% of silane functionalized MWCNTs, the flexural strength of unidirectional basalt fiber/epoxy composites was increased by 38% in comparison with control samples. In another study conducted by these researchers, they reported that the flexural properties of glass fiber/epoxy isogrid stiffened composites was improved up to the addition of 0.4 wt.% of MWCNTs and by adding higher weight percentages, flexural properties due to agglomeration of the MWCNTs was reduced.³⁰

According to the conducted surveys, most research in the field of GSC structures is focused on the optimization of geometrical parameters. But in addition to the the design requirements to improve their performance, microstructural modification also should be considered. Hitherto a little research about the effect of nanoparticles addition on the mechanical properties of these structures has been done. So the purpose of the present study is evaluation of the effect of carboxyl functionalized multi-walled carbon (MWCNT-COOH) on the mechanical properties of AGC panels under flexural loading. For this purpose, AGC

panels with different amounts of MWCNTs (0, 0.1, 0.25 and 0.4 wt.%) were prepared. Finally, electron microscopy studies were conducted on the fracture surface of composites for investigation of the microstructure of specimens containing MWCNTs.

2. Experiments

2.1. Materials

In the current study, ML-506 epoxy resin with hardener HA-11 supplied by Mokarrar Engineering Materials Co., Iran. The resin-hardener ratio was 100:15 by weight, as recommended by the manufacturer. Unidirectional carbon fiber rovings were used as fibrous reinforcement in ribs. Plain weave E-glass fibers with surface density of 400 g/m², supplied by lintex International Co., Ltd, China, were used as fibrous reinforcement in skin part. The multi-walled carbon nanotubes functionalized with carboxyl groups (MWCNT-COOH) with purity of more than 95%, were supplied by Cheap Tube Inc., USA. The miscellaneous traits of the raw materials used in this investigation are displayed in Table 1.

Table 1. Some properties of the materials employed in this study

Material	Feature (unit)	Value
ML-506 epoxy resin	Combined density (gr/cm ³)	1.11
	Viscosity at 25°C (centipoise)	1450
	Flexural modulus (GPa)	3.65
	Flexural strength (MPa)	96.0
	diameter (μm)	7.6
Unidirectional carbon fibers	Bulk density (g/cm ³)	1.76
	Tensile modulus (GPa)	180

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E- glass fabrics	Tensile strength (MPa)	2600
	Surface density (g/m ²)	400
	Tensile strength (MPa)	2100
	Maximum failure strain (%)	2.2- 2.5
Carbon nanotubes	Outer diameter (nm)	10-20
	Length (μm)	10-30
	Specific surface area (m ² /g)	233
	Content of COOH (wt.%)	2

2.2. Mold fabrication

In this study, silicone molds were used for fabrication of the panels. The advantages of silicone molds consist of very high dimensional accuracy, high thermal resistance, high flexibility and appropriate heat transfer. For this reason, they are suitable candidate for making mold of AGC panels. Designed mold in this study have anisogrid geometry which composed of hexagonal cells with helical and longitudinal ribs. The molds were obtained by pouring liquid silicone mixture over a pre-fabricated polyvinyl chloride (PVC) model and were cured for 6 hours in room temperature. PVC model and the silicone mold are shown in Figure 1.

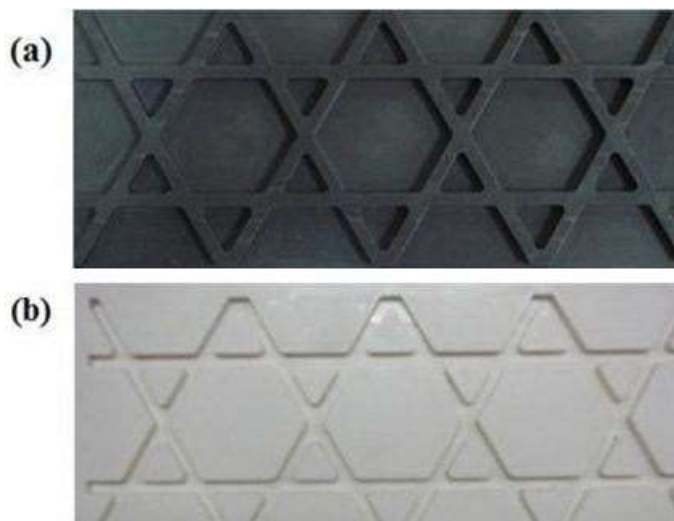


Figure 1. (a) PVC model and (b) silicone mold used for fabrication of specimens.

2.3. Preparation of epoxy/MWCNT mixture

Epoxy resin was diluted for reducing the viscosity of the resin. This work effectively helps for better dispersion of MWCNTs into the epoxy resin. In the next step, the desired amounts of MWCNTs (0, 0.1, 0.25 and 0.4 wt.%) were added into the epoxy resin and the mixture was stirred by a mechanical stirrer for 20 min at 2000 rpm. after that with using a probe sonicator, ultrasonic waves were applied to the mixture for 1 hour. During the sonication, the mixture container was held in ice water to keep the temperature around 45°C. Afterwards, the mixture was degasified under vacuum conditions for 30 min to evaporate the air bubbles in the mixture. After degasification, stoichiometry ratio of curing agent was added and the mixture was stirred manually for 5 min. The resulting mixture was used as matrix material for fabrication of ribs and skin of AGC panels.

2.4. Fabrication of specimens

For fabrication of AGC panels, a hand lay-up method was used. After preparation of the mold, pre-impregnated unidirectional carbon fibers were inserted into grooves of mold layer by layer to form the network of ribs. Immediately after making of ribs, laying up the skin part with using 4 layers of E-glass woven fabrics with orientation of $[0^\circ]$ was accomplished. Afterwards, fabricated specimen between 2-3 hours was placed in room temperature until curing process of resin was performed. According to the manufacturer's recipe in order to ultimate curing and achievement higher mechanical properties, specimens for 7 days were held at room temperature. The fabricated specimens are shown in Figure 2. The fabricated specimens with anisogrid lattice patterned consist of helical and axial ribs had a length of 300 mm, width of 125 mm and the skin thickness of 1.8 mm. All of the ribs had a quadrilateral cross section with the area $6 \times 6 \text{ mm}^2$. For all panels, the volume fraction of fibers in ribs and skin parts were held invariant at contents of 30% and 48%, respectively.

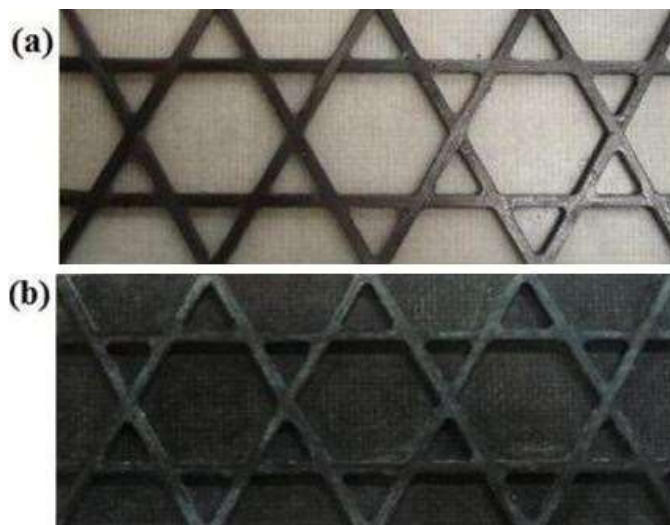


Figure 2. AGC panels, (a) without MWCNTs and (b) reinforced with MWCNTs.

2.5. Three-point bending test

Three-point bending test was performed on the specimens based on ASTM D7264 from the skin side until displacement of 90 mm by using universal testing machine, Hounsfield: H25KS. The loading rate was chosen 5 mm/min. For all of the tests the distance between two supports was considered to 250 mm. Under this circumstance, the support span length to thickness ratio was equal to 32:1. The flexural load-displacement graphs obtained from three-point bending test were used for analysis of flexural properties of AGC panels. To ensure the accuracy of the obtained results, each experiment was repeated at least 3 times.

2.6. Microstructural characterization

The fracture surface of the specimens was analyzed with using a field emission scanning electron microscopy (FESEM, Mira 3-XMU, 25 KV). Before examination, the fracture surfaces were sputter-coated with a thin gold layer in vacuum chamber for conductivity.

3. Results and discussion

3.1. Three-point bending test

Figure 3 illustrates the load-displacement curves of the specimens with various MWCNTs contents obtained from the three-point bending test. Primary failure of the specimens at maximum load point was occurred. After primary failure and significant drop in load, the specimen continued the load bearing and energy absorption. When the load was applied to the panels from the skin side at first, longitudinal ribs were yielded and broken which is characterized as maximum load in the load-displacement curve. It should be noted that under flexural loading a significant part of the energy absorption is obtainable after the maximum load point.

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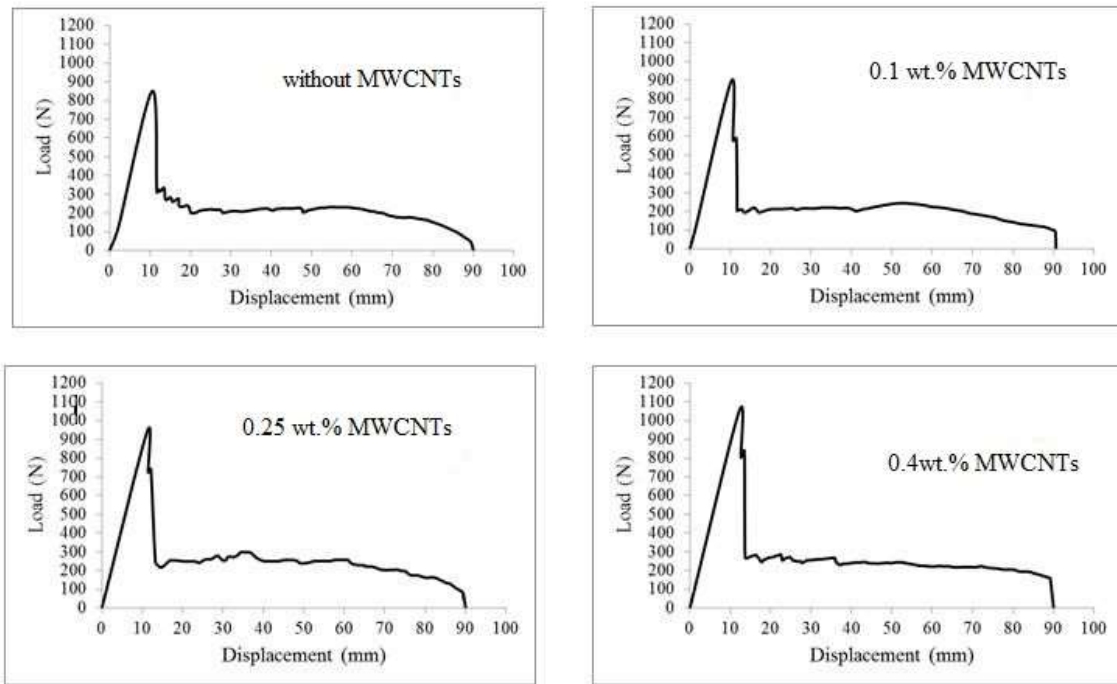


Figure 3. Load-displacement curves of AGC panels consist of diverse MWCNTs content obtained from three-point bending test.

It is evidence from Figure 4 with the increase in weight percentage of MWCNTs, the maximum load bearing of the specimens increased continuously. The greatest increase in the value of maximum flexural load was observed for the specimens with 0.4 wt.% of MWCNTs. In this condition, 24% increase in maximum flexural load was observed compared to the specimens without MWCNTs.

The reason of increment in the maximum flexural load with the addition of MWCNTs was mainly due to the improvement of interface adhesion between fiber and matrix in the presence of MWCNTs as a result the applied load can be effectively transferred from the matrix to the fiber reinforcement.³¹⁻³⁷ when the matrix is modified with MWCNTs, the

slippage of different layers (especially between fibers and matrix) against applied load is restricted, resulting in better stress transferring to the fibers.

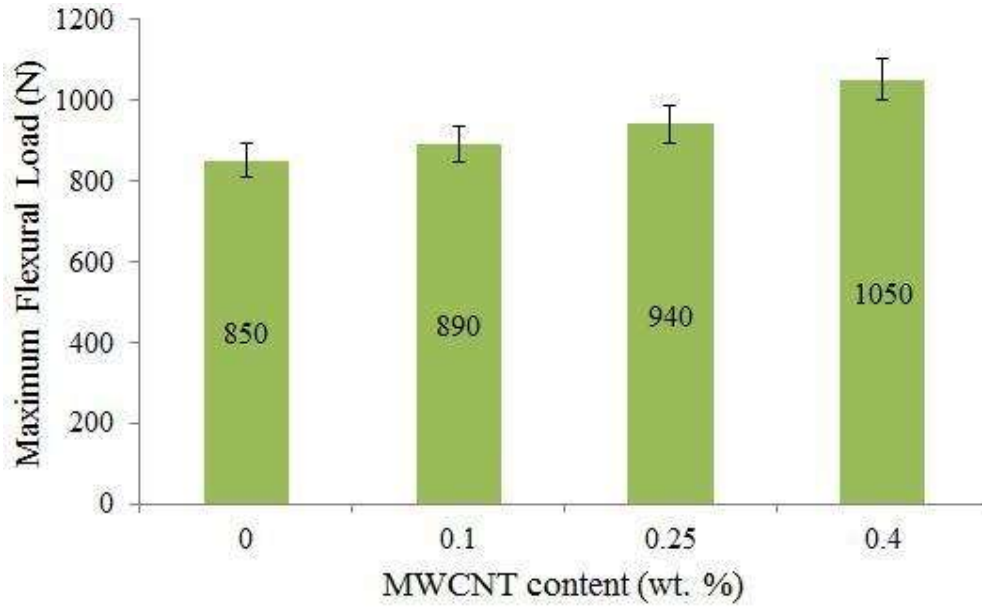


Figure 4. Effect of adding various amounts of MWCNTs on maximum flexural load of AGC specimens.

In addition, as shown in Figure 5, the main failure mechanisms of AGC panels under flexural loading were fiber breakage in longitudinal ribs and fiber microbuckling in skin. In fiber reinforced composites, major part of the applied load is concentrated on the fibers and the fibers are the main load bearing component. Reinforcement of matrix through addition of MWCNTs reduces the stress concentration on the surface of fibers and fiber-matrix interface. As a result the required stress level for fiber breakage in ribs and fiber micro-buckling in skin part is increased. This is because of a part of the applied load through the interface of matrix/MWCNTs is transferred to the MWCNTs and sustained by them.

Flexural stiffness was defined as the slope of load-displacement curve in the linear region. Figure 6 shows the variations of the flexural stiffness versus MWCNTs contents.

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Similar to the maximum flexural load, the flexural stiffness was also increased continuously with increasing the content of MWCNTs from 0-0.4 wt.%. The value of flexural stiffness for specimens without MWCNTs was 58.71 N/mm and for specimens containing 0.4 wt.% of MWCNTs was 79.5 N/mm. With the addition of 0.4 wt.% MWCNTs the flexural stiffness increased by 35%, compared to the specimens without MWCNTs. The increment of flexural stiffness was attributed to the reinforcing effect of the MWCNT. This can be explained as when the MWCNTs were present in the matrix, the strong interaction between the matrix and MWCNTs led to restrict the mobility of polymeric chains. As well as due to higher stiffness of MWCNTs compared with epoxy matrix, enhancement of the flexural stiffness was expected. Also increment on the flexural stiffness in the specimens containing MWCNTs can be attributed to improved interfacial characteristics modified by MWCNTs.³⁸⁻⁴¹



Figure 5. Various modes of failure in AGC panels under bending loading.

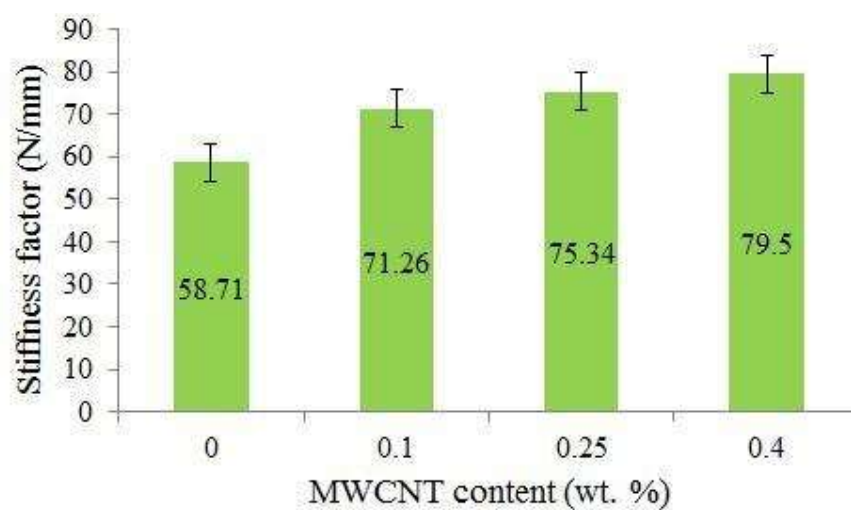


Figure 6. Flexural stiffness of AGC panels reinforced with different MWCNTs content.

According to Figure 7, by increasing the weight percentage of MWCNTs, the energy absorption of the AGC panels significantly increased. The energy absorption of the specimens without MWCNTs was 20.34 J, while by adding 0.4 wt.% of MWCNTs into the epoxy matrix, this value reached 25.39 J, which indicates an increase of 25%. Improvement of energy absorption can be related to two factors: First, improvement of the interfacial bonding of matrix and fiber through incorporation of MWCNTs. the polymer matrix transferred the applied load to the MWCNTs that align into the load direction and reduce the probability of crack creation. The second is toughening mechanism associated to the crack bridging of MWCNTs.⁴²⁻⁴⁶

The most important failure mechanisms in fiber reinforced polymer composites are matrix cracking and fiber-matrix debonding⁴⁷. Because of the remarkable stiffness of MWCNTs compared to the epoxy matrix, high stress gradient in the vicinage of the fillers is created which leads to the formation of stress concentration in these zones and creation of micro-cracks in to the polymer matrix. Also specifications of interface between matrix and fibers have a very important role in energy absorption of AGC panels. If the adhesion of matrix and fibers is not appropriate, cracks that formed during loading easily spread along the interface as a result leads to reduction in energy absorption. MWCNTs with high aspect ratio improve the adhesion between fiber and matrix and prevent the opening of the cracks during its propagation.⁴⁸⁻⁵¹ As a result more energy is required to spread out of the cracks and improve the energy absorption of the specimens containing MWCNTs.

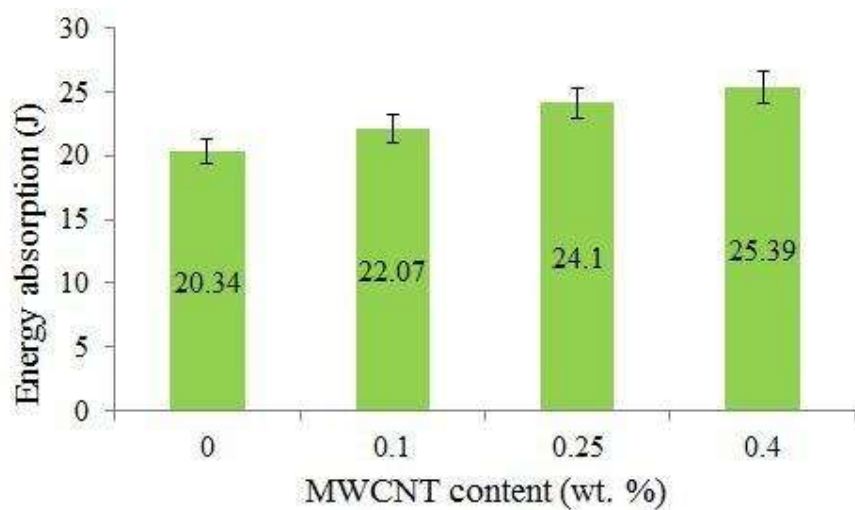


Figure 7. Alterations of Energy absorption at different weight fractions of MWCNTs.

3.2. Electron microscopy studies

Figure 8 shows the FESEM image of fracture surface of longitudinal ribs of AGC panels. For specimens without MWCNTs (Figure 8a), the failure surface of fibers were rather smooth which represent a weak interface between matrix and fibers. In contrary for specimens with MWCNTs (Figure 8b), a part of the matrix is adhered to the fibers which represents the improvement of the interface between the matrix and fibers. In general, when the interface between fiber and matrix is weak, interface debonding is considered as the main failure mechanism. On the other hand if the interface properties are proper, matrix cracking is recognized as the main failure mechanism.

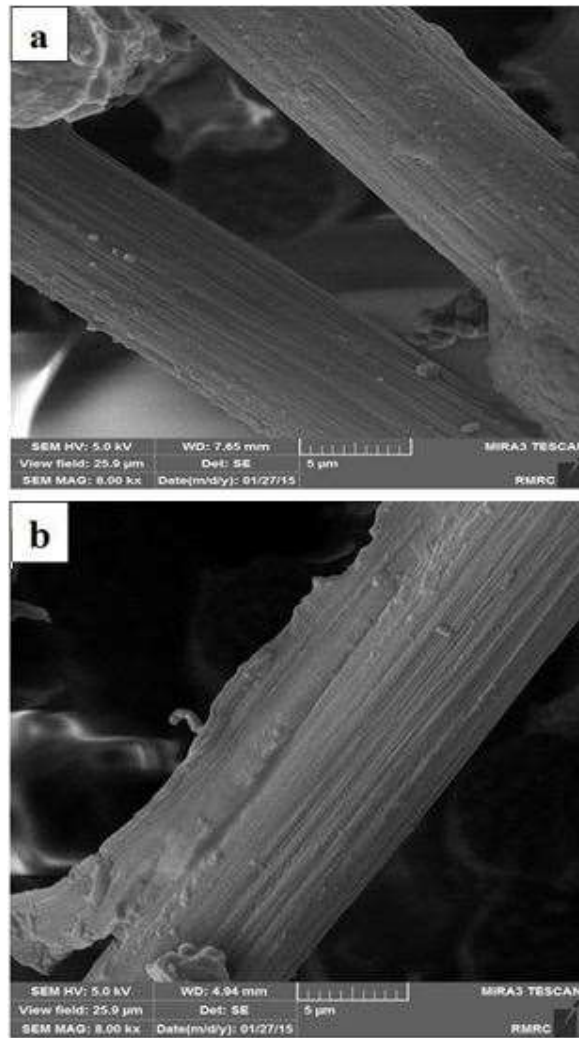


Figure 8. Fracture surface of longitudinal ribs (a) without MWCNTs and (b) reinforced with 0.4 wt. % of MWCNTs.

Figure 9 shows the typical image taken from fracture surface of the matrix of composite panels. The smooth fracture surface ((Figure 9a) indicates a brittle fracture of matrix. With the addition of MWCNTs in to the matrix (Figure 9b), the surface roughness is increased which indicate that the crack initiation and propagation was opposed by MWCNTs.

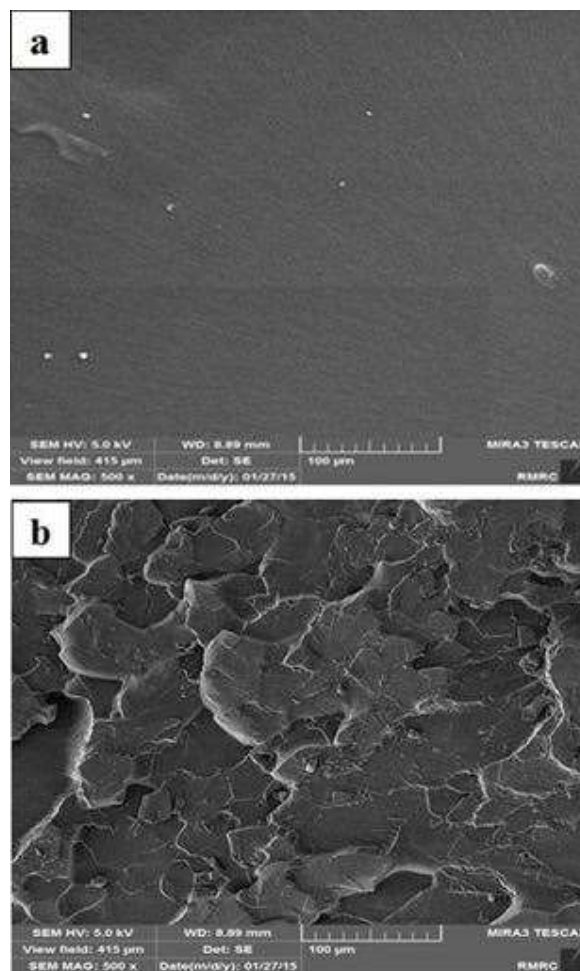


Figure 9. Fracture surface of matrix (a) without MWCNTs and (b) containing 0.4 wt. % of MWCNTs.

Figure 10 indicates the fracture surface of containing MWCNTs at higher magnification. A favorable dispersion of MWCNTs into the epoxy matrix and bridging mechanism are characterized. The MWCNTs which are observed on the fracture surface represents the bridging mechanism.

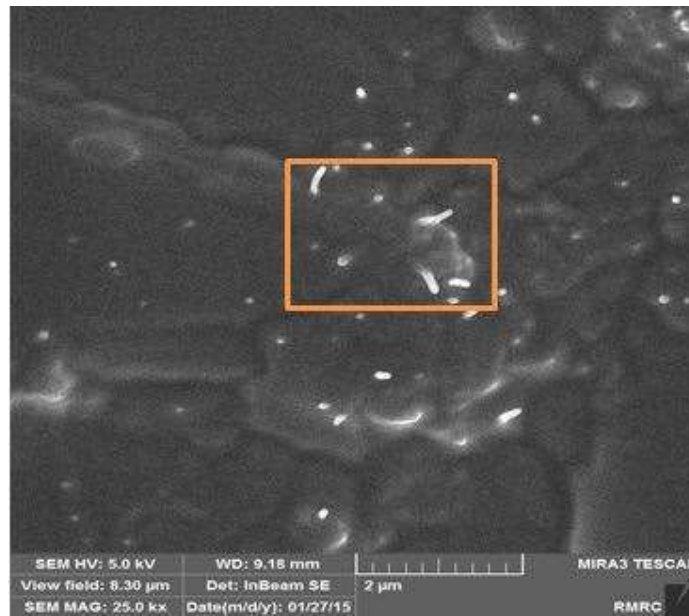


Figure 10. Crack bridging mechanism by MWCNTs.

4. Conclusions

In the current study, the influence of MWCNTs addition on the mechanical performance of anisogrid composite panels under flexural loading was experimentally studied. For this purpose, different values of MWCNTs (0, 0.1, 0.25 and 0.4 wt.%) were utilized as a secondary reinforcement for fabrication of specimens and the obtained results are as follows:

1. Grid-stiffened composite panels because of having distinct ribs in their structure have excellent energy absorption capability and a substantial part of energy absorption is acquirable after primary failure at maximum load point.
2. Flexural properties of anisogrid composite panels with the introduction of MWCNTs noticeably ameliorated and the greatest improvement in flexural properties of anisogrid composite specimens was obtained through addition of 0.4 wt.% of MWCNTs. In this

case, the maximum flexural load, flexural stiffness and energy absorption were increased by 24%, 35% and 25%, respectively, compared with specimens without MWCNTs.

3. Electron microscopy studies manifested that improvement of adhesion between matrix and fiber via introduction of MWCNTs inside the matrix had a considerable role in improving the mechanical properties of anisogrid composite specimens.
4. Altogether, the results of the current investigation confirmed that dispersion of MWCNTs into the epoxy matrix of anisogrid composite panels can effectually meliorate the flexural response of anisogrid composite panels.

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