Materials Research Express

PAPER

Investigation of the effect of multi wall carbon nano tubes on the dynamic characteristics of woven kevlar/carbon fibers-polyester composites

Mohammed Jawad Aubad, Basim Ajeel Abass and Saif Nidhal Shareef

Department of Mechanical Engineering, University of Babylon, Hilla, Babil, Iraq

1 Author to whom any correspondence should be addressed.

E-mail: alrobaimoh@yahoo.com, eng.basim.ajeel@uobabylon.edu.iq and saif_nidhal@yahoo.com

Abstract

This research offers an experimental and numerical study on the influence of multi-wall carbon nanotubes (MWCNTs) addition with different weight fractions on the dynamic characteristics of the unsaturated polyester (UP) reinforced by hybrid laminate composites. The laminate composites were prepared for only three layers as a total number of layers in such composites using Kevlar fibers and/or carbon fibers with different volume fractions. Both types of fibers were in the form of plain woven at (0°/90°) angle direction. Hand lay-up method was used to prepare the test samples. It was found that the best mechanical and dynamic properties based on the experimental study have been obtained for unsaturated polyester reinforced with (MWCNTs) particles at weight fraction (0.4% wt). Composite material made of unsaturated polyester reinforced with (MWCNTs) particles was also prepared with the same weight fraction of MWCNTs. Finite element method was used to model the free vibration of a cantilever beam made of composite material. ANSYS software composite Prep-Post (ACP) integrated within ANSYS Workbench software (18.2) was used to solve the FE problem. Field emission scanning electron microscopy (FESEM) and scanning electron microscopy (SEM) are applied to check the morphological properties of the composite material and the dispersion of MWCNT nanoparticles in the polymer matrix. Experimental and numerical Results obtained in the present work showed that the natural frequency and damping ratio of nano composite specimens increase with increasing weight fraction of MWCNTs. The results also showed that composite and hybrid composite materials with (0.4% wt) MWCNTs have higher values of natural frequency and damping ratio. It was found that the natural frequency for the hybrid nano composite with stacking sequence (UP + K/K + MWCNT) increased by about 10.4% when adding MWCNTs compared with (UP + K/K/K) laminated composite while it becomes 13.82% and 5.8% for (UP + K/C/K + MWCNT) and (UP + C/K/C + MWCNT) hybrid nano composite material in comparison with that without MWCNTs. The increase percentages of the damping ratio of the such materials have been calculated and it was found to be, 12.23%, 15.9% and 8.6%, respectively. An agreement between the experimental and numerical results has been obtained from flexural and vibration tests with maximum errors not exceeded 3.4% and 9.34%, respectively.

1. Introduction

Many modern technologies and industries need materials that have a combination of properties such as high strength to weight ratio which cannot be found in traditional materials. Composite materials are the most familiar materials that are used for this purpose [1]. They are usually coordinated so that one or more discontinuous phases called reinforcement included in a continuous phase called matrix. Polymeric nano composites represent class of materials alternative to conventional filled polymers. In this type of material, fillers with nano scale are dispersed in
The materials employed in this work were unsaturated polyester (UP), woven Kevlar, woven carbon and MWCNT. The unsaturated polyester resin (UP) was provided by (Camelyaf Resins Company/Turkey) in the form of transparent viscous material at room temperature. The resin will be hardened by adding Methyl Ethyl Ketone Peroxide (MEKP) hardener and the cobalt naphthan as an accelerator. One gram of initiator for each 100 g of the resin was used for solidification while 0.2%–0.4% of the accelerator was added to speed up the curing process.

Woven Kevlar-49 and carbon fibers both having angle direction (0°/90°) was supplied by (Haining Anjie Composite Material Company, LTD/China) while Multi-walled carbon nanotubes (MWCNTs) have inside diameter 5–10 nm, outside diameter 20–30 nm, length of 10–30 um and carbon purity >95%wt was supplied by US research Nano material and manufactured by the chemical vapor deposition (CVD) method. The mechanical properties of all used materials were presented in table 1.

### Table 1. Mechanical properties of used material in experiments [20–22].

| Material          | Density (g cm⁻³) | Tensile strength (MPa) | Elastic Modulus (GPa) | Poisson ratio |
|-------------------|------------------|------------------------|-----------------------|---------------|
| Kevlar-49 fiber   | 1.44             | 3260                   | 131                   | 0.35          |
| Carbon fiber      | 1.76             | 3415                   | 240                   | 0.2           |
| MWCNT             | 2.1              | 1500                   | 1200                  | —             |
| Polyester resin   | 1.21             | 50–100                 | 0.85–2.5              | 0.37–0.4      |

polymeric matrix to offer an improvement in its performance properties [2]. Study of dynamic properties of the composite materials is very important for the designer engineers. In polymeric composite materials the energy was dissipated under vibration due to its viscoelastic nature [3]. The damping ratio is the most important factor which affect the dynamic behavior of such materials[4]. Several studies were conducted to find the effect of carbon nanotubes on damping and stiffness of the structures and machines. Enhanced dynamic properties can be obtained by incorporating the MWCNTs within the epoxy resin composite materials[5–10]. The effect of incorporating carbon fibers within epoxy resin composite materials on the damping ratio of such materials have been studied extensively by [7, 11–14]. It has been noticed that using such fibers to reinforce the epoxy resin enhance the damping ratio of such materials. Extensive investigation to the effect of incorporating kavler fibers within the epoxy resin and hybrid composite materials on the dynamic properties of such materials have been studied by [15, 16]. The dynamic behavior of E-glass Polyester composite of three laminate types with different fiber orientations has been studied by Al-Shukri et al [17]. The influence of fiber orientations and the stacking sequences of the laminated layers on the resonance and natural frequencies were investigated under consistent conditions. The results showed that the [±45] laminate apparel more stability under loading than [0°/90°] laminate due to the arrangement of the layers. Mathematical and numerical models in view of Finite Element integration of damping characteristics of Nano–composites, hybrid laminates, sandwich materials and advanced hybrid composites have been discussed by Treviso et al [18]. Bulut [19] investigated experimentally and numerically the effect of adding SiC particles on vibration and damping properties of Frequency responses were evaluated within the frequency range from 0 to 500 Hz. Serious improvement of natural frequency and acceleration decaying curves as a result of ideal interfacial bonding has been obtained.

The present work aimed to an experimental and numerical study of the mechanical and dynamic behavior of laminated composite materials consist of unsaturated polyester resin matrix reinforced by three layers of woven Kevlar and/or Carbon fibers and multiwall carbon nanotubes (MWCNTs) which have been rarely studied, that is the main goal of the present work. However, These composite and hybrid nano composite materials produced in the present work are characterized by lighter weight, high specific modulus, high special strength, high chemical resistance, high damping properties which make it widely used in modern applications, spatially in the basic parts of aeronautical applications, armor industry, safety helmets, car body, renewable energy and transportation pipes.

### 2. Experimental procedure

The materials employed in this work were unsaturated polyester (UP), woven Kevlar, woven carbon and MWCNT. The unsaturated polyester resin (UP) was provided by (Camelyaf Resins Company/Turkey) in the form of transparent viscous material at room temperature. The resin will be hardened by adding Methyl Ethyl Ketone Peroxide (MEKP) hardener and the cobalt naphthan as an accelerator. One gram of initiator for each 100 g of the resin was used for solidification while 0.2%–0.4% of the accelerator was added to speed up the curing process.

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#### 2.1. Manufacturing of hybrid nanocomposite

##### 2.1.1. Resin preparation

The nanocomposite material was produced by adding MWCNTs to UP. The agglomerated MWCNTs were treated by adding centered acetone of 50:1 mass ratio and then sonicated using ultrasonic vibrator (Ultrasonic Cell Crusher Sjia-1200W MTI Corporation) under 30% of power for 30 min in impulse patterns of 2 s on and 1 s off. The sonicated MWCNTs are then added to the required volume of polyester resin and the mixture is fully
mixed using a magnetic hot plate stirrer (Labtech Co. LTD) at a high speed for 4 h at a room temperature to ensure acetone evaporation. Mixing process was done at ambient conditions. Cobalt accelerator was used as a curing and cross linker catalyst for unsaturated polyester resin and the resulted mixture was mechanically stirred for 5 min by mechanical stirrer followed by degassing process for 15 min to remove air bubbles and residual acetone by using vacuum furnace. The hardener was then sequentially added to the mixture at a ratio of 1:100 and the produced mixture was mechanically stirred for 3 min. The mixture containing carbon nanotube is now ready for using in the prepared mold.

2.1.2. Composite and hybrid nanocomposite material preparation
Hand Lay-up process was applied to prepare samples of composite and hybrid nanocomposite material. Such materials were made using a glass mold having dimensions of \((260 \times 140 \times 3.4)\) mm\(^3\). The inward of the mold was covered with thermal sheet which helps in extracting the specimens easily. A MWCNTs was added to UP by \((0.4\%)\) and only woven Kevlar fibers were wetted with the resin that containing MWCNTs nanoparticles. The woven (Kevlar and/or carbon fibers) with angles \([0°/90°]\) were cut based on the shape of the mold and they have been added to the mold and the resin poured on to fibers respectively. This process repeated with each sequence of hybrid nanocomposites. After that the mold left for 48 h to get solid shape. Then the mold was heated to 50 °C for 1 h to complete the curing process. Testing samples have been cutout from the produced composites using CNC machine (Suda ST1212 CNC router) according to (ASTM) standards.

2.2. Evaluation of mechanical and dynamic properties
2.2.1. Flexural test
Three-point flexural test was performed at ambient temperature according to ASTM D790 standard using flexural testing head with testing machine (LARYEE-50 KN) as shown in figure 1. Samples with the dimensions \(127 \text{ mm} \times 13 \text{ mm} \times 3.4 \text{ mm}\) and span extent of 50 mm were used for this test. The load was applied at a constant head feed of 1.25 mm min\(^{-1}\) until the samples fracture. The samples before and after fracture with this test can be shown in figure 2. Five samples of each model were tested to determine the mean values of flexural strength.

The flexural strength in this test can be determined using the following equation [23]:

\[
F_s = \frac{3PL}{2Wh^2}
\]

Where:
- \(F_s\): Flexural strength (Pa).
- \(P\): The applied load (N).
- \(l\): The distance between the two supported points (mm).
- \(w\): Width of the sample (mm).
- \(h\): Thickness of the sample (mm)

2.2.2. Free vibration test
Free vibration test for fixed-free cantilever beam was carried out in order to evaluate the dynamic characteristics of the composite materials(natural frequency, damping ratio and decay behavior). The vibration test output includes acceleration-time response curve, amplitude-frequency time response curve, natural frequencies,
mode shapes and damping ratios. The experimental setup for free vibration test of composite material can be shown in figure 3. The instruments used in the test include Impact hammer model type (086C03-PCB Piezotronics vibration division) [24], accelerometer sensor model type (352C03-PCB piezotronics accelerometer) [25], NI Compact DAQ (USB Data Acquisition Systems) [26], NI 9234 Module [27] and a personal computer (HP/Core-i5). The test was carried out according to ASTM-E756 standard with a rectangular cross section specimen having dimensions of \(20 \times 3.4 \text{ mm}^2\) and a length of 200 mm as shown in figure 4. The test was repeated five times for each model and the average measurement values were adopted.

2.3. Measurement of damping ratio
Half power band width method was used to estimate the resonant frequency and the damping ratio as shown in figure 5. The bandwidth of the system was defined as the difference of the frequencies between the half power points \(R_1\) and \(R_2\) which denoted by \(\Delta \omega\) [28]. The damping ratio (\(\zeta\)) is defined as:

\[
\zeta = \frac{w_2 - w_1}{2w_n}
\]

Where, \(w_1 = w\) at \(R_1\), \(w_2 = w\) at \(R_2\) and \(w_n\) is the natural frequency.

Since the cantilever beam can be considered as continuous system, it has an infinite degree of freedom.
3. Numerical models

3.1. Flexural test modeling
A finite element model was created to simulate flexural test in ANSYS. To perform the numerical simulation, the material is considered as isotropic material and taking into consideration the shape and geometry conditions of the sample according to the experimental procedure. Simulations were performed using ACP integrated within the environment of ANSYS (18.2) Workbench for static structural analysis.

The main material properties, density, Young's modulus and Poisson's ratio, have been defined. While the geometry has been generated as a surface body element with 2 mm thickness as shown in figure 6. The element...
type of the surface bodies used in this work was the quadrilateral dominant (8 nodes) type. The number of elements and nodes using are 1972 and 3564 respectively. Applied boundary conditions (using fixed supports at both ends of the model and vertical force were used as a load distributed on the nodes in the model transverse center).

3.2. Modal analysis
Finite element model was used to analyse the vibration of free fixed beam made of composite material in order to evaluate the natural frequency, mode shapes and corresponding vibration damping. ANSYS composite Prep-Post (ACP) integrated within ANSYS Workbench software, version 18.2, is used for the finite element analysis of the model adopted in the present work. It offers design of complex composites with different materials, fabric thicknesses, and defines the element and fabrics orientations and ply layup efficiently. Modal Analysis was executed according to the steps shown in flow chart of figure 7. Eight nodes quadrilateral elements with thickness 2 mm were adopted to discretize the specimen shown in figure 8. The number of elements and nodes
used in such analysis are 2700 and 4004 respectively. Applied boundary conditions (including the support, which is fixed at one end for the cantilever beam).

4. Morphological properties

The morphological properties of nanocomposite samples with different weight percentages of MWCNTs (0.2, 0.4, 0.6%wt) were tested using field emission scanning electron microscopy (FESEM) model (FEI Nova Nano SEM 450) as can be shown in figure 9. Scanning electron microscopy (SEM) was used to test the morphological properties of MWCNTs/woven Kevlar fibers/polyester nanocomposites as shown in figures 10(a) and (b). Figures 9(c) and (d) shows the good dispersion of MWCNTs nanoparticles into the polyester resin. Figure 10(a) shows the break surfaces of Kevlar/polyester nanocomposites reinforced with (0.4% wt) of MWCNTs. Figure 10(b) shows that the matrix is lost on the break surface of nanocomposites and only bridging of several
nanoparticles between the fibers and matrix is appearing. This can be attributed to the agglomeration of MWCNTs.

5. Results and discussion

5.1. Experimental results

5.1.1. Flexural test results

Figure 11 illustrates that the flexural strength of nano composite specimens increases with increasing weight fraction of MWCNTs. The flexural strength of such nano composite increases from (90.42 MPa) for pure UP to (107.62 MPa) for UP reinforced by 0.6% wt MWCNTs with percentage increase of 19%.

Figure 12 shows a bar chart for the results of the flexural strength of different composite and nano composite materials. The MWCNTs was added by (0.4% wt). It is clearly shown from this figure that the addition of MWCNTs for the composite material causes an increase in flexural strength of such materials. The stacking sequence of the fiber layers on flexural strength has been studied. It was found that the flexural strength of (UP + K/K/K + MWCNT) laminated nano composite was increased by about 21% when adding MWCNTs in comparison with that obtained for (UP + K/K/K) laminated composite while percentage increase of 18% and 17% have been obtained for the flexural strength of (UP + K/C/K + MWCNT) and (UP + C/K/C + MWCNT) hybrid nano composite respectively. This can be attributed to the rich interfacial interaction between modified polyester by (0.4% wt) of MWCNTs and used fibers which limited fibers breakage and fibers pullouts and hence increasing flexural strength of this nano composite and hybrid nano composite materials.
Also this result corroborates an important characteristic of the carbon nanotubes, their high resistance to bending, resulting in a significant improvement in the use of composite material without MWCNTs.

5.1.2. Vibration test results

Figures 13 to 14 show the amplitude versus frequency for some sequences of composite and hybrid nanocomposite materials used in this research. From these figures, the half-power bandwidth method has been used to calculate damping ratios of such materials. It can be seen from time responses shown in figures 15 to 16 that the shape of the peak flattens as the weight percentage of MWCNTs increases, resulting in smaller peak amplitudes indicating of increasing damping ratios. This can be attributed to the ability of energy dissipation of
MWCNTs due to stick and slip of the tubes with matrix upon the applied load and deagglomeration of tubes bundles which reduce the amplitude of isolated vibration. Figure 17 illustrates that the natural frequency of nanocomposite specimens increases with increasing weight fraction of the added MWCNTs. The maximum value of the natural frequency obtained for nanocomposite is (19 Hz) for UP reinforced by (0.4% wt) of MWCNTs, while it decreases to (18.75 Hz) for that reinforced with (0.6% wt) of MWCNTs. Such a behavior related to the good adhesion between the MWCNTs nanoparticles and the polyester matrix which is one of the most important factors that affects the stiffness and damping of such materials. Figure 18 illustrates that the damping ratio of nanocomposite specimens increases with increasing weight fraction of MWCNTs. The values of the damping ratio obtained for nanocomposite at various weight fraction of (0.2, 0.4 and 0.6% wt) of MWCNTs addition are (0.0632, 0.0697 and 0.0707) respectively. The percentage increase in the natural frequency and damping ratio for the composite and hybrid composite materials with (0.4% wt) MWCNTs has been calculated and presented in figures 19 and 20 and table 2. The improvement in natural frequency and
The damping ratio can be attributed to the fact that MWCNTs-based composites have the largest interfacial contact area with the resin and used fibers. The good adhesion between MWCNTs is important to increase the stiffness. The increase in contact area dramatically increases the potential for energy dissipation due to interfacial friction. This explains the reason for increased percentage of the natural frequency and damping ratio of the studied composite and hybrid nanocomposite materials. Higher damping ratio is preferred in structural applications to reduce vibration.

5.2. Numerical results
The numerical results obtained from this analysis have been verified by experimental results obtained as can be shown in tables 3 and 4.
From table 3 show the numerical and experimental results of the flexural strength of the composite materials, it was found that there is a good agreement between the experimental and numerical results obtained and there is no more than 3.4% error. This discrepancy in estimation magnitudes of mechanical properties attributed to true loading condition, method of composite fabrication, the environmental influence and experimental flexural test. Figure 21 show the flexural strength for some laminated composite and nano composite material.

Table 2. The natural frequency and damping ratio for different materials.

| Material            | Increased percentage in natural frequency | Increased percentage in damping ratio |
|---------------------|------------------------------------------|--------------------------------------|
| K/K/K + 0.4%MWCNTs  | 10.4%                                    | 12.23%                               |
| K/C/K + 0.4%MWCNTs  | 13.82%                                   | 15.9%                                |
| C/K/C + 0.4%MWCNTs  | 5.8%                                     | 8.6%                                 |

From table 3 show the numerical and experimental results of the flexural strength of the composite materials, it was found that there is a good agreement between the experimental and numerical results obtained and there is no more than 3.4% error. This discrepancy in estimation magnitudes of mechanical properties attributed to true loading condition, method of composite fabrication, the environmental influence and experimental flexural test. Figure 21 show the flexural strength for some laminated composite and nano composite material.

From table 4 show the numerical results of the natural frequency for first mode shape obtained experimentally have been compared with that obtained numerically. It can be shown from this table that the maximum error between the results is 9.34%. This discrepancy in estimation magnitudes of the natural frequency attributed to experimental modal analysis, the process of fixing the samples and stabilizing the sensor on this samples using a specific adhesive to conduct the test has a significant effect on the accuracy of the experimental results of this test. In addition to these reasons, there is a major cause for this error is the high frequency noise of the laboratory. Figure 22 shows the modal analysis response (ANSYS 18.2 Workbench...
Table 3. Percentage discrepancies of flexural strength between experimental and numerical results.

| Material types | Flexural strength (MPa) |
|----------------|------------------------|
|                | Experimental results   | Numerical results | Errors % |
| UP             | 90.42                  | 91.627            | 1.3      |
| UP + 0.2% MWCNT| 95.4                   | 96.795            | 1.5      |
| UP + 0.4% MWCNT| 100.4                 | 103.77            | 3.36     |
| UP + 0.6% MWCNT| 107.62                | 110.63            | 2.8      |
| UP + K/K/K     | 171.6                  | 174.93            | 2        |
| UP + C/C/C     | 159.2                  | 162.02            | 1.8      |
| UP + K/C/K     | 165.24                 | 170.29            | 3.1      |
| UP + C/K/C     | 162.3                  | 164.74            | 2.44     |
| UP + K/K/K/MWCNT| 208                   | 215.33            | 3.4      |
| UP + K/C/K/MWCNT| 194.86               | 196.87            | 1        |
| UP + C/K/K/MWCNT| 189.5                | 194.6             | 2.7      |

Table 4. Percentage discrepancies of vibration test between experimental and numerical results.

| Material types | Modes       | Natural frequency (Hz) | Damping ratio (ζ) |
|----------------|-------------|------------------------|-------------------|
|                |             | Experimental results   | Numerical results | Errors % |
| UP             | Mode 1      | 16.5                   | 16.306            | 1.2      |
|                | Mode 2      | —                      | 102.01            | 0.06061  |
|                | Mode 3      | —                      | 285.28            |          |
| UP + 0.2% MWCNT| Mode 1     | 17.8                   | 16.861            | 5.3      |
|                | Mode 2      | —                      | 105.48            | 0.0632   |
|                | Mode 3      | —                      | 294.98            |          |
| UP + 0.4% MWCNT| Mode 1     | 19.0                   | 17.225            | 9.34     |
|                | Mode 2      | —                      | 107.76            | 0.0697   |
|                | Mode 3      | —                      | 301.34            |          |
| UP + 0.6% MWCNT| Mode 1     | 18.75                  | 17.726            | 5.46     |
|                | Mode 2      | —                      | 110.89            | 0.0707   |
|                | Mode 3      | —                      | 310.11            |          |
| UP + K/K/K     | Mode 1      | 24.0                   | 23.606            | 1.64     |
|                | Mode 2      | —                      | 147.68            | 0.04375  |
|                | Mode 3      | —                      | 412.98            |          |
| UP + C/C/C     | Mode 1      | 25.9                   | 23.927            | 7.62     |
|                | Mode 2      | —                      | 149.69            | 0.0454   |
|                | Mode 3      | —                      | 418.6             |          |
| UP + K/C/K     | Mode 1      | 28.0                   | 25.021            | 8.68     |
|                | Mode 2      | —                      | 156.54            | 0.0493   |
|                | Mode 3      | —                      | 437.75            |          |
results), and the first three modes shape for the vibration of the cantilever beam with the stacking sequence of (UP + K/K/K) laminated composite as example.

6. Conclusions

The aim of this research was to an experimental and numerical study of the mechanical and dynamic behavior of laminated composite materials consist of unsaturated polyester resin as matrix reinforced by three layers of woven Kevlar and/or Carbon fibers and multiwall carbon nanotubes (MWCNTs) which have been rarely studied, that is the main goal of the present work. Summarized conclusions of the current study are as follow:

1. The fabricated nanocomposite mechanical and dynamic properties are directly influenced with weight fractions of MWCNTs. Increasing the weight fraction of MWCNTs improve the mechanical and dynamic properties of such material. The best influence on the nanocomposite dynamic properties is with (0.4% wt) of MWCNTs.

2. FESEM and SEM analysis emphasize that uniform dispersion of MWCNTs into both polyester matrix and nano composite material.

3. After adding MWCNTs nanoparticles in (0.4% wt) to composite and hybrid composite that consist of Kevlar and Carbon fibers, the values of the mechanical and dynamic properties of such material were increased significantly. The natural frequency for the hybrid nano composite with stacking sequence (UP + K/K/K + MWCNT) was increased by about 10.4% when adding MWCNTs compared with (UP + K/K/K) laminated composite while it becomes 13.82% and 5.8% for (UP + K/C/K + MWCNT) and (UP + C/K/C + MWCNT) hybrid nano composite material in comparison with that without MWCNTs. The increase percentages in damping ratio of the for mentioned materials have been calculated and found as follows, 12.23%, 15.9% and 8.6%, respectively. The hybrid nano composite for the sequences of layers (UP + K/K/K + MWCNT) and (UP + K/C/K + MWCNT) have the best results of most static and dynamic properties.

4. An agreement between the experimental and numerical results has been obtained from flexural and vibration tests with maximum errors not exceeded 3.4% and 9.34%, respectively.

Acknowledgments

The authors wish to acknowledge the financial and software support were provided by the Department of Mechanical Engineering, University of Babylon.

ORCID iDs

Saif Nidhal Shareef @ https://orcid.org/0000-0002-1257-1156

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